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Transboundary aquifers between Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, Mexico, and Texas, USA: Identification and categorization

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ABSTRACT

Study region: Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, Mexico; Texas, USA.
Study focus: The objective of this study is to identify and classify the transboundary hydrogeological units shared between Chihuahua, Coahuila, Nuevo Leon and Tamaulipas, Mexico, and Texas, and assess their potential transboundary linkages.
New hydrological insights: The transboundary groundwater resources between Mexico and United States are largely uncharacterized due to lack of data, differences in aquifer boundary delimitations and methodologies, and limited cooperation and coordination among federal and local agencies within and between countries to address groundwater challenges from a binational perspective. Our results indicate that the transboundary hydrogeological units identified cover around 180,000 km^2 (110,000 km2 in Texas and 72,000 km2 in Mexico). Between 50% and 60% of this sharable area reports good aquifer potential and good water quality conditions. Some 20–25% is considered to have poor aquifer potential and water quality. The areas of the bolsons southeast of the Hueco-Tularosa Bolson Aquifer in northern Chihuahua and southwestern Texas, and between the Serrania del Burro and Allende-Piedras Negras Aquifers in southern Texas and northern Coahuila, appear to be the most important for transboundary aquifer potential. This study, the first assessment of its kind in this region, will support the development of transboundary management regimes aimed at preventing the degradation of future water supplies in the borderland between Mexico and United States.

1. Introduction

The most recent study on transboundary aquifers between Mexico and the United States finds that there might be up to 36 of them (Sanchez et al., 2016). Fifteen potential transboundary aquifers have been reported between Mexico and Texas, though recognized transboundary linkages are known only for five (Sanchez et al., 2016). Due to lack of data, differences in aquifer boundary delimitations and methodologies, and the limited cooperation and coordination among federal and local agencies within and between countries to address groundwater challenges from a binational perspective, the transboundary groundwater resources shared by the two countries are largely uncharacterized. The recent research on transboundary aquifers (supported by the Transboundary Aquifer Assessment Program) includes the San Pedro and Santa Cruz aquifers between Arizona and Sonora, the Hueco Bolson and Mesilla

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Bolson between Texas, New Mexico and Chihuahua, and the Yuma Aquifer (which is governed by Minute 242 of the International Boundary and Water Commission/Comisión Nacional de Límites y Aguas, IBWC/CILA). Apart from these, the rest of the potential transboundary aquifers in this region remain unexplored.

The challenge of managing the transboundary aquifers between Mexico and Texas, in terms of vulnerabilities and planning scenarios, is greatly magnified by the number of unknowns, including aquifer conditions and transboundary linkages. Rapid urbanization, population growth, and climate change predictions that envision a more drought-prone border region require attention to groundwater resources, as surface water has already reached its supply limit. According to the World Resources Institute, the Rio Grande basin is one of the most water-stressed basins in the world (Maddocks and Reig, 2014), and it supplies close to 90% of all agriculture production in Texas. It is also the source of domestic supply for highly populated cities such as El Paso, Laredo, McAllen and San Antonio in Texas and Ciudad Juarez, Piedras Negras, Nuevo Laredo, Acuna and

Reynosa in Mexico. There are also small communities along the border between Chihuahua and Texas that rely completely on groundwater for domestic use.

The purpose of this study is to develop a methodology to identify and classify the transboundary aquifers between Mexico and Texas. This new approach is designed to provide the first-ever assessment of all the transboundary hydrogeological units shared between Mexico and Texas, identified in this study as HGUs. It is divided into two phases: first, to assess the surficial correlation of geological units to identify hydrogeological connectivity and preliminary aquifer identification; and, to develop a classification of geological units based on hydrogeological parameters and water quality to identify those transboundary units with aquifer potential. Results will identify and visualize the highest- priority regions based on the previous classification.

This study releases important results. Overall, the HGUs identified cover around 180,000 km2 (approximately 110,000 km2 on the Texas side and 72,000 km2 on the Mexico side). The total area considered to have good aquifer potential as well as good water quality ranges between 50% and 60% (of which 60% is in Texas and the rest in Mexico). Some 20–25% of the shared land is considered to have poor aquifer conditions and low water quality, with similar area on the two sides of the border.

This study should be read in light of its intrinsic limitations and research boundaries. First, the geological correlation is based primarily on surficial geology, using structural geology and well depths to define vertical extent, and thus limiting the correlation to the outcrop portions of the formations. This approach was used to efficiently visualize the geological correlation in two dimensions.

A second limitation has to do with the certainty of the reported data in some areas. Some of the reports from CONAGUA on the geological formations at the border with Chihuahua close to Big Bend National Park are limited in terms of data reliability, suggesting the need for more research to confirm their assumptions. The classification of these units should be taken as a preliminary estimate. The same caution applies to formations that have been reported on only one side of the border, assuming limited connectivity to the other side.

In terms of water quality data, some reports are rather general and do not specify the location of the water being tested. If such formations cover a significant area, their water quality values might be over- or underestimated. In addition, some reports contradict each other. In those cases, the HGU has been identified with two categories at the same time, again adding uncertainty in terms of water quality to the whole unit.

This paper has two main parts. The first part addresses geological correlations between Texas and Mexico and describes the lithological and hydrological features of each identified formation, followed by the delineation of boundary and transboundary units and their corresponding boundaries. The second part addresses the classification of transboundary hydrogeological units/formations based on hydrogeological characteristics and water quality and a preliminary identification of priority areas based on their aquifer potential.

2. Methodology

2.1. Geological correlation

Commonly, in hydrogeology the boundaries of an aquifer are defined by lithology changes. Mexico and Texas use different methods to define aquifer boundaries: Texas uses geologic formations, and Mexico uses a combination of hydrogeologic and administrative boundaries (Sanchez et al., 2016). A unified geologic correlation process was developed to identify those units that actually cross the boundary as a sign of potential transboundary aquifers. This geological correlation is limited to surficial and structural geology, as geological maps are representative of surficial geological formations. Vertical analysis based on profiles and well lithological descriptions is used to identify the outcropping limits of the geological boundaries of the formations.

To perform the geological correlation, a review of all available hydrogeological data on geological units between Texas and Mexico was performed, along with an extensive visualization and analysis of geographical information using ArcGIS 10.3 software. Geological data for Mexico were downloaded from the federal agency Servicio Geologico Mexicano (SGM) (Servicio Geológico Mexicano, 2016) as geologic maps in shapefile format at 1:250000 scale. This scale was selected due to its availability in data on both sides of the border. For the Texas side, geological data were obtained from the USGS (United States Geological Service) using the Texas Geologic Map Data website, which covers the entire state (U. S. Geological Survey, 2016a).

To address the problems related to differences of geological equivalence across the border, correlation maps with common geological units were available and complemented those regions for which information was limited: Preliminary Geologic Map of Laredo, Crystal City-Eagle Pass, San Antonio, and Del Rio 1° x 2° Quadrangles, Texas; and Nuevo Laredo, Ciudad Acuna, Piedras Negras, and Nueva Rosita 1° x 2° Quadrangles, Mexico (Page et al., 2009).

Where no geologic maps spanned the two countries, it was necessary to use maps available from either Mexico and Texas at

1:250000 scale. The Texas portions were supplied by the USGS map, "Preliminary Geologic Map of Southernmost Texas, United States, and Parts of Tamaulipas and Nuevo Leon, Mexico: Environmental Health Investigations in the United States-Mexico Border Region" (Corpus Christi, Llano, San Angelo, Pecos, Fort Stockton, Brownwood, Emory Peak- Presidio, Marfa and Van Horn-El Paso sheets) (Barnes, 1979; Barnes et al., 1981; Barnes, 1982; Dietrich et al., 1983; Eifler et al., 1974; Page et al., 2005). For Mexico, the maps were from Servicio Geologico Mexicano: Cartas Geologico mineras Matamoros G14-6-9-12, Linares G14-11, Rio Bravo G14-8, Reynosa G14-5, Nuevo Laredo G14-2, Monclova G14-4, Nueva Rosita G14-1, Piedras Negras H14-10, Ciudad Acuna H14-7, San Miguel H13-12, Manuel Benavides H13-9, Ciudad Juarez − El Porvenir H13-1 H13-2, Nuevo Casas Grandes H13-4, San Antonio del Bravo H13-5, Ojinaga H13-8 and Ciudad Delicias H13-11 (Servicio Geológico Mexicano, 2000; Servicio Geológico Mexicano, 2002; Servicio Geológico Mexicano, 2003a,b; Servicio Geológico Mexicano, 2008a,b,c,d,f).

In case of uncertainty or lack of information of the geological name assigned in either country, the stratigraphic lexicons from both countries were reviewed. Geologic description, age, thickness, stratigraphic position, and correlations were used to determine the corresponding geological formation. The formation identification process also provided the preliminary data to identify the type and quality of the aquifers that could be considered transboundary and those with limited or poor aquifer potential.

After the geological correlation process, a geological structural analysis/vertical geology was developed from the geologic map profiles and well lithology descriptions to delineate the formations' boundaries. This process was necessary because even if there is physical continuity of a geological unit, it can be truncated by folds or faults. Faulting can improve the permeability of the rock, or it can generate secondary porosity in rocks initially considered aquitards (rocks blocking groundwater flow).

2.2. *Classification of hydrogeological units (HGUs)*

The second objective was the classification of geological units, based on the hydrogeological correlation, hydrological features and water quality. This classification is based on previous categorization by CONAGUA (2006), edited to fit the objectives of this research.

CONAGUA (2006) proposes an aquifer classification based on geological characteristics such as porosity and permeability of the lithological features of outcropping units (aquifer potential) and the water quality in those geological units. The categories are: Unit I, poor to very poor aquifer potential and very poor groundwater quality; Unit II, moderate aquifer potential and good to moderate water quality; Unit III, geologic units that work as aquitards, with poor aquifer potential and very poor water quality; Unit IV, moderate to poor aquifer potential and very poor water quality; Unit V, moderate aquifer potential and good water quality; Unit VI, poor to very poor aquifer potential and moderate to poor water quality; and Unit VII, aquitards with poor to very poor water quality. It is important to clarify that CONAGUA (2006) report in which this classification was used applied only to the geologic units in north Tamaulipas, Mexico.

This research uses similar criteria to identify the lithological and hydrogeological potential of those units/aquifers that cross the border between Texas and Mexico, with minor adjustments for the objectives of this research. For this research, "aquifer potential" is defined as the potential that a formation, a group of formations, or a part of a formation contains sufficient saturated permeable material to yield significant quantities of water for wells and springs (U. S. Geological Survey, 2016b). The criteria used to define aquifer potential include lithological features, permeability, porosity, hydraulic conductivity and transmissivity, and water yield when available. Considering the complexity and heterogeneity of the units, as well as the differences in methods used to characterize units on the two sides of the border, a combination of criteria were used to classify aquifer potential as 'good', 'moderate' or 'poor': geological and lithological descriptions of the units; porosity and hydraulic conductivity when available, or standardized values according to the predominant lithology (Hiscock, 2005); permeability reports and assessments and water-yield data from CONAGUA (2006) and technical reports from the Texas Water Development Board (TWDB). Data were collected from federal, state and local agencies, as well as from technical and scientific reports, private (industry) reports, non-public reports and field assessments. The common criterion for water quality was TDS (total dissolved solids), which was available for most of the border region.

This research uses the TDS ranges of the Texas Water Development Board (TWDB, 2017) to classify groundwater quality: freshwater, less than 1000 mg/L; slightly saline (called 'brackish water' in many studies), 1000–3000 mg/L; moderately saline, 3000–10,000 mg/L; very saline, 10,000–35,000 mg/L; and brine, over 35,000 mg/L. Some reports refer to 'parts per million' (ppm), where 1 ppm is equivalent to 1 mg/L; ppm is the term used in this report as well.

Table 1 shows our classification of formations according to aquifer potential and corresponding water quality.

Table 1
Classification of Formations by Aquifer Potential and Water Quality.

Formation classification			Water quality			
			Good < 1000 ppm	Moderate 1000–3000 ppm	Poor > 3000 ppm	No info
			1	2	3	4
Aquifer potential	Good	A	A1	A2	A3	A4
	Moderate	B	B1	B2	B3	B4
	Poor	C	C1	C2	C3	C4
	Aquitard	D	D1	D2	D3	D4
	No info	E	E1	E2	E3	E4

Table 2
Geological Correlation/Equivalence and Hydrological Features.

Unit Name (MEX/Texas)	Age		Location (Mexico/ Texas)	Lithological Description	Hydrological Features	Aquifer
Cox Sandstone (USA) (Figs. 1 and 2).	MESOZOIC	Aptian-Albian.	West Texas.	Fine-grained sandstone with quartz pebbles and iron marks from weathered pyrite nodules Richardson (1904).	–	–
La Pena Formation/Yucca Formation (Figs. 1 and 2).		Aptian-Albian.	Northern Coahuila/ Quitman Mountains, west of Van Horn.	Upper portion: Limestones, mudstones, soft calcareous nodules and some limestone beds, pebbles near the base. Middle portion: Hard siliceous sandstone, conglomeratic mudstones and limestones. Lower portion: Microgranular limestones interbedded with fine-grained sandstones U. S. Geological Survey (2007).	–	–
Loma de Plata Formation/ Espy Limestone (Figs. 1 and 2).		Albian.	Sierra Cieneguilla, northeast Chihuahua/ Pinto Canyon, Presidio County.	Nodular limestones in the lower portion, and stratified limestones in the upper portion Amsbury (1958).	No megascopic porosity; more functionality as an aquitard Hernández-Ríos (1974).	–
Aurora Formation/Glen Rose Formation (Figs. 1–4).		Albian.	Northeast Mexico/ Somerwell County.	Limestone layers, sandy limestones with interbedded sandy clays, sandstone and marl; the top of the unit is slightly sandier and has siliceous content Hill (1891).	Aquifer potential at higher depths; secondary porosity as a result of fracturing; confined to semiconfined conditions CONAGUA (2015c,2015d, 2015e)	–
Edwards Formation/Edwards Formation (Figs. 1–4).		Albian.	Serrania del Burro, Coahuila/South Texas.	Dolomite, calcareous dolomite and anhydrite Humphrey and Díaz (2003).	High variations of transmissivity and hydraulic conductivity which is common in karstic environments Boghici (2002).	Edwards-Trinity Aquifer Boghici (2002).
West Nueces Formation/West Nueces Formation (Figs. 1–3).		Albian.	Serrania del Burro, Coahuila/Southwest Texas.	Shales with mollusk fossils and some limestones Escalante et al. (2002).	Aquifer potential at higher depths; confined to semiconfined conditions CONAGUA (2015e). Upper portion moderately permeable; lower portion is impermeable Barker et al. (1994).	Edwards-Trinity Aquifer Boghici (2002).
McKnight Formation/ McKnight Formation (Figs. 3 and 4).		Albian.	Serrania del Burro, Coahuila/Valverde County.	Brown clayey mudstones with interbedded claystones and anhydrites PEMEX (1988b).	Classified as aquitard Clark and Small (1997).	Edwards-Trinity Aquifer Boghici (2002).
Salmon Peak Fm/Salmon Peak Limestone (Figs. 2–4).		Albian.	North of Coahuila and Chihuahua/Valverde, Kinney and Uvalde counties.	Gray to green limestone with interbedded flint nodules Smith (1970).	Lower portion: Low porosity and low permeability; water is extracted from fractured areas Clark and Small (1997). Upper portion: Porous and permeable Boghici (2002).	Edwards-Trinity Aquifer Boghici (2002).
Kiamichi Formation/Kiamichi Formation (Figs. 1 and 4).		Albian.	North Coahuila and Nuevo Leon/South Texas.	Mudstone and clay wackestone gray colored, distributed in thin layers with interbedded calcareous shale nodules, and hematite and flint nodules PEMEX (1988b).	Works as a barrier between Georgetown Fm and Edwards Fm southeast of the Amistad Dam; in the north, is thin enough to allow circulation between Georgetown and Edwards Fms Reeves and Small (1973).	–

