APPENDIX H

HISTORICAL BACKGROUND ON DEVELOPMENT OF SHARED GROUNDWATER RESOURCES IN THE BINATIONAL SOUTHERN MESILLA BASIN REGION— A HYDROGEOLOGICAL PERSPECTIVE

H1. INTRODUCTION

> **The Paso del Norte on the U.S.-Mexico Border** is [in] a region where economic, social, and cultural lives are intertwined. However, management of natural resources faces sometimes insufficient communication among government agencies responsible for their well-being. The international dimension of the region aggravates the lack of coordination among government agencies of both countries. As the region's main aquifer, the Hueco Bolson's ability to support the region's water needs is coming to an end. Additionally, there is no legal framework that could facilitate the process of bringing all the parties together on common grounds to address the situation. As population growth is expected to continue, so is the demand for water. The white map syndrome, when nothing is considered to exist on the other side of a border line, is a fact of life in the region. The cities of El Paso and Ciudad Juárez are one large metroplex with two distinct water systems. Unless all the actors in the region really work together to jointly develop alternatives for future water supply, the region is on a collision path. Water is a precious resource anywhere, especially in the desert. . . . (Octavio E. Chávez* 2000, p. 237).
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Shared Water-Resource Management in a Binational/Tristate Geopolitical Setting

Emphasis of this "White Paper" supplement to NM WRRI TCR-363 is on the hydrogeological and geopolitical factors that impact the development of shared groundwater resources in the context of the contemporary "realties" of water supply and demand in an arid-semiarid region with a population now approaching 2.5 million. The Report itself represents the first substantial effort by a U.S.-based entity to address Octavio Chávez's "white map syndrome" problem by *filling in* the major gaps in hydrogeologic-framework characterization (*cf.* **Figs. H1-3** and **H1-10**). Brief definitions of commonly used terms in reports on geologic, geohydrologic, and hydrogeologic investigations are listed in **Table H1-1**, primary divisions of Geologic Time are defined in **Table H1-2**, and **Table H1-3** is a compilation of published sources of information that relate to the hydrogeology of the southern Mesilla Basin Region (MBR).

No major physiographic barriers separate the United States and Mexico throughout much of the boundary region west of El Paso del Norte (**EPdN**; *cf.* Hawley 1969b and 1975a, Hawley et al. 2000 and 2005, Rebert 2001). What joins the two nations is an extensive shared aquifer system (Hawley et. al. 2000, 2005 and 2009). Existing barriers to effective communication, on the other hand, are primarily geopolitical in nature, and reflect a long history of cultural and military conflict, some of which date back to the wars of 1836 to 1848 and the early (1836-1848) era of Anglo-American "Manifest Destiny" (**Part H3.3.3**).

Table H1-1. Definitions of Selected Geologic, Geohydrologic, and Hydrogeologic Terms

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Aquifer: A *saturated* geologic unit that is permeable enough to transmit significant quantities of water under ordinary hydraulic gradients (Deming 2002, p. 429).

Aquiclude: A rock layer that completely excludes fluid flow through it. Geologic aquicludes are rare (Deming 2002, p. 429).

Aquitard: A stratum that transmit quantities of water that are very significant for a variety of geologic problems, but is inadequate for supplying economic quantities of water to wells (Deming 2002, p. 429).

Brackish Groundwater (BGW): There are 2 classes of BGW: (1) slightly saline—1,000-3,000 mg/L TDS; and (2) moderately saline—3,000 to 10,000 mg/L TDS (Stanton et al. 2017, Tbl. 1).

Endorheic: pertaining to a closed surface-drainage basin (*cf. exorheic*).

Exorheic: pertaining to an open surface-drainage basin (*cf. endorheic*).

Geology: The study of the planet Earth, the materials of which it is made, the processes that act on these materials, the products formed, and the history of the planet and its life forms since its origin (Neuendorf et al. 2005, p. 267).

Geomorphology: The science that treats the general configuration of the earth's surface; specifically, the study of the classification, description, nature, origin, and development of landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

Groundwater: *Subsurface water* that is in the *saturated* zone (Neuendorf et al. 2005, p. 286).

Hydrology: The study of the occurrence and movement of water at and beneath the surface of the Earth, the properties of water, and its relationship with living and material components of the environment (Hornberger et al. 1998, p. 282).

Hydrogeology [also Geohydrology]: A branch of *hydrology* that studies underground fluids and their interaction with *solid geologic materials* (Deming 2002, p. 433).

Hydrostatic Level: The level to which water will rise in a well under its full [hydrostatic] pressure head. It defines the *potentiometric surface* (Neuendorf et al. 2005, p. 313).

Hydrostatic Pressure: The pressure exerted by the water at any given point in a body of water (Neuendorf et al. 2005, p. 313).

Phreatic Water: (1) A term that was originally applied to only to the water that occurs in the upper part of the saturated zone under water-table conditions (syn. of *unconfined groundwater*), but (2) has come to be applied to all water in the saturated zone (i.e., groundwater [and/or *phreatic zone*]) (Neuendorf et al. 2005, p. 489).

Potentiometric Surface: A surface that depicts the distribution of hydraulic heads in a *confined aquifer*; the water [level] in a well or piezometer penetrating the *confined aquifer* defines that surface (Hornberger et al. 1998, p. 286).

Rift Zone: A large region where Earth-crustal extension results in formation of an array of kinematically related faults, along with associated grabens, half grabens, and horsts. Some active rift zones [like the RG rift] have associated volcanic activity. Many such zones are broad with distributed faults and evolve into deep troughs filled with very thick sequences of sedimentary deposits (Neuendorf et al. 2005, p. 555).

Saturated Zone: A region of the subsurface where pores are completely filled with water; it is bounded at the top by the water table (Hornberger et al. 1998, p. 287).

Subsurface Water: A non-specific term commonly applied to all water below the land surface.

Vadose Zone: The zone in soils or rocks between the Earth's surface and the *water table*; pores are partly filled with water and partly filled with air (Hornberger et al. 1998, p. 291).

Water Table: A surface separating the *saturated* and *unsaturated* zones . . . [that is] defined as a surface at which the fluid pressure is atmospheric (Hornberger et al. 1998, p. 292).

Table H1-2. Divisions of Geologic Time Referred to in this Report

ERA	Period	Epoch (**u/m/l***)	Age (years**)
CENOZOIC (Cz)			
	Post-Quaternary?	Anthropocene?***	Future to 1950? CE
	Quaternary (**Q**)		1950? CE-2.6 Ma
		American SW Histori	*Present-1540 CE*
	Holocene (Qu)		1950? CE-11,700
		Pleistocene	11,700-2.6 Ma
		Late (**Qu**)	11,700-126 ka
		Middle (**Qm**)	126 ka-780 ka
		Early (**Ql**)	780 ka-2.6 Ma
	Tertiary (**T**)		2.6 Ma-65.5 Ma
		Late: Neogene	
		Pliocene (**Tu**)	2.6-5.3 Ma
		Late	2.6-3.6 Ma
		Early	3.6-5.3 Ma
		Miocene (**Tu**)	5.3-23 Ma
		Late	5.3-11.6 Ma
		Middle	11.6-16 Ma
		Early	16-23 Ma
		Early: Paleogene	
		Oligocene (**Tm**)	23-34 Ma
		Eocene (**Tl**)	34-55.8 Ma
		Paleocene (**Tl**)	55.8-65.5 Ma
MESOZOIC (**Mz**)			
	Cretaceous (**K**)		65.5-145.5 Ma
	Jurassic (**Jr**)		145.5-199.6 Ma
	Triassic (**Tr**)		199.6-251 Ma
PALEOZOIC (Pz)			
	Permian (**P**, **Pzu**)		251-299 Ma
	Pennsylvanian (**Pn**, **Pzu**)		299-318 Ma
	Mississippian (**M**, **Pzu**)		318-359 Ma
	Devonian (**D**, **Pzl**)		359-416 Ma
	Silurian (**S**, **Pzl**)		416-444 Ma
	Ordovician (**O**, **Pzl**)		444-488 Ma
	Cambrian (**C**, **Pzl**)		488-542 Ma
PRECAMBIAN-PROTEROZOIC (**XY**)			542 Ma-2.5 Ba
PRECAMBIAN-ARCHAEN (**Z**)			2.5-3.85 Ba

Modified *from* Koning and Read (2010, Table 2; *cf.* Gibbard et al. 2010, Gradstein et al. 2012)
*u/m/l = upper/middle/lower –lithostratigraphic units
**Ba=billion years, Ma=million years, and ka=thousand years
*** https://www.nytimes.com/2024/03/05/climate/anthropocene-epoch-vote-rejected.html?unlocked_article_code=1.aU0.Yoaa.8m5-c7KcfueD&smid=em-share

Table H1-3. Selected Information Sources that Relate to the Hydrogeology of the Borderlands

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A. Published information on the hydrogeologic framework of basin-fill aquifers in the United States part of the southern MBR has four primary sources:

1. Government documents on the geology and groundwater condition in the southern Mesilla Basin Region (e.g., Kottlowski 1960, Leggat et al. 1962, Strain 1966, King et al. 1969 and 1971, Wilson et al. 1981, Bedinger et al. 1989b, Gustavson 1991a, Hawley and Lozinsky 1992, Nickerson and Myers 1993, and Nickerson 2006).
2. Surficial-geologic mapping at a detailed-reconnaissance level, with limited deep-borehole control (e.g., Cliett 1969, Hoffer 1976, Dyer 1989, Drewes and Dyer 1993, Seager et al. 1987, Seager and Mack 1994, Seager 1995, Cliett and Hawley 1996, Collins and Raney 2000, and Hoffer 2001a,b).
3. Reconnaissance-level geophysical surveys (gravity and seismic), with limited deep-borehole control (e.g., Ramberg et al. 1978, Daggett and Keller 1987 and 1995, Adams and Keller 1994, and Klein 1995).
4. Reconnaissance-level geothermal-resource surveys, with some deep-borehole-log control (e.g., Henry 1979, Henry and Gluck 1981, Henry and Price 1985, and Snyder 1986).

B. Available published information on the hydrogeologic framework of basin-fill aquifers in the part of the MBR Chihuahua has five primary sources:

1. Geological and geophysical field investigations of a reconnaissance nature published by Mexican federal agencies, universities and binational geoscientific societies, with facsimile copies of some reports included in **Appendix D** (e.g., Guerrero 1969, Hawley 1969b, Tovar et al. 1978, Cantú-Chapa et al. 1985, SGM 1985, Araurjo-Mendieta and Casar-González 1987, Limón-González 1986, Márquez-Alameda 1992, Zwanzinger 1992, Monreal and Longoria 1999, Lawton 2004, Seager 2004, Carciumaru 2005).
2. Map-based reports on the geology and hydrogeology of northern Chihuahua by Mexican Federal agencies, primarily the Secretaria de Recursos Hidráulicos (SRH) and Instituto Nacional de Estadistíca, Geográfica e Informática (INEGI) published between 1982 and 2012 (e.g., Flores-Mata et al. 1973, SPP 1981, INEGI 1983b-cj, 1999, 2012, *cf.* IBWC 2010). The INEGI (1983b) database for 17 wells inventoried in 1982 provided a source of information on aquifer type, static water level, and water chemistry that was essential for (1) the compilation of Hawley and others (2024) **TABLE 1** and **PLATE 4,** and (2) overall hydrogeologic-framework-model development (*cf.* SARH 1988, Gutiérrez-Ojeda 2001).
3. Reports with maps on the geology and geomorphology of Chihuahua by universities located in both Mexico and the United States, with some investigations involving collaboration with U.S. federal and state agencies. Most were published between 1969 and 1993 (e.g., Bell 1963, Berg 1969, Córdoba 1969a,b, Reeves 1969, Webb 1969, Córdoba et al. 1970, Flores Mata 1970, Schmidt 1973, Lovejoy 1976a and 1979, Schmidt and Marston 1981, Gómez 1983, Chávez-Quirarte 1986, Dyer 1987 and 1989, Hoover et al. 1988, Reyes Cortés 1992, Schmidt 1992, Drewes and Dyer 1993, Haenggi 2001 and 2002, Granados Olivas 2000).
4. Reports on oil and gas exploration drilling, which in this case only involved one deep borehole in the Study Area, the 16,218 ft (4.943 m) Pemex No. 1-Moyotes Well (Thompson et al. 1978; Tovar-R et al. 1978).
5. Three 1:50,000-scale—15 x 20-min. topographic maps (INEGI Cartas topográficas) that cover the area between the International Boundary and 31°30′ N latitude, and 106°30′ and 107°30′ W longitude: Hoja Nos. H13A25-Cuidad Juárez, H13A24-Los Chontes, and H13A23-Nuevo Cuauhtémoc. Even with a minimum-contour interval of 10 m and general absence of ephemeral drainageways on the nearly level basin floors, these maps still allowed approximate delineation of major hydrographic boundaries, particularly where supplemented by Google Earth® imagery.

C. Published information on the geologic framework of the southern MBR that includes reports on oil and gas exploration, geophysical surveys (gravity and seismic) and hydrogeology (e.g., Morrison 1969, Lovejoy 1976b, Thompson et al. 1978, Woodward et al. 1978, Gries 1979, Thompson 1982b, Hibbs et al. 1999, Jiménez and Keller 2000, Hawley et al. 2000 and 2005, Hoffer 2001b, Heywood and Yager 2003, Lawton 2004, Seager 2004, Eastoe et al. 2008, Hawley et al. 2009, IBWC 2010, Lucas et al. 2010, Averill and Miller 2013, Hibbs et al. 2015).

H1.1. Historical Background

The "Pass of the North" region was first "visited" in late 1535 by the Álvar Núñez Cabeza de Vaca party (Adorno and Pautz 1999), and then "explored" in 1581 and 1583 during the Chamuscado-Rodríguez and Antonio de Espejo (Espejo-Beltrán) expeditions (**Part H3.1.1**). In terms of the first *Divine Mandate* for territorial and ideological "conquest," that historical event occurred near the present site of San Elizario (TX) on April 30, 1598 when "Don Juan de Oñate, Governor, Captain General, and Adelantado of New Mexico. . . . in the name of the most Christian king, Don Philip, the second of that name, and for his successors . . . . [took] possession, . . . of the lands of the said Rio del Norte, without exception whatsoever, with all its meadows and pasture grounds and passes. . . . (**H3.2.2**)." River-based irrigation agriculture, on the other hand, dates back to 17th Century "settlement" of El Paso del Rio del Norte by Spanish and Pueblo-Indian "refugees" following the "Pueblo Revolt" of 1680 (**H3.2.4**).

Large-scale GW-resource development in the southern MBR is a 20th Century phenomenon that followed the introduction of steam-railway and petroleum-based automotive transportation. New energy technologies of the 1890s for the first time permitted (1) the drilling of the deep water wells and (2) the use of diesel/gasoline/electric-powered pumps for efficient GW extraction. In addition, geopolitical and economic conditions became much more complex following the arrivals of three major steam-railroad lines in the early 1880s in El Paso (TX) and El Paso del Rio del Norte: The Southern Pacific Railroad (SPRR) in 1880, the A.T. & Santa Fe RR in 1881, and the Mexican Central Railway in 1884 (Darton 1933 [*cf.* **Fig. H3-5**]; Sonnichsen 1968 [p. 227-231]; Julyan 1996). The Mexican Central Railway, founded in Massachusetts in 1880, began operation between Mexico City and El Paso del Rio del Norte in March 1884. It provided connections between the Mexican capital and the Southern Pacific Railroad, Texas & Pacific Railway, and the AT& SF Railway (https://en.wikipedia.org/wiki/Mexican_Central_Railway).

H1.2. Overviews of the Geologic and Physiographic Settings

H1.2.1. The Rio Grande Rift Tectonic Province and Santa Fe Group Rift-Basin Fill

Figure H1-1 is an index map of the southwestern New Mexico border region that shows locations of the NM WRRI Study Area (magenta rectangle, *cf.* **Fig. H1-3**), and major structural basins of the Rio Grande rift (RG-rift) tectonic and southeastern Basin and Range (B&R) physiographic provinces. The southern Mesilla GW Basin (MeB) extends into Chihuahua's "Zona Hidrogeológica de Conejos Médanos (ZHGCM)," which is shown with light-gray shading (INEGI 2012). With the exception of the Malpais Basin (Seager 1989, 1995) and El Parabién Basin (Jiménez and Keller 2000), and Florida-Mimbres subbasin (Averill and Miller 2013), names and general outlines of RG-rift basins are from Seager and Morgan (1979, Fig. 1)

The Rio Grande rift (RG-rift) tectonic province is a subcontinental-scale zone of Earth crustal, extension that crosses central New Mexico between south-central Colorado, and Trans-Pecos Texas and northern Chihuahua (upper-left inset map on **Fig. H1-1**; Chapin 1971 [**Fig. H1-2**]). The rift is characterized by groups of fault-block highlands that are separated by graben or half-graben basins, most of which have a general north-south trend, and the latter are linked by valleys and canyons of the Rio Grande fluvial system. The RG rift was initially named the RG "depression" by Kirk Bryan (1938, p. 197-225). NM Bureau of Mines & Mineral Resources geologist, Charles E. Chapin (1971) introduced "rift" as a much-more appropriate term for use in a modern plate-tectonic context (**Fig. H1-2**; *cf.* **Fig. H4-11***; Chapin and Seager 1975, Hawley 1978, Woodward et al. 1978, Seager and Morgan 1979, Gries 1979 and 1980, Keller and Cather 1994, Keller 2004, Hudson and Grauch 2013).

**Note on use of terms "Bolson de los Muertos" and "Los Muertos Basins:" Texas Tech Professor C.C. Reeves (1969, p. 147) informally proposed the name "Bolson del los Muertos" for a structural-basin complex in the Puerto Palomas-El Barreal area of the Zona Hidrogeológica de Conejos Médanos. It is here recomended that the terms*

*"Bolson de los Muertos" or "Los Muertos Basin" no longer be used in a RG-rift basin context (e.g., **Figs. H1-1** to **H1-3**; cf. **Figs. H1-2** and **H4-11**).*

Sedimentary deposits of the Middle- to Upper-Cenozoic Santa Fe Group (SFG) form the primary basin-fill component throughout the rift province. This major lithostratigraphic unit is described in a hydrogeological perspective herein (*cf.* **Part H1-8**, and Rpt. **Chpts. 4** and **6**). SFG thickness in the deepest RG-rift basins of the Mesilla Basin region (MBR–**Fig. H1-4**) exceeds 2 km (6,500 ft). Extensive basaltic volcanic fields are also commonly present in the MBR section of the RG-rift (*cf.* Hawley et al. 1969b, King et al. 1971, Keller and Cather 1994, Baldridge 2004, Mack 2004, Connell et al. 2005).

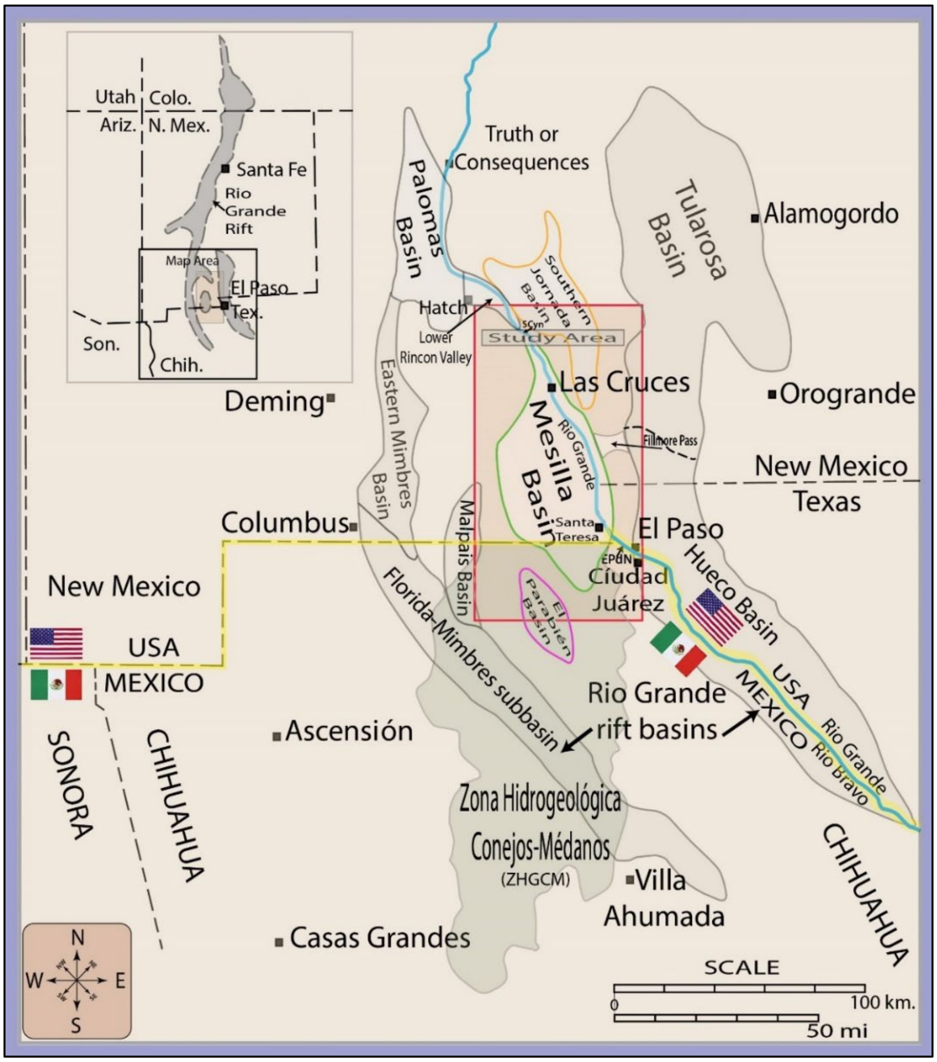

Figure H1-1. Index map of the southwestern New Mexico border region of the Rio Grande rift (RG-rift) tectonic and southeastern Basin and Range (B&R) physiographic provinces, which shows locations of the Mesilla Basin Study Area, and surrounding RG-rift basins (*cf.* **Figs. H1-4** and **H1-6**). The southern Mesilla GW Basin (MeB) extends into Chihuahua's "Zona Hidrogeológica de Conejos Médanos," which is shown with light-gray shading (INEGI 2012; *cf.* **Figs. H1-11** and **H1-13**). With the exception of the Malpais Basin (Seager 1989, 1995), El Parabién Basin (Jiménez and Keller 2000), and Florida-Mimbres subbasin, names and general outlines of RG-rift basins are from Seager and Morgan (1979, Fig. 1) and Averill and Miller (2013, Figs. 1 and 2).

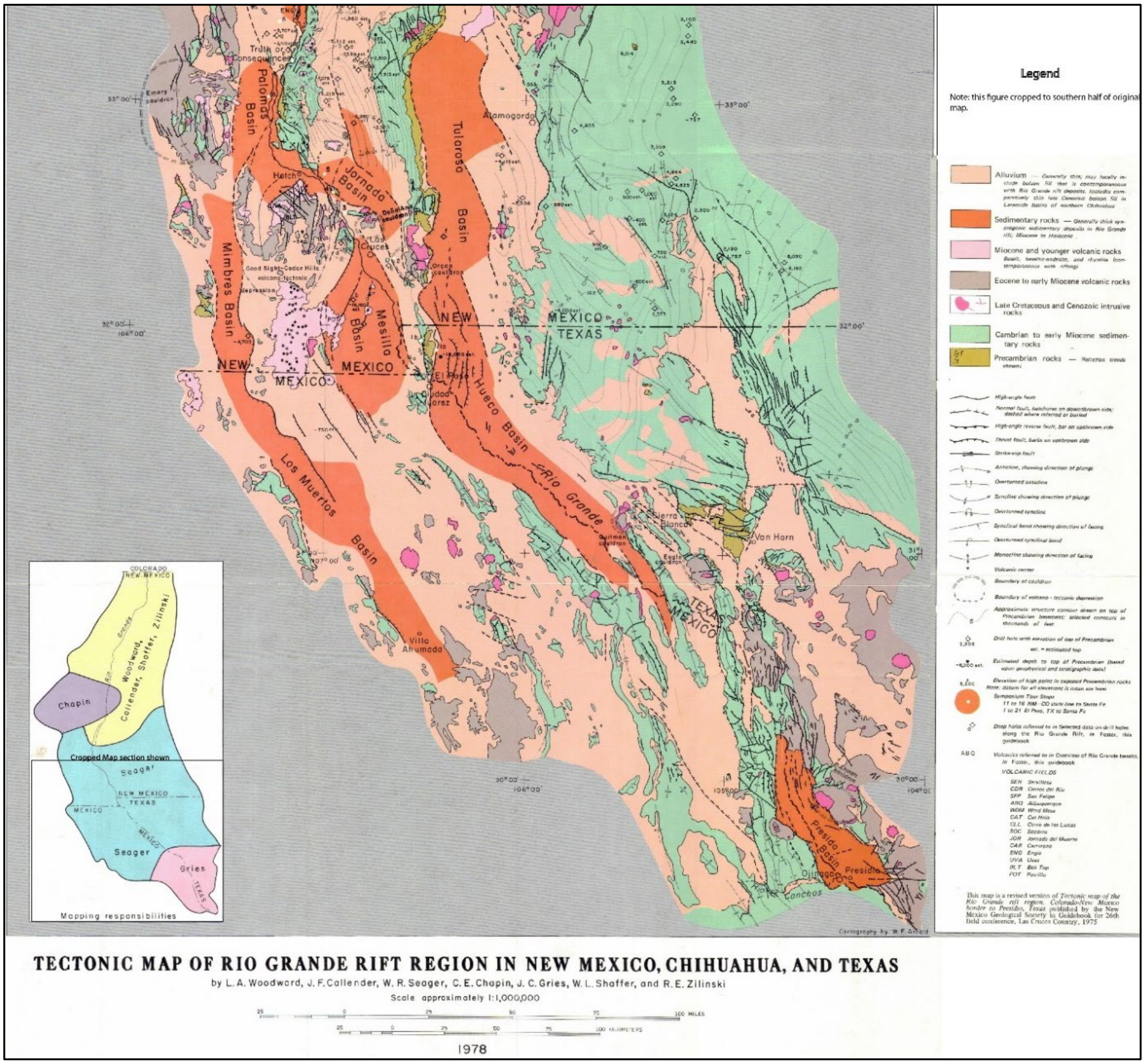

Figure H1-2 (from Hawley 1978, Sheet 2)**.** Southwestern section of the "Tectonic map of the Rio Grande rift region in New Mexico, Chihuahua, and Texas" that was compiled by L.A. Woodward and others (1978), and primarily based on field investigations by W.R. Seager and J.C. Gries (*cf.* Seager and Morgan 1979, and Gries 1979 and 1980). Areas with thick rift-basin fill are in dark orange. Negative numbers at O&G exploration-well sites show below msl depths to the top of Precambrian rocks in feet. Explanation of other color codes: Beige—generally less than 150 m/500 ft of intermontane basin fill (SFG and post-SFG); light-pink—Pliocene and Pleistocene basaltic volcanic (with vent sites marked with an *); gray—Eocene and Oligocene volcanic and epiclastic rocks; light purple—Eocene and Oligocene igneous-intrusive and extrusive rocks; pale-green—Cambrian to Oligocene sedimentary rocks (carbonate and siliciclastic); and greenish yellow—Precambrian igneous and metamorphic rocks. Fault and folds are shown with a variety of linear symbols, with hachures, barbs, and arrows showing directions of offset or warping. Where present, approximate structure-contour lines are drawn on the top of the Precambrian *basement*: selected contours in thousands of feet. Note: "Los Muertos Basin" is no longer used in a RG-rift context. *See* Fig. H1 title reference to Averill and Miller (2013).

Figure H1-3 is an index map for the 8,675 km^2 (3,350 mi^2) NM WRRI Study Area on a hydrogeologic DEM base, with 10,000m UTM and latitude/longitude coordinates. Its UTM Zone 13 (NAD 1983) boundary coordinates are respectively 3,504,000m and 3,611,000m northing, and 302,000m and 367,000m easting. Valley and canyon reaches of the Rio Grande—Rio Grande/Bravo fluvial system are shown with broken-line shading. They include, in northeast to southeast order: lower Rincon Valley, Selden Canyon (SCyn), Mesilla Valley (MeV), El Paso del Norte (EPdN), and the El Paso Valley/Valle de Juárez. The river channel marks the U.S./Mexico Boundary between EPdN and the Gulf of Mexico, and the feature name changes to Rio Grande/Rio Bravo (or Rio Grande/Bravo) in this Report (e.g., **Figs. H1-2** and **H1-3**). The Mesilla, Southern Jornada, and El Parabién groundwater (GW) basins (MeB, SJB, and EPB) are outlined in green, orange, and red, respectively (*cf.* **Fig. H1-10**). Locations of Hydrogeologic Cross-Sections **A-A′** to **S-S′** are shown on **Figure H1-3**).

H1.2.2. Major Physiographic Features of the Mesilla Basin Region

Portrayal of the major physiographic features of Mesilla Basin region (MBR) in **Figure H1-4** is greatly facilitated by use of a 2017 Google Earth® image-base. The NM WRRI Study Area (**Fig. H1-3**) is outlined in magenta, and major structural basins of the Rio Grande (RG)-rift tectonic province are identified by name. From a geohydrological perspective, the most-notable terrain features are the vast areas occupied by intermontane basins of the Basin and Range (B&R) physiographic province, and the very-limited extent of the valleys and constricted reaches of the Rio Grande/Bravo fluvial system. Basin areas below about 1,500 m (5,000 ft) amsl are in the arid-semiarid Chihuahuan Desert ecoregion, and only Sierra Blanca (alt. 3,653 m/11,981 ft), the Sacramento Mountains, and the Black Range in the northern parts of the MBR, have extensive forested-summit areas with altitudes of more than 2,440m (8,000 ft). Blue shading shows the maximum extent of the areas inundated by pluvial-Lakes Otero and Palomas at their respective high stands in the Tularosa Basin (NM) and the Zona Hidrogeológica de Conejos Médanos (ZHGCM) in Chihuahua (**Figs. H1-1** and **H1-10**).

H1.2.2a. Basin and Range Physiographic Province—Mexican Highland Section

Figure H1-5 (Gile et al. 1981, FIG. 1) is an index map to physiographic-province subdivisions and major landforms in the southeastern Basin and Range (B&R) province region of New Mexico, Trans-Pecos Texas, and Chihuahua (*cf.* Hawley 1969b and 1975a). In terms of standard physiographic-division classification in the United States, the Mesilla Basin region (MBR) is in the Mexican Highland section (MHS) of the Basin and Range (B&R) physiographic province (Fenneman and Johnson 1946). Many of the physiographic-unit names and delineations in Mexico are based on pioneering work in northern Mexico by Ezequiel Ordóñez (1867-1950), "se le considera creador de la geología petrolera Mexicana (*cf.* **H4.1.1**). He recognized that the "Provincia Fisiográfica de Cuencas y Sierras" was southward "extension of the [US] Basin and Range Province" into Mexico (*cf.* Ordóñez 1942). Ordóñez (1936, 1289-90), succinctly described the basic landform and hydrogeologic components on an endorheic intermontane basin (aka: bolson, bolsón):

> [p. 1289-1290] . . . the topographic elements of the [intermontane] basin or 'bolson' are the mountain slope, the alluvial fans, the gentle alluvial plain, and the silty bottom land called 'the barrial,' which is temporarily occupied by water immediately after infrequent, but torrential rains

In a more-detailed map of the "Provincias y Subprovincias Fisiográficas del Estado Chihuahua, Professor Ignacio Reyes Cortés of the Universidad Autónoma de Chihuahua (UAC) includes all of the southern MBR in his "Mesa Centrál-Sección Bolsón (1992, p. 19)."

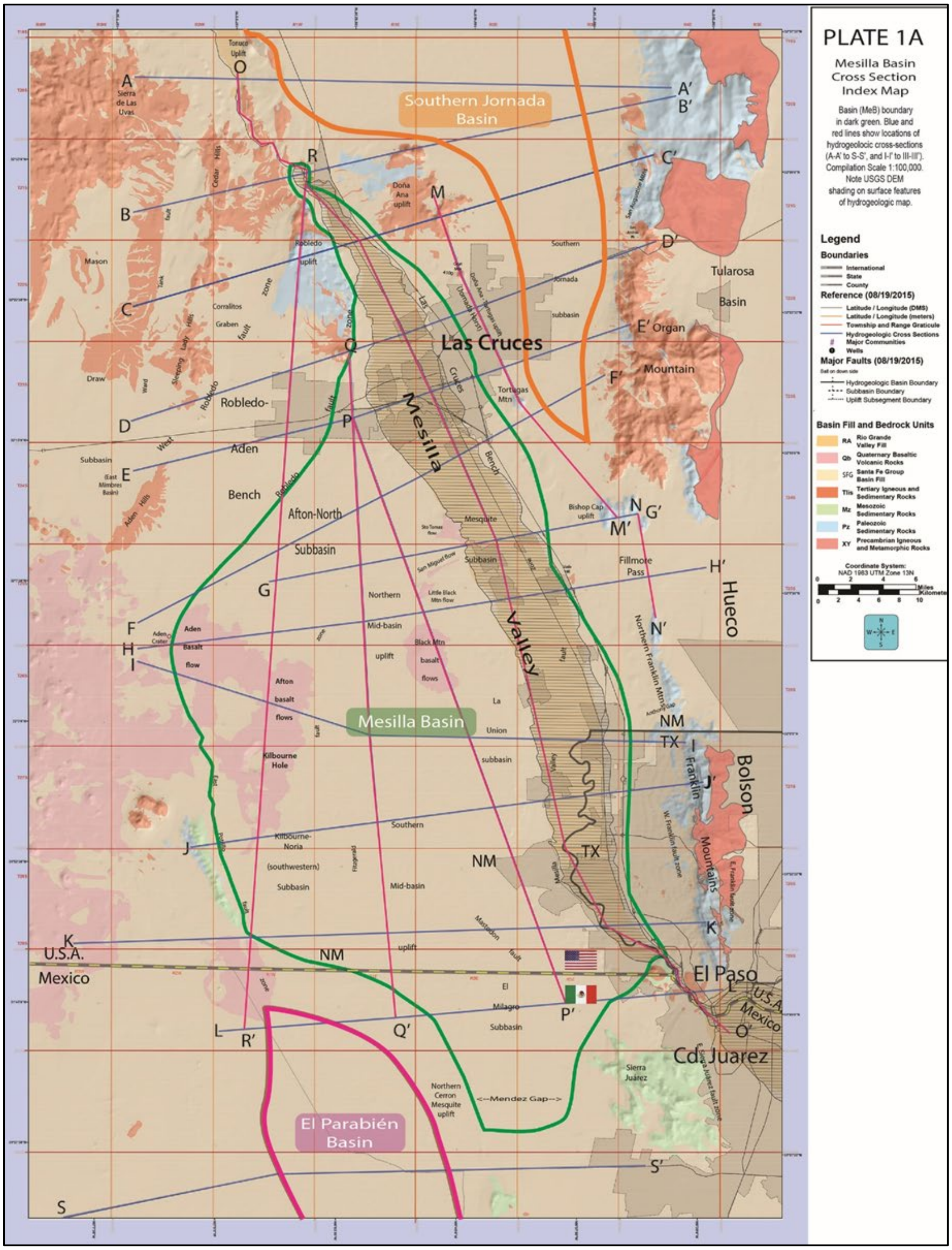

Figure H1-3 (Page-size **PL. 1A).** Index map for the 3,350-mi^2 (8,675-km^2) NM WRRI Study Area on a Hydrogeologic Map base (*cf.* **PL. 1B**). The Mesilla, Southern Jornada, and El Parabién groundwater basins (MeB, SJB and EPB) are outlined in green, orange and red, respectively. Locations of hydrogeologic cross-sections **A-A′** to **S-S′ (PLS. 5a** to **5s**) are shows with purple and red lines. Sections with general W-E and N-S trends are in purple and red, respectively.

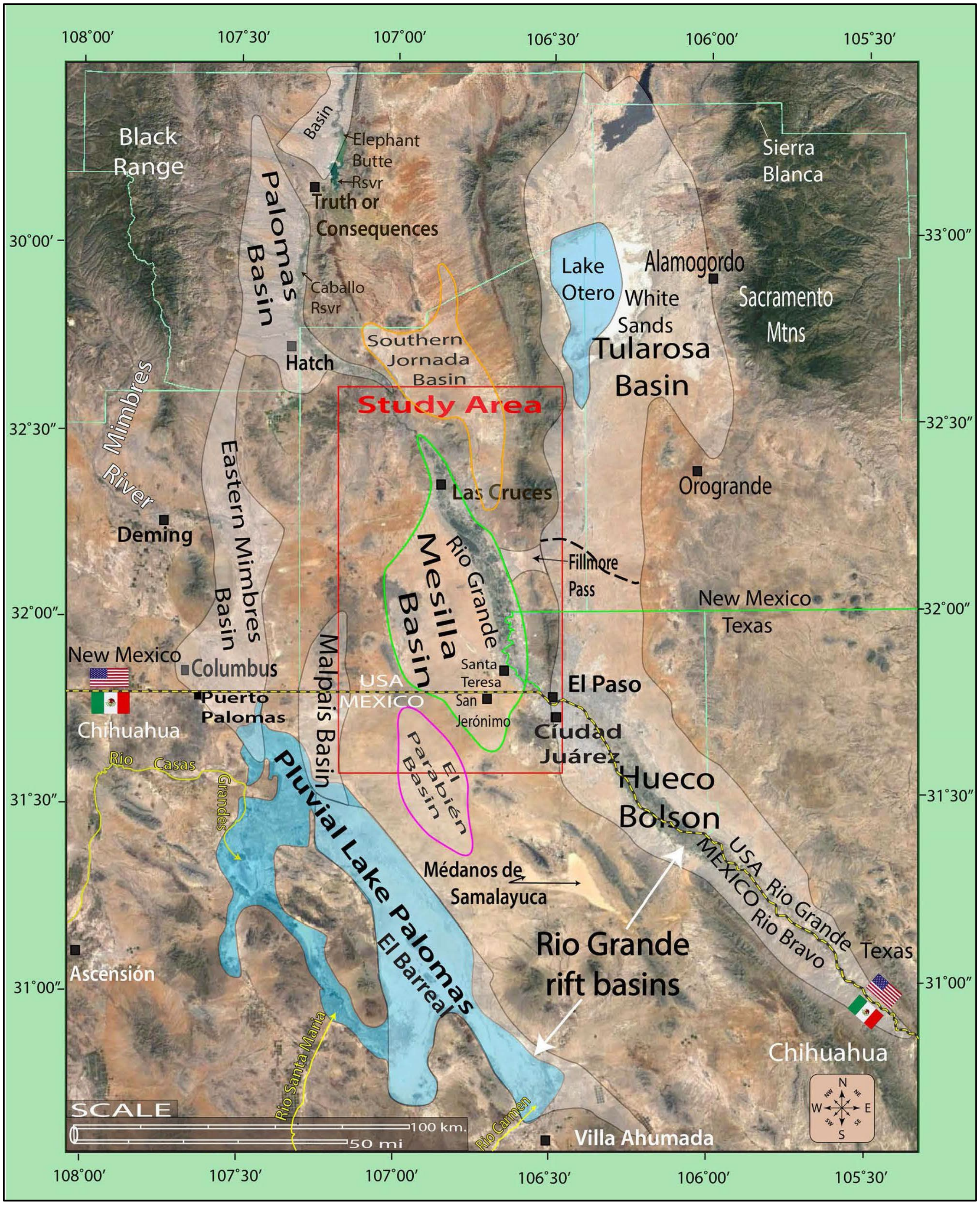

Figure H1-4. Index map of the binational Mesilla Basin region (MBR) showing locations of the NM WRRI Study Area (magenta rectangle–**Fig. H1-3**), major landscape features in the northern Mexican Highland section of the B&R province, and basins of the southern RG-rift province. Blue shading shows the approximate extent of pluvial-Lakes Palomas and Otero at their respective Late Pleistocene high stands in the Zona Hidrogeológica de Conejos Médanos (El Barreal) and Tularosa Basin regions (*cf.* **Fig H1-9**). Swanson Geoscience, LLC compilation on a 2017 Google Earth® image-base.

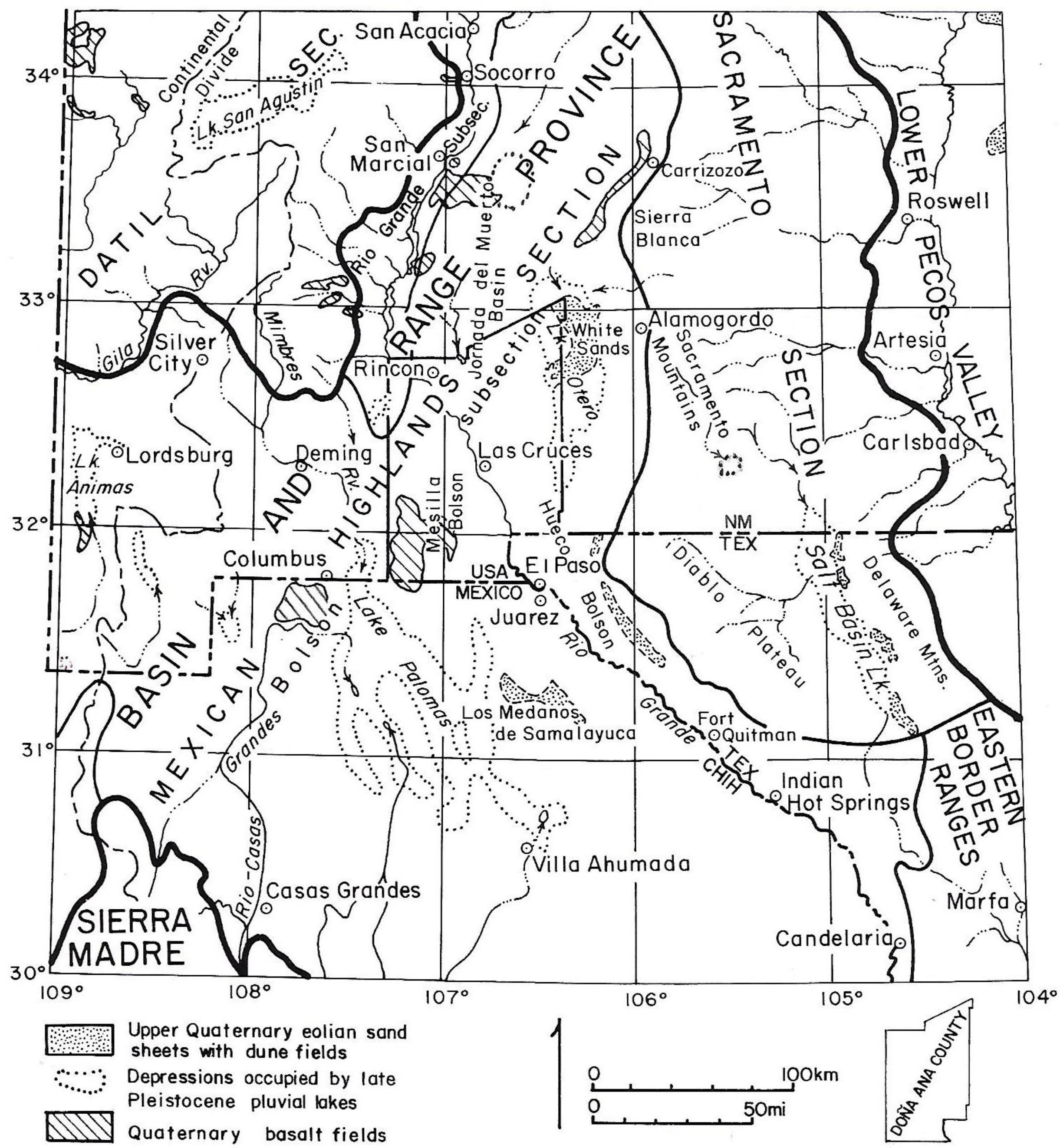

Figure 1. Physiographic subdivisions, major stream systems, pluvial lake basins, and dune and basalt fields in south-central New Mexico region.

Figure H1-5 (Hawley 1975, Fig. 1)**.** Index map to physiographic-province subdivisions and major landforms in southeastern Basin and Range (B&R) province region of New Mexico, Trans-Pecos Texas, and Chihuahua (*cf.* Hawley 1969b). The Study Area (**Fig. H1-3**) covers most of Doña Ana County and includes the 1957-1977 USDA-SCS Desert Soil-Geomorphology Project area; *cf.* Gile et al. 1981; **Part H2.2.3**.

H1.2.2b. Background on the Chihuahuan Desert Ecoregion

In terms of present-day climate and biogeography, much of the B&R Mexican Highland Section below altitudes of about 1,525 m (5,000 ft) is part of the arid to semiarid Chihuahuan Desert ecoregion (Schmidt 1979 and 1992; Van Devender 1990 and 1995; Douglas et al. 1993; Metcalfe et al. 1997 and 2002; Campos-Enriquez et al. 1999). Jorgé Tamayo (1968, p. 162) included much of the Chihuahuan Desert in his "Chihuahua-Potosinense Provincia biótica." Ecoregions are dynamic geomorphic entities, which are sensitive to changes in atmosphere/hydrosphere-related processes that have periodicities in the decadal to multi-millennial range (Omernik 2004). Unlike the relatively fixed temporal boundary criteria for physiographic or tectonic provinces, their transitional borders are determined by subcontinental-scale climatic, hydrographic, and biogeographic conditions with an ever-increasing anthropogenic component (Gutzler 2005; Gutzler and Robbins 2011). Accelerating global-scale climate and associated regional-environmental changes during the past century have probably already marked the end of the well-documented glacial-interglacial cycles of Quaternary Period (i.e., past 2.6 Ma; **Tbl. H1-3** *cf.* **Fig. H1-15**). If so, a proposed new *Anthropocene* Epoch of Geologic Time of uncertain duration and character is well underway (Zalasiewicz et al. 2021, Fig. 2), and planning horizons for prudent water-resource management are now in the multi-decade range, both in arid/semiarid basins of the American Southwest, and elsewhere!

In striking contrast with climate/vegetative-cover conditions of the Middle- to Late-Holocene Chihuahuan Desert, Late Pleistocene glacial maxima in the B&R-MHS were characterized by greater cool-season snowfall and less-intense warm-season (monsoon-type) precipitation, with significantly lower evapotranspiration in both upland and lowland terrains (e.g., Gile et al. 1981, Barry 1983, Smith and Street-Perrott 1983, Spaulding and Graumlich 1986, Betancourt et al. 1990, Ortega-Ramírez et al. 1998, Metcalfe et al. 2002, Palacios-Fest et al. 2002, Allen 2005, Wagner et al. 2010, Jasechko et al. 2015, Eastoe and Towne 2018). This relatively short interval of geologic time occurred in the mid- to later-part of the marine oxygen-isotope stage (OIS) 2, which lasted from about 29 to 11.7 ka (Lisiecki and Raymo 2005; Walker et al. 2018). Montane-forests extended to lower altitudes in many but not all terrains, and the desert-shrub and grassland communities of Chihuahuan Desert's central-basin plains were replaced by savanna-type grasslands analogous to those now present on the semiarid to subhumid Southern High Plains (Spaulding and Graumlich 1986; Van Devender 1995; Monger et al. 1998; Nordt 2003; Pazzaglia and Hawley 2004; Hall 2005; Holliday and Miller 2013).

The resulting increases in effective precipitation and much-lower evapotranspiration during the mid- to late-Quaternary glacial-pluvial intervals of the past 0.75 Ma have led, in turn, to vegetative cover and surface- and subsurface-water flow conditions that were conducive to: (1) river-valley incision and widening, (2) soil formation on stable geomorphic surfaces, and (3) flooding of low-lying parts of the endorheic Zona Hidrogeológica de Conejos Médanos and Tularosa Basins of large intermittent to perennial pluvial-lakes (**Fig. H1-4**; *cf.* **Fig. H1-10**). Evidence for these lakes during cooler and wetter parts the most-recent Pleistocene glacial-pluvial interval (~29 to 12 thousand years ago [ka]) is recorded by a variety of shoreline features, sedimentary deposits, and vertebrate fossils. Under present-day vegetative-cover conditions, desert-scrub flora occupy a much larger part of the Chihuahua Desert landscape than do grasslands (York and Dick-Peddie 1969). Until arrival of the railroads and introduction of large-scale cattle-ranching in the 1880s, however, grasslands remained the primary component of the post-Early Holocene land-cover (Buffington and Herbel 1965; Herbel and Gile 1973; Gile et al. 1981; Dick-Peddie 1993; Monger et al. 2009).

H1.3. Fluvial-Deltaic Features of the Endorheic Ancestral Rio Grande

Prior to the development of a throughgoing (exorheic to Gulf of Mexico) Rio Grande/Rio Bravo (~1 to 0.75 Ma), RG-rift basin lowlands of the Mesilla Basin region (MBR) comprised a complex of terminal *sinks* for the upper part of the ancestral Rio Grande (ARG) fluvial system. The intermittent paleo-lake that formed in this endorheic-basin complex has been named Lake Cabeza de Vaca in honor of Álvar Núñez Cabeza de Vaca who crossed this part of Chihuahua in 1535 (Strain 1966, p.10; *cf.* **Part H3.1.1**). Distal fluvial-deltaic deposits of the ARG are the primary components of the Upper Santa Fe Group (SFG) aquifers in the MBR (**Fig. H1-4**).

The extent and basic geometry of the ARG fluvial-deltaic complex is shown schematically on a 2017 GoogleEarth® image base in **Figure H1-6**, and the explanation of channel-belt symbology is included in **Table H1-4**. This portrayal of the terminal "distributive-drainage network," which was originally developed by Hawley (1975a, Fig. 2), has gone through three stages of conceptual-model development since it was first applied in the MBR (e.g., **Fig. H3-7**). According to Connell, Hawley, and Love (2005, p. 130):

> Drainage of the [Ancestral] Rio Grande can be considered in terms of the contributive and distributive drainage nets of Allen (J.R.L., 1965), where drainage is collected through a contributive network of tributary streams, transferred through a trunk river, and eventually emptied across a distributive drainage network. Headwater basins contain tributaries that form the up-stream contributory (or contributary) section. The San Luis, Española, and Albuquerque basins represent the northern contributory section, defined by the presence of rather large tributary drainages that feed into the main-stem ancestral Rio Grande. A relatively short trunk section is present where drainage is confined within narrow and elongate half-graben basins containing few large tributaries. The Socorro, San Marcial, Engle, and Palomas basins generally represent the central trunk-river section and contain deposits typical of half-graben basins; however, this trunk-river distinction is not clear everywhere. The southern distributary system is recognized by repeated occupation of adjacent basins by the axial river across relatively low-relief topographic (and structural) divides. Below the Rincon area (between Truth or Consequences and Las Cruces. . .), the river forms a quasi-distributary drainage pattern that episodically spills laterally into adjacent basins ([Seager 1981], Mack et al., 1997 [*cf.* **Fig. H1-7**]).

Table H1-4. Definitions of Geomorphic and Physical Geographic (Physiographic) Terms

Alluvial: Pertaining to material or processes associated with transportation or deposition of running water.

Alluvial fan: A body of alluvium, with or without concentrated flood-flow deposits, whose surface forms a segment of a cone that radiates downslope from the point where the stream emerges from a narrow valley or canyon onto a plain. Source uplands range in relief and areal extent from mountains and *plateaus* to gullied terrains on hill and *piedmont slopes*.

Alluvial (aka adobe) flat: A generally narrow *plain* formed by sheetflood deposition of fine sandy clay or adobe brought down by an *ephemeral stream*, and having a smooth hard surface (when dry) usually unmarked by stream channels (Neuendorf et al. 2005, p. 9).

Barreal [barrial] (Mex Span): The silty to clayey bottom of an [*endorheic*] basin that is temporarily flooded after infrequent torrential rains (Ordóñez 1936; Hawley 1969b); heavy clay lands (HarperCollins 2003, p. 123).

Basin (intermontane): A broad structural lowland between mountain ranges, commonly elongated and many miles across. Major component landforms are *basin floors* and *piedmont slopes*. Floors of *endorheic* basins contain one or more closed depressions, with temporary lakes (*barreals, playas [U.S.]*), and alluvial plains.

Basin floor: A general term for the nearly level to gently sloping, bottom surface of an *intermontane basin* (*bolson*). Component landforms include barreals (Mex.), playas (U.S.), broad *alluvial* flats containing ephemeral drainageways, and *alluvial* and/or lacustrine surfaces that rarely if ever are subject to flooding. Where through-drainage systems are well developed, *alluvial* plains are dominant and lake (lacustrine) plains are absent or of limited extent. Basin floors grade mountainward to distal parts of *piedmont slopes*.

Bolson [bolsón-Mex Sp]: An internally drained (*endorheic*), intermontane basin with two major land-form components: *basin floor* and *piedmont slope*. The former includes nearly level *alluvial* and lacustrine plains [e.g., *barreals*]. The latter comprises slopes of erosional origin adjoining the mountain fronts (*pediments*) and complex constructional surfaces mainly composed of individual and/or coalescent alluvial fans.

Endorheic: Pertaining to a topographically closed surface-drainage basin (*cf. exorheic*).

Cienegas: Perennial or intermittent wetlands located in places where the zone of saturation intersects an undissected valley- or basin-floor surface.

Exorheic: Pertaining to a topographically open surface-drainage basin (*cf. endorheic*).

Floodplain: The nearly level alluvial plain that borders a stream and is subject to inundation under flood-stage conditions unless protected artificially.

Fluvial: Of or pertaining to rivers [perennial streams]; produced by river action, as a fluvial plain (syn. riverine).

Geomorphology: The science that treats the general configuration of the Earth's surface; specifically, the study of the classification, description, nature, origin, and development of landforms and their relationships to underlying structures (Neuendorf et al. 2005, p. 267).

Malpais: A term use in the southwestern U.S. and Mexico for a region of rough and barren [basaltic] lava flows (Neuendorf et al. 2005, p. 392).

Mesa: (1) A broad, nearly flat-topped and commonly isolated upland mass produced by differential erosion of nearly horizontal, interbedded weak and resistant rocks, with the latter comprising capping layers. (2) The term is also commonly used in the American SW to designate broad *fluvial-plain* remnants that border the valley of major streams.

Piedmont slope: The dominant gently sloping plain at the foot of a mountain-front or a high plateau escarpment.

Playa: 1. (Mex. Sp.): Coastal beach or strand zone. **2. (**U.S. physical geography): The usually dry and nearly level lake plain that occupies the lowest parts of closed depressions, such as those occurring on intermontane *basin floors*. Temporary flooding occurs primarily in response to precipitation-runoff events. Playa deposits are fine grained and may or may not be characterized by high water table and saline conditions. (*cf. sink*).

Physiographic province: A large region in which all parts are similar in geologic structure and climate, and which has consequently a [relatively] uniform geologic history; a region whose pattern of [major] relief features or landforms differs significantly from that of adjacent regions (*cf.* Fenneman and Johnson 1946, p. 4904). Provinces are commonly subdivided into sections. Examples include the Basin and Range, Colorado Plateau, Rocky Mountains, and Sierra Madre Occidental (Hawley 2005).

Sink (geohydrol.): An *endorheic* depression containing a central *barreal, playa* or saline lake [salina], as where a desert stream comes to an end or disappears by evaporation (Neuendorf et al. 2005, p. 599). (*cf.* **Tbl. 1-3**).

Terrain (geog.): A tract or region of the Earth's surface considered as a physical feature, [or] an ecological environment (Neuendorf et al. 2005, p. 663). (*cf. Terrane [Geol.]*).

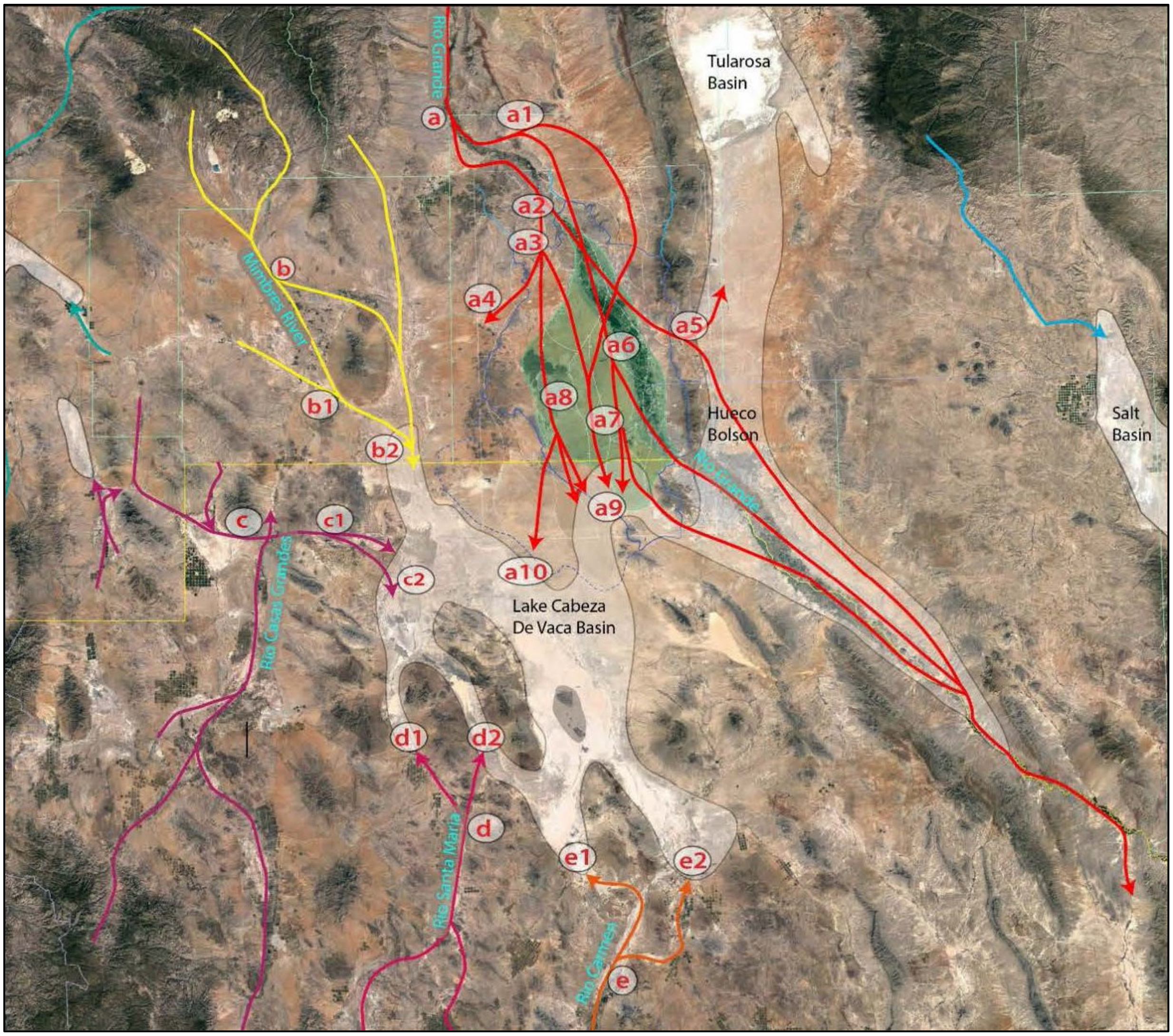

Figure H1-6. Pliocene and Early Pleistocene depositional setting of the Ancestral Rio Grande (ARG) distributive fluvial system (DFS-red lines) on a 2018 Google earth® image base. The system terminated in the paleo-Lake Cabeza de Vaca (LCdV) complex of W.S. Strain (1966, 1971). The Mesilla GW Basin is shown in green. ARG deposits of the Upper SFG Hydrostratigraphic Unit USF2 comprise the region's most productive aquifers. Explanations of symbols for general positions of distributive-fluvial system (DFS)-apices, ancestral-river channelbelt-segments, and LCdV fluvial-deltaic termini are in **Table H1-5**. The location of Fillmore Pass is shown as **a5**. The Rios Casas Grandes (violet), Santa Maria, and Carmen (pink and orange) have headwaters in the Sierra Madre Occidentál, and the Mimbres River (yellow) heads in the Black Range area of New Mexico. These fluvial systems continue to be the primary surface- and subsurface-flow contributors to ephemeral lake-plain (barreal) remnants of pluvial-Lake Palomas (*cf.* **Fig. H1-4**; **Parts H1.4** and **H1.5.1**): Lagunas Guzman, Santa Maria and Patos, and El Barreal-Salinas de Uníon). Only small parts of the Mesilla Basin and Hueco Bolson have surface-flow connection with the Rio Grande at present (Hawley et al. 2000, 2005, and 2009).

Table H1-5. Explanation of Alpha-Numeric Symbols in Figure H1-6 for Pliocene and Early Pleistocene Distributive Fluvial Systems (DFSs) of Ancestral Rivers with Fluvial-Deltaic Termini in the Paleo-Lake Cabeza de Vaca (LCdV) Complex

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A. APEX AREA OF THE ANCESTRAL RIO GRANDE-CAMP RICE FM DFS (ARG-DFS) IN THE SOUTHERN JORNADA BASIN, HUECO BOLSON, AND LOS MUERTOS BASIN (BdLM) —RED LINES

a1. Eastern Rincon Valley head of the ARG-DFS distributary-channel complex in the Southern Jornada Basin.

a2. Upper Selden Canyon head of the ARG-DFS distributary-channel complex in the central and eastern Mesilla Basin area.

a3. Lower Selden Canyon head of the ARG-DFS distributary-channel complex in the western Mesilla Basin area.

a4. Cedar-Corralitos Basin head of the ARG-DFS distributary-channel complex in the northwestern Mesilla and northeastern Mimbres Basin areas.

a5. Fillmore Pass head of the ARG-DFS distributary-channel complex in the western Tularosa Basin and northwestern Hueco Bolson area (Seager 1981 [Fig. 84]).

a6. South-central Mesilla Basin head of the ARG-DFS distributary-channel complex in the El Parabién Basin-Paso del Norte area.

a7. Southeastern Mesilla Basin head of the ARG-DFS distributary-channel complex in the El Parabién Basin, Méndez-Vergel Corridor, and southwestern Hueco Bolson area.

a8. Southwestern Mesilla Basin head of the ARG-DFS distributary-channel complex in the El Parabién Basin and the northeastern LCdV-BdLM.

a9. South-central termini of ARG-DFS fluvial-deltaic distributaries in the northeastern LCdV-BdLM.

a10. Southwestern termini of ARG-DFS fluvial-deltaic distributaries in the northwestern LCdV-BdLM.

B. APEX AREA OF THE ANCESTRAL RIO MIMBRES-UPPER GILA GP DFS—YELLOW LINES

b1. Southeastern Mimbres Basin head of the ARM-UGDFS fluvial-deltaic distributaries.

b2. Southern termini of ARM-DFS fluvial-deltaic distributaries in the northern LCdV-BdLM.

C. APEX AREA OF THE ANCESTRAL RIO CASAS GRANDES-BOCA GRANDE DFS (ARCG-DFS)—PURPLE LINES

c1. Head of ARCG-BGDFS fluvial-deltaic distributaries in the northwestern LCdV-BdLM

c2. Eastern termini of ARCG-DFS fluvial-deltaic distributaries in the northwestern LCdV- BdLM

D. APEX AREA OF THE ANCESTRAL RIO SANTA MARIA DFS (ARSM-DFS)— PINK LINES

d1. Eastern termini of ARSM-DFS fluvial-deltaic distributaries south of Laguna Santa Maria.

d2. Western termini of ARSM-DFS fluvial-deltaic distributaries south of Laguna Fresnal

E. APEX AREA OF THE ANCESTRAL RIO CARMEN DFS (ARC-DFS)—ORANGE LINES

e1. Eastern termini of ARC-DFS fluvial-deltaic distributaries in the southeastern LCdV-BdlM near Villa Ahumada and Laguna Patos.

e2. Western termini of ARC-DFS fluvial-deltaic distributaries northwest of Carrizal in the southeastern LCdV-BdLM

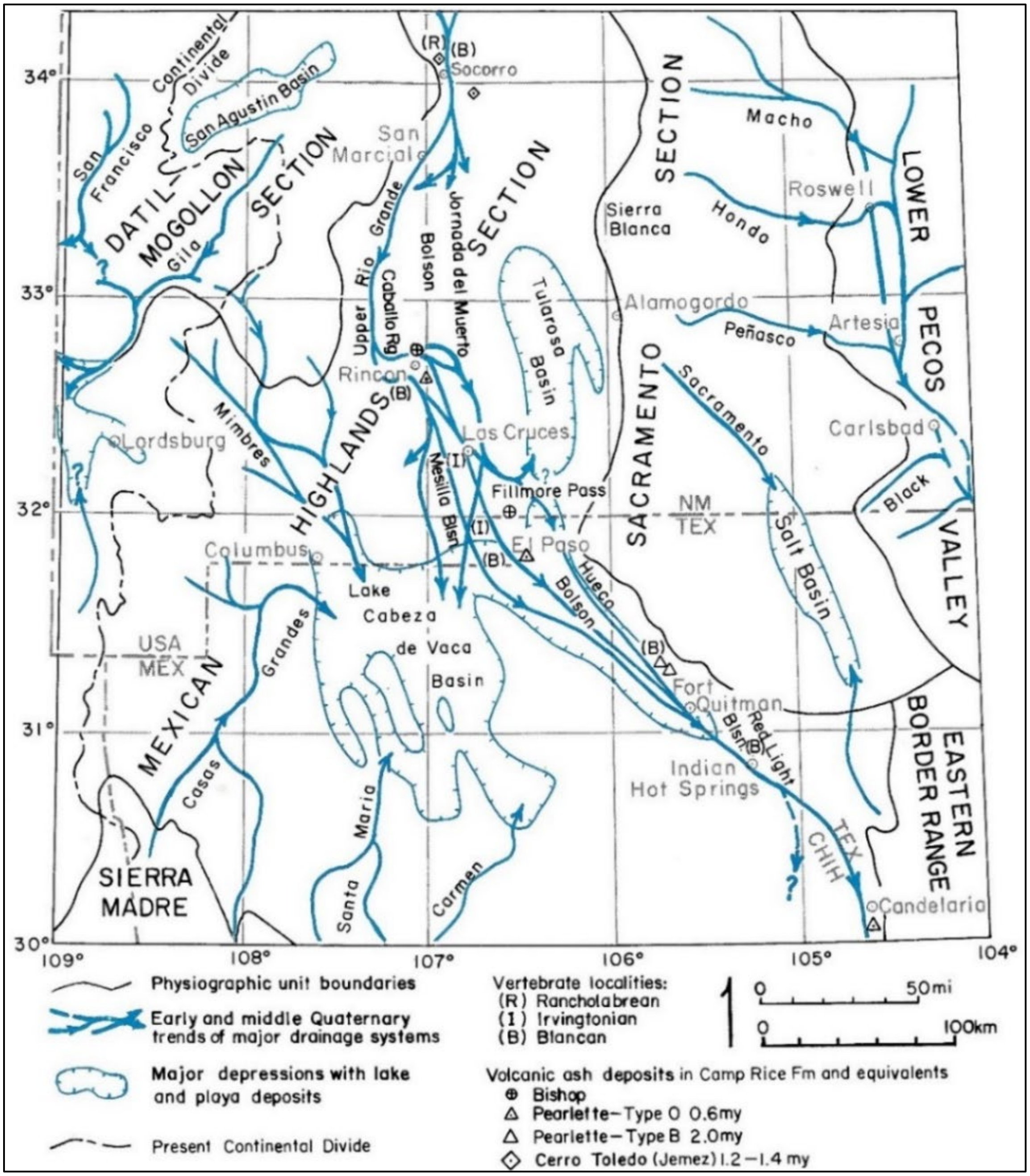


Figure H1-7 (Gile et al. 1981, Fig. 5 [modified from Hawley 1975a, Fig. 2]; *cf.* **Fig. H1-6).** Schematic depiction of the area occupied by the distributive fluvial system (DFS) of the upper ARG during much of Pliocene and Early Pleistocene time (~5 to 0.75 Ma). The apex of the ARG-DFS was located near the present site of Caballo Dam about 20 mi (32 km) NW of Rincon, and it terminated in the paleo-Lake Cabeza de Vaca (LCdV) basin complex in the Mesilla-El Parabién-ZHGCM and Tularosa-Hueco structural depressions of the southern RG-rift region (Strain 1966, 1971). Four of the five large-river systems that discharged to the western section of LCdV remain as endorheic components of the present-day fluvial landscape: Rios Casas Grandes, Santa Maria and Carmen, and the Mimbres River.

