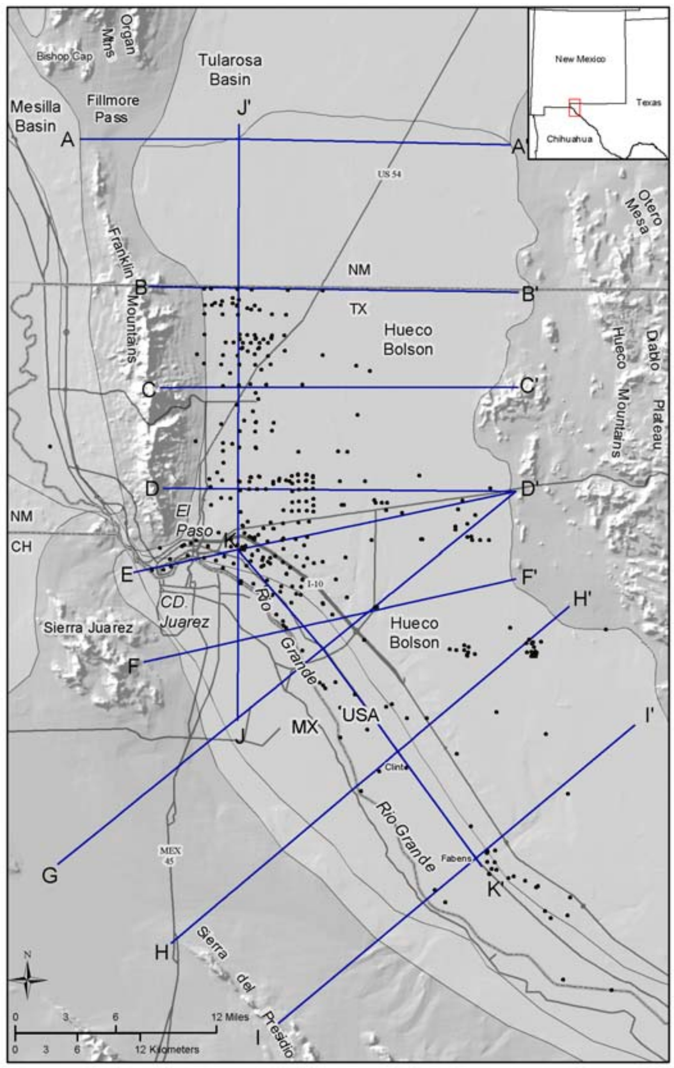
December 2009

HYDROGEOLOGIC FRAMEWORK OF THE BINATIONAL WESTERN HUECO BOLSON-PASO DEL NORTE AREA, TEXAS, NEW MEXICO, AND CHIHUAHUA:

OVERVIEW AND PROGRESS REPORT ON DIGITAL-MODEL DEVELOPMENT

WRRI Technical Completion Report No. 349

John W. Hawley
John F. Kennedy
Alfredo Granados-Olivas
Marquita A. Ortiz



Cross-section index map, showing location of schematic hydrogeologic sections (see Figure 3, page 4).

NEW MEXICO WATER RESOURCES RESEARCH INSTITUTE
New Mexico State University
MSC 3167, Box 30001
Las Cruces, New Mexico 88003-0001
Telephone (575) 646-4337 FAX (575) 646-6418
email: nmwrri@wrri.nmsu.edu

HYDROGEOLOGIC FRAMEWORK OF THE BINATIONAL WESTERN HUECO BOLSON-PASO DEL NORTE AREA, TEXAS, NEW MEXICO, AND CHIHUAHUA:

OVERVIEW AND PROGRESS REPORT ON DIGITAL-MODEL DEVELOPMENT

By

John W. Hawley
New Mexico Water Resources Research Institute

John F. Kennedy
New Mexico State University, Department of Geography

Alfredo Granados-Olivas
Universidad Autónoma de Ciudad Juárez

Marquita A. Ortiz
New Mexico Acequia Association

TECHNICAL COMPLETION REPORT

December 2009

New Mexico Water Resources Research Institute

The research on which this report is based was financed in part by the National Science Foundation, the Environmental Protection Agency through California State University – Los Angeles, and the U.S. Department of the Interior, Geological Survey, through the New Mexico Water Resources Research Institute.

DISCLAIMER

The purpose of the Water Resources Research Institute technical reports is to provide a timely outlet for research results obtained on projects supported in whole or in part by the institute. Through these reports, we are promoting the free exchange of information and ideas and hope to stimulate thoughtful discussions and actions that may lead to resolution of water problems. The WRRI, through peer review of draft reports, attempts to substantiate the accuracy of information contained within its reports, but the views expressed are those of the authors and do not necessarily reflect those of the WRRI or reviewers. Contents of this publication do not necessarily reflect the views and policies of the Department of the Interior, nor does the mention of trade names or commercial products constitute their endorsement by the United States government.

ACKNOWLEDGEMENTS

Recognition and acknowledgement of many substantial contributions by former and present colleagues is being made by specific citations in the report text and reference list. However, a number of individuals and institutions require special mention. First, the entire New Mexico Water Resources Research Institute staff, particularly Associate Director Dr. Bobby Creel, must be credited for their continuing support of this project. El Paso Water Utility staff members (including Thomas Cliett, retired) have provided major assistance in terms of both hydrogeologic database acquisition and GIS support. Without help and advice from Dr. William Hutchison, José Granillo, Scott Reinert, and Eric Bangs, this project could not have been completed. José, with both GIS and structural-geology expertise, provided particularly timely assistance in organization and interpretation of an enormous water-well database. Special thanks is also due to Dr. Granados-Olivas' students and staff associates at the Universidad Autónoma de Ciudad Juárez-Centro de Información Geográfica for ensuring that the Chihuahua section of the Paso del Norte-Hueco Bolson region would be adequately covered in this ongoing endeavor. Dr. Christopher Eastoe of the University of Arizona-SAHRA program provided much of the isotope-geochemical information that has been a major stimulus to our continuing focus on the hydrogeologic-framework of the study area. Long-time geologist and geophysicist colleagues who have been major contributors to our understanding of basin-fill hydrogeology in the Paso del Norte region include Drs. William R. Seager and Greg Mack (New Mexico State University, Geology Department), Drs. Randy Keller and R.P. Langford (University of Texas at El Paso), Eddie Collins (Bureau of Economic Geology, University of Texas at Austin), and Scott Anderholm and Charles Heywood (U.S. Geological Survey). Especially appreciated are very helpful peer reviews of the report manuscript by Dr. Bill Hutchison, Eddie Collins, and Dr. Zhuping Sheng (Texas A&M University System, Texas AgriLife Research). Finally, without the perseverance of our project coordinator, Dr. Barry Hibbs (California State University-Los Angeles), a binational project of such scope and environmental significance would never have been initiated or produced the impressive results obtained to date.

ABSTRACT

The binational western Hueco Bolson-Paso del Norte area of the southern Rio Grande rift (RGr) tectonic province occupies parts of Trans-Pecos Texas and south-central New Mexico, USA, and north-central Chihuahua, MX. It includes a long reach of the Rio Grande Valley, adjacent parts of the southern Mesilla and Tularosa Basins, and the El Paso-Ciudad Juárez metro-area with a population of about two million. This overview and progress report emphasizes recent development of hydrogeologic-framework models and GIS datasets that integrate large amounts of geologic and geochemical information on Neogene RGr basin-fill (Santa Fe Group) and river-valley aquifer systems. The digital GIS format (ESRI ArcGIS®) allows 3-D integration of surface and subsurface information that can be used in numerical groundwater-flow modeling and hydrogeochemical interpretations. Provisional hydrogeologic maps and cross sections completed to date include a surficial map, 11 sections (to mean sea level), and a structure-contour map of the base of the basin-fill aquifer system in the Paso del Norte area. The hydrogeologic framework of basin-fill aquifers is defined in terms of 1) dominant lithofacies-assemblages (*LFA*s) that are grouped as informal hydrostratigraphic units (HSUs) and 2) basin-boundary and intra-basin structural controls.

Late Cenozoic extensional-tectonic features that characterize the entire RGr region have had a profound influence on both basin-fill composition and groundwater flow and chemistry. Primary tectonic components are half-graben basins and flanking ranges that are linked across zones of structural accommodation. Major aquifers comprise coarser-grained *LFA*s deposited by 1) ancestral-river distributaries in Pliocene to Early Pleistocene time and 2) the Late Quaternary fluvial-channel system that occupies the present inner (El Paso/Juárez) valley of the Rio Grande. These poorly consolidated sediments are also grouped into informal upper to middle Santa Fe basin-fill and river-valley HSUs. Aquifer horizontal hydraulic conductivities commonly range from 3-30 m/day, and saturated basin-fill fluvial sequences are as much as 300 m thick and 30 km wide. In marked contrast, inset river-valley fills are less than 30 m thick and 9 km wide. Except for deeply buried eolian-sand facies, subjacent middle to lower Santa Fe basin-floor deposits (Miocene) and intertonguing piedmont-slope *LFA*s have much lower aquifer potential because of finer matrix and more consolidation and cementation.

This report comprises four major sections followed by “Concluding Remarks” and a comprehensive list of more than 165 cited references. The Introduction (Part 1) covers the purpose and scope of the study, the location and physiographic setting of the Hueco Bolson region, and a summary of research methods and major data sources. Relevant conceptual hydrogeologic models are described in Part 2, with emphasis on 1) geohydrologic systems in the Basin and Range province and 2) basic hydrogeologic-model concepts. Part 3 covers the hydrogeologic setting of the Hueco Bolson-Paso del Norte area, first from a general structural-geologic perspective and then with emphasis on the hydrogeologic map and cross-sections. Late Cenozoic evolution of the Hueco Bolson aquifer system and inferences on hydrogeologic controls on groundwater flow and geochemistry are emphasized in Part 4.
Keywords: binnational Hueco Bolson, hydrogeologic model, GIS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES (on CD-ROM)

1.0 INTRODUCTION

1.1 Purpose and Scope

The basin-fill aquifer systems of the Paso del Norte area of the southern Rio Grande rift (**RGr**) tectonic province are a major binational groundwater resource in terms of extent, and economic and environmental significance (Figs. 1 to 3). This trans-international, tri-state boundary region includes adjacent parts of the Hueco Bolson, Tularosa and Mesilla Basins in Trans-Pecos Texas, south-central New Mexico, Chihuahua (Mexico). Groundwater in these aquifers is both fresh (total dissolved solids [tds] <1,000 mg/l) and brackish (tds >1,000 mg/l). Continuing efforts to collect and exchange hydrogeologic information on aquifer characteristics has resulted in an ever-improved understanding of the region's groundwater resources, including advances in groundwater-flow modeling (e.g., Meyer 1976, Boyle Engineering Corp. 2000, Heywood and Yager 2003). Progress in flow modeling has in turn led to an evolving set of water-resource management tools (Sheng and Devere 2005, Hutchison 2006). However, groundwater-flow models developed to date have yet to take full advantage of the available subsurface hydrogeological information, including the recent data collected since 2002 related to drilling of deep wells for both fresh- and brackish-groundwater production.

Initial developmental stages of a digital hydrogeologic-framework model of basin-fill aquifer systems in the western Hueco Bolson area are described in this report (Fig. 3). Our work is part of a larger multi-institutional, interdisciplinary project: "Hydrogeologic and Water Quality Study of the Hueco Bolson Aquifer" and it involves a research team of hydrogeologists, geochemists, hydrologists, and geographic-information system (GIS) specialists. A preliminary hydrogeologic map and five cross sections were submitted with an earlier project summary in August 2004 as final-deliverable items under general terms of an NSF Glue-Grant project-completion agreement between New Mexico Water Resources Research Institute (NMWRRI) and California State University-Los Angeles (CSULA—CEA-CREST): Maps and cross sections/Award #NMSU220381 (NSF HRD-9805529)/ Account 01-4-23980. The following more comprehensive report integrates the 2004 project summary with the results of hydrogeologic studies completed under the terms of CSULA Purchase Order CGA46120 in August 2005.

Major supporting and collaborating (federal, state, and local) institutions include U.S. Environmental Protection Agency-Region 6 (EPA), U.S. Geological Survey-Water Resources Staff (USGS), the International Boundary and Water Commission (IBWC), NM Office of the State Engineer (OSE) and Interstate Stream Commission (ISC), Texas Water Development Board (TWDB), CSULA (CEA-CREST), University of Arizona-SAHRA (UAZ-SAHRA), Universidad Autónoma de Ciudad Juárez-Centro de Información Geográfica (UAJC-CIG), Lower Rio Grande Water Users Organization, and El Paso Water Utilities (EPWU).

This report is in five parts including the Introduction. Basic elements of our conceptual hydrogeologic *template* for basin-fill aquifer systems are reviewed in Part 2, and Part 3 covers the hydrogeologic setting as illustrated by the Hydrogeologic Map (Plate 1) and eleven schematic basin-scale cross sections (Plate 2a-k: AA', BB', CC', DD', EKD', FF', GD', HH', II', JJ', and EKK'). Section locations are shown on Figure 3, and index to Plates 1 and 2 (a-k on CD ROM) follows the Cited References list.

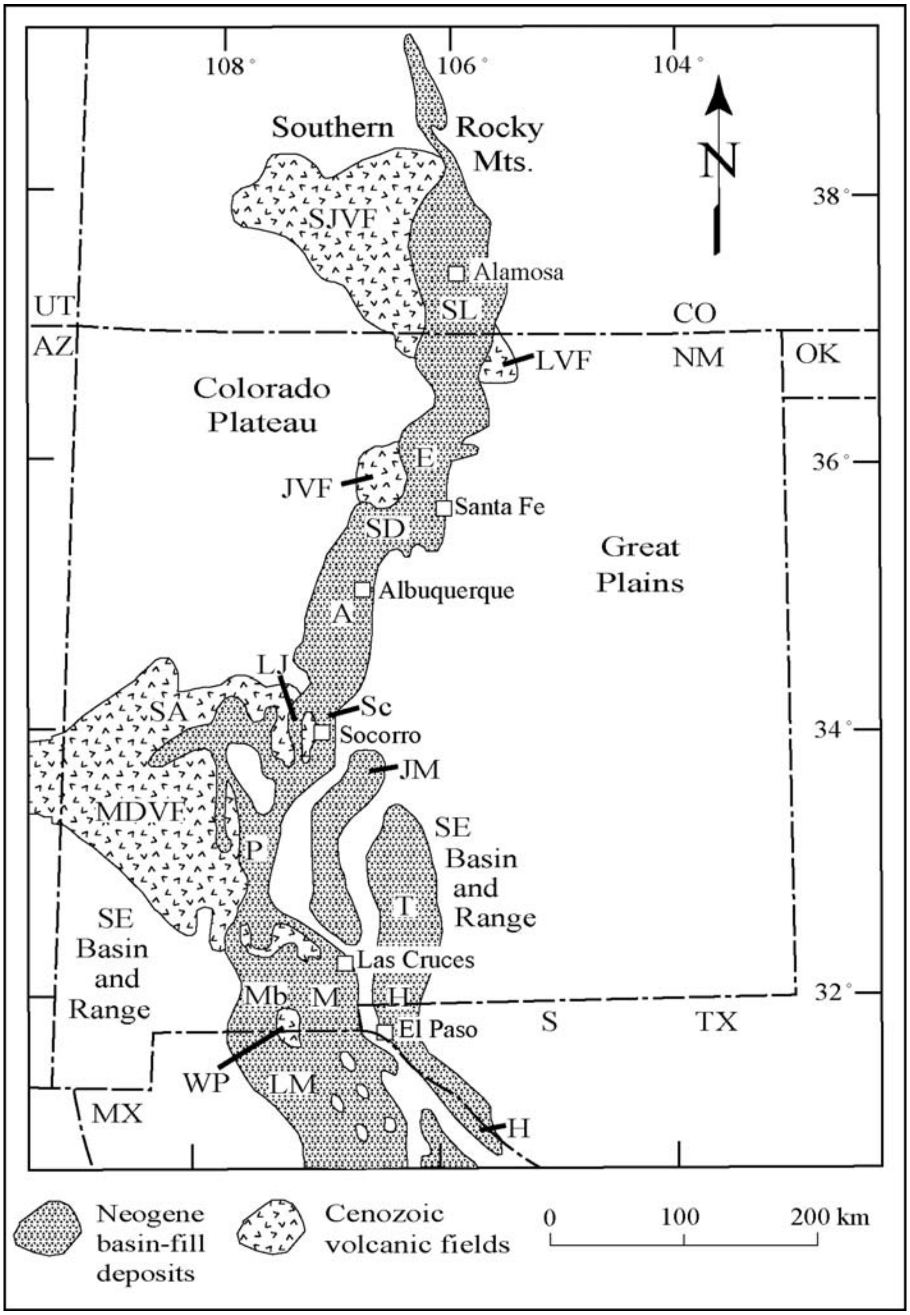


FIGURE 1. Index map showing location of the Hueco Bolson (H) within the regional-hydrogeologic context of major basins and volcanic fields of the Rio Grande rift tectonic province (modified from Keller and Cather 1994). From north to south: San Juan volcanic field (SJVF), San Luis Basin (SL), Latir volcanic field (LVF), Española Basin (E), Jemez volcanic field (JVF), Santo Domingo Basin (SD), Albuquerque Basin (A), Socorro Basin (Sc), La Jencia Basin (LJ), San Agustín Plains (SA), Jornada del Muerto Basin (JM), Mogollon-Datil volcanic field (MDVF), Palomas Basin (P), Tularosa Basin (T), Mimbres Basin (Mb), Mesilla Basin (M), Salt Basin (S), West Potrillo volcanic field (WP), Bolson de los Muertos (LM).