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Table 2 (*continued*)

Unit Name (MEX/Texas)	Age	Location (Mexico/Texas)	Lithological Description	Hydrological Features	Aquifer
Benevides Formation/Benevides Formation (Figs. 1–2).	Albian.	Chihuahua/Quitman and Eagle Mountains, west Texas.	Shale and calcareous sandstone sequence Amsbury (1958).	–	–
Santa Elena Fm/Santa Elena Limestone (Figs. 1–3).	Albian – Cenomanian.	Northwest Coahuila/Black Gap and Big Bend area.	Fossiliferous limestone, with nodules and flintstone lenses CONAGUA (2015d).	Radioactive levels detected; not safe for drinking water Fallin (1990).	Part of Edwards Aquifer on Big Bend area George et al. (2011).
Devils River Limestone (USA) (Figs. 3 and 4).	Albian – Cenomanian.	Valverde County, Texas.	Fossiliferous wackestones locally dolomitized and rudist layers common in the upper portion Lozo and Smith (1964).	The vertical fractures near the top provide paths for effective recharge of the aquifer Clark and Small (1997).	Edwards-Trinity Aquifer Boghici (2002).
Buda-Del Rio Fms./Buda Limestone-Del Rio Clay (Figs. 1–3).	Cenomanian.	Coahuila and Chihuahua/Austin, McLennan, Bell, Williamson, Travis and Moody Counties.	Limestones with massive layers that vary in consistency and hardness, the color of the limestone is yellow and weathered changes to white, yellow and orange Hill (1891).	Porosity is secondary due to fracturing Castillo Aguiñaga (2000). Sulfate taste; not acceptable for human consumption Fallin (1990).	–
Eagle Ford Fm/Eagle Ford Group (Figs. 1–3).	Cenomanian – Turonian.	Serrania del Burro, Coahuila/Southeast Texas.	Carbonous calcareous shale interbedded with limestones Santamaria-O et al. (1991).	Works locally as a confining unit for the western portion of Edwards Aquifer Boghici (2002). Groundwater source only in areas where it is fractured Bennett and Sayre (1962).	–
Boquillas Formation/Boquillas Formation (Figs. 1–3).	Cenomanian – Coniacian.	North Chihuahua/Brewster County.	Laminar limestone, separated by slim claystone layers; color varies from gray to some dark to black lenses Udden (1907).	Few wells in Valverde County that locally yield small quantities of water Reeves and Small (1973).	–
Ojinaga Formation/Ojinaga Formation (Figs. 1–2).	Cenomanian – Maastrichtian.	Chihuahua/Rim Rock, Texas.	Lower portion: Interbedded shales and limestones. Middle portion: Calcareous shales and some limestones. Upper portion: Dark green limestone with concretions Wolleben (1965).	Aquifer potential in Chihuahua with confined to semiconfined conditions CONAGUA (2015g).	–
Pen Formation/Pen Formation (Figs. 1–2).	Coniacian – Santonian.	Coahuila/West and South Texas.	Laminar limestones, interbedded with sandy calcareous shales gray colored, rich in pyrite and flint nodules Servicio Geológico Mexicano (2008e).	One well reported with high concentrations of fluoride, used sporadically for domestic use until 1985 Fallin (1990).	Cretaceous aquifer system Fallin (1990).
Austin Fm/Austin Chalk (Figs. 2–4).	Coniacian – Santonian.	Coahuila/Southeast Texas.	Shales and limestones interbedded with argillaceous limestones Santamaria-O et al. (1991).	Large yields from shallow wells near Uvalde, Texas Boghici (2002). Reeves and Small (1973) consider it the upper confining unit for the Edwards Aquifer.	–
San Carlos Fm/San Carlos Sandstone (Figs. 1 and 2).	Coniacian – Maastrichtian.	Chihuahua/Presidio County.	Mainly terrigenous with brown to grey, fine to coarse grained calcareous sandstones interbedded with brown laminated shales and some fossils of wood fragments Hernández-Noriega et al. (2000)	–	–
					–

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Table 2 (*continued*)

Unit Name (MEX/Texas)	Age		Location (Mexico/Texas)	Lithological Description	Hydrological Features	Aquifer
Upson Fm/Upson Clay (Figs. 3 and 4).		Campanian.	Northeast Mexico/ Medina and Maverick counties.	Gray to green calcareous shale, turning yellow when weathered Sellard et al. (1966).	Considered an aquitard by Boghici (2002).	
Picacho Formation/Picacho Formation (Figs. 1 and 2).		Campanian.	Ojinaga, Chihuahua/ Rim Rock.	Red, yellow and brown sandstones with crossed stratification, interbedded with red and purple claystones; some thin coal layers Vivar (1925).	–	–
San Miguel Formation/San Miguel Formation (Figs. 3 and 4).		Campanian-Maastrichtian.	Northeast Coahuila and Nuevo Leon/Maverick County.	Interbedded, fossiliferous and calcareous sandstones, in some cases muddy sandstones with conglomeratic layers López-Ramos (1979).	In Texas, the small amounts of water pumped are highly mineralized; used for stock Boghici (2002).	–
Aguja Formation/Aguja Formation (Figs. 1 and 2).		Maastrichtian.	San Carlos- Candelaria-Presidio, Chihuahua/ Trans- Pecos, Terlingua- Chisos.	Gray, green and red claystones Rivera-Sylva et al. (2011).	Water extracted in Terlingua Region (Texas) is moderately saline and extremely hard; not suitable for drinking water Fallin (1990).	Cretaceous aquifer system Fallin (1990).
Olmos Formation/Olmos Formation (Figs. 3 and 4).		Maastrichtian.	Sabinas and Burgos Basins in North Mexico/Rio Escondido basin, South Texas.	Coal shales and calcareous shales; some interbedded marl, coquina, mudstone, and coal layers PEMEX (1988b).	Not considered an optimal aquifer due to the limited water transmissivity reported in Texas Boghici (2002).	–
Escondido Formation/ Escondido Formation (Figs. 3 and 4).		Maastrichtian.	Piedras Negras, Rio Grande Valley/South Texas.	Mudstone and dark marl, interbedded with extensive sandstone layers, limestone and fossiliferous banks Adkins (1932).	Permeability generally low; some stock wells in Maverick County Boghici (2002). High sulfate and calcium contents near Allende and Villa Union in Coahuila.	–
Javelina Formation (USA) (Fig. 2).		Maastrichtian.	Big Bend National Park, Texas.	Yellow and gray bentonitic clay with few lenses of yellow to brown argillaceous sandstone; contains dinosaur bones and silicified wood fragments Maxwell (1967).	Considered an aquitard by Fallin (1990); yields small quantities with moderate saline concentrations.	–
Tertiary Igneous Rocks/ Tertiary Igneous Rocks, Rhyolitic Porphyry/ Rhyolitic Porphyry, Rhyolitic tuff (Mex), Andesitic Porphyry/ Andesitic Porphyry Trachyte/Trachyte (Figs. 1–5).	CENOZOIC	Neogene.	North Chihuahua and Coahuila/West Texas.	Rhyolite and rhyolitic tuff stratified with conglomerates and andesite layers, and some areas with trachyte layers U. S. Geological Survey (2007).	Secondary permeability due to fracturing; function as local aquifers CONAGUA (2015g).	Igneous Aquifer Fallin (1990).
Midway Fm/Kincaid Fm, (Figs. 3–5).		Paleocene.	Tamaulipas, Nuevo Leon/South Texas.	Dark gray green shale, with calcareous to sandy composition, occurrence of ferruginous concretions and quartz sandstones PEMEX (1988a).	Confining unit located on the bottom of Carrizo-Wilcox Aquifer Boghici (2002).	–
Wilcox Fm/Indio Fm (Figs. 3–5).		Paleocene- Eocene.	South Piedras Negras, Coahuila/South Texas.	Fine grained sandstones in thin layers, sandy, carbonaceous shale, lignite mantles Boghici (2002).	Fresh to slightly saline water due to infiltration from the Bigford Formation in some areas and oil-field brine infiltration in south Texas Boghici (2002).	Carrizo – Wilcox aquifer Ashworth and Hopkins (1995).

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Table 2 (*continued*)

Unit Name (MEX/Texas)	Age	Location (Mexico/ Texas)	Lithological Description	Hydrological Features	Aquifer
Carrizo Fm/Carrizo Sand (Figs. 3–5).	Eocene.	South Piedras Negras, Coahuila/South Texas.	Gray colored fine to coarse-grained sandstones. Hematite nodules linked to erosion surfaces Santiago et al. (2003).	Water quality is fresh to saline Boghici (2002).	Carrizo – Wilcox aquifer Ashworth and Hopkins (1995).
Bigford Formation/Bigford Formation (Figs. 3–5).	Eocene.	Nuevo Leon and Tamaulipas/Webb county.	Sandstone, mudstone, shale and coal sequence Robledo et al. (1988).	Unit I type (CONAGUA, 2006). Filtration of saline water from Bigford Fm to Carrizo Wilcox Aq. Ashworth and Hopkins (1995).	–
El Pico Clay/El Pico Clay (Figs. 3–5).	Eocene.	Nuevo Leon and Tamaulipas/Webb County.	Shales, mudstones, sandstones and clay material Herrera-Monreal et al. (2003).	Unit I type (CONAGUA, 2006). Groundwater highly mineralized Boghici (2002).	–
Palma Real- Guayabal Fm/ Laredo Fm (Figs. 3–5).	Eocene.	Nuevo Leon and Tamaulipas/South Texas.	Gray – blue and brown shales interbedded with thin calcareous sandstone; some bentonite occurrences PEMEX (1988a).	Two wells identified north of Falcon Dam where saline water was pumped from Laredo Formation Lee et al. (2007). Boghici (2002) reported extraction from wells in Laredo Fm in Texas, with yield up to 3 L/s; used for stock, household and industry.	–
Yegua Formation/Yegua Formation (Figs. 3–5).	Eocene.	Nuevo Leon and Tamaulipas/East Texas.	Sandstones with occasionally interbedded shales, lignite and siltstone Eargle (1968).	Unit I type CONAGUA (2006).	Yegua-Jackson aquifer Boghici (2002).
Jackson Fm/Jackson Group (Figs. 3–5).	Eocene.	Nuevo Leon and Tamaulipas/East Texas.	Calcareous and fossiliferous claystones, with limestone concretions of marine origin Deussen (1914).	Unit I type CONAGUA (2006).	Yegua-Jackson aquifer Boghici (2002).
Chisos Formation (USA) (Fig. 2).	Eocene.	Brewster County.	Massive conglomerates, coarse-grained sandstones, fine-grained tuffaceous sandstone, tuffaceous claystone, siltstone, andesite, tuffaceous andesite and basalt Maxwell (1967).	–	–
Tertiary Basalts/Tertiary Basalts (Figs. 1–4).	Eocene – Oligocen-e.	Chihuahua and Coahuila/Presidio County.	Basalts, trachybasalts and trachyandesites; some intercalations of tuff, sandstone and conglomerate Davis (1961).	Large variations in porosity and permeability Davis (1961) .	
Frio Formation/Frio Formation (Figs. 4–5).	Oligocen-e.	Tamaulipas, Nuevo Leon/Southeast Texas.	Massive dark gray to green claystones, with gypsum and calcareous concretions Barnes (1976a,b).	Hovorka et al. (2004) investigated the potential of this unit and its salinity levels for possible CO2 storage associated with human activity.	Catahoula Confining system TWDB (2017).
Vicksburg Formation/ Vicksburg Formation (Figs. 4–5).	Oligocen-e.	Tamaulipas, Nuevo Leon/Hidalgo County.	Gray calcareous shales sometimes sandy and bentonitic, interbedded with gray clay sandstones with quartz and feldspar fragments PEMEX (1988a).	Poor porosity Loucks et al. (1979).	Catahoula Confining system TWDB (2017).
Catahoula Fm- Vicksburg Fm Undivided (USA) Catahoula Fm/Catahoula Fm (Figs. 4–5).	Oligocene – Miocene.	Tamaulipas, Nuevo Leon/Southeast Texas.	Gray and green shales, gray sandstones and abundant well stratified gray tuff López-Ramos (1979).	Part of the Gulf Coast Aquifer at the bottom; Oakville, Goliad and Flemming Formations overlie the Catahoula system TWDB (2017).	Catahoula confining layer and Jasper Aq. Ashworth and Hopkins (1995).
	Miocene.	Tamaulipas, Nuevo Leon/South Texas.			

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Table 2 (*continued*)

Unit Name (MEX/Texas)	Age	Location (Mexico/ Texas)	Lithological Description	Hydrological Features	Aquifer
Oakville-Lagarto Fm/Oakville-Flemming Sandstone (Figs. 4–5).			Sandstones, some poorly consolidated, shales and conglomerates López-Ramos (1979). Due differentiation difficulties, in some cases, Lagarto Fm is grouped with the Oakville Fm and Oakville Sandstone and Flemming Fm in Duval county (Texas).	Flemming Fm is considered part of the Gulf Coast Aq, as part of the Evangeline Aquifer Ashworth and Hopkins (1995). CONAGUA (2006) considers this formation a Unit II type.	Jasper Aq. and Evangeline Aq. - Gulf Coast Aq. Ashworth and Hopkins (1995).
Reynosa Formation/Goliad Formation (Figs. 4–5)	Pliocene.	Tamaulipas, Nuevo Leon/South Texas.	Pink to gray claystones, gray mid to coarse grained sandstones, marl, caliche and conglomerates Barnes (1974).	CONAGUA (2006) considers this formation a Unit II type.	Evangeline Aq. - Gulf Coast Aq. Ashworth and Hopkins (1995).
Uvalde Gravel (USA) (Figs. 4–5).	Pliocene-Pleistocene.	Highlands of central and South Texas.	Gravel deposits with rounded flint, calcite and quartz pebbles, in a calcareous loam and caliche matrix, with cross-stratification in some areas Sellard et al. (1966). The unit equivalent in Mexico side is Reynosa Formation Montiel Escobar (2005).	Highly permeable aquifer Boghici (2002).	Allende-Piedras Negras Aq Boghici (2002); CONAGUA, 2011).
Neogene Conglomerates (Mex) (Figs. 1–2).	Neogene.	North Chihuahua.	Conglomerates with varied size and composition clasts and some interbedded sandstone; matrix mainly clay with calcareous cement and some fractures filled with calcite CONAGUA (2015b).	Unconfined aquifers in the area; no pumping tests have been performed; unknown hydraulic properties CONAGUA (2015b).	–
Lissie Formation (USA) (Fig. 5).	Pleistocene.	Southeast Texas.	Silt, sand and clay deposits, with minimum amounts of gravel; in some parts iron oxide and iron manganese nodules are common Brewton et al. (1975).	Highest transmissivity and conductivity values in Gulf Coast Aquifer TWDB (2017).	Gulf Coast Aquifer, within the Chicot Aquifer Ashworth and Hopkins (1995).
Beaumont Formation/ Beaumont Formation (Fig. 5).	Pleistocene.	Tamaulipas/Southeast Texas.	Blue and red calcareous clay, with a small quantity of thin sand lenses and limestone concretions Brewton et al. (1975).	Semiconfined low-productivity aquifers, separating Sur de Reynosa from the Reynosa-Matamoros Aquifer CONAGUA (2015h).	Bajo Rio Bravo Aq. CONAGUA (2015h). Gulf Coast Aquifer, within the Chicot Aquifer Ashworth and Hopkins (1995).
Qt to Tertiary Clay and Mud (USA) (Figs. 1–2).	Neogene-Pleistocene.	Southwest Texas.	Fine-grained sandstones with gypsum, and sometimes lenses of pebble to conglomerate in the boundaries of the deposits U. S. Geological Survey (2007).	Relatively impermeable material with saline groundwater, not suitable for domestic use Gabaldón (1991).	Presidio and Redford Bolsons Gabaldón (1991).
Quaternary deposits	Pleistocene-Holocene.	Chihuahua, Coahuila, Nuevo Leon, Tamaulipas/Central and South Texas.	Lacustrine deposits: silt, clay, organic matter and some salt and gypsum disseminations. Eolic deposits: dunes composed by fine sands of plagioclase, shell fragments and flint.	High permeability in Allende Piedras Negras Aq Boghici (2002). Small quaternary deposits identified along Rio Grande in Serrania del Burro and Presa La Amistad regions CONAGUA (2015c,e).	

