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Transboundary Aquifers between Baja California, Sonora and Chihuahua, Mexico, and California, Arizona and New Mexico, United States: Identification and Categorization

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Abstract: In 2016, research suggested there might be up to 36 transboundary aquifers located along the border between Mexico and the U.S. The main contribution of this study was to put together the available segments already existent in the literature without considering the validity of the criteria used to define the boundaries of those segments. In 2018, updated research reported 33 hydrogeological units (HGUs) crossing the boundaries between Mexico and Texas. This later analysis included the homogenization of geological nomenclatures, standardization of geological and hydrogeological criteria, using a specific methodology to correlate, identify, and delineate each HGU. The purpose of this paper is to use this latter methodology and expand the same analysis to include the transboundary aquifers between Baja California/California, Sonora/Arizona, and Chihuahua/New Mexico. Results of this study indicate that a total of 39 HGUs have been identified in this region which accounts for an approximate shareable land of 135,000 km^2 where both countries share half of the area. From the total shareable area, around 40% reports good to moderate aquifer potential and water quality, of which 65% is in the U.S. and 35% on the Mexico side. Border-wide, the total number of HGUs in the border region between Mexico and the United States is 72, covering an approximate area of 315,000 km^2 (180,000 km^2 on the U.S. side and 135,000 km^2 on the Mexico side). The total area that reports good to moderate aquifer potential as well as good to regular water quality ranges between 50 and 55% (of which approximately 60% is in the U.S. and the rest in Mexico).

Keywords: transboundary; aquifers; Mexico; United States; border; groundwater

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1. Introduction

In 2016, Sanchez et al. [1] suggested there might be up to 36 transboundary aquifers located along the border between Mexico and the U.S. This first assessment attempted to represent the first draft of all aquifers across the frontier between the two countries. However, this initial step was only able to put together the available information already existent without considering the validity of the criteria used to define the boundaries of those aquifers. Two years later, Sanchez et al. [2] reported 33 hydrogeological units (HGUs) crossing the boundaries between Mexico and Texas. This later analysis included the homogenization of geological nomenclatures and the standardization of geological and hydrogeological criteria to define aquifer boundaries, and it used a methodology to correlate, identify, and delineate each HGU based primarily on geological parameters. Although this methodology might differ from other transboundary studies in the border region [3–7], it did provide for the first time important physical elements that highlighted the transboundary nature of groundwater at the border at a regional scale. In fact, apart from the available studies performed under the umbrella of the Transboundary Aquifer Assessment Program (TAAP), which include de San Pedro/San Pedro, Santa Cruz/Santa Cruz (including Nogales/Nogales), Valle de Juarez/Hueco Bolson, Conejos-Medanos/Mesilla

Bolson, and Allende-Piedras Negras transboundary aquifers, there are limited references to physical studies of transboundary aquifers at a regional and even transboundary scale. There are some additional projects led by the U.S. Geological Survey (USGS) that have studied the Lower Rio Grande Basin, the Tijuana River basin, Mimbres/Las Palmas Aquifer, and the Lower Colorado River Basin [8]; however, their analysis tends to be limited to the U.S side of the aquifers. Therefore, the rest of the aquifers or shared areas in the border region remain to be explored. As of 2018, from the 33 HGUs identified by Sanchez et al. [2] between Mexico and Texas, only four aquifers have reported some type of assessment at transboundary level.

The purpose of this paper is to use the methodology applied in the border region between Mexico and Texas from Sanchez et al. [2] and expand the analysis to the remaining border region between Mexico and the United States. This study will report on the existing set of transboundary aquifers reported by Sanchez et al. [2] and include Baja California/California, Sonora/Arizona, and Chihuahua/New Mexico. Therefore, the overall result will be a border-wide assessment of transboundary aquifers utilizing one unique methodology that identifies, delineates, and initially assesses the physical conditions of all the hydrogeological units (HGUs) east of the Rio Grande/Rio Bravo across both countries. This information will serve as the basis for future assessments and prioritization analysis of transboundary aquifers in the border region between Mexico and the United States.

Results indicate that a total of 39 HGUs have been identified in the border region between California, Arizona, and New Mexico on the U.S. side and Baja California, Sonora, and Chihuahua on the Mexico side. This region accounts for an approximate shareable area of 135,000 km^2 where both countries share half of the area (65,000 km^2 Mexico and 69,000 km^2 the U.S.) From the total shareable area, around 40% reports good to moderate aquifer potential and water quality, of which 65% is located in the U.S. and 35% on the Mexico side.

From a statewide perspective, the border between Baja California, Mexico, and California, U.S., reports a total of 5 HGUs, from which 3 (Tijuana-San Diego Aq., Valle de Mexicali-San Luis Rio Colorado/Yuma-Imperial Valley and a great portion of the Quaternary deposits of Laguna Salada Aq./Coyote Wells Valley) report good to moderate aquifer potential and generally good to moderate water quality. Available data on water quality varies across the Valle de Mexicali-San Luis Rio Colorado/Yuma-Imperial Valley from good to poor (limited data included), particularly in the southern portions where saline water intrusion has been reported. In the case of Sonora and Arizona, 25 HGUs have been identified, with at least 7 HGUs (Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin, Rio San Pedro Aq./Upper San Pedro Basin, Rio Agua Prieta Aq./Douglas Basin, Rio Altar Aq., San Simon Wash, Sonoyta-Puerto Peñasco Aq., and La Abra Plain) with generally good to moderate aquifer potential and good to moderate water quality. Variability of water quality for Sonoyta-Puerto Peñasco Aq., and San Simon Wash is also reported [9]. Additionally, 4 HGUs reported good to moderate aquifer potential but poor water quality with uncertainty considering the data limitations. Those include Cerro Colorado Numero 3 Valley, Lukeville-Sonoyta Valley, The Great Plain, and Arroyo Seco Aq. In the border region between Chihuahua and New Mexico, good aquifer potential and good water quality were identified in at least 3 out of the 8 HGUs reported. These are Janos Aq./Playas Basin, Ascension Aq./Hachita-Moscos Basin, and Las Palmas Aq./Mimbres Basin. Potrillo Mountains also report good aquifer potential but limited data on water quality.

Border-wide and adding the HGUs previously reported by Sanchez et al. [2] between Texas and Mexico, the total number of HGUs in the border region between Mexico and the United States totals 72, covering an approximate area of 315,000 km^2 (180,000 km^2 on the U.S. side and 135,000 km^2 on the Mexico side). The total area that reports good to moderate aquifer potential as well as good to regular water quality ranges between 50 and 55% (of which approximately 60% is in the U.S. and the rest in Mexico).

The first part of this paper presents the geological correlation of formations along the border across California, Arizona, and New Mexico on the U.S. side and Baja California, Sonora, and Chihuahua on the Mexico side. The second part focuses on integrating and delineating the identified HGUs according to hydrological, lithological, topographical, surficial, and structural geology criteria. The third part of the paper shows the classification of the geological units within the boundaries of the corresponding HGUs according to aquifer potential and water quality. This study uses the same methodology and criteria developed by its predecessor, Sanchez et al. [2], with its corresponding limitations and adaptations considering the differences in geological characterization and data availability described below.

2. Materials and Methods

2.1. Geological Correlation

The basis of the analysis is to perform the geological correlation among units across the border. First, it was necessary to develop a review of available literature of geological units between Mexico, California, Arizona, and New Mexico, along with an extensive visualization and analysis of geographical information using ArcMap 10.5. Geological data, and maps from Mexico were downloaded from the federal agency Servicio Geologico Mexicano (SGM) [10] in shapefile format at 1:250,000 scale: Cartas Geologico mineras Tijuana I11-11, Mexicali I11-12, I12-10 Los Vidrios, Ensenada H11-2, San Felipe H11-3, Puerto Peñasco H12-1, Nogales H12-2, Agua Prieta H12-3, Cananea H12-5, Nacozari H12-6, Ciudad Juarez H13-1, and Nuevo Casas Grandes H13-4 [11–22]. For the states of California, Arizona, and New Mexico, geological data and maps were downloaded from the USGS online spatial data website, which covers the entire states [23,24] in shapefile format at 1:100,000 scale. The map scales were selected according to data availability on both sides of the border.

To address the issues related to differences of geological equivalence across the border, we first correlated the geological units by comparing the ages and stratigraphic lexicons and matched the geological units with their corresponding equivalent on the other side of the border. We used the lexicons available on the SGM website since they offer detailed lithological descriptions and geologic ages of the units across the border. After identifying the geological age ranges, name, and description of the units in Mexico, we correlated them with their equivalents using the USGS lexicons as reference.

Once the geological correlation process was performed, a geological structural and stratigraphic analysis (vertical geology) was developed using the geologic map profiles and well lithology descriptions to identify and delineate the boundaries of the formations. The physical continuity of geological units can be truncated by folds, lineaments, or faults, and in other cases, several formations were clustered together considering their lithological and hydrogeological similarities. A challenging issue was the igneous and metamorphic bodies outcropping at different regions. Due to their uneven distribution as outcrops, it is not possible to confirm their continuity underground, in contrast to the sedimentary rocks that are usually distributed as tabular masses and whose continuity across the border is easily traceable. Therefore, the criteria are that only geologic units outcropping on the international border (boundary formations) or crossing the border (transboundary formations) are considered in the analysis of classification of HGUs. Though there is no evidence of geological continuity across the border of the boundary formations, they are considered in the analysis as they constitute important geological and hydrological pieces within their corresponding HGUs. They appear in bold (Mex or U.S.) in the legends of the maps. As for the geologic units that outcrop only on one side of the border but do not appear close to the international border, they are considered in the geological correlation analysis and in the maps for visualization purposes but do not appear in bold in the map legends. This criterion was applied to most of the igneous and metamorphic rocks.

2.2. Delimitation of HGUs

As in Sanchez et al. 2018, this paper uses the term hydrogeological unit or HGU to refer to any soil or rock unit or zone that by virtue of its hydraulic properties has a distinct influence on the storage or movement of groundwater [25]. Therefore, considering the different hydrogeological conditions among units, some may or may not be categorized as aquifers.

The delimitation of the boundaries of the HGUs was the product of the aggrupation of geological units with common lithological features (such as high porosity) from other units where the impermeable rocks dominate. An important methodological criterion that was added as compared to Sanchez et al. [2] was topography. We integrated this variable because it was significantly important in those areas where the surficial geology was not enough to identify the limits of the unit, or the geologic heterogeneity of several units did not provide enough elements to draw a surficial boundary. For these cases, the geological maps were overlapped with the topographic applications of StreamStats from USGS [26], and SIATL from INEGI [27] which provided lineaments and slope changes to complement the HGUs' delineation. If the topography was still not definitive to identify a specific portion of the boundaries, we reviewed the available literature to confirm or adjust the boundary delineation for each case. Well lithological descriptions were also useful as indicative of aquifer features (aquifer potential) since rocks can have different conditions on the surface as compared to underground, which may modify the capacity of the aquifer to yield water. Therefore, this criterion was also added to the analysis of the HGU delimitation as compared to Sanchez et al. [2].

Another different criterion was the one applied to several HGUs where their delimitations included outcrops of crystalline igneous and metamorphic rocks with low porosity capabilities that appear as isolated hills in the topographic maps. Considering that available information about these hills does not provide enough confidence to discriminate them from the area covered by the corresponding HGU, this study included them within the boundaries of the corresponding HGU, pending further research to clarify if these crystalline rocks have an interaction with the rest of the area of the HGU.

Lastly, we assigned names to the HGUs based on preexistent aquifer names reported in the area on either side of the border. If there were no aquifers identified in previous studies, we used geographical marks, such as mountains, valleys, or towns to assign a name to the corresponding HGU.

2.3. Classification of Geological Formations

The last task was the classification of geological units (boundary and transboundary formations), which is based on hydrogeological features (aquifer potential) and water quality data, according to the same criteria used by Sanchez et al. [2].

"Aquifer potential" is defined as the potential that a geological unit, a group of geological units, or part of a geological unit contains sufficient saturated permeable material to yield significant quantities of water for wells and springs [28]. The criteria used to define aquifer potential considers mainly lithological features, permeability, porosity, hydraulic conductivity, and transmissivity (Table 1). Because the natural complexity and heterogeneity across the units and the different methods that are used to characterize units on both sides of the border, a combination of criteria had to be used to classify aquifer potential as "good", "moderate" or "poor". This study uses geological and lithological descriptions of the units, porosity and hydraulic conductivity when available, or standardized values according to the predominant lithology [29]. We also used permeability reports and assessments from the National Water Commission (CONAGUA), and technical reports from the New Mexico Water Resources Research Institute (NMWRRI), the Arizona Department of Water Resources (ADWR), California Division of Mines and Geology, and the USGS. We obtained data from federal, state, and local agencies, as well as from technical, academic, and scientific reports. The common criterion used in the literature for water quality was TDS (total dissolved solids), which were available for almost the complete border region.

Table 1. Geological formations classified into five groups according to aquifer potential (Good, Moderate, Poor) and water quality (Good, Regular, Poor). The unit of water quality is Total Dissolved Solids (TDS). The colors represent an ID later used in the classification of the units and on the maps. (Adapted from Sanchez et al. [2].)