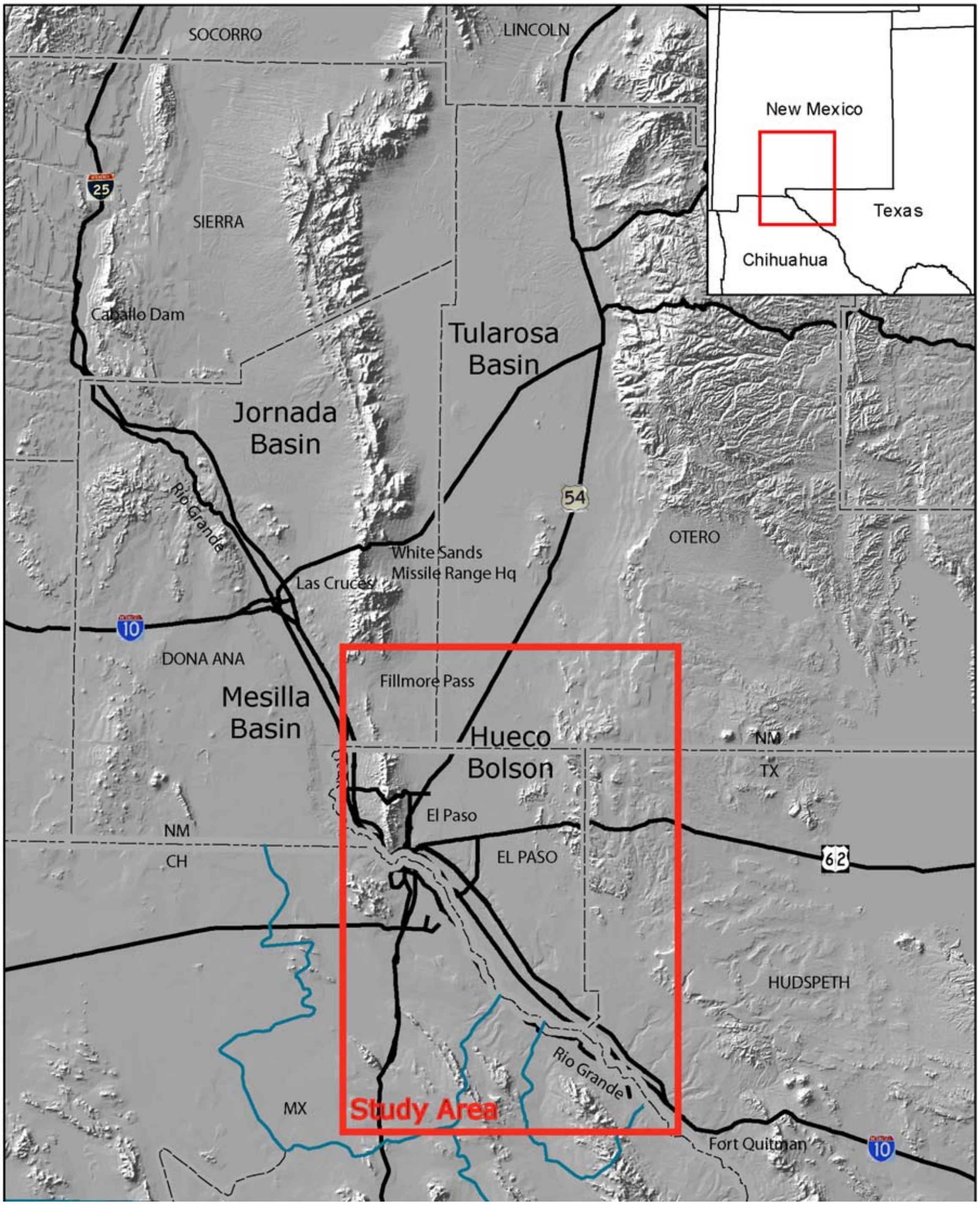


FIGURE 2. Hueco Bolson and Paso del Norte study area. The transitional Tularosa-Hueco basin boundary is located near the north edge of the area (Fig. 3, AA').

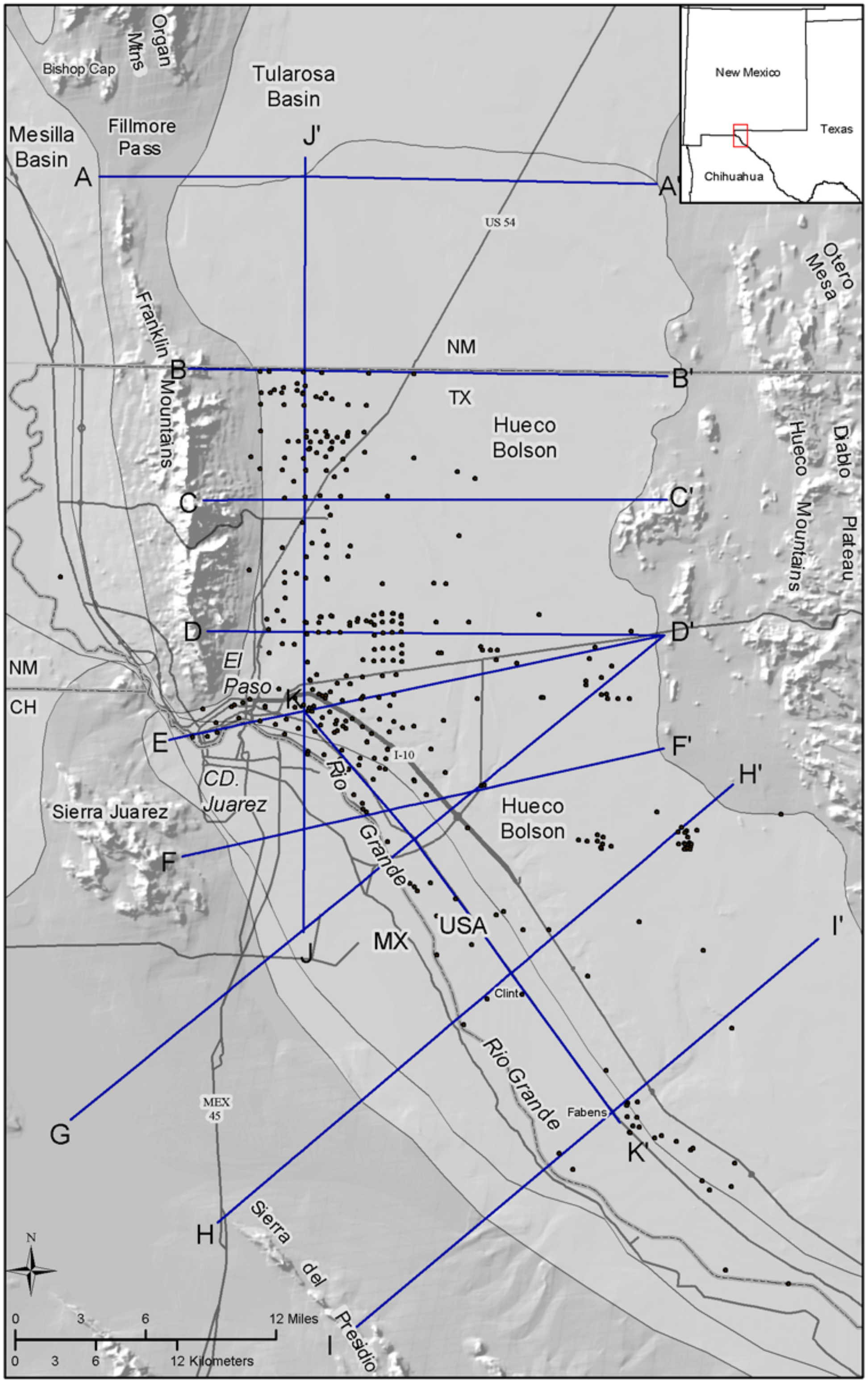


FIGURE 3. Cross-section index map, showing location of schematic hydrogeologic sections AA’, BB’, CC’, DD’, EKD’, FF’, GD’, HH’, II’, JJ’, and EKK’ (Plates 2a-k). Dots indicate well-control points in Texas part of study area.

There are nine representative transverse-basin sections (Plates 2a-i) extending across the Bolson between the NM/TX border zone (AA' and BB') and Fabens area of the (Lower) El Paso Valley (II'). Longitudinal sections JJ' and EKK' (Plates 2j-k) provide, respectively, down-basin and down-valley hydrogeologic perspectives along the western basin margin and between the Rio Grande Valley constriction at El Paso del Norte and the Fabens-Tornillo area of southeastern El Paso County. In addition, linkage between the Mesilla and El Paso/Juárez Valley areas via El Paso del Norte is illustrated by a structure-contour map of the base of the basin-fill aquifer system (Fig. **7**) and a down-valley hydrogeologic section (Fig. 8). Part 4 is an overview of the Late Cenozoic geologic history of the Hueco Bolson-Paso del Norte region, with emphasis on the evolution of the present basin-fill aquifer system and inferences on hydrogeologic controls on complex interrelationships of groundwater flow and geochemistry. Part 5 is a brief concluding statement with recommendations for future research.

The groundwater potentiometric surface, which marks the inferred vadose/saturated-zone boundary, is not shown on the schematic hydrogeologic sections (Plates 2a-2i). Creation of pre-development and present-day potentiometric-surface maps and profiles was not within the scope of this study, but they are available in a number of cited documents (e.g., Sayre and Livingstone 1945, Knowles and Kennedy 1958, Bedinger et al. 1989, INEGI 1999, Heywood and Yager 2003). The essential point is that the top of the pre-development zone of saturation approximated the elevation of the river-channel and floodplain-canal/drain system throughout the study area, with a slight (~0.001) northward rise in the bolson area north of the inner Rio Grande/Bravo Valley.

The New Mexico Bureau of Geology [Mines] & Mineral Resources (NMBG&MR), U.S. Geological Survey (USGS), Texas Water Development Board (TWDB), El Paso Water Utilities (EPWU), Texas Bureau of Economic Geology (BEG), and NMWRRI have been the major USA contributors to hydrogeologic characterization of basin-fill aquifers of the Hueco Bolson-Paso del Norte region for more than 50 yrs (e.g. Knowles and Kennedy 1958, Leggat 1962, Leggat et al. 1962, Hawley 1965, Cliett 1969, Hawley et al. 1969, King et al. 1971, Gates and Stanley 1976, Henry 1979, Alvarez and Buckner 1980, Henry and Gluck 1981, Wilson et al. 1981, White 1983, Hawley 1984, Seager et al. 1987, Bedinger et al. 1989, Hawley and Lozinsky 1992, Orr and Risser 1992, Nickerson and Myers 1993). From a modern hydrogeologic-GIS perspective, however, essential baseline characterization of aquifer-system hydrogeology and geochemistry has only been initiated in the past decade, and the NMWRRI continues to have a major role in development of digital-GIS datasets that integrate geologic, hydrologic, and hydrogeochemical information on transboundary aquifer systems of southwestern New Mexico, western Trans-Pecos Texas and northwestern Chihuahua (e.g., Hibbs et al. 1997, 2003, White et al. 1997, Hawley and Kernodle 2000, Hawley et al. 2000, 2001, Kennedy et al. 2000, Anderholm and Heywood 2003, Hawley and Kennedy 2004, Witcher et al. 2004, Creel et al. 2006, Hibbs and Merino 2006, Nickerson 2006). Furthermore, most binational hydrogeologic and geohydrologic investigations have heretofore terminated at the international border, and other projects simply provided exchanges of existing binational databases (Hibbs et al. 1998).

1.2 Location and Physiographic Setting

The western Hueco Bolson and Rio Grande/Bravo Valley area covered in this report (Figs. 2 and 3) includes all of El Paso County, Texas, and adjacent parts of Doña Ana and Otero counties, New Mexico, and Hudspeth County, Texas. South of the International Boundary, which is now formed by the *canalized* Rio Grande/Bravo channel, the Bolson-study area extends into northern Chihuahua and includes the Ciudad Juárez metropolitan district. As already noted (Part 1.1), this area is near the southern end of the Rio Grande rift (RGr) tectonic province (Figure 1; Keller and Cather 1994, Mack 2004, Pazzaglia and Hawley 2004, Connell et al. 2005). The RGr was originally designated the Rio Grande "depression" in the first definitive hydrogeologic investigations of the region by Kirk Bryan (1938), who also correlated rift-basin fill throughout the region with the Santa Fe "formation" (Group: Hawley et al. 1969, Hawley and Kernodle 2000). From a biogeographic and climatic perspective, the Bolson and flanking uplands are part of the north-central Chihuahuan Desert (Schmidt 1973, 1986, Van Devender 1990).

The Hueco Bolson is located at the edge of the Mexican Highland section of the Basin and Range (B&R) physiographic province (Fenneman 1931, Hawley 2005), and to the northeast, it is flanked by high plateaus at the southern end of the province's Sacramento section (Otero Mesa and Diablo Plateau, Fig. 3). The Hueco and adjacent Mesilla "bolsons" were originally named and broadly defined (both physiographically and structurally) by R.T. Hill (1896, 1900). The Bolson is also transitional northward with the Tularosa Basin of south-central New Mexico (Fig. 2), and they form one of the largest topographic and structural-basin systems in the southeastern Basin and Range province (Meinzer and Hare 1915; Bedinger et al. 1989, Plates 5 & 6). The boundary zone between these geohydrologically connected basins is here arbitrarily placed east of Fillmore Pass (between the Franklin and Organ Mountains, Fig. 3, near Section AA').

The distinctive geomorphic characteristic of this part of the Basin and Range province is the large extent of basin-floor (*bolson-plain*) areas relative to the size of flanking piedmont slopes and mountain uplifts (Figs. 2 and 3, Plates 1 and 2). The crests of mountain ranges that flank the Hueco Bolson on the west and southwest (Franklin Mountains, Sierra de Juárez, Sierra del Presidio) are relatively narrow and low (elev. <6,000-8,000ft, <1,830-2,440m) in comparison with highlands of the upper Rio Grande basin. El Paso del Norte (*El Paso Narrows*) is a constricted reach of the Rio Grande Valley system that separates the Franklin and Juárez uplifts. It is characterized by a narrow river-valley floor (<1,000ft, 300m width) with a buried bedrock channel that has a saturated-alluvial fill thickness of less than 85ft (25m).

The undissected floor of the Hueco Bolson (elev. ~3,900-4,000ft, 1,190-1,220m) occupies most of the study area, both northeast and southwest of the deeply entrenched Rio Grande/Bravo Valley (Plates 1 and 2). Bolson-floor surfaces (*mesa areas*) are primarily *relict* components of ancestral Rio Grande channel and floodplain complexes that occupied basin floors in latest Pliocene and earliest Pleistocene times (~1 to 3.5 million years ago [Ma], Figure 6, Parts 3 and 4 discussions). These *bolson plains* (Tight 1905, Tolman 1909) are for the most part still topographically *closed* (Part 2.1); and they are now veneered by pedogenic calcretes, eolian sediments, and local playa-depression fills (Hawley 1969, 1975, Hawley et al. 1969, Gile et al. 1981, 1995, Seager et al. 1987, Gustavson 1991, Monger 1993, Collins and Raney 1994b, 2000, Buck 1996). The El Paso-Juárez Valley segment of the entrenched river-valley system extends about 40mi (65km) downstream from El Paso del Norte (El Paso Narrows—floodplain elev. 3,715-25ft; 1,132-35m) through the Fabens-San Elizario Island area into western Hudspeth County (El Paso/Hudspeth County Line—floodplain elev. ~3,610ft; 1,100m). The thickness of inner-valley alluvial fill ranges from about 60 to 100 ft (~18-30m).

1.3 Methods

Report emphasis is on <u>basin-scale</u> characterization of the hydrogeologic framework of Upper Cenozoic Hueco Bolson deposits, including Rio Grande/Bravo alluvial fill of the El Paso/Juárez (*Lower*) Valley, that collectively form the major (*shallow and upper to lower*) aquifer systems of the study area. GIS methodology (ESRI-ArcGIS® platforms) has been used to integrate major framework components that include aquifer-system lithology and stratigraphy, basin (*bedrock*) boundaries and internal basin structure (Tremblay 1999, Kennedy et al. 2000, Granados-Olivas and Kretzschmar 2001, Granados-Olivas et al. 2001). GIS components include area features (polygons), such as planimetric units that express the spatial extent of geologic-mapping units, linear elements including surface expression of fault-zones, and points showing locations of very small features, such as “key wells,” that provide significant information on subsurface geology and geophysics (Fig. 3).

The digital “template” for the hydrogeologic-framework model is 3-dimensional and has a combined surface map—fence-diagram format with 1:100,000 map-scale, cross-section vertical exaggeration of 10x, and mean sea level (msl) base elevation. Borehole geological, geophysical, and geochemical data from more than 100 key wells (mainly from published sources and other public records) is being used to create 11 (schematic) hydrogeologic sections (Fig. 3, Sections AA' to EKK'). Much of the basic bedrock and surficial geologic information used in creation of our new hydrogeologic base map (Plate 1) is from cited map publications of the Texas Bureau of Economic Geology and the NMBG&MR (e.g., Collins and Raney 2000, Seager et al. 1987).

Most subsurface information used in this initial stage of cross-section construction is also from cited published sources (e.g., Sayre and Livingston 1945, Knowles and Kennedy 1958, Audsley 1959, Leggat 1962, Mattick 1967, Cliett 1969, Buckner 1974, Gates and Stanley 1976, Henry and Gluck 1981, White 1983, Orr and White 1985, Seager et al. 1987, Buszka et al. 1994, Abeyta 1996). Digital versions of the map and cross sections are available for review and appropriate revisions at the NM WRRI website, and sections are in Adobe Illustrator® format (ftp://wrri.nmsu.edu/pub/hueco), which facilitates upgrade efficiency.

The following discussions (Parts 2 to 5) are limited to topics that relate specifically to the preliminary hydrogeologic interpretations illustrated on Plates 1 and 2. Most published sources of information used in framework-model development are listed in the concluding Selected References section, with Hawley and Kennedy (2004, http://wrri.nmsu.edu/publish/) being the primary source document. *Note that the well-control database, including location of key wells (*Fig. 3*), is still in the process of being developed in cooperation with the EPWU GIS and Hydrogeology Sections, UACJ-Centro de Información Geográfica (UAJC-CIG), and the USGS. This information will eventually be available in both tabular (Excel® spread sheet) and map (ArcGIS®) formats. Furthermore, well-location index codes still reflect the evolution of several generations of well-numbering systems during the past five decades.*

2.0 CONCEPTUAL HYDROGEOLOGIC MODELS

2.1 Basin and Range Geohydrologic Systems

Discussions of groundwater-flow systems on regional, individual-basin, or more-local scales are beyond the scope of this report. However, it is appropriate to introduce this general topic as useful preface to the following discussions of basin-scale hydrogeologic-framework concepts (Part 2.2). The primary groundwater reservoirs of the study area, as elsewhere in the Basin and Range province, are in poorly consolidated deposits (*basin fill*) that have accumulated in the intermontane structural basins (*bolsons* and *semibolsons* of Tolman 1909) during Late Cenozoic time (Figure 6). While these complex landforms are commonly referred to as “alluvial basins” (Kernodle 1992), their fills are not entirely of alluvial origin because they may also contain significant amounts of lacustrine, eolian, and colluvial sediments (Hawley et al. 1969, 2000, 2001, Seager et al. 1987, Gustavson 1991, Collins and Raney 1991, 2000). Fractured volcanic rocks (basalts, andesites, and tuffs) that immediately underlie or are locally interlayered with the basin fill, and carbonate rocks with solution-enlarged fractures form important aquifers in only a few places (Hawley et al. 2000; Hawley and Kennedy 2004, Witcher et al. 2004). 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 rocks.