(*continued on next page*)

Table 2 (*continued*)

Unit Name (MEX/Texas)	Age	Location (Mexico/ Texas)	Lithological Description	Hydrological Features	Aquifer
Qt Lacustrine/Qt Lacustrine Qt Eolic Qt Littoral Qt Colluvium/Qt Colluvium Qt Alluvium/Qt Alluvium (Figs. 1–5).			Littoral deposits: coarse-grained sands with shell fragments. Colluvium deposits: poorly selected conglomerates and sands in creeks and chain mountain flank Estavillo and Aguayo (1985). Alluvial deposits coming from the erosion of igneous material, limestones of the surrounding geological formations, and some surficial sediments from eolian origin Ojeda (2001). Mesilla Bolson and Hueco- Tularosa Bolson are extended through parts of New Mexico Sheng et al. (2001) where the Santa Fe Group is the equivalent unit to Quaternary eolic deposits Green et al. (2005).	Optimal hydrogeological properties CONAGUA (2015e,g,h) Presidio and Reed Bolsons with relatively impermeable gypsum layers with variable water yields and poor water quality depending on depth Ashworth and Hopkins (1995).	Mesilla Bolson Ojeda (2001). Hueco Bolson Hudak (2003). Allende Piedas Negras Aq. Boghici (2002) Conejos Medanos Aq. CONAGUA (2015a) Red Light Draw and Green Valley Bolsons Beach (2008).
Quaternary Conglomerates/ Quaternary Conglomerates (Figs. 1–5).	Pleistoce-ne-Holocene.	Chihuahua, Coahuila, Nuevo Leon, Tamaulipas/South Texas.	Angular clasts of igneous rocks, limestones, sandstones and shales and a silt to sandy matrix CONAGUA (2015f). The quaternary deposits are mainly conglomerates from the Rio Grande River, and are located along the river, covering Mesozoic and Cenozoic rocks U. S. Geological Survey (2007).	–	Bolson aquifers in El Paso Ashworth and Hopkins (1995). Santa Fe del Pino and Allende Piedras Negras CONAGUA (2015f).

This classification is then visualized and analyzed using GIS tools to identify, delineate and propose aquifer boundaries from a hydrogeological perspective.

Names of the aquifers were assigned according to the literature from either the U.S. or the Mexico side. For those formations identified as good potential aquifers according to the classification but whose aquifer has not been named, we maintain the same formation name on both sides, and refer to them as 'hydrogeological units' or HGUs given the lithological differences among them.

3. Results and discussions

3.1. Geological correlation between Mexico and Texas

This section includes the geological features of the formations identified and correlated between Mexico and Texas. They are included and described in detail in Table 2. Geological formations in Table 2 are listed according to the age of the geological unit (oldest first), and in case they have different names on both sides, this study reports first the name according to Mexico, then for Texas. Table 2 also includes hydrological features available as well as the name of those units that have been recognized as aquifers according to the literature.

There are formations that have been reported on only one side of the border (not crossing the boundary); those formations are identified with a parenthetical (USA) or (MEX). The border and transboundary formations are highlighted in bold in the figures. Figs. 1–5 list all the geological formations with their corresponding names reported on both sides (Mex/Texas, even if they are the same), but this section considers only the correlation of formations located on the border (listed in bold in the figures). Other units in the same country or not near the border are not considered.

3.2. Geological formation limits

The formations in the borderland, defining their geologic limits on both sides, are presented in Figs. 6–8. These figures represent the next level of refinement of identification of borderland formations with their corresponding physical delimitations. There are

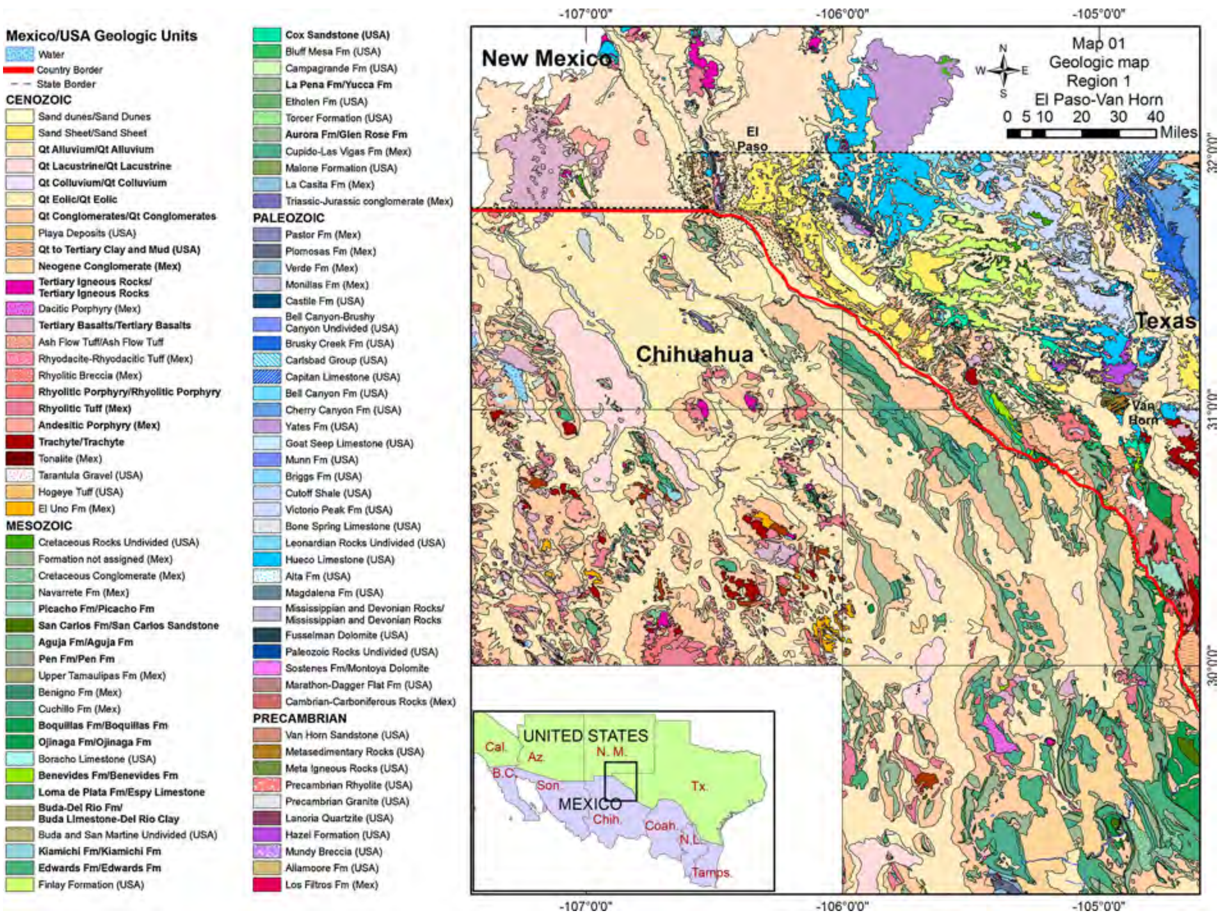

Fig. 1. Geologic map, El Paso-Van Horn.

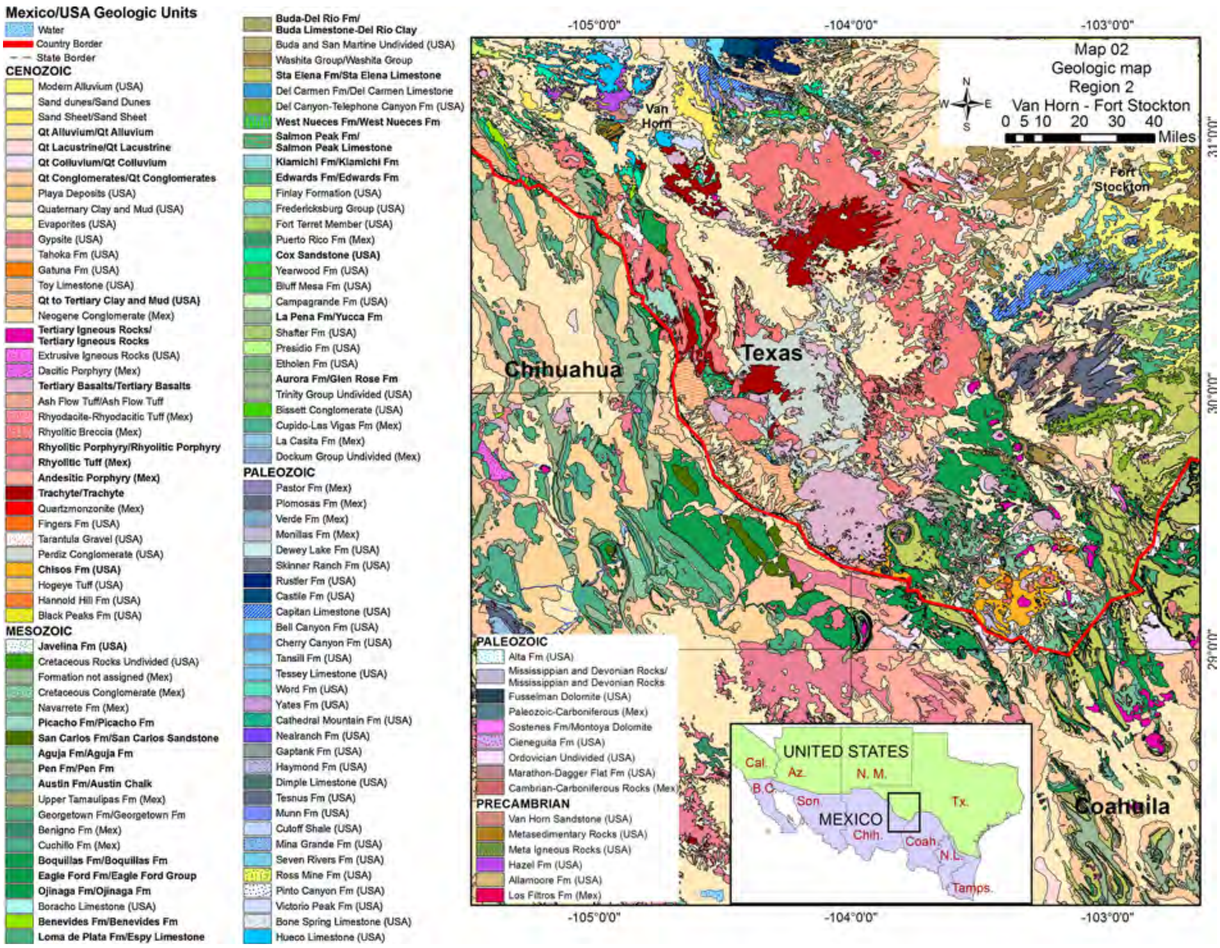

Fig. 2. Geologic map, Van Horn-Fort Stockton.

formations that have only been identified on one side of the border. Examples in Figs. 6, 7 and 8 are Qt to Tertiary Clay and Mud (USA), Cox Sandstone (USA), Javelina Fm (USA), Neogene Conglomerate (Mex), Rhyolitic Tuff (Mex), Andesitic Porphyry (Mex), Devils River Limestone (USA), Uvalde Gravel (USA), Lissie Fm (USA) and Catahoula-Vicksburg Fm Undivided (USA). Though these formations seem to appear only on one side of the borderland, they could be continuous into Mexico. Indeed, the Uvalde Gravel has been proven to be continuous with the Quaternary Alluvial on the Mexico side, forming the Allende-Piedras Negras transboundary aquifer according to some technical studies (Boghici, 2002). Lack of data on these formations prevents further conclusions, and therefore this study will consider them as boundary formations, with reservations on their transboundary linkages, pending further research.

The extension limits of the formations were defined according to structural geological limits, faults, folds and lineaments. In Fig. 6, the formations show great variation in types and sizes and complex distribution along the border area. The geological extensions in this area were defined mainly by geological limits and small faults (U. S. Geological Survey, 2007; Servicio Geológico Mexicano, 2016). The geological limits of the western side of the state of Texas are based on a combination of geological and political boundaries with the state of New Mexico. The entire Mesilla Bolson is mapped and considered in the analysis of this research, even though only a small portion of the aquifer lies in Texas. Geologically speaking, the northern limits of the Hueco Bolson in the state of New Mexico also include the Tularosa basin, but the northern part is not fully mapped, so it is not considered in this study. According to the literature, the Hueco Bolson and the Tularosa basin are hydrogeologically connected in the subsurface, but there is a topographical feature that divides the two basins (Sanchez et al., 2016; Sheng et al., 2001). Therefore, considering the reasonable previous research on this aquifer, this study considers the official extension of the Hueco Bolson to not include the Tularosa Basin, following reports by TWDB (George et al., 2011) and ISARM (International Groundwater Resources Assessment Centre IGRAC, 2015),however, for mapping purposes, Hueco Bolson and Tularosa Basin will be presented as Hueco-Tularosa Basin.The geological limits of the Red Light Draw Bolson (Fig. 9) are defined by the Quitman Mountains in Texas and the Sierra El Trozado in Mexico. In the case of Green River Valley Bolson, it is possible to extend the HGU across the border into Mexico by following the Tertiary and Quaternary deposits. Groat (1972) and Gabaldón (1991) also report the extension of the Presidio and Redford Bolsons across the Rio Grande, up to Sierra de Ventana, Chihuahua, in Mexico, where the limits are defined by Cretaceous and igneous rocks. Fig. 7