Geological Formation			Water Quality			
			Good	**Regular**	**Poor**	**No Info**
			<1000 ppm	**1000–3000 ppm**	**>3000 ppm**	
			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

Following the methodology of Sanchez et al. [2], we used the TDS ranges from the Texas Water Development Board [30] to classify groundwater quality: freshwater, less than 1000 mg/L; slightly saline (usually called "brackish water"), 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 studies refer to "parts per million" (ppm), where 1 ppm is equivalent to 1 mg/L; ppm are the units used in this study. The categories defined in Table 1 for water quality consider freshwater as "good", slightly saline as "regular", and moderately saline with very saline are combined into one category as "poor". Table 1 shows how the formations will be classified into five groups according to aquifer potential for each one and its corresponding reported water quality.

3. Results and Discussion

3.1. Geological Correlation between Mexico (Baja California, Sonora, and Chihuahua) and the U.S. (California, Arizona, and New Mexico)

This section covers the geological features of the formations identified and correlated between Baja California, Sonora, and Chihuahua in Mexico, and California, Arizona, and Nuevo Mexico in the U.S. which are described in detail in Table 2. Geological formations in Table 2 are listed according to their geological age (oldest first), and if their names differ across countries, the first name listed corresponds to what is reported in Mexico and then in the U.S. Table 2 also includes hydrological features available and the reported names of those geological units that have been referred by the literature aquifers.

As in Sanchez et al. [2], there are formations that have been identified only on one side of the border (therefore not crossing to the other side); those formations are identified as boundary formations with a parenthetical (USA) or (MEX) after their name. Boundary and transboundary formations (the formations that cross the border) are the ones subject to classification analysis in this study and are highlighted in bold in the figures. Figures 1–4 list all the identified geological units with their reported names from both sides (Mex/U.S., even if they are the same). Other geological units located in the area but not outcropping the border are not considered in the analysis but are included in the maps and legends (not in bold) for visualization purposes. It is worth mentioning that in comparison to our antecessor, the geological maps in this study include geological faults and main topographic and hydrologic references that were not included in Sanchez et al. [2].

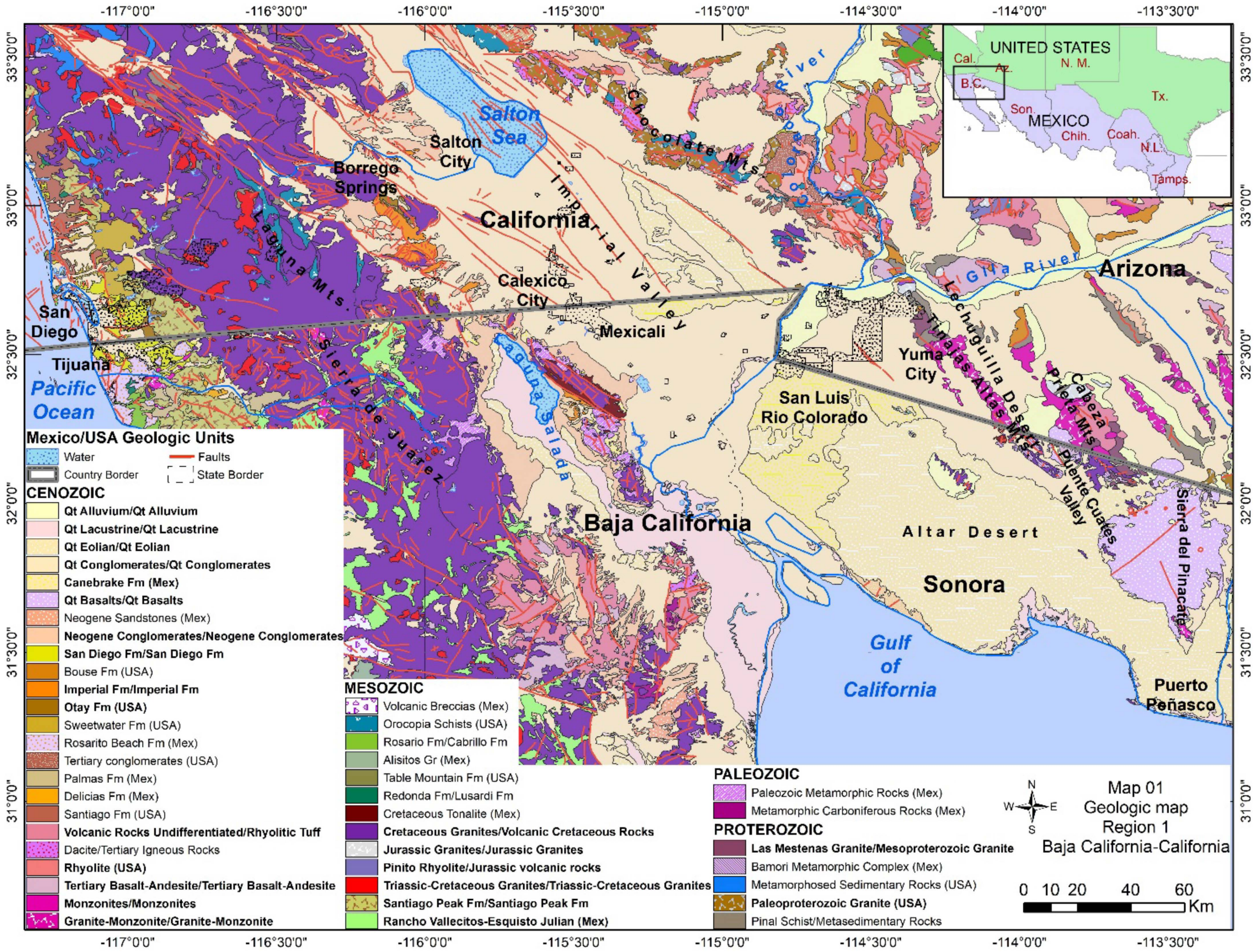

Figure 1. Geologic map, Baja California—California.

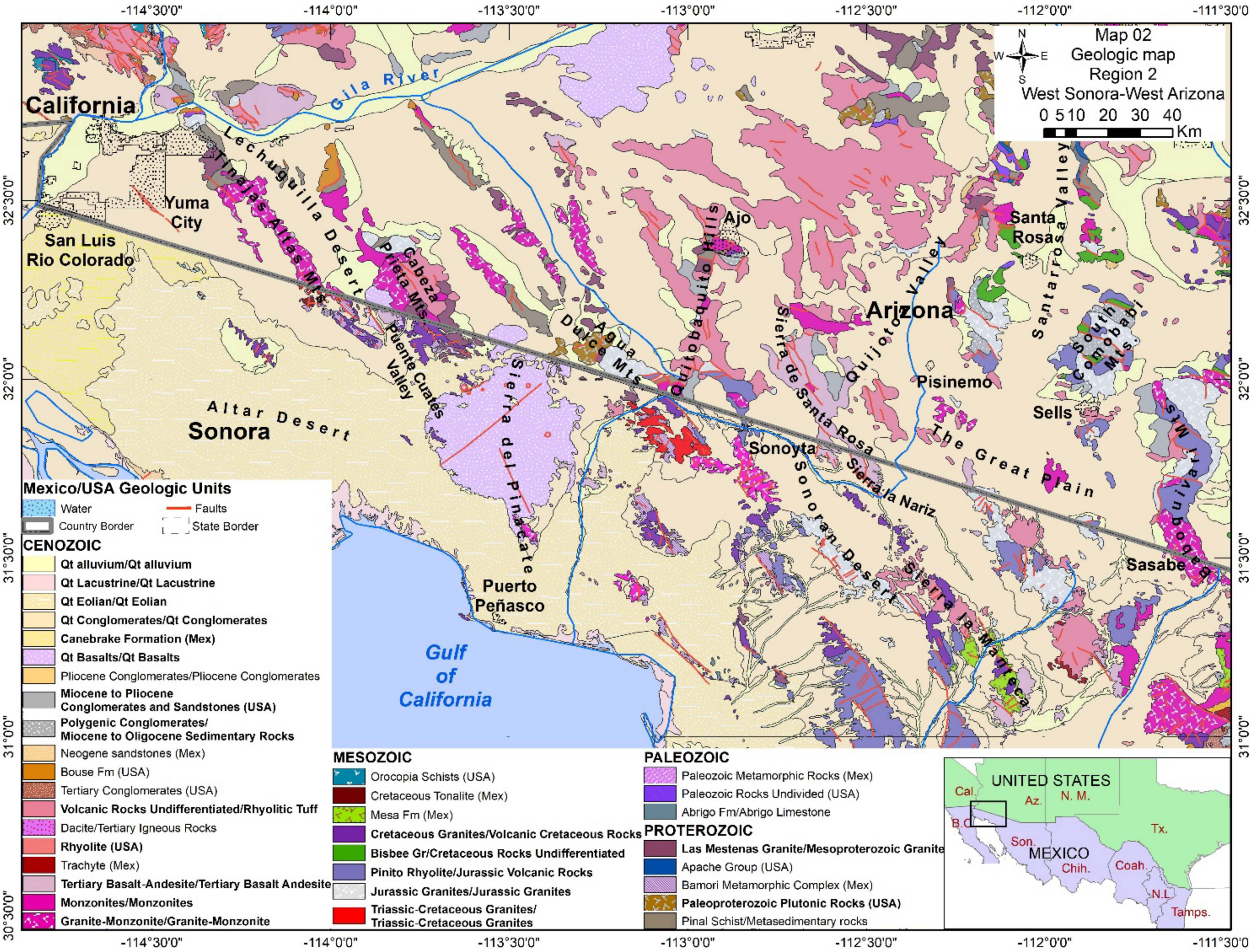

Figure 2. Geologic map, West Sonora—West Arizona.

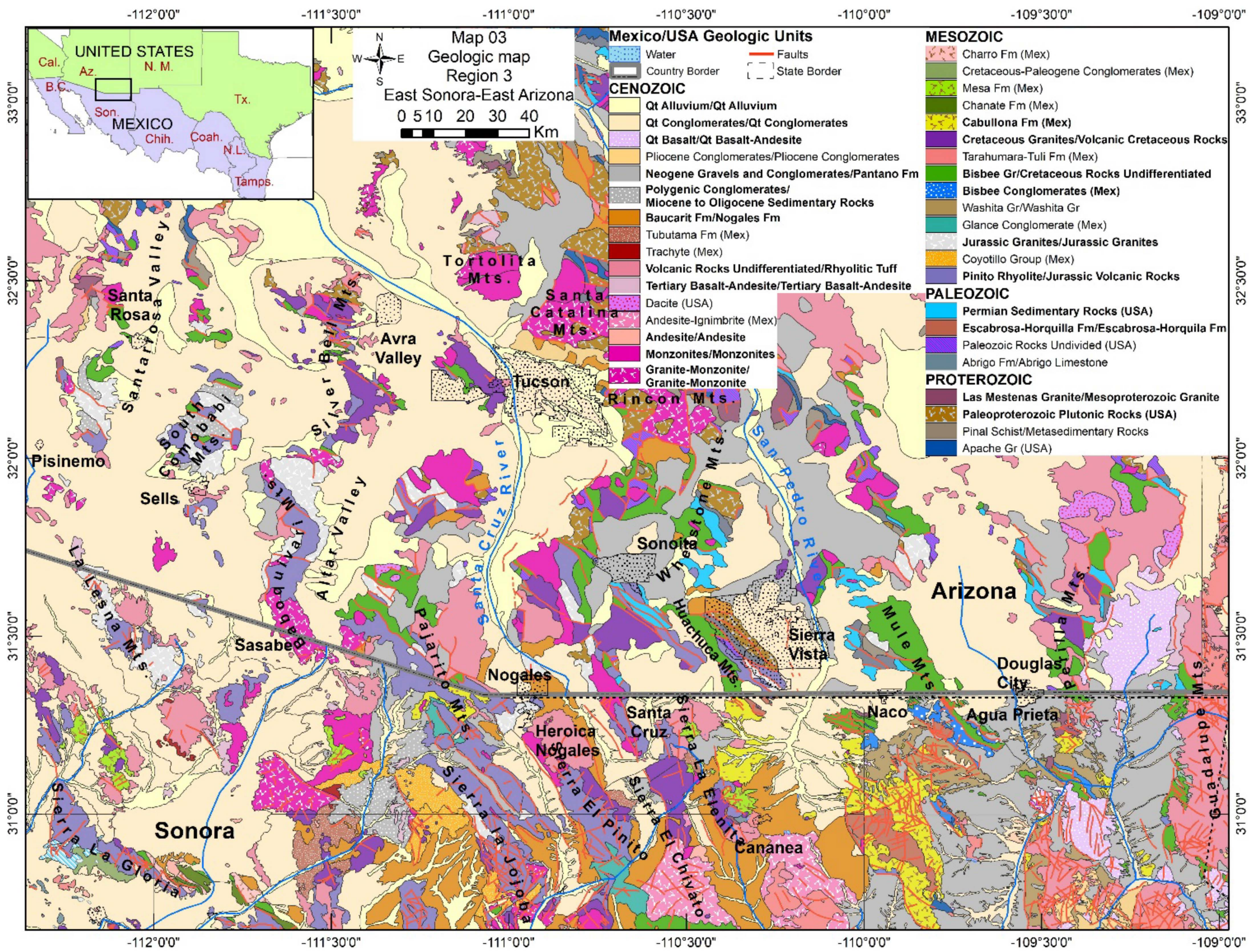

Figure 3. Geologic map, East Sonora—East Arizona.