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. Interbasin 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 eastern Trans-Pecos Texas), there are no extensive bodies of carbonate rock that provide effective conduits for large volumes of regional, interbasin groundwater flow (Winograd and Thordarson 1975, Sharp 2001, Hibbs and Darling 2005). As noted by Hawley and Kennedy (2004), however, bedrock highlands dominated by dissolution-prone carbonate and gypsiferous sedimentary units do serve as localized sources of brackish/saline and/or geothermal groundwater (Witcher et al. 2004). While there is a definite need to further evaluate bedrock aquifer zones, this important topic is beyond the scope of our report.

Figure 4, adapted from Eakin and others (1976) and Mifflin (1988), illustrates the general *conceptual* 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 Basin and Range–Great Basin section, and the Trans-Pecos Texas–Chihuahua region (e.g., Hawley et al. 2000, Mace et al. 2001, Hibbs and Darling 2005). Note that the topographic terms *closed* and *open* are used here 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 interbasin 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 Hueco Bolson and adjacent basins of the Rio Grande rift region, the (intermediate) *partly drained* basin type, which is also "incompletely" *open*, represents the major geohydrologic system.

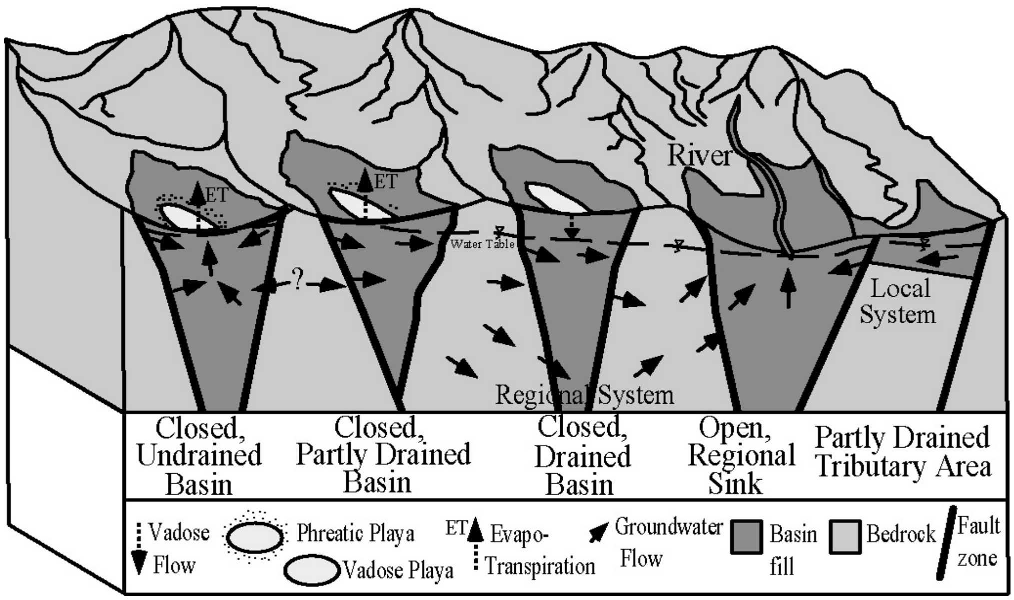


FIGURE 4. Schematic diagram showing hydrogeologic framework and groundwater-flow system in interconnected group of closed and open; undrained, partly drained, and drained intermontane basins (modified from Mifflin 1988).

Under predevelopment conditions, groundwater discharge in the study 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. Recharge to basin-fill aquifers occurs by the mechanisms: "mountain front," "mountain block," and "tributary." In the first case, a small fraction of the precipitation falling on bedrock highlands contributes to the groundwater reservoir along basin margins, primarily at the piedmont termini of major drainage basins (Anderholm 2000, Waltemeyer 2001, Naus 2002). "Mountain-block" recharge is the process where a significant component of precipitation percolates deeply into bedrock of a highland area and emerges into the basin fill as a strictly subsurface-flow component (*cf* Feth 1964; Wasiolek 1995, Hogan et al. 2004). "Tributary recharge" (Kernodle 1992), where the groundwater reservoir is replenished along losing reaches of larger intrabasin streams, is a major recharge process in the parts of the Mesilla and Upper (El Paso-Juárez) valleys (Nickerson and Myers 1993, Scanlon et al. 2001).

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. Therefore, while very large quantities (millions of ac-ft, hectare-m) of fresh to slightly saline water are stored in the basin-fill aquifer system, much of it has not been effectively recharged during the warm-dry environmental conditions of the past ten-thousand years (Holocene). 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 Pleistocene glacial-pluvial cycles prior to about ten-thousand years ago (Plummer et al. 2004, Sanford et al. 2004, Scanlon 2004).

2.2 Basic Hydrogeologic-Model Concepts

The conceptual hydrogeologic-framework model of basin- and valley-fill aquifers in the western Hueco Bolson-Paso del Norte area (Hawley and Kernodle 2000; Hawley et al. 2002, Hawley and Kennedy 2004) is here described in terms of three fundamental components: Lithofacies assemblages (*LFA*s), hydrostratigraphic units (HSUs), and structural-boundary conditions. Hydrogeologic models of this type are simply qualitative to semi-quantitative interpretations of how basin-scale geohydrologic systems are influenced by 1) lithofacies distribution within basin-fill hydrostratigraphic units, 2) bedrock-boundary conditions, and 3) internal-basin structure. They facilitate systematic organization of large amounts of information with wide variation in quality and scale (e.g., from general drillers' observations to detailed bore-hole logs and water-quality data). GIS science and technology now allows graphical and numerical display of hydrogeologic-framework elements in dynamic 3-D formats so that basic information and inferences on geohydrologic attributes (e.g., hydraulic conductivity, transmissivity, anisotropy, and distribution patterns of framework units) may be transferred to basin-scale numerical models of groundwater-flow systems (Hawley and Kernodle 2000, Kennedy et al. 2000). Creation of the basic map/cross-section template is the long-term product of work by Hawley and associates in the Basin and Range province that started in northern Nevada and south-central New Mexico in the early 1960s (e.g., Hawley and Wilson 1965, Hawley et al. 1969, King et al. 1971, Hawley 1984).

2.21 Lithofacies Assemblages

Lithofacies assemblages (*LFA*s) are the basic building blocks of the hydrogeologic model (Tables 1-3); and they are the primary components of Santa Fe Group hydrostratigraphic units (HSUs-Part 2.23-Chart 1). Figure 5 is a schematic illustration of the distribution pattern of *LFA*s observed in the Hueco Bolson-Mesilla Basin region. Lithofacies classes are defined primarily on the basis of grain-size distribution, mineralogy, sedimentary structures, and degree of post-depositional alteration. Inferred environments of deposition form the secondary basis for facies-assemblage definitions (Table 1).

Lithofacies assemblages have distinctive geophysical, geochemical, and hydrologic attributes, and they provide a mechanism for showing distribution patterns of major aquifers and confining units in the hydrogeologic cross sections. Throughout the study region, basin and river-valley fills are subdivided into thirteen major assemblages (*LFA*s *1-10*, *a-c*), which are ranked in decreasing order of aquifer potential (Tables 2 and 3). Note also that lithofacies assemblages represent four major depositional environments:

basin floors (*1-3, 9, 10, c*), piedmont slopes (*5-8*), river-valley floors (*a1-a3*), and valley-border slopes (*b*). *LFA 4* is primarily an ancient (mostly buried) eolian-sand deposit on the eastern (leeward) side of desert basins and major stream valleys. All cross sections (AA' and EKK') illustrate the fact that medium- to coarse-grained fluvial (ancestral Rio Grande), and fine- to medium-grained fluvial-lacustrine sediments deposited in a broad basin-floor environment are the dominant facies assemblages of the western Hueco Bolson aquifer system (*LFA*s *1* and *2*, and *LFA*s *3*, *9* and *10*, respectively).

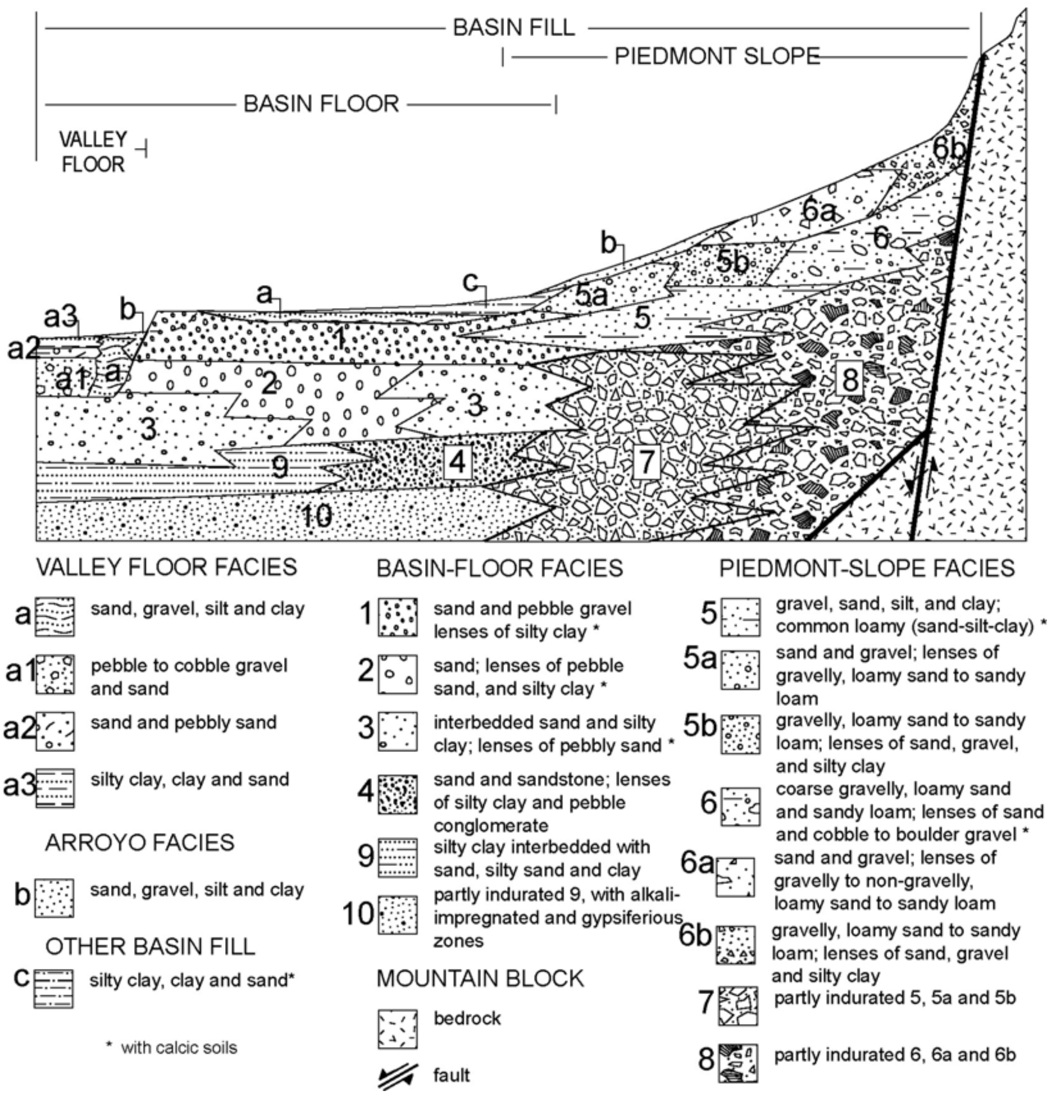


FIGURE 5. Schematic distribution pattern of major lithofacies assemblages (*LFAs*) in basin and valley fills of the Hueco Bolson and Mesilla Basin region (from Hawley and Kernodle 2000).

TABLE 1. Summary of depositional settings and dominant textures of major lithofacies assemblages (*LFAs*) in basin and valley fills of the Rio Grande rift region: Santa Fe Group basin fill (1-10) and post-Santa Fe river-valley and basin fill (a-c). Modified from Hawley and Kernodle (2000).		
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 pebbly 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; associated 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 2 Summary of major sedimentary properties that influence groundwater-production potential of Santa Fe Group basin fill (*LFAs* 1-10). 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 (meters)[3]	Bedding connectivity[4]	Hydraulic conductivity (K)[5]	Groundwater production potential
1	High	>1.5	Elongate to planar	>300	High	High	High
2	High to moderate	>1.5	Elongate to planar	>300	High to moderate	High to moderate	High to moderate
3	Moderate	>1.5	Planar	150 to 300	Moderate to high	Moderate	Moderate
4	Moderate to low*	>1.5	Planar to elongate	30 to 150	Moderate to high	Moderate	Moderate
5	Moderate to high	0.3 to 1.5	Elongate to lobate	30 to 150	Moderate	Moderate to low	Moderate to low
5a	High to moderate	0.3 to 1.5	Elongate to lobate	30 to 150	Moderate	Moderate	Moderate
5b	Moderate	0.3 to 1.5	Lobate	30 to 150	Moderate to low	Moderate to low	Moderate to low
6	Moderate to low	0.3 to 1.5	Lobate to elongate	130 to 150	Moderate to low	Moderate to low	Low to moderate
6a	Moderate	0.3 to 1.5	Lobate to elongate	30 to 150	Moderate	Moderate to low	Moderate to low
6b	Moderate to low	0.3 to 1.5	Lobate	<30	Low to moderate	Low to moderate	Low
7	Moderate*	0.3 to 1.5	Elongate to lobate	30 to 150	Moderate	Low	Low
8	Moderate to low*	>1.5	Lobate	<30	Low to moderate	Low	Low
9	Low	>5	Planar	>150	Low	Very low	Very low
10	Low*	>5	Planar	>150	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.

[5]High 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 medium to coarse-grained beds (as much as 50%)

The distinguishing characteristic of all piedmont-slope *LFA*s (*5-8*), primarily coalescent alluvial-fan deposits is that with the exception of eolian contributions, they are derived from the local highlands that flank a given structural basin. Basin-floor fluvial to deltaic *LFA*s (*1-3*), in marked contrast, have a significant component of clasts (pebble to clay size) derived from distant-upstream source areas. Moreover, subrounded coarser-clast components are dominated by resistant rock and mineral varieties; carbonate rocks are rare or absent.

TABLE 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 (meters)[3]	Bedding configuration[2]	Bedding continuity (meters)[3]	Bedding connectivity[4]	Horizontal hydraulic conductivity (K)[5]	Groundwater production potential
a	High to moderate	>1.5	Elongate to planar	>300	High to moderate	High to moderate	High to moderate
a1	High	>1.5	Elongate to planar	>300	High	High	High
a2	High to moderate	>1.5	Planar to elongate	150 to 300	Moderate to high	Moderate	Moderate
a3	Moderate to low	>1.5	Planar to elongate	30 to 150	Moderate to high	Moderate to low	Moderate to low
b	Moderate to low	0.3 to 1.5	Elongate to lobate	<300	Moderate	Moderate to low	Moderate to low
c	Low to moderate	0.3 to 1.5	Elongate to lobate	30 to 150	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 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.

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

2.22 Hydrostratigraphic Units (HSUs)

"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, 322). H*ydrostratigraphic units* (HSUs) are defined in basin- and valley-fill sequences as mappable deposits that are grouped on the basis of *LFA* composition and position in both litho-(*rock*) stratigraphic and chrono-(*time*) stratigraphic contexts (Hawley and Kernodle 2000). Most intermontane-basin fills in the western Trans-Pecos Texas and south-central New Mexico region are subdivisions of the Santa Fe (lithostratigraphic) Group (Hawley et al. 1969, Hawley 1978, Chapin and Cather 1994, Connell et al. 2005) The bulk of these deposits are of Late Neogene age (Miocene and Pliocene; ~23 to 1.8 Ma; Fig. 6).

In Rio Grande rift basins south of Caballo Dam (Palomas-Rincon, Jornada del Muerto, Mesilla, Los Muertos, and Hueco-Tularosa basins, Figs.1 and 2), 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. 6). From youngest to oldest, these mapping units are formally named the Camp Rice, Palomas, Fort Hancock, Rincon Valley, and Hayner Ranch Formations (Strain 1966, Seager and Hawley 1973, Seager et al. 1971, 1975, Gile et al. 1981, Lozinsky and Hawley 1986, Seager et al. 1984, 1987, Collins and Raney 1991, 1994b, Mack et al. 1998, 2006). In many previous hydrogeologic studies, however, clear distinctions were not made between "bolson or basin fill" and correlative (formal or informal) subdivisions of the Santa Fe Group.

As a first step in organizing information on basin-fill stratigraphy and sedimentology with emphasis on aquifer characteristics, a provisional hydrostratigraphic classification system has recently been developed that is applicable to most basins of the southeastern Basin and Range province (Fig. 6). Note that even-numbered alphanumeric codes (e.g., HSUs USF 2 and MSF 2—Chart 1) designate units made up of basin-floor lithofacies assemblages (*LFA*s *1-3, 9-10*—Fig. 5); odd-numbered codes (e.g., USF 1, MSF 1—Fig. 6) denote units comprising piedmont-slope *LFA*s (*5-9*—Fig. 5). HSU definition is an ongoing process, with progressive refinement occurring with each new study phase. To date, this informal classification scheme has been used in the Albuquerque, Mesilla, and several other "alluvial basins" of the southwestern New Mexico border region (Hawley et al. 1995, 2000, 2002, Hawley and Kernodle 2000, Kennedy et al. 2000, Hawley and Kennedy 2004).

Informal upper, middle, and lower Santa Fe hydrostratigraphic units (HSUs: USF, MSF, LSF) form the major basin-fill aquifer zones in the Hueco Bolson and Mesilla Basin area, and they correspond roughly to the upper (Camp Rice), middle-upper (Fort Hancock/Rincon Valley), and lower (Hayner Ranch) lithostratigraphic subdivisions of the Santa Fe Group (Fig. 6). However, proper identification and correlation of these formations in subsurface remains a significant problem in many, if not most *closed-basin* areas; hence the informal status of our hydrostratigraphic classification system. Dominant sedimentary facies in the upper Santa Fe HSU are basin-floor lithofacies assemblages *1-3* and piedmont-slope *LFA*s *5 and 6* (Fig. 5, Table 1). The middle Santa Fe HSU is characterized by basin-floor *LFA*s *3 and 9, piedmont LFA*s *5-8*, and the transitional (partly eolian) *LFA 4*. The lower Santa Fe commonly includes *LFA*s *4 and 7-10*. Basin-floor facies assemblages *3* and *9* are normally present throughout the Santa Fe Group section in central *closed-basin* (bolson) areas, particularly in HSUs LSF and MSF2; and sandy eolian deposits, which are common constituents of *LFA*s *2 and 4*, are significant Santa Fe Gp facies components on the eastern (leeward) side of the northern and central Hueco Bolson.