A fluvial-deltaic-channel complex of this scale has recently been named a "distributive fluvial system (DFS; *cf.* Hartley et al. 2010, and Weissmann et al. 2011). Saturated channel-belt facies of the ARG-DFS form the most productive aquifers in Upper SFG deposits throughout the southern MBR. British sedimentologist Gary Nichols (2015, p. 1) describes DFSs in terms that apply directly to the ARG fluvial-deltaic and dune-field deposits in endorheic basins of the Mesilla Basin region:

> Stratigraphic models of fluvial successions tend to focus on the 'incised valley' model, which assumes that a marine base level exerts a strong control on the distribution of sandstones deposited by river channels. However, not all rivers flow to the sea and in basins of internal drainage there is no control exerted on river profiles by fluctuations in marine base level. Internal drainage basins are the sites of approximately half of the actively depositing fluvial systems today . . . . In relatively humid endorheic basins, a deep basin-center lake may act as a partial downstream control on fluvial successions. However, in temperate through to arid settings, rivers terminate in a shallow, perhaps ephemeral lake, dry out on an alluvial* plain or interfinger with aeolian environments. In these settings the level of the downstream termination is related to aggradation in the basin, which is itself determined by sediment supply via the rivers. The fluvial system, its depositional patterns, and the stratigraphic architecture are hence controlled by just discharge and sediment supply. A distributive fluvial pattern seems to be dominant in modern and ancient endorheic basins [e.g., **Part H1.3**]. The fluvial successions formed by these systems in endorheic basins have a fundamentally different architecture to the 'incised valley fill' model commonly used in fluvial stratigraphy.
>
> **As in many analogs in nature (e.g., organic branching structures), DFSs have the property of anabranching fractality (Mandelbrot 1982): That is, exhibiting a "repetition of geometric patterns at different scales, revealing smaller and smaller versions of themselves. Small parts resemble, to some degree, the whole (Taleb 2010, p. 257)."*

H1.4. Pluvial-Lake Palomas

During the cooler and wetter intervals of the last Pleistocene glacial stage (between about 29,000 to 12,000 yrs ago), parts of the endorheic Bolsón de Los Muertos (BdlM) and contiguous lowland areas below a present altitude of 1,210 m (3,970 ft) were inundated by pluvial-Lake Palomas (Reeves 1965 and 1969; Castiglia and Fawcett 2006). Its high-stand surface area, shown with light-blue shading on **Figure H1-10** is estimated to have been at least 7,000 km^2 (2,900 mi^2) (Hawley et al. 2000; Castiglia and Fawcett 2006 [p. 114]). By way of comparison, the present surface area of Lake Erie is about 25,745 km^2 (9,940 mi^2). The source watershed of pluvial-Lake Palomas and its five intermittent-lacustrine remnants [barreals-lagunas-salinas] has an area of at least 65,000 km^2 (27,000 mi^2), which is about the same as the 72,520 km^2 (28,000 mi^2) area of the Rio Grande drainage basin above Leasburg Dam (alt.1,207 m/3,960 ft; **Figs. H1-7** and **H2-3**; USGS 2017). The terminal sinks, and their Rio/River sources are listed below in north to south and west to east order (e.g., **Figs. H1-5** and **H1-7**; *cf.* **Fig. H4-2**):

1. Northern El Barreal (Mimbres River *sink*).
2. Laguna Guzmán (Rio Casas Grandes *sink*).
3. Laguna Fresnal (Rio Santa María *sink* [mid- to late-Holocene]).
4. Laguna Santa María (Rio Santa María *sink*).
5. Laguna Patos (Rio Carmen *sink*).

Based on ground and aerial reconnaissance surveys, and use of existing topographic-map control, Texas Tech Professor C.C. Reeves (1930-2013) was the first to identify the major shoreline landforms and sedimentary deposits of Pluvial Lake Palomas (1965 and 1969). The following selection (p. 199) and map (FIG. 1) from Reeves (1965) is the first published description of this major geomorphic and geohydrologic feature (*cf.* Part H4-2.3):

Geologic study of the Lake Palomas basin is in its infancy. The writer first visited the area in the spring of 1964. During the past year and a half emphasis has been on general reconnaissance, mapping of abandoned shorelines, and geomorphological studies. This report lacks quantitative detail, but contains several geologic speculations based on legitimate geomorphic evidence which have a direct bearing on the Pleistocene geologic history of south-central New Mexico. . . .

Lake Palomas is named for the village of [Puerto] Palomas on the international border 35 miles south of Deming, New Mexico (fig. 1). Brand (1937) refers to Guzman, Santa Maria, and Tildio playas and the Franklin Bolson, and the term "Guzman Sink" is used by Martin (1963b) for the northwestern part of the Palomas basin. The Lake Palomas basin is not a sink and is today marked by several separated playas such as Guzman and the Franklin Bolson or "El Barreal." . . .

The geochronologic and paleohydrologic interpretations of Lake Palomas history, as presented herein, are based primarily on intensive (MS thesis) field research by Peter Castiglia (2002) in the Laguna [El] Fresnal, Guzman, and Santa María subbasins of the Lake Palomas basin (**Figs. H1-10** and **H1-12**; *cf.* **Fig. 4-2**). Well-preserved fossil clams (*Pyganodon grandis*) that Castiglia discovered in high-level beach-ridge deposits of the Lagunas Fresnal and Santa María subbasins proved to be ideal for ^{14}C age determinations. This allowed him to establish a relatively precise chronology of Holocene and latest Pleistocene "lake-level variation" that documents the close correlation of early to middle Holocene episodes of increased precipitation with pluvial-lake high stands (Castiglia and Fawcett 2006). Two excerpts from the summary of Castiglia and Fawcett report (p. 113-114) are included here because of their special relevance to the Transboundary GW-flow system described in **Parts H5.3** and **H5.4**:

Lacustrine features preserved in the interior basins of the pluvial Lake Palomas system include wave-cut benches, spits, lacustrine sediments, and constructional beach ridges. Three major constructional beach ridges, first identified and described by Reeves (1969), are located on the eastern flank of Laguna El Fresnal, where sediments of the lower two shorelines contain multiple sites with well-preserved freshwater pelecypods . . . . In Laguna El Fresnal, a partially eroded beach ridge composed predominately of poorly sorted fine-grained sands to gravels is preserved at an elevation of 1,210 m (. .). This high shoreline (beach ridge I) can be found in all other subbasins as a wave-cut bench marking a change in slope above the playa margins. No pelecypods were found in the sediment exposures of this shoreline, and no reliable age could be obtained. Based on its position and degree of preservation, however, beach ridge I must be older than the lower shorelines and is probably late Pleistocene in age. The lake represented by this shoreline was >7,000 km^2 in area, and a 20-km-long spit associated with this beach ridge is at the mouth of the Rio Casas Grandes at the northern end of Laguna Guzman.

Beach ridge II (1,202 m above sea level) is 5 m above an internal sill separating Laguna Guzman from Laguna El Fresnal (. .). In an escarpment on the western side of Laguna Guzman, we measured the altitude of three wave-cut benches with a differentially corrected GPS instrument. A prominent bench at 1,203 m corresponds to the constructional beach ridge in El Fresnal, within the vertical resolution of the GPS. Two dates, 8,456 ± 97 ^{14}C yr B.P. and 8,269 ± 64 ^{14}C yr B.P. (. .) obtained from pelecypods collected from a silt deposit in the shoreface on the southeastern side of El Fresnal subbasin (. .) show that beach ridge II formed during the early Holocene. Using the CALIB 5.0 model of Stuiver and Reimer (1993), the calibrated calendar-year age range of these ^{14}C dates is 9,139 to 9,032 cal-yr BP [about 9,100 calendar-years Before Present (1950 CE).

H1.5. Major Geomorphic Features of the Contemporary Chihuahuan Desert Landscape

Basin-lowland areas that were formerly inundated by pluvial-Lakes Palomas and Otero are now the sites of very large ephemeral-lake (*aka* barreals) plains and associated sand-dune complexes. The latter include (1) El Barreal/Salinas de Unión and the Médanos de Samalayuca dune field in and adjacent to the Zona Hidrogeológica de Conejos Médanos, and (2) Lake Lucero-Alkali Flats and White Sands in the west-central Tularosa Basin (**Figs. H1-4** and **H1-10**; Meinzer and Hare 1915; Kottlowski 1958b; Morrison 1969; Reeves 1965 and 1969; Schmidt 1973 and 1992; Schmidt and Marston 1981; Hawley et al. 2000 and 2009; Allen 2005; Castiglia and Fawcett 2006; Allen et al. 2009; and Love et al. 2020).

H1.5.1. El Barreal

barreal [barrial] (*Mex Sp*): The silty [to clayey] bottom of [an *endorheic*] basin that is temporarily flooded immediately after infrequent torrential rains (Ordóñez[1] 1936, p. 1220; Hawley 1969b, p. 125); heavy clay lands (HarperCollins 2003, p. 123).

Salina[s]: A place where crystalline salt deposits are formed or found, such as a salt flat . . . ; especially a salt-encrusted [floor of an ephemeral lake] (modified *from* Neuendorf et al. 2005, p. 568).

In the Chihuahuan Desert region of northern Mexico, the term "el barreal" is used in two contexts: First as a generic-landform descriptor for the floor of a broad depression on a nearly level plain (e.g., El Barreal area south of the Cd. Juárez Airport [*cf.* **Figs. H5-4** and **Fig. 5-5**]); and second as the specific place name for a large geographical feature (e.g., El Barreal [**Fig. H1-4**; *cf.* **Figs. H1-10** and **H4-15** [Lago El Barreal]). With respect to the regional GW flow system in the above-described Zona Hidrogeológica de Conejos Médanos (ZHGCH), the primary mechanism pluvial-Lake Palomas was by northeast-directed GW flow towards the lower Mesilla Valley (MeV) of the Rio Grande (*cf.* topic review in **Parts H5.2** and **H5.3**). During most of the Holocene Epoch (mainly the past 8,000 years), evapotranspiration (ET) has been the only significant means of GW discharge in the entire BdLM region. The largest area of ET *losses* to the atmosphere is located in the phreatic discharge zone in the southern part of El Barreal at Salina[s] de Unión (alt. ~1,180 m/3,870 ft amsl; *cf.* **Figs. H1-10** and **H1-11**). Following extensive field- and aerial-reconnaissance of the ZHGCH area, Reeves (1969, p. 153-154) provided this summary of the local hydrochemical setting of the Salina[s] de Unión (**Fig. H1-2**):

> Because the basin of pluvial Lake Palomas has always been closed, surrounded by volcanics, and was the terminal reservoir for at least three large rivers [Casas Grandes, Santa Maria, and Carmen in Mexico], it satisfies several of the requisites listed by [George] Smith (1966) for accumulation of continental salines. The high, abandoned shorelines show that evaporation of vast quantities of water took place and the bordering volcanics and stream influents from these terranes have undoubtedly supplied the salts.
>
> Salines la Unión S. A., with general offices in Villa Ahumada, has been producing sodium sulfate for several years at Salinas [de Unión] about 27 miles [43.5 km] northwest of Villa Ahumada [**Figs. H1-10** and **H1-11**]. Production is from confined brines of 13° Beaume which rise to nearly the playa surface, are concentrated by evaporation, and then pumped to concrete evaporation pits. The brine is then pumped, after additional concentration by solar evaporation, over an ammonia cooler which causes precipitation of the sodium sulfate. Production of several tens of thousands of tons per month is easily attained (personal communication, R. C. Ponsford, Jr.).
>
> Extent of the Salinas sodium sulfate deposit is not known; however, waters in other areas show high concentrations of various ions necessary for other salt deposits. Because of the resemblance of the basin of pluvial Lake Palomas to Searles Lake, California [Smith 1966], one may suggest that exploration for continental salines will be highly successful in certain areas of the basin.

H1.5.2. Los Médanos de Samalayuca

The Médanos de Samalayuca dune field is a very distinctive landform that is located on the eastern (leeward) side of a large complex of intermontane basins, in which the dominant lowland feature is the ephemeral-lake plain of El Barreal in the Bolson de Los Muertos (*cf.* Schmidt 1973, Schmidt and Marston 1981, Castillo et al. 1984). According to Robert Schmidt (1992, p. 69):

> El campo de dunas de Samalayuca, localizado aproximadamente a 50 kilómetros al sur Ciudad Juárez-El Paso, cubre cerca de 145 km2 [56 mi2], y constituye un rasgo característico natural, único y magnifico. . . .
>
> No obstante, el área de estudio permanece menos entendida que cualquier otra región cubierta por arena en de hemisferio norte del continente americano. La parte principal de los Médanos de Samalayuca se extiende con un máximo aproximado de 32 [20.5 mi] kilómetros del largo por 13 [8 mi] de ancho. Los cerros de arena están cercados por la sierras del Presidio en la part noreste, y la de Samalayuca en la oeste, y corren paralelos a ellas [Figs. **H1-2** and **H3-7**]. . . .

Donald Webb (1969, p. 184) offers a more-detailed description of the composition, source, and structural-geologic setting of this massive eolian-sand deposit, which is a close analog to the "Great Sand Dunes" of Colorado's east-central San Luis Basin (Valdez and Zimbelman 2020).

> [p. 184]. An outstanding feature of this area is the field to the west of Sierra del Presidio that covers an area of about 97 square miles. The sand is composed primarily of quartz grains which are [extremely] well sorted, with a median size of 2.5 phi [125-250µm, or fine sand]. Sorting ranges from a sigma of 0.26 phi on the crests of dunes to a sigma of 0.41 phi on the flats between the dunes. About 75 percent of the quartz grains are clear and about 20 percent are yellowish, with about 5 percent of the grains being miscellaneous rock and fossil fragments. Some of the clear grains appear to have good cleavage and may be sanidine feldspar rather than quartz. Thus, about 80 percent of the grains are definitely quartz grains, which seem to be bimodal in origin. The yellowish grains are well rounded and frosted; whereas clear grains show some crystal faces, are angular, polished, and have abundant inclusions.
>
> The sand is migrating from west to east, and appears to have been derived from ancient lake deposits west of the area [pluvial-Lake Palomas, **H4.2.3**]. The line of extremely high dunes on the eastern edge of the field has prominent topographic relief standing about 550 feet (170 m) above their eastern base. . . .
>
> The dunes do not appear to conform to any conventional classification of dune forms, but are rather nondescript piles of sand with irregular and inconsistent shapes [*cf*. Schmidt and Marston 1981]. At one point near the southern end of Sierra del Presidio the dunes have [been] blown through a low pass in the sierra and are migrating into the Rio Grande/Bravo Valley to the east.

In their 1981 El Paso Geological Society Guidebook paper "Geomorphic parameters of Los Médanos de Samalayuca, Schmidt and Marsden describe the "echo dune" eolian process as "an alternative explanation for the formation and configuration of the high dunes" in the area west of Sierra del Presidio:

> An alternate explanation for the formation and configuration of the high dunes ls by eolian processes (Schmidt, 1978). The prevailing southwesterly winds approach the mountain front of the Sierra del Presidio and create a standing rotary wave. The winds flow over the ground surface in a direction opposite to the prevailing winds, sweeping away any unconsolidated sand from the pediment between the mountain front and dune field. The rotary action also explains the formation of the high dune ridge as sand accumulates from opposite directions. The high dune

ridge, therefore, is appropriately termed an echo dune*. This eolian process has been noted in a number of desert settings and is responsible for some of the highest dunes in the world.

****Echo Dune**: A sand dune formed in front of a continuous [bedrock] object, such a wind-facing cliff [or mountain front], [and] at distance slightly less than the obstacle's height, because of the formation of the reverse eddy (Neuendorf et al. 2005, p. 201).*

H1.6. Overview of the Regional Hydrogeological Setting
H1.6.1. Groundwater Basins Defined in a Hydrogeologic Context

The USGS-WRD Regional Aquifer-Systems Analysis (RASA)—Southwest Alluvial Basins (SWAB) Program has had a major impact on development of conceptual and digital models of intermontane-basin hydrogeologic systems throughout the eastern Basin and Range and Rio Grande-rift provinces (*cf.* Gates et al. 1984**,** Freethey et al. 1986). A significant contribution of the first major RASA-SWAB Project completed in New Mexico involved making a formal distinction between the deep, structural, Mesilla "groundwater basin (MeB)," and the areally more extensive, physiographic- and hydrographic-basin categories, with the latter being defined, respectively, in terms of Basin and Range topography and surface-watershed divides (**Fig. H1-8**). The MeB boundaries selected by USGS hydrologists Peter Frenzel and Charles Kaehler were specifically designed for an initial-phase "digital model of the Mesilla Basin ground-water flow system (1992, p. C2, Fig. 4)." Except for its southern extension into Chihuahua, these boundaries closely match mapped positions of the Study Area's major RG-rift basin-border fault zones (e.g., Seager et al. 1987, and Seager 1995). MeB boundary locations in all subsequent digital hydrogeologic-framework characterizations and derivative GW flow-models in the United States part of MeB remain in close agreement with those defined Frenzel and Kaehler (1992; Report **PLATES 1** to **5**; *cf.* Nickerson and Myers, 1993, Hawley and Kennedy 2004, Sweetkind 2017 and 2018, Teeple 2017a, Hanson et al. 2018, and Pepin et al. 2022).

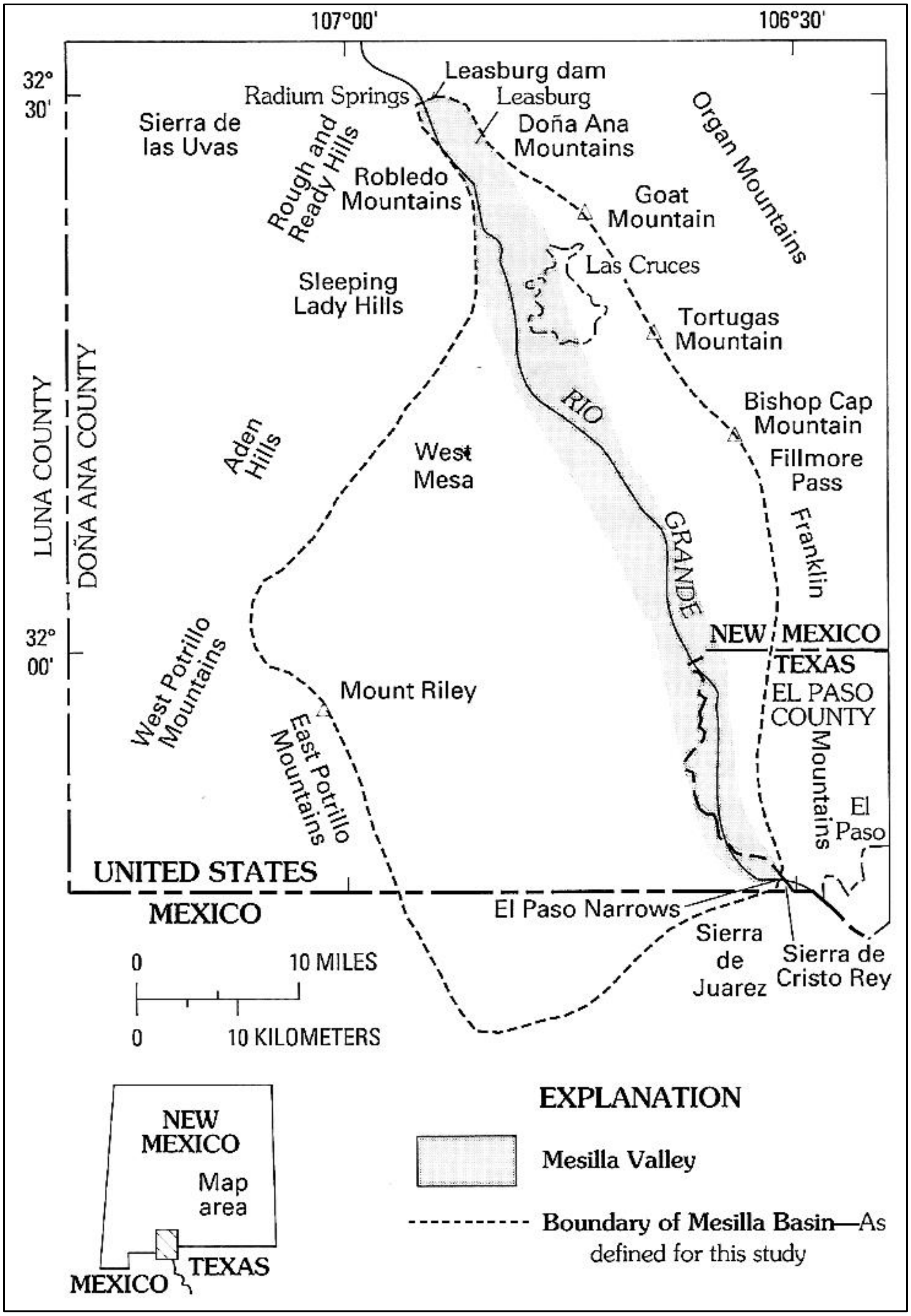


Figure H1-8 (Frenzel and Kaehler 1992, Fig. 4)**.** USGS index map showing locations of the Mesilla "groundwater" Basin (MeB-dashed outline), the Mesilla Valley (MeV-shaded area), the "West Mesa," major bedrock uplifts (Hills, Mountains, Sierras), and "El Paso (del Norte) Narrows."

H1.6.2. Basin-Scale Hydrogeologic-Subdivisions Defined in an RG-Rift Tectonic Context

The inherent complexity and deep-seated nature of the major structural components of Rio Grande rift basins and their bordering bedrock uplifts requires that their characterization in a detailed hydrogeologic context be based on a variety of direct and indirect methods of surface and subsurface investigation (e.g., surface mapping, borehole-sample logging, and geophysical and geochemical surveys; *cf.* **PL. 1** to **PL. 7** series; Seager et al. 1987, and Seager 1995). Former Head of the UTEP Geophysical Laboratory, G.R. Keller describes some aspects of this multi-disciplinary process in a seminal 2004 review paper titled, "Geophysical constraints on the crustal structure of New Mexico (2004, p. 450):"

> Seismic reflection, gravity, and drilling data have delineated the many large, deep basins that form the upper crustal expression of the [RG] rift. Initially, the primary emphasis was on gravity studies (e.g., Cordell, 1976, 1978; Ramberg et al., 1978; Birch, 1982). However, the petroleum industry has released a considerable amount of seismic reflection data for research purposes, and [a] series of papers that focus on the [RG-] rift basins and include many seismic reflection profiles is [cited] in Keller and Cather (1994). In general, the basins are asymmetrical and more complex structurally than their surface expression would suggest [*cf.* **Part H4.6**].

A large body of published information on subsurface conditions in the MBR supports Keller's observation that RG-rift basins are "more complex structurally than their surface expression would suggest" (e.g., Chapin and Seager 1975, Seager and Morgan 1979, Wilson et al. 1981, Seager et al. 1987, Seager 1995, Jiménez 1999, Jiménez and Keller 2000).

Synthesis of geophysical and deep-borehole information has permitted identification and subdivision of the Study Area's major GW basins at a level of detail that has heretofore not been possible. **Figure H1-9** is an index map showing locations of the major hydrogeologic subdivisions of the Mesilla GW Basin (MeB) defined at a *basin scale* (here 1:100,000) in the context of the Mesilla Basin region's RG-rift tectonic setting. The MeB is in blue shades, and the Mesilla Valley (MeV) is in dark blue. The Southern Jornada and El Parabién GW Basins (SJB and EPB) are in light green and red, respectively. SCyn and EPdN show the respective locations of Selden Canyon and El Paso del Norte. Solid and dashed black lines mark the boundaries of interbasin-uplift and intrabasin subdivisions. Acronyms for hydrogeologic-subdivision categories, including fault zones (lines with bar and ball symbols), are listed in **Tables H1-6** and **H1-7**.

The primary Rio Grande-rift features delineated on **Figure H1-9** comprise rift *basins* and interbasin bedrock *uplifts*. Composition details for the latter are described in Report **Chapter 5**, and for the former in **Chapter 6**. Major gaps (erosional and/or structural) that disrupt *uplift* continuity and potentially permit interbasin GW flow are designated *corridors* herein. Informally named *benches* are shallowly buried structural platforms that are transitional between central *basins* and *uplifts*. "Shallow burial" here refers to thicknesses of basin-fill cover of less than about 90 m (300 ft). Because study emphasis is on basin-fill aquifers and associated GW-flow systems (Rpt. **CHPT. 7**), *basins* are described in much more detail than the *uplifts*, parts of which may be shallowly buried by basin-fill deposits. Deeply buried analogs of *uplifts*, which are within or border the Mesilla GW Basin (MeB) are designated structural *highs.* Depths to bedrock *highs* in the rift *basins* of the Study Area range from about 90 to 470 m (300-1,550 ft). Because of the latter's significant influence on deeper parts of the regional GW-flow system, they have also received special attention in this Study (Rpt. **CHAPTS. 6** and **7**).

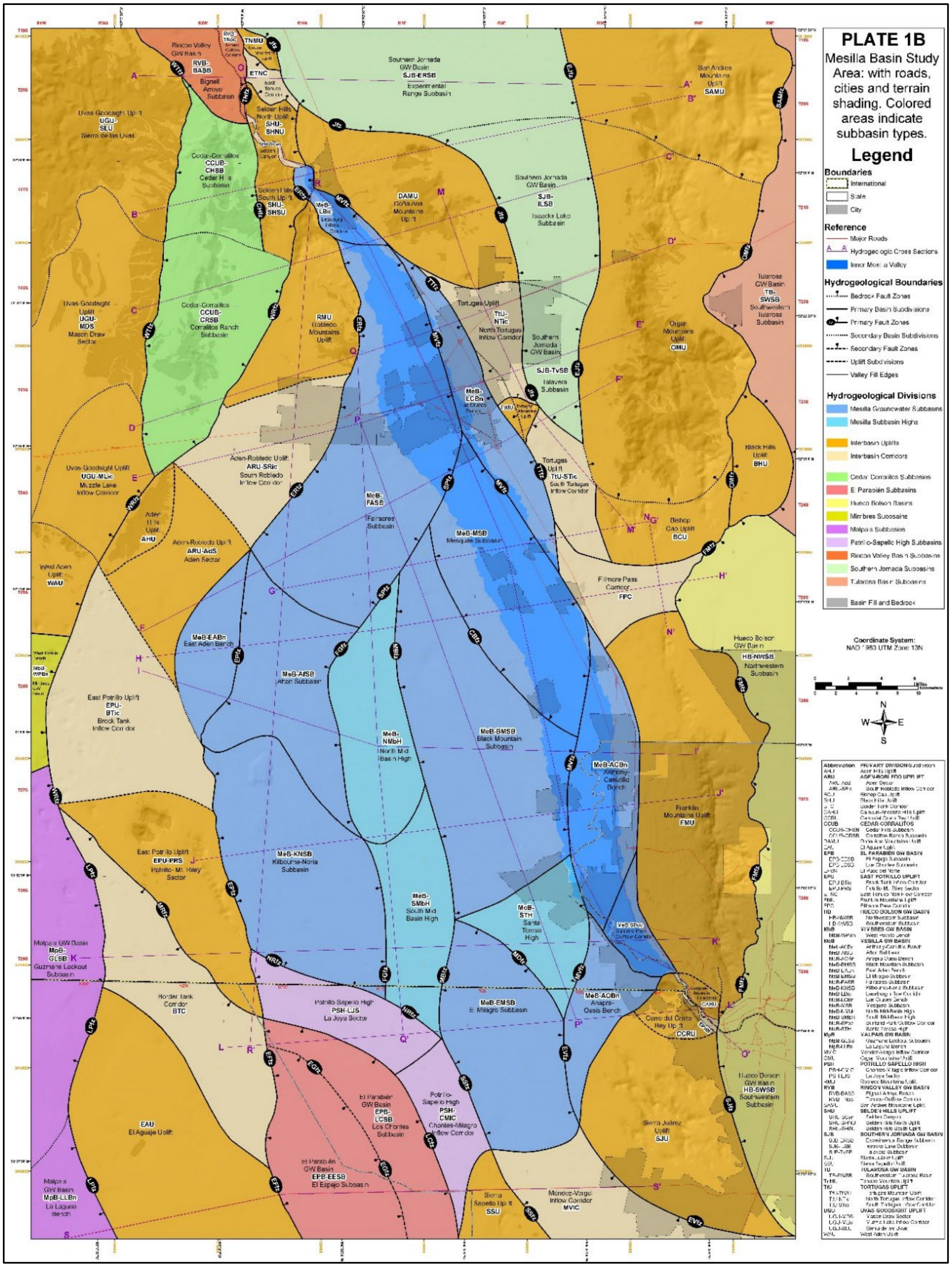


Figure H1-9. Index map for major hydrogeologic subdivisions of the Study Area (**Fig. H1-3**, and **Tbls. H1-6** and **H1-7**). The Mesilla, Southern Jornada, and El Parabién GW Basins are in blue, lime-green, and pale-red respectively. Interbasin (RG-rift) Uplifts are in orange. USGS DEM base

Table H1-6. Acronyms and Names of Hydrogeologic Subdivisions on Figure H1-9

ACRONYM	RIO GRANDE (RG) VALLEY AND CANYONS (NARROWS)	
EPdN	El Paso del Norte (Cyn)	
MeV	Mesilla Valley	
SCyn	Selden Canyon (Cyn)	
EPJV	El Paso-Juárez Valley	
ACRONYM	MESILLA GW BASIN (MeB)	SUBDIVISION (AREA in km²)
MeB-ACBn	Mesilla Basin	Anthony-Canutillo Bench (138)
MeB-AfSB	Mesilla Basin	Afton Subbasin (180)
MeB-AOBn	Mesilla Basin	Anapra-Oasis Bench (72.7)
MeB-BMSB	Mesilla Basin	Black Mountain Subbasin (353)
MeB-EABn	Mesilla Basin	East Aden Bench (70.7)
MeB-EMSB	Mesilla Basin	El Milagro Subbasin (203)
MeB-FASB	Mesilla Basin	Fairacres Subbasin (382)
MeB-KNSB	Mesilla Basin	Kilbourne-Noria Subbasin (278)
MeB-LBic	Mesilla Basin	Leasburg Inflow Corridor (25.4)
MeB-LCBn	Mesilla Basin	Las Cruces Bench (97.5)
MeB-MSB	Mesilla Basin	Mesquite Subbasin (228)
MeB-NMbH	Mesilla Basin	North Mid-Basin High (143)
MeB-SMbH	Mesilla Basin	South Mid-Basin High (121)
MeB-STBn	Mesilla Basin	Santa Teresa High (89.5)
MeB-SPoc	Mesilla Basin	Sunland Park Outflow Corridor (33.4)
ACRONYM	OTHER GW BASINS (B)	SUBDIVISION
EPB	El Parabién Basin (N-part—Drains to MeB)	
EPB-EESB	El Parabién Basin	El Espejo Subbasin (158)
EPB-LCSB	El Parabién Basin	Los Chontes Subbasin (126)
HB	Hueco Bolson (W-edge—Receives inflow from MeB through EPdN)	
HB-NWSB	Hueco Bolson	Northwestern Subbasin
HB-NWSB	Hueco Bolson	Southwestern Subbasin
MbB	Mimbres Basin (No-flow boundary with MeB; surface and subsurface flow to Los Muertos Basin) (Bolsón de los Muertos)	
MbB-WPBn	Mimbres Basin	West Potrillo Bench
MpB	Malpais GW Basin (E-edge—connects with BTC, MbB, and LMB)	
MpB-GLSB	Malpais Basin	Guzmans Lookout Subbasin (SB)
MpB-LLBn	Malpais Basin	La Laguna Bench (Bn)
RVB	Rincon Valley GW Basin (Drains to MeB through SCyn)	
RVB-BASB	Rincon Valley Basin	Bignell Arroyo Subbasin (47.2)
RVB-TNoc	Rincon Valley Basin	Tonuco Outflow Corridor (5)
SJB	Southern Jornada GW Basin (Drains to MeB and RVB)	
SJB-ERSB	Southern Jornada Basin	Experimental Range Subbasin (264)
SJB-ILSB	Southern Jornada Basin	Isaacks Lake Subbasin (164)
SJB-TvSB	Southern Jornada Basin	Talavera Subbasin (68.2)
SWTB	Southwestern Tularosa Basin	
ACRONYM	UPLAND GW BASIN	SUBDIVISION
CCUB	Cedar-Corralitos Upland Basin (UB)	
CCUB-CHSB	Cedar-Corralitos	Cedar Hills Subbasin (96.2)
CCUB-CRSB	Cedar-Corralitos	Corralitos Ranch Subbasin (205)

Table H1-6 (concluded). Acronyms and Names of Hydrogeologic Subdivisions on Figure H1-9

ACRONYM	INTERBASIN HIGH (IBH)	SUBDIVISION
PSH	Potrillo-Sapello High (163)	
PSH-LJS		La Joya Sector (93.5)
PSH-CMIC		Chontes-Milagro Inflow Corridor (69.5)

ACRONYM	INTERBASIN UPLIFT (U)	SUBDIVISION
AHU	Aden Hills Uplift	
ARU	Aden-Robledo Uplift	
ARU-AdS	Aden-Robledo Uplift	Aden Sector (S)
ARU-SRic	Aden-Robledo Uplift	South Robledo Inflow Corridor (145)
BCU	Bishop Cap Uplift	
BHU	Black Hills Uplift	
CAHU	Campus-Andesite Hills Uplift	
CCRU	Cerro del Cristo Rey Uplift	
CMU	Camel Mountain Uplift	
DAMU	Doña Ana Mountains Uplift	
EAU	El Aguaje Uplift (310)	
EPU	East Potrillo Uplift	
EPU-BTic	East Potrillo Uplift	Brock Tank Inflow Corridor (227)
EPU-PRS	East Potrillo Uplift	Potrillo-Mt. Riley Sector (S)
FMU	Franklin Mountains Uplift	
OMU	Organ Mountains Uplift	
RMU	Robledo Mountains Uplift	
SAMU	San Andres Mountains Uplift	
SHU	Selden Hills Uplift	
SJU	Sierra Juárez Uplift	
SSU	Sierra Sapello Uplift (41)	
TNMU	Tonuco Mountains Uplift	
TtU	Tortugas Uplift	
TtMU	Tortugas Uplift	Tortugas Mountain Uplift (U)
TtU-NTic	Tortugas Uplift	North Tortugas Inflow Corridor (63.5)
TtU-STic	Tortugas Uplift	South Tortugas Inflow Corridor (59.2)
UGU	Uvas-Goodsight Uplift	
UGU-SLU	Uvas-Goodsight Uplift	Sierra de las Uvas (U)
UGU-MDS	Uvas-Goodsight Uplift	Mason Draw Sector (S)
UGU-MLic	Uvas-Goodsight Uplift	Muzzle Lake Inflow Corridor (ic, to the Eastern Mimbres Basin)

ACRONYM	INTER-BASIN GROUNDWATER-FLOW CORRIDORS
BTC	Border Tank Corridor (214) (Malpais Basin to El Parabién Basin GW flow)
ETNC	East Tonuco Corridor (13.5) (Jornada Basin to Rincon Valley Basin GW flow)
FPC	Fillmore Pass Corridor (73.7) (Mesilla Basin-Hueco Bolson—Potential inter-basin GW flow)
MVIC	Méndez-Vergel Corridor (115) (Possible SW Hueco Bolson to SE Mesilla Basin GW flow)

Table H1-7. Basin-Boundary Fault Zone Acronyms and Names on Figure H1-9

- I. Groundwater Basin/Intrabasin-Boundary Fault Zones (fz)
  - A. Mesilla and El Parabién Basins
    - 1. Mesilla Basin (MeB)
      - CBfz—Chamberino fz
      - EVfz—El Vergel fz
      - EPfz—East Potrillo fz
      - ERfz—East Robledo fz
      - FGfz—Fitzgerald fz
      - MBfz—Mid-Basin fz
      - MDfz—Mastodon fz
      - MVfz—Mesilla Valley fz
      - NRfz—Noria fz
      - SPfz—San Pablo fz
      - SSfz—Sierra Sapello fz
      - TTfz—Tortugas fz
    - 2. El Parabién Basin (EPB)
      - EFfz—El Faro fz
      - EGfz—El Girasol fz
      - LCfz—Los Cuates fz
  - B. Southern Jornada and Rincon Valley Basins
    - 1. Southern Rincon Valley Basin (SJB)
      - TNfz—Tonuco fz
      - WTfz—Ward Tank fz
    - 2. Southern Jornada Basin (SJB)
      - EJfz—East Jornada fz
      - Jfz—Jornada fz
  - C. Hueco Bolson and Tularosa Basin
    - 1. Northwestern Hueco Bolson (NWHB)
      - FMfz—Franklin Mountains fz
      - SJfz—Sierra Juárez fz
    - 2. Southwestern Tularosa GW Basin (SWTB)
      - OMfz—Organ Mountains fz
      - SAMfz—San Andres Mountains Fz
  - D. Western-Border Basins
    - 1. Cedar-Corralitos Upland Basin (CCUB)
      - CHfz—Cedar Hills fz
      - WRfz—West Robledo fz
      - WTfz—Ward Tank fz
    - 2. Northeastern Mimbres Basin (MbB)
      - WTfz—Ward Tank fz
      - WRfz—West Robledo fz
    - 3. Malpais Basin (MpB)
      - LPfz—La Peña fz
- II. Inter-basin Uplift Fault Zones (fz)—Boundary and Interior
  - A. Aden-Robledo Uplift (ARU)
    - 1. ERfz—East Robledo fz
    - 2. WRfz—West Robledo fz
  - B. Doña Ana Mountain Uplift (DAMU)
    - 1. Jfz—Jornada fz
    - 2. MVfz—Mesilla Valley fz
    - TTfz—Tortugas fz
  - C. East Potrillo Uplift (EPU)
    - 1. EPfz—East Potrillo fz
    - 2. MRfz—Mount Riley fz
  - D. El Aguaje Uplift (EAU)
    - 1. EFfz—El Faro fz
    - 2. LPfz—La Pena fz
  - E. Franklin Mountains Uplift (FMU)
    - 1. FMfz—Franklin Mountains fz
    - 2. WFfz—West Franklin fz
  - F. Organ Mountains Uplift (OMU)
    - 1. EJfz—East Jornada fz
    - 2. OMfz—Organ Mountains fz
  - G. Robledo Mountain Uplift (RMU)
    - 1. ERfz—East Robledo fz
    - 2. WRfz—West Robledo fz
  - H. Sierra Juárez Uplift (SJU)
    - 1. SJfz—Sierra Juárez fz
    - 2. EVfz—El Vergel fz
  - I. Sierra Sapello Uplift
    - 1. SSfz—Sierra Sapello fz
    - 2. LCfz—Los Cuates fz
  - J. Southern San Andres Mtns (SAMU)
    - 1. EJfz—East Jornada fz
    - 2. SAMfz—San Andres Mountains fz
  - K. Tortugas Uplift (TtU)
    - 1. Jfz—Jornada fz
    - 2. TTfz—Tortugas fz
- III. Inter-basin Corridor Boundary-fault zones (fz)
  - A. Border Tank Corridor (BTC)
    - 1. LPfz—La Peña fz
    - 2. MRfz—Mount Riley fz
  - B. Fillmore Pass Corridor (FPC)
    - 1. FMfz—Franklin Mountains fz
    - 2. MVfz—Mesilla Valley fz
  - C. Méndez-Vergel Corridor (MVC)
    - 1. EVFZ—El Vergel fz
    - 2. SSfz—Sierra Sapello fz

H1.7. Hydrogeological Subdivisions and GW-Management Units in the Southern MBR

Major landscape features and GW-resource-management units in parts of the MBR located south of 32° N latitude are shown on a 2017 Google Earth® image base on **Figure H1-10**. The area covered extends southward to latitude 30°30' N, and it includes the western edge of the Hueco Bolson and most of the Zona Hidrogeológica de Conejos Médanos (ZHGCM, **Fig. H1-2**). The southern part of the NM WRRI Study Area (**Fig. H1-3**) is within the black rectangle, and the Mesilla and El Parabién GW Basins are outlined in green and violet. Locations of the Ciudad Juárez Junta Municipal de Agua y Saneamiento (JMAS) well-field and the 1.1-m (42-inch) pipeline that connects the field with storage and distribution facilities in Ciudad Juárez are shown, respectively, with a white oval and a zigzag white line. Other *key-well* sites for the NM WRRI investigation are shown with small red dots (*cf.* Rpt. **PL. 3, Tbl. 1**). **PMN1** shows the location of the deep PEMEX Moyotes No. 1 exploration well, and the still-uninvestigated "Loma Sin Nombre" site on the "El Aguaje Uplift is shown with an **LSN**.

Basin areas inundated by pluvial-Lake Palomas during its 1,210 m (3,970 ft) amsl, Late Pleistocene high stands have light-blue shading. The southern surface-watershed boundary of the Mesilla GW Basin (MeB) is in solid blue in **Figure H1-10**, and the dashed-blue line marks the approximate southern border of the present-day Transboundary GW-flow system. Most of the boundary segment SE of the Camel Mountain Uplift also forms the GW-flow divide between northeast-directed flow toward the lower Mesilla Valley (MeV), and SW-directed flow toward El Barreal in the central part of the ZHGCM. **ZHGCM SILL** shows the approximate location of the lowest part of the watershed divide (alt. ~1, 240 m/4,070 ft amsl) that borders the endorheic "Regiones Hidráulicas-Cuencas Cerradas del Norte" on the east (RH34, INEGI 1999-Figs. 5.3 and 5.3; *cf.* Part **H4.5**, **Figs. H4-14** and **H4-15**). The western part of RH34 includes the Ríos Casas Grandes, Santa Maria, and del Carmen drainage basins (Cuencas D, C, and B, respectively). Together with the Mimbres River (USA) drainage basin, the entire endorheic-basin complex has an area of about 76,290 km^2 (29,955 mi^2).

The northern part of the ZHGCM as delineated on **Figures H1-1** and **H1-10** includes the "Acuífero Conejos-Médanos," which is shown in detail in the 2011 Binational Waters Map of the International Boundary and Water Commission (IBWC; **Fig. H1-11***). Because of the topographic [and hydrogeologic] complexity of the "Acuífero Conejos-Médanos" as shown in **Figure H1-11**, it is here suggested that "Acuífero[s] C-M" would be a more accurate designation for this hydrogeologically and geohydrologically complex aquifer system. This is especially relevant, because only the northernmost part of the "Acuífero Conejos-Médanos" is hydraulicly linked to the present Transboundary GW-flow system (*cf.* **Fig. H1-17**; **Parts H6.2 and H6.3**).

**Note added place- and feature-name annotations.*

The present-day, phreatic-salina (GW-ET discharge) area for the ZHGCM is located between Sierrita Amargosa and Salina[s] de Unión, with a flowing-well head of about 1,180-m (3,870 ft) amsl, at a site near the northeastern base of Sierrita Amargosa (**Fig. H1-11**; *cf.* **Figs. H1-17**, **H6-3**, and **H6-4**). The discharge-zone base level for the regional (predevelopment) GW-flow system is about 1,135 m (3,724 ft) amsl at the lower end of the Mesilla Valley, and since the distance between the two sites in about 100 km (60 mi), the hydraulic gradient of the flow is very low (~0.0005).

Figure H1-10. Major landscape and geohydrologic features, and aquifer-management units in the southwestern part of the binational/tristate MBR (**Fig. H1-2**). Locations of producing wells in the new Ciudad Juárez Junta Municipal de Agua y Saneamiento (JMAS) well-field are shown with dark-red dots in a white oval. The Zona Hidrogeológica de Conejos Médanos (ZHGCM) and the Acuifero[s] Conejos Médanos are outlined, respectively, in solid yellow and dashed black and white. **ZHGCM SILL** shows the approximate location of the lowest part of the watershed divide (alt. ~1, 240 m/4,070 ft amsl) that borders the endorheic ZHGCM-basin complex. The approximate southern edge of the regional Transboundary GW-flow system is shown with a dashed-blue line. Swanson Geoscience, LLC compilation on a 2017 Google Earth® image base.

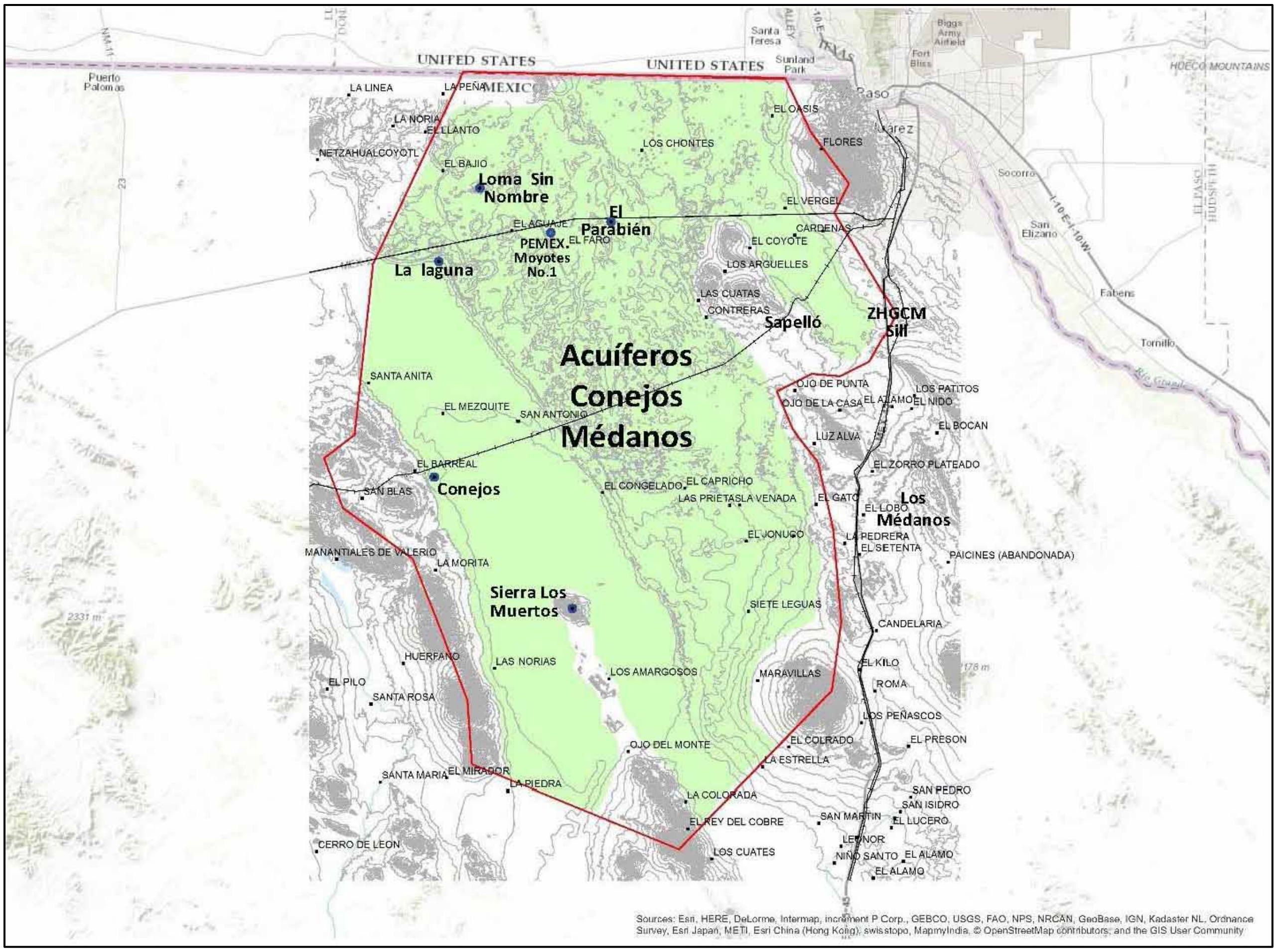


Figure H1-11. IBWC (2011) Acuífero Conejos-Médanos: Binational Waters map.

Figure H1-12 is an enlarged section of **Figure H1-10** that shows the extent of a provisionally defined "International-Boundary Zone (IBZ)." The 17,000 km^2 IBZ is located between 31° and 32° N longitude and the 106°30' and 108° W latitude; and it extends westward from the eastern edge of the Hueco Bolson to the lower Mimbres River and Rio Casas Grandes basins near Columbus, NM and Puerto Palomas, Chihuahua. The new JMASCJ well field is located within the white oval, and the 42 in (1.1 m) water-transmission line is shown in white. Areas inundated during pluvial-Lake Palomas high stands have blue-gray shading. The southern boundary of the MeB's surface watershed is in solid blue; and the approximate position of the southern Transboundary GW-flow system is shown with a dashed-blue line. Most of the flow-boundary SE of the Camel Mountain Uplift also forms the contemporary GW-flow divide between flow directed toward the MeV/EPdN and ZHGCM/El Barreal.

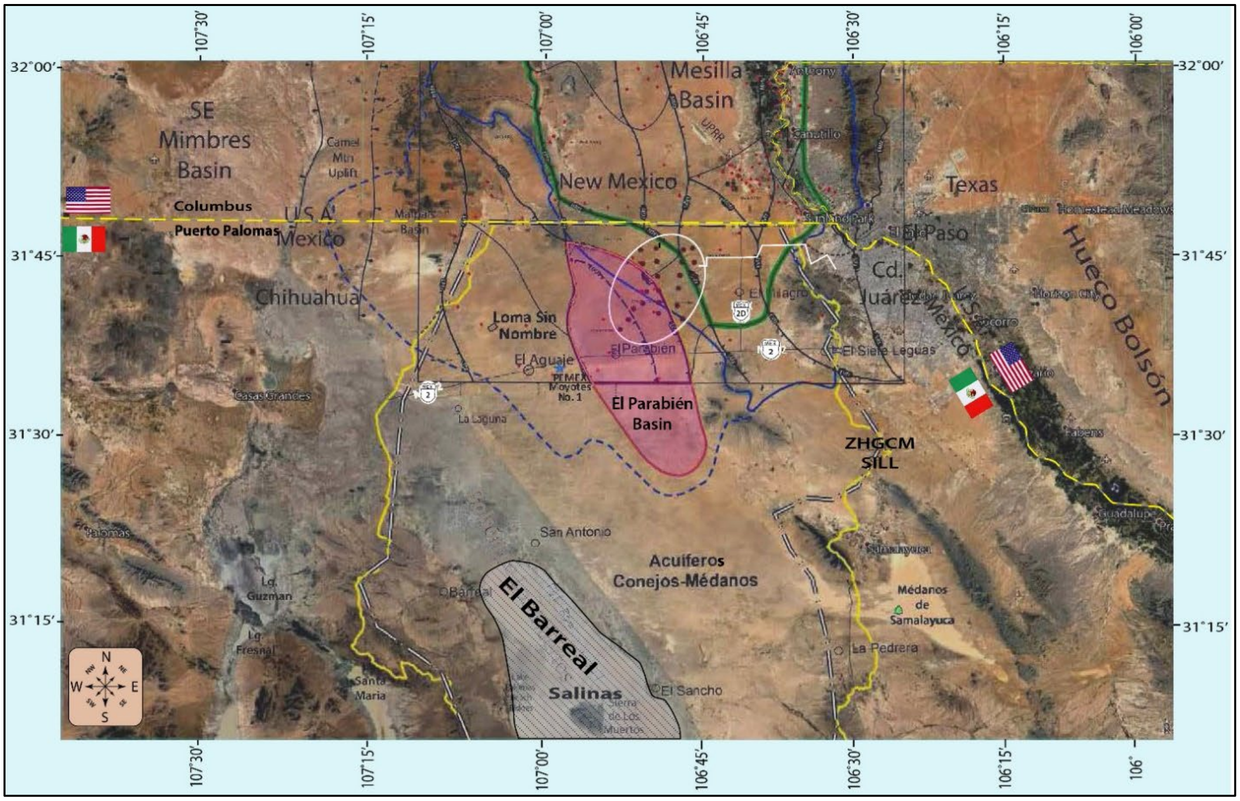


Figure H1-12. Index map of the "International-Boundary Zone (IBZ)" as provisionally defined in this investigation. It is located between the latitudes 31° and 32° N and longitudes 106°30ˈ and 108° W. Swanson Geoscience, LLC compilation on a 2017 Google Earth® image base.

Figure H1-13 is a more-detailed map on a 2017 Google Earth® image base that shows the locations of the new JMASCJ well field and the 42-inch water-transmission line (white-solid and dashed) that connects it with central Ciudad Juárez. Twenty-three of the wellfield's production-well sites are shown with black and white dots within the white oval. Most of the wells are about 300 m (1,000 ft) deep and have designed production capacities of 50 liters/second (793.6 gpm). The white rectangle outlines the southern part of the Study Area, and the southern and northern parts of the Mesilla and El Parabién GW Basins are shown, respectively, in green and beige. Nearby areas of concentrated groundwater production are located south of the San Jerónimo-Santa Teresa Port entry at the Foxconn complex, and north of the International Boundary in the Santa Teresa Industrial Park and the UPRR Intermodal Terminal and Refueling Station (*cf.* Pacheco 2008 and 2012, Robinson-Avila and Villagran 2014, Kocherga 2018a, d and g, ABQ Journal 2019, Robinson-Avila 2020a-e and 2021d, Hamway 2020a and b).

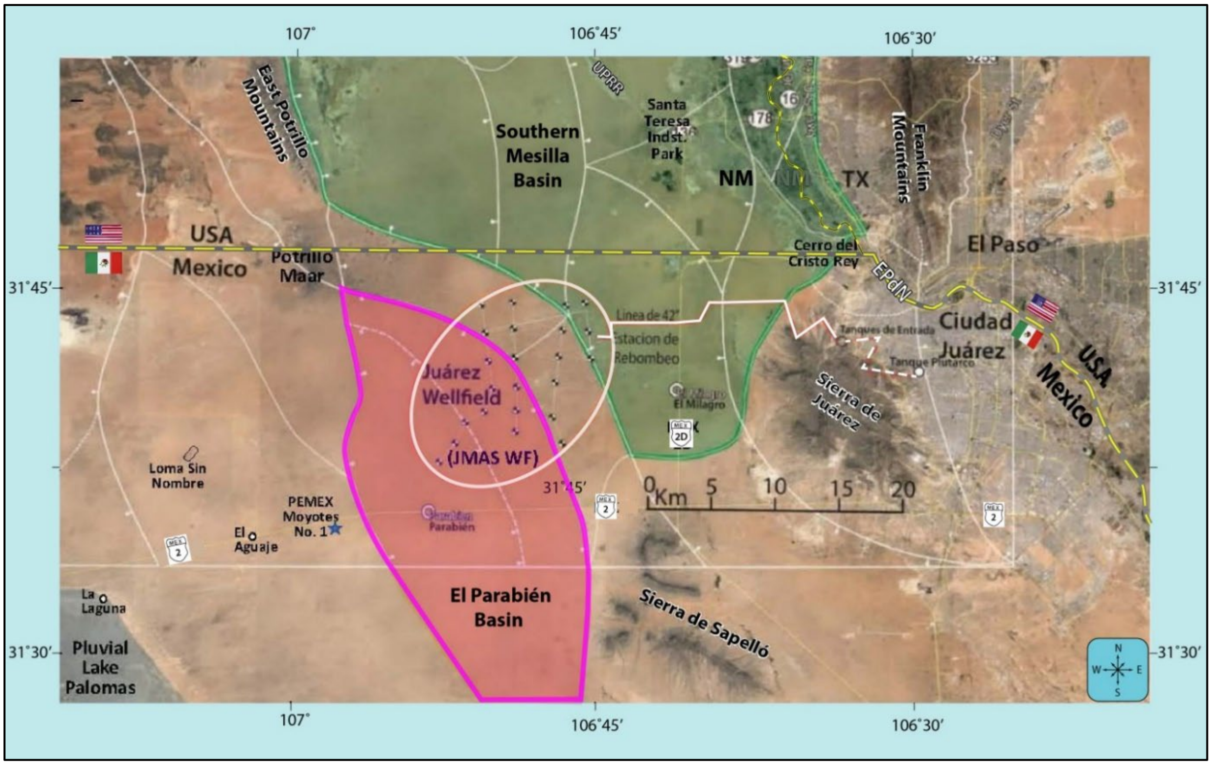


Figure H1-13. Index map showing the location of the new JMASCJ well field and the 42-inch water-transmission line (white-solid and dashed) that connects it with central Ciudad Juárez; 23 of the wellfield's production-well sites are shown with black and white dots within the white oval (**Figs. H1-10** and **H1-11**). The southern Study Area is inside the white rectangle, with respective southern and northern parts of the Mesilla and El Parabién GW Basins shown in green and beige. The area inundated by pluvial-Lake Palomas has blue-gray shading. Swanson Geoscience LLC compilation on 2017 Google Earth® image.

H1.8. Background on Hydrogeologic-Framework Controls on GW Flow and Chemistry in the Southern Mesilla Basin Region

At present, intermittent flow of the Rio Grande/Bravo fluvial system serves as the MBR's only effective groundwater (GW) recharge source. Moreover, GW pumped from SFG basin-fill aquifers is also now the primary source of public water supply for (1) the Ciudad Juárez-El Paso "metroplex" with a population of more than 2.2 million in 2020, and (2) the Las Cruces area with a 2020 population of almost 200,000. In addition, ever-increasing amounts of GW is also used to supplement Rio Grande Project (RGP) surface-water deliveries for irrigation-agricultural (I-Ag) activity that dates to the completion of Elephant Butte Dam construction in late 1915 (*cf.* Kelley et al. 2007). Most GW in basin-fill storage was last effectively replenished during the last Pleistocene glacial stage, which ended about 12,000 years ago (ka). GW-outflow discharge from pluvial-Lake Palomas was also a significant contributor of recharge to Transboundary aquifer systems (**Figs. H1-10** and **H1-10**; *cf.* **H1-17**). While very large quantities of economically producible GW in basin-fill storage is fresh, municipal and industrial (M&I) wells pump increasing amounts of slightly saline brackish groundwater (BGW)*, with the latter here considered to be an asset rather than a liability (*cf.* TWDB 2015).

**Stanton and others (2017, Tbl. 1), define two classes of "brackish groundwater" (BGW): slightly saline—1,000-3,000 mg/L TDS; and moderately saline—3,000 to 10,000 mg/L TDS.*

The following selection from Nickerson (2006, p. 2) represents the first formal recognition by USGS-Water Science Centers of the basin-scale hydrogeologic-framework model developed by Hawley and Lozinsky (1992) in the Mesilla Basin region (*cf.* Sweetkind 2017 and 2018, Sweetkind et al. 2017, Hanson et al. 2018):

> The hydrogeologic framework of the Mesilla Basin was established in Hawley and Lozinsky (1992). Their basinwide conceptual model delineated three hydrogeologic features: (1) bedrock and structural boundaries, (2) lithofacies assemblages, and (3) hydrostratigraphic units. Santa Fe Group basin fill is divided into the informal upper, middle, and lower hydrostratigraphic units based on depositional environment and age. The upper Santa Fe hydrostratigraphic unit (USF) consists primarily of ancestral Rio Grande deposits of medium to coarse sand and [pebble] gravel. The USF includes the Camp Rice and upper Fort Hancock Formations. The middle Santa Fe hydrostratigraphic unit (MSF) consists primarily of alluvial deposits with eolian and playa-lake facies.
>
> Basin-floor sediments of interbedded sand and silty clay are common. The MSF includes the Fort Hancock and Rincon Valley Formations. The lower Santa Fe hydrostratigraphic unit (LSF) consists primarily of eolian, playa-lake, and alluvial facies. Basin-floor sediments include thick-bedded dune sand. The LSF includes the Hayner Ranch and the lower Rincon Valley Formations. Detailed descriptions of the hydrostratigraphic units and associated lithofacies can be found in Hawley and Lozinsky (1992). The Mesilla Basin hydrogeologic framework was recently updated and integrated into a digital format by Hawley and Kennedy (2004).

H1.8.1. Lithofacies Assemblages

Lithofacies Assemblages (LFAs), as defined herein, form the basic components of basin-fill deposits throughout the B&R and RG-rift provinces, and they are the primary components of SFG hydrostratigraphic units (HSUs) in the MBR (Rpt. **Part 3.1.2**). LFA 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 (**Fig. H1-14**; **Tbl. H1-8**). Basin and river-valley fills are subdivided into thirteen major assemblages (LFAs 1-10, a-c), which are ranked in decreasing order of aquifer-production potential (**Tbls. H1-9** and **H1-10**).

LFAs have distinctive geophysical, geochemical and hydrologic attributes (**Apnds. A5** and **C2.2**). In combination with the Hydrostratigraphic Units (HSUs; Part H1), they provide a mechanism for showing the distribution patterns of a wide range of aquifer- and vadose-zone conditions on hydrogeologic cross-sections and isopleth [aka voxel] maps (*cf.* Rpt. **PLS. 5** and **7**; Sweetkind 2017 and 2018). The general distribution pattern of the major LFAs that Mesilla Basin region (MBR) is schematically illustrated in **Figure H1-14**. LFAs represent four major depositional environments (**Tbl. H3-1**): basin floors (1-3, 9, 10, c), piedmont slopes (5-8), river-valley floors (a1-a3), and river-valley borders (b). LFA 4 primarily comprises deeply buried sand-dune fields on the leeward (eastern) sides of lacustrine plains (ephemera to perennial) of endorheic basins and large-stream valleys, and other partly cemented sand-dominated sediments (*cf.* **Apndx. F**: **PLS. F6-1a** to **1f**, and **F6-2a** to **2f**).

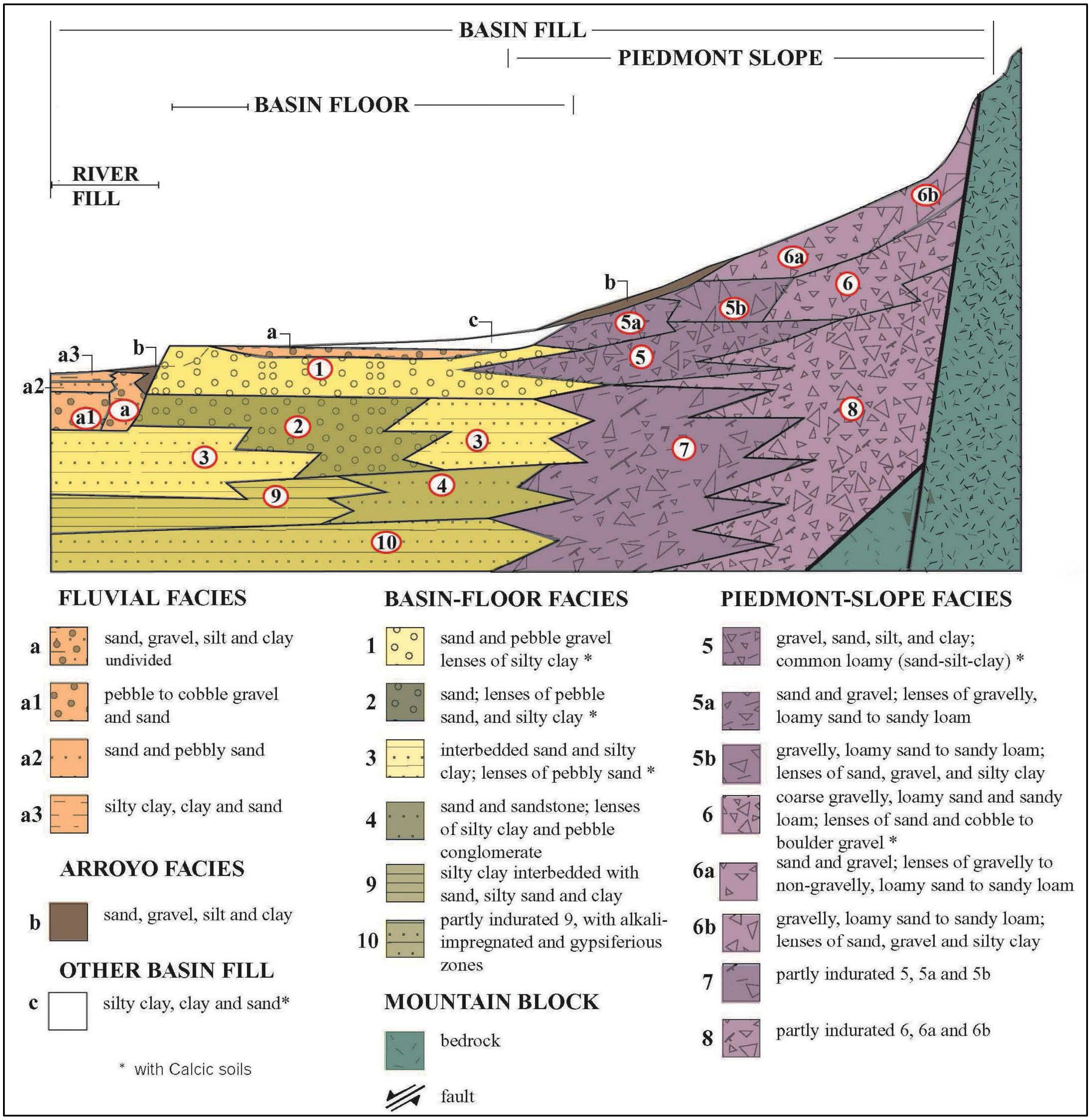


Figure H1-14 (modified from Hawley and Kernodle, 2000, Fig. 5)**.** Schematic diagram that illustrates distribution patterns of major lithofacies assemblages (LFAs) in structural-basin and river-valley fills of the Rio Grande rift tectonic province. Explanations of LFA composition in **Table H1-8** and aquifer-production and GW-flow potential in **Tables H1-9** and **H1-10**.

Table H1-8. Summary of Depositional Setting and Dominant Textures of Major Lithofacies Assemblages (LFAs) in Santa Fe Group Basin Fill (1-10) and Rio Grande Valley Fill (a-c) in Intermontane Basins of the Rio Grande Rift Tectonic Province (Fig. H1-14; *cf.* **Tbls. H1-9** and **H1-10).** 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 H1-9. Summary of Major Sedimentary Properties that Influence Groundwater-Flow and Aquifer-Production Potential of Lithofacies Assemblages (LFAs) 1 to 10 in Santa Fe Group Basin Fill (Fig. H1-14, Tbl. H1-8). Modified from Haase and Lozinsky (1992).

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%)

Table H1-10. Summary of Major Sedimentary Properties that Influence Groundwater-Flow and Aquifer-Production Potential of Lithofacies Assemblages (LFAs) a to c in Post-SFG Deposits (Fig. H1-14; Tbl. H1-8). Modified from Hawley and Kernodle (2000).

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.

H1.8.2. Hydrostratigraphic Units

George Burke Maxey (1964, p. 126) originally defined a hydrostratigraphic unit (HSU) as "a body of rock having considerable lateral extent and composing a geologic framework for a reasonably distinct hydrologic system." HSUs are used in this study, as the primary tool for detailed mapping of rift-basin deposits on the basis on distinctive LFA composition and well-defined lithostratigraphic-sequence positions (Hawley and Kernodle 2000; Hawley and Kennedy 2004; **Apndx. A2.1.1**). General correlations between Cenozoic time-rock classes, and their lithostratigraphic and hydrostratigraphic equivalents are illustrated in **Figure H1-15**. Related bedrock-lithologic, and structural boundary components of GW-basins and interbasin Uplifts are described in terms of both interbasin and intrabasin GW flow in Report **Chapter 7**. The LFA-HSU combination for showing the spatial-distribution patterns of a wide range of aquifer- and vadose-zone conditions on hydrogeologic cross-sections and isopleth (aka voxel) maps (*cf.* **Figs. H1-16** and **H1-17**; Sweetkind 2017 and 2018, Sweetkind et al. 2017).

Organization of hydrogeologic information on basin-fill stratigraphy and sedimentology required development of a provisional hydrostratigraphic classification system that is applicable throughout the eastern B&R and RG-rift provinces. Even-numbered alphanumeric codes (e.g., HSUs USF 2 and MSF 2) designate units composed of basin-floor lithofacies assemblages (LFAs 1-3, 9-10), and odd-numbered codes) denote units comprising piedmont-slope LFAs (5-9; e.g., USF 1, MSF 1). Refinement of HSU definitions is an iterative process, with updates occurring during each study phase. Informal Upper, Middle, and Lower Santa Fe HSUs (USF, MSF, LSF) form the major basin-fill aquifer zones in the Mesilla Basin region; and they correspond roughly to the Camp Rice, Fort Hancock, Rincon Valley, and Hayner Ranch lithostratigraphic subdivisions of the Santa Fe Group (**Fig. H1-15**; Rpt. **Part 3.5.2b**). Proper identification and correlation of these lithostratigraphic units in the deeper subsurface, however, remains a significant problem in parts of many groundwater basins where detailed subsurface information (geological, geophysical, and geochemical) is not yet available, hence the continuing informal status of the hydrostratigraphic terminology.