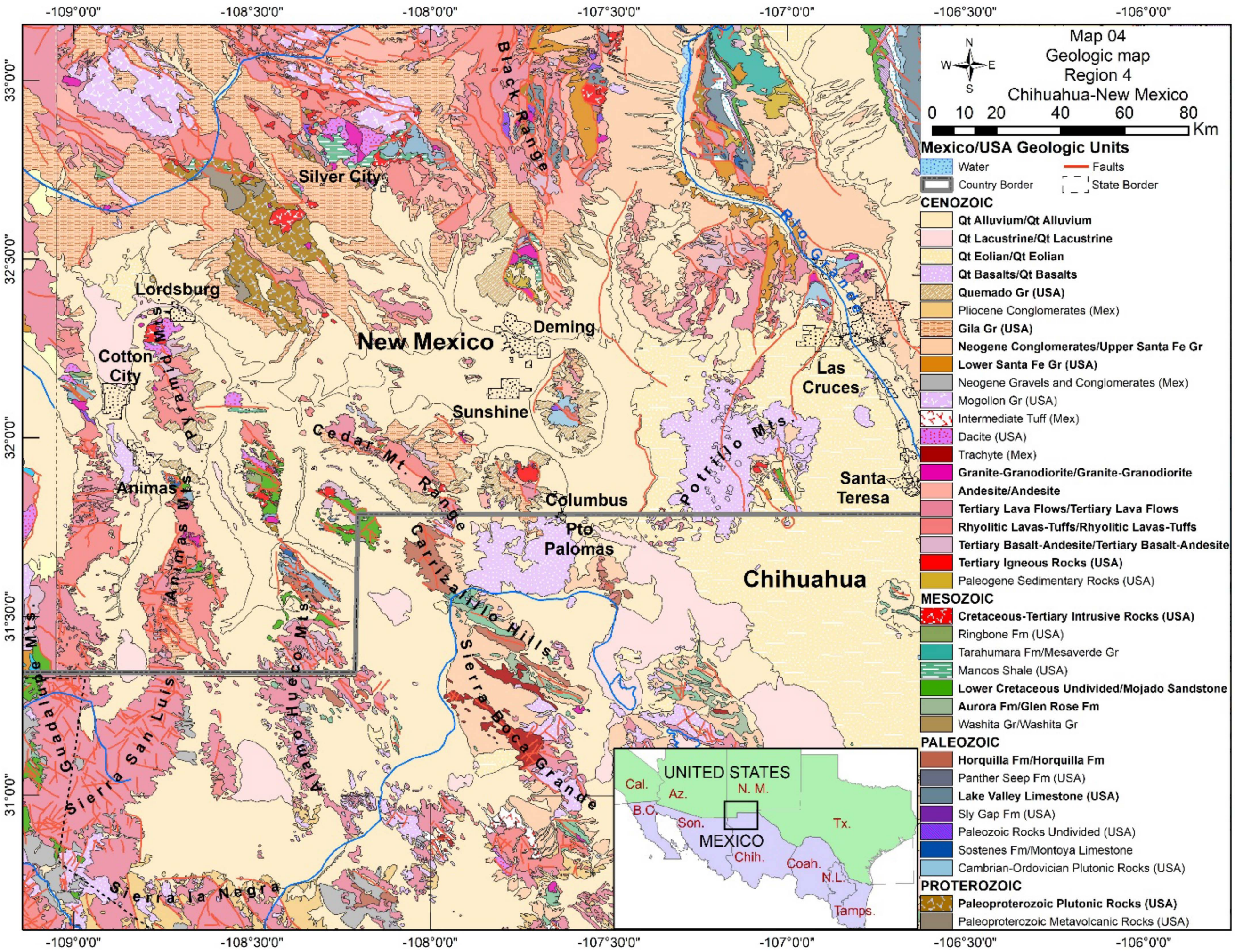

Figure 4. Geologic map, Chihuahua—New Mexico.

Table 2. Geological correlation/equivalence and hydrological features.

Unit Name (Mex/USA)	Age	Location (Mex/USA)	Lithological Description	Hydrological Features	Aquifer
Pinal Schist/ Metasedimentary Rocks (Figures 1–3).	Paleoproterozoic.	Western Chihuahua and Northern Sonora/ Central New Mexico, Southern Arizona, Southern California.	Gray quartzite-sericite schists and quartzites [31].	Low to nonexistent permeability [32]. Local secondary porosity due to fracturing [7].	San Pedro Aq. [7].
Paleoproterozoic Plutonic Rocks (USA) (Figures 1–4).	Paleoproterozoic.	Central New Mexico/ Southern Arizona.	Granitic Gneisses and foliated granites [33].	-	-
Bamori Metamorphic Complex (Mex) (Figures 1 and 2).	Paleoproterozoic.	Northeast Sonora.	Muscovite, biotite and quartz schists [34].	-	-
Apache Gr (USA) (Figures 2 and 3).	Mesoproterozoic.	Central and Southern Arizona.	Quartzites, with few shales and conglomerates [35].	Local secondary porosity due to fracturing [7].	San Pedro Aq. [7].
Las Mestenas Granite/ Mesoproterozoic Granite (Figures 1–3).	Mesoproterozoic.	Northern Sonora/ Southern Arizona.	Granites with coarse- grained holocrystalline texture. Some areas show gneiss texture [36].	Local secondary porosity due to fracturing [7,37]	San Pedro Aq. [7]. Los Vidrios Aq. [37].
Abrigo Fm/ Abrigo Limestone (Figures 2 and 3).	Cambrian.	Northeast Sonora/ Southern Arizona.	Gray-blue limestones, stratified in thin layers [31].	-	-
Cambrian-Ordovician Plutonic Rocks (USA) (Figure 4).	Cambrian-Ordovician.	Southwest New Mexico.	Granites and syenites [38].	Dense, impermeable rocks [39].	-
Sostenes Fm/ Montoya Limestone (Figure 4).	Ordovician.	Central and Northern Chihuahua/ West Texas, Southern New Mexico.	Gray dolomites, some layers are recrystallized limestones. Few mudstones to the top [40].	Montoya Dolomites have not been developed, but some evidence indicates that they may be capable of yielding water to wells [41].	Mimbres Basin [41].
Paleozoic Rocks Undivided (USA) (Figures 2 and 3).	Devonian-Carboniferous.	Southeastern New Mexico, Arizona.	Nodular, silty limestones that locally contain limy shales and siltstones [41].	Few wells yielded water from fractures [7,41].	Mimbres Basin [41]. San Pedro Aq. [7].
Paleozoic Metamorphic Rocks (Mex) (Figures 1 and 2).	Devonian-Carboniferous.	Northern Baja California/ Northern Sonora.	Biotite schists and slates [42].	Local secondary porosity due to fracturing [37].	Los Vidrios Aq. [37].

Table 2. *Cont.*

Unit Name (Mex/USA)	Age	Location (Mex/USA)	Lithological Description	Hydrological Features	Aquifer
Lake Valley Limestone (USA) (Figure 4).	Carboniferous.	Western Texas, southern New Mexico.	Gray limestones filled with nodular cherts [43].	-	-
Panther Seep Fm (USA) (Figure 4).	Carboniferous.	Western Texas, Central New Mexico.	Interbedded dark gray shales and calcareous siltstones [44].	-	-
Horquilla Fm/ Horquilla Fm (Figures 3 and 4).	Carboniferous.	Northern Chihuahua, Northern Sonora/ Southern Mexico, Arizona.	Thin pink limestone layers to the top. Gray massive limestone layers to the top [45].	Massive rocks which constitute limits of adjacent younger deposits [46].	Josefa Ortiz de Dominguez Aq. [46].
Escabrosa Fm/ Escabrosa Fm (Figure 3).	Carboniferous.	Northeast Sonora/ Southeast Arizona.	White to dark gray limestones, coarse stratification [31].	-	-
Permian Sedimentary Rocks (USA) (Figure 3).	Permian.	Southeastern Arizona.	Thick bedded limestones with layers of shales and sandstones [47].	Local secondary porosity due to fracturing [7].	San Pedro Aq. [7].
Triassic-Cretaceous Granites/ Triassic-Cretaceous Granites (Figures 1 and 2).	Triassic-Cretaceous.	Northern Baja California, Northwestern Sonora/ Southern California.	Granodiorites, Tonalites [15].	Poor porosity, secondary porosity on the surface due to alteration [48].	Tecate Aq. [48].
Jurassic Granites/ Jurassic Granites Figures 1–3).	Triassic-Jurassic.	Northern Sonora/ Southern Arizona.	Plutonic and volcanic rocks, with local occurrences of redbeds [47].	-	-
Pinito Rhyolite/ Jurassic Volcanic Rocks (Figures 1–4).	Jurassic.	Northern Sonora/ Southern Arizona.	White to light gray rhyolites and rhyodacites [49].	Low primary permeability but moderate secondary permeability [50,51].	Santa Cruz Aq. [50]. Rio Alisos Aq. [51].
Bisbee Gr/ Bisbee Gr (Figures 2 and 3).	Late Jurassic-Early Cretaceous.	Northern Sonora/ Southeast Arizona.	Conglomerates, sandstones, and argilites [52,53].	-	-
Washita Gr/ Washita Gr	Early Cretaceous.	Northern Chihuahua.	Limestones interbedded with clays [54].	-	-
Cretaceous Tonalite (Mex) (Figures 1 and 2).	Aptian.	Northwest Sonora, Northern Baja California.	Tonalites and Granites	-	-

Table 2. *Cont.*

Unit Name (Mex/USA)	Age	Location (Mex/USA)	Lithological Description	Hydrological Features	Aquifer
Aurora Fm/ Glen Rose Fm (Figure 4).	Albian.	Northeast Chihuahua/ Western Texas.	Limestone layers, sandy limestones with interbedded sandy clays, sandstone and marl [55].	Secondary porosity due to fracturing [56].	Palomas-Guadalupe Victoria Aq. [56].
Lower Cretaceous Undivided/Mojado Sandstone (Figure 4).	Albian-Cenomanian.	Northern Chihuahua/ Central New Mexico.	Quartz sandstone interbedded with gray shales [57]	Local secondary porosity due to fracturing [7,58].	San Pedro Aq. [7]. Arroyo San Bernardino Aq. [58]
Cretaceous Granites/ Volcanic Cretaceous Rocks (Figures 1–3)	Late Cretaceous.	Northern Sonora, Northern Baja California/ Southern Arizona, Southern California.	Rhyolitic to andesitic volcanic rocks, locally associated sedimentary and subvolcanic intrusive rocks [47].	These crystalline rocks are dense and contain only small amounts of water in fractures and weathered zones [59].	Mexicali-Rio Colorado Valley [59]. Santa Cruz Aq. [50].
Mancos Shale (USA) (Figure 4).	Turonian-Coniacian.	Central New Mexico.	Shales with local siltstones, sandstones, and bentonite [60].	-	-
Cabullona Fm (Mex) (Figure 3)	Santonian-Maastrichtian.	Northern Sonora.	Conglomerates, sandstones, shales, and tuffs [61].	-	-
Ringbone Fm (USA) (Figure 4).	Campanian.	Southwestern New Mexico.	Dark shales with conglomerates at the bottom, tuffaceous sandstone at the top [62].	-	-
Rosario Fm/Cabrillo Fm (USA) (Figure 1).	Maastrichtian.	Southwestern California.	Massive medium-grained sandstone with thin siltstone beds and conglomerate lenses [63].	-	-
Orocopia Schists (USA) (Figures 1 and 2).	Late Cretaceous-Paleogene.	Western Arizona, Southeastern California.	Gray quartz-feldspar schists, peridotites, schistose amphibolite, metachert, siliceous marble [64].	-	-
Cretaceous-Tertiary Intrusive Rocks (USA) (Figure 4).	Late Cretaceous-Paleogene.	Southern New Mexico.	Granodiorite, quartz monzonite, monzonite porphyry dikes [65].	-	-
Granite-Monzonite/ Granite-Monzonite (Figures 1–3).	Campanian-Eocene.	Northern Sonora, Northern Baja California/ Southern Arizona.	Muscovite granites with garnets, monzonites [66].	Poor porosity [50]. Secondary porosity [67].	Santa Cruz [50]. San Diego Aq. [67].