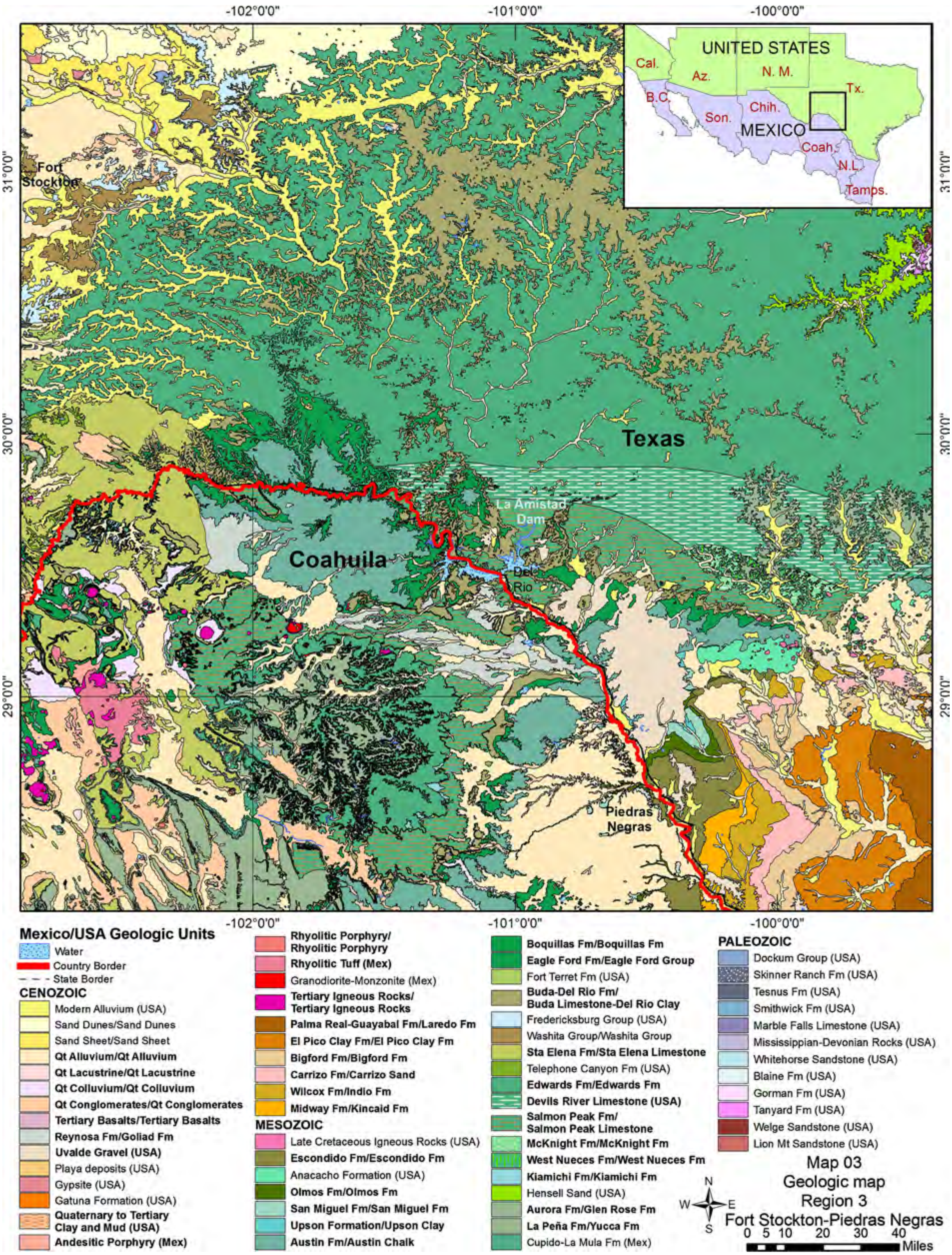

Fig. 3. Geologic map, Fort Stockton-Piedras Negras.

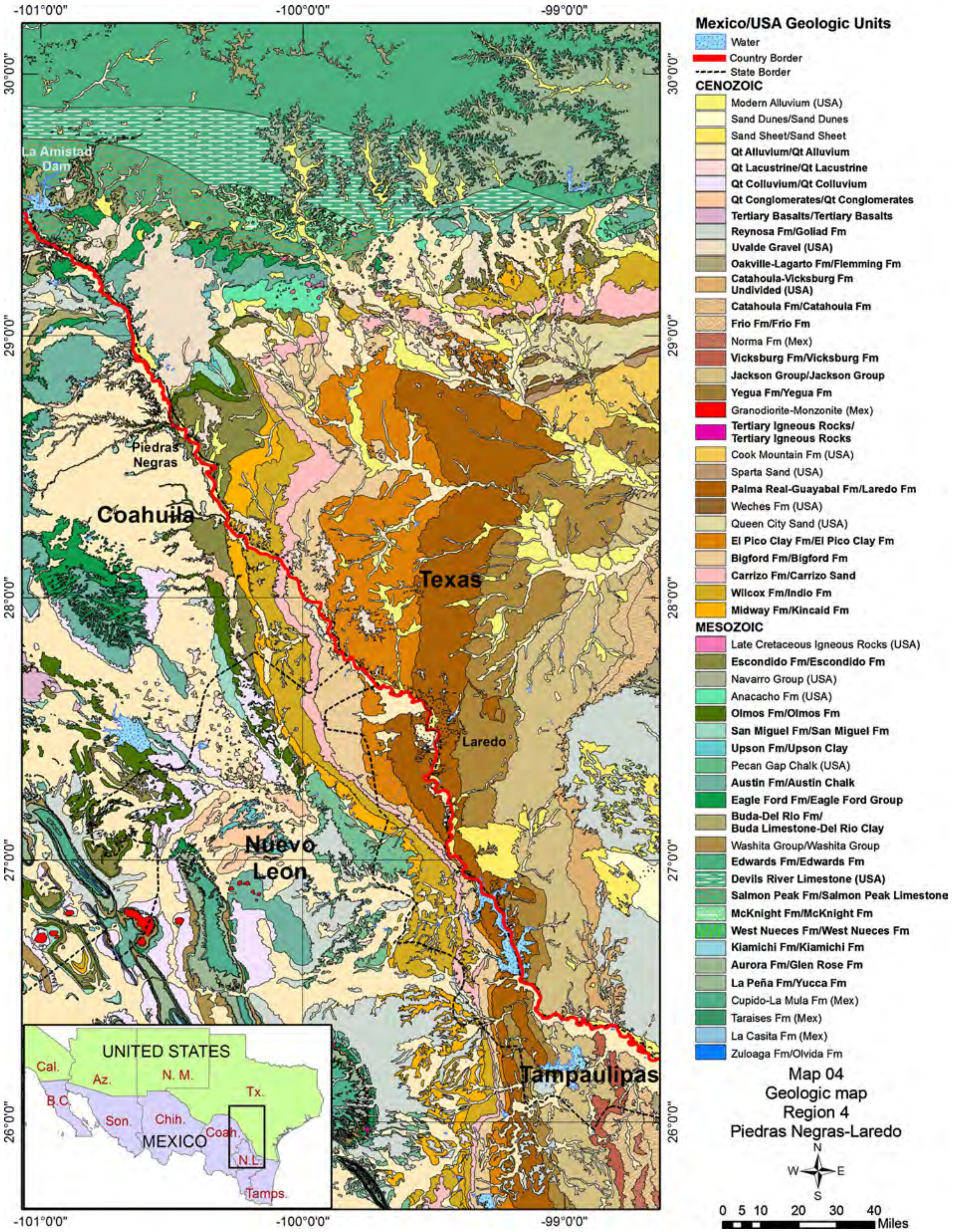

Fig. 4. Geologic map, Piedras Negras-Laredo.

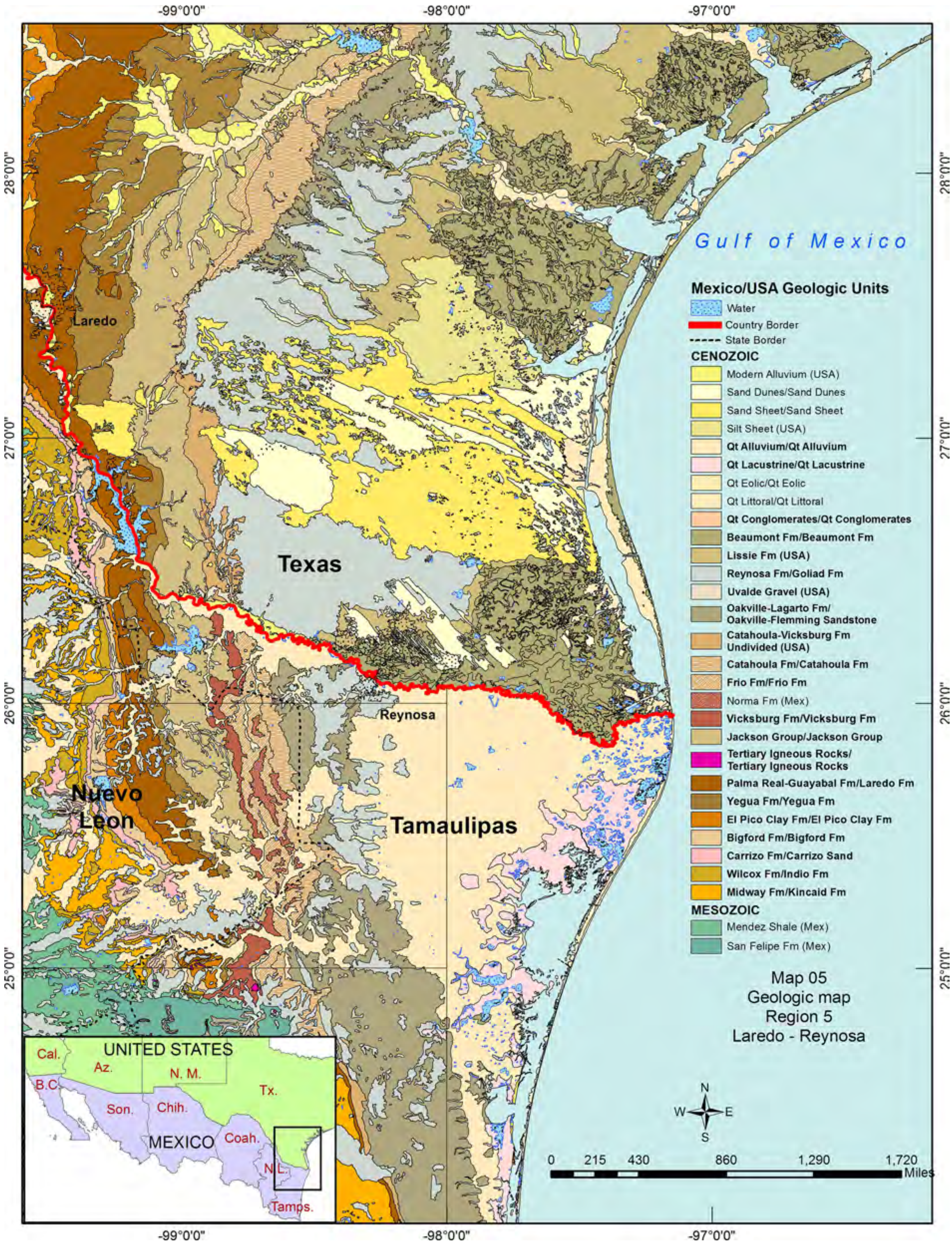

Fig. 5. Geologic map, Laredo-Reynosa.

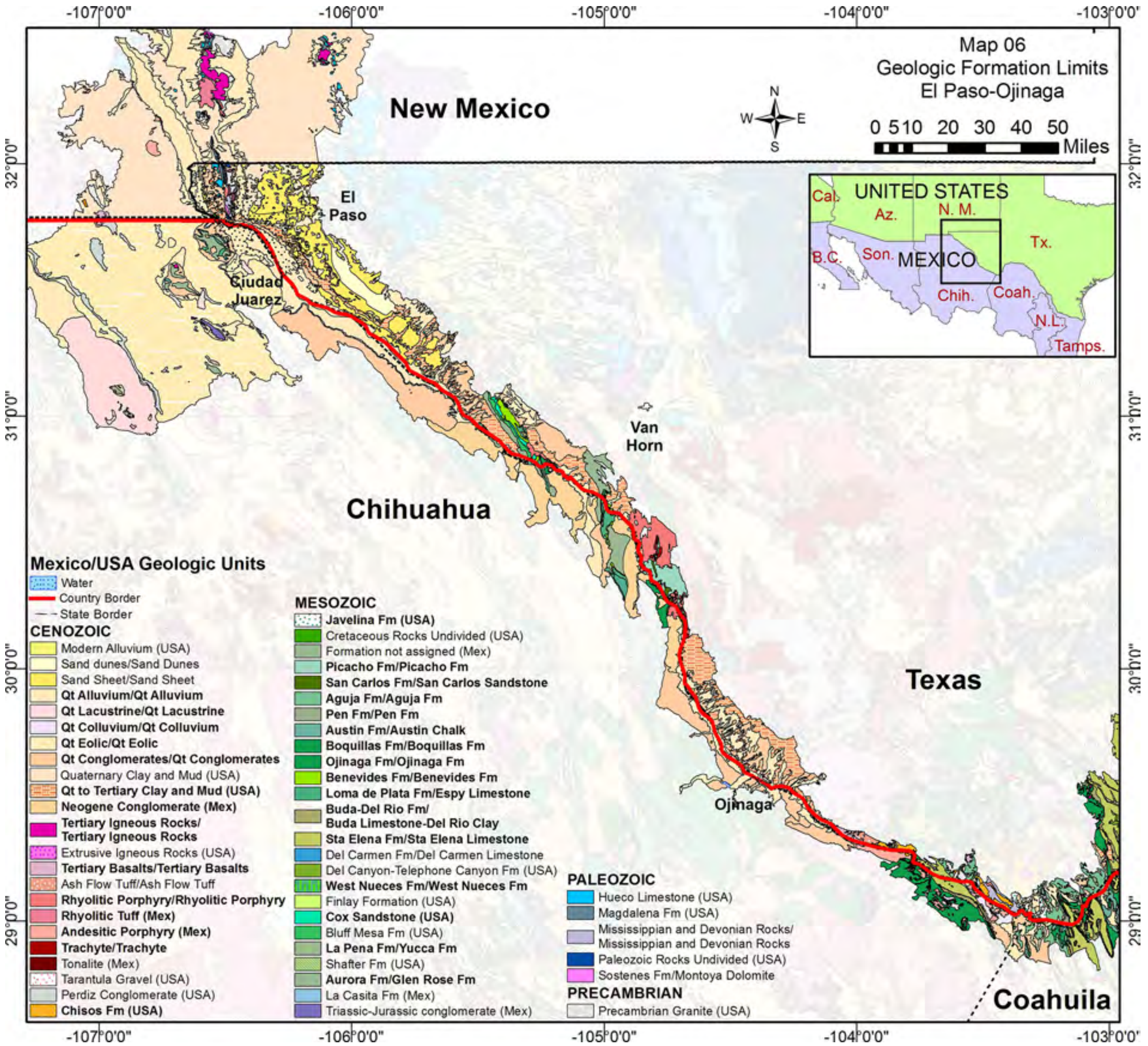

Fig. 6. Geologic formation limits, El Paso – Ojinaga.

represents mostly the geological limits of the Edwards Aquifer and adjacent formations. The north and the west sides are limited by the extent of the geological formation; the east side is limited by the Balcones Fault, and the south (on the Mexico side) by the Boquillas-Sabinas Lineament (Padilla, 2007). Fig. 8 shows the boundaries of the eastern part of the region. The east side of the formations is limited by the coast; the south- side limits (in Mexico) are defined mainly by the Sierra Mojada-China Lineament (Padilla, 2007) and small faults and folds (Servicio Geológico Mexicano, 2016), and the northern limits are defined primarily by the Chittim Anticline, on the east side of Edwards Aquifer (Alexander, 2015), and San Marcos Arch (Baker, 1995), at the northern limit of the Gulf Coast Aquifer.

There are formations that act as extent limits of the boundary formations (those units that do not seem to cross the borderland), or that occur as igneous inclusions within, surrounding or adjacent to the boundary formations. Analysis of these formations was not included in the current study but are included in the figures for mapping and visualization purposes. They are also listed in the corresponding legends of the figures (not highlighted in bold).