General subsurface relationships to a mean sea level (msl) depth in the southern part of the Study Area are shown with a set of five hydrogeologic sections in **Figure H1-16** (I-I' to L-L' and S-S'). They were initially compiled at 1:100,000 map scale, and have 5x vertical exaggeration (VE). Blue lines in the upper part of each section mark the approximate pre-development (1976-1982) (potentiometric-surface altitude; *cf.* **Fig. H1-17**). Santa Fe Group (SFG) Hydrostratigraphic Units (HSUs) are shown with yellow shading, with lighter hues indicating better groundwater-production potential. The general litho-stratigraphy of underlying bedrock units is also shown. Short definitions of commonly used *geologic*, *geohydrologic,* and *hydrogeologic* terms are included in **Tables H1-1**, **H1-2**, and **H1-4**.

Figure H1-18 is an index map to major geohydrologic features of the NM WRRI Study Area (**Fig. H1-2**). It represents the first effort to characterize the principal components of the regional Transboundary groundwater (GW)-flow system that discharges at the lower end of the Mesilla Valley (MeV; *cf.* Rpt. **Part 7.6.2**). Locations of key-well sites are shown on **Figure H1-12** (*cf.* Rpt. **Fig. 2-2**). The Mesilla, El Parabien, and Southern Jornada GW Basin (MeB, EPB, and SJB) boundaries are in green, violet, and orange, respectively. Surface-watershed divides are shown by solid blue lines. Thin, orange lines show the approximate pre-development (~1976) potentiometric-surface/water-table altitude at 5, 10 and 30 m contour intervals. The dashed blue line with arrows in the map's SW corner is the approximate divide between El Paso del Norte-directed GW flow and SW-directed GE flow to El Barreal (intermittent lake) in the Los Muertos Basin of north-central Chihuahua (**Figs. H1-10** and **H1-12**).

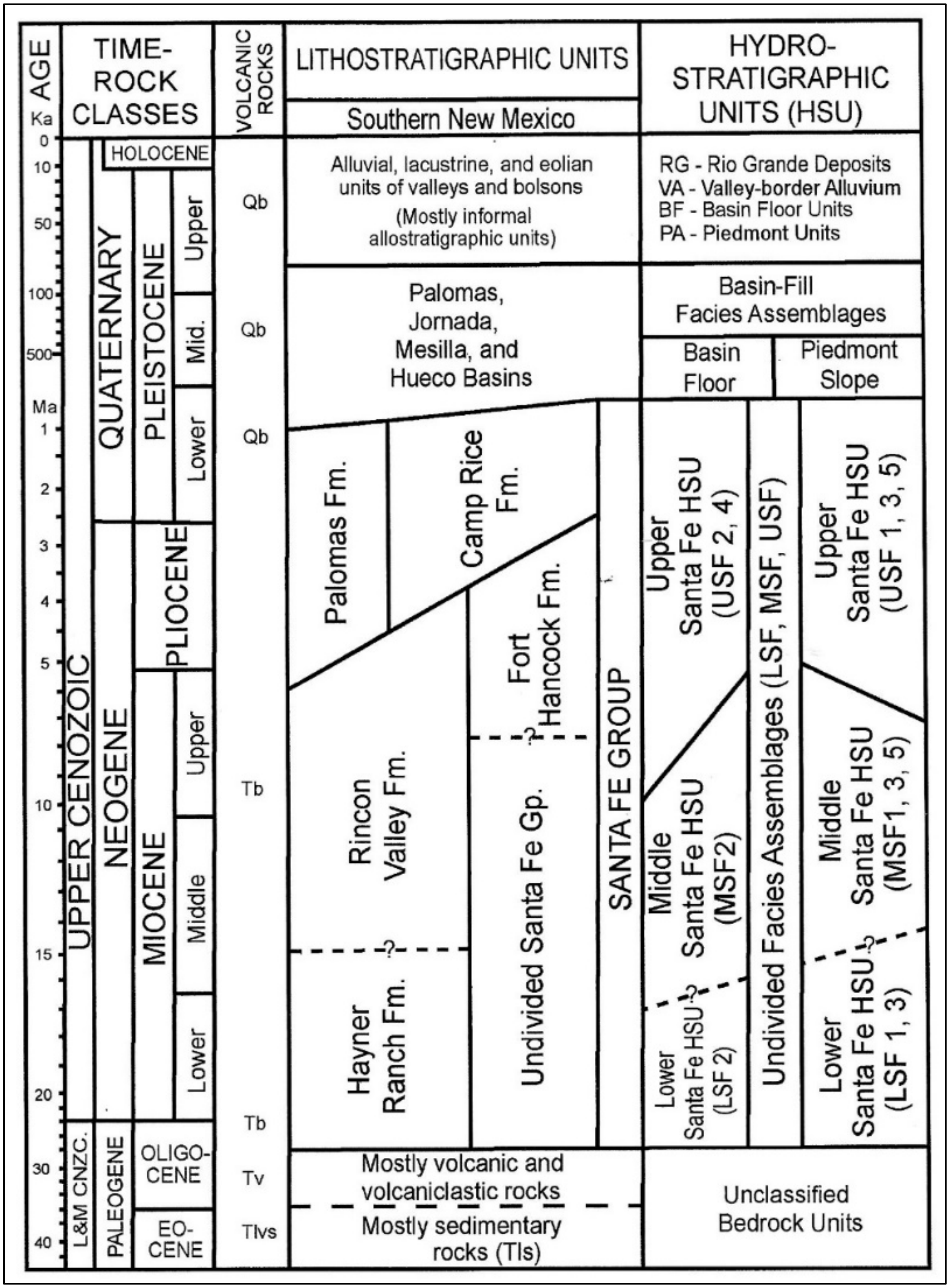


Figure H1-15 (modified from Hawley et al. 2009, Fig. 6)**.** Correlation diagram of major Cenozoic Time-Rock (chronostratigraphic) classes, and lithostratigraphic, allostratigraphic, and hydrostratigraphic units in the southern RG-rift region (**Tbl. H1-2**; *cf.* NACOSN 2005, **Apndx. G**). Bedrock units: Qb–Quaternary basalt, Tb–Tertiary mafic volcanics, and Tv–older Tertiary intermediate and silicic volcanics, and associated plutonic-igneous and sedimentary rocks.

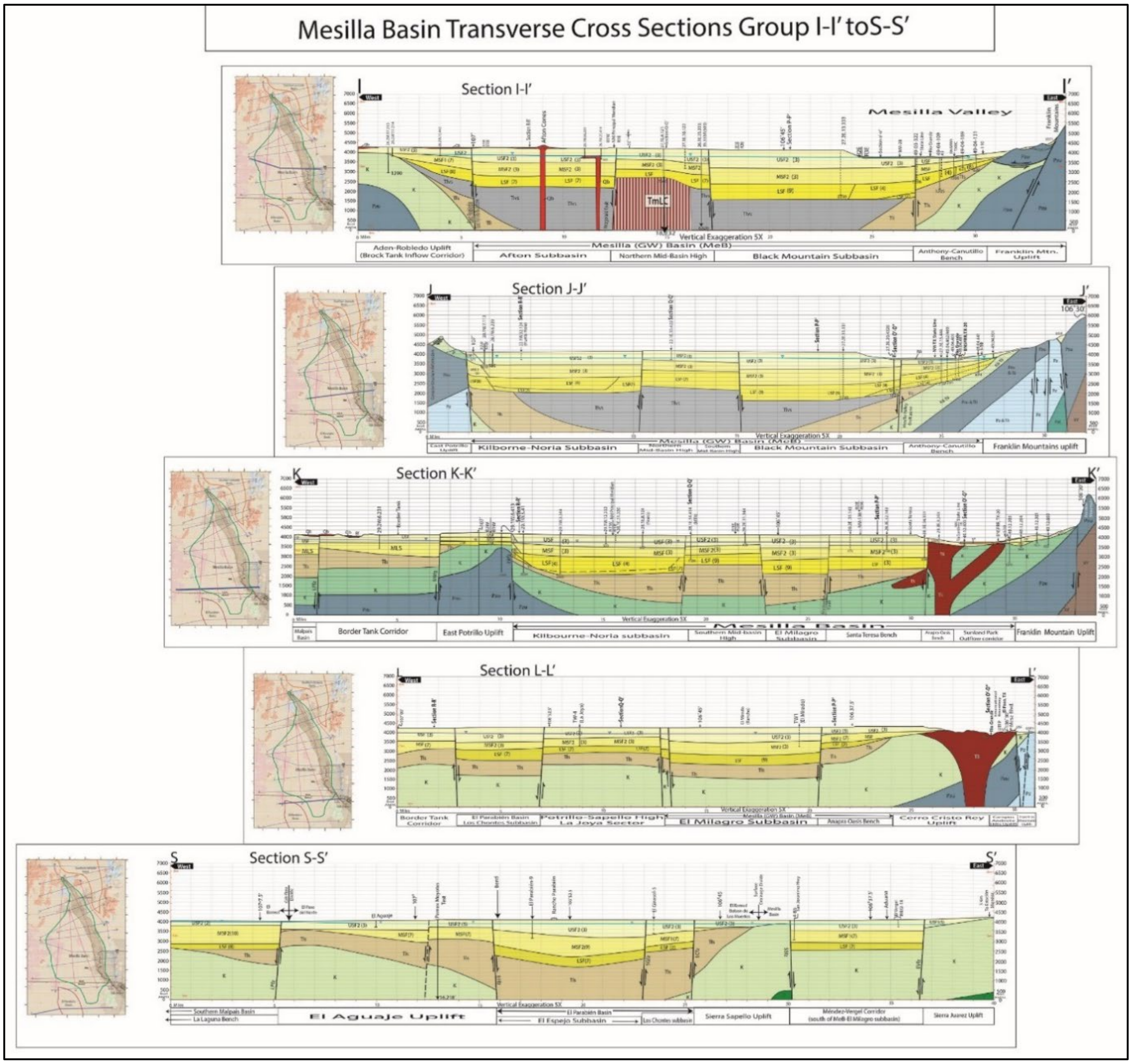


Figure H1-16 (Rpt. **PLS. 5i** to **5l** and **5s).** Hydrogeologic Cross-Sections I-I' to L-L' and S-S', with section locations shown on end panels, and on **Figure H1-3**. The approximate pre-development (1976-1982) water-table/potentiometric-surface altitude is shown with a blue line in the upper part of each section (*cf.* **Fig. H1-17**). Santa Fe Gp (SFG) Hydrostratigraphic Units (HSUs) are shown with yellow shading, with lighter hues indicating better groundwater-production potential. Underlying bedrock units, in order of increasing age, comprise the following lithostratigraphic sequence: Tlvs-Eocene volcaniclastic, epiclastic and volcanic rocks of intermediate composition (gray); Tli-Eocene intrusive igneous rocks of intermediate composition (red); Tls-Lower Tertiary siliciclastic sedimentary rocks (tan); K-Cretaceous marine sedimentary rocks (light green); Pzu/Pzl-Upper and Lower Paleozoic marine sedimentary rocks (dark and light blue); and XY-Proterozoic (Precambrian) igneous and metamorphic rocks (brown).

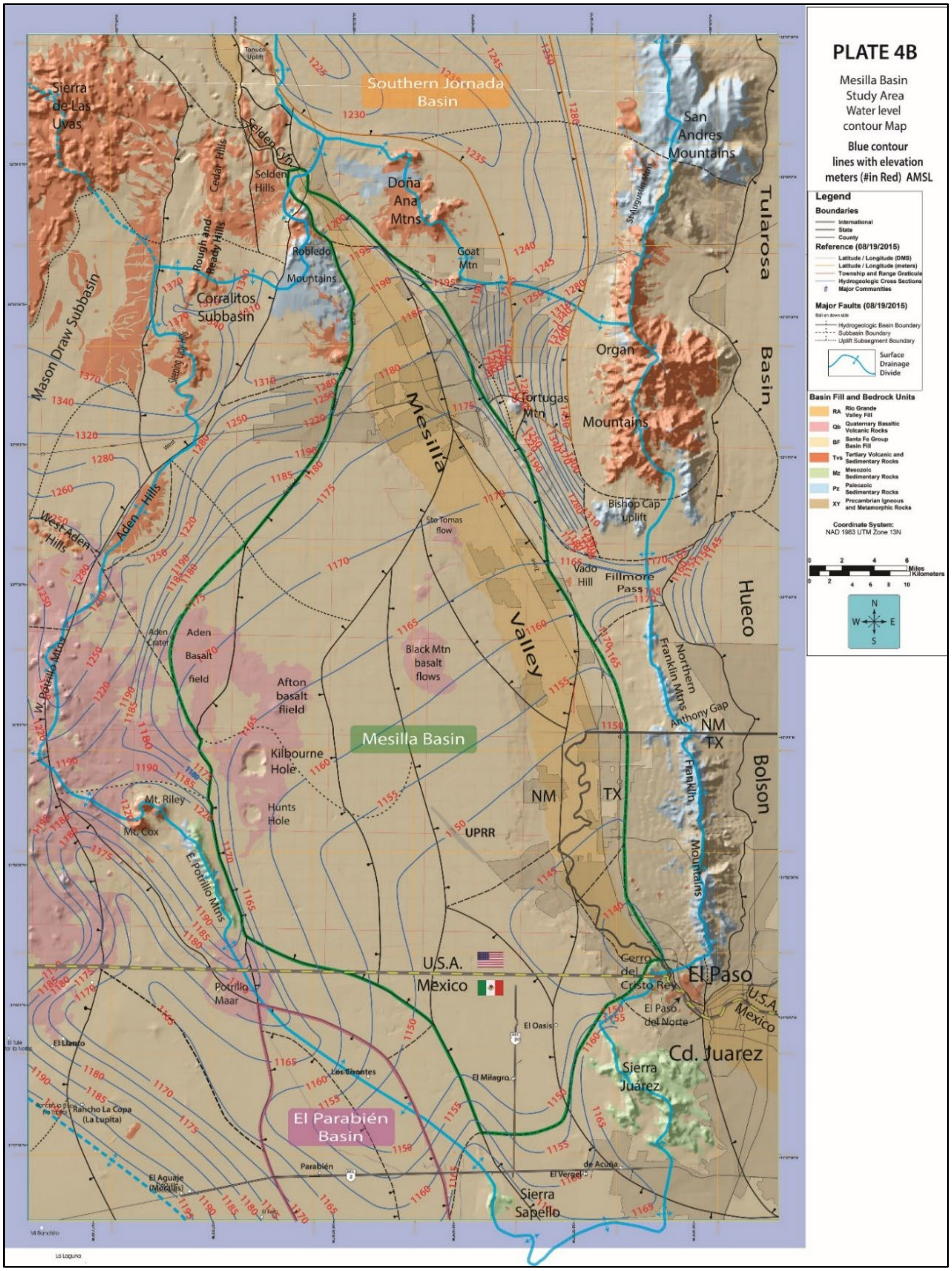


Figure H1-17 (PL 4b). Index map to major geohydrologic features of the NM WRRI Study Area (*cf.* **Fig. H1-3**). The Mesilla, El Parabien, and Southern Jornada GW Basin (MeB, EPB, and SJB) boundaries are in green, violet, and orange, respectively). Surface-watershed divides are shown by solid blue lines. Thin blue lines show the approximate predevelopment (~pre-1976) potentiometric-surface altitude at 5-, 10-, and 30-m contour intervals. The dashed blue line with arrows in the map's SW corner is the approximate present-day divide between EPdN-directed GW low and GW flow to El Barreal (**Figs. H1-10** and **H1-15**).

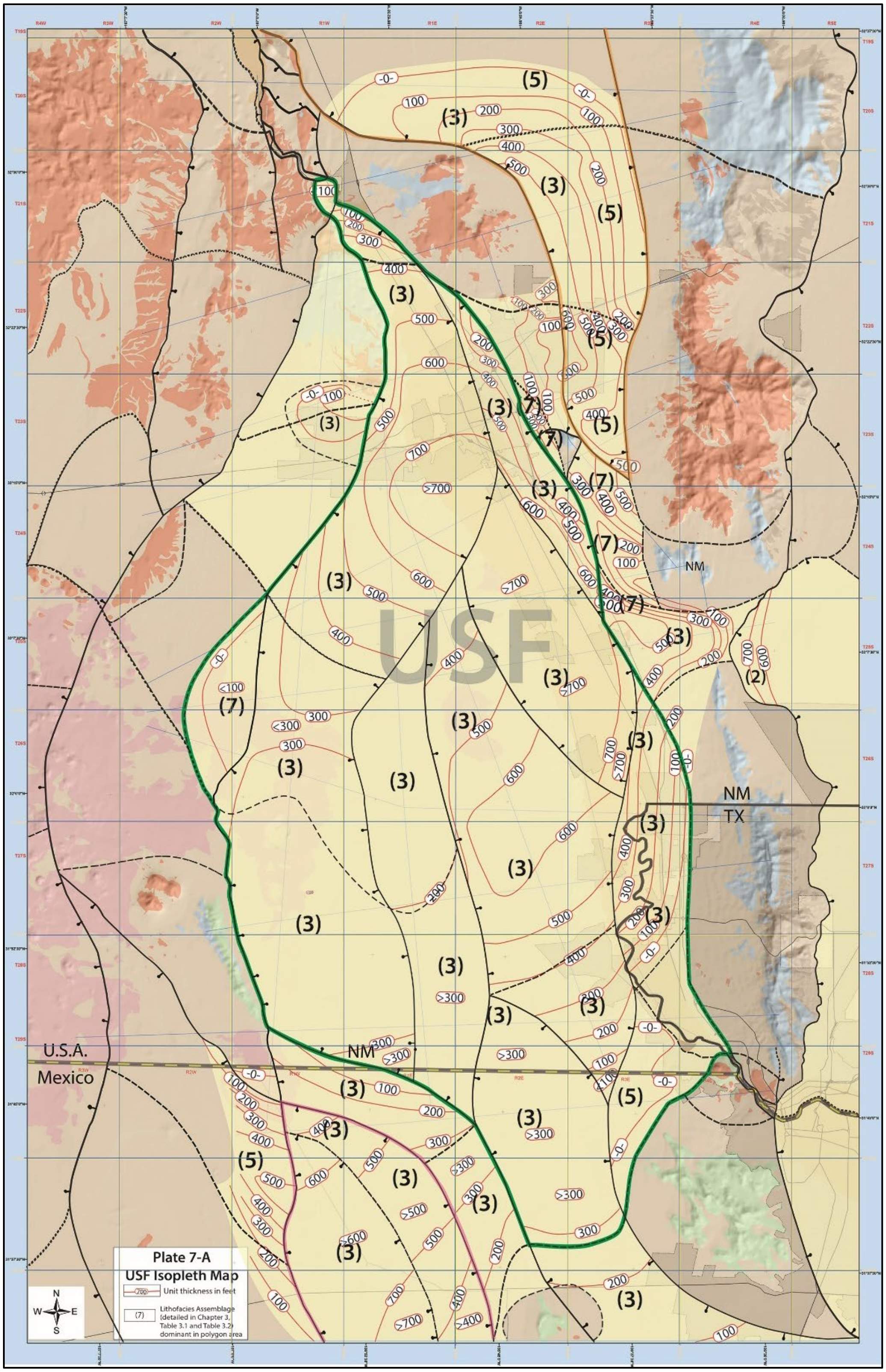


Figure H1-18 (page-size **PL. 7A).** Study Area isopleth map of the saturated part of HSU-USF that schematically depicts LFA composition and saturated thickness. 2017 Google Earth® image-base

At present, intermittent flow of the Rio Grande/Bravo fluvial system serves as the MBR's only effective groundwater (GW)-recharge source. Moreover, GW pumped from SFG basin-fill aquifers is also now the primary source of public water supply for (1) the Ciudad Juárez-El Paso "metroplex" with a population of more than 2.2 million in 2020, and (2) the Las Cruces area with a 2020 population of almost 200,000. In addition, ever-increasing amounts of GW is also used to supplement Rio Grande Project (RGP) surface-water deliveries for irrigation-agricultural (I-Ag) activity that dates to the 1916 Elephant Butte Dam completion (*cf.* Kelley et al. 2007). Most GW in basin-fill-aquifer storage was last effectively replenished by both the Rio Grande and underflow discharge from pluvial-Lake Palomas during the last Pleistocene glacial stage, which ended about 12 ka (e.g., **Figs. H1-10** and **H1-12**; *cf.* García-Vásquez et al. 2022, and **Fig. H1-11**). While very large quantities of economically producible GW in basin-fill storage is fresh, municipal and industrial (M&I) wells pump increasing amounts of slightly saline brackish groundwater (BGW)*, with the latter here considered to be an asset rather than a liability (*cf.* TWDB 2015).

**Stanton and others (2017, Tbl. 1), define two classes of "brackish groundwater" (BGW): slightly saline—1,000-3,000 mg/L TDS; and moderately saline—3,000 to 10,000 mg/L TDS.*

H1.9. Background on Buried-Bedrock Stratigraphy, Structure, and Topography

Figure H1-19 (Rpt. **PL. 1B**) schematically portrays the topography, and primary stratigraphic and structural components of the bedrock terrane that is buried by basin-fill deposits within the NM WRRI Study Area (**Fig. H1-3**). The map represents the first effort to create a binational approximation of the "bottom" of the SFG basin-fill aquifer system in the Study Area. It is based on a synthesis of available geological and/geophysical information that has been acquired by the PI since the 1960s. The primary structure-contour interval on the bedrock surface is 300 ft (~30 m). Red lines show locations of schematic geologic cross-sections (II-II′ to III-III′) on **Figure H1-20** (Rpt. **PL. 1C**). The latter shows general subsurface geologic relationships to a depth of 10,000 ft (~3 km) bmsl at a VE of about 2.5. Section II-II′ illustrates these basic geologic relationships in a central MeB area; and Section III-III′ shows geologic relationships in an area located about 5 mi (8 km) south of the International Boundary. The Mesilla, Southern Jornada and El Parabién GW Basins (MeB, SJB, and EPB) are outlined in green, orange, and violet, respectively; and map-unit stratigraphic subdivisions are defined in **Table H1-10**. The general position of a heretofore unmapped and deeply buried "Lanark igneous-intrusive complex (TmLC)" in the central part of the Mid-Basin High is also shown (*cf.* Rpt. **Part 6.3.2a**).

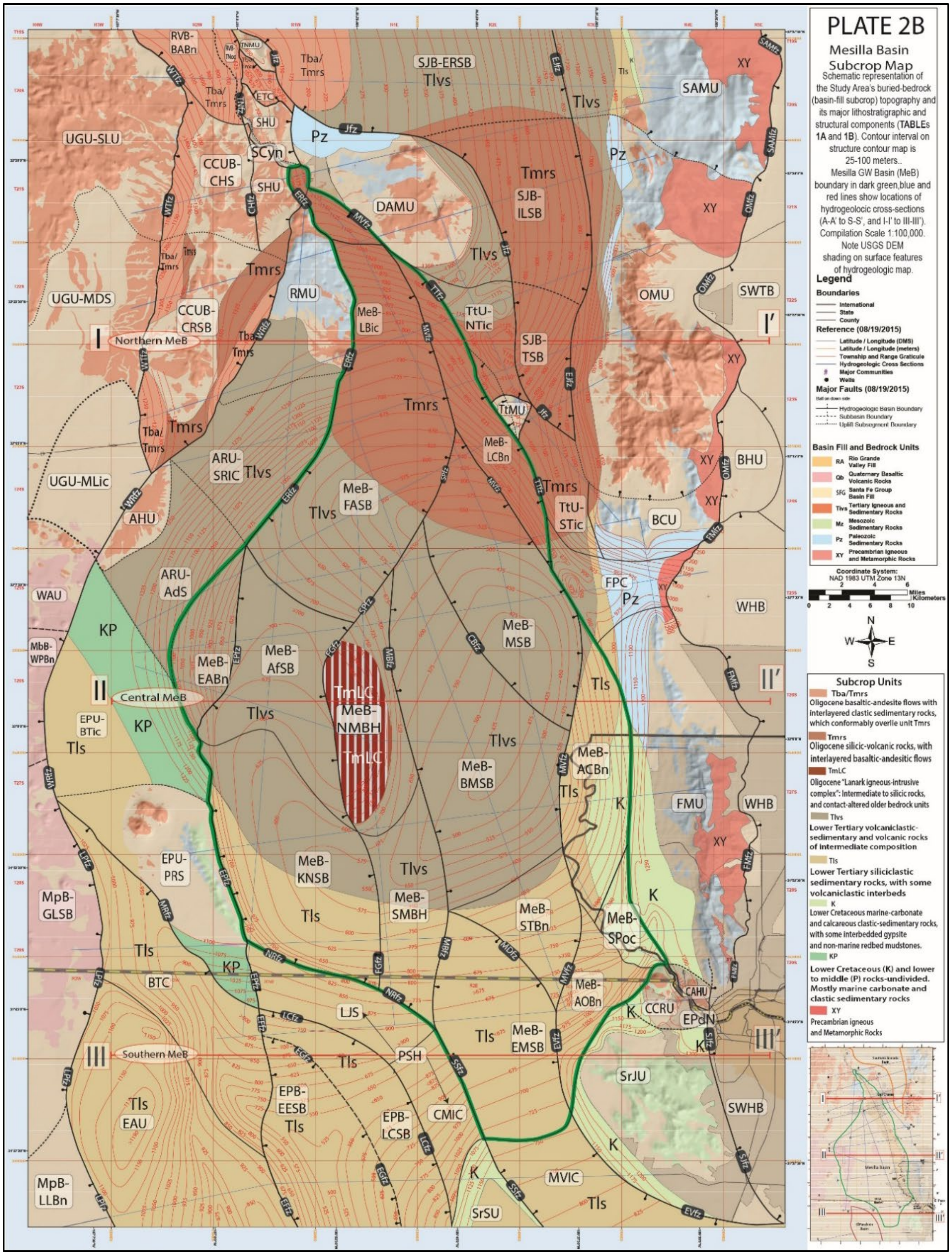


Figure H1-19 (page-size Rpt. **PL. 2B**)**.** Schematic depiction of basin-fill subcrop topography, and primary lithostratigraphic and structural components in the Study Area, with explanation on **Table H1-10**. W-E red lines show locations of geologic cross-sections I-I′ to III-III′ on **Figure H1-20**. Swanson Geoscience LLC compilation on Report **PLATE 1** hydrogeologic-map base.

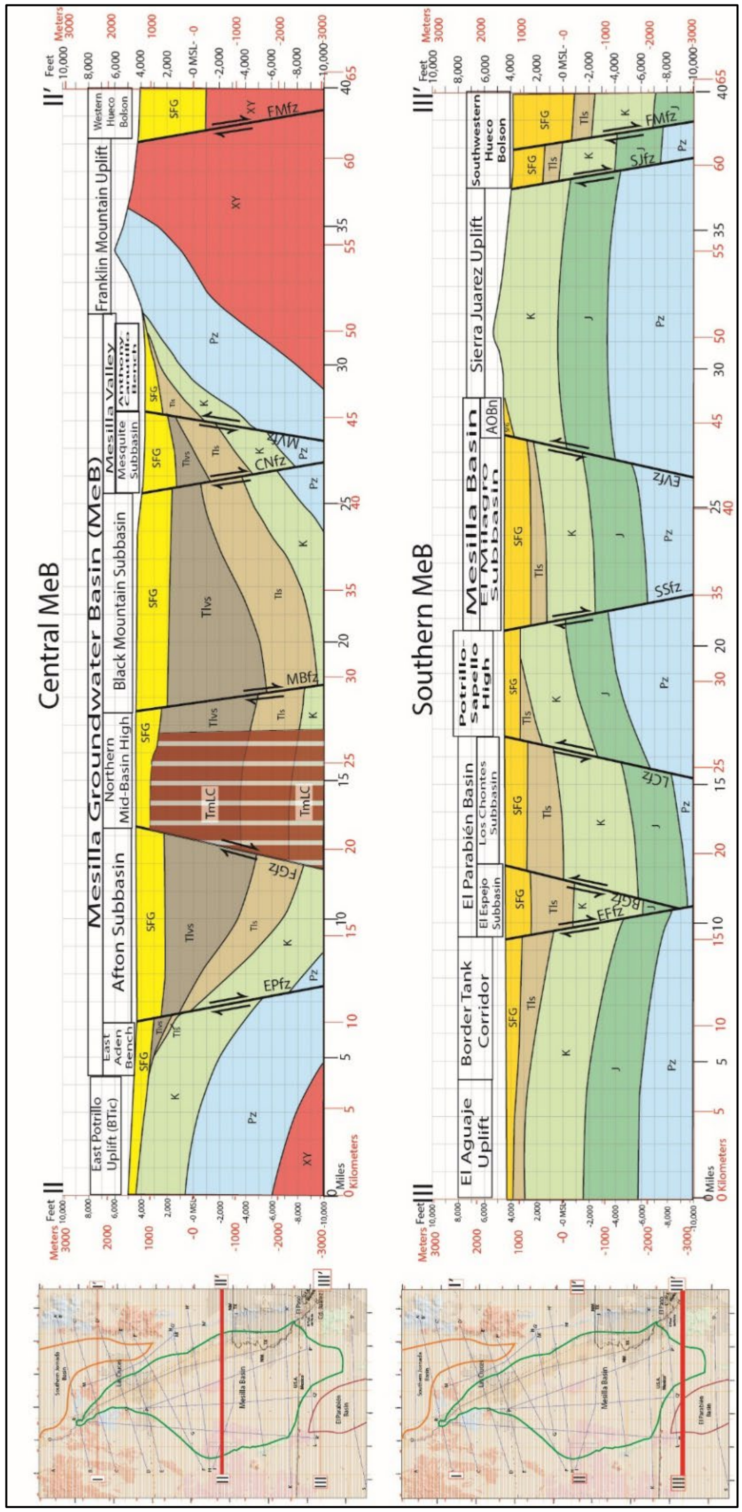


Figure H1-20 (page-size, partial Rpt. **PL. 1C**)**.** Schematic geologic cross-sections II-II′ and III-III′ that show representative RG-rift stratigraphic and structural features in the central and southern part of the Study Area. Base elevation is 10,000 ft (3 km) below mean sea level (bmsl), and vertical exaggeration (VE) is about 2.5. Section locations on **Figure H1-19**, with stratigraphic-unit explanations on **Table H1-10**. Swanson Geoscience LLC compilation.

Table H1-11. Explanation of Stratigraphic Units on Figures H1-19 and H1-20

Rio Grande Rift Basin Fill (Upper Oligocene to Lower Pleistocene)

SFG	Santa Fe Group Hydrostratigraphic Units (HSUs)-Undivided Post-**SFG** HSUs-not shown. Includes alluvial deposits of the inner Rio Grande Valley (**RA**), and thin, but locally extensive basaltic volcanics (**Qb**). Mostly middle to late Quaternary age

Middle to Lower Tertiary Igneous Extrusive/Intrusive and Non-marine Sedimentary Rocks

Tba	Basaltic andesite lava flows and vent-zone units, with interlayered mudstones, sandstones and conglomerates volcanic rocks—late Oligocene Uvas Basaltic Andesite correlative
TmCH	Cedar Hills vent zone. N-S aligned series of flow-banded rhyolite domes and feeder conduits intruded into the Cedar-Corralitos Upland Basin stratigraphic sequence—Oligocene
TmLC	Lanark Complex—Intermediate to silicic igneous-intrusive complex that forms central part of the Northern Mid-Basin High and is buried by at least 1,500 ft (455 m) of SFG basin fill—Oligocene (*cf.* **PLS. 1A, 1B, 3, 5i** and **5q**; Phillips-Sunland oil test: **Tbl. 1,** no. 237; Clemons 1993)
Tmi	Intermediate to silicic (felsitic) plutonic rocks in the Organ and Dona Ana Mountains, and Mt. Riley-Cox and **TmLC** areas, including monzodiorite to syenite stocks—Oligocene and Late Eocene (Seager et al. 1987; Clemons 1993; Seager 1995)
Tmrs	Silicic pyroclastic and volcaniclastic rocks—Oligocene; mainly rhyolite and latite ashflow tuffs and tuffaceous sandstones, with some capping basaltic-andesite flows (**Tba**)
Tlvs	Volcaniclastic and epiclastic-sedimentary rocks, and local basal gypsite beds, with andesitic to dacitic flows and breccias—Eocene Palm Park and Rubio Peak Fm correlative that is exposed in uplifts flanking much of the northern and central Study Area. The unit is about 3,880 ft (1,183 m) thick in the Mobile-Grimm oil test (**PL. 5q**, **Tbl. 1**, no. 180; Clemons 1993).
Tls	Mostly siliciclastic sedimentary rocks, sandstones, mudstones and conglomerates with minor or no volcanic constituents. General correlative of lower Eocene/Paleocene Love Ranch/Lobo Fms. The unit is about 7,000 ft (2,134 m) thick in the Mobil-Grimm oil-test well (**Tbl. 1**, no. 180). An inferred correlative sequence of siliciclastic rocks is at least 1,000 ft (330 m) thick in the Pemex-Moyotes oil-test well (**PL. 5s**, **Tbl. 1**, no. 397; Clemons 1993, Jiménez and Keller 2000)

Mesozoic Sedimentary Rocks-Mostly Marine, and Commonly Structurally Deformed

K	Lower Cretaceous marine rocks-undivided. Sandy to shaly limestone, coquina limestone, silty shale, calcareous sandstone, and limestone-pebble conglomerate; with local occurrences of gypsite beds. Approximately 1550 to 2200 ft (470-670 m) thick were exposed in the Sierras Juárez and Sapello, Cerro Cristo Rey, and the East Potrillo Mountains. 1,050 ft (320 m) penetrated in the Grimm oil-test well (Rpt. **Tbl. 1**, no. 180). In the Pemex-Moyotes oil-test well, the Lower Cretaceous section is 5,512 ft (1,680 m) thick (**PL. 5s**, **Tbl. 1**, no. 397)
J	Jurassic marine rocks-undivided: limestone, shale, and gypsite; with local occurrences of halite beds beneath the southeastern-most part of the Study Area. Present in the shallow subsurface but nor exposed in Sierra Sapello. A 3,380 ft (1,130 m) thick Jurassic section was penetrated in the Pemex-Moyotes oil-test well between Permian (**P**) and Lower Cretaceous (**K**) rocks (**PL. 5s**, **Tbl. 1**, no. 397)

Paleozoic Sedimentary Rocks-Mostly Marine, and Commonly Structurally Deformed

Pz	Paleozoic rocks, **Pzu/Pzl**-undivided
Pzu	Upper Paleozoic (Pennsylvanian and Permian) rocks-undifferentiated: primarily limestone and redbed mudstones, with shale, sandstone, and some gypsite
Pzl	Middle and Lower Paleozoic rocks-undivided: Middle Paleozoic (Devonian and Mississippian)—primarily limestone, with shale. Lower Paleozoic (Cambrian-Ordovician-Silurian)—primarily limestone and dolomite, with thin basal sandstone

Proterozoic (Precambrian) Rocks

XY	Igneous and metamorphic rocks-undivided

H1.10. Inferences on Deep-Seated Geologic Relationships

Inferences on basin-scale interpretations of available information on deep-seated structural and bedrock- stratigraphic relationships in the southern part of the Study Area are schematically illustrated in a block diagram format in **Figure H1-21**. Information sources for illustration preparation include published and unpublished reports on surface-geologic mapping, borehole logging, and surface-geophysical surveys. **Table H1-11** includes **s**ummary descriptions of the diagram's lithostratigraphic components. Its base is 7.6 km (25,000 ft) below msl, there is no vertical exaggeration (VE), and initial-compilation scale was 1:100,000. The diagram faces southwest, and has south- and west-facing border panels. The south-facing panel has an International Boundary (31º47' N) alignment, and extends across the Mesilla Basin between the Early Tertiary andesitic-intrusive centers of Cerro del Cristo Rey and El Paso del Norte and the East Potrillo Uplift (*cf.* cross-sections **K-K'** and **L-L'** *in* **Fig. H1-6**). The diagram's geographic position is shown on a rectangular section of a 2017 Google earth® image, which allows portrayal of surrounding regional landscape features. The north-central Zona Hidrogeológica de Conejos Médanos-El Barreal area that was inundated by pluvial-Lake Palomas at its 1,210 m (3,970 ft) high stands is outlined in blue (**Figs. H1-10** and **H1-12**). The northeast-directed, high-stage lake's subsurface outflow system was toward El Paso del Norte when its Late Pleistocene baselevel for regional GW flow was about 1,135 m [3,724 ft] (*cf.* **Parts H5.2** to **H5.4**; **Figs. H5-2** and **H5-3**).

Table H1-12. Explanation of Basin-fill and Bedrock Units on Figure H1-21. Fault-Zone Names and Acronyms Listed on Table H1-7

RA	Channel and overbank-floodplain deposits of the Rio Grande—Late Quaternary; as much as 100 ft (30 m) thick and mostly in the saturated zone
Qb	Alkali-olivine basalt flows and cinder cones associated with volcanic centers in the Mesilla Basin-West Mesa and West Potrillo Mountains areas—Pleistocene
SFG	Rio Grande-rift basin fill-undivided—mostly Santa Fe Group: HSU's USF/MSF/LSF (LFAs 1-10)—Late Oligocene to Early Pleistocene; thickness locally up to 3,600 ft (1100 m), but less than 2,500 ft (760 m) in the MeB
Tlvs	Volcaniclastic and epiclastic-sedimentary rocks, local basal gypsite beds, and some andesite flows and breccias. Palm Park-Rubio Peak correlative of Eocene age. The unit is locally buried by as much as 1,450 ft (442 m) of SFG basin fill and is about 3,880 ft (1,183 m) thick in no.180 oil test (**Tbls. 1** and **2; PLS. 5h** and **5q**).
Tli	Intrusive igneous rocks of intermediate composition; porphyritic and generally fine grained; and intercalated with Tlvs clastic rocks. Eocene age
Tls	Mostly sedimentary rocks, sandstones, mudstones and conglomerates with minor or no volcanic constituents (non-marine). General Love Ranch/Lobo Fm correlative of Paleocene and Early Eocene age. The unit is about 7,000 ft (2,134 m) thick in no.180 oil test (**PLS. 5h** and **5q**). An inferred correlative sequence of siliciclastic rocks is at least 1,000 ft (330 m) thick in no.397 oil test (**Tbl. 1**, **PL. 5s**).
K	Sandy to shaly limestone, pelecypod-coquina limestone, silty shale, calcareous sandstone, and limestone-pebble conglomerate, with local gypsite interbeds (marine). Early Cretaceous Age, and subject to major Laramide tectonic deformation. Approximately 1550 to 2200 ft (470-670 m) thick in the East Potrillo Mountains. The unit is about 5,512 ft (1,680 m) thick in no. 397 oil test (**Tbl. 1**).
Pz	Primarily limestone, with shale, sandstone, redbed mudstones, and local gypsite beds (mostly marine)—Paleozoic age rocks-undivided
XY	Igneous and metamorphic rocks, undivided. Proterozoic (Precambrian) age

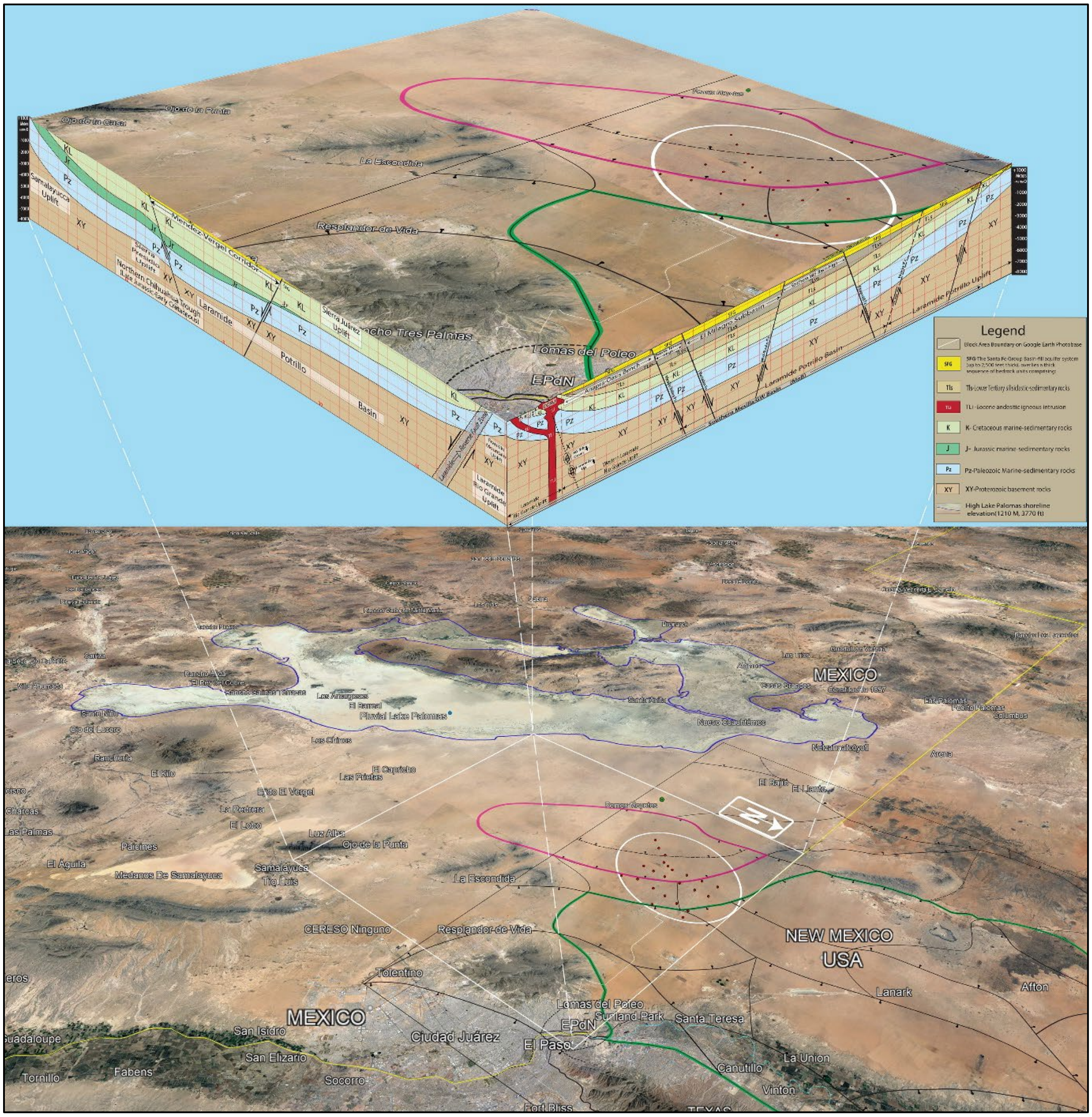


Figure H1-21 (with stratigraphic-unit definitions on **Tbl. H1-11**). Southwest-facing block diagram of the Paso del Norte borderlands region. It schematically portrays major RG-rift stratigraphic and structural features, including the Eocene Cristo Rey igneous-intrusive complex (red), to a base elevation of 25,000 ft (~7.6 km) below mean sea level (msl). The south-facing panel is along the International-Boundary (yellow–31°47' N); and its west-facing panel has a 106°30' West Longitude alignment. The southern NM WRRI Study Area (**Fig. H1-3**) is outlined with a black rectangle. The ZHGCM-El Barreal region, which was inundated by pluvial-Lake Palomas during its Late Pleistocene (≤1,210 m/3,970 ft) high stands, is outlined in blue. The northeast trending subsurface outflow system during highest stands of the pluvial lake contributed to the regional Transboundary GW-flow regime that recharged basin-fill aquifers of the northern Acuífero[s] Conejos-Médanos and southeastern Mesilla Basins (**Figs. H1-10**, **H1-12**, and **H1-17**; *cf.* **Parts H5-2** to **H5-4**).

H2. HISTORICAL BACKGROUND ON INSTITUTIONAL ALTERNATIVES FOR GROUNDWATER MANAGEMENT IN THE NEW MEXICO—CHIHUAHUA REGION

Alfredo Granados Olivas, Bobby Creel, John Kennedy, and Raed Aldouri (2001) Water planning GIS for the Paso del Norte region, *in* Proceedings, First International Symposium on Transboundary Waters Management, Monterrey, MX (p. 147):

A majority of the maps available for water planning in the Paso del Norte region whether produced by Mexico or the US, have the typical "blank" region on the other side of the border [**Part H2**]. This at times has precluded their combined use. The purpose of this project was to develop and create a local geographic information system (GIS) to support regional water planning, which included different coverages related to water resources along the Paso del Norte Region. These coverages integrated the geodetic component which consisted of a database of geographic points, with surveyed location and elevation; the orthoimagery component which consisted primarily of aerial photography that was used as a source of information or as a backdrop to other databases; the elevation component which consisted of two data types: I) a digital elevation model (DEM) incorporating a database that has a regular grid or lattice of points with elevation information tied to each point; and 2) a set of regular interval contours that represented elevation data within a DEM. The transportation component was also included and consisted of linear data that represent the transportation networks. The hydrography component represented surface-water features, such as streams, rivers, lakes, and playas. The governmental units component represented boundaries such as county/state lines and municipal jurisdictions. The cadastral component represented the ownership or control of land parcels. All these items together gave a set of complete digital maps that incorporated both sides of the transboundary region between the two countries, were information is obtainable from the coverages in both languages Spanish and English, and with the same geographical projection, and datum, as well as, with the same units. This effort is an example of an academic exercise showing the benefits of digital data sharing that is substantially advantageous for the region since our natural resources, mainly water resources, are located on transboundary environments.

H2.1. Institutional Alternatives for Mexico-US Groundwater Management

H2.1.1. Prescient Observations by Robert D. Hayton* (1978)

**Robert D. Hayton (1922-2010) was Professor of Law and Political Science, and Dean of Graduate Studies at the City University of New York, Hunter College. He was also Rapporteur on International Ground-Waters-International Committee for Arbitration (cf. Hayton 1978b).*

The following selection is from a 1977 presentation by Robert D. Hayton at the "Symposium on U.S. – Mexican Transboundary Resources" in La Joya, CA. It was published in an article titled "Institutional Alternatives for Mexico-U.S. Groundwater Management" in Volume 18 of the Natural Resources Journal (Hayton 1978a, p. 201-202; *cf.* Lippincott 1939, Clark 1978, Day 1978):

Existing treaty arrangements between Mexico and the United States have failed to take into account, at least expressly, both ground-water aquifers astride the international boundary and the influence that surface waters and ground waters have on each other as a result of the normal functioning of the hydrologic cycle. Such an omission is not at all surprising. Failure to consider the underground environment was characteristic of virtually all agreements on inter-jurisdictional waters until very recent times. National law, worldwide, has also only more recently manifested an informed awareness on the part of legislators and judges of the functioning of hydrosystems generally and the behavior of ground water in particular.

Efforts to optimize the utilization of available water resources in the face of increasing demand pressures have led to intensive investigations and, consequently, to more widespread appreciation of the hydrologic cycle in most parts of the world. The deteriorating quality of most supplies has provided additional emphasis on the resolution of water management problems in which rational development, use, and conservation of underground water have become major factors. However, until a few years ago ground water was, almost everywhere, relegated to separate and, from the managerial point of view, neglected treatment. This is not a forum where this proposition need be elaborated. Nor does the history of Mexico-United States relations with respect to the water resources shared by the two nations require review. Suffice it to say that, seen from a universal perspective, the record of cooperation and collaboration between these two sovereign states, though not without its more difficult periods, is an outstanding one . . . .

. . . . The International Boundary and Water Commission, . . . [was given its name, present form and mission in 1944]. There was at that time little understanding of the behavior of underground water, <u>geologists and geographers excepted</u>. On the contrary, ignorance was gross. In the United States we are still plagued today with the spurious propositions about ground water that were propagated by ingenuous- and ingenious-counsel and became part of common law doctrine through the precedent established by misinformed judges. Practitioners and judges in 'civil law' countries are not often inhibited by prior case determinations; nonetheless, Mexican officials and interested parties similarly lacked knowledge of the physical and chemical dynamics of the 'underground environment.'

In both countries the period of fantasy is largely behind us, though there are those remaining who have not yet taken time to learn. Not only is there widespread dissemination of <u>hydrogeological fundamentals</u>, but greatly increased attention is now devoted to water problems at the highest levels. And basin-wide, integrated management of the resource is accepted, at least in principle [*cf.* Utton and Atkinson 1979, 1981, and 1983].

H2.1.2. International Groundwater Management: The Case for the Mexico-United States Frontier; Albert E. Utton and Clifford K. Atkinson (1979)

[p. viii-ix] The objective of this project is to suggest possible institutional alternatives for the management of transboundary groundwater resources bisected by the U.S.-Mexico border. The report concludes that the heaviest groundwater users in the U.S. are those states which are contiguous to Mexico and yet, paradoxically, the law and institutions of those border states are woefully inadequate to control the exploitation of these ground- water resources. In addition, international competence over aquifers divided by the frontier is largely undefined; it is fair to say that the legal and institutional situation is chaotic. Coincident with this legal near vacuum, significant population increases are projected on both sides of the border which make it reasonable to anticipate that there will be increasing investment in groundwater facilities and accelerating demand placed on groundwater resources which are bisected by the international boundary between the two countries. The coming together of these two factors can be described as a collision course; with increased demand for a limited resource, combined with a striking absence of institutions for either resolving disputes or managing the resource, the potential for dispute between the two countries has to be something more than imaginary. This legal near vacuum is not unique to the U.S.-Mexico frontier in that there has been a failure to focus on the regulation and management of groundwater in most legal systems. In this kind of situation, each quota users water right is insecure because other pumpers may take possession of the mobile resource at any time. Accordingly, the individual surface owner is encouraged to exploit the groundwater resource as quickly as possible, so that the fluid and mobile water resource will not be captured by others. Thus, specifically along the U.S.-Mexican border, it cannot be said that water users have the security of their expectations, nor can it be said that whatever rights they hold to water and its use will be stable and dependable over time. Quite the contrary. We have: 1) projections for growing population on both sides of the border; 2) a situation in which north of the border (with the exception of NewMexico), no state has legal institutions which are adequate to control pumping; 3) no international control except at Yuma under the interim arrangement of paragraph 5 of Minute 242 which can prevent either nation from "stealing its neighbor's water." Therefore, we have a situation which encourages each nation to outdo its neighbor by developing its groundwater resources as rapidly as, perhaps even to the point of depletion of the groundwater resource.

H2.2. In Memoriam—Albert E. (Al) Utton-The Aztec Eagle*

**Aztec, NM native and UNM Law School Professor, Al Utton (1931-1998) founded and directed the International Transboundary Resources Center, where he established The Natural Resources Journal. He also chaired the NM Interstate Stream Commission from 1976 to 1995. In recognition of his contributions to Mexico and humanity, the Mexican government awarded him the Aguila Azteca in 1997, the highest award Mexico can give to a noncitizen.*

…, but as yet there is no 'comprehensive agreement on groundwater' and transboundary aquifers such as the Hueco Bolson and the Mesilla Bolson are subject to uncontrolled, unregulated withdrawals under which neither country is assured of either a secure supply or a fair share. Rather we have the law of 'he who pumps fastest', or the rule of 'we'll race you to the bottom of the aquifer' subject only to general principles of international law (Albert E. Utton, 1983, p. 26).

H2.2.1. "The Al Utton Essence"

"The Al Utton Essence" is eloquently captured in the following quotations from Professor Michelle Minnis (2015), Ambassador Alberto Székely (2010), and Professor Stephen Mumme (2000).

H2.2.1a. Michelle Minnis*, Preface to "Al Utton-Aztec Eagle—International Waters, Research, Diplomacy, and Friendship (2015)"

**Michele Minnis holds a PhD from the University of Kansas in Developmental Psychology. During a 25-year career at the University of New Mexico, she advocated for and practiced cross-disciplinary collaboration in research, writing, and teaching. At the UNM School of Law in the early 1980s, she created a legal writing program for first-year students before becoming associate director of the school's Natural Resources Center, an education, research, and public service arm of the Natural Resources Journal. In the latter capacity, she co-founded UNM's multi-disciplinary Master of Water Resources Program, serving fifteen years on its faculty and twice as its acting director. She retired from the university in 2005.*

[p. xiv] Rare leaders like Al Utton remind us of what is possible. He acted passionately for the commonweal, but no less for the welfare of the person immediately in front of him. He took the long view—so long a view that present law and policy appear short-sighted in comparison. Every issue he opened is still pending, gradually rising into public consciousness. Paths to resolution may be gleaned from the foundations he laid for international networks of preventive diplomacy—*Plan and act now to avoid future catastrophe.* Al's life story may be read as an invitation to build anew on these foundations [*cf.* Hawley 2020].

H2.2.1b. Ambassador Alberto Székely**, Albert E. Utton Memorial Lecture (2003):

*****Alberto Székely** obtained a law degree from the National Autonomous University of Mexico School of Law and went on to earn an MA and MALD from the Fletcher School of Law and Diplomacy, Tufts and Harvard Universities, a PhD in international law at the University of London, and an honorary doctorate in law from the University of New Mexico. His academic career has included teaching international law at El Colegio de Mexico, Arizona State University, Johns Hopkins University, and the University of Houston. His diplomatic work led him to become a career ambassador in the Mexican Foreign Service, where he was in charge of Mexico's legal affairs at the United Nations and at the Organization of American States, performing for eight years as the Chief Legal Advisor of the Mexican Foreign Ministry. He participated in the negotiation of the U.N. Law of the Sea Convention and of many multilateral and bilateral environmental treaties, after which he opened a legal and consulting firm where he has practiced environmental and natural resources law for the last 25 years, including mostly work on conservation and preservation of resources and ecosystems, as well as the creation of various natural protected areas, particularly in coastal and transboundary environments.*

> [p. 193]. . . . Ever since that time [the 1970], Al's words, his questions, were the object of great analysis and they instigated the preparation of publications of great pieces of research, mostly published in the *Natural Resources journal* here in New Mexico. Almost 20 years passed before he gave us his final words. Before he passed away, he published an article . . called "Coping with Drought on an International River Under Stress: The Case of the Rio Grande/Rio Bravo." Twenty years [after the late 1979s] he was not talking about the century of achievement, he was then talking, in his words, of "The Century of the Pinching Shoe." Those of you who know that article remember those words. He said concerning the periods of drought that we had already been undergoing throughout the 1990s, "The shoe will contract, crinkle, and crack and the foot within will be subjected to sharp discomfort and perhaps traumatic dislocation." Those are the words Al used to describe the beginning of a new century.
>
> Al dared to look into a crystal ball as to what may result from the pressures of population and economic growth. He then left us this series of questions and warnings that I am going to relay to you because it describes how wise he was, what a visionary he was in his predictions. I took those words as a testament as to the way I should conduct my work in the years ahead. He said, "...there will be much greater conservation of existing supplies because water supplies will have to be stretched by much more careful usage. Competition between users will greatly increase. Water will increasingly be switched from agriculture to municipal and industrial uses because many more jobs can be produced by industry with an acre-foot of water than can be produced by agriculture." Then he said, "...limits on growth will confront the region; concepts of and the means for sustainable economic development will become imperative; international and interstate apportionments, hard earned in the twentieth century, will be increasingly challenged in the twenty-first century." He had seen that scenario from the beginning of the drought that started in the 1990s and I do not think that anybody could have put it better, because the way things have been happening since have only confirmed his vision. . . .

H2.2.1c. Stephen Mumme*** on "Professor Utton's vision and purpose"

******Stephen Mumme** holds a PhD from the University of Arizona in Political Science. He currently a Professor at the Department of Political Science, Colorado State where he specializes in Comparative Politics with a research emphasis on transboundary water and environmental management along North American boundaries. His current projects are 'U.S.-Mexico transboundary water diplomacy' and 'U.S. Mexico environmental cooperation.'*

Stephen P. Mumme**,** honored "Professor Utton's vision and purpose" in the following review of progress made at the February 1999, "La Paz Symposium on Transboundary Groundwater Management on the U.S. - Mexico Border" (Mumme 2000).

[p. 345-347] Across the gamut of U.S.-Mexico relations, few issues have proven less tractable than arriving at cooperative solutions for managing the vital pools of underground water that cross the international boundary. Over a quarter century has lapsed since Mexico and the United States formally acknowledged the need for a comprehensive agreement on border groundwater. With that pact, the International Boundary and Water Commission's Minute 242, signed in 1973, the United States and Mexico committed to limiting their withdrawals along the border near San Luis Rio Colorado, Sonora, and Yuma, Arizona, pending a comprehensive agreement on groundwater along their common border, and to notifying each other of new national groundwater development in the border area. Now, twenty-six years later, the promise of Minute 242 seems more symbolic than real. While the two nations have complied with the letter of their agreement to inform each other of new groundwater development, the spirit of that agreement, an implied pledge to find a mutually acceptable allocation of their shared groundwater, has not been realized. In the meantime, the two nations have become ever more dependent on this vital resource.

In February 1999, the International Transboundary Resources Center of the University of New Mexico's School of Law, the Udall Center for Studies in Public Policy at the University of Arizona, and the School of Ecology at the University of California, Irvine, convened a group of research scholars and policy practitioners in La Paz, Baja California Sur, for the purpose of revisiting the groundwater issue and exploring potential avenues of cooperation in managing the border's transboundary aquifers. This meeting, supported by the Ford Foundation, was, in no small measure, a tribute to the late Albert E. Utton's enduring commitment to fostering binational cooperation in managing shared groundwaters. The meeting provided a unique opportunity to examine groundwater problems as various as the utilization and development of groundwater in the El Paso-Ciudad Juarez metroplex to the lining of the All-American Canal in California's Imperial Valley and its implications for Mexicali Valley farmers.

The papers and commentaries given at the La Paz symposium and presented in this volume document both countries' increased reliance on transboundary aquifers to sustain traditional water uses in agriculture, urban areas, and industry as well as the critical role these aquifers play in sustaining the region's biodiversity. While many national economic practices and legal rules influencing groundwater utilization on each side of the border remain altered only by a small degree since Minute 242 was signed, these profiles of utilization patterns and conflicting demands for transboundary groundwater depict a dynamic and changing social and institutional context. In various ways these papers demonstrate that a mere allocation of groundwater as contemplated a quarter century back is no longer sufficient; the two countries now face the challenge of cooperatively managing their common groundwater for multiple objectives and sustained yield. The arrival of new stakeholders in water policy is challenging established priorities and practices in border groundwater management and has drawn attention to the needs of communities whose voices have long been excluded from border water policy-making.

The papers and commentaries from the La Paz Symposium also highlight the institutional dimensions of the changing binational context for considering solutions to current and emerging groundwater problems. Institutional developments as diverse as the 1983 Border Environmental Cooperation Agreement, the Border XMI [XXI] Program, the Border Environment Cooperation Commission, and the Commission on Environmental Cooperation are stimulating greater government commitment to sustainable utilization of water resources in the border region [*cf.* **Parts H4.4** and **H4.5**] . . . . While the legal and political impediments to greater cooperation in binational groundwater management remain, these new innovations in binational resource management nurture potential synergies and opportunities to improve the basis for mutual understanding of shared problems and an envisioning of common solutions. The innovative scholarly efforts of Al Utton and colleagues to define credible models in international law for

> international cooperation in transboundary groundwater management complement the recent work of the International Law Association and the United Nations in this area. Such initiatives are setting a sounder foundation for the equitable apportionment and sustainable management of groundwater resources straddling international boundaries.
>
> . . . . The La Paz symposium papers explore the issues, the complexity, and the urgency of grappling with groundwater management at the border. They also point to the elements of possible solutions the two nations may draw upon as they tackle the challenge of husbanding these resources for their common future. To the extent these symposium discussions renew and nurture a spirit of binational dialogue and common purpose in managing the border's groundwater resources, Professor Utton's vision and purpose will be amply fulfilled.

H2.3. Management of "Precious Water Resources" and the "White Map Problem"

The following prescient observations on transboundary groundwater-resources (and the 'white map problem') were made by Al Utton in an award-acceptance address at the 40th Annual New Mexico Water Conference in Las Cruces on October 16-17, 1995 (Utton 1996). The conference theme – "Reaching the Limits: Stretching the Resources of the Lower Rio Grande" still resonates today!

> We are in a special region, this special geographical location where we are standing and seated today-the Lower Rio Grande Valley, the Mesilla Valley. We are talking about lots of issues, but one of those issues which has been raised repeatedly by the great panel this morning is how can we manage the precious water resources in a transboundary situation. How do we do it? Someone has come along and drawn political boundaries all over the place and run a river and some aquifers through it and said, 'Now, you guys deal with it.' That is a real challenge; and we are working on it, although we do not always do it in the best way. We are dealing with three states and Mexico. We tend to ignore each other as the panel this morning pointed out. <u>We have the 'white map' problem. Our maps only show Mexico as being white, with more colors on the United States side; and their maps do just exactly the opposite</u>. We in New Mexico tend to forget about Texas downstream. We heard the story this morning about the governor of New Mexico saying he did not want to give Texas any water. 'Over our dead body,' is what he [Gary Johnson] said. But we would like water from Colorado. And how about when Mexico is short of water and they go to the governor of Texas like they did this last year? It is hard to reach across those boundaries. . . .
>
> [p. ix] Groundwater has been out of sight and out of mind. Mexico would like another 60,000 acre-feet of surface water, and if we do not reach an agreement with Mexico, what is to prevent them from taking it underground, under the table? None of us have any security in this border region. Doña Ana County, El Paso, Chihuahua—we have a game without rules. We have not been able to secure our groundwater relations. We delay reaching agreement and settling our groundwater arrangements with Mexico at our peril. We must move forward on that [,] although politically it is almost impossible. That is all in the vein of saying that we happen to be in one of those special areas which is crisscrossed with political boundaries, and contains the transboundary situation. So we have to work extra hard at trying to seek, share, manage, cooperate, and plan together. . . .

H2.4. Octavio E. Chávez* on "Mining" of the Shared Aquifers in the Paso del Norte Area

**Resident Adviser for Mexico for the International City/County Management Association, and former Co-Director of the Border Information Institute in Ciudad Juárez, Chihuahua.*

Another 1999 La Paz Symposium participant, Octavio E. Chávez (2000) addressed perhaps the most pressing problems facing long-term management of the finite fresh-groundwater resources of the Paso del Norte metropolitan area—"mining" of the area's shared aquifers:

> [p. 238] **The El Paso-Juárez Case:** For centuries the river and shallow wells had been the source of water in the region. With the turn of the [20th] century, the growing urban centers along the Rio Grande, where the river becomes the international boundary, started increasingly to depend on groundwater. The primary source of the region's groundwater is the aquifer called Hueco Bolson, which is being depleted at a dramatic rate. Both communities are mining the same source; however, Ciudad Juárez faces the biggest challenges since it currently depends on the Hueco Bolson for 100 percent of its water supplies. . . . (*cf.* Lippincott 1939)

H2.4.1. A Global Perspective on Groundwater Mining in "Dry Areas"

Dr. Shmuel Mandel (1919-1995) of the Center for Groundwater Research at the Hebrew University, Jerusalem provides a global perspective on groundwater mining in "dry areas" (1979, p. 439):

> In 1975 the late G.B. Maxey* and the author were engaged in studies of groundwater mining. A collection of case histories revealed that overexploitation of groundwater is a very common practice, especially, though not exclusively, in dry areas. Generally, with very few exceptions, overexploitation develops unintentionally and is only belatedly recognized. Available data refer to areas where attempts are being made to rationalize groundwater mining and to plan rescue schemes. Data from areas where groundwater mining "just happens," or where it has run its full destructive course, generally, remain inaccessible. Thus the available data are probably indicative of a problem that will become acute, on a global scale, within the next two or three decades, unless the present trends in groundwater development are reversed. . . .
>
> The respective merits of sustained yield exploitation versus mining may be arguable in each particular area. The wide-spread uncontrolled development of irreplaceable water resources is certainly an undesirable state of affairs. . . .
>
> ****G. Burke Maxey established Nevada's Desert Research Institute's Water-Resources Research Center in 1961 (e.g., Maxey and Shamberger 1961), and he was the recipient of the 1971 Geological Society of America O.E. Meinzer Award for his paper "Hydrogeology of Desert Basins" (Maxey 1968). He was also John Hawley's dissertation-research advisor at the University of Illinois from 1959 to 1962 (cf. Hawley 1962, Hawley and Wilson 1965, Hawley et al. 1961).***

H2.4.2. An Early Legal Perspective on Groundwater Mining in New Mexico

In their 1979 report on "International groundwater management: The case for the Mexico-United States frontier," Al Utton and Clifford. E. Atkinson cite prescient observations by (then) New Mexico State Engineer, Steve Reynolds on "the mining of water" that definitely apply to many parts of New Mexico outside the Lea County-Southern High Plains region:

> As Steve Reynolds points out, it must not be overlooked that in some situations as a matter of policy 'the mining of water can be justified as readily as the mining of any of our other mineral resources such as uranium, oil or coal. It is not practical to operate a groundwater basin on a continuous-yield basis when the amount of water in storage is very large compared with the average annual recharge.'[89]
>
> [89] *from Statement of S.E. Reynolds, State Engineer, Santa Fe, N.M.—9/30/1959, p. 113-114:*
>
> While it is possible to justify the mining of groundwater resources, the practice will make it necessary to face serious water supply problems in the future. In some instances it will be possible to meet these problems only by complete adjustment of the economy of the area. While long range predictions of the value of water in various uses are dangerous, it appears likely that it will not be, in general, economically feasible to import water over appreciable distances for

agricultural purposes when the local groundwater resources have been mined out. However, when reduced well yields or excessive lifts make pumping for agricultural purposes uneconomic, the residual water may well supply the municipal and industrial needs of a vigorous non-agricultural economy for many years.

In Lea County pumping for irrigation will probably be uneconomic when about two thirds of the aquifer is dewatered. At that time there will probably remain substantial valuable reserves of oil and gas in the area. To produce and process those reserves it will be necessary to use numerous low-production wells to pump the residual fresh water, and it may also be necessary to desalinize the abundant brackish waters and brines that occur in the area.

H2.5. The Tragedy of the Commons (*from* Deming, 2002, Introduction to Hydrogeology):

[p. 22, 24] The **tragedy of the commons** is the tendency to deplete and ultimately destroy a resource that has a common ownership. The concept was first developed by Garrett Hardin in his 1968 [*Science*] article, *The Tragedy of the Commons.* Hardin used the example of a pasture that is shared by herdsmen. Each herdsman will graze as many cows as possible, as each added cow enriches him further. This system works so long as the load imposed by the cumulative burden of all herdsmen does not exceed the carrying capacity of the pasture. At that point, Hardin (1968) wrote, "the inherent logic of the commons remorselessly generates tragedy." The logic of the commons is that each individual is logically compelled to add further to the exploitation of the pasture, because altruistic sacrifice is not rewarded. If a herdsman were to withdraw cows from the common pasture, it would still be overwhelmed by other individuals less altruistic moving further cows onto the pasture. The only logical course for each herdsman to follow is to add still more cows to the pasture, and ultimately the common resource is ruined for all. The lesson of the tragedy of the commons is that a shared or common resource such as groundwater or surface water must be regulated by law or it may be destroyed. . . .

H2.5.1. Observations by Robert Glennon (2002) on "Exploitation of a Common-Pool [GW] Resource" in a Sonoran Desert Region

While avoiding use of the term "mining," Robert Glennon (2002, p. 210-211) describes uncontrol groundwater-resource "exploitation" in Arizona's Sonoran Desert region in the following excerpt from Chapter 15 in "Water Follies: The Tragedy of Law and the Commons:"

[1]Robert Glennon, Regents Professor, and Emeritus Morris K. Udall Professor of Law and Public Policy in the Rogers College of Law at the University of Arizona.

So it is with groundwater. The doctrines of capture and reasonable use encourage exploitation of a common-pool resource. The legal rules governing groundwater use reward rational economic individuals by assuring them that the biggest pump wins. Rivers, springs, lakes, wetlands, and estuaries around the country face an uncertain future because most states have separate legal rules for regulating surface water and groundwater. For surface water, riparian law or the prior appropriation doctrine governs; but for groundwater, either a different system of prior appropriation or the doctrines of capture or reasonable use prevail.

Each proposal offers an immediate yet temporary fix to a larger problem. These alternatives are *Band-Aids* that may prevent an infection from getting worse, but they are not cures for the disease. They instead allow us to ignore the inescapable reality that our uses of water are not sustainable over the long term [*cf.* Hardin 1968, Utton and Atkinson 1979, Utton 1994].