Table 2. *Cont.*

Unit Name (Mex/USA)	Age	Location (Mex/USA)	Lithological Description	Hydrological Features	Aquifer
Monzonites/ Monzonites (Figures 1–3).	Paleocene-Eocene.	Northern Sonora/ Southern Arizona.	Monzonites and quartz monzonites [19].	Local secondary porosity due to fracturing [7].	San Pedro Aq. [7].
Paleogene Sedimentary Rocks (USA) (Figure 4).	Paleocene-Oligocene.	Southern New Mexico.	Calcareous sandstones, gray limestones [68].	-	-
Delicias Fm (Mex) (Figure 1).	Eocene.	Northwestern Baja California.	Green shales and dark yellow sandstones [69].	-	-
Tertiary Igneous Rocks (USA) (Figure 4).	Eocene-Pliocene.	Southwestern New Mexico.	Monzonites to granites, andesites, dacites [65].	-	-
Rhyolitic Lavas-Tuffs/ Rhyolitic Lavas-Tuffs (Figure 4).	Oligocene.	Northern Chihuahua/ Western New Mexico.	Rhyolitic tuffs. Tuffaceous and silty sandstones [41].	Rocks rarely developed for groundwater production [41].	Mimbres Basin [41].
Tertiary Basalt-Andesite/ Tertiary Basalt-Andesite (Figures 1–4).	Oligocene.	Northern Baja California, Northern Sonora/ Southern California, Southern Arizona, Southern New Mexico.	Basaltic-andesitic sequence, pyroclastic rocks of silicic to intermediate composition ranging from soft pumiceous ashfall tuff to densely welded ash-flow tuff [70].	Locally fractured rocks allow secondary permeability between 18 and 25% [71].	Mimbres Basin [41].
Tertiary Lava Flows/ Tertiary Lava Flows (Figure 4).	Oligocene.	Northern Chihuahua and Sonora/ Southern New Mexico.	Locally erupted lavas, rhyolitic pyroclastic flows and tuffs [65].	-	-
Andesite/Andesite (Figures 3 and 4).	Oligocene.	Northern Chihuahua/ Southern New Mexico.	Andesitic and rhyolitic rocks [72].	Moderate to good secondary porosity [58].	Arroyo San Bernardino Aq. [58].
Granite-Granodiorite/ Granite-Granodiorite (Figure 4).	Oligocene.	Northern Chihuahua/ Southern New Mexico.	Quartz-Monzonite porphyry and granodiorites [72].	Locally fractured rocks allow secondary permeability between 18 and 25% [71,73].	Mimbres Basin [41]. Santa Cruz Aq. [73].
Trachyte (Mex) (Figures 2–4).	Oligocene.	Northern Chihuahua, Northern Sonora.	Trachyte and volcanic felsic flows [11].	-	-
Rhyolite (USA) (Figures 1 and 2).	Oligocene-Miocene	Southern California.	Volcanic rhyolitic flows and tuffs [74].	-	-

Table 2. *Cont.*

Unit Name (Mex/USA)	Age	Location (Mex/USA)	Lithological Description	Hydrological Features	Aquifer
Neogene gravels and conglomerates/Pantano Fm (Figures 3 and 4)	Oligocene-Miocene	Northern Sonora and Chihuahua/Eastern Arizona.	Well consolidated fine to coarse-grained alluvial fan and playa deposits, volcanic flows, and rock-avalanche beds [75].	Provides water to wells and alluvial deposits [75].	Tucson AMA [75].
Polygenic conglomerates/Miocene to Oligocene sedimentary rocks (Figures 2 and 3)	Oligocene-Miocene	Northern Sonora/Central and western Arizona.	Conglomerates, sandstones and mudstones undifferentiated [19,66].	-	-
Lower Santa Fe Gr (USA) (Figure 4)	Oligocene-Miocene	South-central New Mexico.	Coarse sandstones and alluvial fan deposits [76].	Source of fresh water in the bolsons area [77].	Mesilla Bolson [77].
Palmas Fm (Mex) (Figure 1).	Oligocene-Pleistocene.	Northwestern Baja California.	Polymictic conglomerates with few sandstones and claystones [14].	-	-
Dacite (USA) (Figures 1–4).	Miocene.	Southern New Mexico, Southern Arizona.	Rhyolite and Dacite flows [65].	-	-
Volcanic Rocks Undifferentiated/ Rhyolitic Tuff (Figures 1–3).	Miocene.	Northern Sonora, Northern Baja California/ Southern Arizona.	Flows of rhyolites and rhyolitic tuffs [21].	Poorly water bearing rocks, may form the boundaries of the groundwater reservoir [59].	Mexicali-Rio Colorado Valley [59].
Tertiary Conglomerates (USA) (Figures 1 and 2).	Miocene.	Southern California.	Coarse grained non-marine deposits [59].	These deposits are capable of yielding moderate amounts of fresh groundwater [59].	Mexicali-Rio Colorado Valley [59].
Sweetwater Fm (USA) (Figure 1).	Miocene.	Southwestern California.	Gritty sandstones and red claystones [78].	-	-
Dacite (USA) (Figures 1–4).	Miocene.	Southern New Mexico, Southern Arizona.	Rhyolite and Dacite flows [65].	-	-
Otay Fm (USA) (Figure 1)	Miocene	Southwestern California.	Conglomerates and sandstones with few mudstones and bentonites [79].	Water bearing unit [80].	San Diego Aq. [80].

Table 2. *Cont.*

Unit Name (Mex/USA)	Age	Location (Mex/USA)	Lithological Description	Hydrological Features	Aquifer
Imperial Fm/ Imperial Fm (Figure 1).	Miocene-Pliocene.	Southern California.	Siltstones and conglomerates [81].	Generally low permeability [59].	Yuma Aq. [59].
Bouse Fm (USA) (Figure 2)	Miocene-Pliocene.	Southern Arizona and California.	Basal limestones and a distinctive tuff, interbedded clay, silt, and sandstones [82].	The lower part of the formation is generally poorly permeable, but the upper part is fairly permeable where sand is more abundant [59].	Lower Colorado River and Salton Sea basins [59].
Baucarit Fm/Nogales Fm (Figure 3)	Miocene-Pliocene	Northern Sonora/Southeastern Arizona	Volcanic conglomerates, sandstones and clays with local thin basalt flows [83].	Effective porosity ranges from 16 to 42% and hydraulic conductivity from 4 to 57 cm per day [84]. Some layers from Baucarit Fm. work as confining units [58].	Santa Cruz Aq. [85]. Rio San Pedro Aq. [86]
Gila Gr (USA) (Figure 4).	Miocene-Pliocene.	Central New Mexico/ Central Arizona.	Conglomerates with calcareous cement. Interbeddings of sandstones [87].	Very low hydraulic conductivities and storage coefficients, indicative of semiconfined to confined hydraulic conditions [88].	Mimbres, Hachita, Playas, Animas basins [89]. Mimbres Basin [41].
Pliocene Conglomerates/Pliocene Conglomerates (Figures 2 and 3)	Pliocene	Northern Baja California, Northern Sonora/ Southern New Mexico, Southern Arizona, Southern California.	Conglomerates and sandstones [22].	-	-
Neogene Conglomerates/ Upper Santa Fe Gr (Figure 4).	Pliocene-Holocene.	Northern Chihuahua, Northern Sonora/Southwestern New Mexico.	Semiconsolidated polymictic conglomerates [11]. Fluvial cemented deposits [76].	Major source of fresh water [77].	Mesilla Bolson [77].
Quemado Gr (USA) (Figure 4).	Pliocene-Pleistocene.	Southern New Mexico.	Light brown friable sandstones and gravels [90].	-	-
San Diego Fm/San Diego Fm (Figure 1).	Pliocene-Pleistocene.	Northern Baja California/Southern California.	Sandstones and conglomerates with thin beds of bentonite [91].	Moderate hydraulic conductivity [92].	San Diego aq. [92].

Table 2. *Cont.*

Unit Name (Mex/USA)	Age	Location (Mex/USA)	Lithological Description	Hydrological Features	Aquifer
Canebrake Fm (Mex) (Figures 1 and 2).	Pliocene-Pleistocene.	Northern Baja California.	Gray and conglomerates with few layers of unconsolidated sandstones [93].	-	-
Neogene Sandstones (Mex) (Figure 1).	Pliocene-Holocene.	Northwestern Sonora.	Unconsolidated sands and gravels [17].	-	-
Qt Conglomerates/ Qt Conglomerates (Figures 1–3).	Pleistocene-Holocene.	Northern Sonora/ Southern Arizona.	Terrace deposits of coarse sand and gravel [41].	Deposits saturated with saline water [94]. Moderate porosity [95].	Mimbres Basin [41]. Arroyo Seco Aq. [95]. Puerto Peñasco Aq. [94].
Qt Eolian/ Qt Eolian (Figures 1–4).	Pleistocene-Holocene.	Northern Chihuahua, northwestern Sonora/ Southern California.	Unconsolidated sands [59].	-	Animas Aq. [72]. Yuma Aq. [59]. Laguna Salada Aq. [96].
Qt Lacustrine/ Qt Lacustrine (Figures 1–4).	Pleistocene-Holocene.	Northern Chihuahua, Northwestern Sonora, Northeastern Baja California/ Southern New Mexico.	Unconsolidated gray clay, red shales and bentonite [41].	Deposits with low permeability [37]. The deposits are part of swamps near the coast [97].	Sonoyta-Puerto Peñasco Aq. [97].
Qt Alluvium/ Qt Alluvium (Figures 1–4).	Pleistocene-Holocene.	Chihuahua, Sonora, Baja California/ New Mexico, Arizona, California.	Conglomerates cemented with calcium carbonate in southern New Mexico [39]. The alluvium consists of permeable lenses of sand and gravel interbedded with clay and silt in southeastern Arizona [98]. Clean medium to coarse sand in California [59].	The valley floor is underlain by permeable alluvium, capable of producing large amounts of ground water at Avra Valley [98]. High K, n, and S at San Diego Aq. [67]. High K in unconsolidated deposits at San Pedro Aq. [7].	Avra and Altar Valleys [98], Yuma and Mexicali-Rio Colorado Valley [59]. Mimbres Basin [41]. San Diego Aq. [67]. San Pedro Aq. [7].

3.2. Geologic Transboundary and Boundary Formation Limits

The geologic limits of the formations in the borderland are shown in Figures 5–8. These figures represent a more detailed identification and delimitation of transboundary and boundary geological units. Examples of boundary units in Figures 5–8 are Canebrake (Mex), Rhyolite (USA), Rancho Vallecitos-Esquisto Julian (Mex), Paleoproterozoic Granite (USA), Upper Santa Fe Gr (USA), Gila Gr (USA), Lake Valley Limestone (USA), Cabullona Fm (Mex), and Bisbee Conglomerates (Mex), among others. Though these formations seem to appear only on one side of the border at the surface, they could be continuous across the other side. However, limited information on these geologic units does not allow for further conclusions.

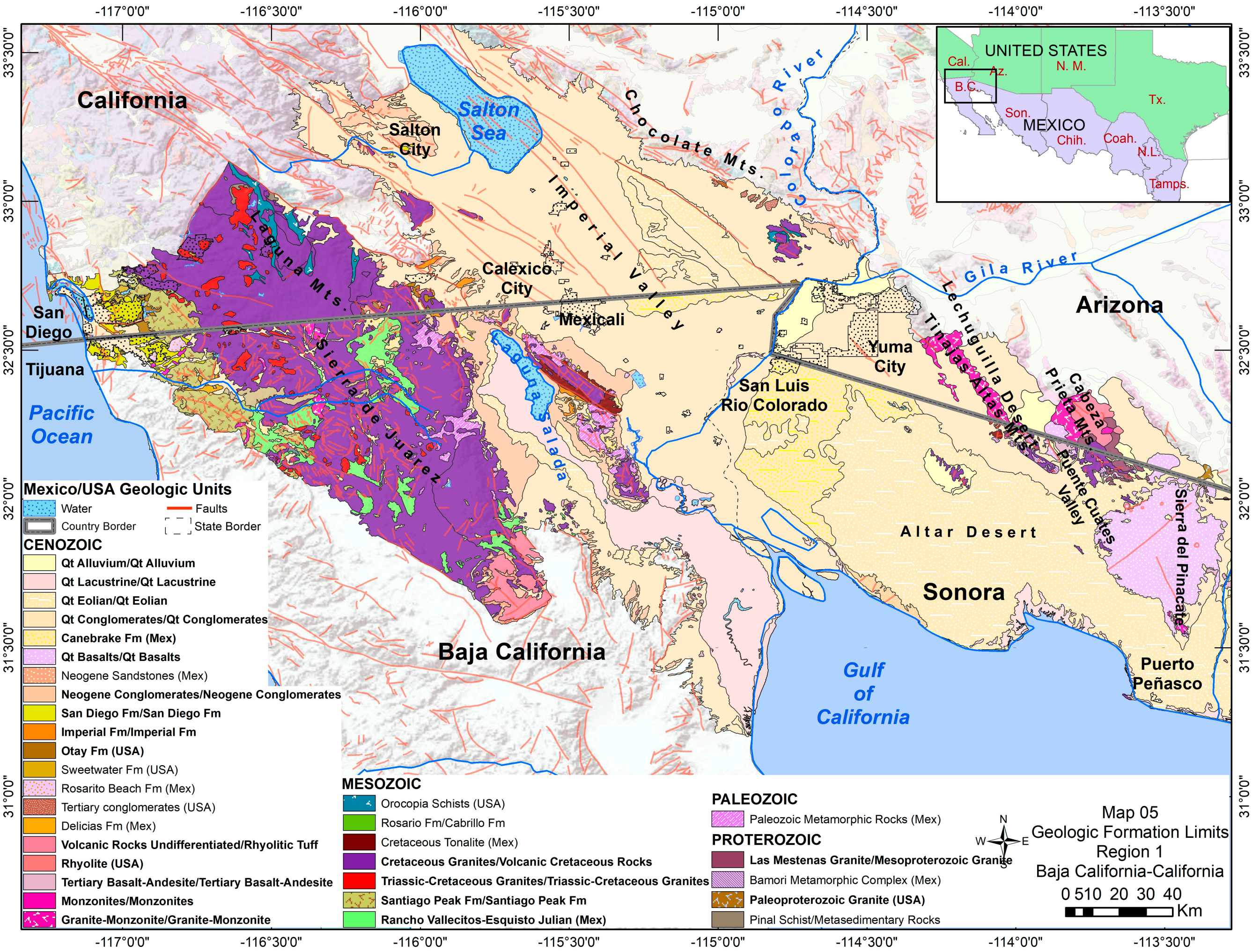

Figure 5. Geologic formation limits, Baja California—California.