3.3. Classification of geological formations/aquifers

Given the geological description and hydrogeological features described in Section 3.1 and Table 2, boundary and transboundary formations were classified according to their aquifer potential and water quality parameters, as described in Section 2.2. The classification shown in Table 3 is based on the predominant conditions of the formations according to available data. Aquifer names are given based on the literature either from the Texas or the Mexico side, except in the case of the Cretaceous-Terlingua Aquifer, which

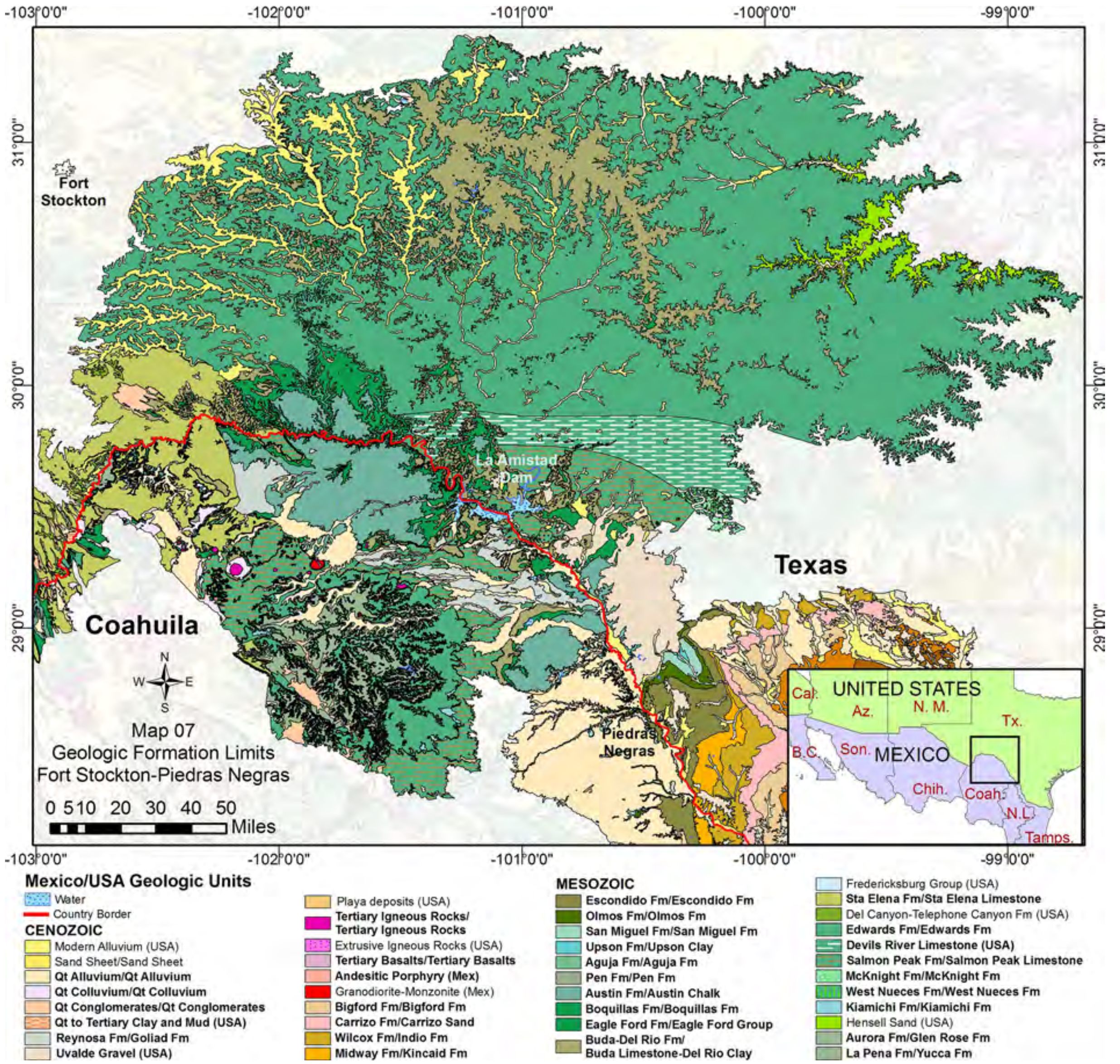

Fig. 7. Geologic formation limits, Fort Stockton – Piedras Negras.

is formed by a section of the Santa Elena Fm/Santa Elena Limestone, a section of Pen Fm, Aguja Fm and Javelina (USA), identified only as Cretaceous strata by Fallin (1990). In contrast with other similar formations, this aquifer shows aquifer potential; therefore, for the purpose of this study and considering its location, it has been identified as the Cretaceous-Terlingua Aquifer. Those formations that have been identified as having good aquifer potential according to the classification but have not been given an aquifer identification name maintain the same formation name on both sides and are referred to as 'hydrogeological units' or HGUs given the lithological differences among them.

Considering the uncertainty of the continuity of the boundary formations (those formations that have been reported only one side of the border) and the randomness of their appearance in the border region with apparent discontinuity in the other side (for example the Tertiary Basalts, Fig. 6), this classification includes both boundary and transboundary formations, pending further research.

To identify and characterize geographically the areas of transboundary groundwater between Texas and Mexico, the IDs from Table 3 are classified into groups with similar characteristics; Table 4 shows the grouping. Five groups were created to identify those geographic areas containing transboundary groundwater with good and moderate potential and differentiate them from those areas with poor potential and water quality. Group 1 (dark green), the most important units/formations in terms of groundwater potential and water quality, corresponds to the A1, A2, B1 and B2 classifications. Group 2 (light green) includes those units/formations that have good to moderate aquifer potential, but poor water quality or with limited water quality information on that area (A3, A4, B3 and B4). Group 2 constitutes a second level of priority representing possible future resource development as desalination projects,

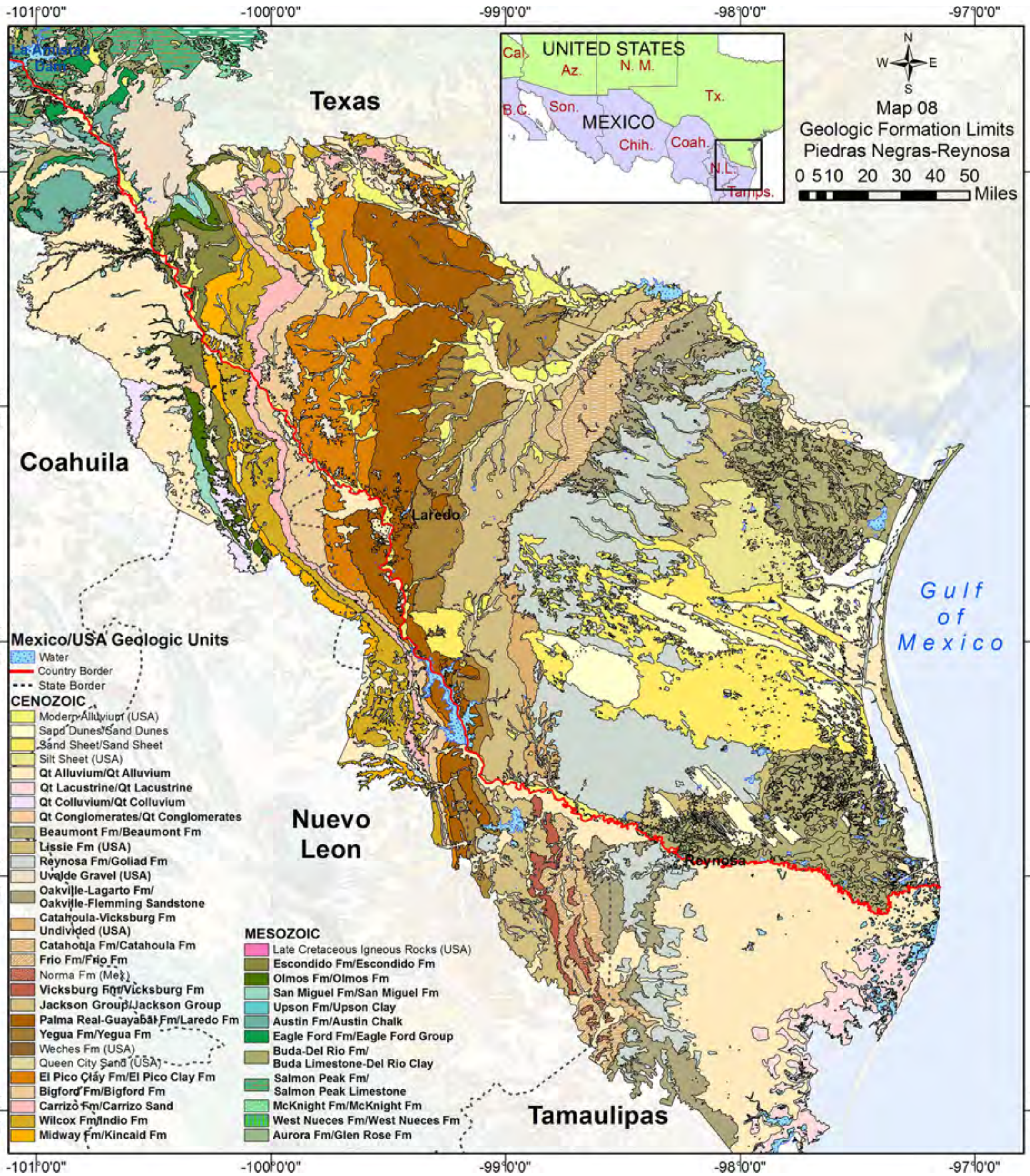

Fig. 8. Geologic formation limits, Piedras Negras – Reynosa.

given the good aquifer potential of those units. Group 3 (orange) includes those units with poor aquifer potential or aquitards with good to moderate water quality. This group may be considered a third level of priority given the limited potential of the aquifer, but still exploitable at the local level for domestic supply in small communities because of good to moderate water quality (C1, C3, D1 and D2). Group 4 (light maroon) is the lowest-priority group: units/formations with poor aquifer potential and with poor water quality or limited information on water quality in that area (C3, C4, D3 and D4). Group 5 (gray) includes those units/formations with limited information on both aquifer potential and water quality. Their priority is undefined, given the lack of data (E1, E2, E3 and E4). Figs. 12, 13 and 14 show the HGUs colored by group. Further details are given in Section 3.4.2.

Interesting findings are shown in Table 3. From the total of 53 boundary and transboundary formations, accounting for differences of geological sections or sub-units within the formation (which add a total of 64), 15 formations/sub-units are considered to

Table 3
Classification of Geological Formations at the Border between Texas and Mexico according to Aquifer Potential and Water Quality (*T = Transmissivity m2/d, K = Hydraulic conductivity m/d, n = porosity%).

BOUNDARY FORMATIONS	TRANSBOUNDARY FORMATIONS	AQUIFER NAME	AQUIFER POTENTIAL	HYDROGEOLOGIC FEATURES	WATER QUALITY	TDS (ppm)	ID
Loma de Plata Fm/Espy Limestone	Loma de Plata Fm/Espy Limestone.		Aquitard.		Unknown.		D4
Aurora Fm/Glen Rose Fm.	Aurora Fm/Glen Rose Fm.		Good.		Moderately to highly saline.	1000 to > 3000	A3
Edwards Fm.	Edwards Fm.	Edwards Aq.	Good.	T=0.15-25100 K=0.0009-221	Predominantly fresh.	< 1000	A1
West Nueces Fm.	Upper West Nueces Fm.		Good.		Unknown.		A4
	Lower West Nueces Fm.		Aquitard.		Unknown.		D4
McKnight Fm.	McKnight Fm.		Aquitard.		Unknown.		D4
Salmon Peak Fm/Salmon Peak Limestone.	Lower Salmon Peak		Poor.		Unknown.		C4
	Upper Salmon Peak.		Good.		Fresh to Saline.		A1-A3
Devils River Limestone (USA).			Good.	n=3% to 15%	Fresh to Saline.		A1-A3
Santa Elena Fm/Santa Elena Limestone	Santa Elena Fm/Santa Elena Limestone.		Moderate.		Unknown.		B4
	Santa Elena Fm/Santa Elena Limestone.		Poor.		Poor.	1130–1303	C2
Pen Fm.	Pen Fm.		Moderate.		Moderate.	2173	B2
Javelina Fm. (USA)		Cretaceous-Terlingua	Poor.		Moderately saline.		C3
Aguja Fm.	Aguja Fm.		Poor.		Poor (saline and hard).	5287	C3
Kiamichi Fm.			Poor.		Slightly saline to moderately saline.		C2
Cox Sandstone (USA)			Unknown.		Unknown.		E4
La Pena Fm/Yucca Formation			Unknown.		Unknown.		E4
Benevides Fm.			Unknown.		Unknown.		E4
Boquillas Fm.	Boquillas Fm.		Poor.		Fresh to slightly saline.		C1-C2
Eagle Ford Fm/Eagle Ford Group.	Eagle Ford Fm/Eagle Ford Group.		Aquitard.		Unknown.		D4
Upson Fm/Upson Clay.	Upson Fm/Upson Clay.		Aquitard.		Brackish.	1000–2500	D2
Austin Fm/Austin Chalk.	Austin Fm/Austin Chalk.		Good.		Unknown.		A4-D4
Buda-Del Rio Fm/Buda Limestone-Del Rio Clay.	Buda-Del Rio Fm/Buda Limestone-Del Rio Clay.		Poor.		Fresh (Reeves) to poor (Fallin).		C1-C3
Ojinaga Fm.	Ojinaga Fm.		Good.		Unknown.		A4
Picacho Fm.			Unknown.		Unknown.		E4
San Carlos Fm/San Carlos Sandstone.			Unknown.		Unknown.		E4
San Miguel Fm.	San Miguel Fm.		Poor.		Highly mineralized.		C4
Olmos Fm.	Olmos Fm.		Aquitard.		Unknown.		D4
Escondido Fm.	Escondido Fm.		Poor.		Brackish.	1000–2500	C2
Chisos Fm. (USA)			Unknown.		Unknown.		E4
Midway Fm/Kincaid Fm.	Midway Fm/Kincaid Fm.		Aquitard.		Saline.		D3
Wilcox Fm/Indio Fm.	Wilcox Fm/Indio Fm.		Moderate.		Fresh to slightly saline.	1000–3000 (TX)	B1-B2
Carrizo Fm/Carrizo Sand.	Carrizo Fm/Carrizo Sand.	Carrizo-Wilcox Aq.	Good.		Fresh to slightly saline / Poor (Mex).	1000–3000 (TX), 482–9334 (MX).	A1-A3
Bigford Fm.	Bigford Fm.		Poor.		Saline.		C3
El Pico Clay Fm.	El Pico Clay Fm.		Poor-Aquitard.		Mineralized/ Poor.		C3-D3
Palma Real-	Palma Real-Guayabal	Palma	Poor.		Saline.		C3

(continued on next page)

Table 3 (*continued*)