H2.5.2. "Associated Press Report raises alarms over Arizona's water supply"

"Associated Press Report raises alarms over Arizona's water supply"— Albuquerque Journal-NATION, Sunday (October 27, 2019). Absence of enforceable rules for governing groundwater overuse is evident in both the above-cited observations by Professor Glennon and this example of prevalent GW-mining practices much of south-central Arizona:

> TUCSON, Ariz.—A new report by an Arizona State University think tank [Kyl Center for Water Policy] says its questionable whether Arizona can find enough water to replenish aquifers for pumping to new homes in fast-growing suburban areas without access to the Colorado River. . . .
>
> The report warns that some suburbs of Tucson and Phoenix will struggle to find enough water to keep growing without damaging aquifers by overpumping groundwater.
>
> According to the report, the result could be land subsidence, including ground fissures, lower water quality and even the possibility of wells drying up [*cf.* Carpenter 1999].
>
> And it said there's a prospect of further hiked water rates for homeowners and financial problems for a three-county agency responsible for finding renewable water supplies for further development in Pinal County located between the two metro areas.
>
> The report suggests that the landmark 1980 Groundwater Management Act is environmentally unsustainable and requires an overhaul. . . .
>
> University of Arizona law professor Robert Glennon [2002], who has written two books about water supply issues, said the new report's authors 'convincingly demonstrate that it's a broken system that will cause great economic and personal hardship if the legislature and DWR [AZ Department of Water Resources] don't act to implement their recommendations.'

H2.6. Groundwater-Resource Conservation in the Context of Climate-Change Realities

H2.6.1. "Climate Change on Future Water-Resource Availability in the American West" (Gutzler 2005, p. 277):

> A computer model simulation of atmospheric conditions 18,000 years ago, during the last ice age, is compared with an ensemble of simulations of future climate warmed by increasing greenhouse gases. We consider whether the ice age simulation and the future "global warming" simulation present opposite climate anomalies in New Mexico compared to current climatic conditions. Not surprisingly, this turns out to be the case for temperatures in both winter and summer (colder 18,000 BP, warmer in the 21st Century). Simulated winter precipitation also exhibits opposite departures relative to current conditions: the ice age simulation shows more precipitation, consistent with a larger meridional temperature gradient across North America, whereas the global warming simulation is drier. Summer precipitation, however, is decreased relative to the current climate in both the ice age and the warmer climate. The combination of wet winters and cold summers in the Pleistocene is consistent with the existence of large lakes in Southwest North America at that time. If the future climate simulation holds true, with drier conditions in both winter and summer, then New Mexico could face quite difficult hydrological conditions that herald persistent drought [*cf.* Gutzler and Robbins 2011, Elias et al. 2015, Knutti et al. 2016, Meixner et al. 2016, Lehner et al. 2017, Chavarria and Gutzler 2018, Randel 2018, Paskus 2020, Williams et al. 2020a, Bryan 2021].

H2.6.2. Climate change and aridification of North America (Overpeck and Udall 2020):

> In the southwest United States and adjacent Mexico, the implications are dire for water security and ecosystems. More severe extreme heatwaves and dust storms are also already occurring, and these and other impacts of aridity will only increase until the cause is halted. Across North America, greater aridity is being offset with increased groundwater use, but this strategy has limits in the many places, such as the Southwest and the High Plains, where groundwater use exceeds recharge and is thus unsustainable [*cf.* Konikow and Leake 2014].

H2.6.3. Climate Change and Upper Rio Grande Watershed Hydrology (Creel 2010):

> Climate change is also likely to affect the availability of water in the future. Although existing climate models are an uncertain tool for estimating change, there is a growing consensus among researchers that precipitation will increase at higher latitudes and decrease in the subtropics as warming occurs [*cf.* Gutzler 2005]. As mean temperature increases, the volume of snowpack will decrease at higher elevations and snowmelt will occur earlier than in the past, causing an earlier release of water and greater losses (Seager et al. 2007). Because the bulk of water supplies in the upper [RG] basin are obtained from snowmelt, any change in the timing of releases will have serious repercussions for management [*cf*. Elias et al. 2015, Rpt. **Part E3.5.3**]. Despite the uncertainty associated with the results of climate forecasting models, simulations made from different assumptions have led to a consensus on several characteristics of the impact of climate change. There is widespread agreement that precipitation will become more variable and will create amplified variations in runoff and streamflow (Houghton 2004, Seager et al. 2007, Christensen et al. 2007). Associated with this increased variability will be an increase in the frequency of extreme events such as floods and droughts (Seager et al. 2007, 2009).

H2.7. Climate Wild Cards and Water-Resource Sustainability in the US-Mexico Border Region

Subjective terms like *sustainability*, *opportunities*, and *challenges* only suggest conceptual starting points in the complex iterative processes involved in (1) hydrogeologic-framework characterization, and (2) evaluation of the anthropogenic factors now involved in all contemporary water-resource development activity. Accordingly, credible positive or negative outcomes are best described qualitatively as belonging to one of three broad event categories: (1) possible to probable, (2) possible to improbable, and (3) possible but highly improbable. The latter category is best described as a "Black Swan" event according to the concept's explanation by Nassim Nikolas Taleb [2010, p. xxii]):

> I stop and summarize the [Black Swan] triplet: rarity, extreme impact, and retrospective (though not prospective) predictability. A small number of Black Swans explain almost everything in our world, from the success of ideas and religions, to the dynamic of historical events, to the elements of our personal lives. Since we left the Pleistocene, some ten millennia ago, the effect of Black Swans has been increasing. It started accelerating during the industrial revolution, as the world started getting more complicated, while ordinary event, the ones we study and discuss and try to predict from reading the newspapers have become increasingly inconsequential.

The nature and timing of *extreme impacts* of Black Swan *outliers* may be quite different in the mountain-highland headwaters areas of major fluvial systems in Colorado, New Mexico, and Chihuahua. This is quite relevant in light of the continental-interior position of the Southern Rocky Mountains region, the near-Pacific Ocean setting of the northern Sierra Madre Occidentál, and their contrasting latitudes. Accordingly, it will be both conservative and prudent to Plan with Nature Now in an arid-semiarid region where the carrying-capacity of water-resource base has already been exceeded (*cf.* McHarg 1969, Steiner et al. 2019, and Dunbar et al. 2022). By all means, at least try to be prepared for:

1. Projected Global and regional climate change that include major shifts in seasonality, type, and intensity of precipitation (e.g., Székely 1991, Gutzler 2005, Creel 2010, Elias et al. 2015, Meixner et al. 2016, Overpeck and Udall 2020, Siegel 2020, Williams et al. 2020a).
2. Potential catastrophic environmental impacts of extreme climatic events and/or wildfire on fluvial-geomorphic processes and hydrogeologic systems in critical upland-watershed areas.

H2.8. Some Realities of Hydrogeologic-Framework Controls on Groundwater-Resource Sustainability in a Chihuahuan-Desert Region

"Reality is that which, when you stop believing in it, doesn't go away." **Philip K. Dick** https://en.wikipedia.org/wiki/Philip_K._Dick

The large size and river-connected nature of the Santa Fe Group (SFG) aquifer system in the Mesilla Basin region was first described in a hydrogeological context in NM WRRI Report No. 6 (King, Hawley, Taylor, and Wilson 1969). King and associates (1969 and 1971) also recognize that at least the upper part of the SFG aquifer was present in Chihuahua are far south as Mexico Federal Highway 2 in the area west of the Sierras de Juárez and Sapelló [aka Mesquite] (**Apndx. D1.1**; Córdoba et al, 1969, p. 3-6). Soon after this report's publication, however, Professor John W. Clark*, PE, past Civil Engineering Department Chair at NMSU and second NM WRRI Director, advised the report's authors not to be overly optimistic in their estimates of the size and production potential of the reservoir's fresh (<1,000 mg/L TDS)-GW component. He recognized that, with increasing distance from the Rio Grande, long-term aquifer-system development might be possible in terms of water quantity, but its initial fresh-water content would eventually be replaced by progressively more-saline water derived from drainage of brackish GW reservoirs in contiguous intermontane-basin and mountain areas.

In the late 1960s, John Clark was also a private civil engineering consultant for border-development visionary, Charles L. (Charlie) Crowder (1932-2018) in the early planning stages of the future Santa Teresa Industrial Park and adjacent parts of the MeB-West Mesa (cf.* ***Part 6.3.4c**; Culbertson 2018, Kocherga 2018e, Pacheco 2018c).*

In February 1985, investigative reporter, Terrance E. Poppa** wrote a short article for the El Paso Herald-Post (Metro section) that was titled "Vast water under Mexico's sands?". In it, he correctly inferred (without citing his geohydrologic information sources) that large amounts of groundwater were in storage in what is now referred to as the "Acuifero Conejos Médanos" section the "Zona Hidrogeológica de Conejos Médanos" of north-central Chihuahua (INEGI 2012). What Poppa did not realize, however, was that much of his "vast water [resource]" was brackish, with a fresh GW component that was not renewable from a 10,000-yr time perspective.

***1. 1987 Pulitzer Prize Finalist for Investigative Reporting: "Terrence Poppa of El Paso Herald-Post For his resourceful investigation of the dealings of Mexican drug lords." 2. Author of: Poppa, T.E, 1998, Drug lord: The life and death of a Mexican Kingpin [Pablo Acosta of Ojinaga]: a true story: Demand, 364 p.* https://druglord.com

H2.9. Global Perspectives on Management of Transboundary Aquifers and GW Flow Systems

H2.9.1. International Borders, Ground Water Flow, and Hydroschizophrenia (Jarvis et al. 2005):

[p. 764] While it is well understood that aquifers cross international boundaries and that the base flow of international river systems is often derived in part from groundwater, transboundary groundwater and surface water systems are usually managed under different regimes, resulting in what has been described as "hydroschizophrenia." Adding to the problem, the hydrologic relationships between surface and groundwater supplies are only known at a reconnaissance level in even the most studied international basins, and thus even basic questions regarding the territorial sovereignty of ground water resources often remain unaddressed or even unasked. . . . Limited groundwater management in the international arena, coupled with the fact that few states or countries regulate the use of groundwater, begs the question: Will international borders serve as boundaries for increased "flows" of hydrologic information and communication to maintain strategic aquifers, or will increased competition for shared groundwater resources lead to the potential loss of strategic aquifers and "no flows" for both ground water users?

H2.9.2. "Knowledge Capsules" on a Transboundary Aquifer (Alfonso Rivera, 2021a)[1]

[1]Chair, International Association of Hydrogeologists-Transboundary Aquifer Commission (*cf.* Rivera 2021b).

H2.9.2a. Transboundary Aquifer -vs- Transboundary Groundwater

A hotly debated subject has emerged under the context of transboundary aquifers (TBA). When planning any type of arrangement to manage an aquifer spanning two or more jurisdictions, MoU, Minutes, legally binding agreements, etc., what should be managed—the aquifer or the groundwater flowing through the aquifer? Is there a trend of misunderstanding between the two terms? In the realm of hydrogeology, there is no dispute on the existence of clarity about the differences between groundwater and aquifers. However, this does not seem to be the case for the law and policy literature, which are strong components of any type of agreement to share a TBA.

A new vocabulary, new concepts, and more accuracy in terminology have emerged over the last 20 years under ISARM (Internationally Shared Aquifer Resources Management). However, there are disagreements because cultural, political, economic, and social factors differ around the world. In addition to its natural boundaries, *jurisdictional boundaries* need to be added to the TBA.

H2.9.2b. Transboundary Zoning: to Zone or Not to Zone

When dealing with a shared aquifer with groundwater crossing from one jurisdiction to the other, we should keep in mind the artificial (jurisdictional) boundary. For example, if we need to build a numerical model of the aquifer for management purposes, we would need to add an additional boundary condition to it: a jurisdictional boundary. This type of boundary condition does not exist in numerical models.

In that case, we are faced with the issue of selecting the best optimal area for shared management. So, should we zone in in the area for managing closer to the jurisdictional boundary only? Or should we consider the full extent of the complete aquifer? If we concentrate in the most urgent and most important areas, e.g., closer to the artificial boundary, we could make use of a specific units for management purposes: a groundwater flow system, the radius of influence, a capture area, a pressure compartment, groundwater age, etc. To do that correctly, however, the dynamics of groundwater within the aquifer (time and space scales) must be well understood closer to the jurisdictional boundary. Further, to complement the knowledge of groundwater dynamics, new elements and/or variables need to be added, e.g., social, economic, and political needs. . . .

H2.9.2c. Sustainable Groundwater Development in a Transboundary Aquifer Context

It is not easy to define the sustainable yield of an aquifer system; there is neither universal consensus, nor a single definition. In many cases, programs for groundwater management pay attention to the integration of groundwater and surface water in the planning process. Those plans usually discuss issues of demand and yield, but never directly address a fundamental issue behind the plans—how to define sustainable yield of an aquifer system. If we add the fact that the aquifer system is shared by two jurisdictions with very different approaches for water management, then defining and adopting a sustainable yield and use of that aquifer becomes mind boggling [i.e., *hydroschizophrenic*—**H1.2.2**].

H3. HISTORICAL BACKGROUND ON TRANSBOUNDARY WATER-RESOURCE ISSUES—1535 to 1963

H3.1. History Meets Pre-History (1535-1583)

H3.1.1. "Who knew what and when did they know it?" (Hartmann* and Flint** 2003):

**William K. Hartmann, Tucson, AZ. Astronomer-Historian-Writer*

*** Richard Flint, Albuquerque, NM. Historian and Research Associate Professor at the UNM Latin American and Iberian Institute.*

[p. 26] . . . It was not until [July 1536] that seemingly indisputable evidence of the rich northern cities [in present-day New Mexico] was received.

It came with four survivors of a shipwreck on the Gulf of Mexico coast eight years before [11/1528]. These wanderers, Álvar Núñez Cabeza de Vaca, Alonso del Castillo Maldonado, Andres Dorantes, and [Dorantes' Moroccan Berber slave] Estéban, had fled westward from native captors toward vaguely known Spanish settlements in Mexico. The tale of their trek became a sensation on both sides of the Atlantic. They told of subsistence as slaves, acceptance as healers, adventures as the first European witnesses of bison. But more especially they told of "towns with many people and very large houses" where the people "wear cotton shirts." These towns, they learned, lay north of where they had journeyed. Furthermore, Cabeza de Vaca and company heard that the people of the north were experienced metalworkers and even saw physical evidence of their handiwork. First, in one town, they were given "some small bags of silver."[3] Then, shortly afterward, according to the so-called "Joint Report of the survivors' experiences" recorded by Gonzalo Fernandez de Oviedo y Valdes, probably in the 1540s, native people "gave the Christians [the Spaniards] a copper hawksbell and some cotton blankets and said [they] came from the north, having crossed the land toward the South Sea [Gulf of California]."

H3.1.2. Tracing the 1535 to 1536 Route of the Núñez Cabeza de Vaca Party

https://en.wikipedia.org/wiki/Álvar_Núñez_Cabeza_de_Vaca

Traveling mostly with this small group, Cabeza de Vaca walked generally west through what is now the U.S. state of Texas, as well as the northeastern Mexican states of Tamaulipas, Nuevo León and Coahuila, and possibly [??] smaller portions of New Mexico and Arizona. He traveled on foot through the then-colonized territories of Texas and the Gulf Coast, but encountered no other Europeans. He continued through Coahuila and Nueva Vizcaya (present-day states of Chihuahua and Durango); then down the Gulf of California coast to what is now [Culiacán in] Sinaloa, Mexico, over a period of roughly eight years. Throughout those years, Cabeza de Vaca and the other men adapted to the lives of the indigenous people they stayed with, whom he later described as Roots People, the Fish and Blackberry People, or the Fig People, depending on their principal foods.

Numerous researchers have tried to trace his route across the Southwest. As he did not begin writing his chronicle until he was back in Spain, he had to rely on memory. He did not have instruments to determine his location; he had to rely on dead reckoning, and was uncertain of his route. Aware that his recollection has numerous errors in chronology and geography, historians have worked to put together pieces of the puzzle to discern his paths (e.g., **Fig. H2.1**).

[*]Álvar Núñez Cabeza de Vaca, *Naufragios y comentarios con dos cartas*, 9th ed. (México, D.F.: Espasa—Calpe Mexicana, 1983); Richard Flint translation p. 81, 92 (*cf.* Adorno and Pautz, editors and translators, 1999, "*Relation of 1542*").

Figure H3-1 (https://en.wikipedia.org/wiki/Álvar_Núñez_Cabeza_de_Vaca)**.** Current interpretation of the route of the Núñez Cabeza de Vaca party between Galveston Island (11/1528) and Ciudad México (7/24/1536) is shown with magenta line. According to this interpretation the group left the valleys and canyons of the Rio Grande/Bravo at the southeastern end of Hueco Bolson near the site of Fort Quitman, TX. In this case, they would definitely have crossed the lower valleys of the Rio Carmen, Rio Santa Maria and Rio Casas Grandes in their trek across Chihuahua. Moreover, it is now clear that Álvar Núñez Cabeza de Vaca was never able to visit El Paso del Norte, as a few earlier historians have suggested (e.g., Horgan 1954, p. 95-96).

H3.2. Conquest Number One: The Spanish Empire—1583 to 1821

The "Pass of the North" area of the Rio Grande/Bravo fluvial system was "visited" in 1535 by the Álvar Núñez Cabeza de Vaca party, and subsequently "explored" in 1581 during the Chamuscado-Rodríguez expedition (Adorno and Pautz 1999; Hammond and Rey 1966). The first relatively detailed description of the area's major terrain features is in "Diego Pérez de Luxán's Account" of the 1583 Antonio de Espejo (Beltrán) "Expedition into New Mexico."

H3.2.1. The Antonio de Espejo Expedition into New Mexico—January 1583

Excerpt *from* Diego Pérez de Luxán's Account (Hammond and Rey, 1966, p. 170-171):

ON THE WAY, THE SPANIARDS FOUND SOME SALINES OF VERY GOOD WHITE ROCK SALT, AND ON THE OPPOSITE BANK MANY MOUNTAINS WITH-ORES [1/15-21/1583].

We left this place on the fifteenth and went five leagues in the present Lower El Paso Valley/Valle de Juárez. Midway we found some salines of white rock salt, wonderful beyond comparison, and very plentiful. On the opposite bank of the river there are many mountains with quantities of ores [Franklin and Organ Mtns]. We did not go to them because it was late and we were unable to cross the river. We stopped at some pools which we named Las Salinas.

We set out from Las Salinas on the sixteenth and traveled five leagues till we reached a pool formed by the river when it overflows its banks. We named it El Charco de San Antonio. We left this place on the nineteenth and in five leagues came to the said river to camp at a spot which we named Las Vueltas del Rio [future site of El Paso], because here it starts to wind as far as the settlements [Middle Rio Grande pueblos]. Leaving this locality on the twenty-first of the month, we continued five leagues to a prominent place overlooking the river [Cerro del Cristo Rey?]. This we named La Barranca de las Vueltas [El Paso del Norte].

THE SPANIARDS LOCATED A STRAND WITH SALINES [1/22-23/1583].

We set out from this place on the twenty-second of January and went five leagues to a spot we named La Playa de las Salinas. These were the first salines that we saw along this river [in the lower Mesilla Valley].

We left La Playa de las Salinas on the twenty-third and traveled four leagues to a place we named La Ciénega Helada, a marsh formed by the river. It was frozen so hard that it was necessary to break the ice with bars and picks in order to get drinking water. We took our horses to the river to water.

A MOUNTAINOUS DISTRICT WITH LARGE VEINS FOR MINING

Leaving La Ciénega Helada on the twenty-fourth of the said month and going five leagues, we came to a place on the river which we named El Frontón de las Minas, because on the way half a league before reaching this spot, there is a mountainous district containing large veins [Organ Mtns.]. These mines we did not assay. During this entire trip we never met any people, although we found numerous traces of them and many abandoned rancherias.

From this place, on the twenty-sixth, we traveled three leagues up the river. Starting with that day's march, we went straight toward the north, that is, the direction from which the Del Norte flows. We halted at an arm of this river which we named Los Humos, because there were many smoke columns on a high sierra [Organ Mtns.] on the opposite side of the river.

H3.2.2. First "Divine Mandate" for Territorial and Ideological Conquest (4/30/1598)

Excerpt from Sonnichsen (1968, p. 15-16; *cf*. Pérez de Villagrá 1610 [1962, F.D. Hodge, ed., and Gilberto Espinosa, trans.]; *cf*. Hammond and Rey 1953, p. 95):

The mighty river flowing swiftly by was such a pleasing sight that its turbulent waters seemed to us a calm and placid lake with scarcely a ripple to disturb its peaceful surface [4/30/1598]. Its bountiful waters teemed with many fish, and we easily caught a great number. The hunters then shot a large number of ducks and geese . . . . We built a great bonfire and roasted the meat and fish, and then all sat down to a repast the like of which we had never enjoyed before. . . . The Governor himself addressed the crowd and described the experience of the main body of travelers. He praised them for their endurance and promised them a day of rest for everybody. . . . [*cf.* **H3.1.3**].

The momentous event is marked and consecrated by a Thanksgiving ceremony: a solemn high mass is celebrated with everyone in attendance then with the soldiers donned in shining armor for the occasion, on horseback and in military formation, Don Juan de Oñate reads the official act of possession which begins:

In the name of the most holy Trinity and of the eternal Unity, Deity and Majesty, God the Father, the Son, and the Holy Ghost . . . and in honor of His most holy and venerable Mother, the holy Virgin Mary, our Lady, Gate of Heaven, Ark of the Covenant, in whom the manna of heaven, the divine rod of justice and His law of grace and love were placed, as the Mother of God, . . ., and Advocate of all human kind . . . and in the name of the most blessed Saint Francis, image of Christ, God in body and soul, His royal ensign and patriarch of the poor whom I adopt as my patrons, advocates, and intercessors that they may intercede with God himself, that all my thoughts, deeds, and actions may be directed to the service of His infinite majesty to increase the number of the faithful and the extension of the holy Mother church, and to the service of the most Christian of kings, Don Philip, our lord, pillar of the Catholic faith. . . .

Be it known that I, Don Juan de Oñate, Governor, Captain General, and Adelantado [*frontier* province governor] of New Mexico, and of its kingdoms and provinces, as well as those in its vicinity and contiguous thereto, as the settler and conqueror thereof, by virtue of the authority of the king, our lord, hereby declare that: Whereas, by virtue of my appointment ... and, whereas

I desire to take possession of this land this 30th day of April, the feast of the Ascension of our Lord, in the year fifteen hundred and ninety-eight, through the person of Don Juan Perez de Donís, clerk to his majesty, secretary of this expedition, and to the government of said kingdoms and provinces.

Therefore in the name of the most Christian king, Don Philip, the second of that name, and for his successors . . . . I take possession, once, twice, and thrice, and all the times I can and must, of the actual jurisdiction, civil as well as criminal, of the lands of the said Rio del Norte, without exception whatsoever, with all its meadows and pasture grounds and passes. . . .

H3.2.3. Events Leading Up to the Dedication of the First El Paso del Norte "Cathedral" in 1668 (Sonnichsen 1968, p. 23-24):

[p. 23] The date traditionally accepted for the founding of the mission at El Paso is December 8, 1659. It took [Franciscan Fray] García [de San Francisco y Zúñiga] almost ten years more to build his church and convent. Construction problems were many - for one thing there were no timbers in this land of little rain. Where were the roof beams to come from? Father [Agustín de] Vetancurt, writing forty years later, had heard how that difficulty was overcome: "Before the building was started, there were no timbers for it; but one day while he was kneeling in prayer, some Indians came and took him a league and a half away where they showed him a grove of pines, very beautiful, which they cut down and transported easily to the pueblo of the Mansos."

That there was ever a grove of pines within five miles of Juarez, Mexico, is a matter for serious doubt. With God, all things are possible, of course, but some say that the pillars supporting the ceiling beams are trunks of palm trees brought from Spain to Vera Cruz and carried to El Paso on the shoulders of faithful Indians.

With the coming of a new custodian to New Mexico in 1661, Father García was relieved of his duties as vice-custodian and had more time for his conversion. He laid the cornerstone of his church on April 2, 1662. Six years later the building was finished along with a convent big enough to house thirty friars. When asked why he had provided for so many, Father García merely observed that the space might be needed later on. And of course it was!

The whole establishment was dedicated to Our Lady of Guadalupe on January 15, 1668. The custodian himself, the Reverend Juan Talaban, sang the mass. Four hundred Mansos attended and a hundred of them were baptized, the men coming in at one door and the women at another. Fresh from the baptism, they found themselves in the middle of the new church undergoing the marriage ceremony. . . .

You can step inside the door of the old cathedral in Juárez, parts of which belong to the original structure, and view the whole scene in your imagination - the priests in their vestments, soldiers in armor, a sprinkling of Spanish ladies, and the long-haired Indians kneeling on the floor. Since then, three sun-soaked centuries have drifted over the roof of Father García's cathedral, "the most beautiful temple of those provinces and that custodia." Some of the [p. 24] years have been bloody and terrible and some have been happy and triumphant, but none has been more exciting and significant than that year of dedication, 1668, when civilization in visible and tangible form was revealed to those poor Indians.

By 1668, says [Fr. Agustín de] Vetancurt [1688-1699, v. III, p. 205], the total number of parishioners at the Pass had reached a thousand, mostly permanent settlers who had their land under cultivation and had accumulated 9,000 head of cattle plus 13,000 sheep and goats [Hughes 1914, p. 309].* Most of them were Indians or mixed bloods, but there was a leavening of Spanish families. The missionaries usually saw to it that their wants and needs were taken care of by a few of their own people who felt that it was a privilege to serve a holy man. The mention of vineyards and orchards in documents of the late sixties points to the presence of many Spaniards at this important way station on the road to Santa Fe [Wals, 1951, p. 22-23].The Indian population would have been predominantly Manso and Suma, but Apache pressure was beginning to tell on the outlying missions in Eastern New Mexico, and natives from Abó, Chilili, Isleta, Humanas, Senecu and Quarai were commencing to filter southward as their pueblos declined (Scholes 1929, p. 56). The presence of all these converts taxed the resources of the mother church and expansion became necessary. Actually, two branches had been established before the cathedral was dedicated. One was San Francisco de los Sumas (1665), located a league and a half from old San Lorenzo, which seems to have occupied a site twelve leagues below El Paso near present-day San Elizario. The second was called La Soledad de los Janos. Nobody knows exactly where it was, but it must have been off to the southwest in the direction of Casas Grandes seventy leagues away in Chihuahua.

This is the first documentation of the ongoing and future potential adverse impact of uncontrolled livestock grazing on the natural landscape of the Paso de Norte area (cf. **Part H3.4.2, Fig, H3-3).*

H3.2.4. "Beginning of the Real Settlement of the EI Paso Valley" by "Refugees" from the August 10, 1680 "Pueblo Revolt" (Sonnichsen 1968, p. 33-34)

In [early] October [1680], with cold weather coming on, [Gov.] Otermín was forced to make a decision. Following a universal muster intended to account for all the refugees and a great council to discuss what was to be done, he received a petition from all the people in camp asking that they be allowed to move across the river to the vicinity of the convent "because of the many dangers and inconveniences which beset them at La Salineta [in the lower Mesilla Valley]." The next day the Governor granted this request. It was the beginning of the real settlement of the EI Paso Valley [Hackett 1942, p. cvii-cxvi].

The influx of those two thousand hungry, disorderly refugees was, of course, a terrible thing. The mission had existed for some twenty years and the Franciscans had things well in hand with gardens, orchards, and herds of cattle for themselves and a reasonable number of dependents and visitors, but there was not enough of anything for two thousand additional people. Something had to be done, however, and something was done.

Before long they had been sorted out and settled in three new towns below the mother church. Farthest to the south the Governor established his headquarters at a place he called the Real de San Lorenzo (after the saint on whose day the revolt broke out). It was six (15 mi/24 km) leagues from the original settlement. Five priests were stationed there and Father Ayeta let them take his portable altar on its cart " as being more decent [Hackett 1942, v. 8, p. 215]." The site of San Lorenzo [near San Elizario] was already a historic spot, for it was "at the place where the wagons arrive on the outward trip" - the spot where the river turned east and where the caravans left the Valley to strike out across the sand dunes [Médanos de Samalayuca] on their way south [Hughes 1914, p. 310]. It was near, perhaps on, the spot where Oñate had taken possession of New Mexico for his God and King [*cf.* **H3.1.2**]. The other two communities - San Pedro de Alcantara [near Socorro del Sur] and El Santisimo Sacramento [near Ysleta del Sur] were spaced two leagues [~5 mi/8 km] apart toward EI Paso.

Each family constructed its own house of "sticks and ranches," a type of building still observable in the EI Paso neighborhood and still called a *jacal.* The houses in San Lorenzo were said to be "built in an orderly manner" but to the colonists, some of them accustomed to a considerable degree of comfort, they must have seemed grim enough [Hackett 1942, v. 8, p. 215; Hughes 1914, p. 316].

H3.2.5. Excerpt *from* "Water Wars During Our Territorial Years" *in* "100 Years of Water Wars in New Mexico—1912-2012" (John W. Hernandez, 2012d, p. 19-20)

Is Our Hispanic Ancestry a Root Source of Our Water Wars?

While not the fundamental problem, the answer is probably, yes. Our heritage of Iberian customs, in the management of scarce water resources, is certainly a contributing factor in our apparent tendency toward water conflicts. One look at the snow-capped mountains and arid, fruitless plains of Andalucía is enough to convince a New Mexican that, yes, this is where many of us came from, followed by an unvoiced certainty that water practices that were used in Spain came with us to New Mexico.

It should be noted that some parts of Spain followed slightly different water codes than others. Some regional differences prevailed. As southern Spain was the last stronghold of the Moors, we probably also inherited some of their customs and technology in designing and managing the early community ditches in New Mexico, the acequias, that were the backbone of much of the farming in our territorial days.

Elements of Spanish and Moorish practices that made it into New World water codes included: the ownership of water in a river belonged to the general public for their free use; the rights of existing water users to divert water from a stream were protected; the rights to use water were tied to the land where application was made; canal systems belonged to those who built them, and right-of-way to ditch for construction and maintenance was guaranteed; these ditch owners annually prescribed their own rules for scheduling cleaning and maintenance of the ditch and the times, amounts, and methods of water diversions from the acequia to farm fields; water use was limited to beneficial purposes; and limits were placed on upstream diversions to that which was absolutely needed. In some areas, constraints were probably imposed on developments of springs, seeps, and shallow groundwater.

H3.2.6. El Paso del Rio del Norte in 1817, *from* the Report of Father Juan Rafael Rascón to Bishop Juan Francisco de Castañiza (Dennis Dailey, ed. and trans., 2021, p. 4-7)

To the Most Excellent Dr. Don Juan Francisco Marqués de Castañiza

October 28, 1817

Most Excellent Sir,

In fulfillment of Your Excellency's official letter dated September 9, last month, which instructed me to prepare a brief report regarding the points that were asked of me in the aforementioned letter, with the goal of determining the area of the diocese, insofar as it is known, I pass along to your excellency accounts that I have at hand, and with information supplied by old and trustworthy persons of this place.

The circumference of this curate of the town of Our Lady of Guadalupe of the Pass of the Northern River (el Paso del Rio del Norte) forms a trapezoidal figure of five leagues, more or less, containing on the surface of this plane the houses, vineyards, orchards and lands that the inhabitants cultivate. The land is watered by the abundant Río del Norte, to the south of whose banks is situated this aforementioned town, and its latitude is judged to be 32 or 33 degrees. Regularly in the month of May, great flows of the river occur when the snows melt on the mountain slopes and give rise during this time to strong, annual floods that wash away the pickets and dam, which at the cost of innumerable hardships and public works are repaired each year on a sandy foundation with woven branches filled with loose stones and bound together with ropes. It's a shame that so much work is required in the most precious season, abandoning or suspending cultivation of the vineyards and crops for the repetitious, common work of dam, bridge, etc.

The longitude of the settlement, or diameter from east to west, is two consecutive leagues, in the west from the house where the lieutenant governor of this jurisdiction lives, to the house called “of Gallegos” in the eastern portion and where the bridge, . . . , is the point that divides this curate from the mission, or town, of San Lorenzo, currently administered by Friar Ysidoro Barcenilla. In the opposite direction [up valley through EPdN] there are no neighboring settlements. In the southeast [down valley], this settlement ends with the houses of Don Bernadino Borrego, Maldonado, and the Villeros. On the hill named Aranda is the dividing line of these lands and those of the mission of the Pueblo of Senecu [founded following the 1680 Pueblo Revolt—**H3.1.3**] . . . , and the Indians of the pueblo annexed to this curacy are the owners of the fields that lie in that direction.

The latitudinal diameter [settlement width] measures one and one half leagues, which is inhabited from north to south, from the banks of the river, or the Playa [shoreline] district, to the home of Benancia García, or the hills to the south, and within the aforesaid limits there are no neighboring settlements until you reach the Presidio of Carrizal, a distance of more than 30 leagues [120 km to the S near Villa Ahumada].

To the northeast [actually the NW], this town ends at the homes named Largo, the widow Guadalupe, and the house of Romano Portillo, and in this same direction [though EPdN], at a distance of about two leagues, are the [Lower Mesilla Valley] campsites known as Salineta [salt beds], where the livestock of the inhabitants and the horse herds of soldiers and civilians are pastured. There are many groves all along the banks of the river and excellent flat, open spaces and river bends for settlements and fields [in the Mesilla Valley], principally in the place called Bracito [now Brazito*], where currently Don Juan Antonio García de Noriega lives [*see following historical note**]. For going on two years he has plowed fields contiguous to those that this community worked three years ago for the use of the Apache Indians, with the goal of persuading them to take an interest in working and staying put, which has been in vain as they cannot accustom themselves to work [Samek Norton 1998]. From this town [El Paso] to Bracito [Brazito] is 18 leagues [~60 km] and in the surrounding hills, as well as in the Organ Mountains, so famous for serving as the refuge of the Apache Indians in time of war, they say there are abundant veins of copper, iron, a little silver, and a lot of lead. . . .

**HISTORICAL NOTE: BRAZITO ([Mesilla Valley] settlement; 5 mi S of Las Cruces). The Spanish brazito means "little arm, or tributary:' and the name of this Hispanic settlement on the Rio Grande has been attributed to "arms," or branches, of the river marshlands near the site, though the name also has been interpreted to mean "little bend on the river." As early as 1776 the locality was called Huerta (Spanish, "orchard") de los Brazitos. About 1822 the Brazito [Bracito] Land Grant, extending 8 miles along the Rio Grande S. of Las Cruces, was made to Juan Antonio García [de Noriega]. . . . (Julyan, 1996, p. 49).*

The mining town of Santa Rita del Cobre is further to the west, measuring about 70 to 80 leagues [~200 km] from this Pueblo and they say it is inhabited by about 400 souls. . . . To go to this mining town, and similarly to Bracito [Brazito], one has to cross the Rio del Norte by a bridge, and only when the strong floods wash it away, the crossing of the river becomes difficult.

The number of souls in this curacy [all in the upper El Paso/Juárez Valley], that live within the circumference stated in part one, exceeds 4,300, including military personnel and Indians, commonly referred to as being from the Pueblo annexed to the community. **. .** The civil government is under the control of a political and military lieutenant governor, presently the veteran lieutenant Don José Ordaz, whose jurisdiction extends to the four neighboring towns that are situated in a line one after the other, called the Real de San Lorenzo and its charge the Pueblo of Senecu, the Pueblo of Ysleta, and Socorro where the Reverend Father Fray Jose Gonzales resides, who also administers Ysleta. And all these towns, including this one [present Cd. Juárez] are the ones that make up the entire jurisdiction of El Paso. Adjacent to Socorro is the presidio of San Elceario [San Elizario]. This pueblo and said presidio are at the edge of the inhabited places that are situated along the banks of the river and beyond these places there are no more, except at great distance, and for this reason during the times when the Apache enemies rise up, one cannot travel except in convoy. During the present time these said Apaches are at peace and they freely and continually wander through all the towns, visiting all the homes in search of food, but always with their weapons at hand [Samek Norton 1998].

The climate of this town of El Paso (and almost the same can be said for nearly all the neighboring towns) is extreme in heat and cold, according to the season. It hardly rains and if it weren't for the benefits of irrigating from the river, [in] some years, like the present one, there would be no produce. For this reason, there is no pasture that is not irrigated by the river. The ground is commonly sandy and full of dunes and in some parts clay. Within the circumference referred to, there are some lakes, ponds or pools. The homes of the inhabitants are in great confusion with interposition of the orchards, groves, and the fields of maize, wheat, beans, cotton, and so forth, to such extent that in times of plague the spiritual administration is very difficult because of the lack of order and communication between homes and for the shortage of bridges that require one to go out of the way in order to cross the irrigation canals.

H3.3. The Mexican Republic—1821 to 1846

H3.3.1. ¡Viva La Independencia!—David J. Weber (1982, p. 4-5)

In the spring of 1821, a stunning piece of news moved quickly north . . . . A Spanish officer, Agustín de Iturbide, had declared Mexico's independence from Spain. . . .

On September 8, a few days after Tucson acted, residents of El Paso del Norte also took the oath of allegiance [to the new nation]. Since 1680 El Paso had occupied the strategic spot some 1,200 miles north of Mexico City where the Rio Grande sliced its way through two mountains. The small center of the' town stood on the site of today's Ciudad Juarez, on what is now the Mexican side of the river, but in 1821 the jurisdiction of New Mexico extended farther south and embraced the town. El Paso and outlying communities supported over 8,000 people. Nearly all lived in a narrow band along the river where a dam and irrigation canals watered fields of wheat and corn as well as orchards and vineyards. Compared to other frontier communities, the paseños seemed prosperous. When compared to cities in the interior of Mexico, on the other hand, El Paso and all of the communities on the northern frontier seemed poor indeed. . . .

H3.3.2. September 9-15, 1839—Josiah Gregg (1844, p. 272-273)

We were still some sixty miles above Paso del Norte [9/9/1839, near Ft. Selden site], but the balance of the road now led down the river valley or over the low bordering hills. During our journey between this and EI Paso we passed the ruins of several settlements, which had formerly been the seats of opulence and prosperity, but which have since been abandoned in consequence of the marauding incursions of the Apaches.

On the 12th of September [1839] we reached the usual ford of the Rio del Norte, six miles above EI Paso; but the river being somewhat flushed we found it impossible to cross over with our wagons. The reader will no doubt be surprised to learn that there is not a single ferry on this 'Great River of the North' till we approach the mouth. But how do people cross it? Why, during three-fourths of the year it is everywhere fordable, and when the freshet season comes on, each has to remain on his own side or swim, for canoes even are very rare. But as we could neither swim our wagons and merchandise . . . our only alternative was to unload the vehicles, and ferry the goods over in a little 'dugout' about thirty feet long and two feet wide . . .

This river even when fordable often occasions a great deal of trouble, being, like the Arkansas, embarrassed with many quicksand mires. In some places, if a wagon is permitted to stop in the river but for a moment, it sinks to the very body. Instances have occurred when it became necessary, not only to drag out the mules by the ears and to . . . . haul out the wagon piece by piece-wheel by wheel.

On the 14th we made our entrance into the town of El Paso del Norte, which is the northernmost settlement in the department of Chihuahua. . . .

The valley of El Paso is supposed to contain a population of about four thousand inhabitants, scattered over the [south]western bottom of the Rio del Norte to the length of ten or twelve miles. These settlements are so thickly interspersed with vineyards, orchards, and cornfields, as to present more the appearance of a series of plantations than of a town: in fact, only a small portion at the head of the valley, where the *plaza publica* and parochial church are located, would seem to merit this title. Two or three miles above the *plaza* there is a dam of stone and brush across the river, the purpose of which is to turn the current into a dike or canal, which conveys nearly half the water of the stream, during a low stage, through this well-cultivated valley, for the irrigation of the soil. Here we were regaled with the finest fruits of the season: the grapes especially were of the most exquisite flavor. From these the inhabitants manufacture a very pleasant wine. . . [*cf.* Moorhead 1954].

H3.3.3. Early Era of Anglo-American "Manifest Destiny"—1836 to 1846

With respect to the absence of equitable sharing of both land and any type of natural resource between the two nations, the geopolitical setting of collaboration vs. confrontation dates back to the 19th Century era of Continental-scale U.S. territorial expansion (*cf.* Merry 2009, Kiser 2018, McDonald 2022). John Louis O'Sullivan (1813-1895) appears to have been the first to name and describe *manifest destiny* in the context of Anglo-American trans-continental territorial expansion in an article that was published in the United States Magazine and Democratic Review (O'Sullivan 1845, v. 17, no. 1, p. 5-10):

A call for the United States to admit the Republic of Texas into the Union (https://en.wikipedia.org/wiki/John_L._O'Sullivan):

Because of concerns in the Senate over the expansion of the number of slave states and the possibility of war with Mexico, the annexation of Texas had long been a controversial issue. Congress had voted for annexation early in 1845, but Texas had yet to accept, and opponents were still hoping to block the annexation. O'Sullivan's essay urged that "It is now time for the opposition to the Annexation of Texas to cease." O'Sullivan argued that the United States had a divine mandate to expand throughout North America, writing of "our manifest destiny to overspread the continent allotted by Providence for the free development of our yearly multiplying millions [*cf.* O'Sullivan 1839]."

H3.4. Conquest Number Two, and the US-Mexico Boundary Survey (1846-1856)

The United States declared war on the Republic of Mexico on May 16, 1846 following annexation of Texas in 1845. From a cultural/historical perspective, the 1846 to 1865 interval encompasses both military and socio-political conquests of Mexican America, starting with Gen. Philip Kearny's 8/1846 to 3/1847 occupations of New Mexico and California (Cutts 1847). Historian George P. Hammond (1896-1993) captures the Anglo-American expansionist mindset of the 1840s in his Foreword to a 1965 reprint of James Madison Cutts (1847, p. ii) "The conquest of New Mexico and California, by the forces of the United States, in the years 1846 & 1847:"

The 1840's found the nation at the peak of its power and its faith in its ultimate "Manifest" destiny. Exuding assurance and self-confidence, the United States recognized no obstacle to the achievement of that goal. The year 1846 became the "Year of Decision," because its neighbor, Mexico, as heir of Spain, claimed much of the same territory by right of discovery, if not actually by right of occupancy, and had no intention of surrendering that right. . . .

The clash that ensued between Mexico and the United States marked a collision of irresistible ideas and forces. President James K. Polk, spokesman for the free nation, championed the right of the pioneers to make beneficial use of the lands and resources of the West [*cf.* Merry 2009]. General Antonio Lopez de Santa Anna of Mexico, a master in the art of political leadership, saw in the situation an opportunity for self-advancement, as well as a patriotic duty to protect the borders and possessions of his country. Unhappily for him, the military might of his armies was no match for that of his opponent. In the war that followed, the forces of the United States, ineptly organized and equipped, but led by men of superb training, experience and determination, soon overcame the forces of their enemies.

H3.4.1. First Binational "Collaboration": The 1850 to 1856 Boundary Survey

Paula Rebert, PhD, an "independent scholar of the history of cartography," introduces her 2001 book "La Gran Línea: Mapping the United States–Mexico Boundary, 1849-1857," with the following quotation from a June 23, 1856 letter from "First Engineer Francisco Jiménez, Mexican Boundary Commission, to Lieutenant Nathaniel Michler, U.S. Boundary Commission":

> Trabajaran con la buena armonia e inteligencia, que siempre ha reinado entre nosotros y ... forrnaran un plano tan exacto como interesante de la gran línea astronomíca que les esta confiada.
>
> They will work with the good harmony and understanding that has always prevailed between us and ... make a map as accurate as [it is] interesting of the great astronomical line that is entrusted to them.

Rebert notes (p. 1) that "The boundary had its painful beginning in the U.S.-Mexican War, which was brought to an end with the Treaty of Peace, Friendship, Limits, and Settlement, signed at Guadalupe Hidalgo, 2 February 1848." The subsequent boundary-location disputes (through 1853) were exacerbated by major cartographic errors in the 7th edition of the *Mapa de los Estados Unidos de Méjico* (John Disturnell Publisher, 1847) that was used in the negotiations that led up to the Treaty of Guadalupe Hidalgo (Rittenhouse 1965 [p. 9-13], Rebert 2001, p. 3-7). Key elements of the "Disturnell Map" controversy are illustrated on a regional map compilation by NM Highway Department geologist, Harold L. James (1969, **Fig. H3-2**; *cf.* Bartlett 1854, Mueller 2000).

The "task of surveying and marking the line" in less than six years was truly challenging considering the geopolitical dynamics of the time, which included: (1) Both nations had a succession of Presidents, with opposing partisan agendas, and (2) The "1848 Treaty" boundary-line controversy was not resolved until the June 8, 1854 "ratification" of the "Treaty of 1853" (aka, "The Gadsden Treaty" in the U.S., and the "Tratado de la Mesilla" in Mexico - Rebert 2001, p. 11).

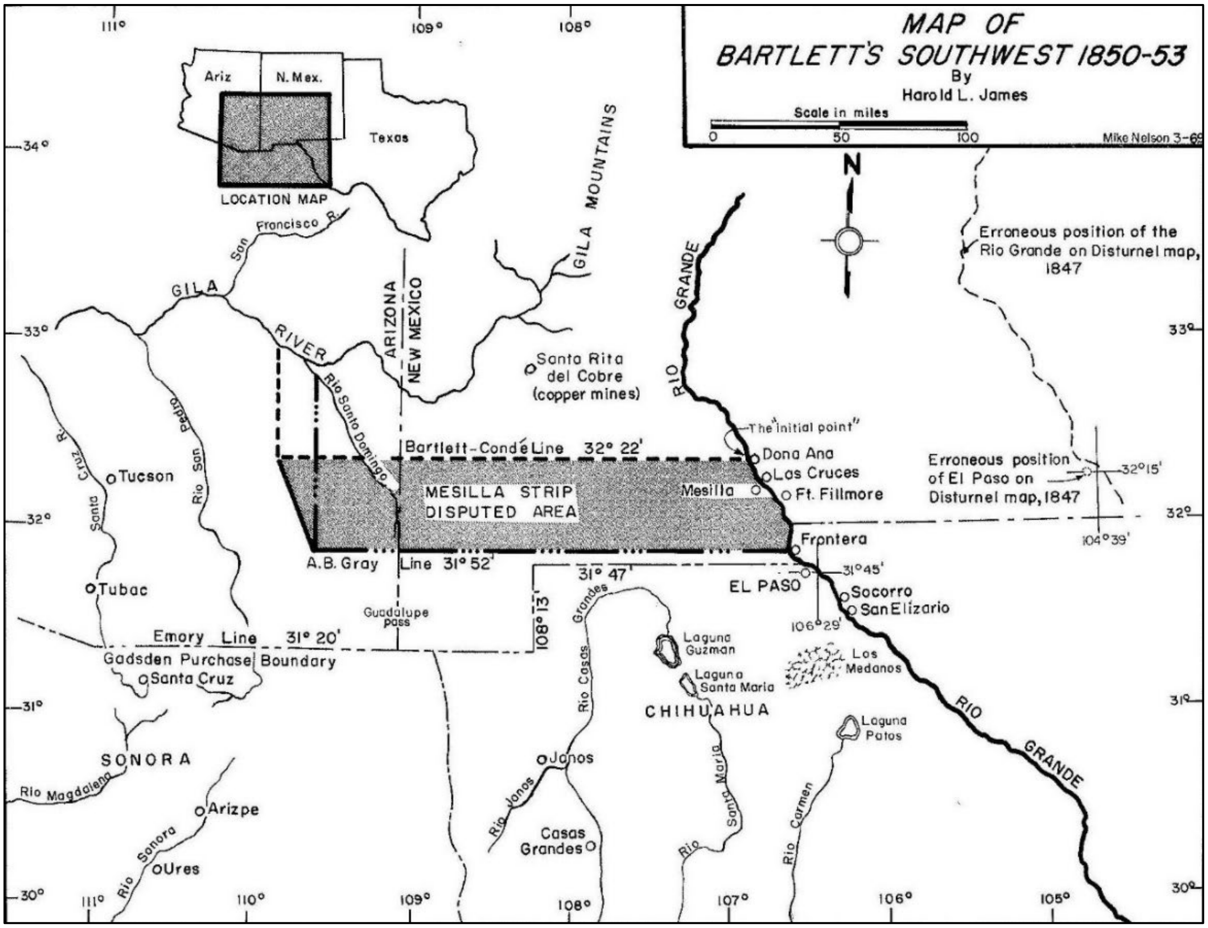


Figure H3-2. Map of John R. "BARTLETT SOUTHWEST 1850-53" compiled by NM Highway Department, geologist Harold L. James (1969, p. 44; *cf.* Bartlett 1854, Rebert 2001 [p. 3-8, 103], 2005 [p. 81-82]). Reproduced with NM Geological Society, Inc. permission.

Rebert (2001, p. 27) summarizes many of the challenges that the teams of surveyor-astronomers and topographic-mappers from both nations faced in their truly collaborative endeavor that resulted in successful completion of 3,200-km (~2000-mi) boundary survey of mostly *terra incognita*. The essence of the Boundary Survey's major scientific accomplishments is captured in this selection from Rebert's 2005 review paper *in* "Terrae Incognitae—the Official Publication of The Society for the History of Discoveries:"

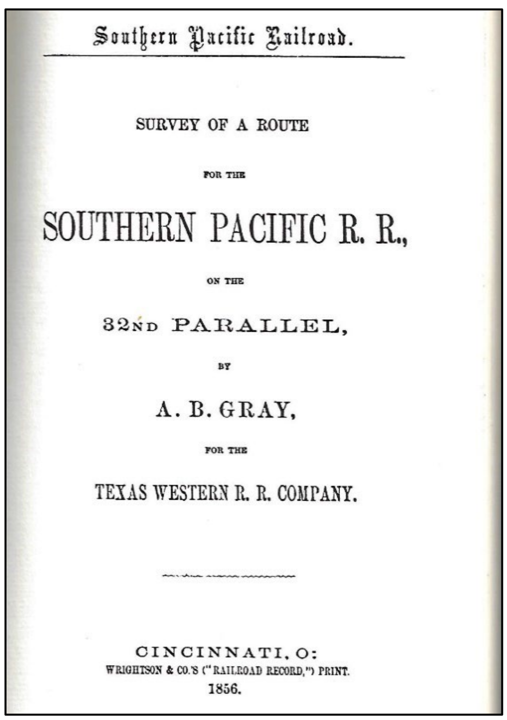
> The U.S.-Mexico boundary *Report* [Emory 1857] was published in two massive volumes, sometimes in three, and its contents make up an encyclopedia of the Southwest. It presents not only the results of the boundary survey, but also the results of the scientific investigations connected with the survey. There are essays on the geography of the region and the Indians who lived in it; articles on geology, paleontology, meteorology, magnetism, minerals, and plant distribution; and vast catalogs of the plants, animals, and fossils that the boundary commission's collectors gathered for study by scientists who eagerly awaited the specimens. The Report contains three maps, including a general map of the West, a geological map, and a map of magnetic observations . . . . Although at least some of the boundary maps were originally planned for publication with the Report, Congress did not provide funds and they were never published (Rebert 2005, p. 76).

H3.4.2. "The A.B. Gray Report; Survey of a Route on the 32nd Parallel for the Texas Western Railroad, 1854"

The following section is a brief review of a transcontinental survey effort that has never received its proper recognition as a major contribution to the history of the American West. In December 1853, former principal surveyor for the 1849-1853 U.S. Boundary Commission (the "Bartlett Survey"), Col. Andrew Belcher Gray was appointed by the Texas Western Railroad Company as leader of the first "Survey of a Route for the Southern Pacific R.R. (**Fig. H3-3**)." The "Second Division" of the survey, from El Paso to Yuma. AZ, which remained close to the Gadsden Purchase Boundary (near latitude 32° N), was completed between mid-February and early June 1854 (the time of formal Gadsden Treaty ratification).

> The *Report* of the Gray reconnaissance, submitted to the directors of the Texas Western Railroad Company the following February [1855] was no mere gathering of survey statistics. It represented the first transcontinental survey along the 32nd Parallel for a feasible railroad route; and laid the basis for the investment by that company in some of the richest mining properties in southern Arizona. The *Report's* thirty odd etchings [by Charles Shuchard] gave the most detailed and graphic portrayal in existence of places and landmarks along the route (INTRODUCTION *by* L.R. Bailey [1963. p. xvi).

Facsimile reproductions include representative "drawings" by Charles Shuchard, the mining engineer/artist who was a member of the survey part. Shuchard was a graduate of the School of Mines in Freiberg, Germany, and the initial "sketches" were made in February 1854 (*cf.* **Figs. H3-3** to **H3-5**). They portray landscape and cultural features of the Paso del Norte area in great detail, and were used with original written permission (1965) from L.R. Bailey and Westernlore Press (Los Angeles, CA).


Southern Pacific Railroad.

SURVEY OF A ROUTE

FOR THE

SOUTHERN PACIFIC R. R.,

ON THE

32ND PARALLEL,

BY

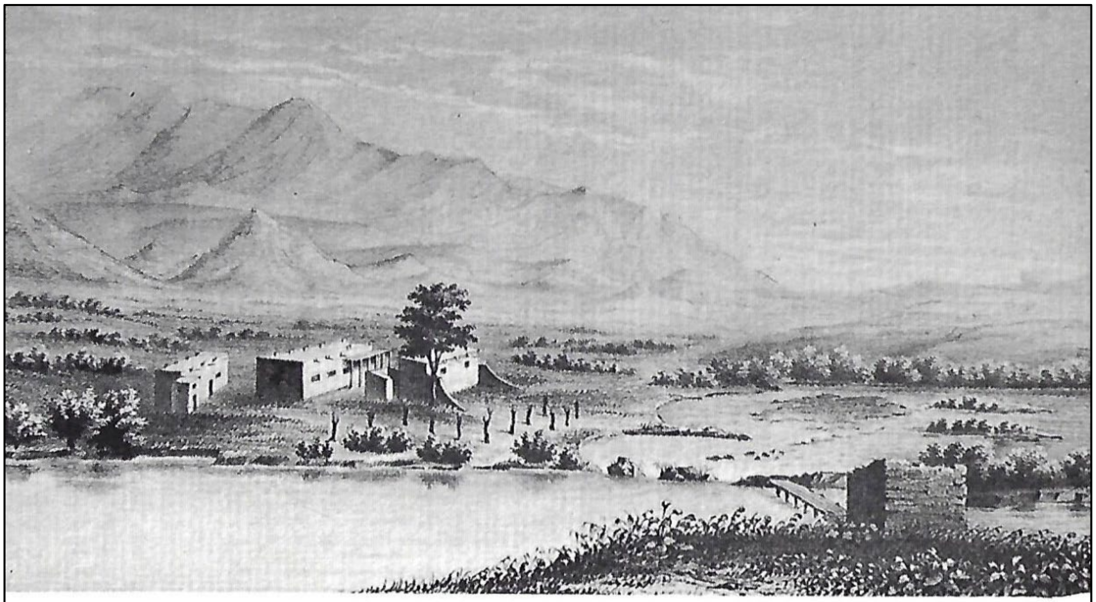
A. B. GRAY,

FOR THE

TEXAS WESTERN R. R. COMPANY.

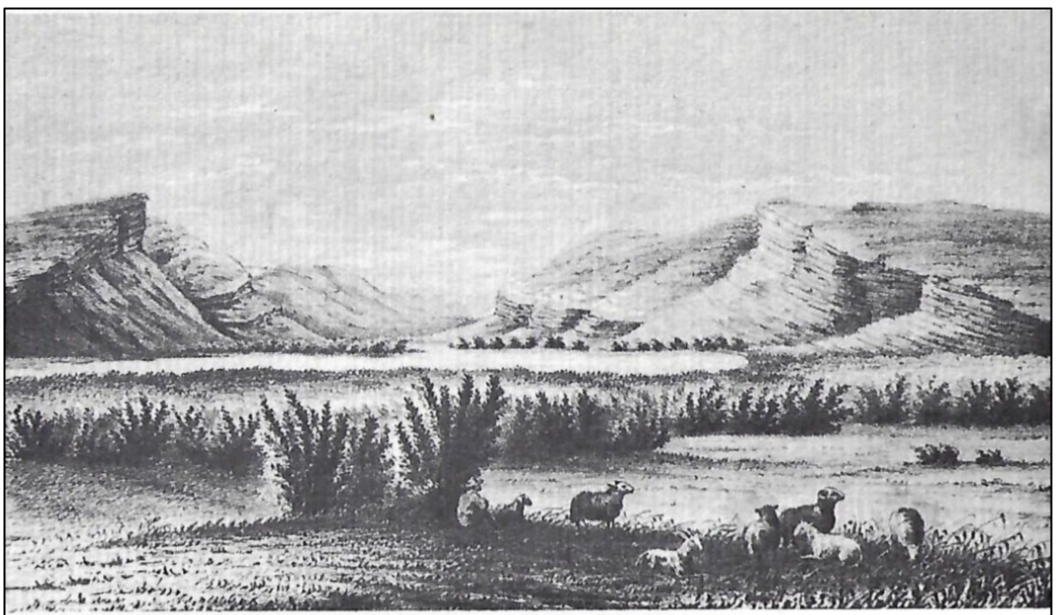
CINCINNATI, O:
WRIGHTSON & CO.'S ("RAILROAD RECORD,") PRINT.
1856.

Figure H3-3 (courtesy of L.R. Bailey and Westernlore Press, Los Angeles [summer 1965])**.** Reproduction of the Original Half Title Page from A.B. Gray's (1856) Report to the Texas Western R.R. Company. *From* facsimile copy of "The A.B. Gray report; Survey of a Route for the Southern Pacific R.R." (Bailey, L.R., ed., 1963).



Falls of the Rio Grande – at the Molino Del Norte

Figure H3-4 (courtesy of L.R Bailey and Westernlore Press, Los Angeles [summer 1965]**).** Charles Shuchard drawing (2/1854) of Hart's Mill ("El Molino Del Norte"), with the southern end of the Franklin Mountains on the eastern skyline. *From* facsimile copy of "The A.B. Gray report; Survey of a Route for the Southern Pacific R.R." (Bailey, L.R., ed., 1963).



Break of the Rio Grande, through the Bluffs near Frontera

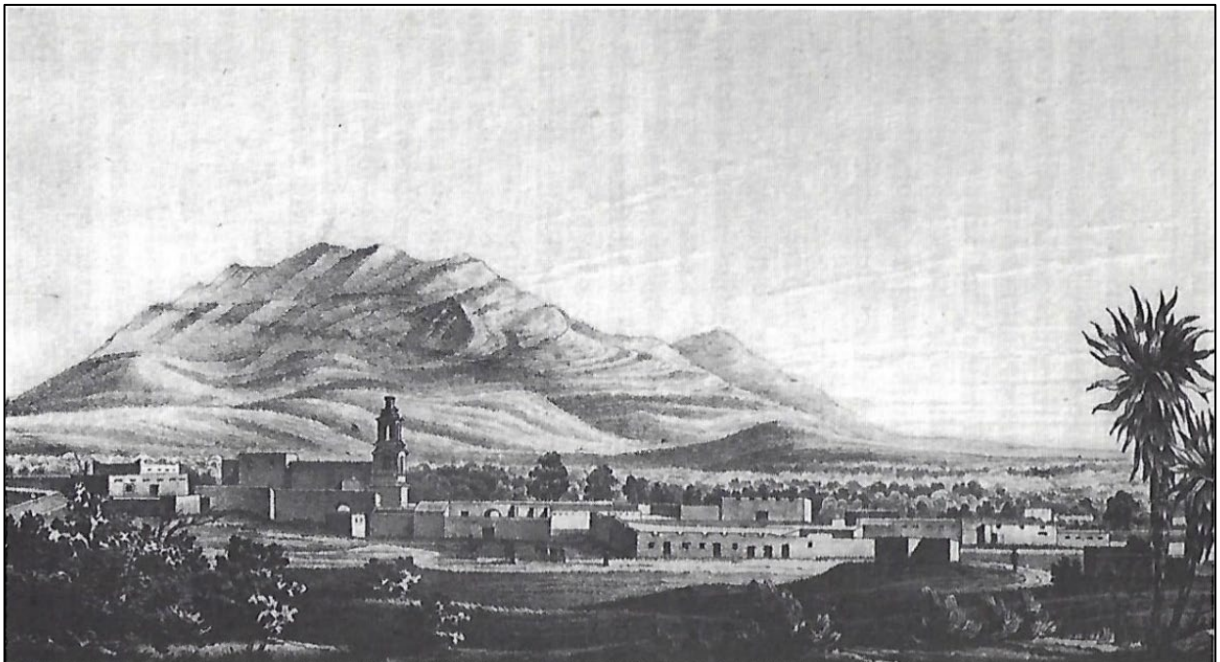
Figure H3-5 (courtesy of L.R Bailey and Westernlore Press, Los Angeles [summer 1965]**).** Charles Shuchard drawing (2/1854) of Historic Frontera area at the lower end of the Mesilla Valley. Upper Paso del Norte in the background; and 4 sheep, 2 goats, and their herder and his dog are in the foreground (*cf.* **Part. 3.2.3**). *From* facsimile copy of "The A.B. Gray report; Survey of a Route for the Southern Pacific R.R." (Bailey 1963).

Figure H3-6 is an oblique 2017 Google Earth® image of the International Boundary zone west of Paso del Norte (courtesy of J.S. Walker). The 2019 Border Wall *(cf.* **Fig. H1-8**) follows the Gadsden Purchase (31° 47' N latitude) boundary alighnment across the floor of the southern Mesilla Basin–West Mesa area (**Fig. H3-2**). The East Potrillo Mountains, Mount Riley, and Cox Peak are on the western skyline beyond the Mesilla Basin. Sierra Alta (alt. 2,302 m, 7,770 ft) on the left-center horizon is located about 40 km (25 mi) west of Puerto Palomas, Chihuahua, and about 5 km (3 mi) northwest of Boca Grande on the Rio Casas Grandes (**Fig. H1-12**). The domal, igneous-intrusive Cerro del Cristo Rey Uplift is in the center foreground (peak alt. 1,425 m/4,675 ft), and the small oval feature in the right foreground is the Sunland Park racetrack (~1,139 m/3,736 ft). The racetrack is near the southern end of the Mesilla Valley (MeV) and north of the Rio Grande channel. The river enters El Paso del Norte at Corchesne Bridge in the far-right foreground, which in near the historic "Frontera" site (**Figs. H3-2** and **H3-5**). The scene illustrates the unlimited potential for solar-electric power generation in the binational southern Mesilla Basin region (*cf.* Robinson-Avila 2020e, 2021c, 2022a).

Figure H3-6. Oblique 2017 Google Earth® image of the International Boundary zone west of Paso del Norte. The East Potrillo Mountains, Mount Riley, and Cox Peak are on the western skyline beyond the Mesilla Basin. Sierra Alta (alt. 2,302 m, 7,770 ft) on the left-center horizon is located about 40 km (25 mi) west of Puerto Palomas, Chihuahua. The igneous-intrusive Cerro del Cristo Rey uplift is in the center foreground, and the Colonia of Anapra occupies borderland area southwest and south of the Union Pacific RR tracks. The Rio Grande channel crosses the southern end of the Mesilla Valley south of the Sunland Park Racetrack (small oval) in the right foreground. The Courchesne Bridge, lower-rght corner, is located at the upper end of Paso del Norte near the historic Frontera site (**Figs**. **H3-1** and **H3-3**).

Descriptions made by the A.B. Gray Texas Western Railroad Survey and E.H. Emory's Boundary-Survey parties in 1854 offer further documentation that much of the southern Mesilla Basin landscape has not changed significantly in the past 166 years. In his "Reminiscences," Gray Party surveyor Peter R. Brady recalls that:

> It was a light sunny morning on about the 10th of March [1854]. We could distinctly hear the church bells in El Paso ringing out their joyous peals [**Fig. H3-7**]. . . . It was the last of civilization that we would see for many a long mile. We started out across the desert, a treeless, sandy plain interspaced here and there with little hillocks of sand, and a sparse vegetation of brush and dwarf mesquite that abounds in the valley of the Rio Grande [**Fig. 3-5**]. Each man packed his canteen with a quart of water and in the ambulance there was a ten gallon keg full for the four mules. We took a southwest course for the extreme end of a chain of mountains [Sierra Alta SW of Columbus?] that we could dimly see in the distance, about eighty or ninety miles away. Between us and the far distant mountains there was nothing but this desolate plain [L.R. Bailey, ed., 1963, p. 187].



Town of El Paso on the Rio Grande

Figure H3-7 (courtesy of L.R Bailey and Westernlore Press, Los Angeles [1965]**).** Charles Shuchard drawing (2/1854) of "Old El Paso" and the southern end of the Franklin Mountains. *From* facsimile copy of "The A.B. Gray report; Survey of a Route for the Southern Pacific R.R." (Bailey 1963).

Brady's recollections are confirmed by more detailed contemporary observations by the Emory Party who covered nearly the same part of the EPdN-southern Mesilla Basin area during their survey of the 31 °47' N parallel Boundary Line (Rebert 2005, p. 81-82):

> *Sketch No 1* [by Survey Artist John E. Weyss] is titled, "View of the initial point of the boundary line on the Rio Bravo del Norte-looking west." From a high point, it looks across the valley of the Rio Grande toward a boundary monument on the river and a background of mountains with a tiny flag atop one of the peaks [**Fig. H1-2**]. Emory's note says, "The flag indicates the point where the line crosses the mountain known as the "Muleras [Cerro (del)

Cristo Rey].” Map "No. 29" shows the boundary as a line tracing the 31 °47' N parallel, beginning at the Rio Grande and running west across a heavily hachured area labeled "Muleras."

Continuing west, the boundary on the map crosses an open area dotted with symbols for sand and gravel, rises over a scarp, and runs on across an open plain. Boundary monument no. 2 is shown deep in the Muleras Mountains and monument no. 3 is placed at the edge of the scarp. Emory's note continues as follows: "Directly west of [the Muleras], the line crosses a very sandy valley, supposed to be a former bed of the Rio Grande*, and strikes the table land (some 200 feet above the river) about three miles from the initial point. Here sketches Nos. 2 and 3 were taken, looking respectively east and west. . . . Emory says that *"Sketch No.2* is a back view, looking towards the initial point, . . . , and also, in the back-ground, the mountains near Franklin, east of the river . . . .

**First recorded recognition of the presence of an Ancestral Rio Grande (ARG) west of the Mesilla Valley.*

Sketch No.3 shows a flag in the foreground, a vast plain stretching away into the distance, a solitary peak far away in the center of the horizon, and a distant mountain range [East Potrillo Mtns, **Fig. H1-4**] on the horizon at the right. Emory notes that it is "a view taken at the same point as No.2; that is, where the line first strikes the table-land, but in the direction of the line westward. The line here leads over an apparently endless level table-land [Mesilla Basin-West Mesa floor], which is very sandy and generally without grass, but thickly covered with dumps of bushes and small sand-hills four or five feet high [mesquite coppice dunes of Gile et al. 1981, Fig. 34]. On the horizon, exactly in the line, is visible the top of an isolated mountain, serving beautifully as a natural monument. The mountains seen on the right hand are the “Sierra del Potrillo [East Potrillo Mtns.]."

H3.4.3. “La Gran Linea” Revisited, and the 2019 Border Wall

Alberto Álvaros Ríos (1999) Capirotada: A Nogales Memoir (p. 49)

“People always talk about the border as that fence between people there in those towns. That's not the border. It's something else, something underscoring the difference between danger and grace, which is not something that separates people. It's something that joins them, as they face the same border.”

Figure H3-8 is a low-elevation aerial photograph of the new, 9.14 m (30 ft) steel-bollard Border Wall and its service roadway where they cross the Mesilla Basin-EPdN section of “La Gran Línea.” This Fall 2019 photo shows adjacent parts of Doña Ana County, NM, and Municipio de Juárez, Chihuahua (Rpt. **Part 3.3**). It was provided to the NM WRRI by PBS-New Mexico in Focus—Our Land (courtesy of Laura Paskus and Kevin Bixby). The photo shows a typical Chihuahuan Desert basin terrain from a viewpoint near the 107° West Longitude, and it covers the southmost part of the Mesilla Groundwater (GW) Basin (MeB), and the northern section of the El Parabién GW Basin (EPB). The 31°47' N Parallel, International Boundary and general photo location are shown with a dashed yellow and gray line on **Figure H1-12**. The northern rim of the Late Pleistocene Potrillo Maar-volcanic crater is in the foreground (*cf.* Hoffer 2001a), and El Paso del Norte of the Rio Grande/Rio Bravo is located in the gap between the southern Franklin Mountains and Sierra [de] Juárez on the eastern horizon. The photo also illustrates the unlimited potential for solar-electric power generation in this still unpopulated binational desert area (e.g., Robinson-Avila 2020e and 2021c).

Figure H3-8. Low-level aerial photograph of the southern Mesilla Groundwater (GW) Basin area that is crossed by the new 9.14 m, steel-bollard Border Wall (courtesy of PBS-New Mexico in Focus—Our Land). This Fall 2019 view of a typical Chihuahuan Desert terrain is eastward across the southern Mesilla Basin floor from near the 107° W Meridian. The basin-floor surface is a remnant of the Early Pleistocene fluvial-deltaic plain of the Ancestral Rio Grande (ARG-**Figs. H1-5** and **H1-7**). The north rim of the Potrillo Maar volcanic crater is in the foreground (*cf.* Hoffer 2001a), and El Paso del Norte of the Rio Grande/Rio Bravo is in the gap between the southern Franklin Mountains and Sierra Juárez on the eastern horizon.