The other major class of hydrostratigraphic units comprises channel and floodplain deposits of the Rio Grande (HSU–RA/*LFA a*) and its major arroyo tributaries (VA, VAY/*LFA b*). These thin (<100ft, 30m) valley fills of Late Quaternary age (<130,000 years old) form the upper part of the region's most productive shallow-aquifer system (Fig. 5, Table 3, Part 4.4). Surficial lake and playa deposits (BF, BFP/*LFA c*), fills of larger arroyo valleys, and piedmont-slope alluvium (PA, PAY) are in the *vadose* zone. However, they may form localized sites of groundwater recharge. Historical *phreatic* conditions exist, or have recently existed, in a few playa remnants of large pluvial lakes (Late Quaternary age) that are located north and southwest of the study area. 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, 2, 10; Reeves 1969, Hawley and Kottlowski 1969, Hawley 1993, 2005, Hawley et al. 2000, Lucas and Hawley 2002, Langford 2003, Allen 2005, Castiglia and Fawcett 2006).

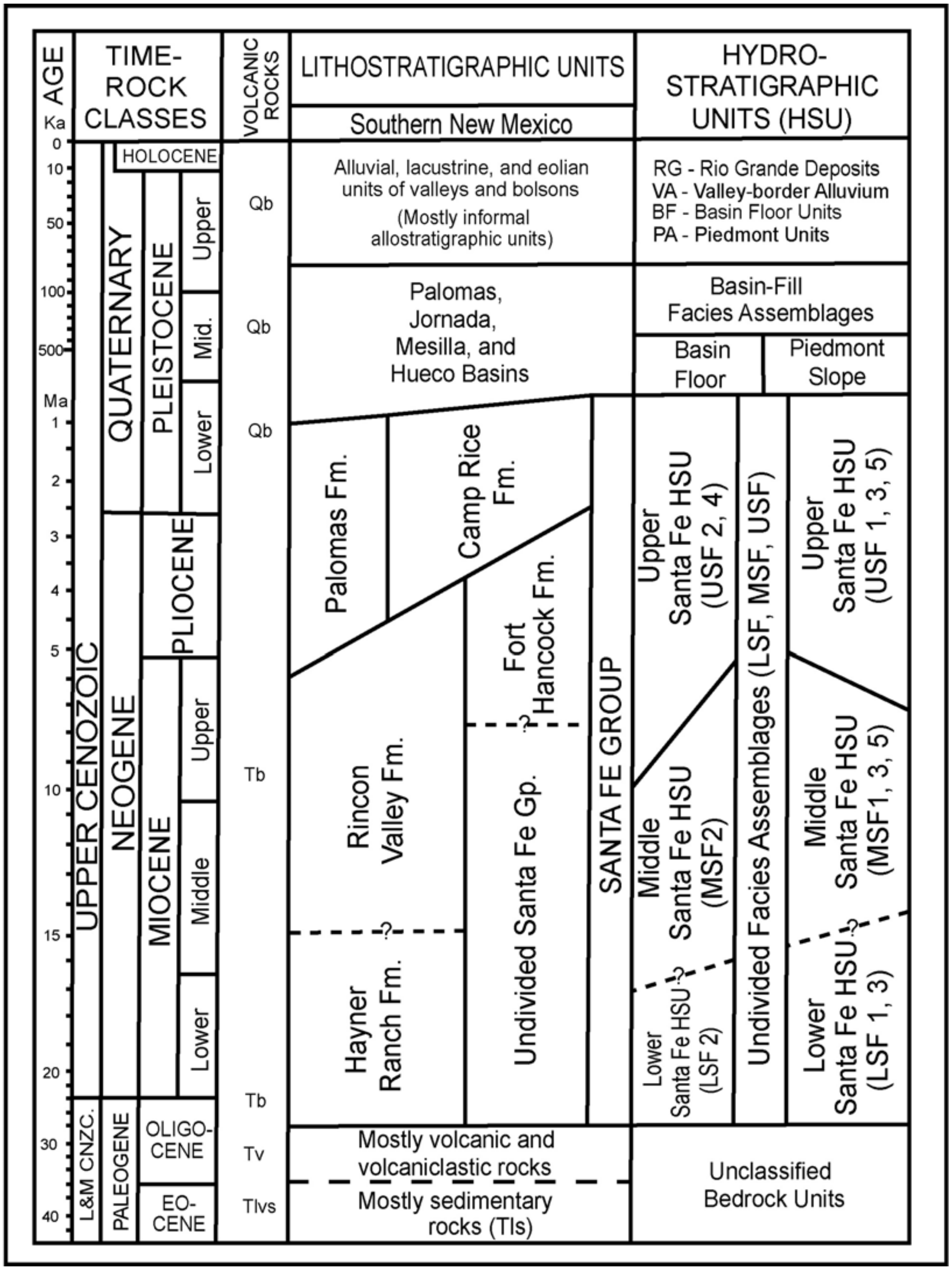


FIGURE 6. Correlation of major chronologic, lithostratigraphic, and hydrostratigraphic units in the Paso del Norte region, south-central New Mexico, western Trans-Pecos Texas, and adjacent parts of Chihuahua, Mexico. Rock symbols: Qb – Quaternary basalt, Tb – Late Cenozoic mafic volcanics and Tv –older Cenozoic intermediate and silicic volcanics, and associated plutonic-igneous and sedimentary rocks (Tlvs, Tls). Modified from Hawley and Kernodle (2000), with adjustment of Pleistocene (Quaternary)/Pliocene boundary from Walker and Geissman (2009).

2.23 Bedrock and Structural Boundary Conditions

Tectonic evolution of the fault-block basins and ranges throughout the southern Rio Grande rift (RGr)—Mexican Highland (B&R) region during the past 25 million years (Ma) has had a profound effect on both the distribution of Santa Fe Group lithofacies assemblages and the timing and style of emplacement of hydrostratigraphic units (Figs. 1, 2, 5 and 6; Plates 1 and 2, Parts 3 and 4). Bedrock and structural boundary conditions that influence the behavior of basin-aquifer systems include: 1) character of bordering highland and buried intrabasin bedrock terranes, 2) fault zones and flexures within and at the edges of basins, and 3) igneous rocks that penetrate or are interbedded with basin fill. The complex bedrock terranes and tectonic features of the area are reflected not only in basin-fill composition but also in groundwater flow and chemistry.

One of the major byproducts of the present study is the reevaluation of the Hueco Bolson's structural evolution and resulting reinterpretation of prevailing models of pre-Santa Fe Group (Early and Middle Tertiary) basin structure and fill stratigraphy (Paleogene, Fig. 6). This unforeseen outcome primarily resulted from the syntheses of published geological map and deep-well logging information with aerial, surface, and subsurface geophysical-survey interpretations that are described in Parts 3.2 and 4.3. For example, we discovered that the very thorough and valuable work of Gates and Stanley (1976) had never been integrated with the equally valuable and more comprehensive research of Collins and Raney (1991, 1994a-b, 1997, 2000) and Paine and Collins (2002).

3.0 HYDROGEOLOGIC SETTING

3.1 General Geologic Setting

Detailed discussion of Cenozoic geologic history is beyond the scope of this paper; the reader is referred to comprehensive reviews in Seager and others (1984), Collins and Raney (1991, 1994a-b, 1997), Gustavson (1991), Keller and Cather (1994), and Mack and Giles (2004). Emphasis here is on those key elements of the geologic setting that directly apply to the Hueco Bolson's hydrogeologic framework and related aspects of groundwater flow and chemistry. As already noted, the Hueco-Tularosa structural basin system is near the southern end of the north-trending series of basins and flanking mountain uplifts that form the Rio Grande rift (RGr) tectonic province (Fig. 1; Albritton and Smith 1965, Chapin and Seager 1975, Hawley 1978, Seager and Morgan 1979, Henry and Price 1985, Chapin and Cather 1994, Mack 2004, Pazzaglia and Hawley 2004, and Connell et al. 2005). The ongoing rifting process began in Oligocene time, about 25 to 30 Ma. Subsequently, extensional forces have stretched the earth's crust, causing large basin blocks to rotate and sink relative to adjacent mountain uplifts. North-trending, tilted-fault-block (half-graben) structures, many with accommodation-zone terminations, are the dominant tectonic forms of the regional RGr terrane; these structures are commonly superimposed on mid-tertiary volcano-tectonic features (e.g., Organ Mountains) and/or still older Laramide compressional uplifts and basins (Lovejoy and Seager 1978, Collins and Raney 1991, 1994a, 1997, Mack 2004, Seager 2004).

The Precambrian-basement-cored Franklin-Organ Mountain chain, which is disrupted only at Fillmore Pass (Fig. 3, Plate 1), forms a well-defined fault-block margin of the west-tilted, northwestern Hueco Bolson and southwestern Tularosa Basin blocks. The Franklin and southernmost Organ uplifts (including Bishop Cap) are capped with thick sequences of Paleozoic carbonate rocks ranging from Ordovician to Permian in age (Harbour 1972, LeMone and Lovejoy 1976, Seager 1981, Kelley and Matheny 1983, Figuers 1987, Seager et al. 1987, Collins and Raney 2000). However, the main mass of the Organ Mountains is formed by Oligocene intermediate igneous-intrusive and silicic volcanic rocks. Of possible concern to local groundwater-quality conditions, upper Pennsylvanian rocks at Bishop Cap and the "Pipeline Hills" (north-central Franklins) also contain thick beds of gypsite (Plates 1 and 2a-b: Sections AA' and BB').

South and southeast of El Paso del Norte, fault-block uplifts of Jurassic (?) and Cretaceous carbonate rocks, with complexly folded and (reverse-) faulted internal structure, form a less-distinct but still relatively continuous southwestern Bolson margin (INEGI 1982 a, Lovejoy 1979). These lower-lying ranges include Sierra de Juárez, Sierra del Presidio, Sierra Samalayuca, and Sierra del Ignacio (Córdoba et al. 1969). The eastern Bolson boundary is formed by the complexly faulted western escarpment of the Diablo Plateau (TX) and Otero Mesa (NM), which includes the Hueco Mountains (Fig. 3). Paleozoic carbonate rocks capping a shallowly buried Precambrian igneous and metamorphic terranes are well exposed in this area. Oligocene silicic to intermediate igneous-intrusive rocks are also present along the western edge of the Diablo Plateau and at Hueco Tanks (Plate 1, Henry and Gluck 1981, Henry and Price 1985, Barker 1997).

Subsidence of the Hueco Bolson *rift basin* was initiated in late Oligocene time, but maximum differential displacement between the major basin and range structural blocks probably occurred between 10 and 3 Ma (Late Miocene to latest Pliocene). Almost all boundaries between major subbasins and flanking uplifts appear to be formed by zones of high-angle normal faults; many of the exposed mountain blocks on the western and southwestern basin margins are strongly tilted. However, dips appear to be relatively low in the central basin areas, and the major subbasins are here interpreted as gently tilted fault blocks that are bounded by high-angle normal faults that do not flatten significantly with depth (Mattick 1967, Collins and Raney 2000, Paine and Collins 2002).

By the end of the Middle Miocene (Fig. 6) rock debris eroded from bordering highlands and possibly from adjacent parts of the Rio Grande rift had filled existing subbasin fault blocks to the point where local intrabasin uplifts (horsts) were buried by *lower* to *middle* Santa Fe Group deposits. The broad topographic basin formed by this infilling process continued to aggrade as a single (*middle to upper Santa Fe*-age) unit during Pliocene and Early Pleistocene time (Vanderhill 1986; Mack et al. 1993, 1996, 2006; Hawley and Kennedy 2004, Mack 2004). 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 (Connell et al. 2005; Mack et al. 2006). The thickest Santa Fe Group fills in the Hueco and Tularosa (structural) basins are located in areas adjacent to the most active segments of major boundary fault zones (Plate 2a-i: Sections AA', BB', CC', DD', EKD', FF', GD', HH', and II').

3.2 General Hydrogeologic Setting

The hydrogeologic map and cross sections of the Hueco Bolson study area were primarily generated for long-term geohydrologic and hydrogeochemical research on basin-scale aquifer and groundwater-flow systems and derivative model development. For example, the color coding and symbolization for hydrostratigraphic units on the map and sections (Plates 1 and 2, Fig. 3) now conform to those used throughout a large *geohydrologic-modeling* region, which now extends from Caballo Reservoir to the El Paso/Hudspeth County Line (near Fabens and Tornillo). In addition to the western Hueco Bolson, this region now includes parts of the southern Palomas and Jornada del Muerto basins, the Mesilla Basin, and all of the Rincon and Mesilla valleys (Hawley and Kennedy 2004). These efforts are obviously works in progress that will be subject to additions and revisions as more basic data and interpretive material are incorporated into this provisional basin-framework model. One notable example of an ongoing hydrogeologic investigation is research by Dr. Rip Langford of the University of Texas-El Paso that includes detailed petrographic analyses of drill cuttings and further interpretation of geophysical data from deep EPWU wells recently drilled in the western Bolson area. Part 4 of this document includes a more thorough discussion of aquifer-system evolution, including some inferences on hydrogeologic controls on groudwater flow and geochemistry.

3.21 Hydrogeologic Map (Plate 1)

The hydrogeologic base map (Plate 1) shows both the surface expression of major bedrock and structural-boundary units of basin-border highlands and the distribution patterns of hydrostratigraphic units and fault zones of intermontane–basin areas. Locations of the eleven completed (but still preliminary) hydrogeologic sections are also indicated (Plate 2a-k, AA' to EKK'). The Texas and New Mexico parts of the map are accurate general portrayals of surficial geologic conditions, because they are primarily derived from maps based on 1:24,000-scale detailed-reconnaissance mapping (e.g., Collins and Raney 2000, Seager et al. 1987). If anything, Plate 1 still contains too much detail on the distribution of thin surficial-cover units, all of which are of "recent" alluvial and eolian origin and in the upper *vadose zone*. On the other hand, widespread complexes of small basin-floor depressions (e.g., unit BFP) include areas of ephemeral or former playa lakes that may have been significant paleo-recharge sites.

South of the international boundary (Rio Grande/Bravo corridor), mapping of surficial geologic and hydrologic units in most areas is of general reconnaissance level at best (INEGI 1982a-b, 1999). However, ongoing cooperative studies with the Centro de Información Geográfica at the Universidad Autónoma de Ciudad Juárez (UAJC), involving combined detailed remote sensing, *ground-truth* field checks, and analyses of shallow-drilling records and soil-survey information should soon produce a map product of equivalent quality to the hydrogeologic coverage north of the Rio Grande/Bravo.

An extremely important buried structural feature that is best described and illustrated by Collins and Raney (1991, 1994a, 2000) is shown by a NW-SE-trending dotted line on Plate 1 that roughly parallels the northeastern border of the Rio Grande/Bravo Valley. This line is here identified as the "limit of Laramide [Lower Tertiary–Paleogene] faulting," and it marks the inferred northeastern edge of a very complex system of thrust and reverse faults and asymmetric anticlinal and synclinal basins. According to current interpretations of Laramide tectonism, this buried structural complex was produced when Jurassic-evaporite and Cretaceous-carbonate terranes of the "Chihuahua trough" were *compressed* and *thrust* northeastward over the relatively stable Paleozoic bedrock terranes of the continental *craton* now represented by the Diablo Plateau-Otero Mesa structural province of the North American plate (Seager 2004).

During ongoing Rio Grande rift—Basin and Range extension, which began in this area in Late Oligocene time (Fig. 6), many of the compressional Laramide structures were reactivated with the opposite sense of displacement, producing an even more complex deformational pattern in Santa Fe Group and subjacent "lower basin fill" of Collins and Raney (1991; Plate 2f-i: Sections FF', GD' HH', II'). Of special interest is the observation that the alignment of a thick *ancestral Rio Grande* channel sequence, which is exposed in valley bluffs northeast of I-10 between Loop Highway 375 and Fabens (USF2-*LFAs 1-3*), appears to have been at least partly controlled by reactivated (Plio-Pleistocene) structures that follow the buried *Laramide* trend. As further discussed in Part 4.32, this major, cross-basin channel feature was first identified in early aeromagnetic-survey interpretations (Gates and Stanley 1976, Fig.5; Plate 2f-I, k: Sections FF', GD' HH', II' and EKK').

3.22 Hydrogeologic Cross Sections (Plate 2)

Intensive research on basin geology and hydrogeologic-model development has been in progress for more than four decades in the Mesilla Basin area. However, even with a much larger deep water-well database (e.g., sample-driller-geophysical-geochemical logs) in the Ciudad Juárez-El Paso/Ft Bliss metropolitan district, there has heretofore been no effort to develop a standard system (or *template*) for characterizing, classifying, and correlating hydrogeologic units in that or other parts of the Hueco Bolson. As already noted, the *schematic* cross sections, which are the major component of our digital hydrogeologic-framework model, represent the first phase of cooperative efforts in creating a valid conceptual and physical portrayal of Hueco Bolson hydrogeology. One important part of this process is to develop a product that will more effectively characterize the linkage between groundwater-flow systems in the latter area with those in the southern Mesilla Basin. For example, Figures 7 and 8 illustrate the hydrogeologic framework of the Paso del Norte bedrock constriction that separates the Mesilla and El Paso/Juárez Valley areas and are part of the recently completed digital model of aquifer systems in Mesilla-Jornada Basin/Rincon Valley area (Hawley and Kennedy 2004, Witcher et al. 2004). The major role that this constriction plays as a control on the geochemistry of deeply circulating groundwater in the southeastern Mesilla Basin has recently been documented by Hogan and others (2007).