Guayabal Fm/ Laredo Fm.	Fm/ Laredo Fm.	Real-Guayabal Fm/ Laredo Fm.					
Yegua Fm.	Yegua Fm.	Yegua-Jackson Aq.	Poor.		Low.		C3
Jackson Fm/Jackson Group.	Jackson Fm/Jackson Group.		Moderate.	T=7.8 K=0.4	Low.	> 3000	C3
Vicksburg Fm.	Vicksburg Fm.	Catahoula Confining System.	Poor.	n=5%	Unknown.		C4
Frio Fm.	Frio Fm.		Aquitard.		Moderately saline.	>3000	D3
Catahoula Fm/Catahoula Fm and Catahoula-Vicksburg Fm Undivided.	Lower Catahoula Formation.		Aquitard.	T=4.5 K=0.2	Slightly to moderately saline.	>3000	D2
	Upper Catahoula Formation.	Bajo Rio Bravo/Gulf Coast Aq.	Moderate.		Brackish	>1000	B2
Oakville-Lagarto Fm./ Flemming Fm.	Oakville-Lagarto Fm./ Flemming Fm.		Moderate.	T=9.3 K=1	Good to moderate.	>1000	B1-B2
Reynosa Fm/ Goliad Fm.	Reynosa Fm/ Goliad Fm.		Moderate.	T=22 K=1.5	Good to moderate.	>1000	B1-B2
Lissie Formation (USA)			Good.	T=46.3 K=8.5	Slightly saline.	800–5000	A2
Beaumont Fm.	Beaumont Fm.		Poor.		Slightly saline.	> 2000	C2
Quaternary Deposits.	Qt Lacustrine.		Aquitard.		Saline.		D3
	Qt Alluvium.		Moderate.		Slightly Saline.		B2
	Qt Alluvium.	Santa Fe del Pino Aq.	Regular.	T=0.77 × 10[-3] to 0.01 × 10[-3]	Slightly Saline.		B2
	Qt Conglomerates.		Good.		Fresh to slightly saline.	400–1500	A1-A2
	Qt Alluvium.	Serrania del Burro Aq.	Good.		Fresh to slightly saline.		A1-A2
	Qt Colluvium.		Unknown.				E4
Qt to Tertiary clay and mud (USA).			Poor.		Saline.	>1000	C2-C3
Quaternary Deposits.	Qt Alluvium.	Presa La Amistad Aq	Good.		Fresh to slightly saline.		A1-A2
Uvalde Gravel (USA).			Good.		Fresh to slightly saline.	<1000-3000	A1-A2
Uvalde Gravel (USA).		Allende-Piedras Negras Aq.	Good.		Fresh to slightly saline.	<1000-3000	A1-A2
Quaternary Deposits.			Good.	T=0.0005 to 0.005	Fresh to slightly saline.	<1000-3000	A1-A2
Qt Conglomerates.	Qt Conglomerates.		Good.		Fresh to slightly saline.	400-1500	A1-A2
Quaternary Deposits.	Quaternary Deposits.	Bolsons: Valle de Juarez, Hueco-Tularosa, Mesilla Aquifer, Conejos-Medanos, Red Light Draw, Green River Valley, Presidio,	Good.	$T=2 \times 10^{-3}$ $K=8.69 \times 10^{-6}$ n=9%	Fresh to slightly saline.	400-1500	A1-A2
Qt Conglomerates.	Qt Conglomerates.		Good.		Fresh to slightly saline.	400-1500	A1-A2
Qt to Tertiary clay and mud (USA).			Poor.		Saline.	>1000	C2-C3
Neogene Conglomerate (Mex).			Moderate.		Fresh water.	710	B1
		Redford					
Tertiary Igneous Rocks.		Tertiary Igneous Rocks.	Poor-Aquitard.		Good.	870–3013	C1-D1
Tertiary Basalts.		Tertiary Basalts.	Poor.		Good.	354	C1

have good to middle aquifer potential with good to moderate water quality, and 4 formations have good aquifer potential but limited information on water quality (Upper West Nueces Fm, Santa Elena Fm/Santa Elena Limestone, Austin Fm/Austin Chalk, and Ojinaga Fm). It is fair to say that approximately 35% of the identified geological units have good aquifer potential, with at least 28% of good to moderate water quality conditions. The predominant formations under this classification are the Edwards Fm, Upper Salmon Peak and Aurora Fm/Glen Rose Fm, all parts of the Edwards Aquifer. Likewise, good aquifer conditions are also prominent in the Quaternary Alluvium Deposits of Santa Fe del Pino, the Serrania de Burro and Presa la Amistad Aquifers and the Quaternary and

Table 4
Formations Classified into Five Groups According to Aquifer Potential and Water Quality.

Formation Classification			Water Quality			
			Good	Regular	Poor	No Info
			1	2	3	4
Aquifer Potential	Good	A	A1	A2	A3	A4
	Middle	B	B1	B2	B3	B4
	Poor	C	C1	C2	C3	C4
	Aquitard	D	D1	D2	D3	D4
	No Info	E	E1	E2	E3	E4

Conglomerate Deposits of the bolsons of Valle de Juarez, Mesilla, Red Light Draw, Green River Valley, Presidio and Redford. The Carrizo Fm/Carrizo Sand part of the Carrizo-Wilcox Aquifer is also in this category. Moderate aquifer conditions but with less than 1000 ppm TDS were found in Oakville-Lagarto Fm/Flemming Fm, Reynosa Fm/Goliad Fm, and Wilcox Fm/Indio Fm.

On the other hand, an estimated 17 formations (32%) have been identified as poor aquifers or aquitards with poor to moderate water quality. The predominant formations in this category are the Yegua Fm (part of the Yegua-Jackson Aquifer); Santa Elena Fm/

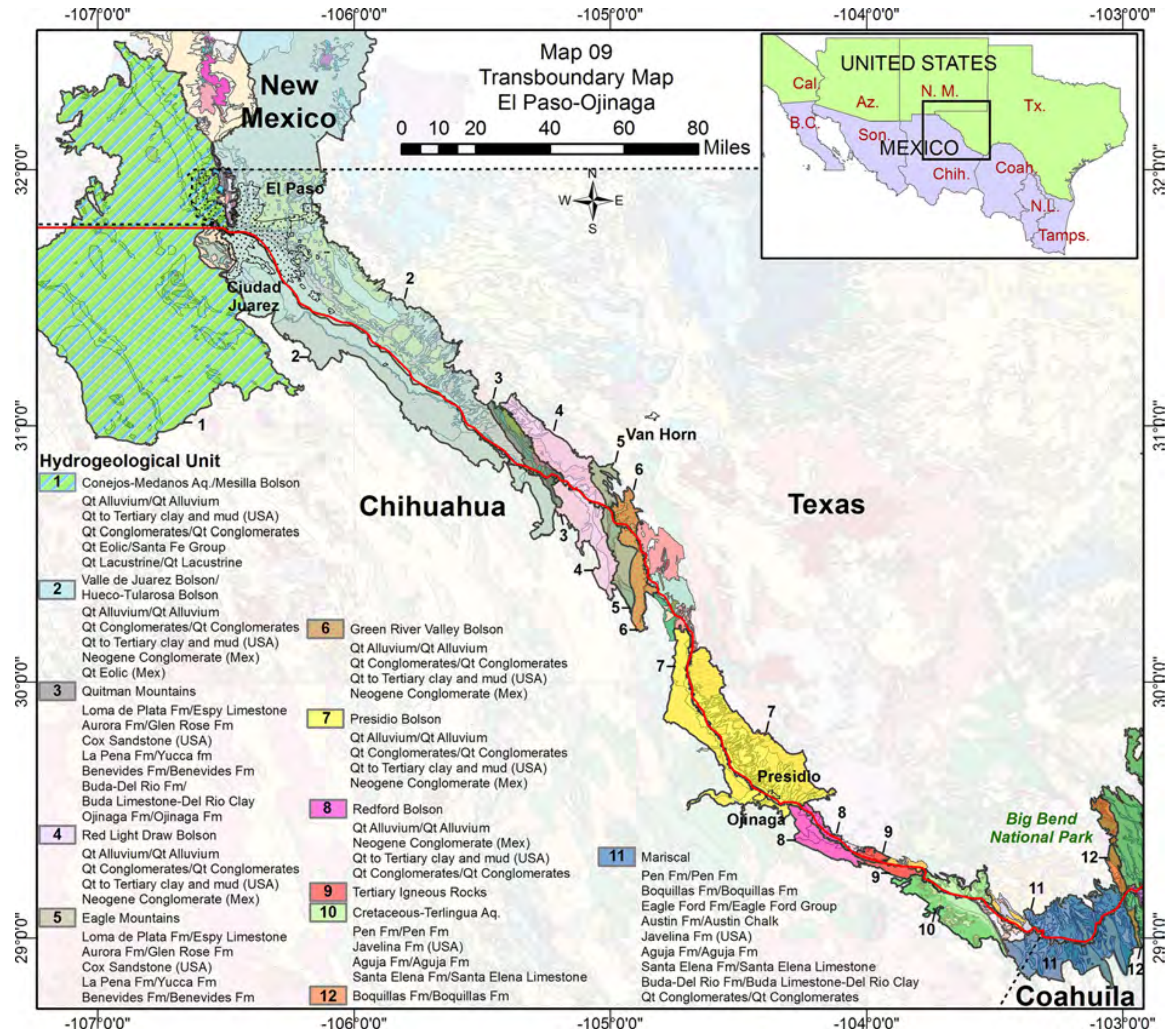

Fig. 9. Transboundary map, El Paso – Ojinaga.

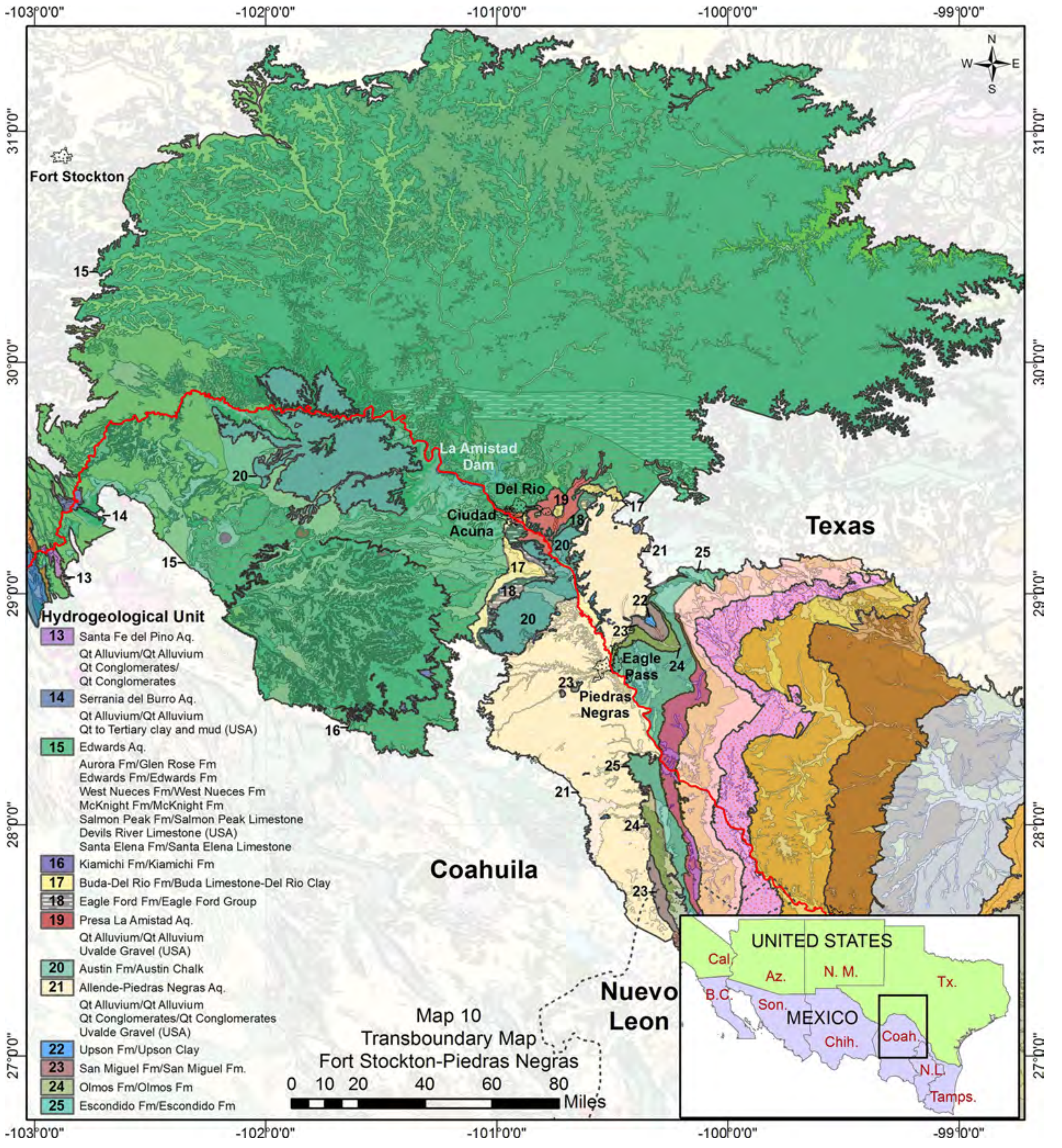

Fig. 10. Transboundary map, Fort Stockton – Piedras Negras.

Santa Elena Limestone (part of the Cretaceous-Terlingua Aquifer); Upson Fm/Upson Clay; Aguja Fm; Escondido Fm; Midway Fm/ Kincaid Fm; Bigford Fm; Palma Real-Guayabal Fm/Laredo Fm; Frio Fm and the Lower Catahoula Formation (both parts of the Catahoula Confining System); and the Beaumont Fm (part of the Gulf Coast Aquifer). The rest of the formations and sub-units (5) are considered aquitards, with no data on water quality, or aquitards with good to moderate water quality (3), and there are 6 boundary and transboundary formations that have no reported data on either aquifer conditions or water quality: San Carlos Fm/San Carlos Sandstone, Chisos Fm (USA), Cox Sandstone (USA), La Pena Fm/Yucca Fm, Picacho Fm and Benevides Fm Caution should be taken in estimates of percentages, considering that these are based on type of formation and not on geographical extent.

From a general perspective, the area of the bolsons southeast of the Valle de Juarez/Hueco- Tularosa Bolson Aquifer in the north of Chihuahua and southwestern Texas, and between the Serrania del Burro and Allende-Piedras Negras Aquifers in south Texas and north of Coahuila, where the Quaternary and Alluvium deposits are concentrated, appear to be the most important areas for transboundary aquifer potential. Section 3.4.1 describes those transboundary formations in more detail.

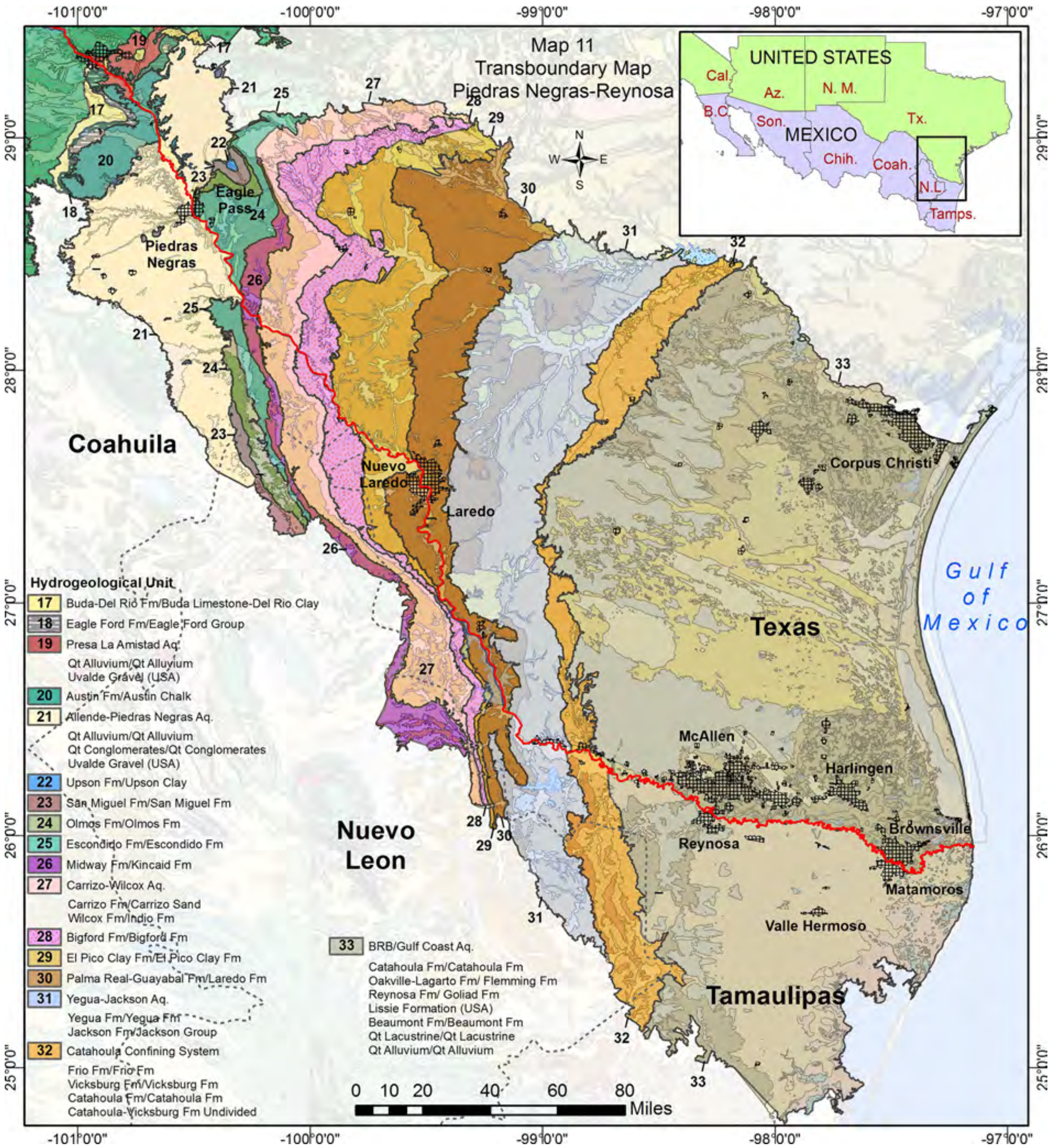

Fig. 11. Transboundary map, Piedras Negras – Reynosa.