The Border Wall is paralled in most places with a hard-suface roadway that is designed for long-term structure maintence and security vehicle operations. Lack of any governmental regulatory constraints during Wall construction, and development of service roadway infrastructure have already had an adverse effect on the land-surface environment and greatly complicated access for binational hydrogeologic research activities (Moya 2007; Banerjee et al. 2018; Attanasio 2019; Attanasio and Galvan 2019; Turner 2019 and 2020b; Bixby and Smith 2020; Spagat 2020; Reisen 2020). Due to *elusive* geopolitical constraints, however, long-term impacts of this "border-security" feature on GW flow and chemistry remain to be assessed (e.g., D'Ammassa 2021, Reisen 2021, Spagat 2021; *cf.* Rpt. **Parts 6.4.1** and **7.6**).

The nearly level Mesilla Basin floor east of the viewpoint in **Figure H3-8** has a mesquite coppice-dune cover that typifies much of the regional Chihuhuan Desert landscape. Most of the land surface is the relict fluvial-deltaic plain constructed by the Ancestral Rio Grande (ARG), which terminated in paleo-Lake Cabeza de Vaca between 0.75 and 5 Ma (**Figs. H1-6** and **H1-7**; *cf.* Rpt. **Part 3.7.3**). This ancient landform predates formation of the deep canyons and valleys of the throughgoing Rio Grande/Rio Bravo (RG/RB) fluvial system with headwaters in the Southern Rocky Mountains (**Fig. H1-1**). Thick ARG deposits in the Upper Santa Fe Group form the primary component of the most productive SFG aquifer systems in the region (**Figs. H1-6** and **H1-16**).

H3.5. Impacts of Early 20th Century Railway Development

Pioneering geologist, Nelson Horatio Darton (Kues 2014a) covered an enormous geographic and geologic-topical area (Darton 1899, 1905, 1916a-b, 1928a-b; Darton et al. 1916). His contributions to Late Cenozoic geology included formally naming the Ogallala formation (1899, 1905). He was a pioneer in the use of modern subsurface-mapping methods in his characterization of Luna County's Mimbres basin aquifer system (1916). Like present-day New Mexico Geological Society (NMGS) guidebooks, the geologic railroad guides compiled by Darton and USGS associates (e.g., 1916, 1933) are invaluable sources of information, not only on the local geologic and geomorphic setting, but also on its history and economy. Darton's 1933 "Guidebook of the Western United States, Part F, The Southern Pacific Lines" (USGS Bulletin 845) covers the present Union Pacific RR route that crosses the southern Mesilla Basin from the western Hueco Bolson and El Paso del Norte to the east-central Mimbres Basin (e.g., **Fig. H3-9**). Guidebook descriptions of geology and hydrogeologic features retain their conceptual validity, as evidenced by the following extended passages, which start with entries on the El Paso area (elev. 3,725 ft/1,135 m; 1930 population about 131,500):

> [**p. 125**] In 1852 a post office, called Franklin [after local land owner Franklin Coonze] was established here, and in 1859 the name was changed to El Paso. There was no town development until after the Civil War—. . . . A few years after hostilities ceased a triweekly schedule was established for this region. The railroad reached El Paso from the east in 1883, and in the next few years brought many immigrants to the Rio Grande Valley. Since that time the city has had rapid growth.
>
> El Paso has long been prominent as headquarters for the mining industry, although there are no notable mines in its immediate vicinity. For many years it has had the largest custom smelter in the United States, . . . and treating ore from New Mexico, Arizona, and Texas [and Mexico]. In 1930 the Nichols copper refinery was completed on the eastern edge of the city. Just west of this refinery are the Pasotex and Texas Co. oil refineries, which receive crude oil by a long pipeline from the Winkle field in Texas. Another pipeline brings gas to El Paso. The large cement plant on the western edge of the city furnished cement for the Elephant Butte Dam; it utilizes the limestone of the [Lower Cretaceous] Comanche series. Beaumont Hospital is a large Government establishment for tubercular soldiers, and Fort Bliss, 5 miles [8 km] northeast of the center of the city, … is the largest cavalry post in the United States. The Texas College of Mines [UTEP], a branch of the University of Texas, and Loretto College are also in El Paso. . . .
>
> [**p. 126**] In New Mexico and Texas above El Paso the Rio Grande flows in a wide valley of alluvium [the Mesilla Valley], bordered by a high terrace plain [La Mesa geomorphic surface]; . . . . At El Paso the valley is constricted to the narrow rock-walled pass that gives name to the city, but the bordering high terrace continues far down the valley. Below the pass the alluvial plain [El Paso/Juárez Valley floor] is a broad flat in which the river meanders widely, often changing its course by cutting new channels at time of freshets. The high terrace plain [western Hueco Bolson floor] that borders this valley terminates in bluffs and steep slopes, in places as much as 200 ft [61 m] above the bottom lands. The smooth [ARG-fluvial] plain at the top of these bluffs [La Mesa surface] extends far north as a wide bolson or desert flat between mountain ranges. Near El Paso there are several distinct benches, 3,800 to 3,950 feet above sea level, mostly in the form of mesas or projections from the base of the Franklin Mountains. These benches slope gently toward the river and are in part capped by caliche, an infiltration of calcium carbonate in the sand, which makes a material so hard that it helps preserve the tabular form and sharp edges of the mesas.

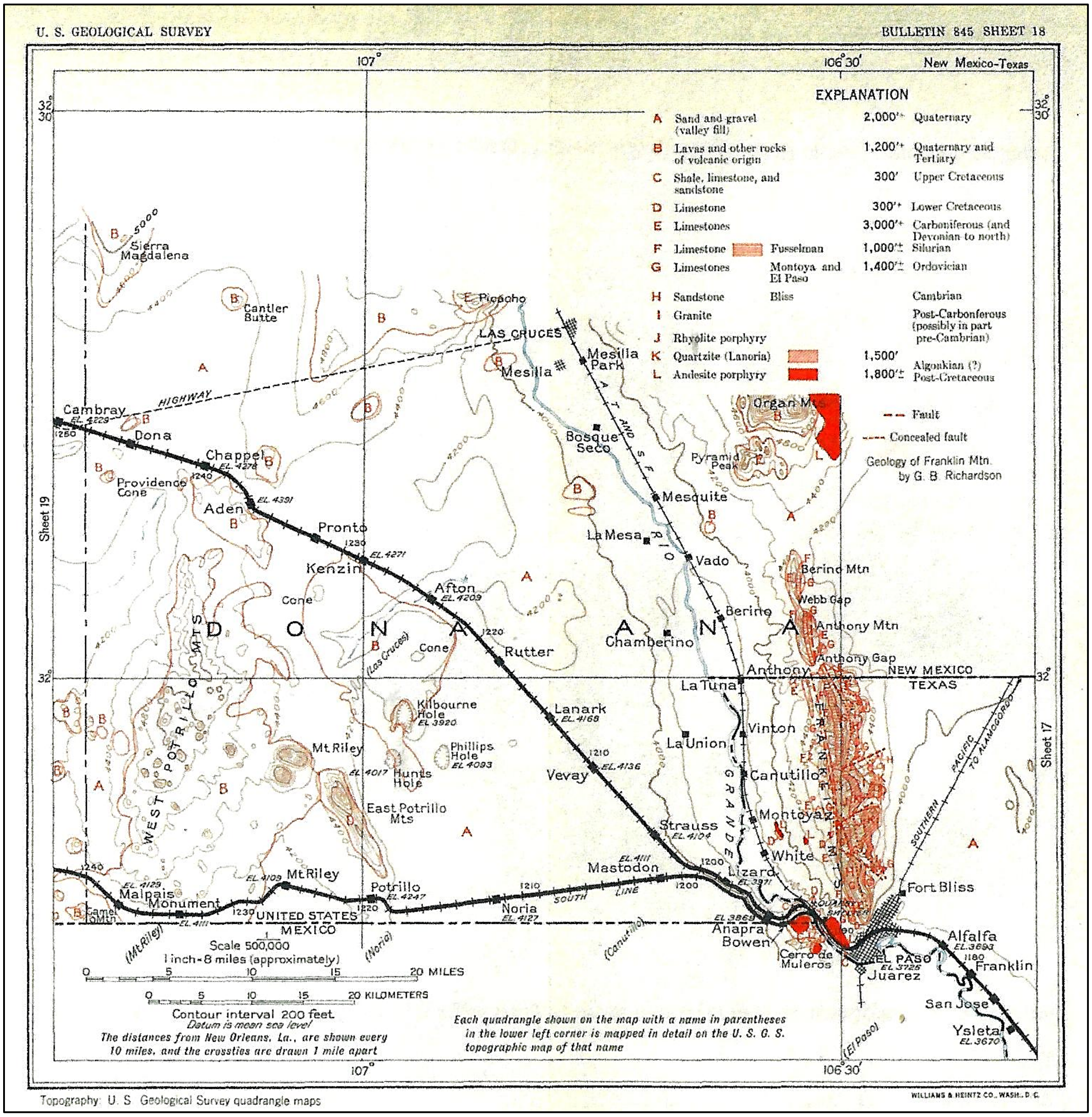


Figure H3-9 (facsimile copy of USGS Bulletin 845, SHEET 18)**.** First reconnaissance geologic map of the Mesilla Basin region by N.H. Darton (1933). Bulletin 845 includes detailed commentary on geology and history along (1) the mainline of the Southern Pacific RR (now Union Pacific) between the El Paso, TX and Cambray, NM area, and (2) the southern (now abandoned) SPRR route between El Paso and Malpais Siding, NM (Darton 1933, p. 123-136, and p. 162-164; *See* Lee 1907, Richardson 1909, Seager et al. 1987, Seager and Mack 1994, Seager 1995, Collins and Raney 2000, Hoffer 2001b).

[**p. 126-127**] The Franklin Mountains form a high ridge on the southern prolongation of an axis of uplift which extends across central New Mexico from the Rocky Mountains. Probably this uplift is cut off to the south by a fault. The range rises abruptly about 3,000 feet [900 m] above the adjoining plains or valleys and culminates in Mount Franklin [north, alt. 7,192 ft/2,192 m]. The west side is mainly a dip slope of heavy beds of limestone with pronounced westerly dip; the east side shows many ridges, irregular lower crests, and buttes, and [is] deeply cut by canyons. The range is a typical tilted block of the basin-range type, which predominates in a large part of the Southwest.

[**p. 128**] . . . . The mountains to the south, in Mexico, are the Sierra Guadalupe [de Juárez] and the Cerro de Muleros [del Cristo Rey; **Fig. H3-5**].

Wells in El Paso are to have penetrated valley fill [SFG basin fill] to a depth of 2,285 ft (696 m). Fossil bones found in Quaternary deposits have been determined as *Elephas [Mammuthus] columbi*, *Equus complicatus*, and *Tapirus haysii*, representing an elephant, an ancient horse, and a tapir, all of which have been extinct for many centuries [millennia] . . . .

[**p. 128-129**] The Southern Pacific [now Union Pacific] lines enter New Mexico on crossing the Rio Grande just west of El Paso, the State line being in midstream. . . .

[**p.131**] NORTH LINE FROM EL PASO, TEXAS TO MESCAL, ARIZONA

From El Paso westward to Tucson the Southern Pacific Railroad has two lines—one going by way of Deming and Benson [present UPRR] and the other (former El Paso & Southwestern Railroad [now abandoned]) by way of Columbus and Douglas [now route of NM Hwy. 9; **Fig. H3-6**; *cf.* Rpt. **PL. 9k**]. Leaving El Paso, the north line of the railroad follows the north [NE] bank of the Rio Grande for some distance, with Mexico in plain view on the opposite bank. In about 1 mile [1.5 km] a large smelter* is passed, and in 2 miles a cement plant, near which are large quarries in limestones (of Comanche or Lower Cretaceous age) in a downfaulted block at the south end of the Franklin Mountains. It is the presence of this rock and a mass of intrusive [Campus Andesite] porphyry that cause the [EPdN] constriction of the river valley at El Paso (Spanish, the pass). At the entrance of this pass the railroad crosses the river into New Mexico and skirts the north side of Cerro de Muleros [del Cristo Rey], a high ridge which lies mostly in Mexico. . . .

American Smelting and Refining Corporation (ASRCO) copper- and lead-ore smelter in the Smeltertown District in El Paso del Norte (cf. Part H7.3).

[**p. 131-132**] The Cerro de Muleros [Cristo Rey] consists of a mass of limestone, shale, and sandstone of [Lower] Cretaceous age penetrated and tilted by a large mass of [Eocene andesite] porphyry. The lower or quarry limestone in this succession is well exposed in the first railroad cut west of the river. It is overlain by nodular and slabby limestones and shales containing large numbers of Washita fossils and grading upward in to a thick mass of dark shale in which there are deep cuts extending to and beyond Brickyard siding. This shale is extensively worked for brick, hollow tile, etc., on the west bank of the river below the 2 railroad bridges. . . [**Figs. H3-5** and **H3-6**].

[**p. 132**] Just above Anapra siding [alt. 3,869 ft/1,179 m; pop. 27], where north [main SPRR] and south [now abandoned] lines are close together and joined by switches to be used in case of necessity, the railroad grade ascends the terrace of valley fill [Upper SFG], the edges of which margins the Rio Grande Valley in a long line of steep slopes. The top is attained near Strauss siding [alt. 4,110 ft/1,253 m]. Along the upgrade are many fine exposures of gravel and sand of which the terrace is composed. This material was deposited by the Rio Grande at an earlier stage of its history, when it flowed west of the Cerro de Muleros [Cristo Rey] and another high range to the south [Sierra de Juárez] and emptied into Guzman [Los Muertos] Basin in Chihuahua, Mexico. This was before its present course was developed through the "pass" at El Paso. . . .

[**p. 133**] From Strauss siding* the railroad goes northwest over the wide alluvial plain that extends entirely across the southwestern part of New Mexico. . . [**Fig. H3-6**]. The northerly trend of the railroad in this area is taken to avoid the large rugged area of volcanic rocks [basalt flows] of the West Potrillo Mountains and its extension to the north.

Present site of the Santa Teresa Industrial Park (Fig. H1-7**).*

The thick body of sand and gravel underlying the plain has been drilled for water at several points along the railroad. A boring at Lanark [alt. 4,168 ft/1,270 m; pop. 40] passed through 950 ft (390 m) of beds, all supposed to be valley fill but possibly including some underlying Tertiary or Cretaceous strata [Lee 1907b, Tbl. 5; Rpt. **Tbl. 1**, no. 242]. It found water which rises approximately to the level of the Rio Grande Valley, 15 [8 mi/13 km] miles east. . . [**Fig. H3-5**].

H3.6. First Formal Recognition of a Shared Surface-Water Resource: United States and Mexico, 1907, Convention between the United States and Mexico on Equitable Distribution of the Waters of the Rio Grande (United States and Mexico 1907; *cf.* Follett 1898, Hundley 1966)

PROCLAMATION by the President of the United States of America

Whereas a Convention between the United States of America and the United States of Mexico, providing for the equitable distribution of the waters of the Rio Grande for irrigation purposes, and to remove all causes of controversy between them in respect thereto, was concluded and signed by their respective Plenipotentiaries at Washington on the twenty-first day of May, one thousand nine hundred and six, the original of which Convention being in the English and Spanish languages, is word for word as follows:

The United States of America and the United States of Mexico being desirous to provide for the equitable distribution of the waters of the Rio Grande for irrigation purposes, and to remove all causes of controversy between them in respect thereto, and being moved by considerations of international comity, have resolved to conclude a Convention for these purposes and have named as their Plenipotentiaries:

The President of the United States Of America, Elihu Root Secretary of State of the United States; and The President of the United States of Mexico, His Excellency Señor Don Joaquin D. Casasus, Ambassador Extraordinary and Plenipotentiary of the United States Of Mexico at Washington; who, after having exhibited their respective full powers, which were found to be in good and due form, have agreed upon the following article:

Article I of the "Convention*" also specified that (Kelley et al. 2007, p. 538):

After the completion of the proposed storage dam near Engle, New Mexico, and the distributing system auxiliary thereto, and as soon as water shall be available in said system for the purpose, the United States shall deliver to Mexico a total of 60,000 acre-feet of water annually in the bed of the Rio Grande at the point where the head works of the Acequia Madre, known as the Old Mexican Canal, now exist above the city of Juárez, Mexico.

**Signed at Washington, May 21, 1906: ratified by the President, December 26, 1906; ratified by Mexico, January 5, 1907; and proclaimed, January 16, 1907.*

H3.7. The 1912 New Mexico State Constitution (Tessa T. Davidson, J.D., 1998, p. 35)

. . . Water was placed in a unique category in our Constitution - something that cannot be said of lumbering, coal mining, or any other element or industry. The reason for this is of course too apparent to require elaboration. Our entire state has only enough water to supply its most urgent needs. Water conservation and preservation is of utmost importance. Its utilization for maximum benefits is a requirement second to none, not only for progress, but for survival.

H3.8. Elephant Butte Dam, Reservoir, and the Rio Grande Project

Elephant Butte Dam was completed on 5/13/1916. In an address at the dam's dedication on 10/19/1916, Arthur P. Davis, Director and Chief Engineer of the Reclamation Service, reviewed the reasons for its size and storage capacity (Kelley et al. 2007, p. 539):

> There were evidences in the records - which were of considerable extent - that some years only about 200,000 acre-feet of water were discharged in this river and that in other years more than 2,000,000 acre-feet were discharged. Sometimes a series of those dry years occurred together, and at other times more than one of those wet years occurred in a series; and, looking over the ground and having studied that water supply, I made up my mind that the full utilization of this water supply could not be obtained without a reservoir of immense dimensions - one large enough, first, to hold the waters of those great years when 2,000,000 acre-feet were discharged, and to provide for evaporation and hold that water here until a dry year should come. . . .

H3.8.1. The Rio Grande Project (Clyde Conover 1954, p. 17)

> The Rio Grande Project (RGP) of the [US] Bureau of Reclamation includes most of the valley lands of the Rio Grande in New Mexico and Texas from Caballo Dam southward to a point about 40 miles [64.4 km] below El Paso, a distance of about 130 miles [209 km] (**Fig. H1-10**). From Caballo Dam to Selden Canyon, a distance of about 30 miles [48 km], the Rio Grande flows in the Rincon Valley, . . . Below Selden Canyon the valley floor widens into the Mesilla Valley, which extends about 55 miles [88.5 km] southeastward to "The Pass [EPdN]," 4 miles [6.4 km] above El Paso. . . . The El Paso Valley [Valle de Juárez] extends about 90 miles [145 km] southward from El Paso . . . , but only the upper 40 miles [64.4 km] is included in the Rio Grande Project.
>
> The water for the Rio Grande Project is stored in Elephant Butte Reservoir, which has a capacity of 2,197,600 acre-feet [2,711 hm^3], and in Caballo Reservoir, which has a capacity of 345,870 acre-feet [426.6 hm^3], about 28 miles [77 km] below Elephant Butte Dam. Water released from Caballo Reservoir is diverted into canals in the Rincon Valley, . . . ; in the Mesilla Valley . . . ; and in the El Paso Valley by the American Dam, about 3 miles [4.8 km] northwest of El Paso. Water for the Mexican side of the El Paso Valley, generally referred to as the Valle de Juárez, is diverted at the International Dam, about 2 miles [3.2 km] below the American Dam.

H3.8.2. The IBWC Rio Grande Canalization Project (Andrea Glover, 2018, p. 63)

> The levees [between Caballo Dam and El Paso] are owned, constructed, and maintained by the United States Section of the International Boundary and Water Commission (originally named International Boundary Commission (IBC) but name was changed to International Boundary and Water Commission with the Treaty of 1944 [*cf.* Sandoval Solis, 2011]). The levees, river, and floodplain fall under International Boundary and Water Commission's (IBWC) Rio Grande Canalization Project. The project extends along the Rio Grande from Percha Dam, just south of Caballo Dam in Sierra County, to American Dam and Canal in El Paso, TX [**Fig. H1-10**]. These levees exist because of a treaty with Mexico. The Convention of 1906 (34 Stat. 2953) requires that the United States (US) deliver an annual appropriation of water to Mexico at their Acequia Madre headgates in El Paso, TX (IBC, 1936, p. 2) and while the US Government owns Elephant Butte and Caballo Dams, prior to the Canalization Project they did not own the river channel. Measuring treaty water deliveries was almost impossible because of private water diversions along the 125 river mi (201 km) in the US.
>
> The unregulated flows also allowed Mexico to sometimes exceed their allotment (IBC, 1936, p. 3). Public Resolution No. 648, Act of June 4, 1936, authorized the canalizing of the Rio Grande from Caballo Dam, NM, to El Paso, TX. Construction began on January 15, 1938 and was

completed in February 1943 (History and Development of the International Boundary and Water Commission, unpubl. report, revised 1954). The project was meant to establish a normal flow and flood channel confined between parallel levees sized to carry the estimated maximum flood flows (IBC, 1935, p. 5). When the initial project was complete, 125.92 mi (202.6 km) of levee were constructed, almost 3300 ac (1334 ha) of floodway were leveled, the river was shortened by approximately 10 mi (16 km), and 7395 ac (2993 ha) of land were acquired at a total project cost of $2,996,052 (Baker, 1943, p. 4, 18, and 32).

H3.9. The 1938 Interstate Rio Grande Compact (Kevin Flannigan 2007, p. 518-519)

The Rio Grande Compact, an interstate agreement that apportions waters of the Rio Grande between the states of Colorado, New Mexico, and Texas, was executed in 1938 and became effective in 1939. Under the Compact, New Mexico is allowed to consume on average roughly twice as much water as Colorado and three times as much as Texas. New Mexico's share includes the amount of water it is entitled to consume between the Colorado-New Mexico state line and the Otowi gage, the amount in the Middle Rio Grande valley between Otowi gage and Elephant Butte Reservoir (including all tributary inflow and San Juan-Chama Project water), and the amount in the Elephant Butte Irrigation District below Elephant Butte in the Lower Rio Grande [*cf.* Littlefield 2000 (p. 21-28); Ortega Klett 2000 (p. 17)].

H3.10. The 1963 US-Mexico "Chamizal Convention" and Beyond

From a long-term "geopolitical" perspective, setbacks in binational collaboration in studies of transboundary aquifers have only been temporary since ratification of the "Chamizal Convention" of August 1963 (www.ibwc.gov/Files/ChamizalConvention1963.pdf). This treaty resolved a long-term Rio Grande/Bravo, International Boundary problem at El Paso and Ciudad Juárez. As reported by Dr. Jerry Mueller in "Restless River (1975, p. 99-104)":

> **[p. 99]** Article 1 of the 1963 Treaty provided for a relocation of the River in a 4.3-mile cement-lined* channel between El Paso and Juarez, on an axis determined in Minute No. 214 of the International Boundary and Water Commission. The Chamizal Channel, with a discharge capacity of 24,000 c.f.s., opened in 1968 and became a fixed reach of the international boundary. . . .
>
> **~7-km [reinforced-concrete]-lined.*
>
> [**p. 103-104**] In order to implement the Chamizal Treaty, it was necessary for the United States Government to purchase 743.54 acres of land, or slightly more than a square mile, of south El Paso. Nearly 85 percent of this area, 630.38 acres, was transferred directly to Mexico in the fall of 1967. The remaining 15 percent, 113.16 acres, was required for the Chamizal Channel, a port of entry, relocation of the Texas and Pacific, Santa Fe, and Southern Pacific Railroads, and the relocation of a principal irrigation canal. These property acquisitions alone cost the United States more than 27 million dollars. . . . Additional tens of millions have been spent in relocating public facilities of the affected zones, in constructing bridges and the Chamizal Channel, and in building an ultra-modern port of entry and customs complex at the Cordova crossing. At present, a multi-laned divided highway shuttles visitors between El Paso and the PRONAF commercial center of east Juarez via the Cordova route, crossing the [new] Chamizal Channel and the inconspicuous dry bed of the pre-1968 Rio Grande.

H4. REVIEW OF HYDROGEOLOGY-RELATED STUDIES OF TRANSBOUNDARY AQUIFER SYSTEMS SINCE 1890

H4.1. Hydrogeology-Related Investigations in Northwestern Mexico (1890-1940)

In the 1880 to 1911 period, the Porfirio Diaz regime's encouragement of active U.S. involvement in mineral-resource development in Chihuahua and Sonora led to a number of reconnaissance studies that provide a limited amount of groundwater-resource information, primarily on upland-area mining districts (e.g., Hill 1891, 1892a and b, 1896, 1900, Burrows 1909). Social and political unrest between 1911 and 1930 was also not conducive to any type of natural-resource investigation (e.g., Tompkins 1934, Clendenen 1961, Lister and Lister 1966, Samek Norton 1998, Wasserman 2015 and 2017, Guinn 2021). By 1930, however, there was a resurgence in interest not only in hard-rock mineral exploitation, but also in regional geologic mapping.

H4.1.1. Geology-Based Contributions by Ezequiel Ordóñez* (1936 and 1941)

**Ezequiel Ordóñez [Aguilar] (1867-1950) "was a Mexican surveyor, geologist, researcher and academic. He is considered the creator of Mexican oil geology. . . . He was a member of the Antonio Alzate Scientific Society, the Mexican Society of Natural History, the Société Géologique de France. He conducted research for the Geological Institute of Mexico in 1892, and . . . was appointed deputy director of the same in 1897. He was a consultant and vice president of the Pan-American Petroleum Co. from 1927 to 1930. He was a member of the American Institute of Mining and Metallurgical Engineers, the American Association of Petroleum Geologist, and the American Academy of Arts and Sciences . . . . He was named honorary director of the Institute of Geology of Mexico [in May 1943; and he] was a founding member of El Colegio Nacional . . . https://es.wikipedia.org/wiki/Ezequiel_Ordóñez*

The following selections are from Ordóñez' seminal paper titled: "Principal Physiographic Provinces of Mexico," which was published in the October 1936 Bulletin of the American Association of Petroleum Geologists (AAPG; v. 20, no, 10). The paper was initially "read before the Association at the mid-year meeting, in Mexico City, October 16, 1935;" and it represents a pioneering, geology-based contribution to the geomorphologic research in western North America. Ordóñez (1942) published an updated Spanish-language edition titled "Las provincias fisiográficas de México" *in* Revista Geografía de Instituto Panamericano Geografía e Historia:

INTRODUCTION [p. 1277-1278]

The object of this paper is to outline the principal physiographic provinces of Mexico and to discuss briefly their outstanding characteristics, Mexico is a very mountainous country, with areas of high relief occupying at least three-fifths of its total area. A few of its physiographic provinces are only extensions of similar physiographic provinces in the western part of the United States and follow the same general trend of high relief. There are, however, physiographic provinces in Mexico [e.g., Sierra Madre Occidentál] which have no connection with the adjoining part of the United States.

PPROVINCE VI. CENTRAL PLATEAU OF MEXICO

SUBPROVINCE A, NORTH-CENTRAL PLATEAU

[p. 1289] The North-Central Plateau of Mexico contains the so-called "[Mexican] high lands" and the great "Bolson," or basin areas. This province is really the southern extension of the Basin and Range Province of the southwestern United States, in Arizona and New Mexico. The North-Central Plateau with the Sonora Desert occupies about two-filths of the area of Mexico. From Monterrey or Monclova to Saltillo by railroad or automobile, the ascent is made to the eastern edge of this highland area where the elevation is approximately a mile above sea level. The North-Central Plateau of Mexico is a desert and semi-desert.

In the plain the average annual rainfall does not exceed 12 inches [300 mm] and in some places it is very much less than 10 inches [250 mm]. In the mountains it rains a little more. There are, in this area, wide daily variations of temperature, hot during the middle of the day and mild or cold early in the morning. In the most northern part, winters are cold and sometimes snow covers the tops of the higher mountains. Vegetation is scarce and consists of sage, mesquite, and many species of thorny plants and weeds. In some mountains, especially those of [p. 1290] eruptive and intrusive rocks, pines and other trees grow on the higher parts of ravines.

The North-Central Plateau, with more plains than mountains, extends as a large south-north inclined plane from its southern limit near the city of San Luis Potosi to the Rio Grande and east of Ojinaga. Though in San Luis Potosi, the altitude of the plain is 6,130 feet [1,870 m] above sea-level, in Torreon and Ciudad Lerdo in the "Bolson de Mapimi," it is only 2,560 feet [780 m]. Northeast of Ojinaga, and west of the Rio Grande, the highlands and bolsons again rise to higher altitudes above sea- level; the elevation of El Paso and Ciudad Juárez is 3,800 feet [1,158 m].

With the exception of the Rio Grande drainage basin, the North-Central Plateau of Mexico has no outlet to the sea. This plateau consists mostly of large plains, which really are inclosed [endorheic] basins between long, narrow, isolated sierras. Many of these sierras are more than 65 miles [105 km] in length, while their width rarely exceeds 10-12 miles [16-20 km]. The sierras, in general, extend northwest and southeast, but in a few sections, west of Monterrey and in in central Coahuila, they extend predominantly cast and west. Almost all the sierras of the North-Central Plateau consist of sedimentary rocks with a remarkable abundance of Cretaceous limestone. Triassic, Jurassic, and, in places, Paleozoic sedimentary rocks occupy the cores of the axes of the sierras where the more advanced erosion or faulting has left the older rocks uncovered. Post-Cretaceous intrusives also appear in several mountains, and have lifted the sedimentary rocks into a quaquaversal position. Eruptive rocks, like andesites, are also common, as well as some basalts, but these are usually found in the synclinal valleys.

The sierras generally have crests of even and uniform altitudes and their flanks are usually steep with deeply carved V-shaped ravines. The lower part of the [piedmont] slopes are commonly covered with extensive fans that form a continuous belt of alluvial material solidly cemented with caliche along the flanks of the mountain. In some places, especially in narrow basins or bolsons, or on mountains built with eruptive or intrusive rocks, the fans are small and independent, causing a sharper contrast between the mountains and the plain. In some of these basins, the [alluvial-fan] bases of the sierras extend toward the middle of the plain like a very gently inclined plane [piedmont-slope] which ends at the "barrial [aka barreal]," improperly called "playa"*by the American geologists and geographers.

** Note that Ordóñez restricts use the term "playa" to shoreline features of large permanent bodies of water (e.g., "beach").*

[p.1290] The topographic elements of the basin or "bolson" are the mountain slope, the alluvial fans, the gentle alluvial plain, and the silty bottom of the basin called the "barrial [aka barreal]" which is temporarily occupied by water immediately after the infrequent but torrential rains. Isolated ranges are explained [interpreted] as fault blocks in sedimentary rocks previously [p. 1291] folded in large anticlines and synclines. In many places, more complicated folds are seen, such as fan folds and asymmetric anticlines; but the big intervening synclines are usually occupied by basins. Thick masses of conglomerates intercalated with clays fill the bottoms of many of the basins and, in some places, loess [eolian-silt] deposits are found . . . .

In general, the actual forms of the ranges of this province do not show a very advanced cycle of erosion. Only in certain types of rocks has erosion reached any degree of maturity. In some areas, fault blocks in rocks not previously folded have produced extensive mesas, monadnocks [high-relief erosion remnants of igneous and metamorphic rocks], and buttes, some with lava sheets on top.

H4.1.2. Geography-Based Contributions of Donald Dilworth Brand (1929-1938)

American geographer and anthropologist, Donald Dilworth Brand (1905-1984) was born to missionary parents in Peru. His 1933 Ph.D. in anthropology from the University of California, Berkeley, is based on detailed (1929-1931) field research on the prehistoric settlements of the Sierra Madre Occidentál province. His later biogeographic and physical-geographic investigations in Chihuahua and Sonora occurred between 1934 and 1936.During his tenure as a professor in the Department of Anthropology of the University of New Mexico (1936-1944). Brand's pioneering studies on the cultural geography in Chaco Canyon (NM) and northern Mexico took into account their environmental contexts. His papers on the biology and physiography of northern Mexico appeared in *The New Mexican Anthropologist*, a series of irregular bulletins published by the university and co-edited by Brand between 1936 and 1944. Brand also worked in Mexico for the Smithsonian Institution during the Second World War. After a two-year professorship at the University of Michigan (1947-1949), he moved to the University of Texas, where he founded the Department of Geography. He served as chair of the department until 1960 and retired in 1975.

Brand's 1937 monograph on the "Natural Landscape of Northwestern Chihuahua" remains the most comprehensive English-language description of the region's cultural and physical. It is based on his (1929-31 and 1934-1936) field studies in Sonora and Chihuahua, and it includes short, but informative summaries of previous work by Mexican, American, and European geologists and geographers, as well as detailed descriptions of biota, notes on climate, and astute geomorphological observations. An example of his unique style of descriptive writing follows:

> [p. 11] Northern Chihuahua offers to view two geomorphic complexes: the Basin and Range landscape, in which a practically continuous flat, gently rolling, or sloping plain is broken by short, frequently parallel mountain chains which rise above the basin floors like "islands out of a sea"; and the Sierra Madre Occidentál, which is a great plateau of extrusives [mostly rhyolitic volcanics], having NNW-SSE narrow structural depressions between smooth-topped ridges, mesas, and minor plateaus, and segmented by the gorges of transverse, antecedent or headward-eroding streams flowing through deep gorges to the Pacific lowlands.

H4.2. Geoscientific Investigations in the Northern Chihuahua Borderlands Region (1941-1969)

H4.2.1. Mexico Based Investigations

Hydrogeologic contributions by Alfonso de la O-Carreño, Professor of Geophysical Exploration Methods at the Universidad Nacional Autónoma de México (UNAM)-Instituto de Geológia, and early Chief of the National Irrigation Commission-Bureau of Geology deserve special recognition (e.g., de la O-Carreño 1944, 1948, 1951, 1954). His 1957 and 1958 reports* to the Secretaria de Recursos Hidráulicos (SRH), Jefatura Irrigación y Control de Ríos (JICR) were the first to describe subsurface relationships in the Ciudad Juárez area from a detailed hydrogeologic perspective. The 1958 report on the "Investigation of subsurface geohydrologic conditions at Juárez, Chihuahua, applying electrical geophysics" is comparable with work of that time in the USA part of the Hueco Bolson (*cf.* Knowles and Kennedy 1958; **Part H5.4**).

**From English translations, courtesy of Barry J. Hibbs 11/12/2021.*

Luis Blásquez-Lopez (1959) of the UNAM, Instituto de Geológia compiled the first reconnaissance-level report on the hydrogeology of Mexico's northern desert regions. He presented detailed summaries of available information on physiography, climate, and extent of surficial basin-fill deposits, bedrock type, geohydrology, and hydrologic-budget analyses for major drainage basins. Of special importance to past and ongoing groundwater investigations was his inclusion of the basins of the Rios Casas Grandes, Carmen, and Santa Maria (*cf.* **Fig. H1-6a**, **b**; **Apndx. D**).

More advanced hydrogeological characterization of basin-fill aquifer systems in Chihuahua was initiated at both federal and state levels in 1967. With support from the UNESCO World Food and Agriculture (FAO) Program, initial field work was done under the auspices of the SRH-JICR Dirreción de Agrología and the Soil Survey Investigations Desert Project of the USDA-Soil Conservation Service (Hawley 1969b; Morrison 1969; Flores Mata 1970; *cf.* **Fig. H4-9**). Geomorphologic, hydrogeologic, and soil-survey aspects of this multi-disciplinary investigation are reviewed by Hawley (1969b). Development of detailed classification of "geomorphic features of northwestern Chihuahua . . ." was one of his early contributions to this binational effort (*cf.* **Figs. H4-6a** and **6b**; **Tbl. H4-1**; **Apndx. D1**; Córdoba et al. 1969, Schmidt 1973 and 1992, Reyes Cortés 1992 [**Fig. H1-7**]).

H4.2.2. 1958 West Texas Geological Society (WTGS) Field Trip Guidebook to the Franklin and Hueco Mountains

The 1958 WTGS guidebook paper on the "Geologic history of the Rio Grande near El Paso" by N.M. Bureau of Mines geologist Frank E. Kottlowski offers an excellent summary of available information on both the Late-Cenozoic geology of the El Paso del Norte region, and the geomorphic evolution of the Rio Grande/Bravo fluvial system. His "PHYSIOGRAPHIC SKETCH MAP OF THE LAS CRUCES-EL PASO AREA (**Fig. H4-1**) is the first to illustrate major landscape feature of the Mesilla Basin region in relative detail. Terminal *sinks* (lagunas) of the Rios Casas Grandes and Santa Maria are designated as "lakes" rather than "playas," and the feature named "Lake Guzman" includes Laguna [de] Fresnal in its southern part. The general location of El Barreal is shown in an area referred to by Brand (1937) as the "Franklin Bolson."

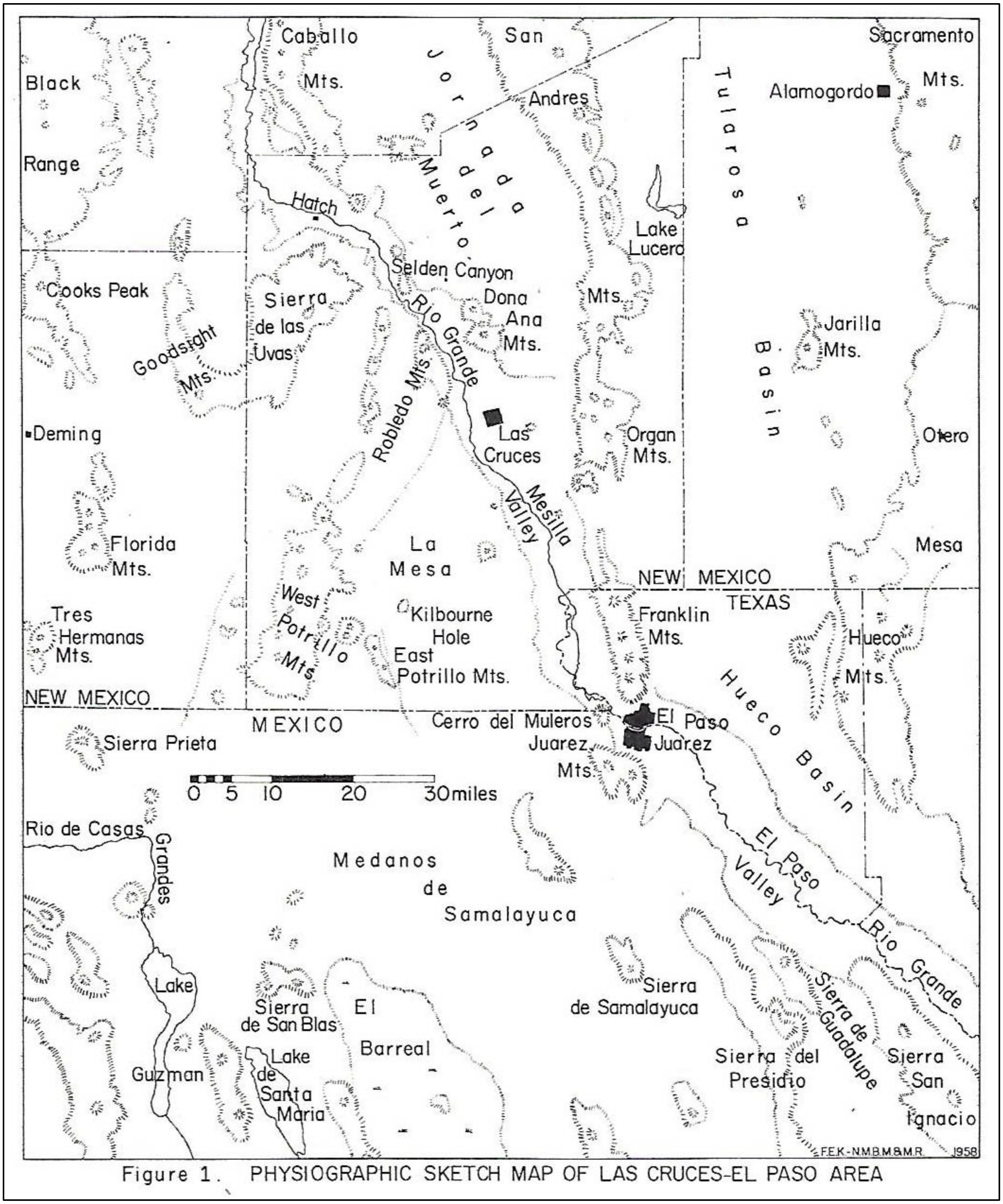


Figure H4-1 (Kottlowski 1958a, Fig. 1; with West Texas Geological Society, Inc. permission)**.** First published map of major landscape features of the south-central New Mexico, western Texas, and north-central Chihuahua region. The general location of El Barreal is shown in an area referred to by Brand (1937) as the "Franklin Bolson."

Excerpt from Kottlowski (1958a, p. 40)—REGIONAL AND HISTORIC SETTING:

. . . [The] middle or late [Early] Pleistocene* Rio Grande meandered across wide bolson valleys from San Luis Valley in southern Colorado down to La Mesa plain northwest of El Paso, and thence probably south-southwestward to evaporate in the 'playa' region of northwestern Chihuahua southwest of El Paso. As noted by Brand (1937) and by Sayre and Livingston (1945), the lake region of north-central Mexico still contains large shallow, seasonable lakes; but these are mere remnants of much larger lakes whose wave-cut cliffs are 30-50 [~100] feet higher than present high-water marks. One of these 'playas,' now a level day flat called el Barreal (fig. 1 [**Fig. H4-1**]), has an approximate north- west-southeast extent of 30 miles and is 10-20 miles wide. When brim-full, the Barreal was a lake containing about 8½ million acre-feet of water, compared with the two million acre-foot capacity of Elephant Butte reservoir, whereas the average annual flow of the Rio Grande at El Paso is only ¾ million acre-feet.

About 40 miles north-northwest of El Paso, near Las Cruces, the Mesilla Valley of the Rio Grande is cut about 400 feet below the high-level surface of Jornada del Muerto to the northeast and that of La Mesa to the southwest; although modified by relatively recent faults, the Jornada surface was once continuous south-southwestward with La Mesa surface. It was on this aggradational desert plain that the Rio Grande began its meanderings near El Paso. Southwest of Las Cruces the sediments atop La Mesa are reported to contain a late [early -middle] Pleistocene* vertebrate fauna, and in places consist of typical rounded foreign-pebble river gravels the cross-bending of which indicates stream flow to the southwest. In contrast, the gravels on and beneath the Jornada surface northeast of Las Cruces are of angular, locally derived pebbles and boulders - contradicting Lee's [1906] suggestion that the Rio Grande (or any large throughgoing river) once flowed down the Jornada del Muerto from San Marcial to Las Cruces. The original course of the Rio Grande from Socorro to Las Cruces was close to the present river valley; south of Hatch the first overflow from the Hot Springs [T or C]-Palomas-Hatch bolson (west and southwest of the Caballo Mountains) was funneled through Selden Canyon, cut into structurally low, faulted zones between Sierra de las Uvas and Robledo Mountains on the southwest, and San Diego Mountain, Selden Hills. and Doña Ana Mountains on the northeast. Debouching from this Selden narrows, the ancestral Rio Grande [ARG] waters followed the lower part of La Mesa-Jornada bolson surface near the present location of Mesilla; at that time (middle or late [late-early] Pleistocene*) the lowest areas of the desert plain were probably south and southwest from Las Cruces, with long alluvial fans extending westward from the Organ Mountains; many of the late Pleistocene/Recent [late Pleistocene] basalt flows and cones (that now dot La Mesa) had not yet been erupted.

**All geologic-time estimates prior to 1969 are based on antiquated geochronologic models that were developed before development of advanced radiometric-dating methods and plate-tectonic concepts.*

H4.2.3. NM Geological Society 16th Annual Field Conference—Southwestern New Mexico II (1965)

An important contribution to Pleistocene geology of northwestern Chihuahua was made by Texas Tech Geology Professor C.C. Reeves (1931-2013) in his NMGS Field Conference Guidebook paper titled: "Pluvial Lake Palomas, northwestern Chihuahua, Mexico; and Pleistocene geologic history of south-central New Mexico (Reeves 1965, p. 199-203):"

[p. 199] Geologic study of the Lake Palomas basin is in its infancy. The writer first visited the area in the spring of 1964. During the past year and a half emphasis has been on general reconnaissance, mapping of abandoned shorelines, and geomorphological studies. This report lacks quantitative detail, but contains several geologic speculations based on legitimate geomorphic evidence which have a direct bearing on the Pleistocene geologic history of south-central New Mexico. Discovery of Lake Palomas and a high-water predecessor verifies the presence of an early Pleistocene pluvial lake surrounding the El Paso area [paleo-Lake Cabeza de Vaca], sheds new light on the mysterious La Mesa rounded gravels (Ruhe, 1962 [*cf.* Strain 1966]), and hopefully resolves the conflicting arguments on the age of the Rio Grande Valley.

Lake Palomas is named for the village of [Puerto]Palomas on the international border 35 miles south of Deming, New Mexico (fig. 1 [**Fig. H4-2**]). Brand (1937) refers to Guzman, Santa Maria, and Tildio playas and the Franklin Bolson, and the term "Guzman Sink" is used by Martin (1963b) for the northwestern part of the Palomas basin. The Lake Palomas basin is not a sink and is today marked by several separated playas such as Guzman and the Franklin Bolson or "El Barreal." Previous terminology is not only misleading but in- correct.

The Lake Palomas basin extends from about the Juarez-Chihuahua highway on the east to about 107°30' W., and from the southern end of the Florida Mountains south to somewhat past Villa Ahumada (fig. 1 [**Fig. H1-10**]). . . .

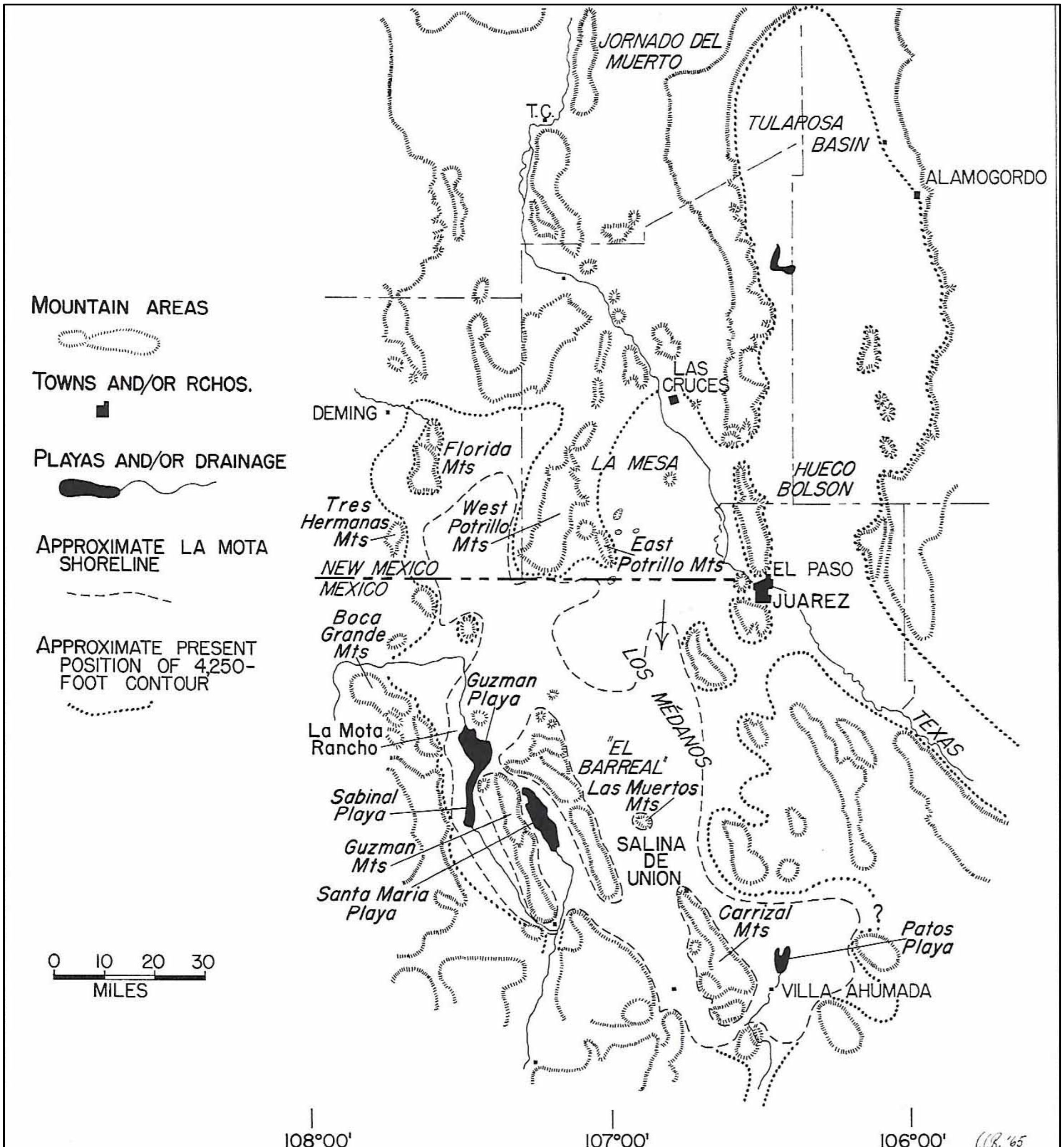


FIGURE 1

Index map of south-central New Mexico and northwestern Chihuahua, Mexico. The south-pointing arrow 20 miles west of El Paso and immediately south of the international border marks the suspected ancestral Rio Grande influent to the Lake Palomas basin. The present position of the 4,250-foot contour marks the approximate *minimum* extent of ancient Lake Cabeza de Vaca.

Figure H4-2 (Reeves 1965, FIG. 1; with NM Geological Society, Inc. permission)**.** Second published map that shows the locations of major landscape features of the south-central New Mexico, western Texas, and north-central Chihuahua region. Lagunas [intermitentes] Guzman, Patos, and Santa Maria are precisely located, but are incorrectly identified as "playas." The general location of 'EL BARREAL' is also noted. The feet amsl estimates of contour lines, however, are 130 to 200 ft (40-60 m) too high, and the highest mapped lacustrine deposits now attributed to "Lake Cabeza de Vaca" are below about 1,235 m (4,050 ft) amsl (Gustavson 1991a).

H4.2.4. Border Stratigraphy Symposium of the American Association for the Advancement of Science-Southwestern and Rocky Mountain Division (El Paso, TX, April 1968)

Preface to N.M. Bureau of Mines & Mineral Resource Circular 104
Frank E. Kottlowski and David V. LeMone, Editors

[p. iv] The Border Stratigraphy Symposium was held at the University of Texas in El Paso, April 30, 1968, as part of the Forty-Fourth Annual Meeting of the Southwestern and Rocky Mountain Division of the American Association for the Advancement of Science. Interest in the data presented, particularly by geologists unable to attend the symposium technical session, led to requests for publication of the papers.

Some of the material has been published in abstracts and in part in other journals, particularly McGlasson's, LeMone's, and Kottlowski's data. Compilation of descriptions of most of the rock units in the El Paso border region in a single volume should aid future geologic work in this area. Descriptions of the Cenozoic strata, the surface and near-surface rocks on which the cities of the border region are built, should be of much aid in the urban development of El Paso, Las Cruces, and Juárez.

Hawley, J.W., Kottlowski, F.E., Seager, W.R., King, W.E., Strain, W.S. and LeMone, D.V., 1969, The Santa Fe Group in the south-central New Mexico border region: N.M. Bureau of Mines and Mineral Resources, Circular 104:

[p. 52] The Santa Fe Group in the south-central New Mexico border region is a complex sequence of piedmont-slope alluvium; playa [barreal/barrial], lacustrine, and fluvial deposits; and some basaltic volcanics preserved in structural basins within and adjacent to the Rio Grande depression [**Fig. H4-3**].

The upper limit of the group is the surface of the youngest basin fill predating initiation of the Rio Grande Valley entrenchment. The lower limit is placed above volcanic and associated sedimentary rocks of Oligocene- early(?) Miocene age that are well exposed in the Caballo [Reservoir]-[Fort] Selden area. Studies of vertebrate and invertebrate faunas, determination of the potassium-argon age of interbedded basalt, and correlation of volcanic ash lenses have established a general Miocene to mid-Pleistocene age for the Santa Fe Group in the border region [**H5-4**]. Early stages of intermontane basin filling occurred in a closed-basin (classic bolson) environment, while later stages were marked by coalescence of basin floors and development of a regional system of through-drainage. Thus, Santa Fe group deposition in the border region corresponds with Bryan's [1938] idealized concept of basin filling in the type Santa Fe region to the north.

Important economic resources in the Santa Fe Group include ground water, sand, gravel, clay, and caliche.

Figure H4-3. The first published map that shows the surface distribution of major geologic units and landscape features of the New Mexico-Texas-Chihuahua "BORDER REGION" (*cf.* Woodward et al. 1978). The solid line with barbs shows the approximate outer limit of basin-floor areas where deposits of the Ancestral Rio Grande (ARG) "FLUVIAL FACIES" are the dominant component of the Upper Santa Fe Group (SFG). Dashed lines with barbs outline endorheic basin areas that were the sites of pluvial Lakes Otero (Tularosa) and Palomas (El Barrial) during Late Pleistocene glacial-pluvial stages (*cf.* **Fig. H4-10**; Reeves 1965, FIG. 1). "EL BARRIAL" (rather than "EL BARREAL") is the spelling recommended by Ordóñez (1936; **H4.1.1**). Major geochronologic and lithostratigraphic units, and lithofacies-distribution patterns in Santa Fe Group basin-fill are shown on **Figure H4-4**, which is the first schematic diagram of this type prepared for the "BORDER REGION."

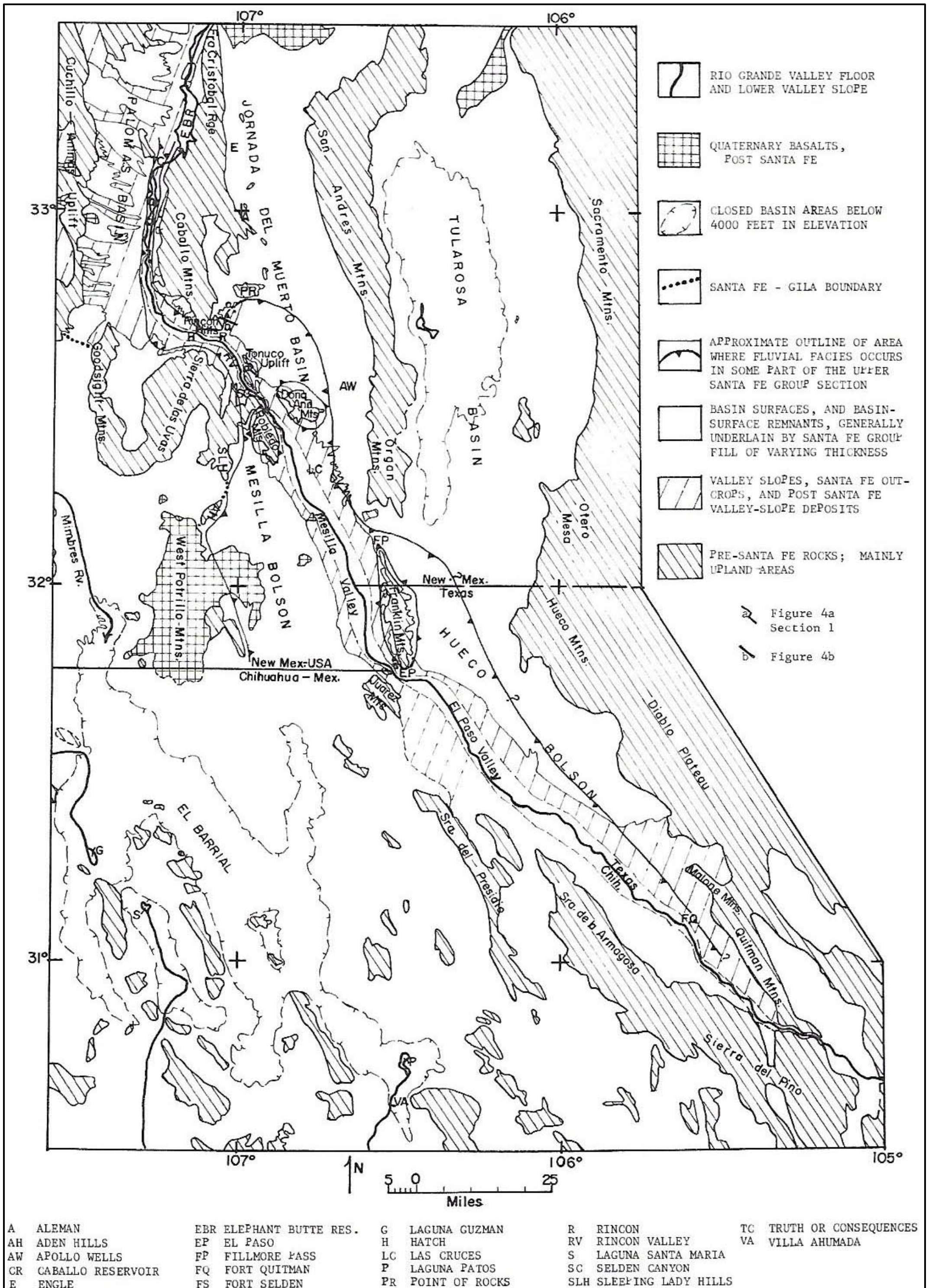


Figure 1

INDEX MAP OF THE BORDER REGION, NEW MEXICO, TEXAS, AND CHIHUAHUA SHOWING OUTCROP AREA OF THE SANTA FE GROUP

Figure H4-3 (Hawley et al. 1969b, Fig. 1)**.** First published map that shows the surface distribution of major geologic units and landscape features of the New Mexico-Texas-Chihuahua "BORDER REGION."

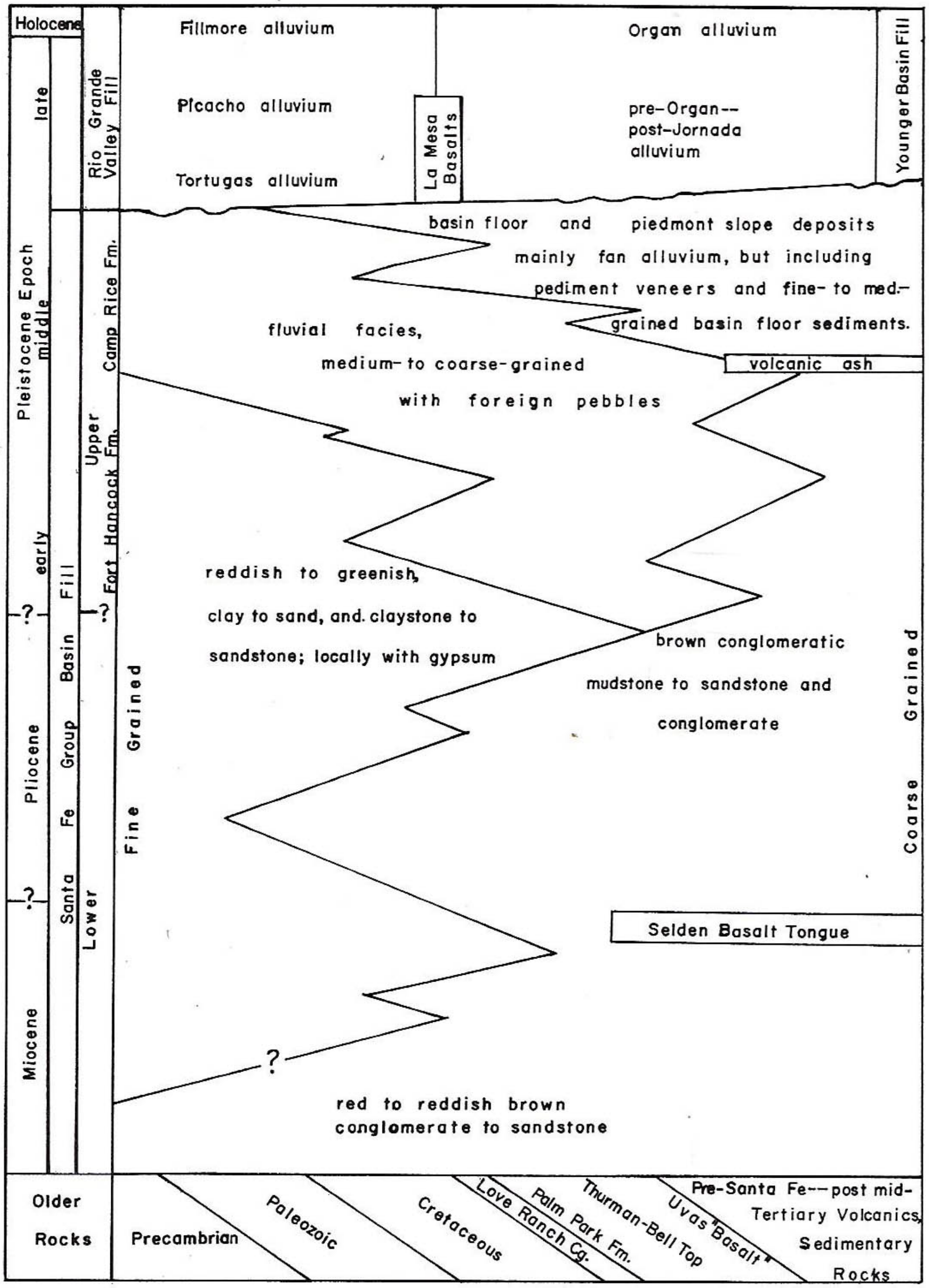


Figure 5

DIAGRAMATIC SUMMARY OF SANTA FE GROUP STRATIGRAPHIC TERMINOLOGY AND GENERAL LITHOFACIES DISTRIBUTION IN THE BORDER REGION

(Facies boundaries may be gradational or sharp erosional contacts)

Figure H4-4 (Hawley et al. 1969b, Fig. 5)**.** First published schematic diagram of lithostratigraphic and geochonologic units, and lithofacies distribution in Santa Fe Group basin-fill in the south-central New Mexico "BORDER REGION."

Hawley, J.W., and Kottlowski, F.E., 1969, Quaternary Geology of the south-central New Mexico border region: N.M. Bureau of Mines and Mineral Resources, Circular 104:

[p. 89] In early to mid-Quaternary time, the intermontane basins of the south-central New Mexico border region were still internally drained [endorheic]. Environments of deposition ranged from alluvial-fan piedmont slopes to broad basin floors that were often sites of lacustrine sedimentation. In later stages of basin filling, local upland sediment sources were supplemented by the ancestral upper Rio Grande, which extended into the region by early Kansan [Pleistocene] time. Studies of vertebrate and invertebrate faunas and correlation of volcanic ash lenses indicate that basin filling in extensive areas adjacent to the Rio Grande Valley culminated in late Kansan to early Illinoian [early middle-Pleistocene] time. The complex of late Cenozoic basin fills predating Rio Grande Valley entrenchment comprises the Santa Fe Group. The Jornada and La Mesa geomorphic surfaces cap the Santa Fe sequence.

Cyclic entrenchment of the Rio Grande was initiated after [early middle] mid-Pleistocene integration of the lower and upper segments of the ancestral Rio Grande. Subsequently, four major, climatically controlled cycles of valley cutting have taken place. Aggradation of basin surfaces has continued in broad areas still not integrated with Rio Grande drainage. Parts of basin floors were occupied by large lakes during late Pleistocene pluvials [pluvial lakes Otero and Palomas]. Significant structural deformation of basin- and valley-fill deposits and extrusion of basalts and maare formation in Mesilla bolson represent continuation of deep-seated disturbances in Quaternary time.

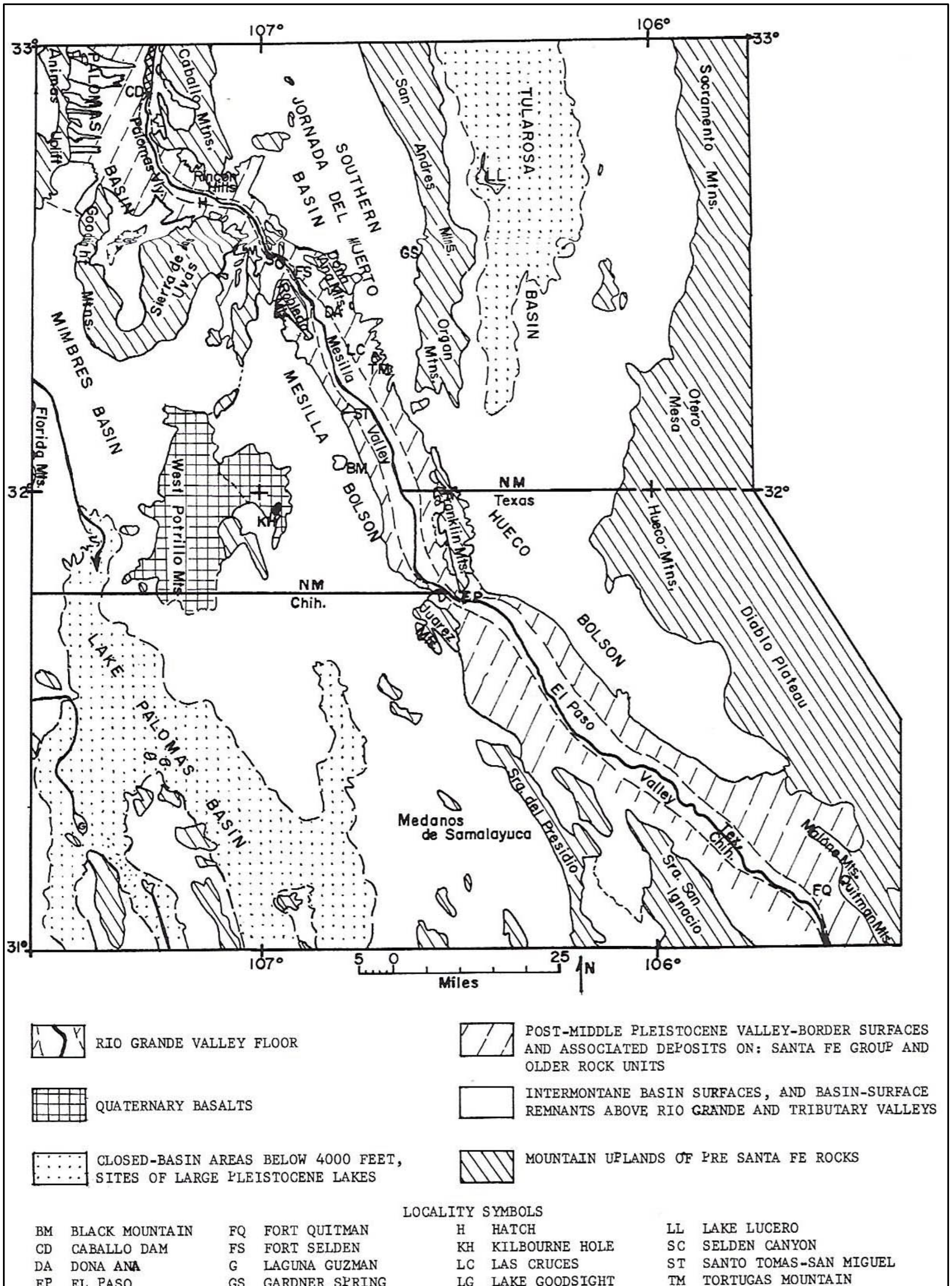


Figure 1

INDEX MAP OF THE BORDER REGION, SHOWING BASIN AND VALLEY AREAS THAT HAVE BEEN SITES OF SIGNIFICANT AMOUNTS OF EROSION AND DEPOSITION

Figure H4-5 (Hawley and Kottlowski 1969, Fig. 1)**.** First published map that shows the distribution of major physiographic features of the New Mexico-Texas-Chihuahua "BORDER REGION."

H4.2.5. New Mexico Geological Society 20th Annual Field Conference in the New Mexico—Chihuahua Border Region (October 1969)

The following comments from the two co-chairman and two co-editors illustrate the amount of work and types of institutions involved in the October 1969 New Mexico—Chihuahua Border Region Field Conference that was organized by the New Mexico Geological Society, Inc.:

SOME COMMENTS BY THE GENERAL CHAIRMEN (Cordoba et al. 1969, p. iv)

Whether it will become apparent or not in the next three Days, this Field Conference has been in preparation for over two years. Many problems not common to field trips in the United States have had to be solved. The cooperation of the Instituto de Geología, Petróleos Méxicanos and Secretaria de Recursos Hidráulicos, as well as the aid of many individual Mexicans, has been invaluable.

The Conference will be beneficial to geologists of both nations in the understanding of the geology of the Border Region. It is our hope also that many lasting friendships will be fostered. . .

If the coverage of some aspects of the geology is less than adequate, remember that Chihuahua is relatively virgin territory, and little is known about some parts of this beautiful region. . . .

Bienvenidos á Chihuahua y feliz viaje!