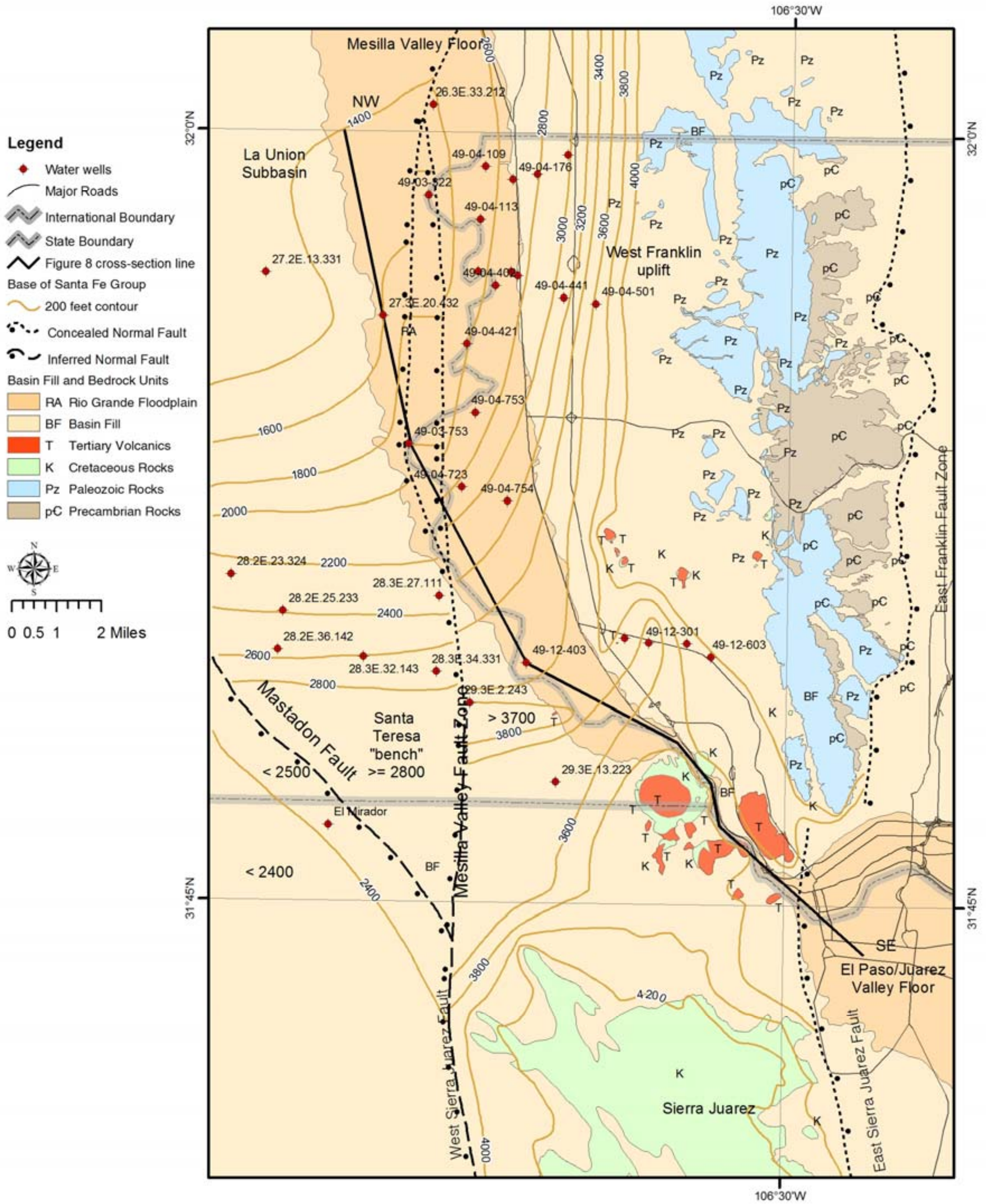


FIGURE 7. Structure-contour map of the base of Santa Fe Group basin fill in the Lower Mesilla Valley and Paso del Norte area, showing location of Figure 8 (NW-SE down-valley cross-section). From Hawley and Kennedy (2004).

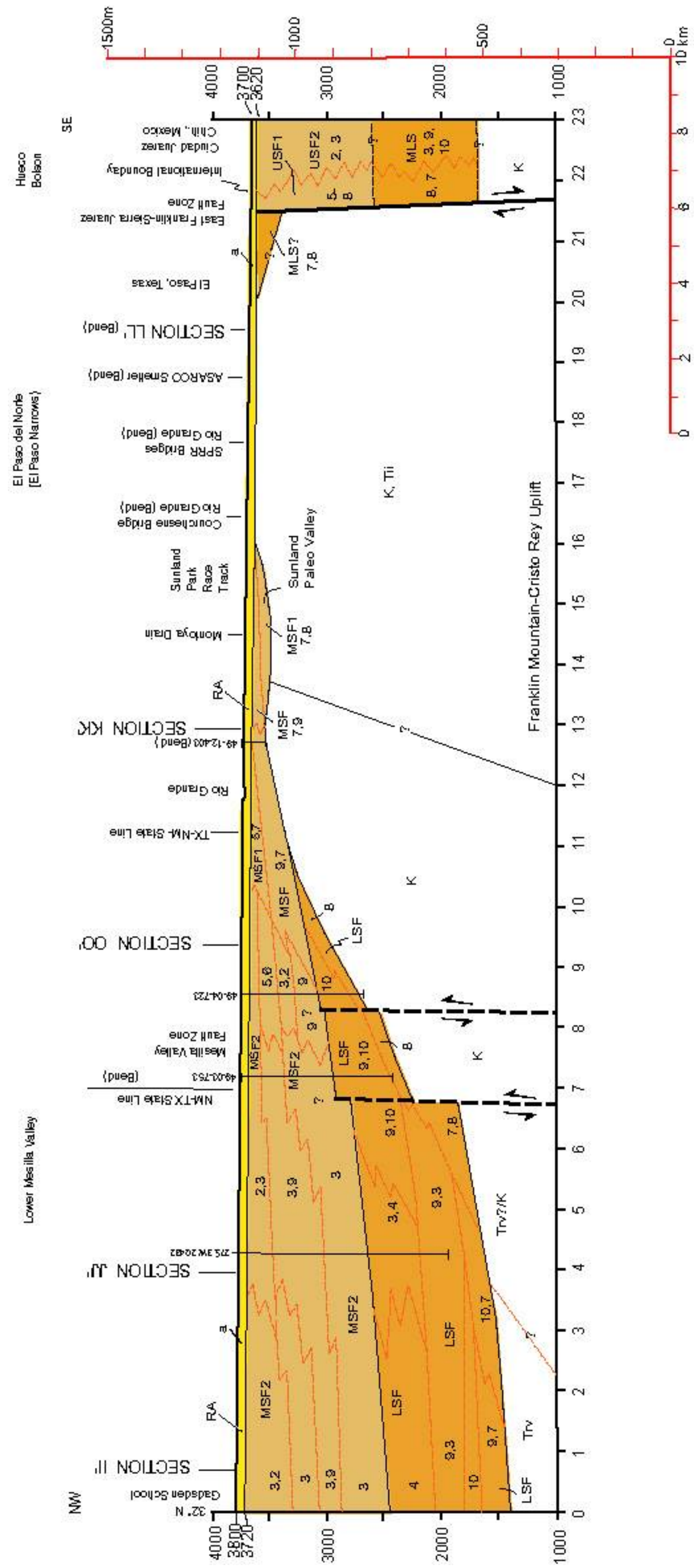


FIGURE 8. Down-valley hydrogeologic cross-section of the Lower Mesilla Valley-Paso del Norte reach of the Rio Grande Valley; Anthony-Gadsden School area (NW) to Central El Paso-Cd. Juárez (SE). River-valley fill at the Paso del Norte bedrock constriction is less than 1 km (0.6 mi) wide and 25 m (85 ft) thick. Line of section located on Figure 5. From Hawley and Kennedy (2004)

Our approach to cross-section construction was to start with and build upon published studies with high quality well-log data and interpretations and/or information from surface-geophysical surveys [gravity, seismic, resistivity and aeromagnetic (e.g., Knowles and Kennedy 1958, Audsley 1959, Leggat 1962, Leggat et al. 1962, Mattick 1967, Zohdy 1969, Buckner 1974, Gates and Stanley 1976, Uphoff 1978, Henry 1979, Henry and Gluck 1981, Daggett et al. 1986, Collins and Raney 1991, Keller et al. 1998, Kucks et al. 2001, Paine and Collins 2002)]. Hawley has also been especially fortunate in having been able to interact, at least briefly, with geologists and geophysicists who participated in early Hueco-Mesilla basin studies (e.g., R.L. Kennedy, E.R. Leggat, A.A. Zohdy, E.L. Uphoff, and C.D. Henry). In addition, his long-term association with Drs. W.S. Strain and E.M.P. Lovejoy (UTEP), Tom Cliett (EPWU), Eddie Collins (Texas Bureau of Economic Geology), and Drs. W.E. King and W.R. Seager have been of immeasurable value in developing concepts of basin tectonic and hydrogeologic framework. This approach to model development is illustrated amply by the provisional section interpretations presented in this report.

In order to provide overall basin characterization, the nine *transverse-basin* sections (Plate 2a-i:AA', BB', CC', DD', EKD', FF', GD', HH', and II') are almost evenly spaced between the Tularosa-Hueco basin boundary in New Mexico and the Fabens-San Elizario Island area of southeastern El Paso County (Fig. 3; Hibbs and Merino 2006, 2007). In addition, *longitudinal-basin* section JJ' is integrated with a *down-valley* section EKK' between El Paso del Norte and Fabens, and the latter section also connects with Mesilla Valley and Paso del Norte cross sections in our recent Mesilla Basin report (Hawley and Kennedy 2004; Figs. 5-2, 5-3; Plates 4f, 7).

Sections AA', BB', CC', and DD' (Plate 2a-d), illustrate the general half-graben-structural and lithofacies-distribution models first developed, respectively, by Mattick (1967) and Cliett (1969) for Hueco Bolson area in El Paso County north of US 180-62. Basin asymmetry is well illustrated by 1) the westward tilt of the Bolson (*half-graben*) block toward the eastern frontal fault zone of the Franklin Mountain (*footwall*) block, and 2) the concentration of thick (>1,000ft, >300m) ancestral Rio Grande deposits in adjacent parts of the basin (*hanging-wall*) block. It should be noted, moreover, that there has also been substantial displacement of faults along the Bolson’s eastern border with the “foothills” complex of the Hueco Mountain-Diablo Plateau uplift (Henry and Gluck 1981, Collins and Raney 2000, Granillo 2004). In addition, a large number of intrabasin faults, many of which were active during the Pleistocene, have been identified by Seager (1980), Seager and others (1987), Buck and others (1998), and Collins and Raney (1997, 2000), and Paine and Collins (2002). Of special significance to ongoing studies in the northeastern Bolson area (Plate 2c-h) is a detailed geophysical and hydrogeological survey by Paine and Collins (2002) to depths of about 920 ft (280 m) that clearly demonstrates tectonic controls on the position of one or more ancestral Rio Grande distributary channels in the Upper Santa Fe HSU (USF2).

Interpretations of southern parts of Sections GD', II', JJ', and the western segments of Sections EKK' and FF' were developed in collaboration with Dr. Barry Hibbs at California State University at Los Angeles, and Dr. Chris Eastoe at University of

Arizona-SAHRA. These cross sections (Plate 2f, g, i, j, k) illustrate the south to southeastward continuation of the *western basin-border* fault zone from the base of the Franklin Mountain block and across the upper end of El Paso/Juárez Valley to frontal-fault zones of the Sierra de Juárez and del Presidio uplifts. Moreover, much of central and southern Ciudad Juárez (business district to airport-industrial area) is underlain by the southward continuation of the thick, ancestral Rio Grande fluvial sequence (USF2/MSF2: *LFAs 1-3*) shown on Plate 2a-g (Sections AA' to GD').

Sections FF', GD', HH', II' (Plate 2f-i), and the southeastern half of Section EKK' (Plate 2k) illustrate the complex deep basin structure and fill stratigraphy that was briefly introduced in the preceding Hydrogeologic Map discussion (Part 3.21). Of great significance to conceptual models of basin-scale groundwater flow is the existence of a north-trending, western Hueco Bolson whose deep-basin structural framework is distinctly different from the NW-SE *structural grain* of the central and southern parts of the Bolson ("northwest vs. southeast subbasins" of Collins and Raney 1991). These "subbasins" are separated by major *intrabasin,* buried bedrock high near Clint (Plate 2h, k: Sections HH' and EKK'; Laramide "Clint fault" of Uphoff 1978, and Collins and Raney 1991, 1994a). Section II' (Plate 2i) also illustrates the inferred structural and stratigraphic relationships in and near the "ancestral-river channel" zone (Gates and Stanley 1976) between Fabens and the "San Felipe Arroyo" fault and the adjacent buried Laramide structural high. *Note that in areas of such structural complexity, 10x vertical exaggeration never permits accurate portrayal of geometric relationships.*

Comparison of borehole electric-log interpretations of the "older basin-fill" stratigraphy in the Fabens area, northern "southeast subbasin" of Collins and Raney (1991), with those for deep-basin deposits of the Mesilla and Jornada basins suggests that deepest parts of the central Hueco *structural* basin have thick sedimentary sequences that predate "upper basin-fill" (Santa Fe Gp) deposits associated with Rio Grande rift extension (*cf* Audsley 1959, Buckner 1974, Gates and Stanley 1976, Uphoff 1978, Seager et al. 1987, Hawley and Lozinsky 1992, Hawley and Kennedy 2004). Collins and Raney (1991, Fig. 2) tentatively correlated these units with early rift-basin fill deposited in Late Oligocene-Early Miocene time (Fig. 6: basal HSU-LSF). Our alternative interpretation is that the bulk of the "older basin-fill," which is deeply buried beneath the river-valley downstream from the Clint-San Elizario area (*cf* Collins and Raney 1991, Fig. 10b-f), was deposited in a synclinal basin complex formed during NE-directed *Laramide* compression of Early Tertiary (Paleogene) age (Plates 1 and 2: Tls).

4.0 HUECO BOLSON AQUIFER SYSTEM EVOLUTION AND SOME INFERENCES ON HYDROGEOLOGIC CONTROLS ON GROUNDWATER FLOW AND GEOCHEMISTRY

4.1 Background

Because the Hueco-Tularosa Basin system is part of the Neogene Rio Grande rift (RGr) tectonic zone (Fig. 1), the distribution of lithostratigraphic and hydrostratigraphic units and associated lithofacies assemblages (Plates 1 and 2) must be interpreted in terms of ongoing, but episodic crustal extension and basin subsidence (Machette 1987, Keaton 1993, Gile 1994, Collins and Raney 1994b, 1997, Kelley and Chapin 1997, Mack 2004). Regional extension and differential displacement, including rotation, of basin and range blocks clearly have acted 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 Pleistocene glacial-interglacial cycles, demonstrate that forces other than rift tectonism can also materially influence depositional processes (Gile et al. 1981, 1995, Leeder et al. 1996, Mack et al. 1997, 2006). However, considering the large time and space scales represented by Santa Fe Group deposits, structural deformation and associated igneous activity must be recognized as the major factors influencing the basin-formation/filling process.

The Lower Santa Fe hydrostratigraphic unit (Fig. 6-LSF: Early to Middle Miocene) and associated lithofacies assemblages (primarily *LFAs 3, 4, 7, 9, 10*) were deposited in a broad, shallow basin that predated major uplift of the flanking mountain and plateau blocks bounded by the East Organ-Franklin—Sierra Juarez-Presidio fault zone and (unnamed) western-boundary faults of the Diablo Plateau-Otero Mesa uplift (Plates 1 and 2a-i, Sections AA', BB', CC', DD', EKD', FF', GD', HH', and II'). The deepest and most actively subsiding part of the Hueco Bolson *half-graben complex* appears to be along its western and southwestern margins, east and northeast of the Franklin and Sierra Juárez-Presidio uplifts (Fig. 2).

With respect to the evolution of groundwater-flow and hydrogeochemical systems throughout the study area, Pleistocene onset of river-valley entrenchment has had profound implications (Fig. 6). Prior to about 700 thousand years ago, near the end of the Early Pleistocene, almost all of the Santa Fe Group beneath the floor of the Hueco Bolson was saturated. Subsequent (Middle and Late Pleistocene) Rio Grande/Bravo Valley incision has caused a water-table drop of 300 to 350 ft (~100m) beneath the extensive *mesa-surface* areas.

It is also important to note that analogs of early Pleistocene groundwater-flow regime and hydrogeochemical environments still exist both in the Tularosa Basin (Bedinger et al. 1989) and in the southern Mimbres River basin and Bolson de Los Muertos west and southwest of the southern Mesilla Basin (Figs. 2 and 10, Hawley et al. 2000 [Chapters 3 and 4], Hawley and Kennedy 2004). Recent studies at those localities provide excellent models of early stages of flow-system evolution throughout the Paso del Norte region (e.g., Love and Seager 1996, Mack et al. 1997, Hibbs et al. 1999). It must be emphasized, moreover, that because the lower Mimbres-Los Muertos basin system has continued to aggrade during the Middle and Late Quaternary, it is one of only two local basin-floor areas with significant groundwater-outflow potential, the other being the Tularosa Basin. The lacustrine deposits of "pluvial" Lake Palomas (Bolson de los Muertos-Castiglia and Fawcett 2006) and Lake Otero (northern Tularosa Basin–Lucas and Hawley 2002) demonstrate that paleo-water-table elevations during Late Pleistocene and Early Holocene deep-lake intervals were as much as 330ft (100m) higher than the lowest Late Quaternary potentiometric surface in the Paso del Norte-*Upper Valley* area (~3,970ft vs. 3,640ft, ~1210m vs 1110m).

4.2 Early-Stage Bolson Filling

Depositional environments in *lower Santa Fe time* contrast markedly with those in younger basin fill deposits based on petrographic studies of drill cuttings, and interpretations of borehole-sample, driller, and geophysical logs in nearby parts of the Mesilla Basin (Hawley and Lozinsky 1992, Hawley and Kennedy 2004). During early stages of rift-basin filling, the Mesilla-Los Muertos and Hueco-Tularosa basin systems received a major influx of fine- to medium-grained sediments (silt-clay to sand, *LFA*s *9, 10, 3, 4*) from adjacent upland source areas that were sites of late Eocene and Oligocene volcanic activity (Mack 2004). Ephemeral (playa) lake plains and alluvial flats with down-wind eolian depositional tracts were the primary environments of deposition (much like the present floors of Tularosa Basin and Bolson de los Muertos: Figs. 1 and 2). Because representative sections of the lower Santa Fe Group are not exposed and have only been penetrated by a few deep (hydrocarbon and water) exploration wells in the Hueco Bolson, formal lithostratigraphic nomenclature has never been developed. The Lower Santa Fe HSU (LSF), however, does appear to be generally correlative with the Hayner Ranch Fm of the Rincon Valley-San Diego Mountain area of Doña Ana County, NM (Seager et al. 1971, 1975, Seager and Hawley 1973, Hawley and Kennedy 2004).