3.4. Classification of transboundary hydrogeological units (HGUs)

3.4.1. Transboundary hydrogeological units (HGUs)

In order to assess the classification of transboundary hydrogeological units it was necessary to group the transboundary geological formations into hydrogeological units/aquifers. Figs. 9–11 show the transboundary geological formations grouped into hydrogeological units. The clustering of formations is based on the geological and lithological description of the units in Section 3 and in the literature cited mainly in Table 2. These maps represent a more refined identification of transboundary geological formations considering hydrogeological linkages and boundary limitations. They are referred to as 'hydrogeological units' or 'HGUs' (instead of aquifers) because of the different hydrogeological conditions among formations that may or may not be categorized as an aquifer.

Fig. 9 shows the region including the population centers of El Paso/Ciudad Juarez and Presidio/Ojinaga. Twelve HGUs are identified and delineated. Starting from the west, the Conejos Medanos/Mesilla Bolson and Valle de Juarez/Hueco-Tularosa Bolson

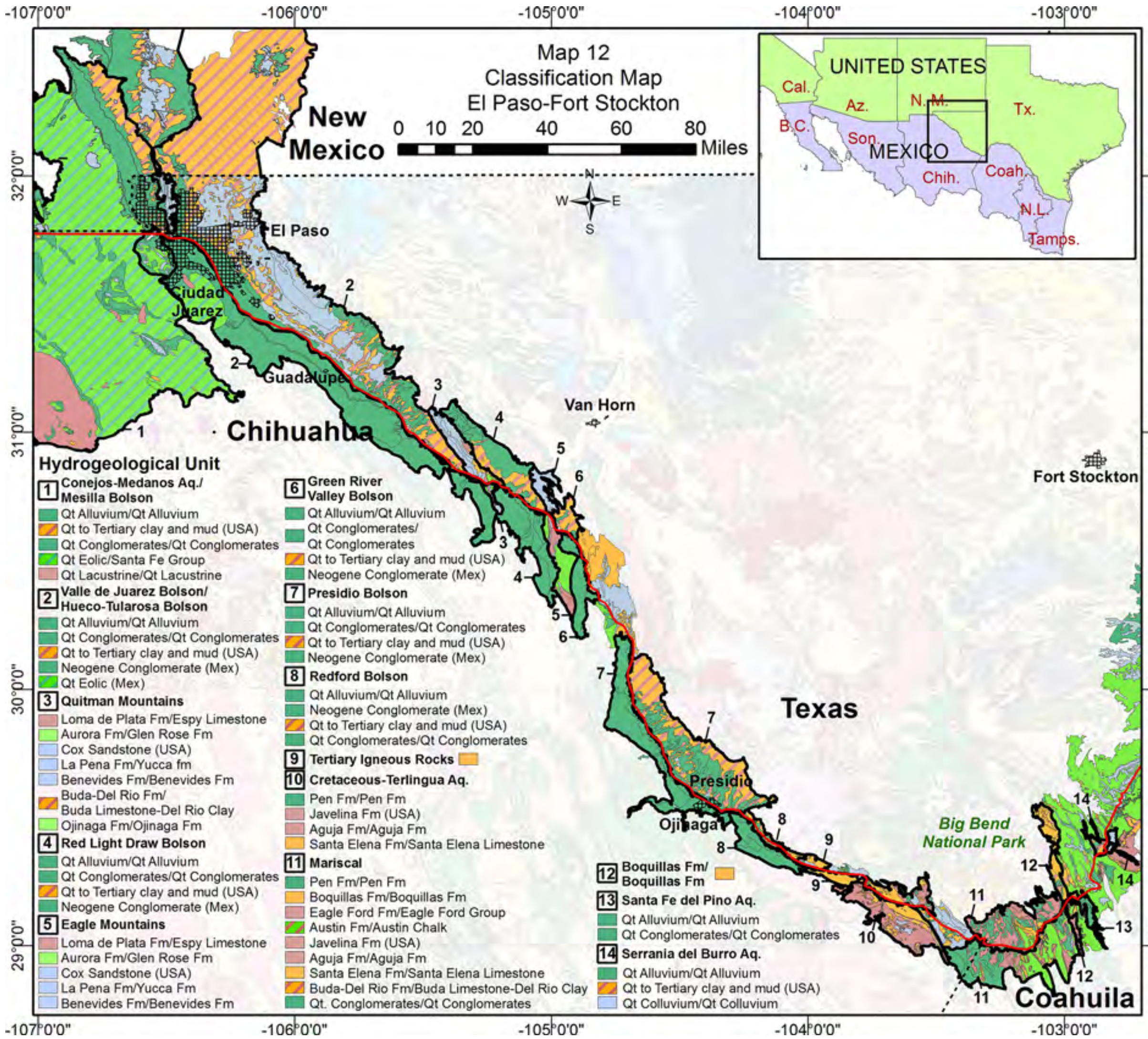

Fig. 12. Classification map, El Paso – Fort Stockton.

aquifers are the most studied aquifers in the region and officially recognized as transboundary aquifers by both countries (Sheng et al., 2001), and therefore hydrogeological conditions and boundaries have been addressed according to the literature. These aquifers are formed by Quaternary Alluvium and Quaternary Conglomerates on both sides of the border, Quaternary Clay and Mud on the Texas side and Neogene Conglomerate in the Hueco-Tularosa Bolson on the Mexico side. It is important to clarify that the areal extension of these aquifers crosses into New Mexico, where the geological formation is recognized as the Santa Fe Group, which is equivalent to Quaternary Clay and Mud in the Hueco-Tularosa Bolson and Quaternary Eolic in the Mesilla Bolson.

Moving east, there are multiple formations with different hydrogeological properties. These formations are continuous across the border, therefore have been grouped (instead of divided) into the Quitman Mountains HGU. This HGU groups a series of small formations with limited aquifer potential (except for Aurora Fm/Glen Rose Fm and Ojinaga Fm) that act primarily as a boundary between the neighboring bolsons (Beach, 2008; Groat, 1972). The next HGU identified is the Red Light Draw Bolson which is composed of the same geological features as the Valle de Juarez/Hueco-Tularosa Bolson. Likewise, the next group of formations, the Eagle Mountains HGU, has very limited aquifer potential and acts as a boundary of the adjacent bolson. Similar to the Quitman Mountains HGU, The Eagle Mountains HGU has limited aquifer potential and acts as a hydrogeological boundary between adjacent HGUs. Is formed by portions of the same formations identified in the Quitman Mountains, except for the Buda-del Rio Fm/Buda Limestone-Del Rio Clay and the Ojinaga Fm. (Beach, 2008).

From west to east, the next three HGUs, the Green River Valley Bolson, the Presidio Bolson and the Redford Bolson, are formed by the same formations as the previous bolsons and are considered to have good aquifer potential, but more research is needed to confirm both aquifer capabilities and transboundary linkages (Gabaldón, 1991). East of the Redford Bolson, the HGU designated as Tertiary Igneous Rocks is an aquifer of limited potential because of the igneous material prominent in this area. The next formation to

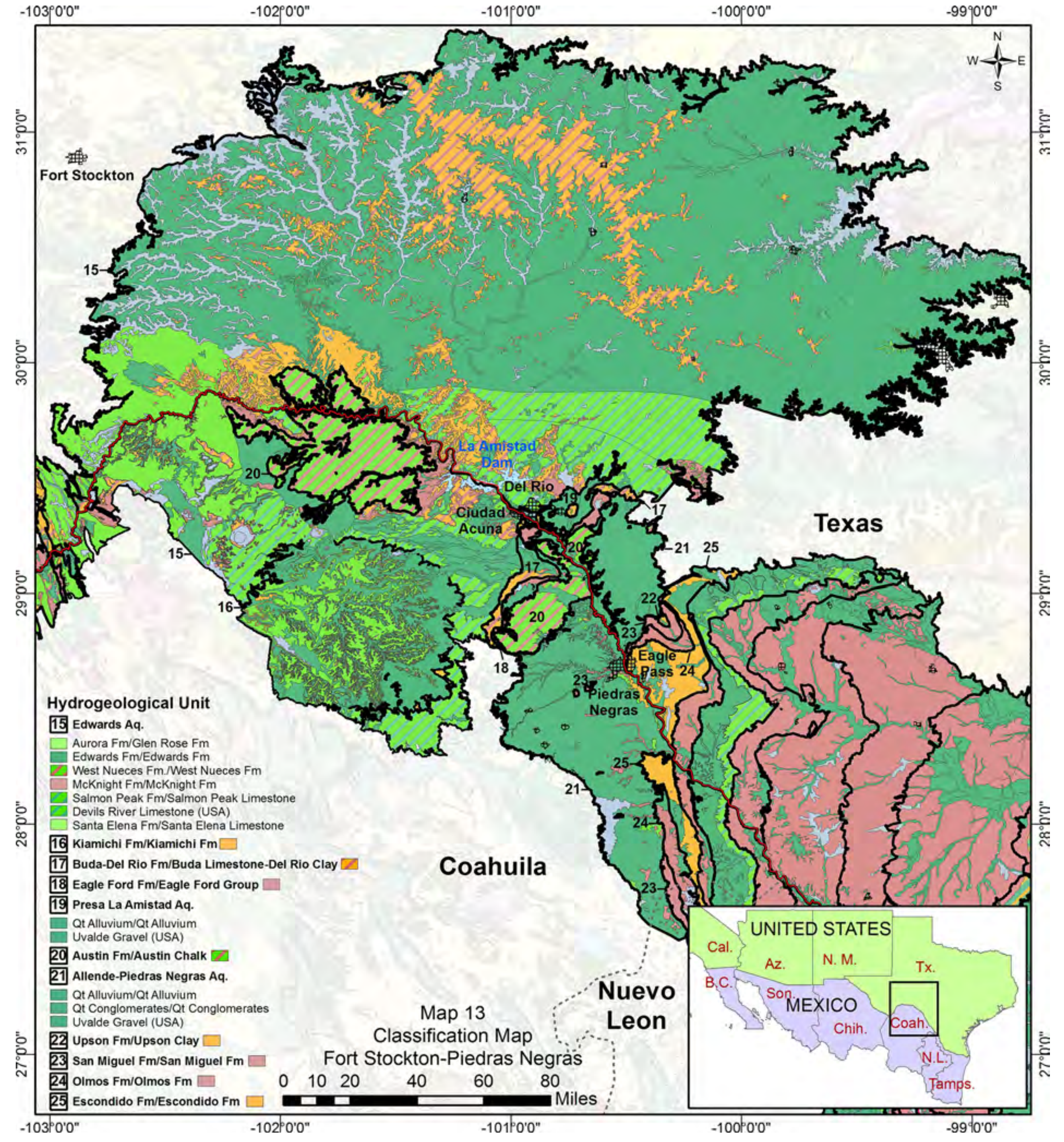

Fig. 13. Classification map, Fort Stockton – Piedras Negras.

the east has been referred in this study as the Cretaceous-Terlingua Aquifer. The literature refers to this area mainly as Cretaceous strata (Fallin, 1990), but because of the broad presence of formations of Cretaceous age in the region and to geographically identify this particular formation which shows aquifer potential, this study refers to this HGU as the Cretaceous-Terlingua Aquifer. This aquifer includes four formations, but only one (Pen Fm) is considered to have some aquifer potential. The next group of trans-boundary formations, located mostly in the Big Bend region/Maderas del Carmen, Coahuila, is referred to as the Mariscal HGU, after the Mariscal Mine in Big Bend National Park. It includes a variety of laterally discontinuous layers that cross the boundary at varying locations, making their separation problematic. This HGU act as a barrier to neighboring water-bearing formations. Apart from a small section of the Austin Chalk Fm and the Quaternary Conglomerate lenses present in this region, the Mariscal HGU does not have good aquifer potential.

East of the Mariscal HGU is the Boquillas Fm, which has no important aquifer potential. Finally in Fig. 10 there are two

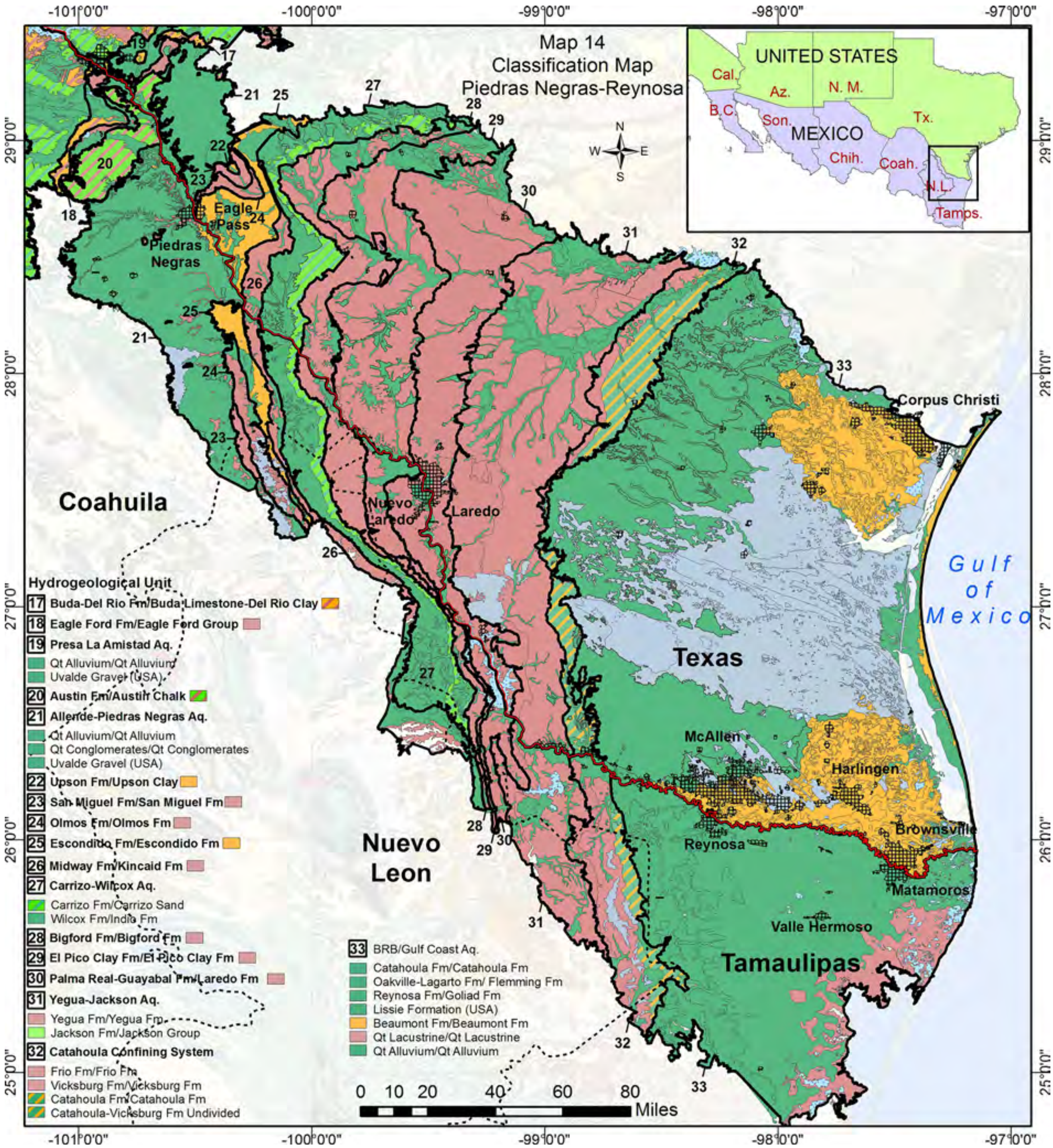

Fig. 14. Classification map, Piedras Negras – Reynosa.