Bill (William E.) King, Chairman, Earth Sciences Department, NMSU

John Hawley, Soil Survey Investigations, U.S Soil Conservation Service

SOME OBSERVATIONS BY A CO-EDITOR (Cordoba et al. 1969, p. v)

Appropriately enough, this Guidebook for the 20th Field Conference is one of the most comprehensive yet published by the New Mexico Geological Society, and, although the articles cover a large segment of the Border Region of northern Mexico and the southwestern United States, the entire trip is in Chihuahua, our first conference entirely outside the United States! Always a large state filled with big enterprising people Chihuahua has produced a great part of the mineral wealth of Mexico and has nurtured some of Mexico's most dedicated revolutionaries in that country's fight for freedom. The political stability and financial acumen of this fast-growing Republic allow one now to tum the coin around and call Mexico today a veritable "Colossus of the South.". . ..

Quién no se atrevé, no pasa el mar.

Sherman A. Wengerd, Department of Geology, UNM

Co-Editor (United States)

A CO-EDITOR'S LETTER FROM MEXICO (Cordoba et al. 1969, p. v)

September 1969

Sr. John W. Hawley

Presidente de la Sociedad Geológica de Nuevo México

Presente.

Estimado John:

Par fin hemos terminado la edición del vigésimo Libreto Guía de la Conferencia Anual de Campo. Creeme que la labor de editor en un trabajo de esta envergadura no es nada sencilla y en ocasiones es cansada, pero puede llegar a ser agradable, como en este caso, cuando se ha tenido una colaboración, tan amplia de toda la Mesa Di-rectiva de la Sociedad Geológica de Nuevo México. Creo que la Sociedad puede, una vez mas, estar orgullosa de la calidad de este libreto Guía, no sólo par las trabajos que contiene, sino por su presentación y principalmente por su significado.

Los geólogos méxicanos que hemos colaborado en la edición, preparación y en la presentación de trabajos geológicos en este Libreto Guía, estamos orgullosos de la labor realizada par la Sociedad Geolóogica de Nuevo México, al lograr la integración de una serie de estudios cientificos en la zona fronteriza. Este esfuerzo debe servir coma ejemplo para otras organizaciones, tanto mexicanas como norteamericanas.

Estoy seguro de que una vez más, nuestra Conferencia de Campo será un éxito.

Tu amigo,

Diego A Córdoba, Instituto de Geología, UAM

Co-Editor (México)

H4.2.5a. Hawley (1969b) Notes on the Geomorphology and Late Cenozoic Geology of Northwestern Chihuahua: NM Geological Society Guidebook 20:

[p. 131] The geomorphology and late Cenozoic geology of a 71,500 square kilometer (27,600 square mile) area of northwestern Chihuahua and adjacent parts of Sonora, New Mexico and Texas are discussed. Emphasis is on description of three major physiographic units: The Sierra Madre Occidentál, and two subsections of Mexican Basin and Range section. Formal names are proposed for the latter two subdivisions [**Figs. H4-6a** and **6b**, and **Tbl. H4-1**]. The larger unit is characterized by broad desert basins and isolated ranges of southern and eastern Chihuahua and is designated the Bolson Subsection. The higher unit, designated the Babicora-Bustillos subsection, occupies a region that is transitional, in terms of terrain and geologic features, between the Bolson unit and the Sierra Madre. Physiographic boundaries were selected on the basis of study of recently-compiled 1:250,000 scale topographic maps and some field work. Control in the northern part of the area was also provided by photos taken from Apollo and Gemini spacecraft.

Studies of basin- and valley-fill geology and geomorphology in the New Mexico-Chihuahua border region since 1950 have resulted in considerable [development] of basic concepts of the late Cenozoic landscape evolution [that were] developed notably by Hill, Lee, Baker, Bryan and P.B. King. The fundamental concept of middle to late Tertiary and Quaternary development and filling of intermontane basins, followed by local establishment of the entrenched Rio Grande Valley system during middle to late Pleistocene time, appears to be generally applicable to the Basin and Range area under discussion. The important influence of a cyclic climatic change during the Quaternary period on landscape evolution is also recognized.

Figures H4-5a and **5b,** and **Table H4-1 (**Hawley 1969b, Fig.1 and Tbl. 1) illustrate the first detailed classification of “geomorphic features of northwestern Chihuahua . . . .” This information was developed in 1968 and 1969 as part of binational study of regional soil-geomorphic relationships, and soil and groundwater resources in northwestern Chihuahua. Work was co-sponsored by the Secretaria de Recursos Hidráulicos (SRH), and the UDSA-Soil Conservation Service (SCS-now Natural Resources Conservation Service [NRCS]; **Part H4.2. 5**). As illustrated in **Figure H4-7**, results of this early binational collaboration were used by Professor Reyes Cortés of the Universidad Autónoma de Chihuahua in the 1992 edition of his map of the “Provincias y Subprovincias Fisiográficas del Estado Chihuahua [Ilustración 7].”

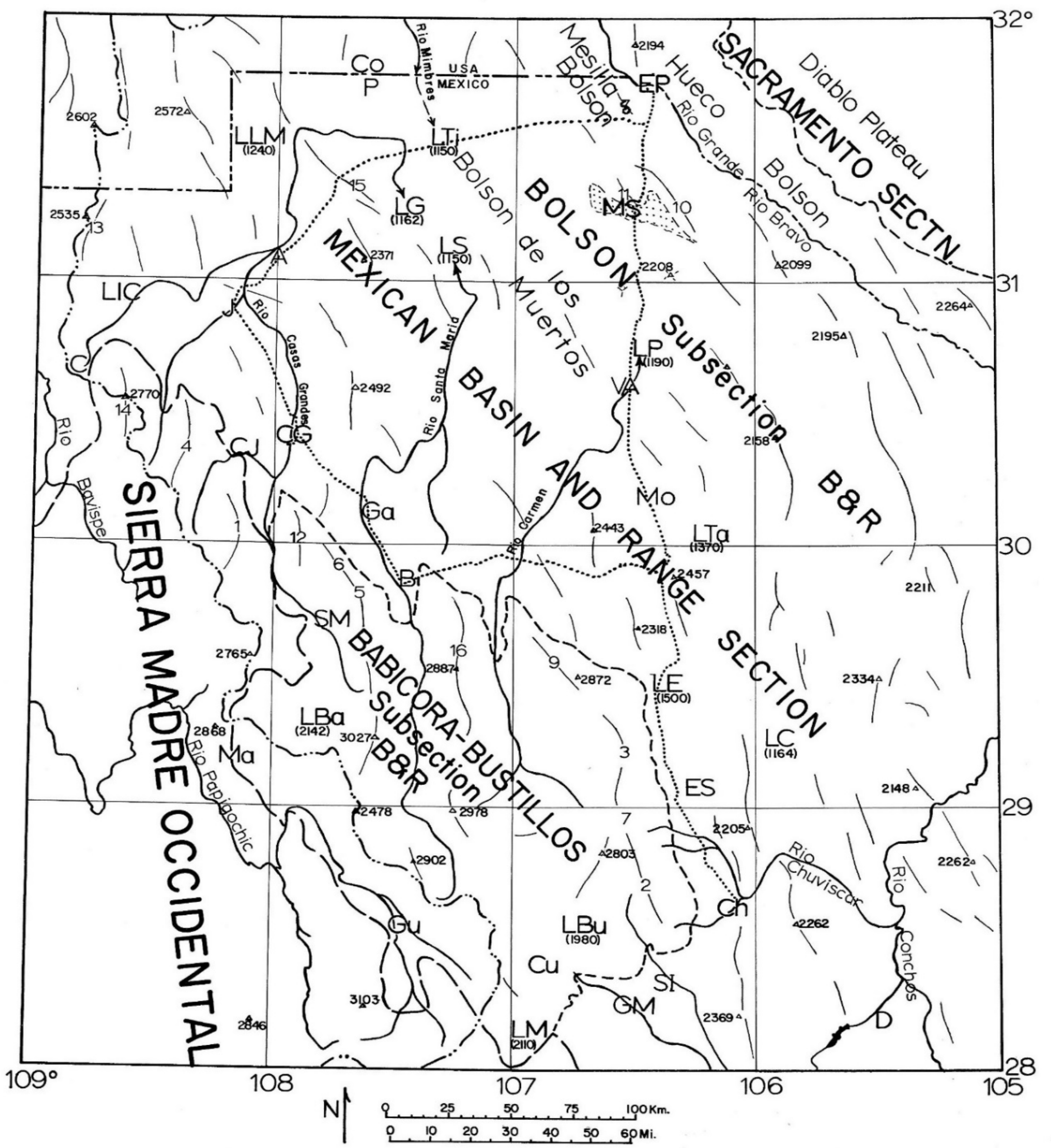


FIGURE 1. INDEX MAP—GEOMORPHIC FEATURES OF NORTHWESTERN CHIHUAHUA AND ADJACENT AREA
(Explanation on facing page)

Figure H4-6a (Hawley 1969b, FIG. 1; with NM Geological Society, Inc. permission)**.** The dotted line shows the loccation of the 1969 NMGS Field Conference "Tour Route (*cf.* **Fig. H4-8**)." See **Figure H4-6b** for an explanation on acronyms and symbols. The "Mexican Basin and Range Section" coincides with the "Basin and Range-Mexican Highland section" in **Fig. H1-4.**

EXPLANATION

Localities

- A La Ascensión
- B Buenaventura
- C Carretas Pass
- Ch Chihuahua City
- Co Columbus, N. M.
- Cu Cuauhtémoc
- CG Nuevo Casas Grandes
- CJ Colonia Juárez
- D Delicias
- EP El Paso-Juarez
- ES El Sauz
- Ga Galeana
- Gu Guerro
- GM Gran Morelos
- J Janos
- LlC Llano de Carretas
- Ma Madera
- Mo Moctezuma
- MS Médanos de Samalayuca
- P Las Palomas
- SI Santa Isabel
- SM San Miguel de Babicora
- VA Villa Ahumada

Mountain Ranges

- 1 Sierra de La Breña
- 2 Sierra de La Calera
- 3 Sierra de La Compana
- 4 Sierra de Carcay
- 5 Sierra de La Catarina
- 6 Sierra del Cristo
- 7 Sierra Cumbres de Majalca
- 8 Sierra de Juárez
- 9 Sierra del Nido
- 10 Sierra del Presidio
- 11 Sierra de La Samalayuca
- 12 Sierra de San Joaquin
- 13 Sierra de San Luis
- 14 Sierra de San Pedro
- 15 Sierra de Santa Rita
- 16 Sierra de Las Tunas

Lake Plains
(elevation in meters)

- LBa Laguna Babicora
- LBu Laguna Bustillos
- LC Laguna del Cuervo
- LE Laguna Encinillas
- LG Laguna de Guzman
- LM Laguna de Los Mexicanos
- LLM Laguna de Los Moscos
- LP Laguna de Los Patos
- LS Laguna de Santa Maria
- LTa Laguna Tarabillas
- LTi Laguna Tildio

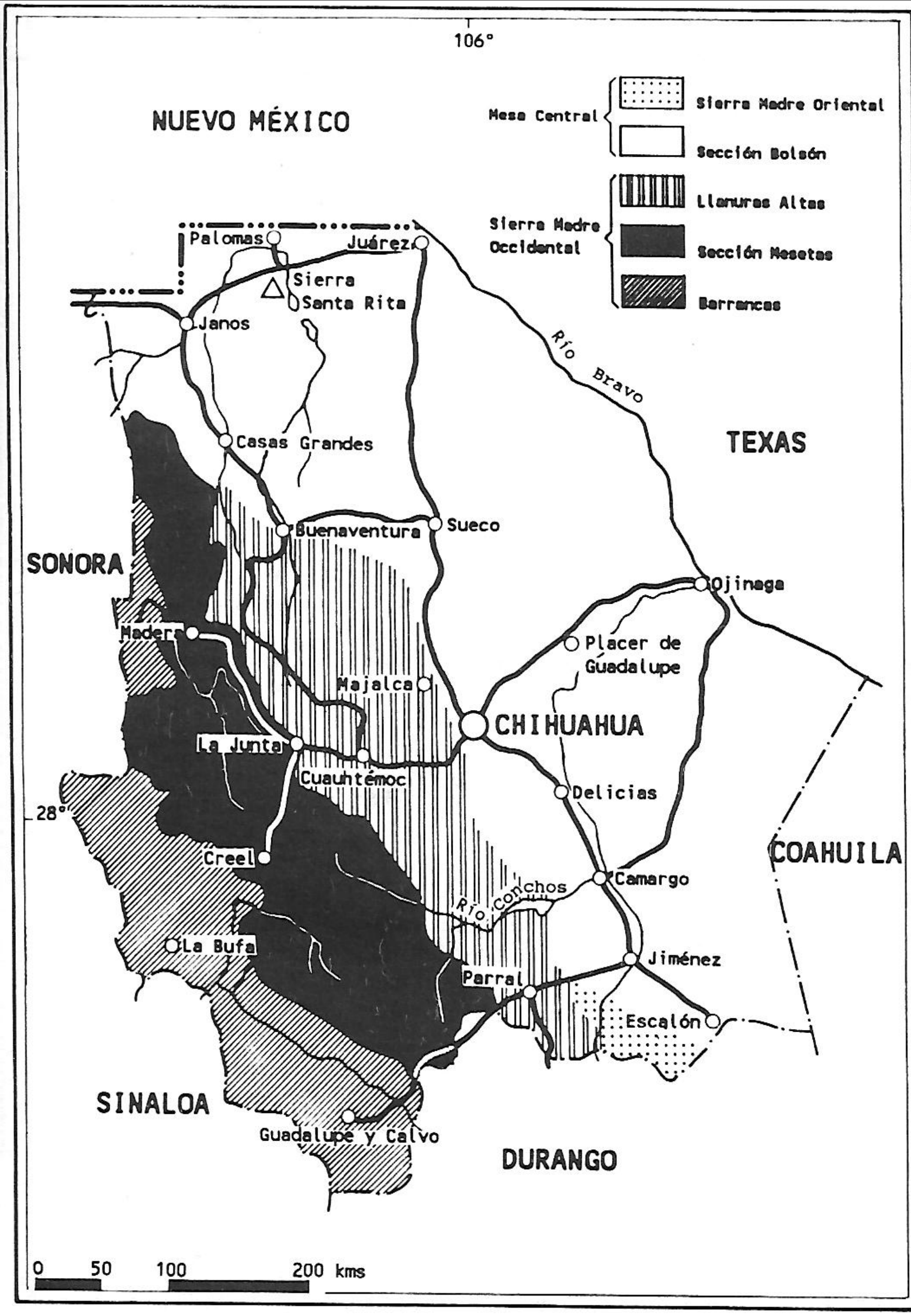
- 12 — Ranges Designated in Figure 1 and Text
- Other Ranges
- △ 2868 — Elevations of Major Peaks in Meters
- Tour Route
- Continental Divide
- Sierra Madre/Basin and Province Boundary
- Basin and Range Section Boundaries

Figure H4-6b. Explanation of names and symbols on **Figure H4-5a** (facsimile copy of the explanation for FIG. 1 in Hawley 1969b; with NM Geological Society, Inc. permission).

Table H4-1. Facsimile copy of Hawley 1969b, TBL. 1; with NM Geological Society, Inc. permission**.** Regional geomorphic "CHARACTERISTICS OF [Major] PHYSIOGRAPHIC UNITS" in Northwestern Chihuahua and Adjacent Areas (105° to 109° W. Longitude, and 28° to 32° N. Latitude [**Figs. H4-6a, b**]).

TABLE 1. CHARACTERISTICS OF PHYSIOGRAPHIC UNITS IN NORTHWESTERN CHIHUAHUA AND ADJACENT AREAS (107° to 109° W. Longitude, 28° to 32° N. Latitude)

PHYSIOGRAPHIC UNIT	SIERRA MADRE OCCIDENTAL	MEXICAN BASIN AND RANGE SECTION BOLSON SUBSECTION	MEXICAN BASIN AND RANGE SECTION BABICORA-BUSTILLOS
Total Area (Km^2)	31,000	107,500	25,000
Area of Internal Drainage/Total Area (%)		70	29
Area of Ranges/Total Area (%)		19	37
Percentage of Ranges Composed of:			
Mainly carbonate sedimentary rocks	<0.2	35	<0.3
Mainly rhyolitic and andesitic volcanics	>99.6	61	>99.7
Mainly igneous intrusive rocks	<0.2	<2	
Mainly basalt (Quaternary?)		<3	
Percentage of Basin Areas in Active Dunes		>0.5	
Percentage of Basin Areas in Playas (Barrials)		2.5	<2
Percentage of Total Area Below 1220m. (4000 ft.)	9	15	0
Percentage of Total Area Above 1830m. (6000 ft.)	54	2.4	97.5
Percentage of Total Area Above 2440m. (8000 ft.)	5.5	<0.02	3.5
Highest Elevation in Meters (Feet)	3103(10,180)	2602(8532)	2978(9774)
Lowest Elevation			
Basin Floor		1150±(3770±)	1980±(6490±)
River Valley floor	550(1800)	850(2785)	1600(5250)
Range in Mean Annual Precipitation (mm)	<400->1100	<150->400	<300->600
Range in Mean Annual Temperature (°C)	<10-20	15-20	10-18
Range in Aridity Index ($I = \frac{P}{T+10}$)	15-50	<5->15	10-30



Hawley, 1969. (Adaptado).

PROVINCIAS Y SUBPROVINCIAS FISIOGRÁFICAS DEL ESTADO DE CHIHUAHUA

Figure H4-7 (Reyes Córtes, 1992, Ilustración 7)**.** Adapted in part from Hawley, 1969b (**Fig. H4-5a**).

H4.2.5b. Photointerpretive Mapping from Space Photographs of Quaternary Geomorphic Features and Soil Associations in Northern Chihuahua

Figure H4-8 (Morrison 1969, FIG. 3) is the first systematic space-photo-interpretive map of a large terrestrial area to be published (Explanation on **Tbl. H4-2**). This information was developed in 1968 and 1969 as part of collaborative, binational study of regional soil-geomorphic relationships, and soil and groundwater resources in the northwestern Chihuahua region. As noted in **Figure H4-9**, Morrison's pioneering investigation was part of a collaborative effort by the Secretaria de Recursos Hidráulicos (SRH-JICR, Dirección de Agrología), U. S. Soil Conservation Service (SCS-Soil Survey Investigations Div.), and the U.S. Geological Survey (Geologic Div.).

Morrison, R.B. (1969) Photointerpretive Mapping from Space Photographs of Quaternary Geomorphic feature and Soil Associations in northern Chihuahua, and Adjoining New Mexico and Texas: N.M. Geological Society Guidebook 20:

[p. 116] Space photographs of the earth cover large regions under instantaneous, uniform lighting conditions. The better ones have many advantages over air-photo mosaics in providing synoptic views of both strongly and subtly imaged geologic, soil, and geomorphic features, without distracting detail. To be most useful for photointerpretive mapping of such features, space photographs should have: (1) ground resolution of at least 200 ft, and preferably 100 ft or better; (2) color or multi- spectral imagery, with high discrimination in the yellow-red region of the spectrum and also (3) vertical, stereoscopic, and continuous cloud-free coverage over the region to be mapped.

The accompanying maps of Quaternary geomorphic features and soil associations are the first systematic space-photo- interpretive maps of a large terrestrial area to be published. Geomorphic features are mapped both according to type, which requires relatively little interpretation, and as to age, which requires considerably more interpretation (*cf.* **Fig. H4-8** and **Tbl. H4-2**).

The soil-association map is a pedologic, not an engineering soils map. Its small scale generally precludes the differentiation of individual soil series or even single "great groups" of soils; commonly it is necessary to map composites of several great groups, called soil associations, that occur together in a given kind of terrain unit. In selecting the map units, primary emphasis is placed on features that can be determined directly from the space photos, namely (1) color of the ground surface, or where possible, the soil surface, and (2) topographic-geomorphic relations. The photointerpreter who understands the interrelations of soils and various kinds and ages of landforms under different climatic, geologic, and vegetation conditions, can interpret the soils that typify a given terrain unit. Some ground data are necessary to control the interpretation of soil features such as the character of the B and, if present, Cca horizons; these data were obtained from unpublished soil-survey reports of a few areas and from field traverses by the author.

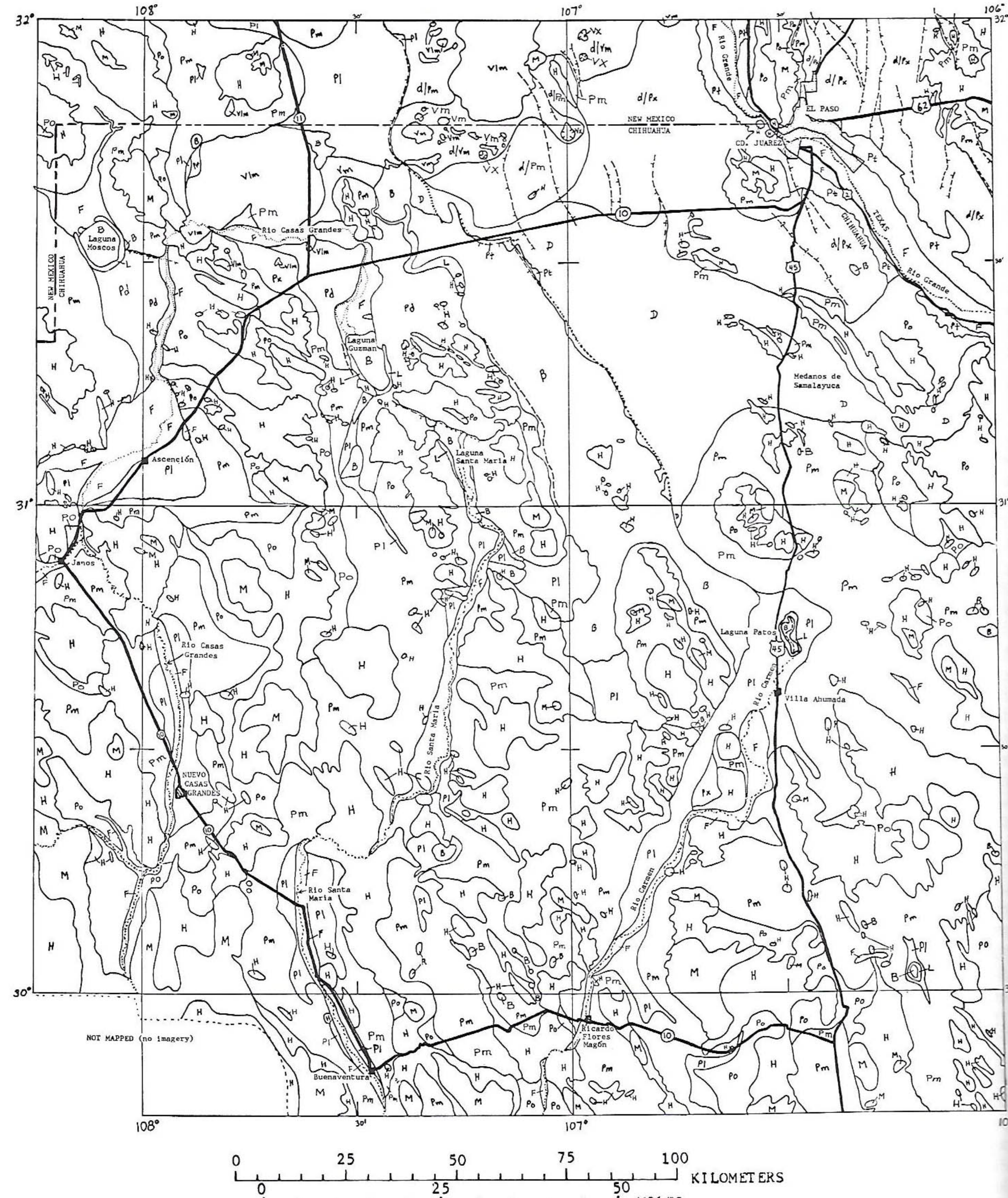


FIGURE 3.
Quaternary geomorphic features of northern Chihuahua and adjoining New Mexico and Texas map. See table 2 for explanation of map.

Figure H4-8. Facsimile copy of Morrison 1969, FIG. 3; with NM Geological Society, Inc. permission. Explanation on **Table H4-2**. Solid black line shows the location of the 1969 NMGS Field Conference "Tour Route (**Fig. 4-6a**)."

Table H4-2. Facsimile copy of EXPLANATION of FIGURE 3 in Morrison 1969 (**Fig. H4-8**; with NM Geological Society, Inc. permission).

EXPLANATION

AGE (predominant)	ALLUVIAL UNITS		LACUSTRINE UNITS	EOLIAN UNIT	VOLCANIC UNITS
Holocene	[F] *Flood plains* (and locally, very young terraces) of rivers and major washes, underlain by alluvial silt and sand, with gravel and clay locally, of Holocene age. Level to gently undulating; local relief < 20 ft.				
Late Quaternary (Wisconsinan & Holocene)	[Pl] Young river terraces and lowermost piedmont toe slopes and flats, underlain by alluvial sand, silt, and gravel of late Quaternary age. Level to gently undulating.		[B] Barrials ("playas" of customary but incorrect US usage). Level lake floors, usually dry, underlain by lacustrine silt and clay, with sand in places, mostly of late Quaternary age, but locally (where exposed by deflation) of middle Quaternary age.	[D] Sand dunes, mostly of late Quaternary age. Alluvium and lacustrine sediments of late and middle Quaternary age locally underlie depressions. Local relief generally is less than 50 ft, but attains 550 ft, (170 m) in Medanos de Samalayuca.	[Vl] Basaltic lava flow of late Quaternary age.
Late & middle Quaternary	[Pt] Highly dissected areas below Px plains, chiefly bordering the Rio Grande, in alluvium and lacustrine sediments of middle and early Quaternary age, with local terrace-gravel veneers of Illinoian and Wisconsinan age. Local relief 150 to 350 ft.	[Px] [d/Px] Alluvial plains, level to gently undulating, of middle Quaternary age (antedating the entrenchment of the Rio Grande), in places veneered with alluvium and/or eolian sand of late Quaternary age. (d/Px symbol indicates areas of eolian sand veneer.)	[L] Shore zones of pluvial lakes, Underlain by lacustrine sand and gravel of late (and locally middle) Quaternary age. In places includes eolian sand. On west side of Laguna Guzman includes carbonate spring deposits.		[Vlm] Basaltic lava flows and cinder cones of late and middle Quaternary age. Extensive thin veneer of eolian sand and sandy alluvium.
Middle Quaternary	[Pm] [d/Pm] Piedmont alluvial slopes. Principal upland surfaces are veneered by alluvial gravel of middle Quaternary age. They generally are dissected 10 to rarely more than 50 ft into alluvial gravel of middle and/ or early Pleistocene (locally perhaps late Pliocene) age. (Symbol d/Pm denotes areas of coppice sand-dune veneer.)	[Pd] Old deltaic plains of Rio Casas Grandes. Nearly level, underlain by alluvial sand and gravel, probably mainly of late-middle Pleistocene age, with local late Quaternary veneers.			[Vm] [d/Vm] Basaltic lava flows and cinder cones of middle Quaternary age. Symbol d/Vm denotes thick veneer of eolian sand. [Vx] Maare (explosion craters), probably of middle Quaternary age.
Early and/or middle Quaternary	[Po] Older piedmont alluvial slopes. Underlain by alluvial gravel of early-middle and/or early Pleistocene age. Deeply dissected (50 to > 100 ft.).				
Pre-Quaternary	ROCKLAND AREAS [H] Hilly, low-mountain, and other rockland areas, with local relief less than 1,000 ft (300 m). Bedrock is widely exposed or is within a few feet of the surface in most places.			[M] Mountains with local relief greater than 1,000 ft (300 m). Bedrock is widely exposed.	

FAULTS

— — — —?— . . . . .

Inferred fault, probably of middle Quaternary age (no faults of late Quaternary age have been identified in the map area). Dotted where concealed by younger sediment; queried where problematic. Tick marks indicate down-dropped side.

FORMA 110 - 1

SECRETARIA
DE
RECURSOS HIDRAULICOS

JEFATURA DE IRRIGACION Y CONTROL DE RIOS
DIRECCION DE AGROLOGIA

OFICIO NUM. 6.15.1 362

ASUNTO: Verificación geomorfológica en Chihuahua.

México, D.F., Septiembre 5, 1969.

GEOL. JOHN W. HAWLEY
SOIL SURVEY INVESTIGATIONS
UNIVERSITY PARK, NEW MEXICO 88001
U.S.A.

Adjunto tengo el gusto de enviar a usted una copia del informe rendido por los Ings. José M. Estrada y Rubén Rodríguez G. del viaje de estudio que realizó el personal técnico de esta Dirección en la parte noroeste del Estado de Chihuahua, en compañía de usted y del Dr. Roger B. Morrison, en donde se han obtenido conocimientos muy interesantes por ambas partes en lo que respecta al estudio de suelos y la geomorfología y sus relaciones con el Cenozoico.

Atentamente.
SUFRAGIO EFECTIVO. NO REELECCION.
EL DIRECTOR

ING. GAUDENCIO FLORES MATA.

Anexo.

c.c.p. C. Ingeniero en Jefe de Irrigación y Control de Ríos.
c.c.p. C. Segundo Ingeniero en Jefe.
c.c.p. Ofna. de Publicaciones.- Dirección de Agrología.

GFM/vra.

T. G. N.—6174-68

Figure H4-9. Facsimile copy of letter of 9/5/1969 from Ing. Gaudencio Flores Mata, Dirección de Agrología, SRH-Jefatura de Irrigación y Control de Ríos to John Hawley concerning collaborative SRH-USDA-SCS, USGS Field investigations in northwestern Chihuahua (*cf.* Hawley 1969b, Morrison 1969).

H4.2.5c. Pluvial Lake Palomas and Bolson de los Muertos (Reeves 1969, p. 143-154)

Based on additional reconnaissance mapping, C.C. Reeves (1969) was able to describe pluvial-Lake Palomas in more detail, but high-quality topographic information on the region would still not be available for another 40 years. In one short sentence, Reeves also introduced the name–Bolson de los Muertos for "a large basin complex" that includes "El Barreal"* (**Figs. H4-10** and **H4-11**).

> Pluvial Lake Palomas, which once inundated approximately 3,000 square miles of Chihuahua, Mexico during [mid- to late-Pleistocene] time, was confined mainly to Chihuahua by incisement of La Mesa [present MeB West Mesa] by the Rio Grande. Measured sections and field traverses show the Camp Rice Formation [**Fig. H1-10**] continuous from La Mesa into Chihuahua, but outcrops of older fluvial [Ancestral Rio Grande-ARG] and lacustrine units are unknown. Evidence of Lake Palomas such as abandoned beaches, spits, wave-cut escarpments, multiple shorelines and lacustrine deposits, is widespread, the highest well-established Wisconsin [~29 to 12 ka] being about ±4,018 feet [~1210 m/3,978 ft, according to Castiglia and Faucett, 2006].
>
> Gravity profiles and regional geology indicate that the eastern [and western] part of the Lake Palomas basin is of tectonic origin, . . . Regional geology also indicates that the discovery of commercial continental salines are especially promising in the lacustrine sections [Reeves 1969, p. 143].
>
> **Laguna de Palomas and El Barreal occur along the axis of the floor of a large basin complex, termed* Bolson de Los Muertos *in this report, . . . [Reeves 1969, p. 147].*

Reeves took the name "Bolson de los Muertos (BdLM)" "from Sierra de los Muertos, a small outlier of Lower Cretaceous sedimentary and Tertiary igneous-intrusive rocks in the south-central part of El Barreal" (**Figs. H1-10**, **H4-9**). That latter comprises the large basin-floor depression that has the generic-name "ALCALI" on the 1:250,000-scale maps that predate 1965 (*cf.* INEGI 1983c and 1995, CONAGUA 2020, Fig. 2). Reeves's work in the area, moreover, was primarily of a reconnaissance nature, much of which involved overflights with a light plane in the mid-1960s. With the exception of some preliminary ground-based gravimeter surveys, he made no further effort to define the BdLM's boundaries. Most of his conceptual BdLM is in the endorheic Zona Hidrogeológica de Conejos Médanos (ZHGCM), with the northern half of the latter including the Acuífero Conejos-Médanos, both of which are delineated on the 2012 Instituto Nacional de Estadística, Geografía e Informática (INEGI) map (**Figs. H1-1**, **H1-10**, and **H1-11**; *cf.* https://www.inegi.org.mx/inegi/contacto.html).

In English-language reports, the names "Los Muertos Basin" and "Bolson de los Muertos" continue to be used in reference to a structural-basin complex at the southwestern end of the RG rift province (e.g., **Figs. H1-1** and **H1-2**; Chapin and Seager 1975, Woodward et al. 1978, and Seager and Morgan 1979). On the other hand, neither term is mentioned in any publication on the water resources of the State of Chihuahua (e.g., INEGI 1999 and 2012, and CONAGUA 2020). The original map of the Rio Grande rift by C.E. Chapin (1971, Fig. 2), which is included here as **Figure H4-11** illustrates how the term "Los Muertos Basin" was initially used in a continental-rift zone context (**H1-2**).

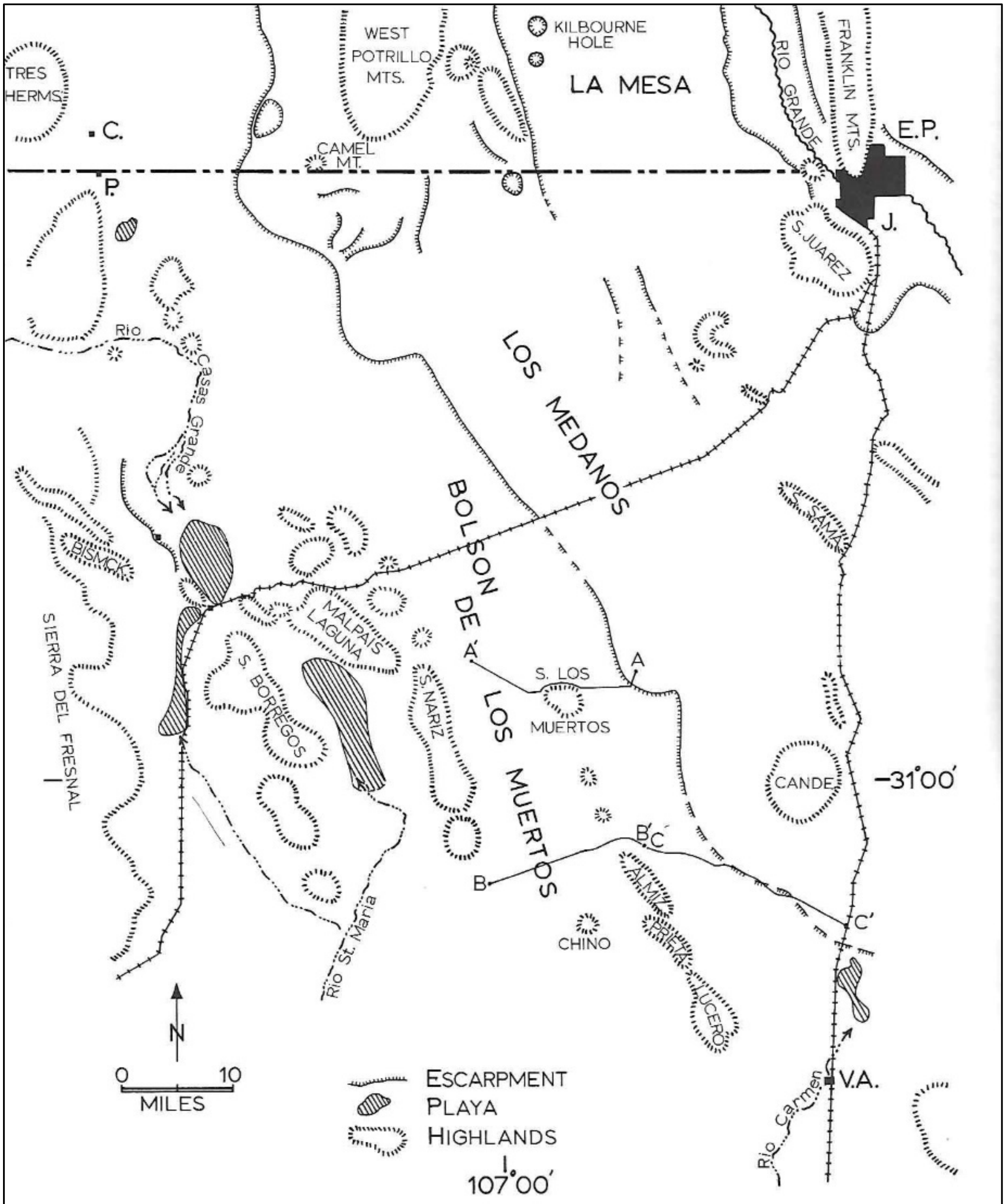


FIGURE 1.

Index map of northwestern Chihuahua showing the general area of pluvial Lake Palomas and the major physiographic and cultural features. Gravity traverses are lettered A-A′, B-B′, and C-C′. Columbus, New Mexico = C, Palomas, Mexico = P, El Paso, Texas = E.P., V. Ahumada, Mexico = V.A., Ciudad Juárez = J.

Figure H4-10 (Reeves 1969, FIG. 1; with NM Geological Society, Inc. permission)**.** Index map showing the general area of pluvial Lake Palomas, and the major physiographic and cultural features (*cf.* **Figs. H4-2** and **H4-3**). A'—A, B—B', and C—C' show location of Bouger-Anomaly gravity traverses. "Playas" are intermittent lakes on *sinks* at the end of the Rios Casas Grandes, Santa Maria, and Carmen fluvial systems (**Figs. H1-5** and **H4-7**; **Tbl. H1-6**).

El Bolsón de los Muertos is only mentioned briefly in the "Història general de Chihuahua I–Geología, geografía y arqueología (Márquez-Alameda, 1992 [coordinador del volumen])," which was published by the Universidad Autónoma de Ciudad Juárez y Gobierno del Estado Chihuahua. The following short description by Robert H. Schmidt, Professor of Geography at the University of Texas-El Paso appears to refer mainly to a basin-floor area that includes El Barreal (*cf.* Rpt. **Apndx. D3**):

> [p. 64] El Bolsón de los Muertos [Reeves 1969], a menos de 75 kilómetros al suroeste de Ciudad Juárez, es la playa más grande en el estado y en Mexico. . . . La superficie actual de la playa contigua cubre 1,245 km^2, su longitud de norte a sur es de 69 kilómetros y tiene poco mas de 24 kilómetros de ancho. Las enormes grietas[2] formadas al secarse el lodo, también llamadas grietas de desecación, llegan a ser de hasta tres metros de ancho; algunas de estas grietas se encuentran en la parte noroeste de la playa [El Barreal herein]. . . .

Note that Schmidt uses "playa" in the sense that the term is commonly defined by physical geographers and geomorphologists in descriptions of various-sized ephemeral lakes throughout the western United States. Ordóñez (1936, p. 1289), on the other hand, considers such usage to be improper. In reference to "Las enormes grietas…, de desecación:" Identical features were described by W.B. Lang in a 1943 paper in *Science* titled "Gigantic drying cracks in the Animas Valley, New Mexico." Large-scale (or "king-size") desiccation cracks in fine-grained sediments of intermontane-basin floors and bordering piedmont slopes are attributed to two types of water-table drawdown conditions that have occurred in many "deep alluvial basins" of the B&R province during the Late Quaternary: (1) Natural—desiccation of pluvial lakes, and groundwater drawdown due to incision of nearby stream valleys; and (2) Anthropogenic—overdrafts (mining) of groundwater reservoirs (e.g., Reeder 1957, Willden and Mabey 1961, Chico 1968, Fleischhauer and Stone 1982, Haneberg and Friesen 1995, Krider 1998, and Carpenter 1999).

H4.3. International Symposium on Tectonics and Magmatism of the Rio Grande Rift (October 1978)

The RG rift was initially named the Rio Grande "depression" by Kirk Bryan (1938, p. 197-225), who also included most the "depression's" fill in an undivided "Santa Fe formation." NM Tech geologist, C.E. Chapin (1971) introduced "rift" as a much more appropriate term for use in a modern plate-tectonic context (**Fig. H4-11**; Chapin and Seager 1975; Seager and Morgan 1979; Keller and Cather 1994; Hudson and Grauch 2013). The following quotation is from the Introduction to "Evolution of the Rio Grande rift in the Socorro and Las Cruces areas" by C.E. Chapin and W.R. Seager (1975, p. 197):

> Much controversy in recent years surrounding the Rio Grande rift has been caused by failure to look beyond its present geomorphic expression at its past history. . . .
>
> The purpose of this paper is to document the sequential development of the Rio Grande rift in two areas where the [Santa Fe Group] basin-fill deposits are well-exposed and where extensive field studies have provided the necessary stratigraphic detail. The similar geologic histories of these two areas (interpreted independently until our collaboration on this paper) gives us confidence that the data may be of wider applicability. . . .

NEW MEXICO GEOLOGICAL SOCIETY—TWENTY-SECOND FIELD CONFERENCE

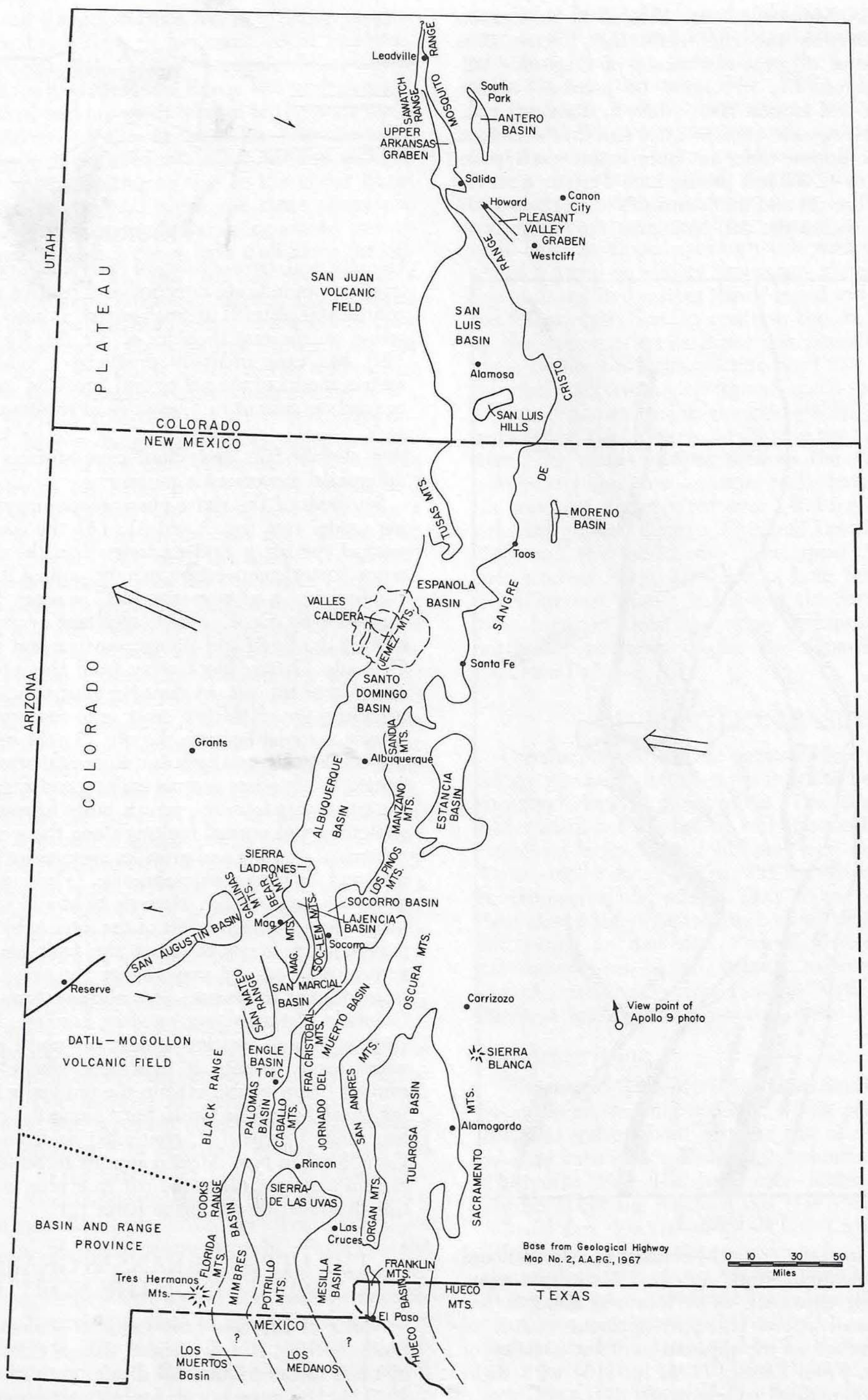


FIGURE 2.
Generalized map of the Rio Grande Rift.

Figure H4-11. FIGURE 2 *in* Chapin 1971; with New Mexico Geological Society, Inc. permission.

John W. Hawley, compiler (1978) Guidebook to Rio Grande Rift in New Mexico and Colorado: N.M. Bureau of Mines and Mineral Resources, Circular 104 (Fig. H1-2; *cf.* Riecker 1979):

The Rio Grande rift is one of the more significant structural and topographic features of the earth. To understand its geologic history is to begin to understand the geologic history of the western United States—including the Rocky Mountains, the Colorado Plateau, the Basin and Range province, and the Great Plains. In addition, the geologic, topographic, geophysical, magmatic, tectonic, and geomorphic features of the Rio Grande rift are similar to those of other rift zones of the earth. Evaluation of these facets will contribute to knowledge of all rift zones and their relationships to worldwide tectonics.

This guidebook is designed to acquaint those who take the field trips with the details of geologic features along the rift zone. Included are short papers on topics relative to the overall region. These papers and the road logs are of special interest to anyone pursuing further study of the rift. In its own way, the guidebook is a symposium volume on the field features of the rift and is, therefore, a companion to the many papers presented at the symposium *Rio Grande Rift: Tectonics and Magmatism* to be published by the American Geophysical Union.

As the New Mexico agency charged with the study of the state's geology and required to give scientific assistance in the exploration, development, and conservation of New Mexico's mineral wealth, we publish this guidebook to the landscape and geology of the heart of New Mexico—the Rio Grande rift.

Many scientists have contributed their time and talents in the preparation of the road logs and articles, but major credit goes to John W. Hawley, who solicited papers and contributions, assembled the illustrations, wrote and rewrote most of the road logs, and who had full responsibility as compiler. The comprehensiveness and scientific excellence of this material are the result of John's efforts.

Frank E. Kottlowski

Frank E. Kottlowski
Director
New Mexico Bureau of Mines
and Mineral Resources

H4.4. 1983 La Paz and 1994 North American Free Trade Agreement Activities

The La Paz Agreement is a "presidential-level accord that resulted from a 1983 summit meeting between Presidents Ronald Regan and Miguel de la Madrid" in La Paz, Baja California Sur (Barry et al. 1994, p. 215). According to D. Woodward and Duval (1996, p. 1):

> The 1983 La Paz Agreement defined the United States-Mexico border area as a corridor extending 100 kilometers on each side of the international boundary between the two nations. From a variety of different perspectives, this somewhat pragmatic definition of the border area may have been reasonable. Recent [1994] passage of the North American Free Trade Agreement (NAFTA) and the subsequent establishment of the North American Development Bank and the Border Environment Cooperation Commission indicate the importance each country places on the U.S.-Mexico border region. NAFTA-related development has affected, and will continue to affect, the border resources we share [*cf.* Lee and Ganster 2012; Pacheco 2017a-b, 2019c; Kocherga 2018g and 2019a; Pacheco 2021c-d]. However, for describing and assessing the shared-water resources of the border region, the arbitrary delineation of the "border area" defined in the 1983 agreement is not sufficient; relevant hydrologic and hydrogeologic criteria must be used to delineate the extent of the border area [*cf.* Mumme 1994, Parcher et al. 2010].

H4.4.1. Early La Paz Agreement-Border XXI Program Activity (1994-1997)

Effective implementation of the La Paz Agreement of 1983 did not occur until enactment of the "Integrated Environmental Plan for the Mexican-U.S. Border Area—Border XXI Program" in February 1992. This action in turn stimulated the first round of Transboundary aquifer studies that continued during the next 15 years. Focus of the initial geohydrological and hydrochemical investigations in the La Paz Agreement Border XXI Program was on the Hueco Bolson area, with work in the Mesilla Basin being limited to the United States. Barry Hibbs, then with the Texas Water Development Board (TWDB), and Bobby Creel of the NM WRRI served as lead principal investigators, and the U.S. Environmental Protection Agency-Region VI was the primary research funding source (Hibbs et al. 1997 and 1998). With respect to subsequent hydrogeologic research in the Mesilla Basin region (MBR), the "Transboundary aquifers and binational ground-water data base" exchange was this early work's most significant contribution (e.g., **Fig. H4-12a, 12b**).

Very little information of hydrogeologic value was available for the southern part of the Mesilla Basin region at the time of the Hibbs and others (1997) study (*cf.* **Part H6.4.1**, **Fig. H6-5**). Nonetheless, their report includes an invaluable TWDB compilation of hydrochemical information on CD-ROM and map cover inserts. Water-quality data for wells located in Chihuahua are based on analyses of samples collected by the SRH in 1982 (INEGI 1983c-cj; *cf.* Rpt. **Part 7.6.1**, Gutiérrez-Ojeda 2001 [p. 26]; García-Vásquez et al. 2022). **Figure H4-12a** is a facsimile copy of a section of the TWDB map that shows GW-quality information in a Stiff-diagram format, with map-symbol explanations on **Figure H4-12b**. Four color-coded total dissolved solid (TDS)-range categories are presented: blue—0 to 1,000 mg/L; green—1,000 to 3,000 mg/L; yellow—3,000 to 5,000 mg/L; and red—>5,000 mg/L. Because there are no local highland recharge sources, it is here inferred that low-chloride (<1,000 mg/L TDS) water from the seven sampled wells located in the central part of **Figure H4-12a** had a Late Pleistocene pluvial-Lake Palomas GW-discharge source (**Figs. H1-10, H1-12** and **H1-17**; and Rpt. **Parts 7.6.2**).

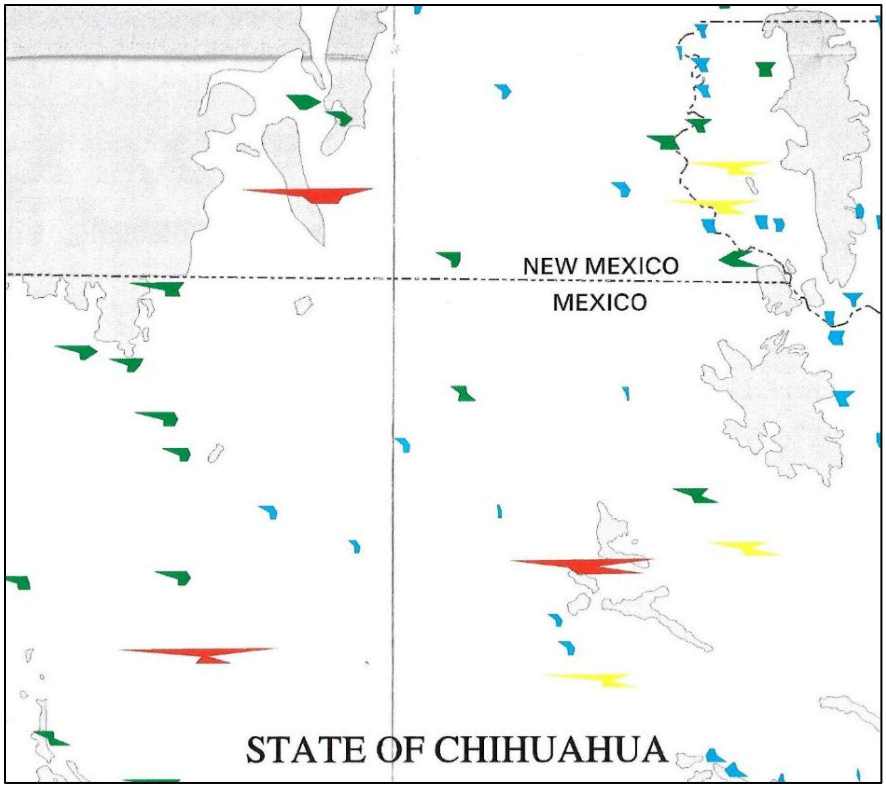


Figure H4-12a. West-central part of **PLATE 10.** Facsimile copy of the Texas Water Development Board (TWDB) Stiff-diagram compilation of "Water Quality" data on CD-ROM for region SW of El Paso/Ciudad Juárez (Hibbs et al.1997). Stiff diagram explanation on **Figure H4-10b**.

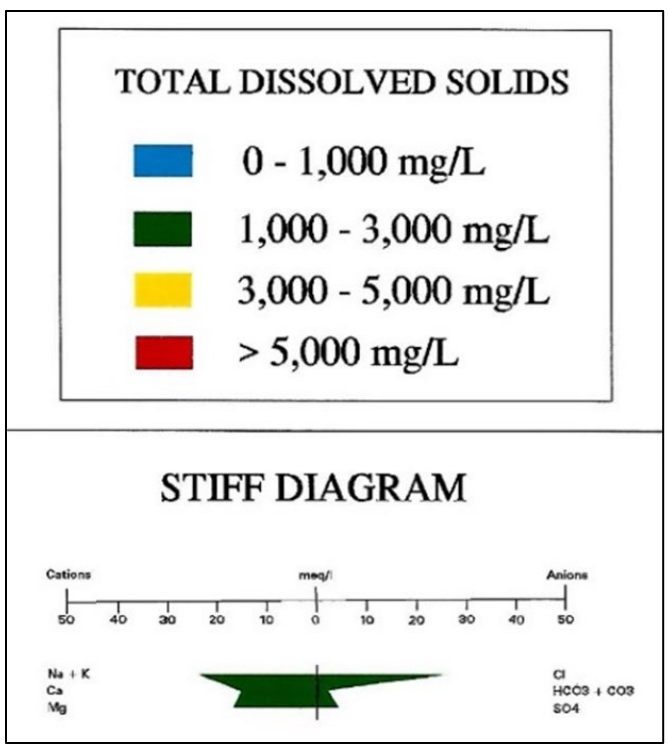


Figure H4-12b. Explanation of Stiff-diagram symbols on **Figure H4-12a**.

H4.4.2. Border XXI Program Hydrogeologic Investigations (1997-2000)

After retirement from the New Mexico Bureau of Geology & Mineral Resources (NMBGMR), John Hawley joined Creel and Hibbs in 1998 as co-PI for subsequent Border XXI program investigations (Interagency Contract X-996350-01-3). Reconnaissance-level hydrogeologic characterization of "Trans-International Boundary Aquifers" began in 1997. Study emphasis was on aquifer systems in Santa Fe Group (SFG) and correlative basin-fill (Gila Group) deposits in the Transboundary region west of the Mesilla RG-rift basin (Hawley et al. 2000). The 2000 project completion report of Hawley and others incorporated contemporary GIS and GPS technology, and included reviews of published information on the hydrogeology and hydrochemistry in an area that extended about 60 mi (100 km) north and south of the International Boundary (*cf.* INEGI 1983c-cj and 1999, Hibbs et al. 1999 and 2000, Kennedy et al. 2000). Lithologic character, geologic structure, and geohydrologic-boundary properties of major hydrostratigraphic units were schematically illustrated at map scales in the 1:250,000 to 1:500,000 range, with a cross-section network at 10x VE that extended to mean sea-level depths.

The above cited TWDB—NM WWRI study, however, only covered the westernmost part of the present NM WRRI Study (mostly west of the 107° W longitude). There, hydrogeologic interpretations were made primarily on the basis of (1) Hawley's previous field work in the region, and (2) preliminary analyses of then-available borehole records and groundwater-geochemical data (e.g., Córdoba et al. 1969, Hawley 1969b, Flores Mata 1970, INEGI 1983b-cj and 1983b; **Part H4.2**). Of special interest, with respect to interpretation of the Mesilla Basin region's Transboundary GW-flow system are the Texas Water Development Board (TWDB) map-compilation of "Water Quality" data in Stiff-diagram format in Hibbs and others (1997; **Fig. H4-12a**), and new INEGI-sourced, hydrochemical information compiled by Hibbs and others (1999), and Hawley and others (2000 [Fig. 4-8]).

The "Chloride in wells" map (**Fig. H4-13**) is representative of the INEGI (1983b) database. Most of the sampled wells of interest are located in the southeastern-most parts of the "Mimbres Basin" in an area initially designated "Bolson de los Muertos."***** The very low chloride content and high quality of groundwater sampled in the area shown in the southeasternmost part of **Figure H4-13** are of special relevance in the interpretation of the Transboundary GW-flow system in the El Parabién and southern Mesilla GW Basin (EPB and MeB) area (e.g., 14.2 mg/L Cl and 596 mg/L TDS in Rpt. **Tbl. 1**-well no. 382 [INEGI 1983c-cj, no. 26]). These occurrences, and the general presence of fresh water in the Upper/Middle Santa Fe Gp aquifer zone in the El Parabién Basin (EPB) and contiguous parts of the El Aguaje Uplift can only be explained by significant amounts of GW recharge derived from pluvial-lake high stands during Late Pleistocene glacial/pluvial intervals between 12,000 to 29,000-yrs ago (**Figs. H1-10** and **H1-12**; Rpt. **Tbl. 1-**wells 364, 365, 367, 368, 373, 377, 379, 380, 382, 385, 387, 389, 393 and 394; Gutiérrez-Ojeda 2001; García-Vásquez et al. 2022).

******Independent geological and geophysical investigations now show that much of the area covered by* ***Figure H4-13*** *comprises parts of the Malpais and El Parabién GW Basins, and El Aguaje Uplift (****Figs. H1-9*** *and* ***H1-12****; cf. INEGI 1983b-cj, Seager 1995, Jiménez and Keller 2000).*

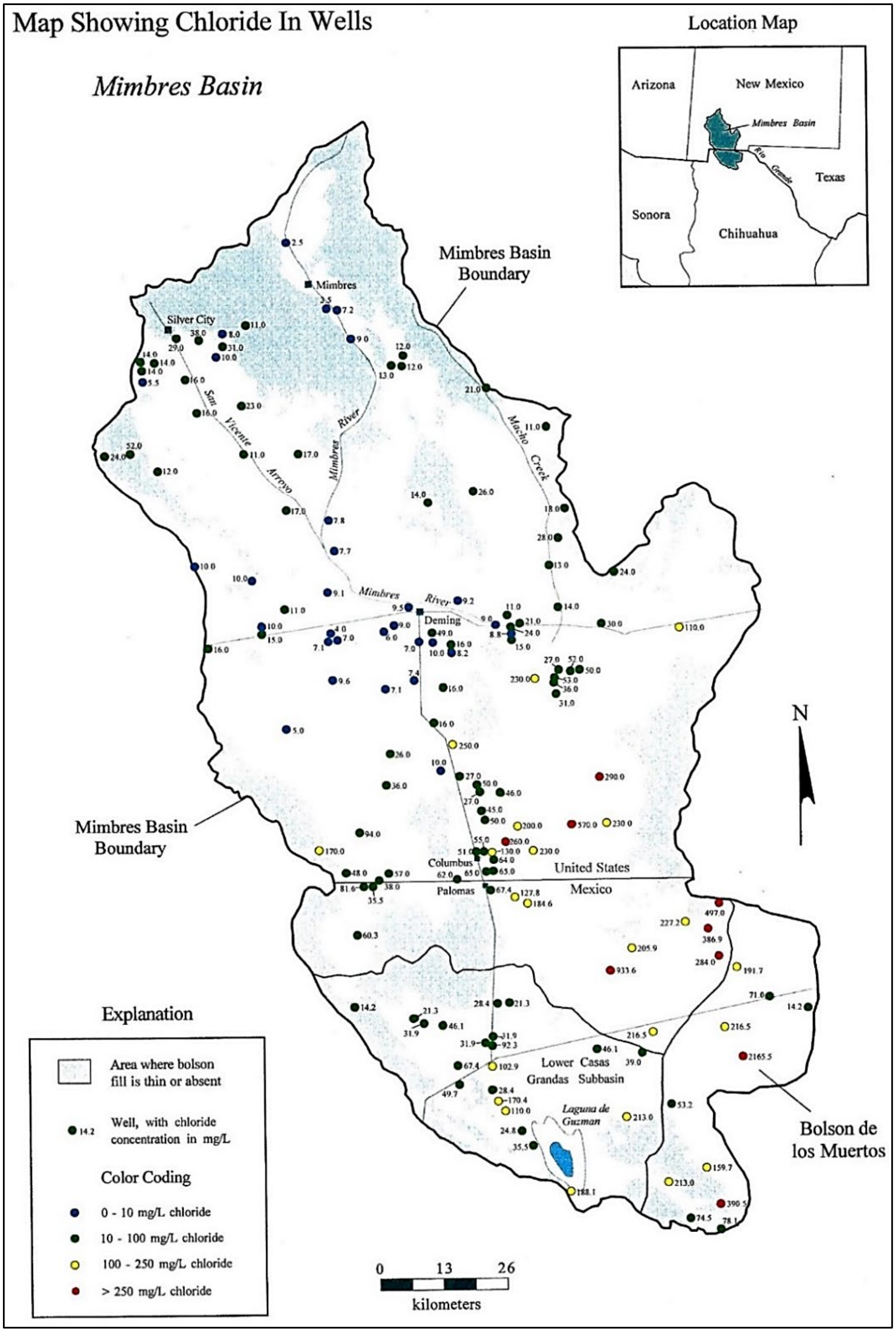


Figure H4-13 (Hawley et al. 2000, Fig. 4-8)**.** Chloride concentrations (Mg/L TDS) of water sampled from selected wells in the Mimbres Basin and contiguous parts of the Bolson de los Muertos area (Malpais, El Parabién, and El Aguaje Uplift; *cf.* Hibbs et al. 1999, INEGI 1983c-cj).

H4.5. Related Geohydrological Investigations in Chihuahua (INEGI 1999)

H4.5.1. First Formal Use of "Conejos-Médanos" in an "Agua Subterránea (GW)" Context

Prior to 2000, the most detailed review of geohydrologic studies in northwestern Chihuahua was included in "Estudio Hidrológico del Estado de Chihuahua" (INEGI 1999). Relevant parts of Capítulo (Chapt.) 6 on the "Panorama Generál del Agua Subterránea en el Estado de Chihuahua" were translated into English in 2017 by Ana Cristina García Vásquez*, and are included in **Part H4.5.4**.

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H4.5.2. Analysis and Overview of Aquifer-System Characteristics in Geohydrological Zones

The scope of the presented material is described in the following selection from Chapter-section 6.2 on the "Análisis y Panorama de las Cacterísticas del Agua Subterránea en Cada Zona Geohidrológica [Analysis and Overview of Groundwater Characteristics in individual Geohydrological Zones]":

> [p.48] After the general summary, we now evaluate information as a reference point into each pumping zone. On this section, we only describe 24 out of 32 aquifers [or aquifer systems] that have geohydrological information; . . .
>
> The particular description for the areas of greatest relevance, takes into account its geographical setting and geohydrological features, such as: reservoir lithology, recharge and established natural flow. Furthermore, we provide transmissibility parameters, water quality and type of water uses. Also mentioned is [well] discharge distribution and volume, the number and characteristics of wells involved; and the effects that groundwater pumping has on groundwater flow, on piezometric levels, and the relationship between recharge and discharge, thus providing a reference point, which is the main objective for understanding the geohydrological conditions at each area of interest. . . .

H4.5.3. Early Formal Use of "Conejos-Médanos" in an "Agua Subterránea (GW)" Context

INEGI (1999) illustrates an early formal use of the term "Conejos-Médanos" in an "Agua Subterránea" or groundwater/aquifer system context. Note that the term "Valle" [literally 'valley'] is used in the following translated passages to refer to formally designated "Acuíferos" (or aquifer system), which would subsequently include the "Acuífero Conejos-Médanos," CONAGUA GW-resource management unit (SGM 2011; INEGI 2012; CONAGUA 2015b) (**Figs. H1-10** and **H1-11**; *cf.* **Part H6.2, Figs H6-3** and **H6-4**):

> [p.48] Valle Conejos-Médanos is located in the northern portion of the state of Chihuahua to the west of Ciudad Juárez. It is in the northern part of Hydrologic Region No. 34 [**Fig. H4-5**], within the Northern-Closed Basin and Range Province, and partially includes the municipalities of Ascension and Juárez. Its boundaries are: United States of America to the north, a western part that includes the Barreal paleolake [pluvial-Lake Palomas], and the Sierra Juárez to the east.

Two "División Hidrologíca" maps of Chihuahua (**Figs. H4-14** and **H4-15** [Figs. 5.2 and 5.3.A]) are included to show the extent of the "hydrographic basins" of interest. Note that the "Zona Hidrogeológica de Conejos Médanos (INEGI 2012)" is in "Región Hidrologíca RH34—Cuencas Cerradas del Norte ("**C**" in **Fig. H4-5**)." In addition, "L. [Laguna] El Barreal" is shown in **Figure H4-15** (Fig. 5.3.A) as occupying much of the eastern basin of Pluvial-Lake Palomas (**Figs. H1-10** to **H-12**; Rpt. **Part 3.3.2**).

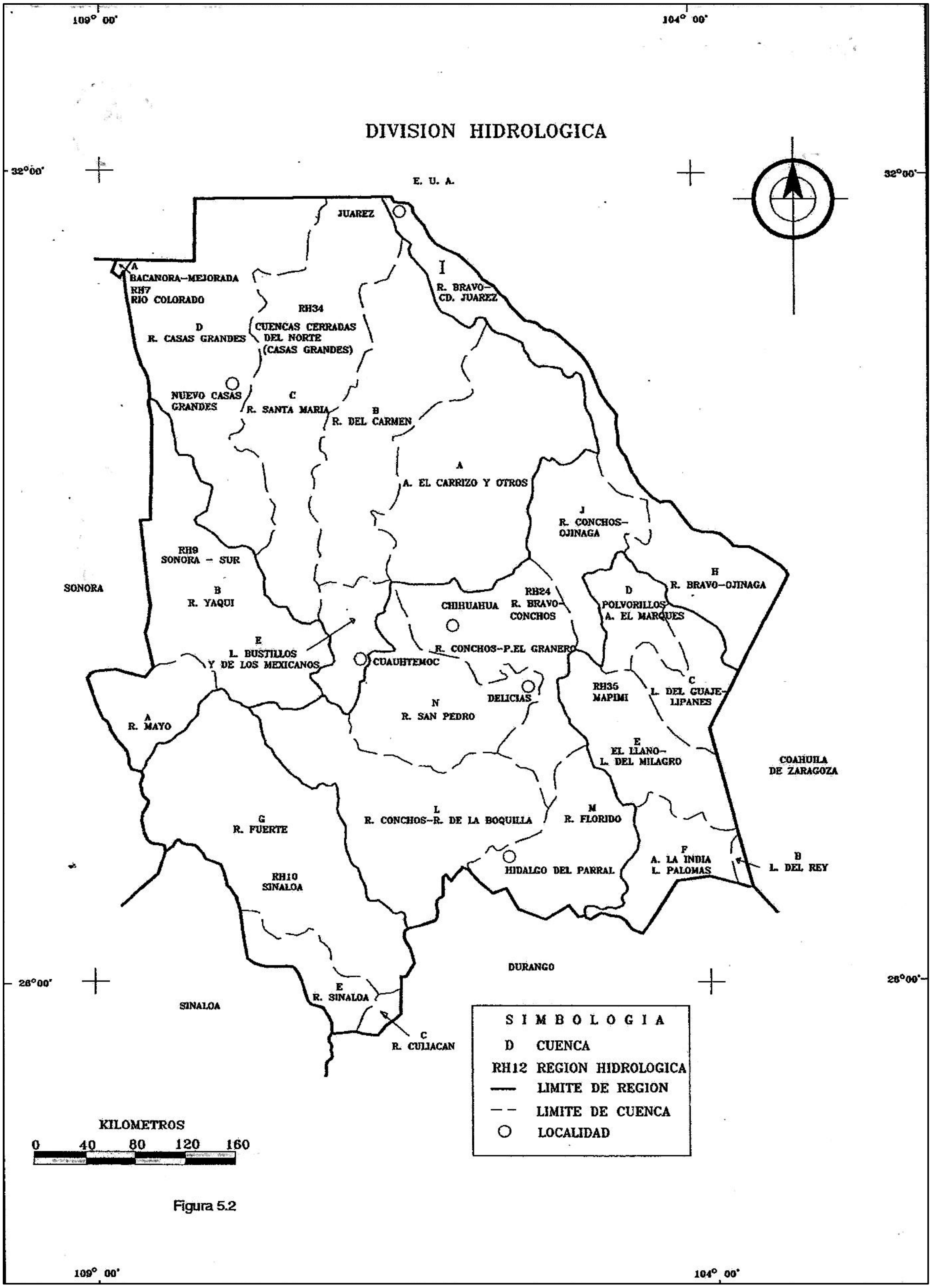


Figure H4-14 (INEGI 1999, Fig. 5.2). Index map for the "Regiones Hidrológicos" of Chihuahua.