Since higher-mountain terrains (such as the present San Andres-Organ-Franklin-Juarez chain) had not yet formed, wedges of coarse-gained piedmont deposits were limited to the outermost basin margins. A geohydrologically important lithofacies component of the Lower Santa Fe hydrostratigraphic unit (LSF: *LFA 4*) comprises thick deposits (up to 660ft, 200m) of fine to medium eolian sand, which are present in the deep-subsurface beneath the lower Mesilla Valley (including the EPWU-Canutillo well field area; Leggat et al. 1962, Cliett 1969, Wilson et al. 1981, Hawley and Lozinsky 1992, Nickerson and Myers 1993, Hawley and Kennedy 2004). This poorly consolidated lithofacies assemblage (*LFA*) is also extensively preserved beneath the eastern (leeward) part of the Hueco Bolson surface throughout the Santa Fe Gp. However, there it is thinner and interbedded with *LFA*s *3* and *5-9*. In the latter area, moreover, borehole electric logs and geochemical samples show that almost the entire saturated section of basin-fill deposits contains slightly saline-to-saline groundwater (Knowles and Kennedy 1958, Cliett 1969).

4.3 Middle and Late Stages of Bolson Filling

Distribution patterns of basin-floor and piedmont-slope lithofacies assemblages (*LFA*s *1-3, 9, 10*, and *5-8*) in Middle and Upper Santa Fe hydrostratigraphic units (HSU's MSF and USF) of the Hueco Bolson have also been mainly controlled by active differential subsidence of *half-graben* and *graben* basin blocks between the Franklin—Sierra Juarez-Presidio fault zone and the western boundary faults of the Diablo Plateau-Otero Mesa uplift (Plates 1 and 2a-i, Sections AA', BB', CC', DD', EKD', FF', GD', HH', and II'). *Note that coarse-grained piedmont-slope alluvium* (*LFA*s *5-8*) *is generally restricted to very narrow belts adjacent to these basin-border uplifts and most of the Bolson area is underlain by basin-floor lithofacies assemblages* (*LFA*s *1-3*, and *9*).

4.31 Middle to Upper Santa Fe Events

Structural deformation has produced at least 3,000ft (900m) of subsidence along the western Hueco Bolson margin since the Middle Miocene (past 11 Ma, Fig. 6), with thickest basin-floor sequences (both MSF2 and USF2) occurring along the western (*hanging-wall*) edge of west-tilted Tularosa Basin and Hueco Bolson (*half-graben*) blocks between the WSMR Headquarters area and Ciudad Juárez (Fig. 3). This defining feature of the western Hueco Bolson aquifer system is schematically illustrated on Plate 2a-g, j (Sections AA', BB', CC', DD', EKD', FF', GD', and JJ'). Substantial differential-subsidence has also occurred along intrabasin faults in all basins of the southern Rio Grande rift province in the past 5 million years, and tectonic processes clearly influenced the final position of the ancestral Rio Grande and the distribution patterns of Upper Santa Fe lithofacies assemblages. As already noted (Part 3.3), much of Ciudad Juárez (business district to airport-industrial area) is underlain by the southward continuation of the thick, ancestral Rio Grande fluvial sequence (USF2/MSF2: *LFA*s *1-3*) that is present in the Texas-New Mexico part of the western Hueco-Tularosa basin system.
Special Note: Pre-development southward groundwater flow in this primary aquifer system of the WSMR-Chaparral-Fort Bliss-El Paso-Ciudad Juárez corridor received mountain-front and tributary recharge from as far north as Fillmore Pass (Orr and Risser 1992) and Soledad Canyon (Organ Mountains, Naus 2002).

The Middle Santa Fe hydrostratigraphic unit (HSU-MSF) was deposited primarily during the Late Miocene time when accelerated basin subsidence occurred between the western Hueco Bolson block(s?) and the Organ-Franklin-Juarez-Presidio uplifts. Basin-floor lithofacies assemblages (*LFA*s) *3* and *9* are the major components of HSU-MSF2 in the broad central-basin area that extends east from the Franklin Mountain piedmont (U.S. 54-“War Highway” corridor) to the Hueco Mountain-Otero Mesa foothill belt (Plate 2a-e: Sections AA', BB', CC', DD', EKD'). This unit is more than 2,000 ft (600 m) thick in the most-rapidly subsiding western *half-graben* area of the Bolson. Only the uppermost part of this generally fine-grained sequence has interbedded sand strata with significant aquifer potential, and water quality is usually *marginal* (slightly saline) even in productive-sand zones. The primary lithofacies assemblages (*LFA*s *3* and *9*) were deposited in alluvial-flat and ephemeral-lake environments (Table 1).

Complex intertonguing of piedmont-slope and basin-floor sediments is observed in the *middle* Santa Fe unit beneath the eastern part of the Bolson floor (Plate 2a-e: Sections AA', BB', CC', DD', EKD'). Detailed analyses of drillers and sample logs (Knowles and Kennedy 1958) show a mixture of piedmont-alluvial and basin-floor facies derived from both local and *extra-basin* sources. As early as four million years ago (4 Ma), a precursor to the through-going (ancestral) Rio Grande system entered the northwestern part of the

Bolson via Fillmore Pass (Figs. 3 and 9), and it contributed large volumes of fluvial sand and mud to actively subsiding areas adjacent of the Organ and Franklin (*footwall*) uplifts during latest stages of Middle Santa Fe deposition. These sediments prograded over and intertongued with alluvial-flat and playa-lake facies that continued to be deposited in the central and southeastern parts of the Hueco Bolson system (Stuart and Willingham 1984). In the Hudspeth County *type area* of the Fort Hancock Fm (mid- to upper Santa Fe) and the Camp Rice Fm (upper Santa Fe), the Fort Hancock (>2.5 Ma) is primarily an ephemeral-lake deposit, and the Camp Rice (<2.5 Ma) records the entry of the ancestral Rio Grande fluvial system into the southeastern Hueco Bolson (Strain 1966, Hawley et al. 1969, Vanderhill 1986, Gustavson 1991).

4.32 Upper Santa Fe Events

Upper Santa Fe Group sedimentation processes have been influenced by a complex combination of active but episodic tectonism and cyclic shifts in a semiarid to arid climatic regime (Gile et al. 1981, 1995, Mack and Seager 1990, Leeder et al. 1996, Mack et al. 1997, 2006). During a 3 million-yr interval of Pliocene and Early Pleistocene time (Fig. 6), distributaries of the ancestral upper Rio Grande, which headed as far north as the San Juan and Latir volcanic fields (Southern Rocky Mtns., Fig. 1), delivered large volumes of sediments to basins of the southern Rio Grande rift region (Fig. 9, *cf*. Gile et al. 1981, Fig. 5, Connell et al. 2005, Fig. 11). These deposits make up the bulk of the Upper Santa Fe HSU (USF) in the Mesilla Basin-Hueco Bolson area. Prior to its integration with lower Rio Grande/Bravo drainage to the Gulf of Mexico, this major fluvial system discharged at various times into playa-lake depressions of an initially *closed* Hueco-Tularosa basin complex (via Fillmore Pass, Figs. 3 and 9, Plate 2a: Section AA'), as well as to the southern Mimbres Basin and Bolson de Los Muertos (Strain, 1966; Hawley 1969, 1975; Reeves 1969, Gile et al., 1981; Seager, 1981; Seager et al., 1987; Mack et al. 1997, 2006; Hawley and Kennedy 2004, Connell et al. 2005). Long-time UTEP Geology Professor, W.S. Strain (1966) named the complex of ephemeral and perennial lakes collectively that occupied much of the region's basin floors, *Lake Cabeza de Vaca* (after the early Spanish explorer Alvar Nuñez Cabeza de Vaca-*circa* 1536).

It is now well documented that part of the "Fillmore Pass" distributary channel network (**Fig. 9**), which was active between about 2 and 3.5 Ma, extended southward through the *type area* of the *upper* Santa Fe-Camp Rice Formation near Fort Hancock in Hudspeth County, TX (Strain 1966, Hawley 1975, Gates and Stanley 1976, Gustavson 1991). An ash-fall bed derived from the 2.01 Ma Huckleberry Ridge eruption of the Yellowstone volcanic center is preserved in lower Camp Rice fluvial deposits at 2 localities northeast of Fort Hancock (Izett and Wilcox 1982). In addition, the Camp Rice type section contains a Blancan vertebrate fauna (Early Pleistocene, Fig. 6) and is within the early Matuyama (~1.9 to 2.6 Ma) magneto-stratigraphic chron (Vanderhill 1986, Connell et al. 2005, Mack et al. 2006).

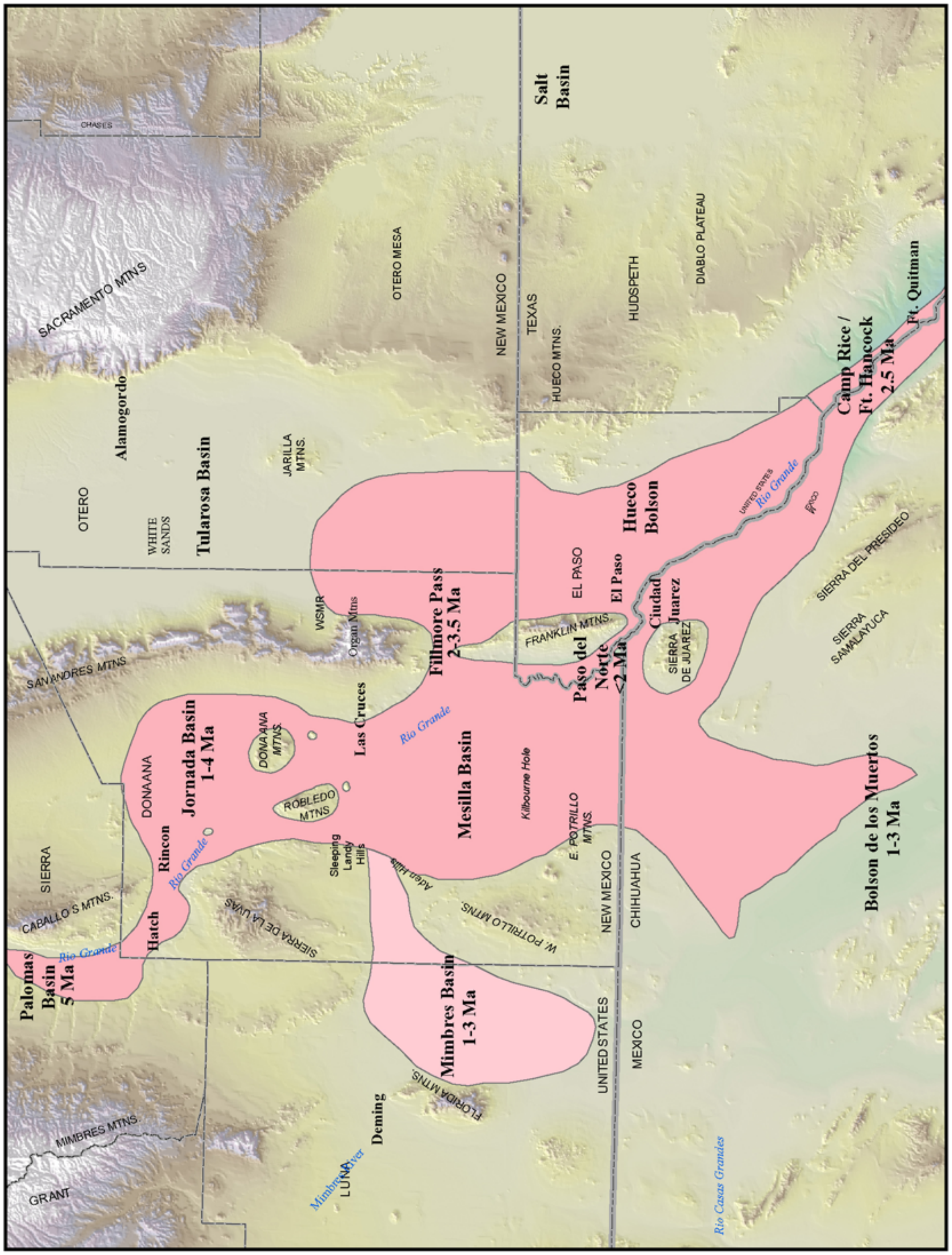


FIGURE 9. Evolution of the Ancestral Rio Grande fluvial system (pink) during the Pliocene and Early Pleistocene.

The final stage of widespread basin aggradation in the Hueco Bolson-Mesilla Basin region (USF2: *LFA*s *1* and *2*) also occurred during major eruptions in the Jemez volcanic field (Fig. 1: JMVF) that produced the Bandelier Tuff (Valles caldera) and Puye Fm between 1 and 5 million years ago (Mack et al. 1996, 1997, 2006, Goff and Gardner 2004, Mack 2004, Connell et al. 2005). Upper Santa Fe beds contain silicic tephra (ash-fallout and water-transported pumice) from these eruptions and include beds of pumice (~2 Ma) on both sides of Fillmore Pass (Mack et al. 1996). The latter deposits demonstrate conclusively that the ancestral Rio Grande was flowing through the Pass into the Tularosa Basin-Hueco Bolson area as early as 3.5 Ma and as late as 2 Ma. During that interval braided to meandering distributaries of the ancestral river shifted across a broad fluvial plain that included not only the Hueco Bolson floor, but also much of the Mesilla and southern Tularosa Basins (Fig. 9, Hawley et al. 1969, Hawley 1975, Fig. 2; Gile et al. 1981; Seager 1981; Seager et al. 1987; Collins and Raney 2000; Fig. 5; Connell et al. 2005, Fig 11b-c, Mack et al. 2006, Fig. 8).

Medium- to coarse-grained (USF2) fluvial deposits are locally as much as 1,000 ft (300m) thick in the most-rapidly subsiding part of the western Hueco Bolson *half-graben*. This area extends across the upper reach of the El Paso/Juárez Valley to the airport-industrial district of Ciudad Juárez (Plates 1 and 2). Between the latter area and White Sands Missile Range Headquarters in the Tularosa Basin (Fig. 2), a narrow zone of intertonguing ancestral Rio Grande and piedmont-slope facies assemblages characterizes the Upper Santa Fe HSU along the eastern base of the Sierra Juárez, Franklin, and Organ fault-block uplifts (Plates 2a-g and 2j: Sections AA'-GD' and JJ'; *LFA*s *1-3, 5-8*). We concur with Gates and Stanley (1976, p. 33, Fig. 5) that the fluvial-channel sequence of medium- to coarse-grained deposits (USF2-*LFA*s *2* and *1*) is a continuation of the same "channel feature" that they identified in a series of 40 detailed aeromagnetic surveys between Ysleta-Zaragosa and Fort Hancock (USF2, Plate 2g, I, k: Sections GD' to II' and EKK'). Furthermore, these sediments are at least in part correlative with the Strain's (1966) type-section of the Camp Rice Formation near McNary.

Sometime in the early Pleistocene, probably by 2 Ma, differential mountain uplift and basin subsidence along the Organ-Franklin-Sierra Juárez frontal fault zone caused a permanent shift of ancestral Rio Grande distributaries into the southern Mesilla Basin. Once fluvial aggradation of the Hueco Bolson essentially ceased, a *relict* bolson plain with numerous playa-lake depressions (Plate 1, BF/USLM) would have quickly developed across much of the basin-floor east of Fillmore Pass and El Paso del Norte. While the western Bolson area continued to receive some fresh-water recharge from the eastern Organ-Franklin Mountain watersheds, the major river-recharge source would have been abruptly cut off. By early Middle Pleistocene time (about 0.7 Ma), however, the ancestral (upper) Rio Grande was again flowing into the Hueco structural basin via the Paso del Norte saddle between the Franklin and Juárez uplifts (Figs. 6 and 7). Rapid, but episodic incision of El Paso del Norte and the El Paso-Juárez Valley would have been well under way by 0.64 Ma. This is the age of a Yellowstone-derived volcanic-ash bed (Lava Creek-B) that is preserved in a high river-terrace remnant about 250ft (75m) above the present Rio Grande floodplain in the ASARCO-UTEP-Mesa Street area (Hawley et al. 1969, 1976, Izett and Wilcox 1982, Hawley and Kennedy 2004, Plate 4f).

These well-documented, but only approximately dated, intrabasin/interbasin shifts in ancestral-Rio Grande distributaries during bolson late aggradation and subsequent river-valley entrenchment have had profound impacts on not only deposition environments, but also the evolution of groundwater-flow and hydrogeochemical regimes throughout the Mesilla Basin and Hueco Bolson region (Fig. 9). A very important remaining question relates to how many *evulsive* shifts of ancestral-river distributaries occurred between the western Hueco and southern Mesilla structural basins during an Upper Santa Fe depositional interval of at least 1.5 million years. This query is of particular concern with respect to the origin and distribution of lithofacies assemblages in the upper El Paso/Juárez Valley "artesian area," and their influence on groundwater flow and chemistry (e.g., Leggat 1962, Gates et al. 1980, White et al. 1997, Hibbs et al. 1997, 2003, Hibbs and Merino 2006, 2007, Druhan et al. 2008, Eastoe et al. 2008, Hutchison and Hibbs 2008; Plates 2j-k: Sections JJ' and EKK'), and it is currently being addressed in ongoing cooperative studies with EPWU and other institutions.

4.4 Quarternary Bolson Evolution, Including River-Fall Incision

Late Cenozoic tectonism is still the primary control on the general trends of the Mesilla and Lower (El Paso/Juárez) Valleys, including the reach between Paso del Norte and Fort Quitman (southeastern Hueco Bolson). Significant (up to 100ft, 30m) movement along segments of the major basin-bounding and intrabasin fault zones (Plates 1 and 2) has continued episodically in post-Santa Fe time. Middle and Late Quaternary piedmont-slope deposits (HSUs PA and USF1) units are offset along segments of the East Franklin-Organ fault zone, and Late Pleistocene offset on basin-boundary faults has also been documented in the southeastern part of the Hueco Bolson near Fort Hancock (Harbour 1972, Lovejoy and Hawley 1978, Gile et al. 1981, Seager 1981, Machette 1987, Seager et al. 1987, Hawley and Lozinsky 1992, Keaton 1993, Gile 1994, Collins and Raney 1991, 1994b, 1997, 2000, Hawley and Kennedy 2004).

Re-establishment of a through-going fluvial system late in the Early Pleistocene, including integration with glaciated-headwaters basins in the Southern Rocky Mountain, resulted in episodic entrenchment of the present river valley (Kottlowski 1958, Hawley and Kottlowski 1969, Hawley 1975, Gile et al. 1981, 1995, Connell et al. 2005 [Fig. 11], Mack et al. 2006). From a geohydrologic perspective, Middle to Late Pleistocene valley incision has also caused progressive drainage of aquifers in contiguous "alluvial-basin" (bolson) areas (Fig. 10; *cf.* Gile et al. 1981, p. 56, Fig. 6). This geomorphic process has had profound geohydrologic and hydrochemical effects on both groundwater and surface-water systems that are just beginning to be understood, but addressing the topic is well beyond the scope of our study.