The extension limits of the transboundary formations (crossing the border) were defined according to lithology and regional structural geology, such as faults, folds, and lineaments. Additionally, topography and hydrological features were also used to complement the analysis. The geological extensions shown in Figures 5–8 were defined mainly by deformation due to transpressive regimes, which originated the lineament systems known as the Walper Lineament and the Mojave-Sonora Megashear [99]. These lineament systems cross Baja California, Sonora, and Chihuahua in Mexico. In the northeastern part of the study area, the Texas Lineament defined the geological boundaries of most of New Mexico and Texas on the U.S. side [100]. Steep faults with orientation NW-SE formed as a response to the movement on the Mojave-Sonora Megashear, developing pull apart basins, which later filled with sediments originating most of the HGUs identified in this study area [99]. We will expand on the lithologic/structural boundaries on the individual descriptions of the HGUs in the following section.

As it has been mentioned before, there are formations that perform 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. Analyses 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).

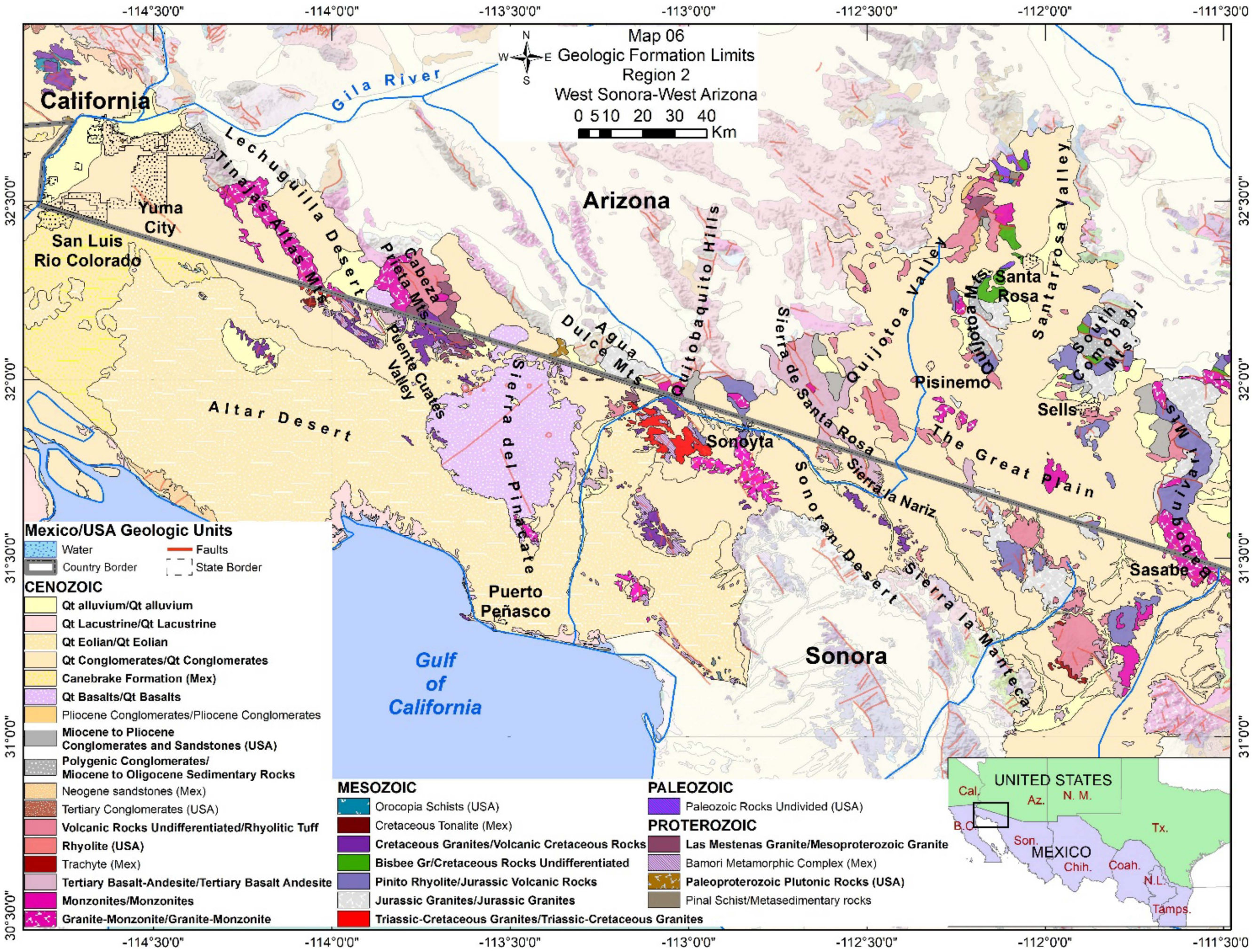

Figure 6. Geologic formation limits, West Sonora—West Arizona.

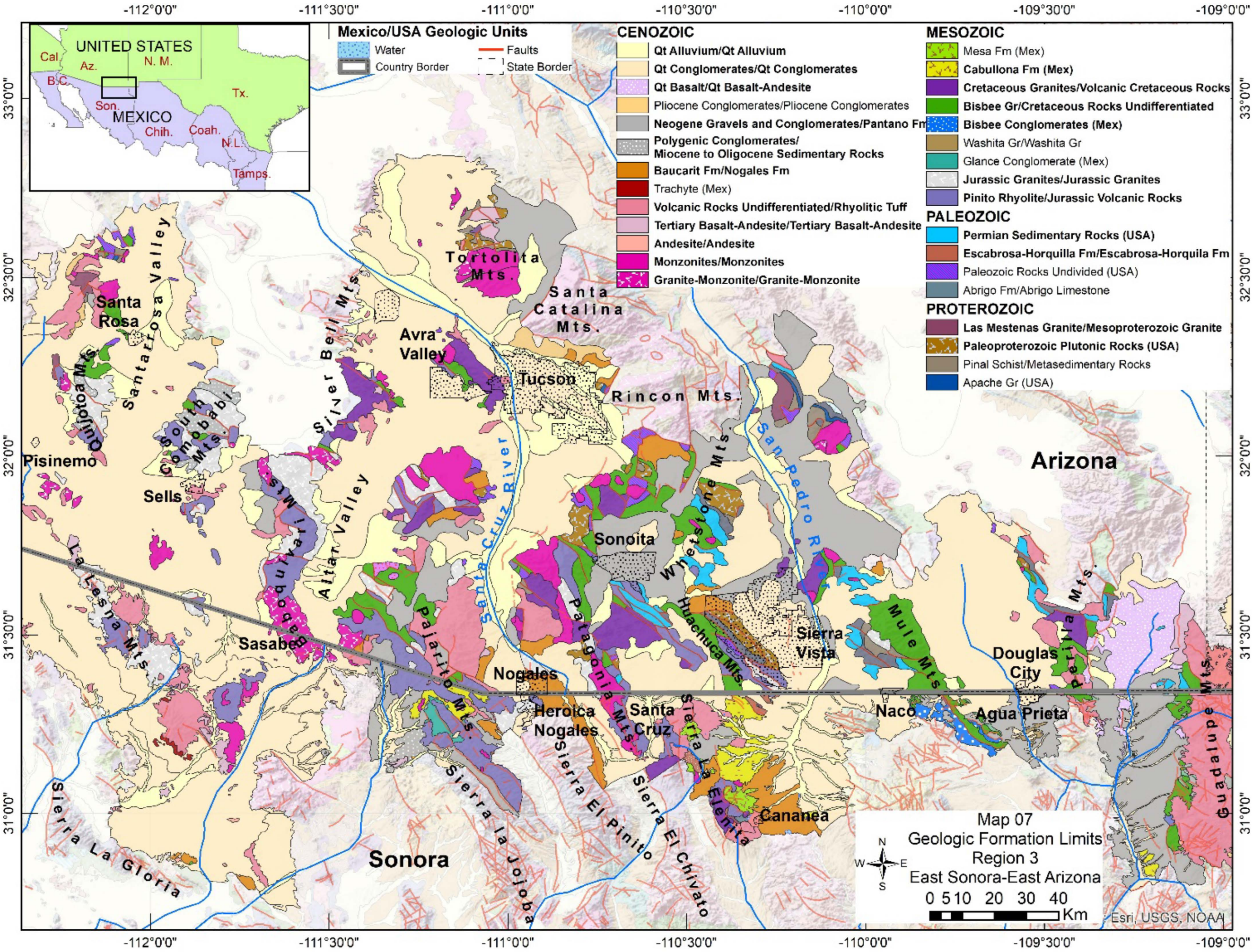

Figure 7. Geologic formation limits, West Sonora—West Arizona.

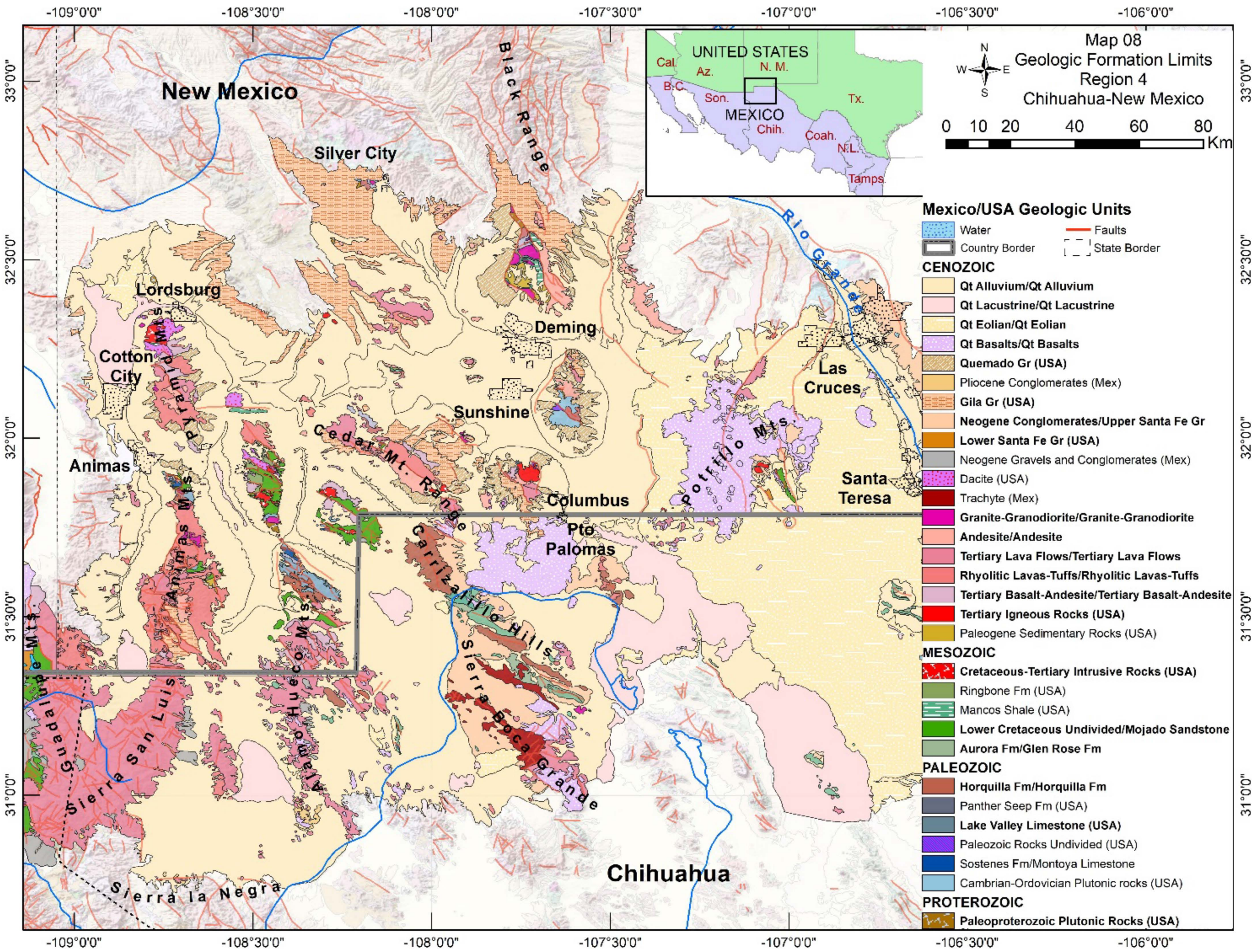

Figure 8. Geologic formation limits, West Sonora—West Arizona.

3.3. Delineation of Transboundary Hydrogeological Units (HGUs)

Figures 9–12 show the transboundary and boundary geological formations grouped into HGUs. This clustering of geological formations represents a refined delineation of transboundary geological formations considering lithological features, hydrogeological linkages and boundary limitations described in Table 2. As it has been mentioned earlier, they are referred to as "hydrogeological units" or "HGUs" (instead of aquifers) considering the different hydrogeological conditions among units that may or may not be categorized as aquifers. This section will cover how this clustering was integrated for each identified HGU.

The physical limits of the HGUs located across Baja California and California (Figure 9) are a combination of structural and lithological variations. The physical limits on the northern portion of Baja California have a stronger structural component. The Tijuana-San Diego Aquifer northern and southeastern boundaries are defined by the contact with volcanic rocks of local secondary permeability to non-existent permeability characteristics. According to the Internationally Shared Aquifer Resources Management (ISARM) [101], the official reported boundaries of this aquifer on the U.S. side match with the quaternary deposits shown in Figure 9; however, we extended the boundaries to include neighboring Neogene rocks, since groundwater flows from the recharge zone on the Otay Reserve towards the coast [80]. On the Mexico side, aquifer boundaries are delineated according to administrative criteria [1], and therefore, the physical boundaries presented in this study will mostly not coincide with those recognized officially by the CONAGUA.