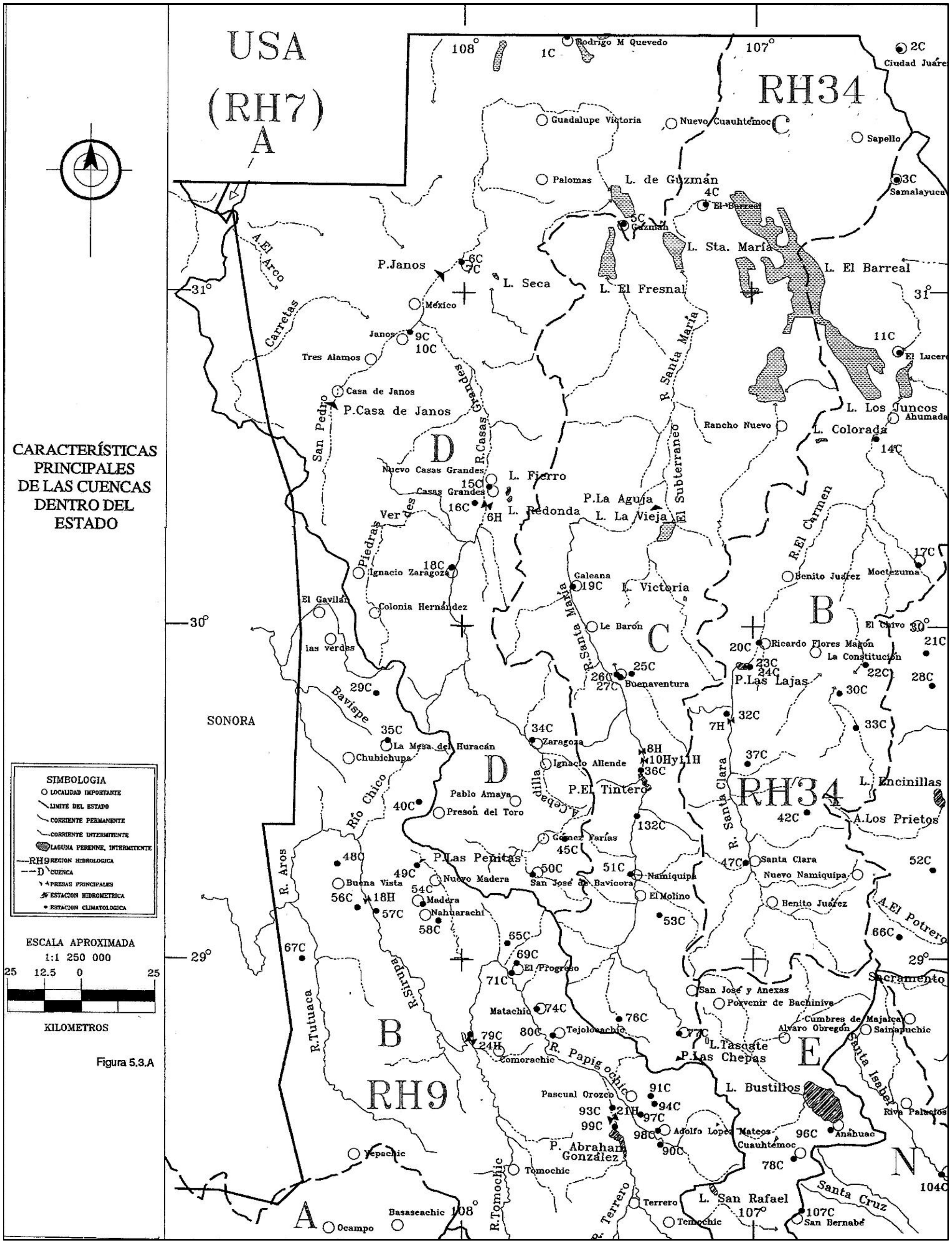


Figure H4-15 (INEGI 1999, Fig. 5.3.A)**.** Index map for fluvial system-based hydrographic units in Región Hidrologíca (Hydrologic Region) RH34—Cuencas Cerradas del Norte (closed basins of the north) in northwestern Chihuahua.

H4.5.4. García Vásquez Translation of INEGI (1999) Chapter (Capítulo) 6-Part 6.2

The García Vásquez translation comprises sections of **Chapter** (**Capítulo**) **6-Part 6.2** on the Groundwater hydrology of the State of Chihuahua that provide an "Analysis and Overview of Groundwater Characteristics" of the following "Geohydrological Zones:

1. Valle Juárez (**4.5.4a**)-Región Hidrologíca RH24—Rio Bravo-Conchos.
2. Valle Conejos Médanos (**4.5.4b**)-Región Hidrologíca RH34.
3. Valle Palomas (**4.5.4c**)-Región Hidrologíca RH34.
4. Valle Samalayuca (**4.5.4d**)-Región Hidrologíca RH34.
5. Valle Ascensión (**4.5.4e**)-Región Hidrologíca RH34.

H4.5.4a. Valle Juárez [Rio Grande/Bravo basin]

The Valle Juárez is located in Hydrologic Region No. 24, Rio Bravo-Conchos, at the extreme north-northeast part of the State of Chihuahua. It includes the municipalities of Juárez, Guadalupe, and Praxedis G. Guerrero. The valley has an elongated northwest-southeast orientation, in which its natural limits are: to the north and east by the right bank of the Rio Bravo/Grande and to the west and south by isolated mountain ranges.

The aquifer system consists of two units: the first lower unit has Tertiary age bolson deposits composed by sandstones, siltstones and shales, as well as fluvial deposits composed by gravels, sands, clays, and silt, interbedded with conglomerates and sediment deposits. The second unit, of upper Quaternary age is represented by exposures of: alluvial fans, foothills, fluvial and eolian granular deposits that can vary from gravel to silt. Both units form a single-unit, semi-confined aquifer with a thickness greater than 500 m. It has an average permeability and its transmissivity average is 1.8 x $10^{-3\ m^2}$/sec.

The exploitation of groundwater is carried out by means of 1,313 water wells pumping about 310 Mm^3/year, with capacities ranging from 15 to 80 lps and discharge pipe diameters ranging from 10.2 to 20.3 cm (4 to 81 in). The average annual recharge is estimated at 290.00 million m^3, mainly from infiltration that occurs throughout the main stem of the Rio Bravo as well as from vertical infiltration generated by rain. The balance between recharge and discharge shows an overexploited geohydrological condition. The water in this area is primarily utilized for agricultural and municipal-industrial activities.

During the period 1980-1990, the evolution of the static water levels showed recoveries from 0.5 to 6 m and drawdowns of 1 to 15 m. These differences were present almost everywhere in the valley due to the influence of the Rio Grande; however, the maximum cones of depression were found in the west side of Ciudad Juárez (map 6.1). The depth of static water levels for 1990 ranged from 1 to 80 m (map 6.2) with the deepest values being located in the urban area of Ciudad Juarez, while shallow depth values were located along the floodplain of the Rio Bravo with values of 1-5 m, where there are even some groundwater levels at depth of a few centimeters. In 1990 the static groundwater level elevations ranged from 1,060 to 1,115 masl (map 6.3), representing a groundwater flow moving from northwest to southeast along the course of the Rio Bravo/Grande. This flow direction is changed from its initial trend with a direction from east to west due to overexploitation of the aquifer happening in [the Ciudad Juárez] area, but then continues [southeastward] along its previous course.

The quality of groundwater ranged from 600 to 5000 mg/L of total dissolved solids for 1994; indicating that water quality ranges from fresh to salty; having the best quality water in the area of Ciudad Juárez; while moving to the southeast, the water quality deteriorates. The salinity may be due to groundwater residence time in contact with the geological aquifer formation; due to 1) solubility of the rocks that make up the aquifer; 2) salinity water recharge; and 3) finally, evaporation rate. The types of water families according to Palmer-Piper scale are: sodium-calcium-chlorinated and sulfate-bicarbonate.

The Juárez Valley aquifer contamination includes the occurrence of heavy metals, hydrocarbons (point-source), nitrates, and products of wastewater from urban and industrial sources.

H4.5.4b. Valle Conejos-Médanos [Intermontane-basin complex]

Valle Conejos-Médanos is located in the northern portion of the state of Chihuahua to the west of Ciudad Juárez. It is in the northern part of Hydrologic Region No. 34, within the Northern-Closed Basin and Range Province, and partially includes the municipalities of Ascension and Juárez. Its boundaries are: United States of America to the north, a western part that includes the Barreal paleolake [pluvial-Lake Palomas], and the Sierra Juárez to the east.

The aquifer is unconfined, and is formed mainly by Bolson deposits such as gravels, sands, silts and clays, also of eolian sediments (dunes). The sediments have a thickness greater than 300 m (according to some authors is greater than 1,500 m) in the central area; but in its eastern part, it only reaches about 200 m in depth. It has an average permeability and a transmissivity ranging from 2.0×10^{-3} to 4.4×10^{-3} m^2/sec.

The valley [basin] has 114 groundwater wells, with the most common depths are from 90 to 115 m. [However, some] groundwater wells are 200 to 300m in depth, and windmills [locally] produce from shallow aquifers at depths ranging from 8 to 15m. Discharge-pipe diameters range from 15.2 to 20.3 cm (6 inches to 8 inches), and provide average flows of 45 to 50 lps. Pumping in this aquifer is of approximately 1.58 Mm^3 per year and recharge with the same period is of about 50 Mm^3. Recharge is the product of vertical infiltration of precipitation and groundwater flow, coming from the southeast and northwest parts [SE-Rio Carmen; NW-Rios Casas Grandes and Santa Maria, and Mimbres River]. Water uses are for agriculture, livestock, industrial and municipal. The aquifer is currently [prior to 2010] in an under-exploited condition.

The evolution of the static water level (swl) in the years of 1982 to 1985 showed drawdowns of about 1.5 m per year. The depth of static water level in 1985 ranged from 1 to 120 m, with the shallowest depths to the west and southwest of the valley [basin] and the deepest swl in the north and northeast portion. The elevation of swl in 1985 ranged from 1150 to 1180 m; groundwater flow occurs in several directions and these are: northeast towards the Rio Bravo/Grande, and to the southwest towards the Barreal paleolake [Lake Palomas] and probably [no longer verified] an eastward exit flow through the narrow corridor between the Sierra Juárez and Sierra Sapello [Méndez-Vergel Corridor of this report].

Best water quality in 1982, was of 500 to 800 mg/L of total dissolved solids [TDS], with concentrations of more than 1,000 mg/L existing in most of the area; this represents a water quality ranging generally from tolerable to salty. The water family group according to the classification of Palmer-Piper is sodium-bicarbonate-sulfate with a tendency to increase in chloride; this increase in salts is partially found in the area and part is due to the evapotranspiration of shallow groundwater, therefore it is a natural pollution.

H4.5.4c. Valle Palomas [Intermontane-basin complex]

Valle Palomas is located in the northern portion of the state of Chihuahua, in the Northern Closed Basin and Range Province north of Hydrological Region No. 34; and it is entirely located within the municipality of Ascension. This valley bordered on the north and west by the USA [Mimbres Basin], and southwest with La Biznaga Hills and Ascension Valley, south to the Sabina valley, and west of Conejos-Médanos valley.

Aquifer pumping happens mainly along old floodplains and paleo-lakes, which have lacustrine and alluvial sediments of Quaternary Age, such as silts, clays and sand pits; along these formations, they have found interbedded lenses of Quaternary basalts with average thickness of 6m, all together form a deposit with a thickness of about 300 m. The aquifer is an unconfined aquifer with fine particle size sediments, its permeability is average, has a transmissivity ranging from 3.9 x 10^{-4} to 1.5 x 10^{-2} m^2/sec. Underlying this unit are Cretaceous limestones which are believed likely to contain water.

The average annual volume of pumped water reaches 22.04 Mm^3, from 309 operating wells with depths of 60 to 200 m; which produce an average of 40 lps discharged into pipe diameters ranging from 10.2 to 20.3 cm (4 inches to 8 inches). The average annual recharge is estimated at 52 Mm^3, coming from the mountains to the north and northwest, plus the infiltration through the Casas Grandes River while it has runoff effluents. The relationship between recharge and discharge condition shows an underexploited aquifer. Water is use mainly for agriculture purposes.

During the period from 1976 to 1985, the evolution of the static water levels drawdowns range from 1 to 8 m. The biggest drawdowns are located south and southeast of Guadalupe Victoria which is the area corresponding to the largest concentration of groundwater wells; whereas the region with the lowest aquifer depletion with depths ranging under 1 to 2 m is located east and west of the valley (map 6.4). The depth of the static water level for 1985 (map 6.5) fluctuates between 15 m and 35 m, where the greater depths occurs in Los Sauces and San Jose, and the shallowest are located east of the town of Guadalupe Victoria. Static water levels in the area varies from 1160 to 1210 m asl for 1985 (map 6.6); defining the direction of flow, first to the east; while changing its course towards the south, southeast and southwest.

Water quality is generally sweet it presents a tolerable concentrations less than 2,000 mg/L of total dissolved solids, except near Lake Guzman which was determined to be up to 5000 mg/Ll. Family water group predominant according with Palmer-Piper diagrams is sodium-sulfate-bicarbonate.

H4.5.4d. Valle Samalayuca [Intermontane-basin complex]

Valle Samalayuca is located in the northern portion of the state; in the hydrologic region No. 34, Northern Closed Basin and Range Province, politically belongs to the municipality of Juárez. It has hydrogeologic limits: Presidio Hills to the east, to the south the small mountains of Rancheria and La Candelaria, to the west by the Sierra Samalayuca and to the north the Valle Juárez.

Three units integrating an unconfined aquifer, a confined aquifer and an aquiclude define the aquifer system at the Valle Samalayuca. The unconfined aquifer is integrated mainly by a lacustrine sequence of gravels, sands and clays of Quaternary Age with an average thickness of 75 m. At the top of this unconfined aquifer evaporite sediments are present occurring mainly by gypsum, with a thicknesses of about 50 m. Furthermore, at the base of this unconfined aquifer it is composed of continental lacustrine Tertiary clastic sediments, silt and clay, interbedded with extrusive igneous rocks that integrating the aquiclude. Given the heterogeneity presented by the materials that integrate this aquiclude, it is possible that occasionally a hydraulic connection could happen with the unconfined aquifer and with the confined aquifer that underlies it. The confined aquifer is of Pre-Jurassic [Permian] Age, and is defined as a series of calcareous sandstones with interbedded limestones and shales, in which this unit has important karstic conditions with fractures. The unconfined aquifer has a medium to medium-high permeability and a transmissivity ranging from 2.4 x 10^{-2} to 1.6 x 10^{-2} m^2/sec and the average permeability for the confined aquifer ranges from medium-high and the average transmissivity is of 1.4 x 10^{-2} m^2/sec.

The Samalayuca valley has 164 groundwater wells with depths ranging from 70-300 m, with discharge diameters ranging from 10.2 to 20.3 cm (4 inches to 8 inches) that produce average discharge ranging from 3 to 60 lps. The pumping from the system is about 8.49 Mm^3 per year;

and it has an estimated recharge of about 16 Mm^3 per year coming from groundwater inflow and from the mountains ranges that are in the area. The given parameters between recharge and discharge present a balanced geohydrological underexploited aquifer system. The main use is agriculture.

Piezometry for the unconfined aquifer (granular or higher). The evolution of the static water level for the period 1985-1986 (map 6.7), shows recovery values up to 1 meter and drawdowns of 1 to 3 meters towards the Samalayuca town and into the thermoelectric plant. The depth of the static water level for 1986 varies from 4 to 12 m (map 6.8), locating the shallow values in the central part of the valley and the deepest values to the northeast and south of the area. In regards to the static water level for 1986, shows that the equipotential lines vary from 1256 to 1276 m asl (map 6.9), indicating a flow towards the northwest.

Piezometry for confined aquifer (lower or fractured). In the evolution of the static water levels for the years 1985 and 1986 (map 6.10), it shows a recovery that reach 10 m and drawdowns of about 2 m at the thermoelectric plant and towards the Samalayuca town. This is in connection with the activation and operation of the cluster of wells located in that area. The depth to the static water level in 1986 (map 6.11) ranges from 5 to 50 m. Regarding the static water level for 1986 (map 6.12) it shows equipotential lines values ranging from 1 210 to 1 286 masl, reaching the highest elevations in the southeast portion and the lowest toward the valley to the west. In general, groundwater flow is toward the northwest; however, locally there is a concentric radial flow in the western part of the region, changing the general direction of flow to the area where wells of the Federal Electricity Commission are located.

The groundwater quality due to its concentration of total dissolved solids varies from 450 to 1200 mg/L indicating that the water goes from sweet to tolerable, with the possibility of finding local poor water quality water or salty water due to evaporites that are located in the area. The water family groups found according Palmer-Piper are: sulfated-bicarbonate-calcium and calcium sulfate, sodium sulfate and calcium sulfate.

H4.5.4e. Valle Ascensión [Intermontane-basin complex]

Valle Ascensión is located in the northwestern portion of the state and west of Hydrological Region No. 34, Northern Closed Basin and Range Province (Casas Grandes); it [is] located between the municipalities of Ascension and Janos. The limits of the valley are: to the north its boundary is with the United States of America, to the west with the Cerro Nevado, to the south with the hills of Sierra El Venado and El Capulin, and to the east with the Boca Grande and El Fresnal mountain range.

The aquifers at this area are mainly of alluvial deposits and granular deposits such as gravels, sands, silts and clays, they are of Tertiary and Quaternary Age; this package has a thickness of about 2000 m. The aquifer is considered semi-confined type of medium permeability and transmissivity ranging from 1.8×10^{-3} to 7.9×10^{-3} m2/sec and with average values of 3 to 5×10^{-3} m2/sec.

The groundwater extraction is performed while using 632 groundwater wells with depths ranging from 5 to 215 m, with discharge diameters of 2.5 to 25.4 cm (1 inch to 10.1 inches) which produce an average pumping from 0.5 to 62 lps. The average annual extraction is of 192.01 Mm^3, against an estimated 150.00 Mm^3 of recharge giving a geohydrological bad condition of the aquifer that is considered over pumped. Recharge comes from the Janos Valley throughout the floodplain channels of the Casas Grandes River system and from the contributing stream of Salto del Ojo. In addition, recharge occurs as a product of vertical infiltration of rain in the area, as well as, from the mountains located south and east of the area and from the irrigation returns. The agricultural sector is the main user of the aquifer; also used for livestock and municipal-industrial and domestic uses.

Piezometry for the years 1987 until 1996, shows an evolution of the static water level that fluctuates between 20 and -25 m (map 6.14); maximum recovery of 20 m is located south of the area and the biggest drawdowns is located to the southwest and east of the community of Ascensión. The depth of the static water level for 1996 (map 6.5) fluctuates between 10 m and 55 m, with dominant values in the Valley of 15 to 40 m. Static water levels in the same year varies from 1,250 to 1,320 m asl (map 6.15); the direction of groundwater flow maintains that of the general gradient of the Rio Casa Grandes; except where locally masked by pumping effects of wells in the Ascension population center.

Water quality is sweet to tolerable, with concentrations of 250 to 1,200 mg/L of total dissolved solids. The water-family group according to the classification of Palmer-Piper is sodium-bicarbonate and sodium-sulfate-bicarbonate.

H4.6. Pioneering Geophysical Study of "Rift Basin Structure in the Border Region of Northwestern Chihuahua" (Jiménez and Keller 2000)

As noted in **Part H1.7**, the internal complexity and deep-seated nature of many structural components of RG-rift basins and their bordering bedrock uplifts requires that hydrogeologic-framework characterization be based on a wide variety of direct and indirect methods of surface and subsurface investigation (e.g., detailed mapping, borehole-sample logging, and geophysical and geochemical surveys). The Bouguer [isostatic-residual] gravity maps and cross-sections of Jiménez and Keller (2000, Figs. 4 and 7) have served as an essential source of information on the locations of major deeply buried bedrock and structural-boundary features in southern MBR (*cf.* **CHAPTS. 5** and **6**). Map and cross-section compilation is described in more detail in **Part 2.3.3** and **Appendix A3**.

Binational collaborations in the border region initially had a geological and geophysical emphasis, and were well underway by the late 1960s (**Part H4.2.5**; e.g., Córdoba et al. 1969, Thompson et al. 1978, Tovar et al. 1978; **Tbl. H1-3**). More-detailed studies of deep-seated RG-rift basin structure, however, were not initiated until the 1990s, but active, field-based collaborations still remain to be implemented (*cf.* **Part H6.4.1**). Interpretations in this report on deep structural and stratigraphic components of the border regions hydrogeologic-framework are primarily based on "the integrated analysis of gravity, drilling, geologic, and remote-sensing data" by Alberto Jiménez and G.R. Keller at the UTEP Pan American Center for Earth & Environmental Sciences-Geophysical Research Laboratory (Rpt. **Parts 3.6.1**; **6.4.1** and **6.4.2**). According to Jiménez and Keller (2000, p. 79-82):

> [p. 79]. . . We have delineated a new feature that we have named the El Parabien basin, and a smaller feature to the east that Mexican workers call the Conejo Médanos basin*. There is a series of gravity highs that connect the East Potrillo Mountains, Sierra de Sapello, Sierra Samalayuca, and Sierra de Presidio. The trend and relative continuity of this anomaly suggest that it correlates with an older structure that played a role in the development of subsequent Laramide and rift structures . . . .
>
> **This is not the much larger "Acuífero Conejos-Médanos" (cf.* ***Fig. H1-7****; INEGI 2912).*
>
> [p. 80] The region of primary interest is situated immediately west of Ciudad Juarez. The definition and investigation of the gravity lows in this area was the chief aim of this study. These gravity lows correspond to a series of [RG-rift] basins west of the El Paso-Ciudad Juarez metroplex that may contain important water resources. . . .
>
> [p.81] The gravity model was constructed using all available geological and geophysical data as controls [,] and should be considered to be geophysically constrained geologic cross section. The [Pemex] Moyotes 1 well [**Figs. H4-6a, b**] was a particularly important constraint.
>
> [p.81] **Figs. H4-6a, b** Relatively low gravity values (-160 to -170 [milligals]) obtained in the El Parabién Ranch area [**Fig. H1-7**] indicate the presence of a deep basin containing sedimentary

fill with a thickness of 2.2 km [7,218 ft - SFG/Tls]. Here we name this feature* as the El Parabién basin [p. 81-82, Figs. 7 and 6; *cf*. Rpt, **Parts 3.6** and **6.4**] . . . .
* The identical "feature" is named "BASIN DE LA MESILLA" in CONAGUA 2020 (p. 20, cross-section B-B'; **Fig. H4-7**; *cf.* **Figs. H1-11** and **H1-12** [**III-III'**]).
[p. 82] A NW-trending series of gravity highs is associated with the East Potrillo Mountains, Sierra Sapello, Sierra Samalayuca, and Sierra del Presidio. A significant point from water-resources point of view is that the gravity anomalies show that the Mesilla Basin is separated from the basins in Mexico [e.g., El Parabién basin by a rift] structural high. In addition, the basins in Mexico are relatively small in areal extent suggesting that the deep ground-water resources are limited.

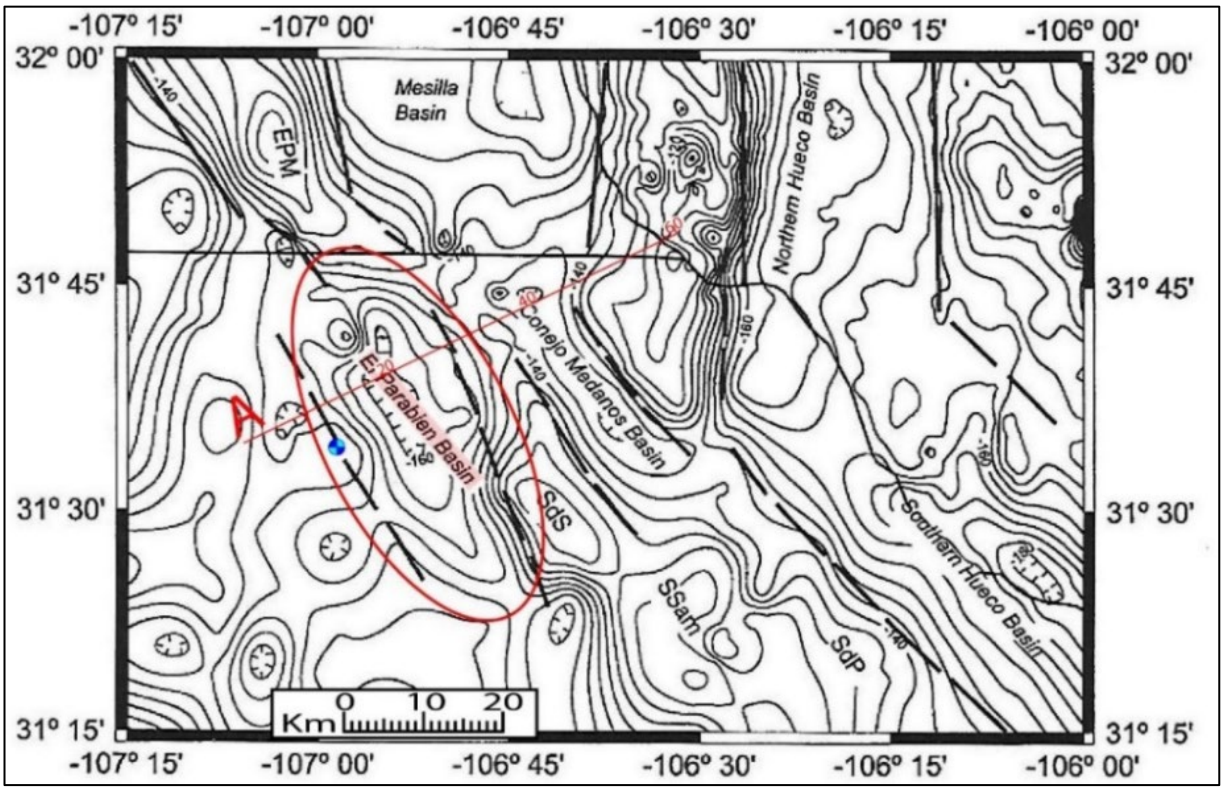


Figure H4-16a (Jiménez and Keller 2000, Fig. 7; with permission from New Mexico Geological Society, Inc.)**.** Gravity map (4 milligal contour interval) with an interpreted extent of the major RG-rift basins in the border region that is "based on the integrated analysis of gravity, drilling, geologic, and remote-sensing data." El Parabién Basin-red outline, Profile A-red line (**Fig. H4-16b**), and Pemex Moyotes No. 1-blue circle, with +). The "Conejo Medanos Basin" comprises most of the Méndez-Vergel Inflow Corridor south of the MeB-El Milagro Subbasin as defined herein (*cf.* Rpt. **Part 5.1.6**). Acronyms: EPM-East Potrillo Mountains, SdS-Sierra de Sapello [SSU], SSam-Sierra Samalayuca, and SdP-Sierra del Presidio.

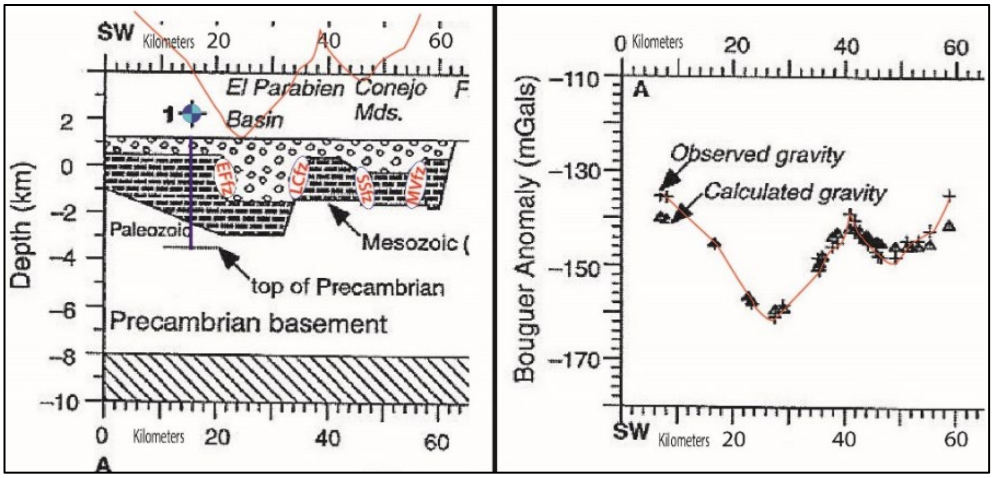


Figure H4-16b (modified from Jiménez and Keller 2000, Fig. 6; with permission from New Mexico Geological Society, Inc.)**.** Western part of computer model of gravity profile A-A' (right; and red line, right and left), and schematic geologic section (left), with Cenozoic Laramide and RG-rift basin fill shown with open polygons (SFG/Tls–**Tbls. H1-10** and **H1-11**). Location of Profile A shown on **Fig. H4-16a**. Pemex Moyotes No.1-blue circle (*cf.* **Parts 5.6.4** and **6.5**). Fault zones (**Tbl. 1-3**): EFfz-El Faro, LCfz-Los Cuates, SSfz-Sierra Sapello, and MVfz-Mesilla Valley.

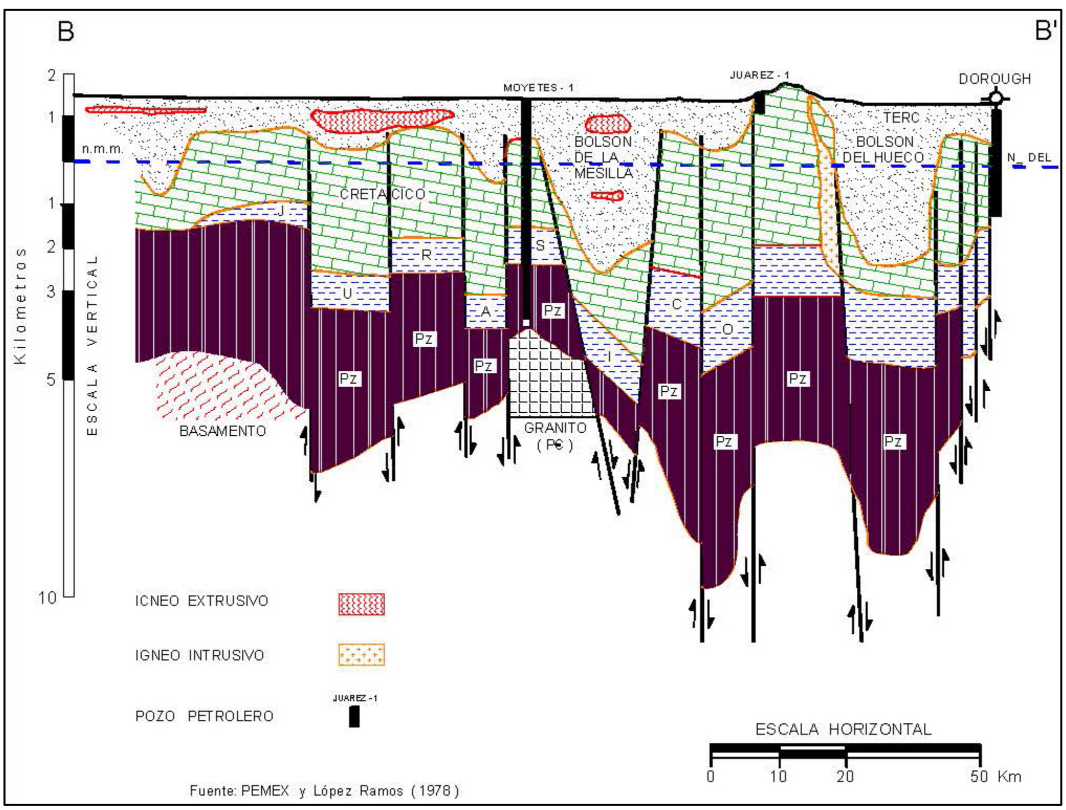


Figure H4-17 (CONAGUA 2020, p. 20)**.** Geologic Cross-Section (BB') that is located near 31°40-45' N, and extends from the Palomas volcanic field south of Columbus, NM to the Hueco Bolson east of Ciudad Juárez (**Figs. H1-11** and **H4-16b**). It shows regional stratigraphic and deep-seated structural relationships at a vertical exaggeration (VE) of about 8x (*cf.* **Figs. H1-19** and **H1-20** [**III-III'**]).

H5. BINATIONAL HYDROGEOLOGIC-RESEARCH COLLABORATIONS (2000-2009)

H5.1. Background

Between 2000 and 2009, investigations with a major hydrogeological component were mainly restricted to GW-basin areas north of the International Boundary, and included parts of the Southern Jornada Basin, Rincon Valley-Palomas Basin, and Hueco Bolson (Hawley et al. 2005 and 2009; Creel et al. 2006; Hutchison 2006; Nickerson 2006). Hydrogeologic investigation in the Mesilla Basin region after 2000 were funded by grants to the NM WRRI from the NM Interstate Stream Commission (NM ISC), Lower Rio Grande Water Users Organization (LRGWUO), and USGS-State Water-Science Centers (e.g., Hawley et al. 2001, Hawley and Kennedy 2004, Witcher et al. 2004, Creel et al. 2006). Substantial *pro bono* support for all hydrogeology-related research administered by the NM WRRI was also provided by the private-consulting firm of HAWLEY GEOMATTERS between 1997 and 2018.

NM WRRI Technical Report TCR-332 (Hawley and Kennedy 2004; Hawley et al. 2005) was the first comprehensive report on the Mesilla Basin region's hydrogeologic framework with a digital map and cross-section base. Its preparation involved close collaboration with the USGS-NM Water Science Center and the NM Bureau of Geology and Mineral Resources (BGMR) at NM Tech. Illustrations include 1:100,000-scale maps of surface hydrogeology and basal basin-fill topography, and a 17 cross-section grid at 10x vertical exaggeration that extends to an altitude of 1,000 ft (~300 m) above msl. Basic ArcGIS and Adobe-Illustrator digital formats were used, respectively, in map and cross-section preparation. Borehole logs and production data for about 160 deep test and water wells provided subsurface control for the hydrostratigraphic and lithofacies interpretations.

Information on aquifer systems in the Chihuahua part of the TCR-332 study area was limited to acquisition of borehole records (logs and construction data) for nine exploration wells drilled in 1988 as part of an Secretaria de Recursos Hidráulicos (SRH) "Programa de Exploracíon-Zona Conejos Médanos (*cf.* Gutiérrez-Ojeda 2001, p. 26; SARH 1988; Rpt. **Tbl. 1**, nos. 359-368). This valuable database was acquired by the IBWC-U.S. Section from Mexican federal-government sources in 1989, and it was shared with the EPWU and collaborating U.S. federal and state agencies in 1989 and 1990 for informal research purposes. It could not be officially released for publication, however, until the formal signing of project agreements for interagency enactment of the Transboundary Aquifer Assessment Act in 2009 (**Part H6**).The original digital hydrogeologic-framework model for the Mesilla and Southern Jornada Basins was expanded in 2005 to include both the Rincon Valley-Palomas Basin area south of Caballo Reservoir, and the El Paso-Ciudad Juárez metropolitan area of the western Hueco Bolson (Hawley et al. 2005, 2009).

Work in the Hueco Bolson was part of a "Hydrogeologic and Water Quality Study of the Hueco Bolson Aquifer," which involved a multi-institutional team of hydrogeologists, geochemists, hydrologists, and geographic-information system (GIS) specialists. The National Science Foundation (NSF) provided funding support through a "Glue-Grant" agreement between the NM WRRI and California State University-Los Angeles (CSULA—Interagency Contract no. X7-976401-01). Collaborating institutions included the EPA- Region VI, IBWC-US), CSULA, University of Arizona-SAHRA, Universidad Autónoma de Ciudad Juárez-Centro de Información Geográfica (UAJC), USGS-Water Science Centers, EPWU, and Texas Water Development Board (TWDB). NM WRRI contributions to this project were published as TCR-349 on the "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" (Hawley et al. 2009; *cf.* Hibbs et al. 2015).

Substantial progress was made between 1996 and 2009 in the hydrogeologic characterization of basin-fill aquifer systems in the Mesilla Basin region north of the International Boundary (Creel et al.

2006; *cf.* **Figs. H5-2** and **H5-3**). Information in Hawley and Kennedy (2004) also includes updated interpretations of borehole-log data (sedimentological, geophysical, and geochemical) in a series of hydrogeologic cross-sections that were originally developed by Hawley and Lozinsky for the USGS and the NMBM&MR (1992, PLATES 2-11, Table 4). The initial fence-diagram grid of 17 cross-sections in TCR-332 was expanded to 23 sections to cover the area between Rincon and Caballo Dam (Hawley et al. 2005 [CD-ROM, PLATES 4 to 6]).

Figure H5-1. Dr. Bobby J. Creel (R), with Dr. Alfredo Granados Olivas (C), and NM WRRI GIS Coordinator Marquita (Quita) Ortiz at a February 21, 2005 progress review of Transboundary aquifer-system mapping. UACJ Department of Civil and Environmental Engineering GIS Laboratory (Hawley Geomatters photo).

H5.2. UTEP Dissertation Research Contributions (2000-2006)

A major contribution to the understanding of Transboundary GW-flow dynamics was made by John Kennedy in his (2000-2004) Ph.D. dissertation research on the hydrogeology of the New Mexico-Chihuahua border region at the University of Texas, El Paso (Kennedy 2004). The scope of this work is summarized in Kennedy and Hawley (2003, p. 181):

> During major glacial-pluvial intervals of the Late Quaternary, a complexly linked system of intermontane basin lakes and through-going streams dominated the geohydrologic setting the Paso del Norte region of southern New Mexico, Trans-Pecos Texas, and Chihuahua, Mexico. Hydrogeologic setting and fluctuating paleoclimatic conditions were the major controls on size and permanence of lakes and streams in this now arid to semiarid Chihuahuan Desert region of the Basin and Range—Mexican Highland section [**Figs. H1-5** and **H4-6a**]. Bolson complexes of the region have both *open* and *closed* topographic components, but many *closed* subbasins are *partly drained* hydrologic systems with groundwater inflow and outflow links with adjacent

areas. The entrenched Rio Grande/Bravo fluvial system formed the regional discharge zone or *sink* for large amounts of surface and subsurface flow during much of the Middle and Late Quaternary [**Fig. H5-1**; *cf.* **Fig. H3-4**].

The Mesilla and El Paso/Juárez Valleys of the Rio Grande/Bravo (1,090-1,175 m [amsl]) bisect the floors of the Los Muertos-Guzman-Santa María and Tularosa-Hueco bolson complexes (1,175-1,210 m), which are the sites of the region's two largest pluvial lakes, Palomas (Chihuahua) and Otero (NM). At highest (Wisconsinan) stages, Lakes Palomas and Otero had areas of at least 7,500 and 2,000 km2, respectively. Linked *closed* basins with smaller pluvial lakes include the Playas-Basilio and Hachita-Moscos basins that drain to the Rio Casas Grandes Valley of northwestern Chihuahua. Watersheds (~3,000-m max elev.; 63,700 km2 area) contributing to Lake Palomas include highlands bordering the northern Sierra Madre Occidental (Rios Casas Grandes, Santa Maria and Carmen headwaters) and southeastern ranges of the Datil-Mogollon—Transition Zone province (Mimbres River source). . . . In many places, major shoreline features with good age control are visible on LANDSAT imagery; and advanced GIS technology enables basin-scale paleohydrologic and hydrogeologic reconstructions [**Part H1-4**; *cf.* Rpt. **Part 3.1.4**; Castiglia and Fawcett 2006, p. 114; Hawley et al. 2000, Tbl. 3-1].

H5.3. Provisional Assessment of GW-Outflow Contributions Pluvial-Lake Palomas to Southern Mesilla Basin Region's Transboundary Aquifer Systems

Based on an initial analysis of GW-flow conditions in the southern Mesilla Basin area Hawley and Kennedy (2004, p. 74-75) made the following observations:

> Unpublished water-level data from several 1,000-ft [300-m – SRH] test wells in the Mexican part of the basin indicate that, at least the shallow part of the groundwater-flow system in HSU MSF2 (mostly *LFA 3*) is northeastward toward the Santa Teresa area (e.g., El Mirador and La Joya [also El Girasol and El Parabién] tests; . . . [Rpt. **Tbl. 1**, nos. 359, 362, 364 and 359]).
>
> Current research on the Late Quaternary history of "pluvial Lake Palomas (Reeves 1969)" by Castiglia and Fawcett (2006), and Castiglia (2002) demonstrates that the floor of Bolson de los Muertos, and adjacent parts of the Mimbres, Casas Grandes, Santa Maria, and Fresnal basins were periodically inundated by very large and deep lakes as late as early to middle Holocene time (8,400 to 6,500 ^{14}C yrs BP). The watershed contributing to these basin systems is about 12,650 mi^2. Elevations of the deep-lake stages are in the 3,940 to 3,965-ft range, or 160 to 185 ft above the "predevelopment" potentiometric surface (3,780 to 3,770 ft) in the Noria to Santa Teresa area about 30 mi to the northeast (. . . ; Wilson et al. 1981 [PL. 9]). Furthermore, the floor of the Wisconsinan "Ice Age" bedrock channel of the ancestral Rio Grande at El Paso Narrows was scoured out to a depth of about 85 ft below present floodplain level (channel-base elev. of ~ 3,635 ft.). Therefore, during these Lake Palomas high stands, the northeastward gradient of (at least) the shallow part of the groundwater-flow system would have been at least 5 ft/mi [0.005], with [GW] flow discharge to the Mesilla Valley shallow aquifer system in the Anapra, Sunland Park, [and] (lower) Santa Teresa area. Since the present potentiometric surface [altitude amsl] in the north-central part of the Bolson de los Muertos is about 3,775 ft (Córdoba et al. 1969, p. 7), there may still be a slight northeast-trending pressure gradient toward the International Boundary area northwest of Cerro del Cristo Rey . . . .

For at least the past 8,000 years, however, none of the intermittent lakes that episodically flooded parts of El Barreal-Salinas de Union plain in the Zona Hidrogeológica de Conejos Médanos have reached shoreline levels that were high enough (e.g., about 1,195 m amsl) to contribute significant amounts of recharge (either fresh or brackish) to the Transboundary GW-flow system. As shown on **Figures H1-10** and **H1-12**, a GW-flow divide (alt. ~1,210 m [3,979 ft] amsl) located between the El Aguaje and La Laguna well sites forms the present-day no-flow boundary between NE-directed underflow toward the lower Mesilla Valley and EPdN, and SW-directed underflow toward El Barreal in the Bolsón de los Muertos (**Figs. H1-6 and H7-2** [Section S-S′]). As also shown on **Figures H1-12** and **H1-17**, the respective altitudes of the predevelopment (~1976) water-table were about 1,194 m [3,918 ft] amsl at El Aguaje and 1,192 m [3,911 ft] at La Laguna.

H5.4. El Paso del Norte's Control on Regional GW-Flow and Chemistry

Hydrogeologic research since 2000 has recognized the key role played by the El Paso del Norte (EPdN) constriction on the hydrochemistry of upwelling deep-sourced saline groundwater at the lower end of the MeV; and the development of viable salinity-management methods has been a pressing issue (e.g., Phillips et al. 2003, Hogan et al. 2007, Doremus and Michelson 2008, Moore et al. 2008, Kubicki et al. 2021). **Figures H5-2 and H5-3** are preliminary products of a 2004 NM WRRI effort to semi-quantitatively portray the effect of the EPdN bedrock constriction on GW-flow systems in the three basin areas that it separates: (1) Lower MeV, (2) the Hueco Bolson-El Paso/Juárez area, and (3) RG-rift basins west of Sierra Juárez (Kennedy and Hawley 2003, Hawley and Kennedy 2004, Figs. 5-2 and 5-3; Hawley et al. 2009, FIGS. 7 and 8).

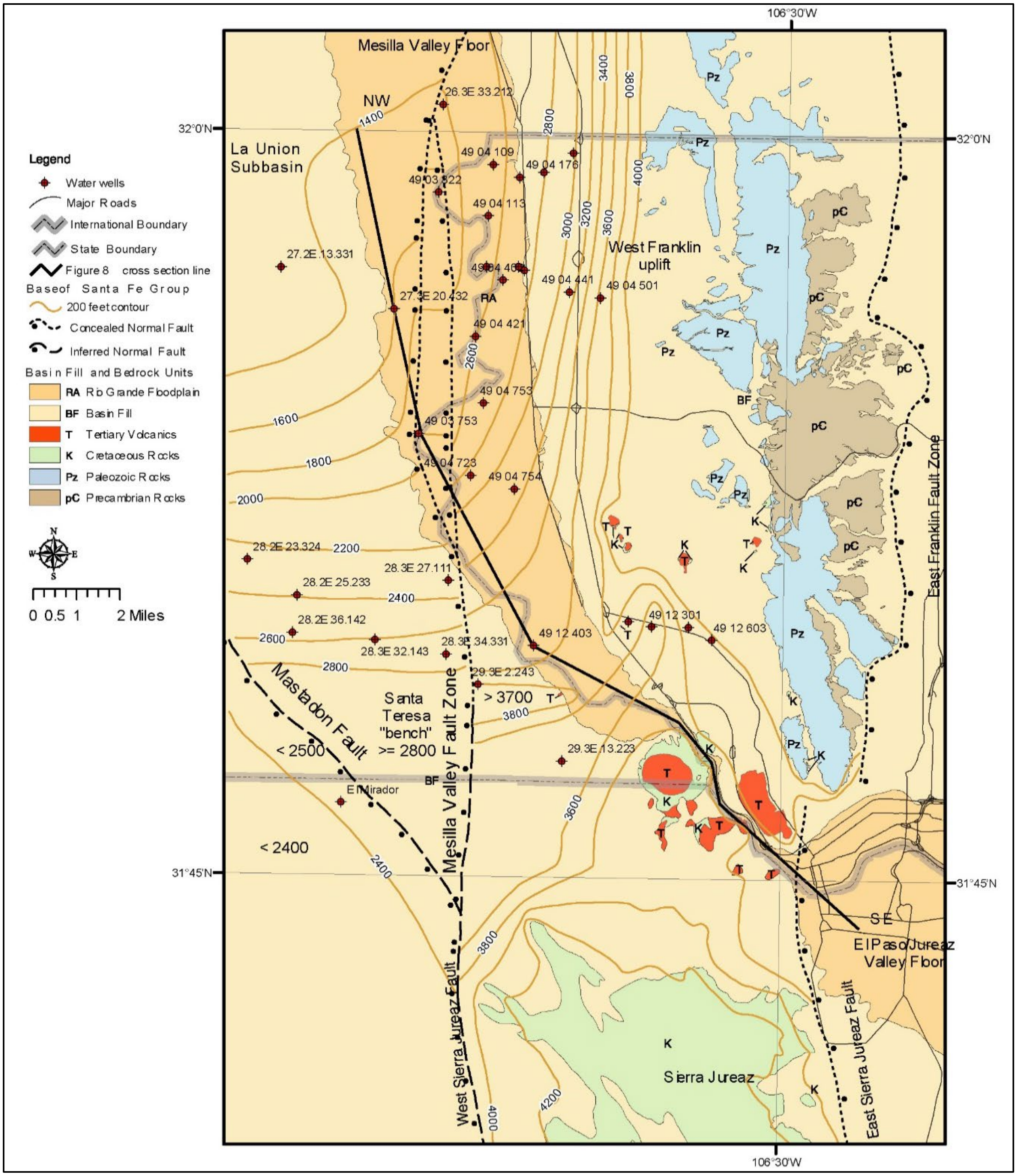


Figure H5-2 (Hawley and Kennedy 2004, Fig. 5-2). *First-generation* **s**tructure-contour map of the base of Santa Fe Group basin fill in the Lower Mesilla Valley and Paso del Norte area. Contour interval: 200 ft (~60 m). Heavy black line shows location of NW-SE down-valley hydrogeologic cross-section (**Fig. H5-3**).

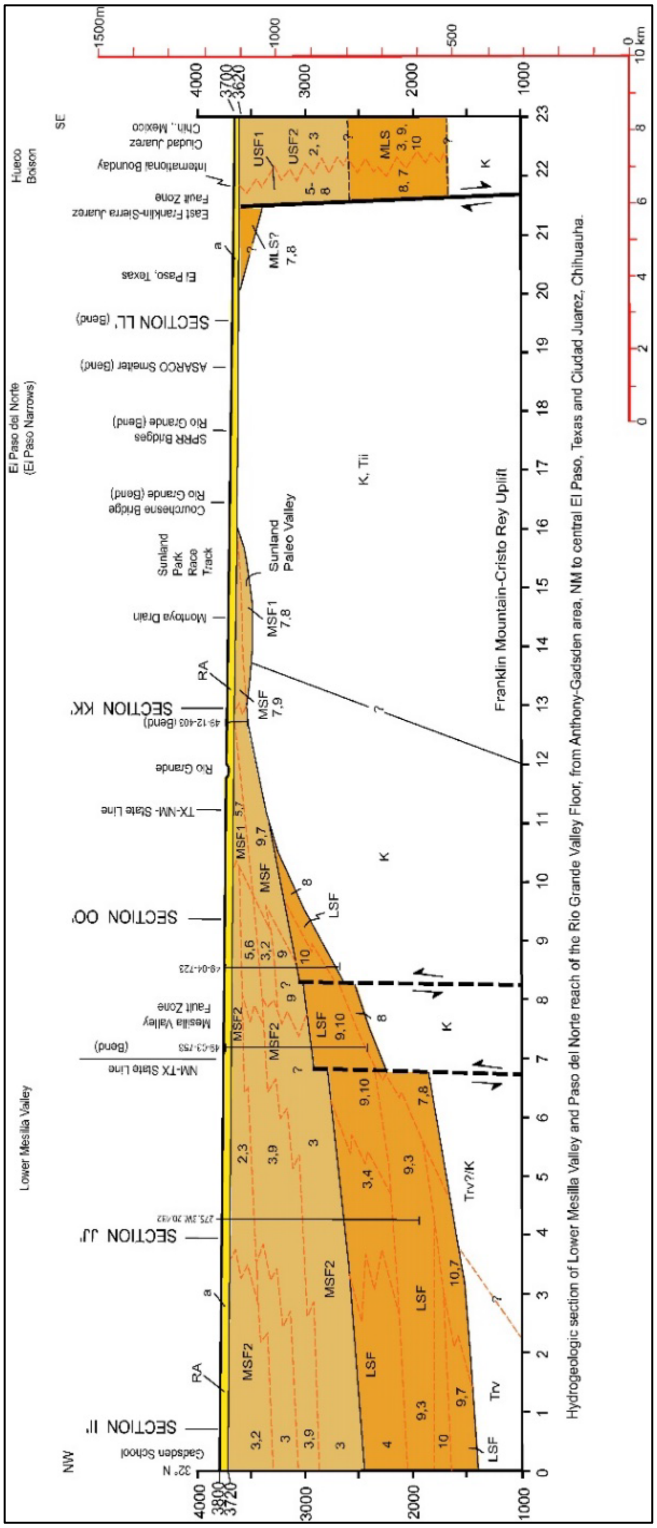


Figure H5-3 (Hawley et al. 2009, Fig. 8; modified from Hawley and Kennedy (2004, Fig. 5-3)**.** Hydrogeologic cross-section of the Lower Mesilla Valley-El Paso del Norte-El Paso/Ciudad Juárez reach of the Rio Grande/Bravo Valley. Vertical exaggeration (VE) ~10x. Heavy black line on **Figure H5-2** shows location of NW-SE cross-section that extends from Lat. 32° N to central Ciudad Juárez near Long. 106°30' W (*cf.* Rpt. **PLS. 5o** and **5l**).

Figure H5-2 is a *first-generation* **s**tructure-contour map of the base of SFG basin fill in the Lower Mesilla Valley and Paso del Norte (EPdN) area that was compiled by Hawley and Kennedy (2004, Fig. 5-2). The contour interval is 200 ft (~60 m). **Figure H5-3** is a schematic hydrogeologic cross-section of the Rio Grande/Bravo's Lower MeV-El Paso/Ciudad Juárez reach (Hawley et al. 2009, Fig. 8). It was initially compiled by Hawley and Kennedy (2004, Fig. 5-3); and its location is shown with a heavy black line on **Figure H5-2**. The base altitude of the section is about 300 m (1,000 ft) amsl, and its vertical exaggeration (VE) is about 10x. EPdN is incised in low-permeability bedrock units of the Cerro Cristo Rey Uplift and Campus-Andesite Hills (*cf.* Rpt. **Part 5.1.4**).

The following calculations illustrate the EPdN's effect on limiting interbasin GW flow and forcing upwelling of a regional-flow system that has binational sources: River-channel gradient in EPdN reach between the MeV's lower end (1,135 m [3,724 ft] amsl) and the western Hueco Bolson (1,126 m, 3,694), is ≤0.003. Minimum alluvial-channel width is about 100 m, and maximum saturated thickness of alluvial fill (RA) is about 23 m. With an estimated hydraulic conductivity (K_{hsat}) of ≤30 m per day, maximum underflow discharge through EPdN would approximate, or be even less than the 0.1 hm^3/yr (81 ac-ft/yr, 0.11 cfs) discharge rate calculated for the EPdN-American Dam site area by Slichter (1905b, p. 13; *cf.* **Apndx. C1.1**).

Figure H5-3 also schematically illustrates the hydrogeologic controls on recharge to the thin river-alluvial and thick SFG basin-fill aquifer systems in the western Hueco Bolson downstream from El Paso del Norte. Eastoe and others (2008, p. 746) use stable-isotope data to distinguish four water types the Basin-Fill:

> Two types [their Groups A and B] relate to recharge from the Rio Grande: pre- [Elephant Butte] dam (pre-1916) river water [Grp. B] with oxygen-18 and deuterium (δ^{18}0, δD, %o) from (-11.9, -90) to (-10.1, -82), contrasts with present-day river water [Grp. A] (-8.5, -74) to (-5.3, -56). Pre-dam water is found beneath the Rio Grande/Bravo floodplain and Ciudad Juárez, and is mixed with post-dam river water beneath the floodplain. . . .

In their Hueco Bolson example, Eastoe and others (2008, p. 746) demonstrate that "recharge to regional aquifers in alluvial basins can be dominated by stream-bed infiltration where the geology and local groundwater conditions are favorable [e.g., MeV below Selden Canyon]." With regards to the "stream-bed infiltration" recharge process that has occurred for thousands of years in the Rio Grande/Rio Bravo reach just downstream from El Paso del Norte, an *unintended consequence* of the concrete-lined, canalized river of the "Chamizal Convention (**H2.3.5**)" was the effective termination of that process in this particular reach of the river (*cf.* Mueller 1975 [p. 99], Hibbs et al. 1997 [p. 57]. Eastoe et al. 2008, Hawley et al. 2009). Nonetheless, the hydrogeologic framework that underlies much of central Ciudad Juárez (Historic El Paso del Rio de Norte) remains ideal for a very large "managed-aquifer-recharge" (MAR) project that would utilize treated metropolitan "waste water" from wide variety of sources including storm runoff. (*cf.* **Part H7.2**; Buszka et al. 1994, Sheng 2005, EPW-ND, Wolf et al. 2020).

H5.5. Basic Hydrogeologic Framework Components of the Southwestern Hueco Bolson Area

Figure H5-4 (courtesy of the UACJ Instituto de Ingeniería y Tecnología [IIT]). This (*circa* 2005) Landsat-5 color-IR image of the binational/tristate southwestern Hueco Bolson area includes much of Ciudad Juárez and eastern El Paso. The eastern Sierra de Juárez is at the image's western edge, and the lower end of EPdN is in its NW corner. The gray sinuous line marks the 1963 Chamizal Treaty Boundary and the location of the concrete-lined Rio Grande/Bravo channel (Mueller 1975). The floor of the upper El Paso/Juárez Valley (alt. ~ 1,120 m amsl) includes large areas of irrigated cropland (red). The SW—NE solid black line shows the location of the hydrogeologic section on **Figure H5-4**, which is located near the southwestern part of Section GD' in Hawley and others (2009, PL. 2g). The dashed black line marks the approximate position of the East Sierra Juárez fault zone (ESJfz; Zona de Fallamiento), and the structural boundary between the Sierra Juárez uplift and the Hueco Bolson. The dominant landform south of the river valley comprises remnants of Early- to Mid-Pleistocene Bolson floor that are underlain by thick USF2-ARG deposits. The Abraham González International Airport, which appears as a black-X pattern in the north-central part of the image, is near the northeastern edge of the Bolson floor.

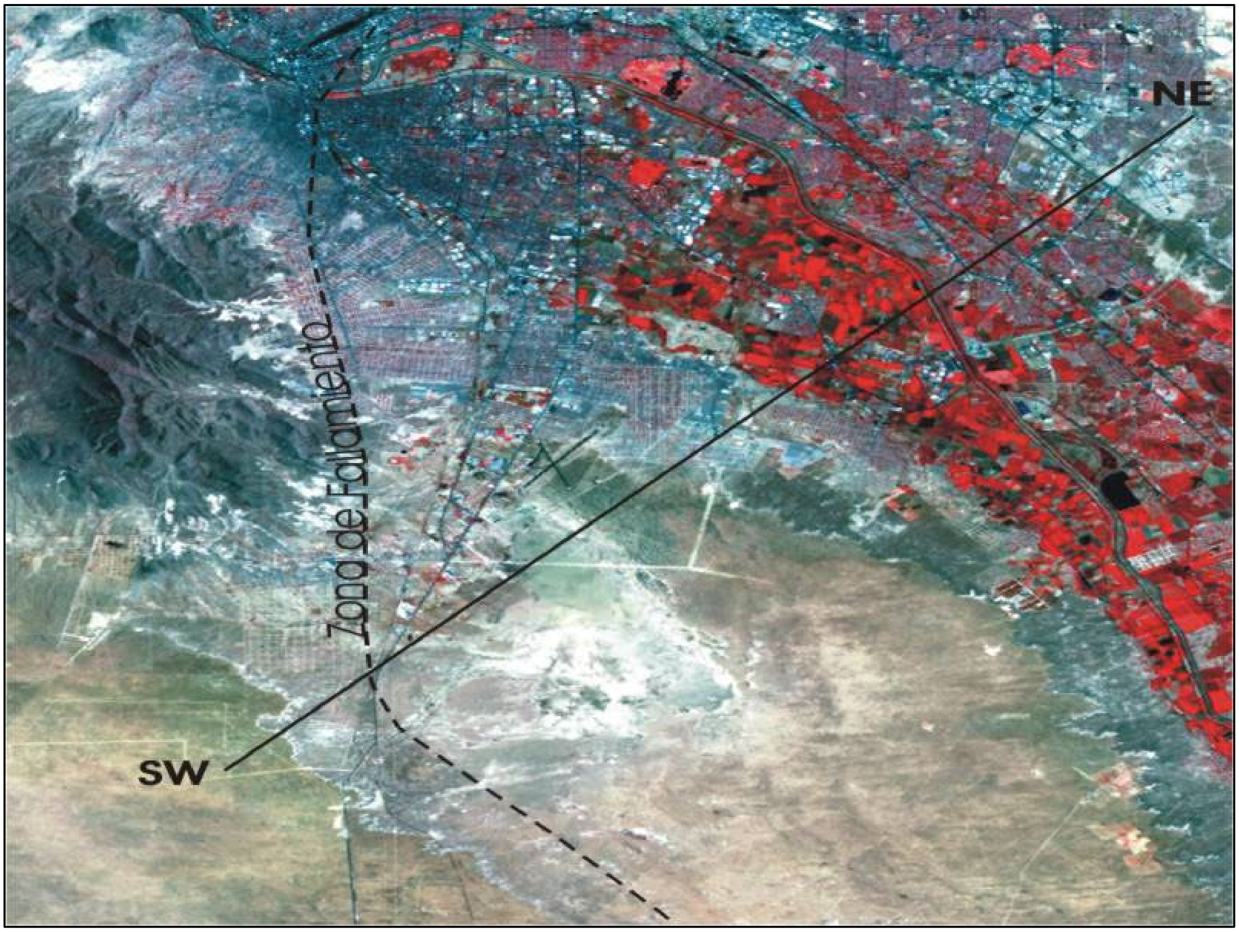


Figure H5-4. Landsat-5 color-IR Image (*circa* 2005) of the southwestern Hueco Bolson area that includes much of Ciudad Juárez/El Paso metroplex (mostly blue-gray tones). The eastern Sierra de Juárez is at the image's western edge, and the lower end of EPdN is in its NW corner. The gray sinuous line marks the International Boundary and the location of the concrete-lined Rio Grande/Bravo channel. The dashed black line shows the approximate position of the East Sierra Juárez fault zone (Zona de Fallamiento). The SW–NE solid black line shows the location of **Figure H5-5**; and principal runways of the Abraham González International Airport appear as black-X pattern in the north-central part of the image. Site of the 287 m SRH test well shown on **Figure H5-5** is near the SW edge of the Airport.

Figure H5-5 (also courtesy of the UACJ-IIT) is a schematic hydrogeologic cross-section of the Upper Valle de Juárez and-El Paso Valley (TX). The Rio Bravo/Rio Grande marks the International Boundary and the location of the reinforced-concrete-lined, 1963 Chamizal Treaty channel. The cross-section location is shown with the SW–NE solid-black line on **Figure H5-4**. Its base is mean sea-level (msl) and vertical exaggeration (VE) is about 10x. The approximate potentiometric surface is shown by a blue-dashed line with triangles. The site of the SRH-JICR 287 m test well shown on **Figure H5-5** is near the SW edge of the Airport (**P183**, **186**; alt. ~1185 m amsl; Córdoba et al. 1969, p. 3; **Apndx. D1.1**).

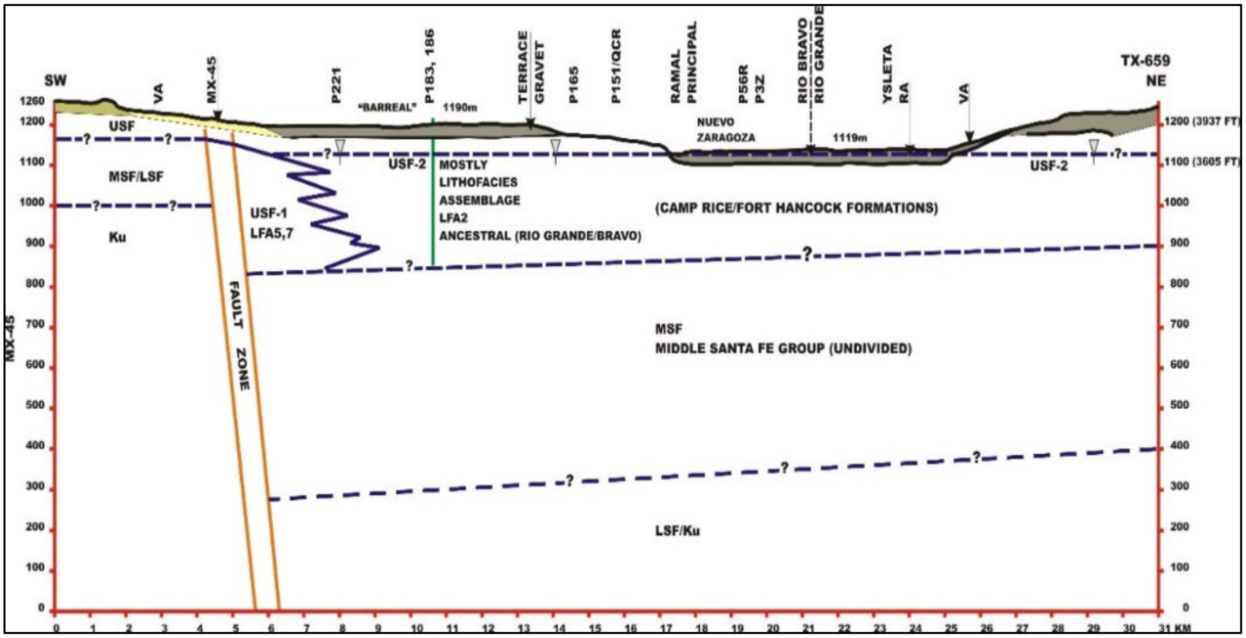


Figure H5-5 (courtesy of the Instituto de Ingeniería y Tecnología, UACJ**)**. Hydrogeologic cross-section of the Upper Valle de Juárez-El Paso Valley (TX), with the Rio Bravo/Rio Grande marking the International Boundary and the reinforced-concrete-lined, Chamizal Treaty channel. The cross-section location is shown with a SW–NE solid-black line on **Figure H5-4**. The vertical green line (Wells P183, 186) also shows the approximate locations of the respective 1,204 m (3,950.3 ft) Petroleum Company of Juárez, and 270 m (940 ft) SRH-JICR test wells that were drilled southwest of the Abraham González International Airport. The section base is at mean sea-level, and VE is about 10x. The approximate potentiometric surface is shown by a blue-dashed line with triangles.

The basic hydrostratigraphic and structural components of the hydrogeologic framework in the southwestern Hueco Bolson-Sierra Juárez-area were initially described by Alfonso de la O-Carreño, Professor of Geophysical Exploration Methods at the UNAM (1957b*, 1958; **Figs. H5-4** and **H5-5**; **Part H4.2**; Hibbs 1997 [p. 47]). Prof. de la O-Carreño's pioneering geological and geophysical investigations were part of a larger groundwater-resource study in the vicinity of Ciudad Juárez. Of special merit was his analysis of borehole cuttings from a 1,204 m (3,950.3 ft) test well that was drilled for the Petroleum Company of Juárez near the western entrance of the International Airport (land-surface alt. ~ 1,185 m/3,888 ft). The site is about 2 km NE from the fault that separates the Sierra Juárez uplift from the southwestern Hueco Bolson. While Cretaceous limestones of the uplift were "not reached" the borehole, it is possible that "pink and gray shales" penetrated between 1,019 and 1,028 m may be of Cretaceous age. Nonetheless, all material sampled above 1,013 m (3,324 ft) is here interpreted as Santa Fe Gp basin fill, and at least the upper 305 m (1000 ft) of the sand-dominant section above 506 m (1,660 ft) has been identified as an Upper Santa Fe Group (USF2-ARG deposit; Córdoba et al. 1969 [p. 1-3]; Hawley et al. 2009 [PLS. 1, 2f and 2g]).
**English translation of de la O-Carreño (1957b) provided by B.J. Hibbs on 11/12/2021.*

Ancestral Rio Grande/Bravo deposits in the Upper Santa Fe Group (USF-2) form the primary source of fresh and slightly saline (<3,000 mg/L TDS) GW. Underlying SFG basin fill (MSF/LSF) is not a significant GW producer due to fine-grained texture and/or induration, and water salinity is mostly in the 3,000 to 5,000 mg/L TDS range. Marine Cretaceous bedrock units (Ku), which are exposed in the Sierra Juárez, fault-block uplift, are primarily composed of limestone, shale, and sandstone with some interbedded gypsum layers (**Figs. H1-19** and **H1-20** [III-III']; **Tbl. H1-10**). As noted above, central Ciudad Juárez's hydrogeologic setting is ideal for a large managed-aquifer-recharge (MAR) project that would utilize treated "waste water" from a variety of sources, including storm runoff from an urban/suburban watershed of about 150 km^2 (**Figs. H1-13** and **H5-2** to **H5-5**).

H6. THE TRANSBOUNDARY AQUIFER ASSESSMENT PROGRAM (TAAP)

H6.1. Overview

Rapidly diminishing fresh-groundwater reserves throughout the International Boundary Zone (IBZ-**Fig. H1-12**) have had a major negative impact on equitable allocation of "Transboundary" water resources—surface, subsurface, and tristate. Moreover, absence of effective mechanisms for timely collection and exchanges of hydrogeologic information on aquifer-system characteristics has been a significant impediment to effective water-resource management, especially with respect to opportunities for conjunctive use of the Transboundary region's groundwater supplies (Hathaway 2011; Ortega Klett 2012; Ward et al. 2019).

The transboundary character of this study required that special emphasis be placed on features of significant binational and interstate concern, both public-institutional and private-entity. Research therefore has been closely linked with previous and concurrent studies of multi-institutional and multi-disciplinary nature, some of which continue to have sensitive binational-political and/or interstate-compact implications (*cf.* **Apnds. B** to **D**). They include the USGS Southwest Alluvial Basin Regional Aquifer-System Analysis (SWAB) and EPA-La Paz—Border XXI projects, and the ongoing Transboundary Aquifer Assessment Program (TAAP) (e.g., Wilkins 1986, Frenzel and Kaehler 1992, Kernodle 1992a, Nickerson and Myers 1993, Hibbs et al. 1997, Wilkins 1998, Hawley et al. 2000 and 2009, Hawley and Kennedy 2004, Creel et al. 2006, Granados Olivas et al. 2009 and 2012, Sheng et al. 2013, Sweetkind 2017 and 2018, Sweetkind et al. 2017, Teeple 2017a, and Hanson et al. 2018).