The final episode of major valley entrenchment and widening occurred sometime during the last full-glacial (pluvial) cycle, at least 10,000 to 25,000 years ago (Hawley 1975). Since that time, the entire river-valley floor from the Albuquerque-Santo Domingo Basin through the Hueco Bolson (Map 1) has back-filled about 60 to 100ft (18-30m) to form HSU-RA, with *LFA*s *a1* and *a2* making up the dominant lithofacies assemblage. The only significant difference between HSU-RA: *LFA a* and basin-fill ancestral-river deposits (HSU-USF2: *LFA*s *1-3*) is that 1) the former unit contains no zones of secondary-carbonate accumulation and/or cementation, and 2) it is commonly coarser grained. The following observations by Hawley and Kottlowski (1969, p. 98) are especially relevant to characterization of Late Quaternary fluvial deposits associated with the inner valley of the Rio Grande throughout Mesilla Basin-Paso del Norte-Hueco Bolson area:

> The maximum stage of entrenchment of the Rio Grande in latest Pleistocene time . . . may be represented by a buried surface occurring at relatively shallow depths below the present floodplain surface (Lee [1907]; Kottlowski, 1958; Hawley, 1965). Information from well drillers, examination of cuttings from several wells, and review of information on local ground-water conditions (Sayre and Livingstone, 1945; Conover, 1954; Leggat, Lowry, and Hood, [1962]; Davie and Spiegel, 1967) indicate that the late Quaternary river deposits extend no more that 80 feet (24 meters) below the floodplain level. The depth represents the approximate thickness of unconsolidated sediments over bedrock at the International Dam site in El Paso ([Fig. 5 and 6] Slichter, 1905) and over Tertiary volcanics and sediments in the lower Selden Canyon area [at head of the Mesilla Valley]. The deepest occurrence of [river-channel] gravels below the floodplain (more than 200 feet-61 meters-near Las Cruces) does not represent the depth of late Quaternary entrenchment (Conover [1954]) or the depth of scour of great floods (Bryan [1938]). Rather, these deeper gravels are part of ancient basin fill [Upper Santa Fe Group] and are stratigraphically below the basin deposits exposed in the valley walls.

Outside of the valleys of the Rio Grande and its major arroyo tributaries, adjacent bolson surfaces stabilized or continued to aggrade, particularly on distal piedmont slopes and playa-lake plains (Figs. 5 and 10). With respect to the evolution of groundwater-flow and geochemical systems in the Hueco Bolson-southern Mesilla Basin area, the Middle and Late Quaternary depositional history of the Tularosa (*Lake Otero*) Basin, Bolson de los Muertos and lower Mimbres Basin is also very important (Fig. 10; Lucas and Hawley 2002, Mack 2004, Connell et al. 2005, Hawley 2005). For example, lacustrine deposits (both lake-floor and strand-line) of pluvial-Lake Palomas (Reeves 1969) 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 and downstream in Paso del Norte-El Paso/Juarez Valley reach (Figs. 7 and 8, Hawley et al. 2000, Hawley and Kennedy 2004, Castiglia and Fawcett 2006).

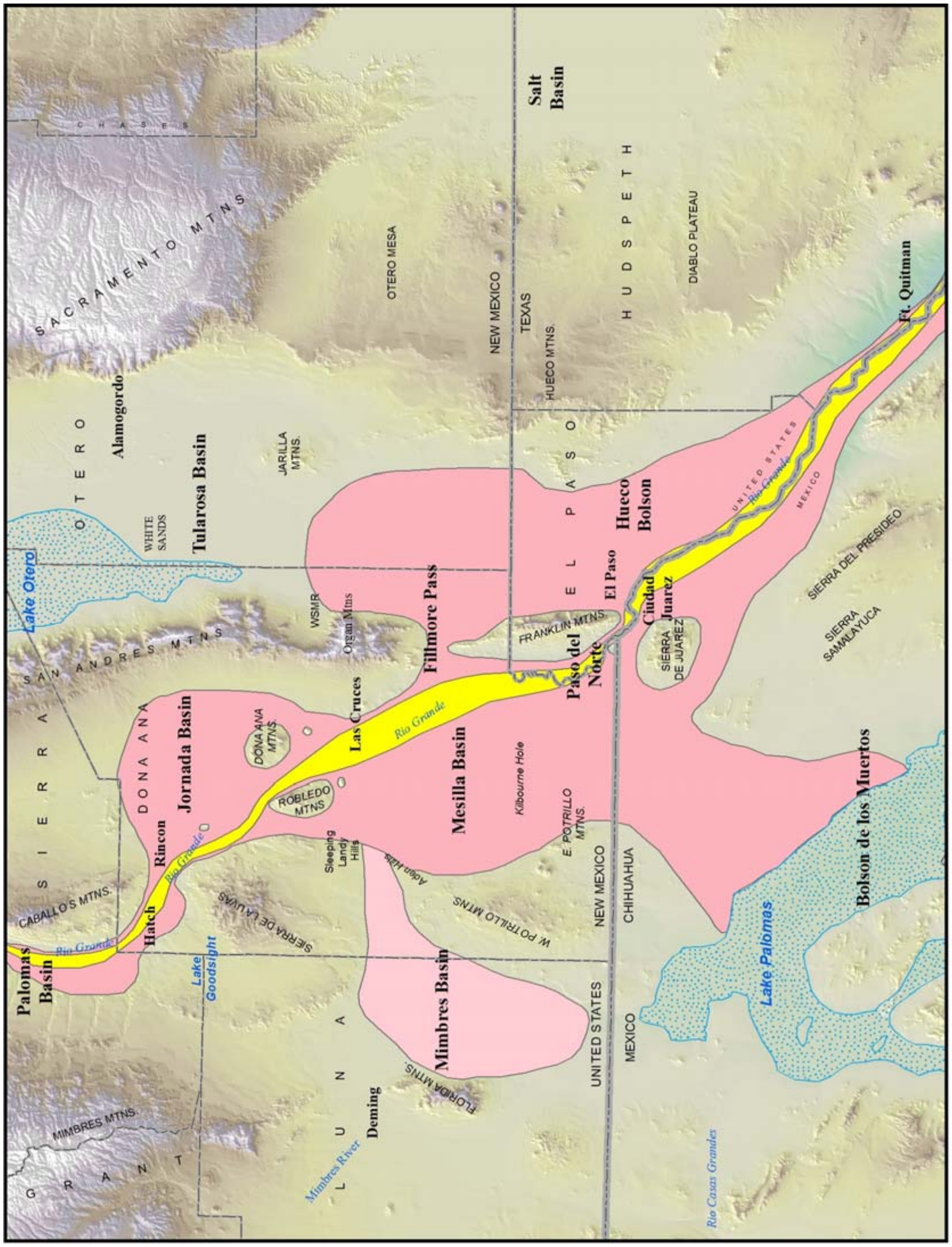


FIGURE 10. Entrenched Late Quaternary Rio Grande Valley (yellow) and lacustrine plains (stippled light green) of pluvial-Lakes Palomas (Bolson de los Muertos) and Otero (Tularosa Basin) in relation to ancestral Rio Grande fluvial deposits (pink).

5.0 CONCLUDING REMARKS

Our study represents the first synoptic integration of hydrogeologic information on the Hueco Bolson-Paso del Norte region in a digital GIS format. The study area includes the eastern part of the binational, tri-state El Paso-Ciudad Juárez metropolitan district in Texas, New Mexico, and Chihuahua (Figs. 2, 3, and 7; Plate 1). 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. Emphasis here is on 1) the hydrogeologic framework of intermontane-basin and river-valley fills, which collectively form the Hueco Bolson aquifer system; and 2) the major hydrogeologic controls on groundwater flow and chemistry within this complex of basin deposits and bedrock-boundary units.

While all geology-based models are "works in progress," we believe that this digital hydrogeologic model represents a significant scientific and technological advance over previous work (Figs. 7 and 8; Plates 1 and 2). The study is a continuation of a series of recent binational and multi-state investigations of "alluvial-aquifer" systems in the Trans-Pecos Texas-New Mexico-Chihuahua border region. Emphasis has been on development of GIS coverages related to hydrogeology, geohydrology, and hydrogeochemistry (*cf.* Hibbs et al. 1997, 1998, 1999, 2003, Kennedy et al. 2000, Hawley and Kernodle 2000, Hawley et al. 2000, 2001, Hawley and Kennedy 2004, Witcher et al. 2004, Creel et al. 2006, Granados-Olivas et al. 2006, Hibbs and Merino 2006, Hogan et al. 2007, Druham et al. 2008, Hutchison and Hibbs 2008).

Where and how do we proceed in future phases of this binational, interdisciplinary, and multi-institutional "Hydrogeologic and Water Quality Study of the Hueco Bolson Aquifer?" From our perspective, one very high-priority area simply relates to the myriad basic-data gaps that must be filled before truly robust well-log, geophysical, and hydrogeochemical databases can be developed. For example, a comprehensive database (spreadsheet format) needs to be developed that includes not only standard information on all well-control sites, but also the best-available interpretations of hydrostratigraphy and hydrogeochemistry. Examples of this type of well-data compilation are available in Hawley and Kennedy (2004), and ongoing EPWU work in the Canutillo well field area. This of course requires not only well-funded, state-of–the-art binational GIS programs, but also mechanisms for archiving items such as borehole cuttings and cores, and *hard-copy* materials that are not now or may never be *computer friendly*. The defining characteristic of the current project that must be nourished is the synergistic atmosphere of unfettered collaboration between geologists, hydrologists, isotope-geochemists, GIS specialists, students, and practitioners in a variety of other related disciplines.

CITED REFERENCES

Abeyta, C.G., 1996, Geohydrologic site characterization of the municipal solid waste landfill facility, U.S. Army Air Defense Artillery Center and Fort Bliss, El Paso County, Texas: U.S. Geological Survey Water-Resources Investigations Report 95-4217, 36p.

Albritton, C.C., Jr., and J.F. Smith, Jr., 1965, Geology of the Sierra Blanca area, Hudspeth County, Texas: U. S. Geological Survey Professional Paper 594-J, 131p.

Allen, B.D., 2005, Ice Age lakes in New Mexico, *in* Lucas, S. G., Morgan, G., and Zeigler, K.E., eds, 2005, New Mexico's Ice Ages: New Mexico Museum of Natural History & Science Bulletin No. 28, p. 107-114.

Alvarez, H.J., and A.W. Buckner, 1980, Ground-water development in the El Paso region, Texas, with emphasis on the resources of the lower El Paso Valley: Texas Department of Water Resources Report 246, 346p.

Anderholm, S.K., 2000, 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, 36p.

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, 16p.

Audsley, G.L., 1959, Records of wells and results of exploratory drilling by the Texas Water Development Board in the vicinity of San Elizario, Texas: U.S. Geological Survey Open-File Report, 144p.

Barker, D. E., 1997, Tertiary alkaline magmatism in Trans-Pecos Texas: Geological Society of America, Special Publication No. 30, p. 415-431.

Bedinger, M.S., K.A. Sargent, and W.H. Langer, eds., 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, 42p.

Boyle Engineering Corporation, 2000, El Paso Las Cruces regional sustainable water project: hydrologic modeling report, draft final: Boyle Engineering Corporation, Parsons Engineering Science, Inc., Albuquerque, New Mexico, 202p.

Bryan, K., 1938, Geology and groundwater conditions of the Rio Grande depression in Colorado and New Mexico; *in* [U.S.] Natural Resources Committee, Regional Planning part VI–The Rio Grande joint investigations in the upper Rio Grande basin in Colorado, New Mexico, and Texas, 1936-1937: Washington, D. C., U. S. Government Printing Office, v. 1, part 2, p. 197-225.

Buck, B.J., 1996, Late Quaternary landscape evolution, paleoclimate, and geoarchaeology, southern New Mexico and west Texas: Las Cruces, New Mexico State University, unpublished Ph.D. dissertation, 381p.

Buck, B.J., J.M. Kipp, Jr., and H.C. Monger, 1998, Eolian stratigraphy of intrabasinal fault depressions in the northern Hueco and southern Tularosa Basins: Evidence for neotectonic activity: New Mexico Geological Society, 49th Field Conference, p. 79-86.

Buckner, A.W., 1974, Results of exploratory drilling in the El Paso Valley and Hueco Bolson southeast of El Paso, Texas of the El Paso Valley, Texas: Texas Water Development Board, Open-File Report, 42p.

Buszka, P.M., R.D. Brock, and R.P. Hooper, 1994, Hydrogeology and selected water-quality aspects of the Hueco Bolson aquifer at the Hueco Bolson Recharge Project area, El Paso, Texas: U.S Geological Survey Water-Resources Investigations Report 94-4092, 41p.

Castiglia, P.J., and P.J. Fawcett, 2006, Large Holocene lakes and climate change in the Chihuahuan Desert: Geology, v. 34, no. 2, p. 113-116.

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* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift–structure, stratigraphy, and tectonic setting. Geological Society of America Special Paper 291, p. 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, Guidebook 26, p. 297-321.

Cliett, T., 1969, Groundwater occurrence of the El Paso area and its related geology: New Mexico Geological Society Guidebook, 20th Field Conference, p. 209-214.
Collins, E.W., and J.A. Raney, 1991, Tertiary and Quaternary structure and paleotectonics of the Hueco Basin, Trans-Pecos Texas and Chihuahua, Mexico: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular GC 91-2, 44p.
Collins, E.W., and J.A. Raney, 1994a, Impact of late Cenozoic extension on Laramide overthrust belt and Diablo platform margins, northwestern Trans-Pecos Texas: New Mexico Bureau of Mines and Mineral Resources Bulletin 150, p. 71-81.
Collins, E.W., and J.A. Raney, 1994b, Tertiary and Quaternary tectonics of the Hueco Bolson, Trans-Pecos Texas and Chihuahua, Mexico, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift–structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 265-282.
Collins, E.W., and J.A. Raney, 1997, Quaternary faults within intermontane basins of northwest Trans-Pecos Texas and Chihuahua, Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 245, 59p.
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., J.W. Hawley, and D.W. Love, 2005, Late Cenozoic drainage development in the southeastern Basin and Range of New Mexico, southeasternmost Arizona and western Texas, *in* Lucas, S. G., Morgan, G., and Zeigler, K.E., eds., New Mexico's Ice Ages: New Mexico Museum of Natural History & Science Bulletin No. 28, p. 125-150.
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, 200p.
Córdoba, D.A., S.A. Wengerd, and J.W. Shomaker, (eds.), 1969, Guidebook of the Border Region: New Mexico Geological Society Guidebook, 20th Field Conference, 218p.
Creel, B.J., J.W. Hawley, J.F. Kennedy, and A. Granados-Olivas, 2006, Groundwater resources of the New Mexico-Texas-Chihuahua border region: New Mexico Journal of Science, v. 46, p. 11-29.
Daggett, P.H., G.R. Keller, P. Morgan, and C.L. Wen, 1986, Structure of the southern Rio Grande rift from gravity interpretation: Journal of Geophysical Research, v. 91, n. B6, p. 6157-6167.
Davie, W. Jr., and Z. Spiegel, 1967, Geology and water resources of Las Animas Creek and vicinity, Sierra County, New Mexico: New Mexico State Engineer, Hydrographic Survey Report, 44p.
Druhan, J.L., J.F. Hogan, C.J. Eastoe B.J. Hibbs, and W.R. Hutchison, 2008, Hydrogeologic controls on groundwater recharge and salinization: a geochemical analysis of the northern Hueco Bolson aquifer, Texas, USA: Hydrogeology Journal, v. 16, no. 2, p. 281-296.
Eakin, T.E., D. Price, and J.R. Harill, 1976, Summary appraisals of the nation's ground-water resources–Great Basin region: U.S. Geological Survey Professional Paper 813-G, 37p.
Eastoe C.J., Hibbs, B.J., Granados-Olivas, A., Hogan, J.F., Hawley, J., and Hutchison, W.R., 2008, Isotopes in the Hueco Bolson aquifer, Texas (USA) and Chihuahua (Mexico): Local and general implications for recharge sources in alluvial basins: Hydrogeology Journal, v. 16, no. 4, p. 737-747.
Feth, J.H., 1964, Hidden recharge: Ground Water, v. 2, no. 4, p.14-17.
Fenneman, N.M., 1931, Physiography of the western United States: New York, McGraw- Hill Book Co., 534p.
Figuers, S.H., 1987. Structural geology and geophysics of the Pipeline complex, northern Franklin Mountains, El Paso, Texas: [unpublished Ph.D. thesis]: El Paso, University of Texas, 279p.
Gates, J.S., and W.D. Stanley, 1976, Hydrologic interpretation of geophysical data from the southeastern Hueco Bolson, El Paso and Hudspeth Counties, Texas: U.S. Geological Survey Open-File Report 76-650, 37p.
Gates, J. S., D.E. White, W.D. Stanley, and H.D. Ackermann, 1980, Availability of fresh and slightly saline ground water in the basins of westernmost Texas: Texas Department of Water Resources, Report 256, 108p.
Gile, L.H., 1994, Soils, geomorphology, and multiple displacements along the Organ Mountains fault in southern New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 133, 91p.

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

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, 96p.

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

Goff, F., and J.N. Gardner, 2004, Late Cenozoic geochronology of volcanism and mineralization in the Jemez Mountains and Valles caldera, north-central New Mexico; *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico: A geologic history: New Mexico Geological Society, Special Publication 11, p. 295-312.

Granados-Olivas, A., and T. Kretzschmar, 2001, Uso de sistemas de informacíon Geográfica y sistemas de teledetecció en la identificación y mapeo de potenciales zonas de recarga hacia acuiferos del Desierto Chihuahua: VIII Reunión Nacional sobre Sistemas de Captación de Agua de Lluvia, Cd. Chihuahua, Chih, SEMARNAT [Mexico]. 17p.

Granados-Olivas, A., B. Creel, J. Kennedy, and R. Aldouri, 2001, Water planning GIS for the Paso del Norte region, *in* Aldama, A., Aparicio, F.J., and Equihua, R., eds. First International Symposium on Transboundary Waters Management, Proceedings: Asociación Mexicana de Hidráulica, Avances en Hidráulica 10, p.147-154.

Granados-Olivas, A., C. Brown, J. Greenlee, B. Creel, J.W. Hawley, J. Kennedy, O. Dena-Ornelas, and B. Hurd, 2006, Geographic information systems at the Paso del Norte region. The academic accomplishments and challenges for a Transboundary water resources GIS cooperation: New Mexico Journal of Science, v. 46, p. 45-56.