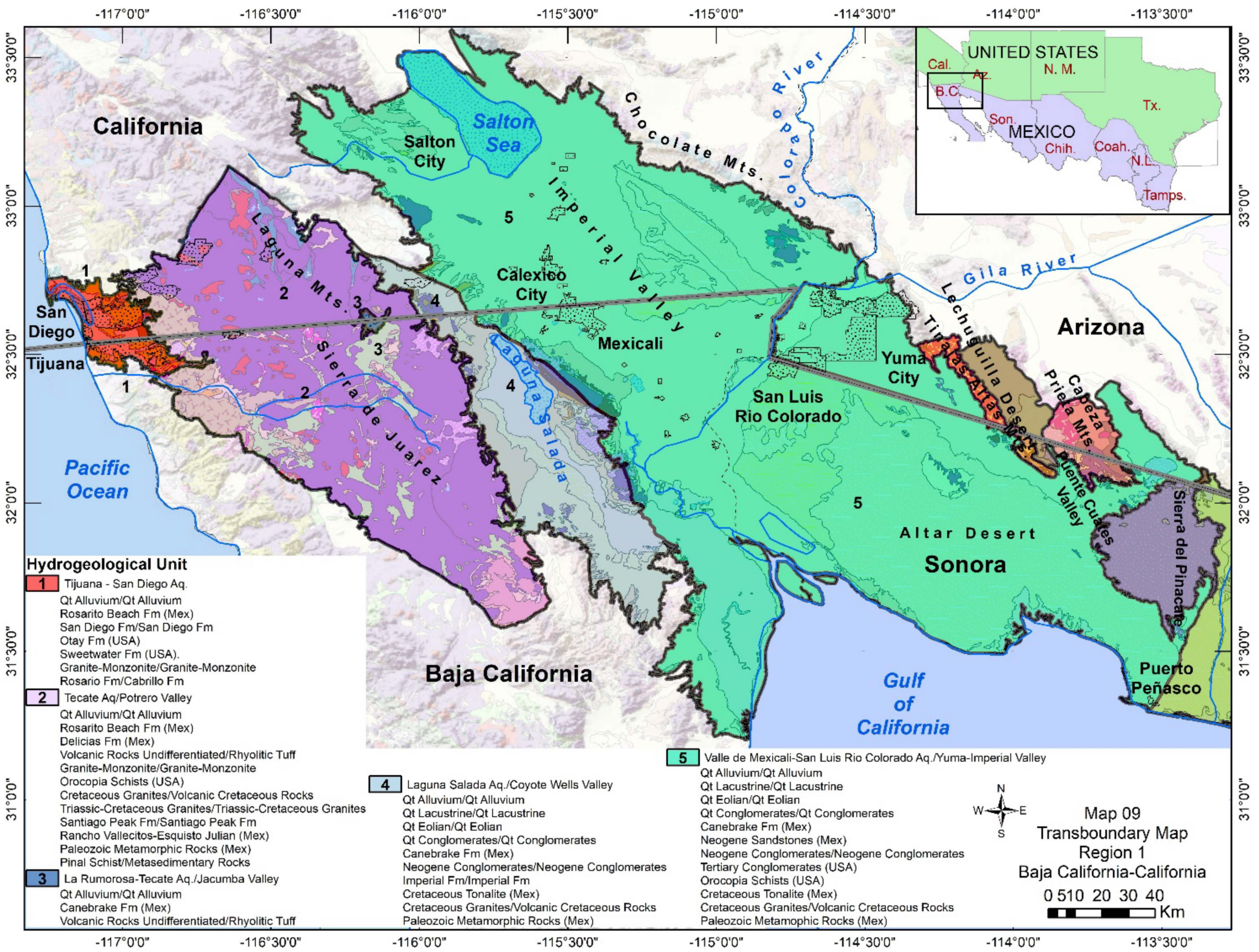

Figure 9. Transboundary map, Baja California—California.

The Tecate Aquifer/Potrero Valley is formed mainly by crystalized Triassic to Neogene igneous bodies with secondary permeability. This HGU has a strong structural control: the northern and eastern boundaries are defined by the Elsinore Fault Zone [102], and the southern boundary is defined by the San Miguel-Vallecitos Fault [14]. La Rumorosa-Tecate Aquifer/Jacumba Valley comprises quaternary deposits accumulated in a depression surrounded by impermeable granitic and metamorphic rocks of Neogene and Mesozoic age [103], and therefore, the physical limits are exclusively lithologic. Laguna Salada Aquifer/Coyote Wells Valley has a predominant structural control with the Sierra Juarez Fault to the west and the Laguna Salada Fault to the north-northeast. The southern limit is defined by Neogene volcanic rocks outcropping on Sierra Las Tinajas [96].

Moving towards the western side of Arizona and Sonora, the Valle de Mexicali-San Luis Rio Colorado Aq./Yuma-Imperial Valley HGU (Figures 9 and 10) western limit is defined by Sierra Cucapa, where granitic rocks of Cretaceous age and the Cucapa Fault comprise this side of the boundary. The crystalline rocks of Mesozoic age configure the northeastern boundary of the HGU at Chocolate Mountains [104], which together with the Salton Sea comprise the northern boundary in California [59]. The eastern boundary is defined by differences in lithology between the quaternary deposits forming this HGU and the Mesozoic-Neogene granites and Quaternary Basalts that formed the neighboring HGUs of Tinajas Altas Mountains and Los Vidrios Aquifer. The southern boundary is defined by the extension of the Rio Colorado deltaic deposits into the Gulf of California which constitutes a physical rather than lithological feature. The northern and eastern boundaries of the Valle de Mexicali-San Luis Rio Colorado Aq./Yuma-Imperial Valley on the U.S. side appear to be based on lithological differences [105], which are very similar to the boundaries presented in this study. The southern and western boundaries on the Mexico side are defined as well by lithology and match the official reports [105]; however, the eastern boundary does not coincide with official reports as they seem to respond to an administrative boundary [105,106].

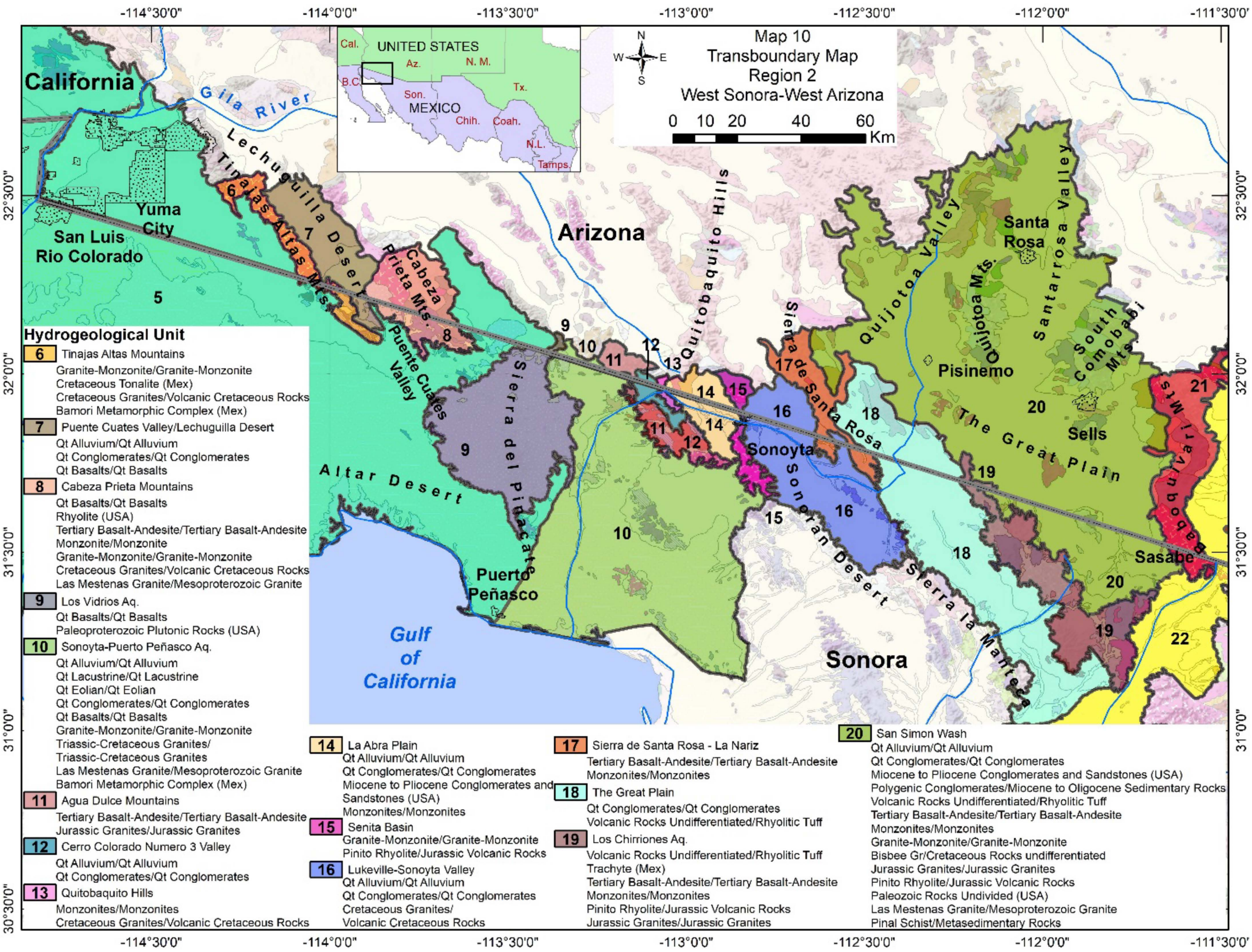

Figure 10. Transboundary map, West Sonora—West Arizona.

The geological limits of the western side of the state of Sonora and Arizona (Figure 10) are based on a combination of lithological variations. Boundaries are mostly defined by contrasting quaternary deposits in contact with old crystalline rocks with limited to non-existent permeability. These older units work as a basement for the identified HGUs in this area.

The Tinajas Altas Mountains, Puente Cuates Valley, Cabeza Prieta Mountains, and Sonoyta-Puerto Peñasco Aquifers have a strong structural component, since the boundaries are defined by pull apart basins associated with the Mojave-Sonora Megashear [99]. Due to this structural feature, it is possible to identify a sequence of Precambrian to Mesozoic crystalline rocks outcropping as mountains, with depressions filled with recent quaternary deposits. The exception to this structural feature is the Los Vidrios Aquifer, which is the product of recent quaternary volcanic activity, and it is located in an area where the volcanic outcrops work as a boundary between the Valle de Mexicali-San Luis Rio Colorado Aq./Yuma-Imperial Valley and the Sonoyta-Puerto Peñasco Aquifer.

The HGUs located between Agua Dulce Mountains and Baboquivari Mountains are the result of a similar structural environment related to the Mojave-Sonora Megashear, where Jurassic rocks intruded through the thrust faults, originating a series of volcanic and metamorphic belts intercalated with depressions filled by Quaternary deposits across the Sonoran Desert [107]. Topography also plays an important role in defining the northern boundaries of these HGUs. We identified these depressions in Figure 6 and integrated them into their corresponding HGUs as shown on Figure 10. The HGUs that are worth mentioning due to some degree of aquifer potential are Cerro Colorado Numero 3 Valley, Quitobaquito Hills, La Abra Plain, Lukeville-Sonoyta Valley, the Great Plain, and San Simon Wash. Initially, the USGS [9] used the term San Simon Wash to refer to the San Simon River watershed and the Papago Indian Reservation; however, in this report, the USGS also stated that the boundary of the San Simon Wash was "arbitrary". ISARM [105] also identified the Sonoyta-Papagos TBA (Transboundary Aquifer), which includes the San Simon Wash area in the U.S. as well as the administrative boundaries of the Sonoyta-Puerto Peñasco aquifer on the Mexico side.

The eastern side of Sonora/Arizona (Figure 11) consists of a combination of small faults and lithological changes in the north, as well as topography and drainage features particularly in southern Arizona. The differences in lithology are the predominant feature that this study used in the northern region of Sonora to define the HGUs' boundaries. The Arroyo Seco Aquifer and the Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin consist of two parallel north–south trending alluvial basins, separated by blockfaulted mountains formed by Jurassic to Cretaceous igneous rocks. The first one outcrops at the Baboquivari and Silver Bell mountains on the west of Arroyo Seco Aquifer [108]. The second one is the mountain chain between the Tortolita Mountains and Pajarito Mountains that separates Arroyo Seco Aquifer and Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin. The mountain chain between Santa Catalina and Huachuca Mountains defines the boundaries on the eastern side of Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin [85]. The northern boundary of the system in this paper does not align with the official reports [105,109] mainly because we use a geological approach, and the published reports are based on watershed and management delimitations. The southern boundaries of the Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin rely on a natural barrier formed by Sierras El Pinito and El Chivato, where crystalline volcanic rocks are abundant. The eastern boundaries are defined by the Whetstone and Huachuca Mountains that comprise the surroundings of Upper Sonoita Creek which is a basin fill alluvial aquifer that constitutes an important tributary of the Upper Santa Cruz feeding the underlying sediments [110,111]. The Rio Altar Aquifer is formed by the interaction of Neogene and Quaternary deposits, limited on the north by the Pajarito Mountains as well.