Quaternary Alluvium aquifers: the Santa Fe del Pino and the Serrania de Burro. These names are from official reports on the Mexican portion of the aquifer (CONAGUA, 2015d, 2015e). In addition to Quaternary alluvium, the Santa Fe del Pino is formed by Quaternary Conglomerates on both sides of the border, and the Serrania del Burro is formed by Quaternary Clay and Mud on the Texas side. Though small, both transboundary aquifers are characterized as having good aquifer potential (CONAGUA, 2015d, 2015e), but more research is required.

Fig. 10 shows the transboundary HGU from Fort Stockton to Piedras Negras. The largest HGU in this figure is the Edwards Aquifer. One of the largest aquifers in the state of Texas, it supplies groundwater to the southcentral part of the state and extends into the northern and western parts of the state of Coahuila. This aquifer is composed of a variety of formations with mostly good aquifer potential. Except for the lower portions of the West Nueces Fm and the Salmon Peak Fm, which are considered to have poor aquifer potential, and a portion of Santa Elena Fm/Santa Elena Limestone, which is considered to have moderate aquifer potential, the rest of the formations in the Edwards Aquifer have good aquifer potential as well as good water quality (Boghici, 2004). All of the identified formations have been reported on both sides of the border, except for the Devils River Limestone (USA).

Considering the extension of the Edwards aquifer, which covers the largest area in the borderland, there are geological features worth mentioning. First, the Kiamichi Fm outcrops as a linear feature at the southern limit of the Edwards aquifer in Coahuila, creating an open circle around this region (dark purple) stratigraphically underlying the Edwards aquifer. Likewise, the Austin Fm/Austin Chalk has also been identified as overlying a portion of the Edwards Aquifer, adjacent to the border between Texas and northeast Coahuila, acting as an upper confining unit of the system (Boghici, 2004). As mentioned in Section 3, some reports describe this formation having a good aquifer potential (Boghici, 2002), but others classify it as an aquitard (Clark and Small, 1997; Reeves and Small, 1973). The Austin Fm/Austin Chalk is also present to the east of the Buda-Del Rio Fm/Buda Limestone-Del Rio Clay, which is the next HGU to the east. The Buda-Del Rio Fm/Buda Limestone-Del Rio Clay is continuous across the border into Texas, underlying the Uvalde Gravel and outcropping as small islands inside and to the north of the Presa La Amistad Aquifer. This formation and the Eagle Ford Fm/Eagle Ford Group have poor aquifer potential (Boghici, 2002). The next identified HGU is the Presa La Amistad Aquifer, named from Mexico's official reports (CONAGUA, 2015a,b,c,d,e,f,g,h). This HGU is formed by Quaternary Alluvium on both sides of the border and the Uvalde Gravel (USA) on the Texas side. It is reported to have good aquifer potential as well as good water quality (CONAGUA, 2015a,b,c,d,e,f,g,h). It is worth mentioning The Presa La Amistad Aquifer underlines the region where the International Amistad Dam is located, and according to official reports from CONAGUA (2015c), there is groundwater flow from the aquifer to Amistad Reservoir/Dam. Hydrogeological information for this region is limited on both sides of the border; therefore, more research is required to confirm surface and groundwater interactions from this aquifer. East of the Presa La Amistad Aquifer is the Allende-Piedras Negras Aquifer. Though it has not been recognized officially as a transboundary aquifer, technical studies are available that report transboundary linkages in this aquifer (Boghici, 2002). This aquifer is formed by Quaternary Alluvium and Quaternary Conglomerates on both sides of the border and the Uvalde Gravel (USA) on the Texas side.

Fig. 11 shows the HGUs moving east towards the coast, starting from a small outcrop section of the Upson Fm/Upson Clay, which appears as blue points in the middle of the San Miguel Fm on the Mexico side of the border, with several points east of the Allende-Piedras Negras aquifer on Texas side. Next are the Escondido Fm, Olmos Fm and Midway Fm/Kincaid Fm, which act as aquitards or have poor aquifer potential and poor water quality (saline/brackish). The next HGU to the east is the Carrizo-Wilcox Aquifer, which is formed by the Carrizo Fm/Carrizo Sand and the Wilcox Fm/Indio Fm. There is a reasonable amount of data on this aquifer from both sides of the border that agree that aquifer potential is good to moderate and water quality is fresh to slightly saline, depending on location (Klemt et al., 1976; Ashworth and Hopkins, 1995; Boghici, 2002). East of the Carrizo-Wilcox Aquifer, the three HGUs (Bigford Fm, El Pico Clay Fm and Palma Real-Guayabal Fm/Laredo Fm) and the Yegua Fm, which is part of the Yegua-Jackson Aquifer, are reported to have aquifer characteristics similar to the Escondido and Olmos Formations (Boghici, 2002; CONAGUA, 2006). The remaining portion of the Yegua-Jackson Aquifer (Jackson Fm/Jackson Group) is reported to have moderate aquifer potential but poor water quality (Boghici, 2002; CONAGUA, 2006). Between the Yegua-Jackson Aquifer and the Gulf Coast Aquifer, referred to in Mexico as the Bajo Rio Bravo Aquifer, lies the Catahoula Confining System. None of the formations that are part of this confining system are reported to have good aquifer potential or water quality (Ashworth and Hopkins, 1995; TWDB, 2017). The Upper Catahoula portion of the Catahoula Fm is part of the Gulf Coast Aquifer and is reported to have moderate aquifer potential and brackish water (Ashworth and Hopkins, 1995; TWDB, 2017). All formations the Gulf Coast Aquifer have good aquifer potential and good water quality, except for the Beaumont Fm (TWDB, 2017), which is adjacent to the Quaternary Lacustrine in the vicinity of the state of Tamaulipas. The transboundary portion of this aquifer seems to rely on the Quaternary Alluvium located along the Rio Grande (CONAGUA, 2015h). Details of the potential transboundary portions of the HGU are addressed in the next section.

3.4.2. Classification of transboundary HGUs by group

Figs. 12–14 map the HGUs, colored by category (Group ID, Table 4). Fig. 12 shows the western region of Texas, bordering the state of Chihuahua. The most important aquifers in the region are the HGUs designated as bolsons, which are classified as good production potential aquifers. However, except for the urban centers in the region, including the cities of Presidio and Ojinaga and small towns that use groundwater for irrigation and livestock on both sides of the border (Guadalupe in Chihuahua and Sierra Blanca, Valentina and Van Horn in Texas), not much research or groundwater development is reported in this region. Given the limited surface water availability in this border area, there is a high dependency on groundwater, which has had impacts on the sensitive ecosystem in some areas of the Chihuahua desert (Sanchez et al., 2016). Moreover, there seems to be interest in developing groundwater storage in the igneous portion of the western bolsons for the future water needs of the city of El Paso (Sanchez et al., 2016). More research and data collection on aquifer properties and water quality on both sides of the border in this region is of high priority for both countries.

The Big Bend region does not represent an important source of groundwater development given the complexity and limited continuity of the formations that surround the transboundary area, some classified as good aquifers and others as aquitards. The fact that this region is a national park and a protected area on the Mexican side (Maderas del Carmen) makes significant groundwater development in the region unlikely. However, two small Quaternary Alluvium transboundary aquifers, Santa Fe del Pino and Serrania del Burro, have been identified on the eastern side of the Big Bend area, which should be noted for future research and water needs in the area. Generally, 60–65% of the land in this area is estimated to have good aquifer potential and good water quality.

Fig. 13 predominantly shows the Edwards Aquifer and adjacent HGUs. According to the classification system (Table 4), 80–85% of the Edwards Aquifer HGU is classified as having good to moderate aquifer potential, with both good and poor water quality areas. Exceptions are a portion of the border region between Texas and Coahuila, north of the Austin Chalk and a small portion in the western extent of the aquifer. Given the generally good aquifer potential of the Edwards Aquifer, which extends almost to the center of the state of Coahuila, the Edwards Aquifer in Coahuila is considered of high priority for future research. The Mexican side of the aquifer is considered an ecological priority for the state of Coahuila because it includes the Serrania del Burro Mountains, which serves as the headwaters of all perennial rivers in the state. These rivers provide water for the cities of Ocampo, Muzquiz and Cuatrocienegas in the Five Springs Region (Region de los Cinco Manantiales). Cuatrocienegas is outside the limits of the Edwards Aquifer. There is high dependency on the Presa La Amistad Aquifer in the cities of Del Rio/Acuna (bordering the Edwards) and on the Allende Piedras Negras Aquifer in the bordering cities of Piedras Negras/Eagle Pass (Sanchez et al., 2016). There are reports of high transmissivity along the border area, as well as groundwater confinement that increases water yield in the area of the Amistad Aquifer close to Acuna (George et al., 2011). Other small communities in Uvalde, Kinney, Edwards and Val Verde Counties in Texas also rely on groundwater from the Edwards Aquifer, and a reverse hydraulic gradient has been reported north of Uvalde City due to surface drainage variations and overpumping (Boghici, 2002).

Continuing eastward from the area covered in Figs. 13, 14 shows the classification of HGUs from the Allende Piedras Negras Aquifer to the BRB/Gulf Coast Aquifer. Within this area, it can be seen that apart from the Carrizo-Wilcox Aquifer and sections of the Gulf Coast Aquifer along the border, which are considered to have good aquifer potential and good water quality on both sides of the border, the rest of the region falls into the poor-quality category for aquifer and water. This region is known to have high salinity (TDS 1000–3000 mg/L) and is referred to as the “bad water zone” (Sanchez et al., 2016); reliance on groundwater in this region is limited. Good aquifer potential associated with the Gulf Coast Aquifer extends from Texas across the border to the state of Tamaulipas. Groundwater supply is reported to be significant in the border cities of McAllen/Reynosa and Brownsville/Matamoros and the surrounding area. Extensive irrigation districts on both sides depend on groundwater for economic development. In the Texas counties of Harris, Galveston, Fort Bend, Jasper and Wharton, land subsidence has been reported in the Gulf Coast Aquifer (George et al., 2011), and reverse groundwater flow because of over-pumping has been reported around the cities of Crystal City and Cotulla.

Further, because of the location of the Amistad and Falcon international dams in this region as well as the groundwater–surface interactions that contribute to the Rio Grande/Rio Bravo river flow and its tributaries, a portion of the groundwater on the Mexico side is considered to be committed to fulfill Mexico’s water obligations with the United States under the 1944 Water Treaty for the “Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande”, adding pressure on groundwater resources in this region (CONAGUA, 2015c). Based on the classification system (Table 4), it is estimated that around 30–35% of the borderland in this region has good aquifer potential.

Overall, the identified HGUs in the borderland between Texas and Mexico cover around 180,000 km2 (approximately 110,000 km2 on the Texas side and 72,000 km2 on the Mexico side). It is worth mentioning that, excluding the area of the Edwards Aquifer, which has a large areal extent primarily on the Texas side (approximately 35,000 km2), the proportion of land on both sides of the border is similar. Between 50% and 60% of this area is considered to have good aquifer potential as well as good water quality, of which approximately 60% is in Texas and 40% in Mexico. Approximately 20–25% of the borderland is considered to have poor aquifer conditions and poor water quality, with approximately equal areas on both sides of the border.

4. Conclusions

From the total of 53 boundary and transboundary formations identified between Mexico and Texas, there are 15 formations/subunits considered to have good to moderate aquifer potential and good to moderate water quality. Approximately 35% of the identified geological units have good aquifer potential, and at least 28% good to moderate water quality. The predominant formations classified as good to moderate are the Edwards Fm, Upper Salmon Peak and Aurora Fm/Glen Rose Fm (part of the Edwards Aquifer), the Quaternary Alluvium Deposits of Santa Fe del Pino, the Serrania de Burro and Presa la Amistad Aquifers, and the Quaternary and Conglomerate Deposits of the bolsons of Valle de Juarez, Mesilla, Red Light Draw, Green River Valley, Presidio and Redford. The Carrizo Fm/Carrizo Sand part of the Carrizo-Wilcox Aquifer is also in this category. On the other hand, an estimated 17 formations (32%) have been identified as having poor aquifer potential or as aquitards with moderate to poor water quality. The predominant formations in this category are the Yegua Fm (part of the Yegua-Jackson Aquifer); Santa Elena Fm/Santa Elena Limestone; Upson Fm/Upson Clay; Aguja Fm; Escondido Fm; Midway Fm/Kincaid Fm; Bigford Fm; Palma Real-Guayabal Fm/Laredo Fm; Frio Fm and the Lower Catahoula Formation (both parts of the Catahoula Confining System); and the Beaumont Fm (part of the Gulf Coast Aquifer).

Overall, the area covered by the identified HGUs in the borderland between Texas and Mexico is around 180,000 km2 (approximately 110,000 km2 on the Texas side and 72,000 km2 on the Mexico side). The total area considered to have good aquifer potential as well as good water quality ranges between 50% and 60%, of which approximately 60% is in Texas and 40% in Mexico. Approximately 20–25% of the borderland is considered to have poor aquifer potential and poor water quality. From a general perspective, the areas of the bolsons southeast of the Hueco-Tularosa Bolson Aquifer in northern Chihuahua and southwestern Texas, and between the Serrania del Burro and Allende-Piedras Negras Aquifers in southern Texas and northern Coahuila, where the Quaternary and Alluvium deposits are concentrated, appear to be the most important for transboundary aquifer potential.

This is the first assessment of its kind in this region. Further research must incorporate new data to better define the physical characteristics of the HGU, such as three-dimensional distribution of HGU; the extension of the main hydrogeological basics; evidence of groundwater flow systems across the borderland; distribution of hydraulic heads, and, chemical and isotopic composition of the residence times of groundwater. This efforts will support the development of transboundary management regimes aimed at preventing the degradation of future water supplies in the borderland between Mexico and the United States.

Conflict of interest statement

The submitted article represents an original research/review work that has not been considered for publication in any other journal, book, conference proceedings, or government publication of substantial circulation. All works referred to in the article have been acknowledged by proper citation, and there are no real or apparent conflict of interests in its content.

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