Granillo, J.A., Jr., 2004, A gravimetric study of the structure of the northeast portion of the Hueco Bolson, Texas employing GIS technology [M.S. thesis]: The University of Texas at El Paso, 127p.

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 198, 49p.

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

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

Hawley, J.W., 1965, Geomorphic surfaces along the Rio Grande Valley from El Paso, Texas to Caballo Reservoir, New Mexico: New Mexico Geological Society Guidebook 16, p. 188-198.

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

Hawley, J.W., 1975, Quaternary history of Doña Ana County region, south-central New Mexico: New Mexico Geological Society, 26th Annual Field Conference, Guidebook, p. 139-150.

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, 241p.

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, 10p.

Hawley, J.W., 1993, Geomorphic setting and late Quaternary history of pluvial-lake basins in the southern New Mexico region: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 391, 28p.

Hawley, J.W., 2005, Five million years of landscape evolution in New Mexico: An overview based on two centuries of geomorphic conceptual-model development, *in* Lucas, S. G., Morgan, G., and Zeigler, K.E., eds, New Mexico's Ice Ages: New Mexico Museum of Natural History & Science Bulletin No. 28, p. 9-93.

Hawley, J.W., and J.F. Kennedy, 2004-2005, Creation of a digital hydrogeologic framework model of the Mesilla Basin and southern Jornada del Muerto Basin: N. M. Water Resources Research Institute, NMSU; prepared for Lower Rio Grande Water Users Organization; Technical Completion Report 332, 105p., with CD ROM including *2005 Addendum extending model into Rincon Valley and adjacent areas*. http://wrri.nmsu.edu/publish/techrpt/tr332/downl.html

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* Ortega-Klett, C.T., ed., Proceedings of the 44th Annual New Mexico Water Conference: New Mexico Water Resources Research Institute Report 312, p. 79-102. http://wrri.nmsu.edu/publish/watcon/proc/proc44/contents.html

Hawley, J.W., and F.E. Kottlowski, 1969, Quaternary geology of the south-central New Mexico border region, *in* Kottlowski, F.E., and Le Mone, D.V., eds., Border stratigraphy symposium: New Mexico Bureau of Mines and Mineral Resources, Circular 104, p. 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, 55p.

Hawley, J.W., and W.E. Wilson, III, 1965, Quaternary geology of the Winnemucca area, Nevada: Desert Research Institute, Univ. of Nevada, Technical Report 5, 66p.

Hawley, J.W., G.O. Bachman, and K. Manley, 1976, Quaternary stratigraphy in the Basin and Range and Great Plains provinces, New Mexico and western Texas, *in* Mahaney, W.C., ed., Quaternary stratigraphy of North America: Stroudsburg, PA, Dowden, Hutchinson, and Ross, p. 235-274.

Hawley, J.W., C.S. Haase, and R.P. Lozinsky, 1995, An underground view of the Albuquerque Basin, New Mexico, *in* Ortega-Klett, C. T., ed., Proceedings of the 39th Annual New Mexico Water Conference, New Mexico Water Resource Research Institute Report 290, p. 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 hydrogeolgic framework and related aspects of groundwater flow and chemistry, *in* Mace, R.E., Mullican, W.F. III, and Angle, E.S., eds., Aquifers of West Texas: Texas Water Development Board Report 356, p. 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), p. 164-172 [electronic version available on request].

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

Hawley, J.W., B.J. Hibbs, J.F. Kennedy, B.J. Creel, M.D. Remmenga, M. Johnson, M.M. Lee, and P. Dinterman, P., 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, 126p. http://wrri.nmsu.edu/publish/otherrept/swnm/downl.html

Henry, C.D., 1979, Geologic setting and geochemistry of thermal water and geothermal assessment, Trans-Pecos Texas: Texas Bureau of Economic Geology, Report of Investigations 96, 48p.

Henry, C.D., and J.K. Gluck, 1981, A preliminary assessment of the geologic setting, hydrology, and geochemistry of the Hueco Tanks geothermal area, Texas and New Mexico: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 81-1, 48p.

Henry, C.D., and J.G. Price, 1985, Summary of the tectonic development of Trans-Pecos Texas: The University of Texas at Austin, Bureau of Economic Geology, Miscellaneous Map No. 36, 8p.

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. 27p.

Hibbs, B.J., and B.K. Darling. 2005. Revisiting a classification scheme for U.S.-Mexico alluvial basin-fill aquifers. Ground Water. 43.5:750-763.

Hibbs, B. J., and M. Merino, 2006, A geologic source of salinity in the Rio Grande aquifer near El Paso, Texas: New Mexico Journal of Science, v. 46, p. 165-181.
Hibbs, B.J., and M. Merino, 2007, Discovering a geologic salinity source in the Rio Grande: Southwest Hydrology, v. 6, no. 4, p. 20-21, 33.
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, v. 15, no. 1-4, p. 52-65.
Hibbs, B.J., B.J. Creel, R. Boghici, M. Hayes, J. Ashworth, A. Hanson, Z. Samani, J.F. Kennedy, P. Hann, and K. Stevens, 1997, Transboundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region: U.S. Environmental Protection Agency, Region 6; Technical Contract Report prepared by the Texas Water Development Board and the New Mexico Water Resources Research Institute.
Hibbs, B., F. Phillips, J. Hogan, C. Eastoe, J. Hawley, A. Granados, and B. Hutchison, 2003, Hydrogeologic and Isotopic Study of the Groundwater Resources of the Hueco Bolson Aquifer El Paso/Juárez Area: Hydrological Science and Technology, v. 19, no. 1-4, p. 109-119.
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. Nunez, 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 database, City of El Paso/Ciudad Juarez area; Base de datos binacional del acuifero transfronterizo, de Ciudad Juarez, Chih./El Paso, Tex.: first binational aquifer report and database sanctioned by the governments of the United States and Mexico, 47p. + 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 Juarez.
Hill, R.T., 1896, Descriptive topographic terms of Spanish America: National Geographic, v. 7, p. 291-302.
Hill, R.T., 1900, Physical geography of the Texas region: U. S. Geological Survey Topographical Atlas Folio 3, 12p.
Hogan, J.E., F.M. Phillips, and B.R. Scanlon, 2004, Introduction and overview, *in* Groundwater recharge in a desert environment: the southwestern United States: Washington, DC, American Geophysical Union, Water Science and Application 9, p. 1-14.
Hogan, J.F., F.M. Phillips, S. K. Mills, J.M.H. Hendrickx, J.T. Ruiz, J.T. Chesley, and Y. Asmeron, 2007, Geologic origins of salinization in a semi-arid river: The role of sedimentary basin brines: Geology, v. 35, no. 12, p. 1063-1066.
Hutchison, W.R., 2006, Groundwater management in El Paso, Texas: Ph.D. Dissertation, Center for Environmental Resource Management, The University of Texas at El Paso. Dissertation.com, Boca Raton, FL, 329p.
Hutchison, W.R., and B.J. Hibbs, 2008, Ground water budget analysis and cross-formational leakage in an arid basin: Ground Water, v. 46, no. 3, p. 384-395.
INEGI, 1982a, Ciudad Juárez H13-1, Cartas Geologica: SPP Programación y Presupuesto. Coordinación General de los Servicios Nacionales de Estadistica, Geografía e Informática. Dirección General de Geografía del Territorio Nacional. Escala 1:250,000.
INEGI, 1982b, Ciudad Juárez H13-1, Cartas Hidrologica de Aguas: SPP Programación y Presupuesto. Coordinación General de los Servicios Nacionales de Estadistica, Geogafía e Informática. Dirección General de Geografía del Territorio Nacional. Escala 1:250,000.
INEGI, 1999, Estudio Hidrológico del Estado Chihuahua: Instituto Nacional de Estadistíca, Geografía e Informática; Dirección General de Difusión, 222p. http://inegi.gob.mx
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.
Keaton, J.R., 1993, Maps of potential earthquake hazards in the urban area of El Paso, Texas: U.S. Geological Survey, technical report prepared under contract 1434-92-G-2171, 87p.

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, 304p.
Keller, G.R., B.S. Penn, B.S., and S.H. Harder, 1998, Las Cruces country: a geophysical and remote sensing perspective: New Mexico Geological Society Guidebook, 49th Field Conference, p. 87-91.
Kelley, S.A., C.E. and Chapin, 1997, Cooling histories of mountain ranges in the southern Rio Grande rift based on apatite fission-track analysis – a reconnaissance survey: New Mexico Geology, v. 19, no. 1, p. 1-14.
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., 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, Guidebook 51st Field Conference, p. 235-244.
Kernodle, J.M., 1992, 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, 81p.
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, 64p.
Knowles, D.B., and Kennedy, R. A., 1958, Ground-water resources of the Hueco Bolson northeast of El Paso, Texas: U.S. Geological Survey, Water-Supply Paper 1426, 186p.
Kottlowski, F.E., 1958, Geologic history of the Rio Grande near El Paso: West Texas Geological Society, Guidebook 1958 Field Trip, p. 46-54.
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, version 1.0: U.S. Geological Survey Open-File Report 01-0061. Available at: http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-01-061
Langford, R.P., 2003, The Holocene History of the White Sands Dune Field and influences on Eolian Deflation and Playa Lakes. Quaternary International, v. 104, p. 31-39.
Lee, W.T., 1907, Water resources of the Rio Grande Valley in New Mexico: U.S. Geological Survey, Water-Supply Paper 188, 59p.
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, v. 24, no. 1, p. 87-90.
Leggat, E.R., 1962, Development of ground-water of the El Paso district, Texas: Texas Water Commission, Bulletin 6204, 56p.
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.
LeMone, D.V., and E.M.P. Lovejoy, eds., 1976, El Paso Geological Society symposium on the stratigraphy and structure of the Franklin Mountains: El Paso Geological Society, Quinn Memorial Volume, 250p.
Love, D.W., and W.R. Seager, 1996, Fluvial fans and related basin deposits of the Mimbres drainage: New Mexico Geology, v. 18, p. 81-92.
Lovejoy, E.M.P., ed., 1979, Sierra de Juarez, Chihuahua, Mexico: Structure and history: El Paso Geological Society, Special Publication, 59p.
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, p. 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, v. 8, no. 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, Guidebook 53, p. 277-283.
Mace, R.E., W.F. Mullican, III, and E.S. Angle, 2001, eds., Aquifers of West Texas: Austin, Texas Water Development Board Report 356, 272p. http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20 Report%20htm%20files/Report%20356.htm

Machette, M.N., 1987, Preliminary assessment of paleoseismicity at White Sands Missile Range, southern New Mexico: Evidence for recency of faulting, fault segmentation, and repeat intervals for major earthquakes in the region: U.S. Geological Survey, Open-File Report 87-444, 46p.

Mack, G.H., 2004, Middle and late Cenozoic crustal extension, sedimentation, and volcanism in the southern Rio Grande rift, Basin and Range, and southern Transition Zone of southwestern New Mexico; *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico: A geologic history: New Mexico Geological Society, Special Publication 11, p. 389-406.

Mack, G. H., and K.A. Giles, eds., 2004, The geology of New Mexico, A geologic history: New Mexico Geological Society, Special Publication 11, 474p.

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, v. 102, p. 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, v. 44, p. 637-652.

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, v. 293, p. 49-77.

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, v. 103, p. 1-8.

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, Guidebook 49th Field Conference, p. 229-236.

Mack, G.H., W.R. Seager, M.R. Leeder, M. Perea-Arlucea, and S.L. Salyards, 2006, Pliocene and Quaternary history of the Rio Grande, the axial river of the southern Rio Grande rift, New Mexico, USA: Earth-Science Reviews, v. 77, p. 141-162.

Mattick, R.E., 1967, A seismic and gravity profile across the Hueco bolson, Texas: U.S. Geological Survey, Professional Paper 575-D, p. D85-D91.

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

Meyer, W.R., 1976, Digital model for simulated effects of ground water pumping in the Hueco Bolson, El Paso area, Texas, New Mexico, and Mexico: U.S. Geological Survey Water-Resources Investigations 58-75, 31p.

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

Monger, H.C., 1993, Soil-geomorphic and paleoclimatic characteristics of the Fort Bliss Maneuver Areas, southern New Mexico and western Texas: U.S. Army Air Defense Artillery Center, Fort Bliss; Directorate of Environment; Environment Management Division, Cultural Resources Branch; Historic and Natural Resources Report No.10, 233p.

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

Nickerson, E.L., 2006, Description of piezometers and ground-water-quality characteristics at three new sites in the Lower Mesilla Valley, Texas, and New Mexico: U.S. Geological Survey Scientific Investigations Report 2005-5248, 27p. Persistent URL: http://pubs.water.usgs.gov/sir20055248

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, 89p.

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, 92p.

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, 88p.

Paine, J.G., and E.W. Collins, 2002, Evaluating potential groundwater resources on State Lands in El Paso County, Texas using airborne geophysics: Report prepared by the University of Texas Bureau of Economic Geology for the General Land Office under contract no. 02-306R, 87p.

Pazzaglia, F.J., and J.W. Hawley, 2004, Neogene (rift flank) and Quaternary geology and geomorphology, *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico: A geologic history: New Mexico Geological Society, Special Publication 11, p. 407-438.

Plummer, L.N., L.M. Bexfield, S.K. Anderholm, W.E. Sanford, and E. Busenberg, 2004, Hydrochemical tracers in the Middle Rio Grande basin, USA: 1. Conceptualization of groundwater flow: Hydrogeology Journal, v. 12, no. 4, p. 359-388.

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

Sanford, W.E., L.N. Plummer, D.P. McAda, L.M. Bexfield, and S.K. Anderholm, 2004, Hydrochemical tracers in the Middle Rio Grande basin, USA: 2. Calibration of a groundwater-flow model: Hydrogeology Journal, v. 12, no. 4, p. 389-407.

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

Scanlon, B.R., 2004, Evaluation of methods of estimating recharge in semiarid and arid regions in the southwestern U.S., *in* Groundwater recharge in a desert environment: the southwestern United States: Washington, DC, American Geophysical Union, Water Science and Application 9, p. 235-254.

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

Schmidt, R.H. Jr., 1973, A geographical survey of Chihuahua: El Paso, Texas Western Press (UTEP), Southwestern Studies Monograph No. 37, 63p.

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, Chihuahuan Desert Research Institute, October, 1983, p. 40-63.

Seaber, P.R., 1988, Hydrostratigraphic units, *in* Back, W., Rosenshein, J.S., and Seaber, P.R., eds., Geology of North America–Hydrogeology: Geological Society of America, Decade of North American Geology, v. 0-2, p. 69-78.

Seager, W.R., 1980, Quaternary fault system in the Tularosa and Hueco Basins, southern New Mexico and west Texas: New Mexico Geological Society Guidebook, 31st Field Conference, p. 131-135.

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, 97p.

Seager, W.R., 2004, Laramide (late Cretaceous to Eocene) tectonics of southwestern New Mexico; *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico: A geologic history: New Mexico Geological Society, Special Publication 11, p. 183-202.

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

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, 38p.

Seager, W.R., J.W. Hawley, F.E. Kottlowski, and S.A. Kelley, 1987, Geologic map of east half of Las Cruces and northeast El Paso 1º x 2º sheets, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 57, scale: 1:125,000, 3 sheets.

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

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

Seager, W.R., M. Shafiqullah, J.W. Hawley, and R.F. Marvin, 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande: Geological Society of America Bulletin, v. 95, no.1, p. 87-99.

Secretaria de Programación y Presupuesto (SPP), 1981, Carta Hidrologica: Aguas Subterráneas, Chihuahua: Escala 1:1,000,000.

Sharp, J.M., Jr., 2001, Regional groundwater flow systems in basins in Trans-Pecos Texas, *in* Mace, R.E., Mullican, W.F. III, and Angle, E.S., eds., Aquifers of West Texas: Austin, Texas Water Development Board Report 356, p. 66-75.

Sheng, Z., and J. Devere, 2005, Understanding and managing the stressed Mexico-USA transboundary aquifer in the Hueco bolson aquifer in the El Paso del Norte region as a complex system: Hydrogeology Journal, v. 13, no. 5-6, p. 813-825.

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

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

Stuart, C.J., and D.L. Willingham, 1984, Late Tertiary and Quaternary fluvial deposits in the Mesilla and Hueco bolsons, El Paso area, Texas: Sedimentary Geology, v. 38, p. 1-20.

Tight, W.G., 1905, Bolson plains of the Southwest: American Geologist, v. 36, p. 271-284.

Tolman, C.F., 1909, Erosion and deposition in southern Arizona bolson region: Journal of Geology, v. 17, p. 136-163.

Tremblay, T.A., 1999, ARCINFO database for geologic data of the west Hueco Bolson, El Paso region, Texas: The University of Texas at Austin, Bureau of Economic Geology, open-file digital database.

Uphoff, T.L., 1978, Subsurface stratigraphy and structure of the Mesilla and Hueco bolsons, El Paso region, Texas and New Mexico [M.S. thesis]: The University of Texas at El Paso, 66p.

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

Van Devender, T.R., 1990, Late Quaternary vegetation and climate of the Chihuahuan Desert, United States and Mexico; *in* Betancourt, J. L., Van Devender, T. R., and Martin, P. S., eds. Packrat middens, the last 40,000 years of biotic change: Tucson, University of Arizona Pres, p. 104-133.

Walker, J.D., and J.W. Geissman, compilers, 2009, Commentary –2009 Geologic Time Scale: GSA Today, v. 19, no. 4/5, p. 6061.

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. 8p.

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. 43p.

Wilson, C.A., R.R. White, B.R., Orr, and R.G. Roybal, 1981, Water resources of the Rincon and Mesilla Valleys and adjacent areas, New Mexico: New Mexico State Engineer, Technical Report 43, 514p.

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, 126p.

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 Institute, Technical Completion Report—Account No. 01-4-23960B, New Mexico State University, Las Cruces, 168 p., with appendices and plates on CD ROM.

White, D.E., 1983, Summary of hydrologic information in the El Paso, Texas area, with emphasis on ground-water studies, 1903-1980: U.S. Geological Survey Open-File Report 83-775, 77p.

White, D.E., E.T. Baker, Jr., and R. Sperka, 1997, Hydrology of the shallow aquifer and uppermost semiconfined aquifer near El Paso, Texas: U.S. Geological Survey Water-Resources Investigations Report 97-4263, 37p.

Zohdy, A.A.R., 1969, The use of Schlumberger and equatorial soundings in groundwater investigations near El Paso, Texas: Geophysics, v. 34, p. 713-728.