The Rio San Pedro Aq./Upper San Pedro Basin is limited on the west by the Rincon, Whetstone, Huachuca Mountains, and Sierra La Elenita, where volcanic and metamorphic rocks from Precambian to Neogene age outcrop, working as a barrier between this aquifer and the Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin. The eastern boundary is defined by sedimentary crystalline rocks of Paleozoic to Cretaceous age with limited permeability that outcrop on the Mule Mountains (Figure 11). These natural barriers minimize groundwater connections with adjacent aquifers, even in the northern portion of the HGU [7]. The northern boundaries that we defined for this aquifer are close to those reported by ISARM [105], but they extend beyond what Callegary et al. [109] reports as the northern boundary. As in the case of Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin, slight differences rely on our geology-based approach as compared to the watershed approach used by published official reports.

It should also be noted that the slight differences in extent presented here for both the Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin and the Rio San Pedro Aq./Upper San Pedro Basin, as compared to those reported by TAAP, might also be related to the administrative and regulatory boundaries on the Arizona side (e.g., the Santa Cruz Active Management Area (AMA) jurisdiction). Nevertheless, the main geological features according to the ADWR for both San Pedro and Santa Cruz aquifers are in close agreement with our study [112,113].

The Rio Agua Prieta Aquifer/Douglas Basin and the Arroyo San Bernardino Aq./San Bernardino Valley are depressions filled by Neogene to Quaternary deposits and separated by the Perilla Mountains, where there are volcanic and old sedimentary rocks with limited permeability outcrop. The eastern boundary of the Arroyo San Bernardino Aq./San Bernardino Valley consists of half a graben structure located on the piedmont of the Guadalupe Mountains [114]. This HGU is locally covered by fractured Quaternary Basalts, which have the potential to work as aquifers or as confining layers.

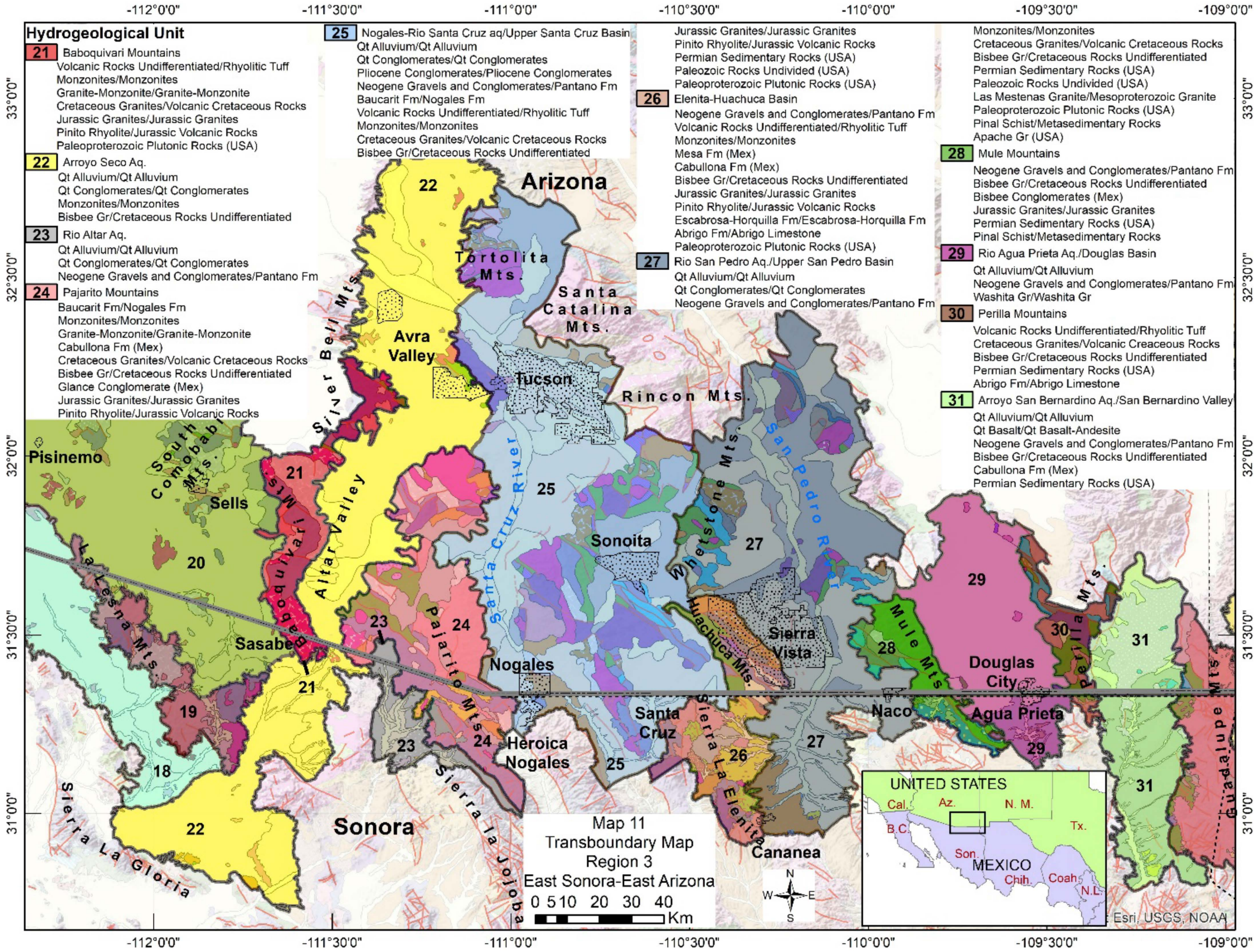

Figure 11. Transboundary map, East Sonora—East Arizona.

Figure 12 shows the formation limits between Chihuahua and New Mexico. Changes in geologic structures and lithology were definitive in delineating the boundaries of the units, and topography to a lesser extent. This area is dominated by graben structures associated to the Rio Grande Rift, and each individual graben is commonly bounded by steep faults, where old sediments and crystalline rocks outcrop [115], and the depressions or bolsons are filled with unconsolidated and coarse grain sized sediments [114]. The Continental Water Divide, located at the northern end of the area of interest works as a groundwater divide as well [39,114]; therefore, we used this topographic feature to define the northern boundary of some of the HGUs between Chihuahua and New Mexico. We defined the southern boundaries based on contrasting lithologic differences between crystalline rocks and the unconsolidated bolson-like sediments.

The Animas Basin is bounded on the west by the Guadalupe Mountains, comprising mostly igneous crystalline and volcanic rocks with limited permeability. The northern limit follows the surface seepage and groundwater flow divide between the Gila River Basin and the Animas Basin. The eastern boundaries are comprised by the Continental Water Divide, the Pyramid Mountains, and the mountain chain between Animas Mountains in the U.S. and Sierra San Luis in Mexico [114]. The latter mountain chains also work as the western boundary for the Janos Aq./Playas Basin. Sierra La Negra in Mexico bounds the Janos Aq./Playas Basin to the south. The Alamo Hueco Mountains separate the Janos Aq./playas Basin from the Ascension Aquifer/Hachita Moscos Basin, restraining the water flows between these two HGUs. The northern boundary of the Ascension Aq./Hachita Moscos is defined by the Continental Water Divide [39], and the cedar Mountain Range to the east, or what we have named as the Josefa Ortiz de Dominguez Aquifer, where Neogene volcanic rocks with limited to nonexistent permeability configure this HGU.

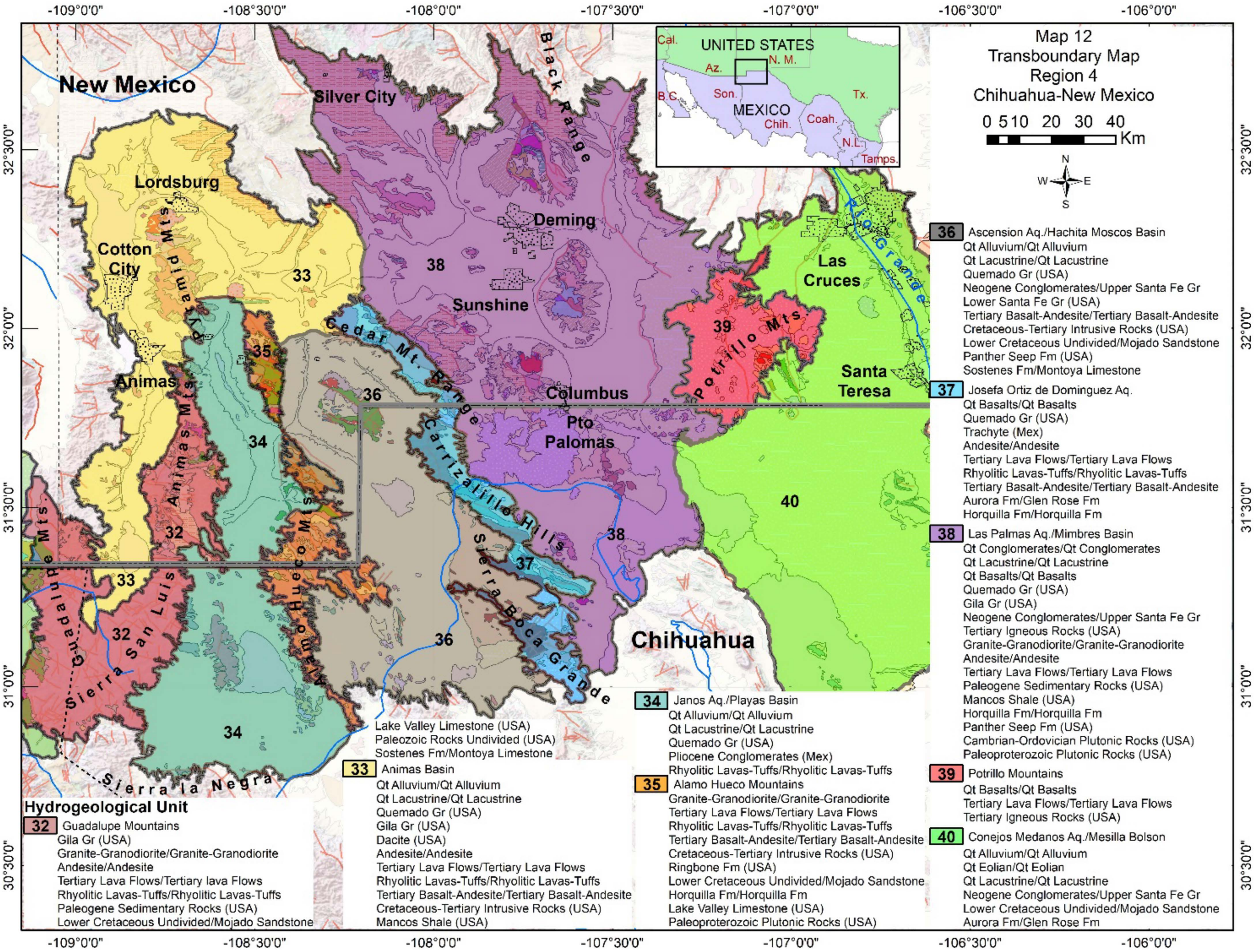

Figure 12. Transboundary map, Chihuahua—New Mexico.

The Cedar Mountain Range and Carrizalillo Hills are part of the Cedar Arc [39], which is one of several complex basin and range Province fault-block systems, and work as the western limit of Las Palmas Aq./Mimbres Basin. The Sierra Boca Grande in Mexico represents a similar echelon fault-block system that forms part of the southwestern boundary of the Mimbres Basin [41]. This HGU is bounded to the north by the Continental Water Divide and the Black Range [114] and to the east by the Potrillo Mountains, where fractured Quaternary Basalts occur. The southern limit is defined according to lithological and topographic differences with the Conejos-Medanos Aq./Mesilla Bolson which was already addressed in Sanchez et al. [2], but it is included in the maps for visualization purposes.

3.4. Classification of Geological Formations/Aquifers

According to the geological description and hydrogeological features noted in previous sections and in Table 2, boundary and transboundary formations within each HGU were classified with an ID value (color) with similar characteristics of aquifer potential and water quality. Table 1 shows the grouping and the corresponding ID value for each group. According to aquifer potential and water quality parameters, Group 1 (dark green), the most important units/formations in terms of groundwater potential and water quality, corresponds to A1, A2, B1, and B2. 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 areas because they could represent future resource development as water treatment options become more feasible. Group 3 (orange) includes those units with poor aquifer potential or aquitards with good to moderate water quality (C1, C3, D1, and D2). This group is considered the third level of priority due to the limited aquifer potential but is still useful for small communities and because the water quality is good to moderate. Group 4 (light maroon) is the lowest-priority group: this units report poor aquifer potential and poor water quality, or alternatively, they report limited information on water quality in that area (C3, C4, D3, and D4). Group 5 (gray) includes those units/formations with lack of information on both aquifer potential and water quality; therefore, their priority is undefined (E1, E2, E3, and E4).

The classification shown in Table 3 is based on the predominant hydrogeological conditions of the formations based on the available data. The formations (boundary and transboundary) are organized and listed within the limits of their corresponding HGU/aquifer described in the previous section. Therefore, the first column contains the corresponding name of the HGU or the reported Aquifer name according to Section 3.3, followed by the formations that integrate each HGU and the specific ID value for each one according to aquifer potential and water quality. Figures 13–16 show the HGUs colored according to the classification of each formation that integrates them, therefore showing the predominant ID value for each HGU. According to Table 3, a total of 39 boundary and transboundary formations were identified in the region that cover an approximate shareable area of 135,000 km^2 of which both countries share almost half (65,000 km^2 Mexico and 69,000 km^2 the U.S.). From the total shareable area, around 40% reports good to moderate aquifer potential and water quality, of which 65% is in the U.S. and 35% on the Mexico side.