Current NM WRRI hydrogeologic investigations were initially designed to integrate binational aspects of these research activities into appropriate parts of the Transboundary Aquifer Assessment Program (**TAAP**, Alley 2013). The program originated in U.S. Public Law 109-448, which was signed by President George W. Bush on December 22, 2006 as the United States-Mexico Transboundary Aquifer Assessment Act (US-MX TAA, 2006). The act (S.214-1) authorizes: "The Secretary of the Interior to cooperate with the States on the border with Mexico and other appropriate entities in conducting a hydrogeologic characterization, mapping, and modeling program for priority transboundary aquifers, and for other purposes."

The NM WRRI was selected as the lead institution in three major TAAP activities: **Task 1** - Water-resource economics, with Dr. Bobby Creel as co-PI; **Task 2 -** Binational bibliography compilation (**Apndx. B**); and **Task 4** - Hydrogeologic-framework characterization. The scope of work described in Report **Part 1.3** conforms to Sections 1 and 3 of the "Act," which specifically involves the process of "systematically assessing priority transboundary aquifers" in the "Hueco Bolson and Mesilla aquifers underlying parts of Texas, New Mexico, and Mexico; …." From a hydrogeologic perspective, the primary NM WRRI Statement of Work objectives are outlined in **Tasks 2** and **4** in the "Updated U.S. Joint Work Plan for Mesilla Basin/Conejos Médanos (11/30/2010, p. 3-6)." The range of interdisciplinary and multi-institutional involvement in TAAP activity is illustrated in **Figures H4-17**, **H6-3** and **H6-4**, and **H6-6** to **H6-9.**

Task 2 activities involved the identification, review, and evaluation of previous hydrogeologic studies in the Mesilla Basin and Hueco Bolson region. This ongoing binational effort exemplifies the basic TAAP theme of database sharing, and involves compilation of published information, in an annotated-bibliographic format, on Transboundary aquifer systems in a large binational region that extends beyond the Study Area into surrounding parts of Chihuahua, New Mexico and Trans-Pecos Texas (e.g., Granados Olivas et al. 2009 and 2012). Primary topical categories in **Appendix B1**, each with an alpha-numeric cross-referencing code, include: bibliographies and reviews, historical documents, environmental and geologic topics, basic hydrogeologic concepts, GIS/remote sensing and land-use planning, regional geohydrology, and basin to local-scale aquifer systems (hydrogeology, hydrochemistry, geophysics, groundwater-flow models, and paleohydrology). Short explanatory annotations will be created for specific references where needed, and the MS Word format is designed to facilitate bibliographic conversions using EndNote® software (*cf.* Hawley et al. 2012). An annotated list of 2,214 references has been compiled as of June 10, 2023.

Task 4 primarily involved updating the initial Mesilla Basin hydrogeologic-framework model (Hawley and Kennedy 2004) to better "define aquifer characteristics and further support development of scientifically sound groundwater-flow models." Transboundary-aquifer characteristics and hydrogeologic-boundary conditions in contiguous parts of the Mesilla GW Basin (MeB) and the "Acuífero Conejos-Médanos" section of the "Zona Hidrogeológica de Conejos Médanos" have received special attention (*cf.* INEGI 2012). The substantial progress made to date on **Task 4** completion is covered in detail in Report **Chapters 3** to **7 (**e.g., Hydrogeologic maps, cross-sections, and block diagrams [**Figs. H1-6**, **H1-14**, and **H1-17** to **H1-21**]). Some progress in **TAAP** research was made prior to the untimely death of NM WRRI Associate Director Dr. Bobby Creel in early 2010. Moreover, loss of his seasoned and dynamic leadership in both statewide and in regional water-resources research programs coincided with an unanticipated curtailment of federal and state funding support for TAAP activities. The resultant interruptions in GIS laboratory-service availability led to major delays in completion of the **Task 4** hydrogeologic investigations that were originally designed to be an integral part of ongoing numerical-modeling efforts at Regional USGS Water Science Centers. Nonetheless, even without adequate funding support, TAAP-related studies have led to some very productive collaborations (**Figs. H6-1** and **H6-2**; e.g., Eastoe et al. 2008, Granados Olivas et al. 2009 and 2012, Hawley et al. 2009 and 2012, Sheng et al. 2013, Hibbs et al. 2015, Sweetkind 2017, Sweetkind et al. 2017, Teeple 2017a, Hanson et al. 2018, Kubicki et al. 2021, García-Vásquez et al. 2022, Hawley and Swanson 2022).

The challenges that face the still unfunded binational component of **TAAP-Task 4** are illustrated in the following selection from the 'Future Plans' part of the 2013 review of "Mesilla Basin/Conejos-Médanos section of the Transboundary Aquifer Assessment Program" by Sheng and others (2013, p. 28):

> The Conejos-Médanos well field began full operation in 2010 with initial drawdown effects observed across the southwestern part of the basin. This new hydrologic stress is not yet accounted for in existing groundwater-flow models. A fully binational resource such as the Mesilla Basin/Conejos-Médanos aquifer system requires a coordinated approach and a joint effort to achieve consistency and acceptability from all parties. Accordingly, future plans include (1) integration of the hydrogeologic framework across the border, (2) development of a joint conceptual water budget for the Mesilla Basin/Conejos-Médanos aquifer system, and (3) selection, construction, and application of a mutually acceptable, fully integrated hydrologic flow model that will simulate the inflows and outflows of the groundwater and surface water of the transboundary region. Depending on funding levels, the TAAP may further the development of a binational model and promote the exchange of information between specialists in the United States and Mexico.
>
> The integration of the hydrogeologic framework is a critical step in improving the understanding of the transboundary resource. Recently completed **TAAP** hydrostratigraphic studies (J.H. [W.] Hawley, New Mexico State University, written commun., 2011) extend across the border area and will be digitized and distributed. Although these studies are based on

preliminary data from test holes at the Conejos-Médanos well field, the recently completed TAAP study of the Conejos-Médanos aquifer system (Mexican Geological Service, 2011a and 2011b [**Figs. H6-3** and **H6-4**]) provides new data and suggests a much broader aquifer extent toward the southeast, with important inferences on regional basin recharge and inflow of saline groundwater. Electromagnetic profiles in Mexico and other new data in the TAAP Conejos-Médanos report (Mexican Geological Service, 2011a and 2011b) will be compared with the newly published interpretations (J.H. [W.] Hawley, New Mexico State University, written commun., 2011) and integrated into a basin-wide hydrogeologic framework. Analysis of microseismic events may also allow definition of faults and flow boundaries, which have been found to play an important role in Mesilla Basin hydrogeology. The final product of joint work sessions would be an improved understanding of the hydrogeologic framework across the entire basin. . . .

Lessons learned from the Mesilla Basin activities could also be used in developing joint work plans for the Hueco Bolson and Presidio-Redford Basin in west Texas and the Mimbres Basin in southwest New Mexico.

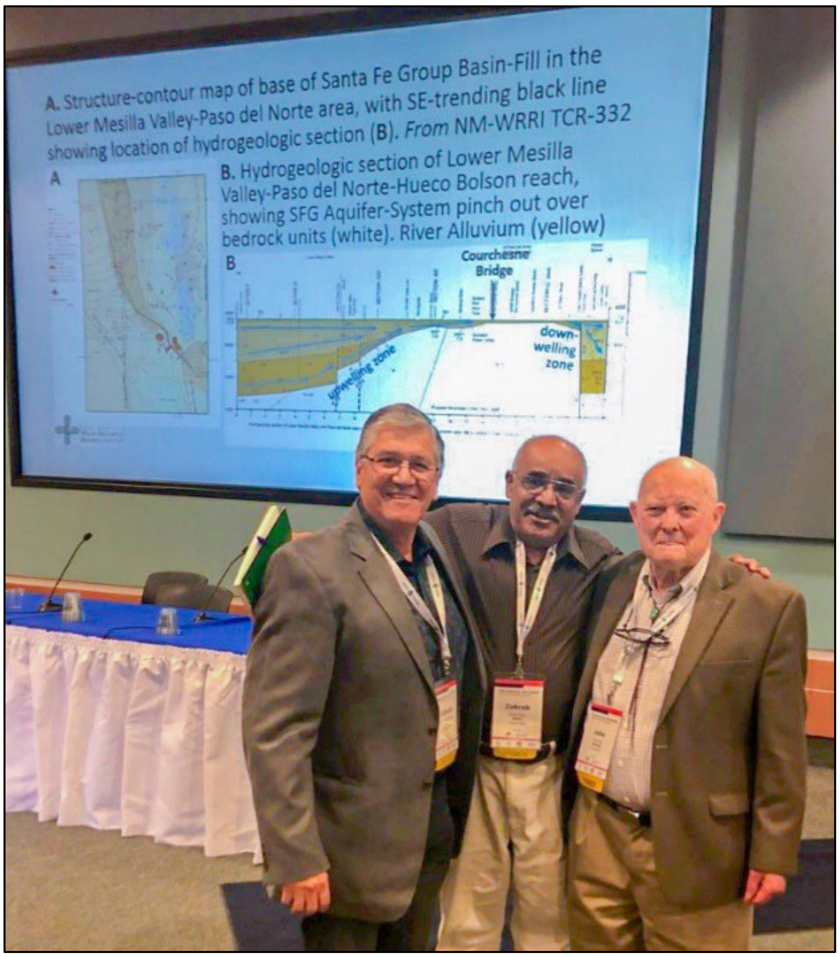


Figure H6-1. Drs. Alfredo Granados-Olivas (UACJ-L), Zohrab Samani (NMSU-C), and John Hawley (NM WRRI) following their presentations on Transboundary-Aquifer Management issues "US-Mexico Border Water Summit—Two Nations One Water," El Paso Water TecH$_2$O Center, March 1-2, 2018. PPT-slide on screen in background is based on the first digital portrayal of hydrogeologic-framework controls on the El Paso del Norte (EPdN) groundwater-flow system (**Figs. H5-2** and **H5-3**). Photo courtesy of Mariana Chew (3/2/2018).

Figure H6-2. Group photograph after talk by John Hawley on "Hydrogeologic-Framework Controls on Transboundary Groundwater Flow in the Mesilla Basin Region" at the April 2019 "Binational Summit on Groundwater at the U.S-Mexico Border," El Paso Water TecH_2O Center. From left to right: Bill Cunningham, Director of the USGS Water Mission-Earth System Process Division; Sam Fernald, Director of the NM Water Resources Research Institute; Gilbert Anaya, Chief of the Environmental Management Division, International Boundary and Water Commission (IBWC); Roberto Fernando Salmón Castelo, IBWC Mexican Section Commissioner; Jayne Harkins, IBWC United States Section Commissioner; and John Hawley. The PPT-slide on screen shows deep-subsurface hydrogeologic conditions in the binational Mesilla Basin area (**Figs. H1-11** and **H1-12**). Photo courtesy of Swanson Geoscience, LLC (4/10/2019).

H6.2. Progress in Hydrogeologic-Framework Characterization of the "Acuífero Conejos-Médanos" Region of Northwestern Chihuahua (2010-2015)

The below-listed cited publications and two SGM (2011) maps illustrate the substantial progress that was made between 2010 and 2015 Hydrogeologic-Framework Characterization of the "Acuífero Conejos-Médanos" and "Acuífero Valle de Juárez" region of northern Chihuahua (**Figs. H6-3** and **H6-4**). While TAAP involvement was important, the primary financial impetus for more detailed GW-resource evaluation involved creation of the very robust public/private-sector partnership that led to development of the new Junta Municipal de Agua y Saneamiento-Ciudad Juárez (JMAS) well field in less than five years.

Servicio Geológico Mexicano (SGM), 2011, Hydrogeological activities in the Conejos-Médanos aquifer, State of Chihuahua, Phase I: Servicio Geológico Mexicano, Volume 1, 109 p.

INEGI, 2012, Zona Hidrogeológica Conejos-Médanos: Instituto Nacional de Estadística, Geografía e Informática, Edificio Sede.

CONAGUA, 2015a, Actualización de la Disponibilidad Media Anual de Agua en el Acuífero Conejos Médanos (0823), Estado de Chihuahua: Subdirección General Técnica, México DF, p. 1-32.

CONAGUA, 2015b, Actualización de la Disponibilidad Media Anual de Agua en el Acuífero Valle de Juárez (0833), Estado de Chihuahua: Subdirección General Técnica, México DF, p. 1-36.

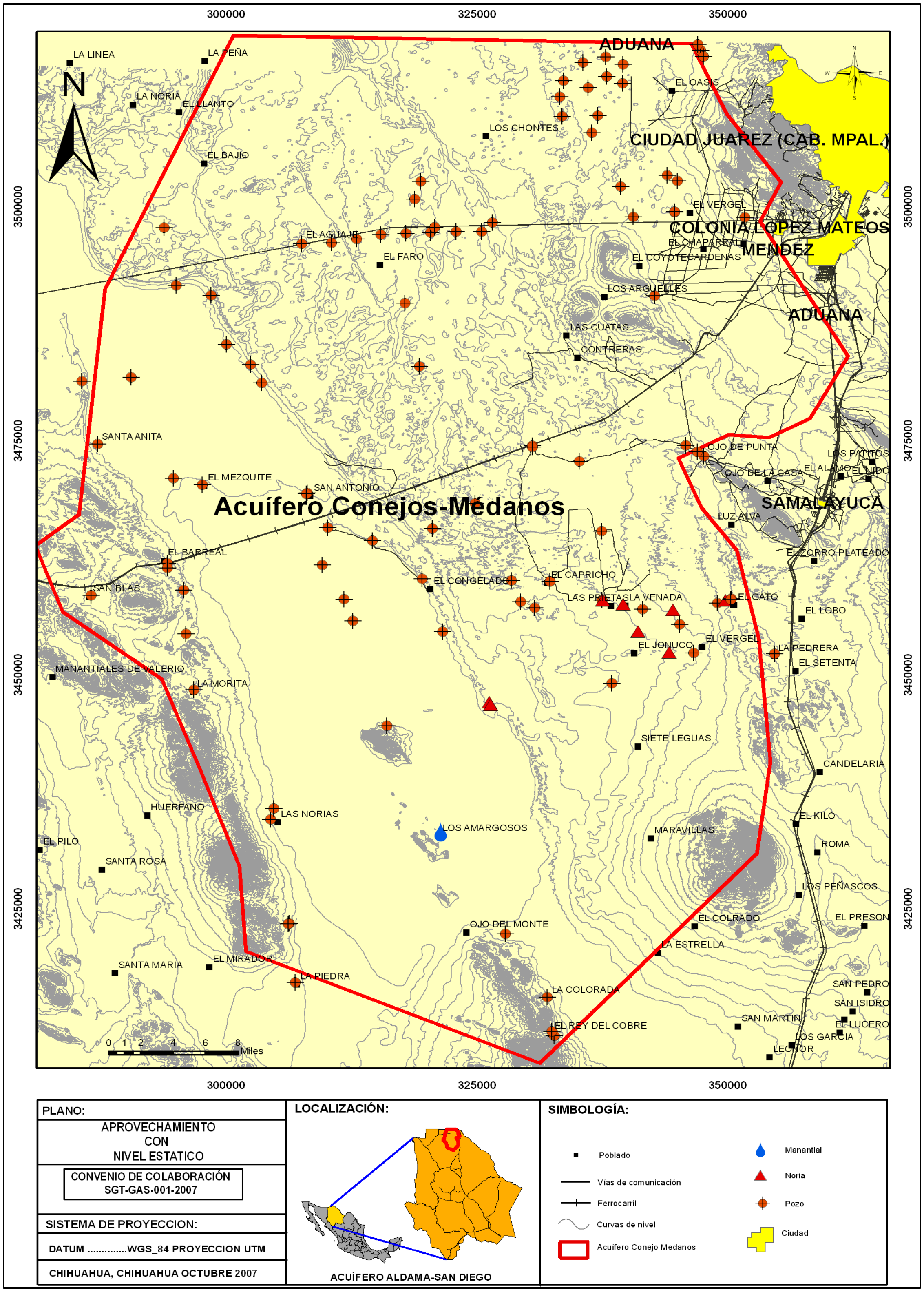


Figure H6-3. Location-index map for the Acuífero Conejos-Médanos on a topographic-map base (10 m contours). Water wells (pozo) shown with crosses in red circles (*cf.* **Fig. H6-4**). Servicio Geológico Mexicano (SGM), 11/30/2010.

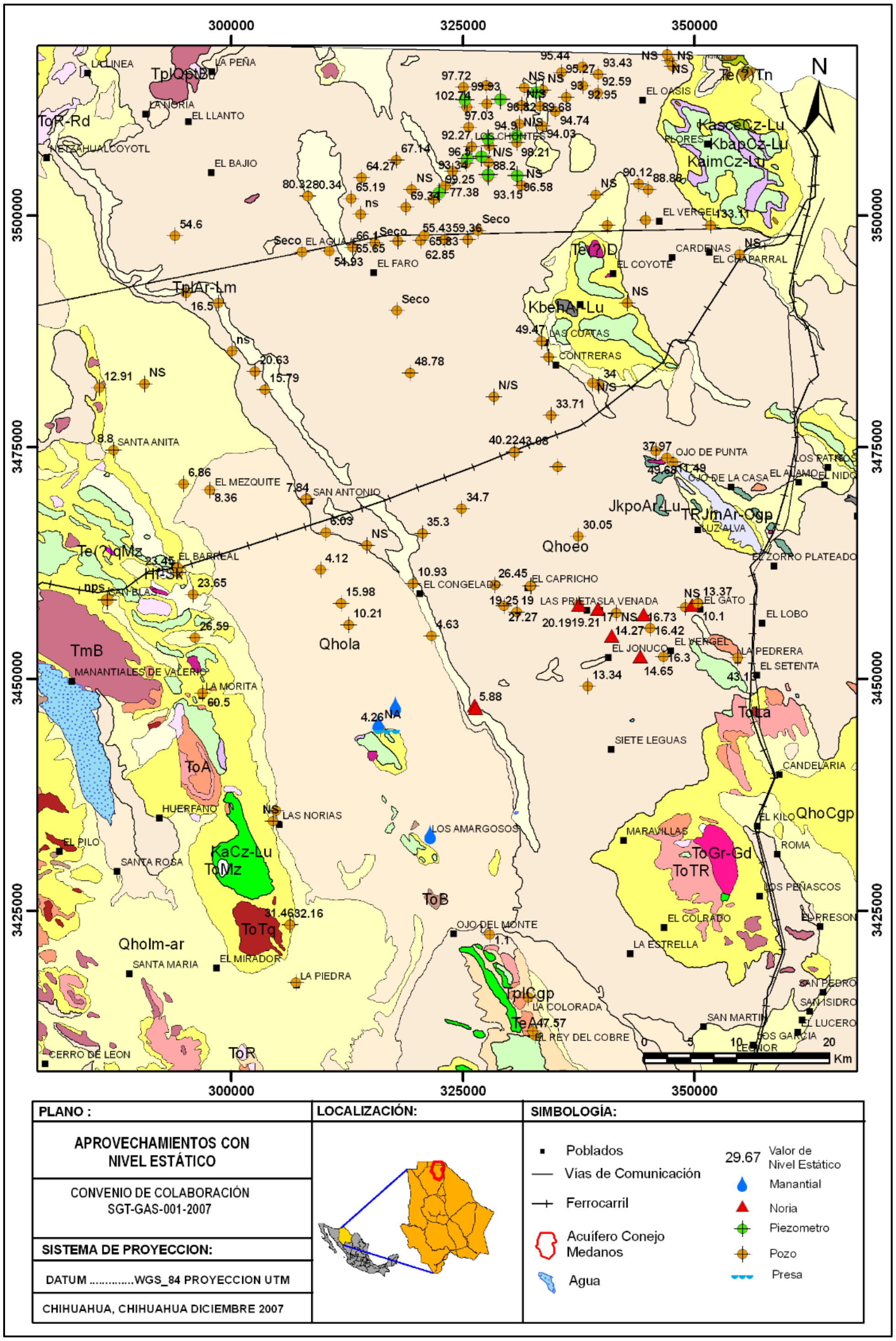


Figure H6-4. Well-location index map (11/30/2010) for the Acuífero Conejos-Médanos region (**Fig. H6-3**). Servicio Geológico Mexicano geologic-map base (SGM 2011). Water wells (pozos) and piezometers shown, respectively, with crosses in red and green circles. Note clusters of new JMAS[CJ] public water-supply wells in the north-central part of the map (Figs, **H1-11** and **H1-12**). Well numbers are keyed to hydrologic-database tables in SGM (2011).

H6.3. Recent Developments in Transboundary GW-Flow System Characterization

The interpretations presented herein on the Late Quaternary evolution of the Transboundary GW-flow system at the southern part of the Study Area (**Figs. H1-10**, **H1-12**, and **H1-17**), have been confirmed by a recent "Investigation of the origin of Hueco Bolson and Mesilla Basin aquifers (US and Mexico) with isotopic data analysis" by Ana C. García-Vásquez and others (2022). With regards to tritium, an unstable isotope of hydrogen (^3H or T), García-Vásquez and others (2022) make the following observation (p. 8):

> The tritium results obtained in this study . . . in the Conejos Médanos Basin varied from −0.70 to 0.58 Tritium Units (TU), which is a non-significant tritium content . . . . This is an important finding because it indicates that the water present in this zone is not of recent origin, which demonstrates that there is no recharge in this zone. Furthermore, this study does not report any significant tritium concentrations in the Conejos Médanos Aquifer [in the general MeB-EPB area].

Stable isotopes for oxygen are ^{16}O, ^{17}O, ^{18}O, and for hydrogen are protium (^1H) and deuterium (^2H, D). When these isotopes are combined to form a water molecule, they also provide an isotopic composition that translates into a powerful hydrology tracer. A pair of isotopes commonly used in hydrology is the $\delta^{18}O$ combination, which is compared using the global meteoric water line (GMWL [*cf.* Craig 1963]) to show the percentage of isotope present in the sample. With regards to $\delta^{18}O$, García-Vásquez and others (2022) observe that (p. 12):

> In conclusion, the samples collected and analyzed by this study complete the description of the Hueco Bolson and the Mesilla/Conejos-Médanos Basin at the US-Mexico transboundary area. According to previous study results shown for Group 2, a stable isotope $\delta^{18}O$ concentration falls below the GMWL in the evaporated zone, which indicates that these are old waters that have undergone evaporation, horizontal infiltration, or dissolution processes. Moreover, groundwater values indicate that groundwater recharge sources include precipitation, bedrock fissure water, or both. Furthermore, results are consistent with findings by Eastoe et al. (2008), Teeple (2017a), Hawley and Kottlowski (1969), Witcher et al. (2004), and . . . ., whose findings indicate that the groundwater is not recent and that it was recharged thousands of years ago when the climate was more humid, which could be the cause for the same isotopic content in the Hueco Bolson and Conejos-Médanos/Mesilla Basin aquifers near the Juarez Mountains.

In the description of their Study Area, García-Vásquez and others (2022) also note that (p. 4):

> In regard to groundwater quality in the transboundary Mesilla/Conejos-Médanos Basin aquifer, Hawley and Swanson (2022. . . .) [state] that the ongoing research has demonstrated that very large quantities of fresh to slightly saline water are stored in the basin-fill aquifer system, where most groundwater in storage is at least 11ka and was recharged during the last glacial/pluvial stage of the Late Pleistocene Epoch (~29 to 11 ka).

H6.4. Remaining Problems in Delineation of the Mesilla/Conejos-Médanos Transboundary Aquifer System

International borders, ground water flow, and hydroschizophrenia (Jarvis et al. 2005, p. 764):

> While it is well understood that aquifers cross international boundaries and that the base flow of international river systems is often derived in part from groundwater, transboundary groundwater and surface water systems are usually managed under different regimes, resulting in what has been described as "hydroschizophrenia." Adding to the problem, the hydrologic relationships between surface and groundwater supplies are only known at a reconnaissance level in even the most studied international basins, and thus even basic questions regarding the

territorial sovereignty of ground water resources often remain unaddressed or even unasked. . . . Limited groundwater management in the international arena, coupled with the fact that few states or countries regulate the use of groundwater, begs the question: Will international borders serve as boundaries for increased "flows" of hydrologic information and communication to maintain strategic aquifers, or will increased competition for shared groundwater resources lead to the potential loss of strategic aquifers and "no flows" for both ground water users?

Transboundary Aquifer (TBA) -vs- Transboundary Groundwater (Rivera, 2021a, p. 10):

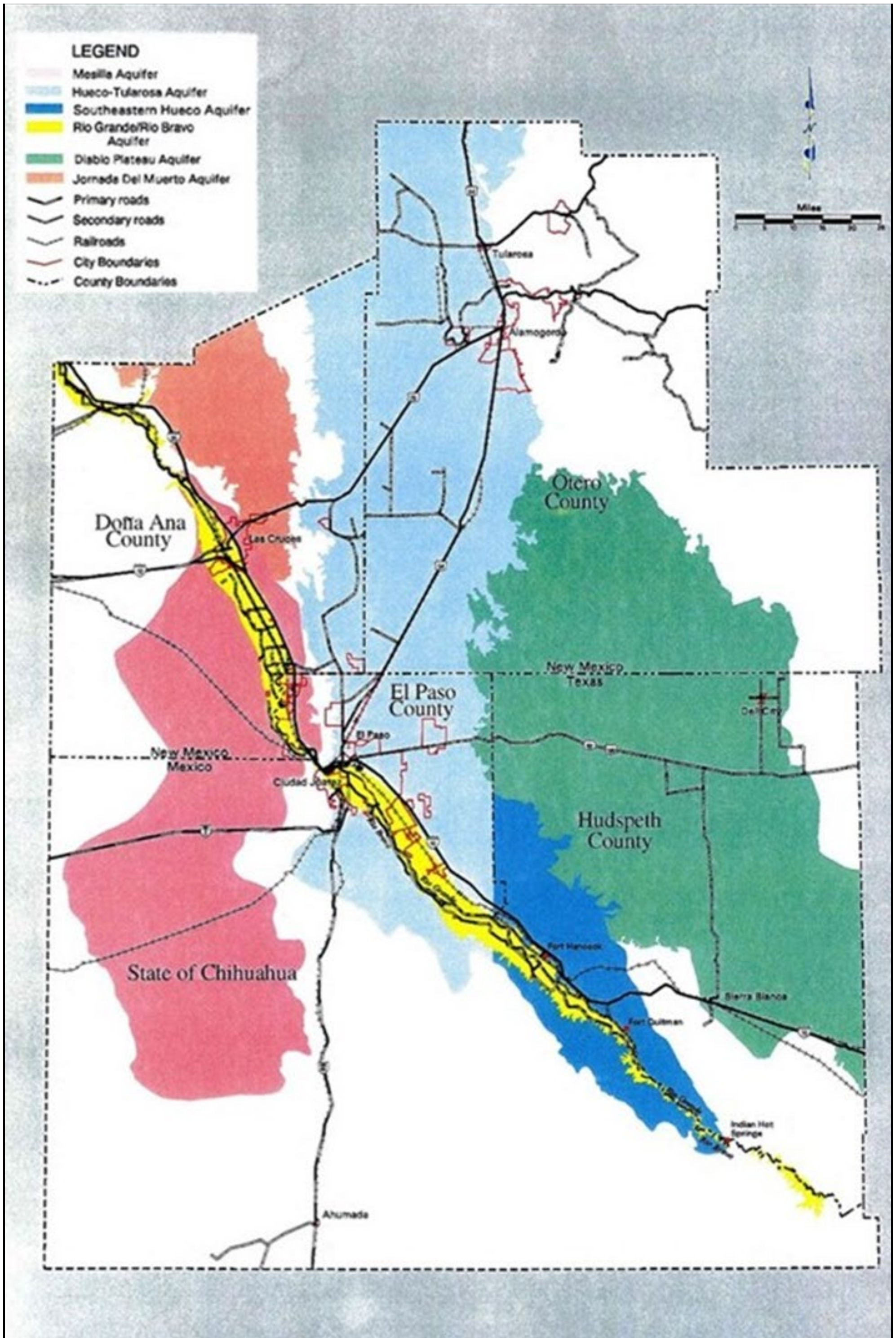
A new vocabulary, new concepts, and more accuracy in terminology have emerged over the last 20 years under ISARM (Internationally Shared Aquifer Resources Management). However, there are disagreements because cultural, political, economic, and social factors differ around the world. In addition to its natural boundaries, *jurisdictional boundaries* need to be added to the TBA.

Contemporary socio-economic and geopolitical circumstances continue to limit effective communication on many issues impacting the Paso del Norte-southern Mesilla Basin region, particularly those relating to joint investigations of shared groundwater resources and related environmental concerns (e.g., Utton and Atkinson 1979, 1981 and 1983, Teclaff 1982, Utton 1983, Malagamba 1990, Barry et al. 1994, Creel et al. 1998, USEPA 2003a-b, Sheng and Devere 2005, Hurd et al. 2006, Macías-Coral et al. 2006, Hawley et al. 2009, Granados Olivas 2010, Mumme 2010, Pacheco 2008 and 2010, 2018c-d, 2019c, Székely 2010, Hathaway 2011, Lee and Ganster 2012, Harris 2012, Fleck 2013, Robinson-Avila and Villagran 2014, USEPA 2015c and 2019, Suthersan et al. 2016a [Fig. 1], Kocherga 2017 and 2018a-g, Villagran 2017a-b, Davis 2020b, 2020f, Hamway 2020a-b). A special challenge faced in binational investigations in the NM WRRI "IBZ" relates to resolving problems in definition of geohydrologic boundaries in a geopolitical environment that is not yet conducive for collaborative field-based research (Rpt. **Figs. 1-6** to **1-8** and **1-11** to **1-13**, vs. **Fig. H6-4**). A special challenge faced in binational investigations in the south-central New Mexico/West Texas border regional relates to the pressing need for precision in geohydrologic/hydrogeologic boundary definition in a geopolitical environment that is not yet conducive for field-based research collaborations (e.g., Rpt. **Figs. 1-6** to **1-8** and **1-11** to **1-13**, vs. **Figs. H6-5** and **H6-6**).

H6.4.1. Mesilla Basin/Conejos-Médanos Aquifer System Conceptual-Model Development – Stage 1

Figures H6-5 to **H6-9** illustrate important aspects of the "White Map" and "hydroschizophrenia" problems that have been described by O.E. Chávez (2000), and Jarvis and others (2005). **Figure H6-5** is a facsimile copy of Figure 1.2 in Hibbs and others (1997; *cf.* Hibbs et al. 1998). It was designed for 1994-2000, La Paz Agreement-Border XXI Program studies of "Transboundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region," at a time when there was only a small amount of geohydrologic information available on what would later be named the "Acuífero Conejos-Médanos" (**Parts H4.3.1** and **H6.9**; *cf.* SPP 1981, SARH 1988, and INEGI 1983b-cj, 1999, 2012). It was never intended to be a *template* for subsequent more detailed characterizations of Transboundary aquifer systems in the southern Mesilla Basin region. According to the following written communication of January1, 2003 from Barry H. Hibbs:

The southern boundary of the Mesilla Bolson in Mexico, for example, was delineated on a very preliminary basis by the author and his colleagues at the Texas Water Development Board [TWDB], as part of their EPA funded binational study (Hibbs et al., 1997; Figure 1.2). The delineation was done in less than an afternoon using 1:50,000 topographic, geologic, and groundwater maps obtained from Instituto Nacional de Estadistica Geografia e Informatica [INEGI] and is best described as a back of an envelope sketch. This preliminary delineation was never intended to become so widely used, but due to an oversight it was printed with the report by Hibbs et al. (1997), and became available as a GIS coverage.



1.2. Transboundary aquifers in the study area.

Figure H6-5 (Figure 1.2 *in* Hibbs et al. 1997**).** The "Mesilla Aquifer" area shown in pink is the first conceptualization of what would later be formally named the "Mesilla Basin (United States)/Conejos Médanos (Mexico) aquifer system" (*cf.* EPWU 2007, IBWC 2010, and Sheng et al. 2013 [**Fig. H6-6**]).

H6.4.2. Mesilla Basin/Conejos-Médanos Aquifer System Conceptual-Model Development – Stage 2

Figure H6-6 is a facsimile copy of Figure 2 in USGS Open-File Report 2013-5028 (Alley 2013; Sheng et al. 2013). The locations of the Mesilla Basin/Conejos-Médanos and Hueco Bolson aquifer systems are shown on a USGS DEM map base. Sheng and others (2013, p. 19) state that the "Mesilla Basin/Conejos-Médanos (MB/C-M) aquifer system" constitutes one of the largest transboundary aquifer systems in the Rio Grande/Rio Bravo Basin region of the United States and Mexico. However, they do not describe the rational for "system" delineation, and they do not seem to be aware of the above-described "very preliminary" "delineation" by the TWDB that was part of a collaborative endeavor with the NM WRRI (e.g., Hibbs et al. 1997; *cf*. Hibbs and 30 others, 1998). While two written communications from John H. [W.] Hawley are cited in Sheng and others (2013; **Part H6.1**), there are no other direct references to NM WRRI hydrogeologic investigations in the Hueco and MB/Conejos-Médanos area (e.g., Hawley et al. 2009).

Figure H6-7 is a location-index map in USGS Scientific Investigations Report 2017-5028 (Teeple 2017a, Fig. 1). It shows the *inferred extent* of interlinked aquifer systems in the hydrogeologically complex Jornada del Muerto, Mesilla, and Conejos-Médanos "Basins" of the south-central New Mexico–northwestern Chihuahua region (**Figs. H1-1** and **H1-6**; e.g., EPWU 2007, IBWC 2010, Sheng et al. 2013, Hanson et al. 2018). There is no indication that the authors of the above-cited documents were even aware of the initial map-compilation process that is described in **Part H6.3.1** (Hibbs et al. 1997). The following statements from Teeple (2017a, p. 3) illustrates how an out-of-context interpretation of the very schematic, 1997-2013 portrayals of an inter-linked Mesilla–Conejos-Médanos basin aquifer system has led to some serious misconceptions of the basic GW flow dynamics in the Transboundary aquifers of the southern Mesilla Basin region west of the Mesilla Valley (MeV) of the Rio Grande and El Paso del Norte (EPdN):

> The hydrogeologic units of the U.S. part of the aquifer system consist of the Rio Grande alluvium and the underlying hydrogeologic units of the Santa Fe Group in and near the Mesilla Basin in Dona Ana County, New Mexico, and El Paso County, Texas.... The Mesilla Basin aquifer system in the United States and the Conejos-Medanos aquifer system in Chihuahua, Mexico, are hydrologically one aquifer system with no natural boundaries separating them….[1*]
>
> The Mesilla Basin/Conejos-Medanos aquifer system is one of the largest rechargeable groundwater systems by total available volume in the Rio Grande Basin region of the United States and Mexico (Alley, 2013), …. The Rio Grande has been identified as a major source of recharge to the aquifer system in the form of seepage losses from the river-bed to the Rio Grande alluvium in parts of the Mesilla Valley…in New Mexico….[2*]
>
> **Footnotes 1 and 2 point out some specific problems that have been caused by continued acceptance by some entities of an antiquated conceptual model of a well-integrated Mesilla Basin/Conejos-Médanos aquifer system (e.g., **Figs. H6-6** to **H6-8**; cf. Pepin et al. 2022 [Fig. 1], Robertson et al. 2022 [Fig. 1]):*
>
> [1] The hydrogeologic, geophysical, and hydrochemical information presented in this report clearly demonstrates that the "Mesilla Basin' and the "Conejos-Médanos aquifer system" are definitely not "hydrologically one aquifer system with no natural boundaries separating them."
>
> [2] SFG basin-fill aquifers in the "Acuífero Conejos-Médanos" area <u>have not</u> received any significant amount of recharge from the Rio Grande basin for at least the past 350 thousand years (Rpt. **Part 3.9**). The Conejos-Médanos part of the GW-flow system, however, does contribute a still unquantified amount of recharge to the "Rio Grande alluvium" and SFG basin fill at the lower end of the MeV (**Figs. H1-10**, **H1-12** and **H1-17**; *cf.* Rpt. **Part 7.7**).

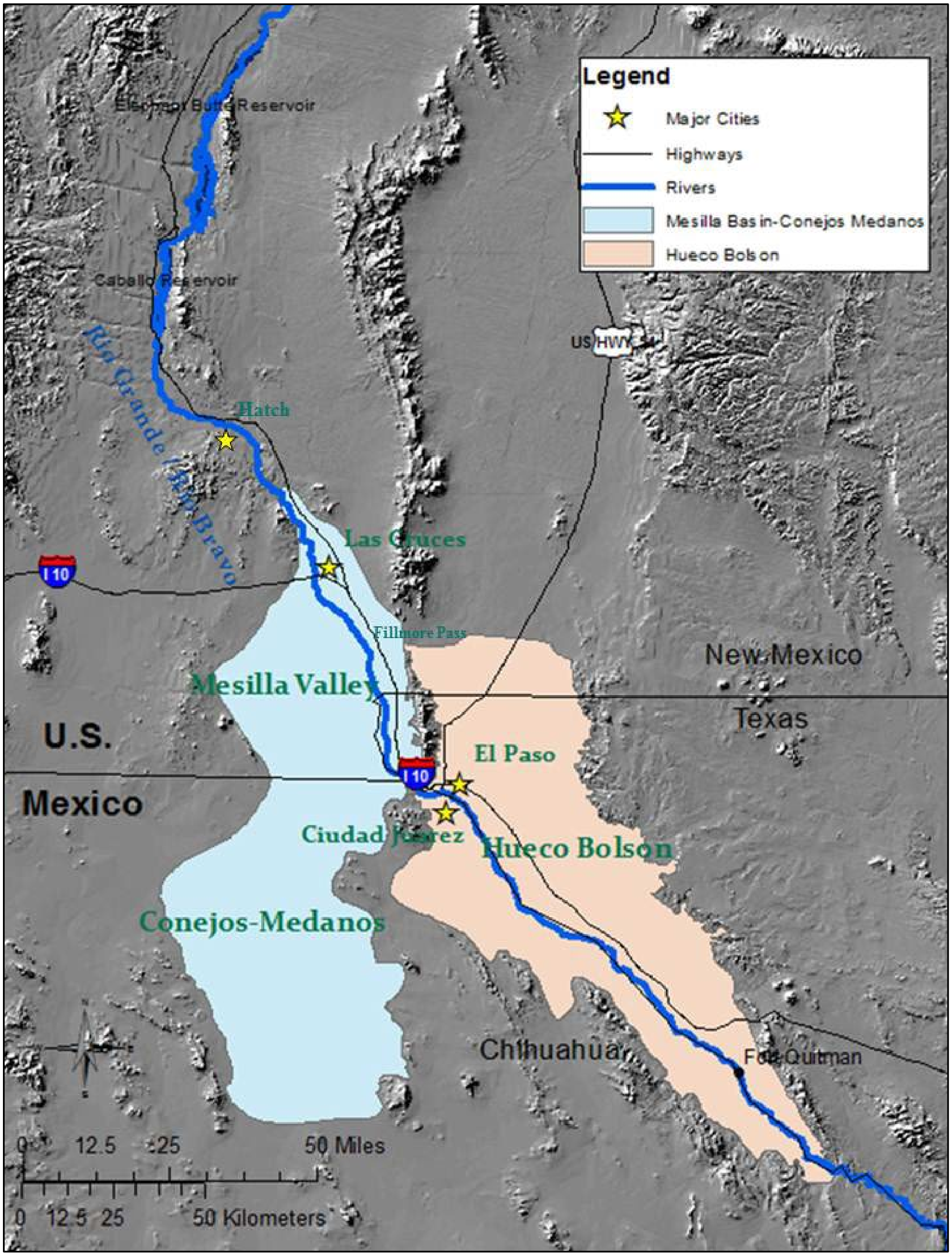


Figure H6-6 (Figure 2 *in* Sheng et al. 2013)**.** The location of the "Mesilla Basin/Conejos Médanos (C-M) aquifer system is shown in blue (*cf.* **Figs. H6-4**, **H6-6** and **H6-7**; and EPWU 2007 and IBWC 2010). Note, however, that no information on the source of the aquifer-system delineation is provided.

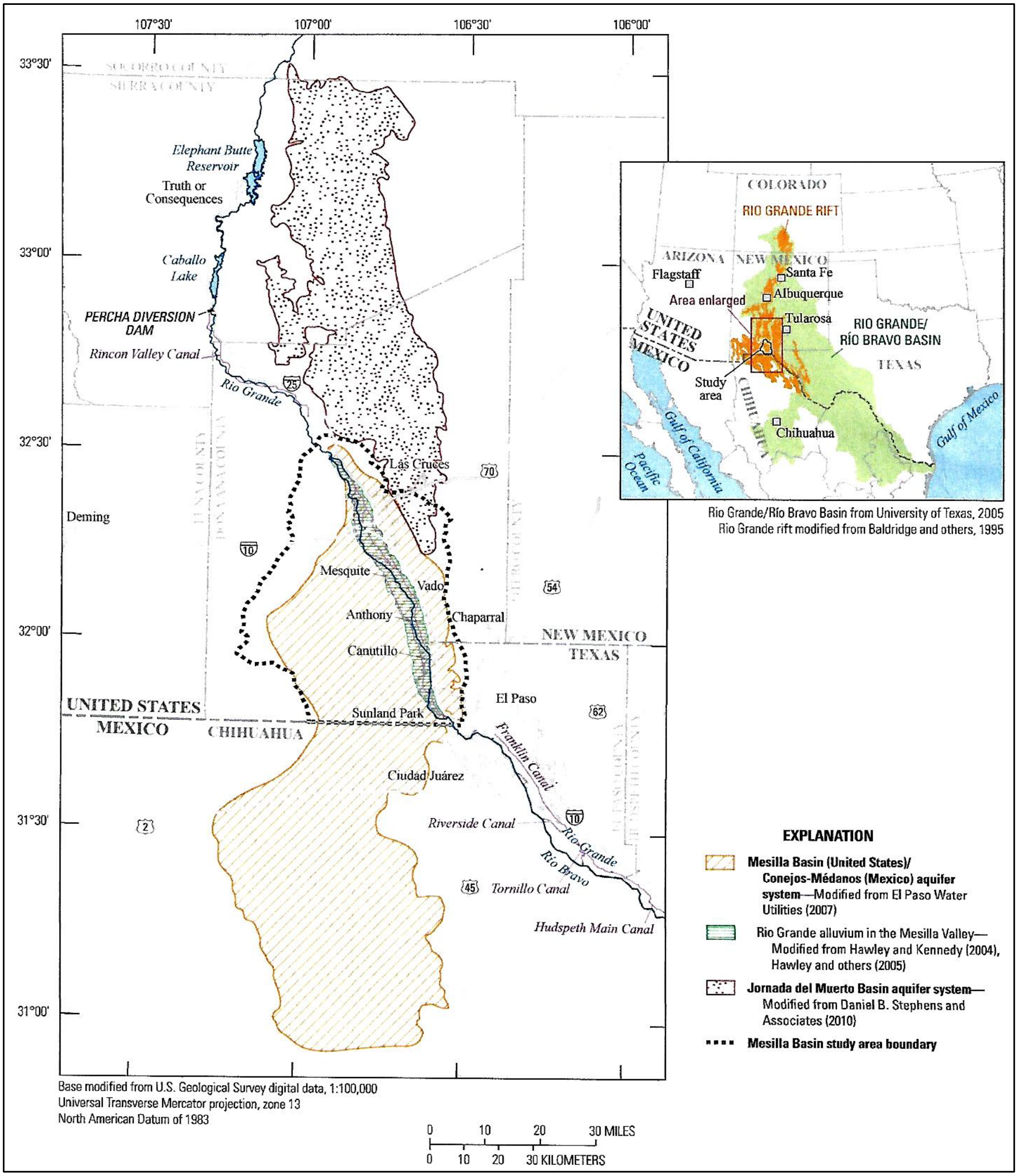


Figure H6-7 (Teeple 2017a, Fig. 1)**.** Index map in USGS Scientific Investigations Report 2017-5028 showing locations of *inferred* interlinked basin-fill aquifer systems in the Jornada del Muerto, Mesilla, and Conejos-Médanos basin complexes of the south-central New Mexico–northwestern Chihuahua region (**Figs. H1-1** and **H1-6**; Hibbs et al. 1997; Hawley et al. 2005; EPW-ND and EPWU 2007; DBSAI 2010; IBWC 2010; Sheng et al. 2013).

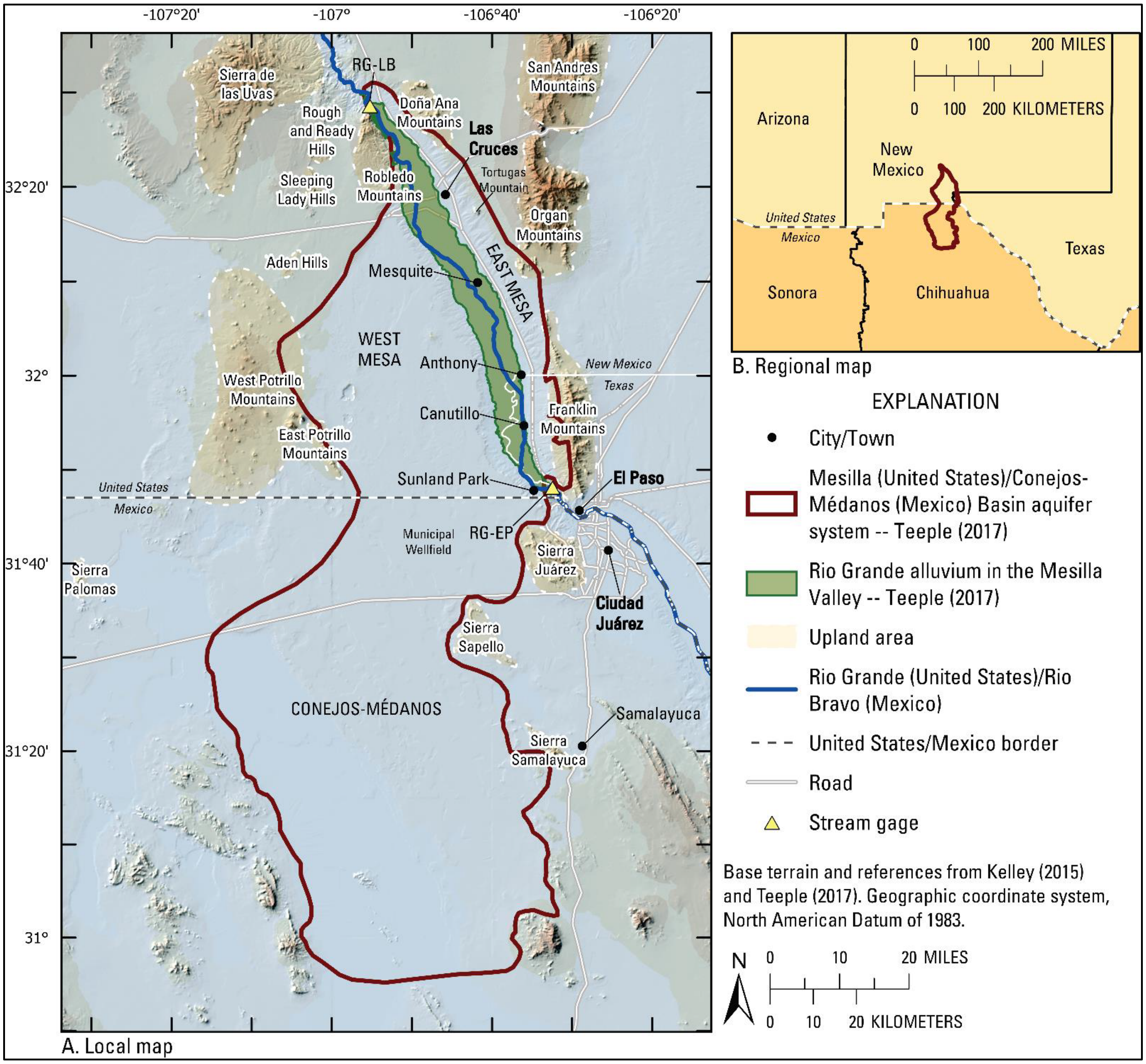


Figure H6-8 (Pepin et al. 2022, Fig. 1)**.** Local (**A**) and regional (**B**) maps showing the location of the study area in the United States (New Mexico and Texas) and Mexico (Chihuahua) [Kelley 2015, Teeple 2017a]. All analyzed temperature data in this work were collected in the United States, while interpreted groundwater elevation mapping covers substantial portions of the aquifer system in both countries. Stream gage abbreviations are as follows: RG-LB = USGS 08363510 Rio Grande below Leasburg Dam at Fort Selden, New Mexico; RG-EP = USGS 08364000 Rio Grande at El Paso, Texas.

Figure H6-9 (Robertson et al. 2022, Fig. 1**).** Location of the Mesilla/Conejos-Médanos Basin in Texas and New Mexico (U.S.), as well as Chihuahua (Mexico). Base terrain and geographic references from U.S. Geological Survey (2021), Teeple (2017a), and Driscoll and Sherson (2016). The geographic coordinate system is the North American Datum of 1983.

H7. CHALLENGES FACING, AND OPPORTUNITIES FOR LONG-TERM GW-RESOURCE DEVELOPMENT IN THE MESILLA BASIN-PASO DEL NORTE REGION

In the context of challenges facing and opportunities for long-term GW-resource development in the southern Mesilla Basin region, opportunities will always exist for building truly binational partnerships in addressing a variety of Transboundary water-resource issues. This is well documented by the long history of collaborative relationships between the NM WRRI, NMSU, USGS-Water Science Centers, El Paso Water (EPW), the International Boundary and Water Commission (IBWC and CILA), the Universities of Texas at Austin and El Paso (UT and UTEP), and the Universidades Autónoma de Ciudad Juárez and México (UACJ and UNAM; *cf.* Archuleta 1995 and 2010; **Figs. H6-1** and **H6-2**).

H7.1. Challenges

Challenges facing implementation of groundwater-resource conservation activities of an environmental and political-institutional nature will always exist in the International-Boundary Zone, particularly in light of the region's Chihuahuan Desert geographical setting and complex geopolitical history (**Parts H1** to **H5**).

1. Perhaps the greatest challenges facing long-term GW development simply involves accepting the "reality" of climate change (*cf.* **Parts H2.6** and **H2.7**) in a Chihuahuan Desert ecoregion where annual GW consumption greatly exceeds annual aquifer recharge.
2. Contamination of irreplaceable GW resources by ongoing irrigation-agriculture, feedlot, and municipal and industrial (M&I) activity (e.g., USCDC 1997*, Creel et al. 1998, Macias-Coral et al. 2006, Walker et al. 2015, USEPA 2015c and 2019, Suthersan et al. 2016a, Prokop 2024; Rpt. **Apndx. E5.2.2)**. **See **Part 9.3** review of the toxic environmental legacy of the 20th Century operation of the American Smelting and Refining Corp. (ASARCO) copper- and lead-ore smelter in the Paso del Norte–"Smeltertown" District (**Part 3.7**).*
3. Of immediate concern is the rapid expansion of groundwater pumping related to development of the Ciudad Juárez Junta Municipal de Agua y Saneamiento (JMASCJ) well field, and ever-expanding M&I activity in the binational San Jerónimo-Santa Teresa (maquiladora) area since 2007 (**Figs. H1-10** and **H1-12**; *cf.* Pacheco 2017a-b, 2018a-b, 2019c, Villagran 2017a-c, Kocherga 2018b, Robinson-Avila 2018a, ABQ Jrnl. 2019, Hamway 2020a-b, Pacheco 2019f and 2021d, Robinson-Avila 2020d-e). A significant component of the regional groundwater-flow system that discharged for millennia to the Lower Mesilla Valley reach of the Rio Grande now has the potential for being intercepted by such binational aquifer-system development.
4. An unanticipated challenge that appeared in 2018 involves potential impacts of the new Border Wall and associated infrastructure operations on not only the land-surface environment but also subsurface-water quality (*cf.* **Fig. H3-8**; **Part H3.4.3**).

H7.2. Opportunities

From a hydrogeologic-framework perspective, overdevelopment (i.e., mining) of the Transboundary aquifer system is not sustainable on a multi-generational Human-time scale in any part of the southern Mesilla Basin Region west of the MeV and EPdN. Nonetheless, opportunities clearly remain for long-term GW-resource development due to the following:

1. The fluvial origin, sedimentary composition, and great (up to 400 m) thickness of the RG-rift basin-SFG aquifer media (Rpt. **Chpts. 3**, **4** and **6**).
2. Optimum quantity and quality of fresh to moderately brackish (<3,000 mg/L TDS) water stored in SFG basin-fill aquifers (at least 40,000 hm3; Rpt. **Chpts. 6** to **8**; *cf.* **Part H1.8.2**; Stanton et al. 2017).

3. Many available locations ideally suited for siting facilities for reverse-osmosis (RO) membrane desalination treatment of brackish groundwater (BGW). Treatment-facility scale ranges from relatively small unit operations to the EPW 27.5 mg/d [~104,123 m^3/d] Kay Bailey Hutchison desalination plant in the western Hueco Bolson (*cf.* EPW-ND, Hightower 2003, TWDB 2010 and 2015, Gude 2016, Erlitski and Craver 2020).
4. In addition to advances in the high-recovery RO membrane technology, other effective methods for BGW desalination are either now available or in advanced stages of development (e.g., Kocherga 2018b, Davis 2020f, Pacheco 2020c).
5. Optimum locations for concentrate-management operations, including Chihuahuan Desert basin sites where treatment methods other than permanent disposal are feasible (Rpt. **Chpts. 3**, **5** and **6**). **Chapter 5** also includes short descriptions of localities in and adjacent to the East Potrillo Uplift (EPU) with potential for siting concentrate and other types of waste-water management activities (e.g., Rpt. **Parts 5.4.1a**, **5.6.2**, **5.6.3**).
6. Optimum locations for managed aquifer recharge (MAR), with water sources that include very large quantities of treated M&I wastewater (Rpt. **Chpts. 3**, **6** and **8**; *cf.* Garza et al. 1980, Knorr and Cliett 1985. Knorr 1988, Buszka et al. 1994, Sheng 2005, EPW-ND, Wolf et al. 2020).
7. While facilities for natural-gas fueled electricity generation are already locally available, there is no limit on site locations for future solar-energy development in this Chihuahuan Desert terrain (**Figs. H3-6** and **H3-8**; Muñoz-Meléndez et al. 2012, p. 310-11). In addition, the general area has potential for geothermal- and wind-energy project development, and perhaps also for Hydrogen (H^2) fuel production (Rpt. **Chpts. 5**, **6** and **8**; *cf.* Robinson-Avila 2020a-d, and 2021c and d; Polich 2021).

H7.3. Remaining Environmental Legacy of 20th Century Operation of the ASARCO Smelter at El Paso del Norte

As part of its continuing commemoration of U.S. Center for Decease Control's (CDC's) 50th anniversary in June 1996, the Morbidity and Mortality Weekly Report (MMWR) reprinted selected MMWR articles of historical interest to public health, accompanied by a current editorial note (U.S. CDC, 1997, p. 871-877). Quoted below are selections from the first published report (published December 8, 1973) of a large-scale systematic study of community exposure to emissions from a lead smelter*, and some passages of special note are underlined. While not mentioned as a source of GW contamination in the shallow (alluvial) aquifer in the upper El Paso Valley/Valle de Juárez area, the fallout area of smelter-stack emissions shown in the below-copied 1970s "Figure 1" map of "LEAD SURFACE SOIL LEVELS" coincides with a large part of the shallow aquifer-recharge zone (**Part H5.4**; **Figs. H5-2** and **H5-3**; ***cf.*** Landrigan et al. 1975, Ordóñez et al. 1976).

****American Smelting and Refining Corporation (AS&RC) copper- and lead-ore smelter in the Smeltertown District of NW El Paso.*

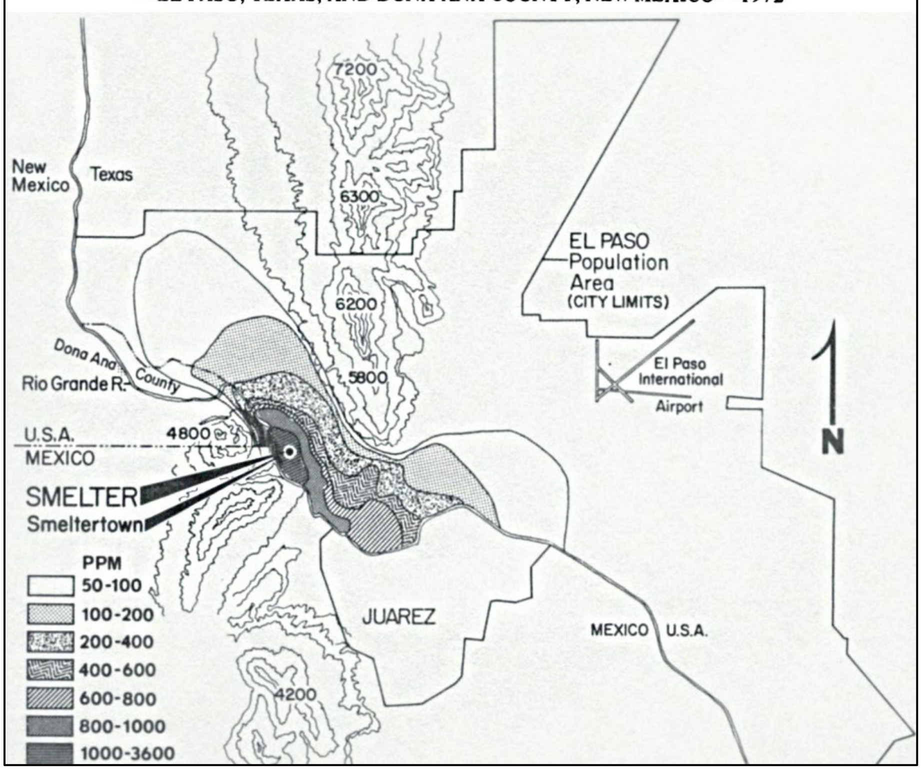
> In December 1971, the City-County Health Department in El Paso, Texas, discovered that an ore smelter in El Paso was discharging large quantities of lead and other metallic wastes into the air. Between 1969 and 1971, this smelter had released 1,116 tons of lead, 560 tons of zinc, 12 tons of cadmium, and 1.2 tons of arsenic into the atmosphere through its stacks (Tbl. ref).
>
> Twenty-four hour air samples to determine the amounts of lead and other heavy metals suspended in the atmosphere were collected throughout 1971 and again between July 1972 and June 1973 by the local health department. Both series of tests showed that mean concentrations of metallic wastes in the air were highest immediately downwind of the smelter and that levels decreased logarithmically with distance from the smelter. The annual mean lead level immediately downwind of the smelter in 1971 was 92 uG/m3 and in 1972-73 was 43 uG/m3; the U.S. Environmental Protection Agency's proposed safe upper limit for airborne lead content is 2.0

uG/m3 of air (1). No metallic emissions were found near any of 15 other industrial establishments studied in El Paso.

Similarly, soil samples taken by the health department at selected sites within the urban area between June and December 1972 showed the highest concentrations of lead and other metals to be in surface soil from within 0.2 miles of the smelter (Figure 1). Samples of drinking water, milk, and food obtained from homes in El Paso between January and March 1972 by the health department were uniformly free of lead.

Preliminary testing programs to evaluate the effect of the environmental contamination on human blood lead levels were conducted in El Paso between January and March 1972 by the local health department, the smelting company, and CDC. These initial studies showed that 43% of persons in all age groups and 62% of children through age 10 years living within 1 mile of the smelter had blood lead levels greater than or equal to 40 uG%, a level considered to be evidence of undue lead absorption (2). There was a lower prevalence among persons living at greater distances from the smelter. No cases of overt lead poisoning were noted.

Figure 1
LEAD SURFACE SOIL LEVELS
EL PASO, TEXAS, AND DONA ANA COUNTY, NEW MEXICO – 1972



In August 1972, a random survey of the entire population living within 4.1 miles of the smelter in south and west El Paso was conducted by the health department and CDC. The area was divided along census tract lines into 3 strata, roughly concentric about the smelter and each with a radius of 1.0-1.5 miles. In the small, innermost stratum, all households were visited; in the 2 outer strata, approximately 2% of households were selected. Of 833 occupied households included in the survey, 672 (80.6%) were reached for the interview. A venous blood sample for lead analysis by atomic absorption spectrophotometry (AAS) was obtained from all persons up to age 20 years and from every other person above that age; samples of paint, soil, household dust, and pottery were also collected in each home for lead analysis by AAS. In all age groups, the percentage of blood levels greater than or equal to 40 uG% was found to be highest in those persons living nearest the smelter (Figure 1), and the prevalence was highest in the youngest individuals; migration rates among these persons were low. In area I, 5 (8.5%) of 59 persons 1-19 years of age with blood lead levels greater than or equal to 40 uG% had moved into the area in the 2 years preceding the survey. In areas II and III, the migration rate for persons 1-19 years of age with blood levels greater than or equal to 40 uG% was 8.2% (4 of 49); 1 person in this group had moved from area I. . . .

1997 CDC Editorial Note (Thomas Matte, MD, MPH, Medical Epidemiologist, Henry Falk, MD, Director, Division of Environmental Hazards and Health Effects, National Center for Environmental Health, CDC).

When a team of Epidemic Intelligence Service officers from CDC, led by Dr. Philip Landrigan, joined the local health department in El Paso, Texas, in March 1971 to investigate lead exposure associated with an ore smelter, the scientific understanding of pediatric lead toxicity was about to enter a period of rapid progress. Many studies have since documented the public health threat posed by poorly controlled lead emissions from lead smelters around the world (1). The range of lead exposure produced in populations living near lead smelters has, in turn, facilitated studies of the mechanisms and health consequences of pediatric lead exposure.

A major objective of the El Paso investigation was to determine whether high blood lead levels (BLLs) in children were associated with smelter emissions or were explained by other lead sources also found in the community. A high level of lead emissions in a residential area was not then assumed to be a public health threat, as it is today. A 1972 National Academy of Sciences report on lead, while motivated by growing concern about widespread dispersal of lead in the environment, stated in its preface: "lead attributable to emission and dispersion into the general ambient environment has no known harmful effects" (2). In El Paso, the inverse gradient in air (3), dust, and soil contamination as one moved away from the smelter, and the parallel blood lead gradient (also found in a complementary investigation of lead exposure in Juarez, Mexico {4}) supported the argument that soil and dust are important vehicles of exposure. This finding foreshadowed subsequent research demonstrating the pathway from lead in soil and dust to lead contamination of hands to lead in blood, presumably from normal hand-to-mouth behavior and ingestion of contaminated soil and dust (5-7).

In 1975 and 1976, CDC investigators, led by Dr. Edward Baker, documented the potential for exposure to leaded dust among children of workers at a secondary lead smelter in Tennessee (8). Their findings and those of other investigations of "take-home" lead exposure that followed brought about provisions in the 1978 Occupational Safety and Health Administration (OSHA) standard for occupational lead exposure requiring hygienic measures in general industry to prevent lead workers from carrying lead dust home on their skin, shoes, and clothing (9).

In the 1960s and 1970s, children living near smelters or in the households of smelter workers were only a small part of a widespread national problem of "undue lead absorption" (10). In urban areas, deteriorated lead paint in older housing made the problem especially acute. In the same year as the El Paso survey, a door-to-door survey of inner-city children in Rochester, New York, found a mean BLL of 44 ug/dL (5), which was close to that measured near the El Paso smelter.

Since the early 1970s, it also has become more clear that lead is a multimedia contaminant and that demonstrating the importance of a given source does not rule out the contribution of other sources. For example, data from the Second National Health and Nutrition Examination Survey (NHANES II) conducted from 1976 through 1980 indicated that the mean BLL among children aged less than 6 years residing in rural areas was 14 ug/dL (average levels were 3-6 ug/dL higher among children living in more urbanized areas) (11). During the same period, widespread population exposure to lead emissions was reflected in average BLLs that declined in close parallel to the decreasing consumption of leaded gasoline (12). Thus, children living near the El Paso smelter, children in the homes of lead workers, and children in downtown Rochester probably shared with children across the country a contribution to their BLLs from lead in gasoline. Local sources, added to the higher background exposure prevalent at the time, resulted in BLL distributions that are extremely high by today's standards.

Perhaps the most telling indication of how the scientific view of lead exposure has changed since 1971 is that, in 1971 "undue lead absorption" referred only to BLLs greater than or equal to 40 ug/dL. Numerous subsequent studies documented that BLLs much lower than 40 ug/dL, then considered acceptable, adversely impact the health of children without causing overt symptoms. For example, investigators from CDC's Bureau of Epidemiology, again led by Dr. Landrigan, found an inverse relation between BLLs and nerve conduction velocities among children exposed to emissions from a smelter near Kellogg, Idaho (13). As the decade closed, Dr. Herbert Needleman's landmark study was published, demonstrating lower cognitive test scores and higher teachers' ratings of behavioral problems among children with higher tooth lead levels but no history of clinically overt lead poisoning (14).

Epidemiologic studies identified subclinical effects of lead by comparing the health of children with different levels of lead exposure. For most U.S. populations studied in the 1970s, the least exposed children had BLLs well above the average in the U.S. population today. Thus, health effects at lower levels could not be detected. As population BLLs decreased through the 1980s, careful prospective studies found subtle effects of lead on learning and behavior at BLLs well below those of the least exposed children in El Paso (15).

In addition to contributing to scientific knowledge about lead exposure and its effects on health, findings from the El Paso survey and others precipitated measures to reduce emissions at lead smelters. In 1977, a follow-up investigation by CDC and the El Paso Health Department found that BLLs among children living nearest the smelter had decreased by approximately 50% (16). More importantly, the El Paso survey was a prelude to a large body of continuously refined epidemiologic investigations that provided the impetus for actions to dramatically reduce population lead exposure from lead in gasoline, soldered food cans, drinking water conduits, and other sources in the United States. As a result, mean BLLs among children have declined nationally by greater than 80% overall and by similar amounts in population subgroups defined by age, race, ethnicity, income levels, and urbanization (17, 18). More recently, international agreements to reduce the use of leaded gasoline may bring about significant reductions in worldwide lead exposure. Ironically, the unfortunate epidemics of lead toxicity near smelters in El Paso and elsewhere ultimately enabled more rapid progress in understanding and controlling lead exposure than might otherwise have been possible.

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Topic/Subtopic Categories, with Alphanumeric Cross-Reference Codes (Appendix B)

A. Bibliographies, Dictionaries, Glossaries, Biographies, Reviews, and News Items
- A1. Bibliographies, Dictionaries, and Glossaries
- A2. Biographies and Reviews
- A3. News Items

B. Time: Geologic, Prehistoric, and Historic
- B1. Geologic and Prehistoric Time
- B2. Prehistoric Perspective: US Southwest and Northern Mexico
- B3. Historic Perspective: US Southwest and Northern Mexico

C. Environmental, Physiographic, and Geologic Setting
- C1. Climatic, Hydrographic, Ecologic, and Paleoenvironmental Setting
- C2. Geologic and Geomorphic Setting
  - C2a. Geologic and Geomorphic Setting: Pre-1990
  - C2b. Geologic and Geomorphic Setting: Post-1989
- C3. Soil-Geomorphic Relationships and Soil Surveys
- C4. Geophysical/Geochemical Data and Interpretations

D. Basic Hydrogeologic Concepts
- D1. Conceptual Models, Definitions, and Regional Overviews
- D2. Groundwater-Flow Systems, Including Recharge

E. GIS/Remote Sensing and GW-Resource Management/Planning
- E1. GIS/Remote Sensing
- E2. Resource Management/Planning
  - E2a. Desalination
  - E2b. Recharge and Recovery
  - E2c. Groundwater-Quality Projection and Waste Management
- E3. Legal and Environmental Issues and Constraints

F. Transboundary Regional Hydrogeology and Geohydrology
- F1. Binational
- F2. USA
- F3. México

G. Early Documents on Mesilla Basin Regional Aquifer Systems (1858-1970)
- G1. 1858 to 1935
- G2. 1935 to 1970

H. Contemporary Documents on Mesilla Basin Regional Aquifer Systems
- H1. Hydrogeology
- H2. Hydrochemistry
- H3. Flow Models

I. Paleohydrology: Ancestral Fluvial and Pluvial Lake Systems
- I1. Regional Overviews
- I2. Transboundary Region Paleohydrologic Systems
- I3. Evolution of the Rio Grande Fluvial System