In the area between Baja California and California, the HGUs with predominant good aquifer potential and good to moderate water conditions are Laguna Salada Aq./Coyote Wells Valley (Qt Alluvium, Qt Eolian, Qt Conglomerates and Neogene Conglomerates), followed by variable water quality conditions in the Tijuana-San Diego Aq. (Qt. Alluvium, Imperial Fm./Imperial Fm.) and the mostly overall extension of the Valle de Mexicali-San Luis Rio Colorado Aq./Yuma-Imperial Valley (Qt Alluvium, Qt Eolian, Qt Conglomerates and Neogene Conglomerates) covering an important area across California, Baja California, and West of Arizona and Sonora (Figure 13). The latter area of this HGU is well known for its high dependency on surface and groundwater, particularly, for intensive and extensive irrigated agriculture on both sides of the border, and also for the connectivity of the surface–groundwater systems from which native ecosystems and endangered species are equally dependent [1]. This HGU also encompasses the area of what is referred to as the Yuma Aquifer (which is also shared by Arizona and Sonora) that is subject to the only agreement between Mexico and the United States that has established pumping limitations and binational monitoring on both extraction rates and salinity levels (Minute 242 of the International Boundary and Water Commission, IBWC) [116]. The Tijuana-San Diego Aq. is the main water supply for the sister cities of Tijuana and San Diego and has good aquifer potential but has important salinity issues that are recurrent in the whole borderland between California and Baja California and that also expand into the western side of Arizona and Sonora.

Table 3. Classification of geological formations (within their corresponding HGU) in the border region between California, Arizona, and New Mexico, U.S., and Baja California, Sonora, and Chihuahua, Mexico, according to aquifer potential and water quality (*T = Transmissivity m^2/d, K = Hydraulic conductivity m/d, n = porosity %). The colors represent the differences among geological units. It is based on Table 1.

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
(1) Tijuana–San Diego Aq.	Qt Alluvium/Qt Alluvium.	Good.	T = 3024 m^2/d K = 190 m/d	Fresh to Saline.	600–4900	A1-A3
	*Rosarito Beach Fm (Mex).	Good.	T = 346 m^2/d K = 0.17 m/d	Fresh to Saline.	600–4900	A1-A3
	San Diego Fm/San Diego Fm	Moderate.	K = 0.02 m/d	Poor.	-	B3
	*Otay Fm (USA).	Good	-	Poor		B4
	*Sweetwater Fm (USA).	Unknown.		Unknown.		E4
	Granite–Monzonite/Granite–Monzonite.	Moderate–Poor.		Unknown.		B4-C4
	Rosario Fm/Cabrillo Fm (USA).	Unknown.		Unknown.		E4
(2) Tecate Aq./ Potrero Valley.	Qt Alluvium/Qt Alluvium.	Moderate.	T = 2074 m^2/d K = 81.6 m/d	Good.	300–900	B1
	*Rosarito Beach Fm (Mex).	Moderate.	T = 55 m^2/d K = 0.82 m/d	Good.	300–900	B1
	*Delicias Fm (Mex).	Unknown.		Unknown.		E4
	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
	Granite–Monzonite/Granite–Monzonite.	Moderate–Poor.		Unknown.		B4-C4
	*Orocopia Schists (USA).	Unknown.		Unknown.		E4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Moderate–Poor.		Unknown.		B4-C4
	Triassic–Cretaceous Granites/Triassic–Cretaceous Granites.	Moderate–Poor.		Unknown.		B4-C4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
	*Santiago Peak Fm/Santiago Peak Fm.	Unknown.		Unknown.		E4
	*Rancho Vallecitos–Esquisto Julian (Mex).	Unknown.		Unknown.		E4
	*Paleozoic Metamorphic Rocks (Mex).	Unknown.		Unknown.		E4
	*Pinal Schist/Metasedimentary Rocks.	Poor.		Poor.		C3
(3) La Rumorosa–Tecate Aq./ Jacumba Valley.	Qt Alluvium/Qt Alluvium.	Good.	T = 52–95 m^2/d	Moderate to good.	1184–1236	A2
	*Canebrake Fm (Mex).	Good.		Moderate to good.	1184–1236	A2
	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
(4) Laguna Salada Aq./ Coyote Wells Valley.	Qt Alluvium/Qt Alluvium.	Good.	T = 43–173 m^2/d K = 0.05–22 m/d	Brackish.	1180	A2
	Qt Lacustrine/Qt Lacustrine.	Poor.		Brackish.	1180	C2
	Qt Eolian/Qt Eolian.	Good.	T = 43–173 m^2/d K = 0.05–22 m/d	Brackish.	1180	A2
	Qt Conglomerates/Qt Conglomerates.	Good.	T = 43–173 m^2/d. K = 0.05–22 m/d	Brackish.	1180	A2
	*Canebrake Fm (Mex).	Moderate.		Brackish.	1180	B2
	Neogene Conglomerates/Neogene Conglomerates.	Moderate.		Brackish.	1180	B2
	Imperial Fm/Imperial Fm.	Low.		Brackish.	1180	C2
	*Cretaceous Tonalite (Mex).	Poor.		Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.		Unknown.		C4
	*Paleozoic Metamorphic Rocks (Mex).	Poor.		Unknown.		C4
(5) Valle de Mexicali–San Luis Rio Colorado Aq./ Yuma–Imperial Valley.	Qt Alluvium/Qt Alluvium.	Good.	N = 28% T = 4300–30,200 m^2/d	Fresh to Saline.	498–7280	A1-A3
	Qt Lacustrine/Qt Lacustrine.	Poor.		Brackish.	498–7280	C2-C3
	Qt Eolian/Qt Eolian.	Good.	N = 28% T = 4300–30,200 m^2/d	Fresh to Saline.	498–7280	A1-A3
	Qt Conglomerates/Qt Conglomerates.	Good.	N = 28% T = 4300–30,200 m^2/d	Fresh to Saline.	498–7280	A1-A3

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
	*Canebrake Fm (Mex).	Moderate.		Brackish.	498–7280	B1-B3
	*Neogene Sandstones (Mex).	Moderate.		Brackish.	498–7280	B1-B3
	Neogene Conglomerates/Neogene Conglomerates.	Moderate.		Brackish.	498–7280	B1-B3
	*Tertiary Conglomerates (USA).	Unknown.		Unknown.		E4
	*Orocopia Schists (USA).	Unknown.		Unknown.		E4
	*Cretaceous Tonalite (Mex).	Poor.		Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.		Unknown.		C4
	*Paleozoic Metamorphic Rocks (Mex).	Poor.		Unknown.		C4
(6) Tinajas Altas Mountains.	Granite–Monzonite/Granite–Monzonite.	Poor.		Unknown.		C4
	*Cretaceous Tonalite (Mex).	Poor.		Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.		Unknown.		C4
	*Bamori Metamorphic Complex (Mex).	Poor.		Unknown.		C4
(7) Puente Cuates Valley/Lechuguilla Desert.	Qt Alluvium/Qt Alluvium.	Good.		Unknown.		A4
	Qt Conglomerates/Qt Conglomerates.	Good.		Unknown.		A4
	Qt Basalts/Qt Basalts.	Poor.		Unknown.		C4
(8) Cabeza Prieta Mountains.	Qt Basalts/Qt Basalts.	Poor.		Unknown.		C4
	*Rhyolite (USA).	Poor.		Unknown.		C4
	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
	Granite–Monzonite/Granite–Monzonite.	Poor.		Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.		Unknown.		C4
	Las Mestenas Granite/Mesoproterozoic Granite.	Poor.		Unknown.		C4
(9) Los Vidrios Aq.	Qt Basalts/Qt Basalts	Poor.		Unknown.		C4
	*Paleoproterozoic Plutonic Rocks (USA).	Poor.		Unknown.		C4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
(10) Sonoyta–Puerto Peñasco Aq.	Qt Alluvium/Qt Alluvium.	Good.	T = 4400 m^2/d	Fresh to Saline.	353–25,076	A1-A3
	Qt Lacustrine/Qt Lacustrine.	Poor.	T = 1550 m^2/d	Fresh to Saline.	353–25,076	C1-C3
	Qt Eolian/Qt Eolian.	Good.	T = 4400 m^2/d	Fresh to Saline.	353–25,076	A1-A3
	Qt Conglomerates/Qt Conglomerates.	Good.	K = 302 m/d	Fresh to Saline.	353–25,076	A1-A3
	Qt Basalts/Qt Basalts.	Poor.		Unknown.		C4
	Granite–Monzonite/Granite–Monzonite.	Poor.		Unknown.		C4
	Triassic–Cretaceous Granites/Triassic–Cretaceous Granites.	Poor.		Unknown.		C4
	Las Mestenas Granite/Mesoproterozoic Granite.	Moderate–Poor.		Unknown.		B4-C4
	*Bamori Metamorphic Complex (Mex).	Moderate–Poor.		Unknown.		B4-C4
(11) Agua Dulce Mountains.	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	Jurassic Granites/Jurassic Granites.	Poor		Unknown		C4
(12) Cerro Colorado Numero 3 Valley.	Qt Alluvium/Qt Alluvium	Good.		Unknown.		A4
	Qt Conglomerates/Qt Conglomerates.	Good.		Unknown.		A4
(13) Quitobaquito Hills.	Monzonites/Monzonites.	Moderate–Poor.		Good.	662–783	B1-C1
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Moderate–Poor.		Good.	662–783	B1-C1

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
(14) La Abra Plain.	Qt Alluvium/Qt Alluvium.	Good.	K = 15–30 m/d	Slightly saline.	1500	A2
	Qt Conglomerates/Qt Conglomerates.	Good.		Slightly saline.	1500	A2
	*Miocene to Pliocene Conglomerates and Sandstones (USA)	Poor.		Unknown.		C4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
(15) Senita Basin.	Granite–Monzonite/Granite–Monzonite.	Poor.		Unknown.		C4
	Pinito Rhyolite/Jurassic Volcanic Rocks.	Poor.		Unknown.		C4
(16) Lukeville–Sonoyta Valley.	Qt Alluvium/Qt Alluvium.	Good.		Unknown.		A4
	Qt Conglomerates/Qt Conglomerates.	Good.		Unknown.		A4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.		Unknown.		C4
(17) Sierra de Santa Rosa–La Nariz.	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
(18) The Great Plain.	Qt Conglomerates/Qt Conglomerates.	Good.		Poor.	4880	A3
	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
(19) Los Chirriones Aq.	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
	*Trachyte (Mex).	Poor.		Unknown.		C4
	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
	Pinito Rhyolite/Jurassic Volcanic Rocks.	Poor.		Unknown.		C4
	Jurassic Granites/Jurassic Granites.	Poor.		Unknown.		C4
(20) San Simon Wash.	Qt Alluvium/Qt Alluvium.	Good.		Fresh to Saline.	180–4900	A1-A3
	Qt Conglomerates/Qt Conglomerates.	Good.		Fresh to Saline.	180–4900	A1-A3
	*Miocene to Pliocene Conglomerates and Sandstones (USA)	Unknown.		Unknown.		E4
	Polygenic Conglomerates/Miocene to Oligocene Sedimentary Rocks	Unknown		Unknown		E4
	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
	Granite–Monzonite/Granite–Monzonite.	Poor.		Unknown.		C4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
	Bisbee Gr/Cretaceous Rocks Undifferentiated	Poor.		Unknown.		C4
	Jurassic Granites/Jurassic Granites.	Poor.		Unknown.		C4
	Pinito Rhyolite/Jurassic Volcanic Rocks.	Poor.		Unknown.		C4
	*Paleozoic Rocks Undivided (USA).	Poor.		Unknown.		C4
	Las Mestenas Granite/Mesoproterozoic Granite.	Poor.		Unknown.		C4
	*Pinal Schist/Metasedimentary Rocks.	Poor.		Poor.		C3
(21) Baboquivari Mountains.	Volcanic Rocks Undifferentiated/Rhyolitic Tuff	Poor.		Unknown.		C4
	Granite–Monzonite/Granite–Monzonite.	Poor.		Unknown.		C4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks	Poor.		Unknown.		C4
	Jurassic Granites/Jurassic Granites.	Poor.		Unknown.		C4
	Pinito Rhyolite/Jurassic Volcanic Rocks.	Poor.		Unknown.		C4
	*Paleoproterozoic Plutonic Rocks (USA).	Poor.		Unknown.		C4
(22) Arroyo Seco Aq.	Qt Alluvium/Qt Alluvium.	Good.	$T = 86\ m^2/d$	Unknown.		A4
	Qt Conglomerates/Qt Conglomerates.	Moderate.		Unknown.		B4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Poor.		Unknown.		C4
(23) Rio Altar Aq.	Qt Alluvium/Qt Alluvium.	Good.		Good.	243–640	A1
	Qt Conglomerates/Qt Conglomerates.	Good.		Good.	243–640	A1
	Pantano	Moderate.		Unknown.		B4
(24) Pajarito Mountains.	Baucarit Fm/Nogales Fm..	Moderate.		Unknown.		B4
	Granite–Monzonite/Granite–Monzonite.	Moderate–Poor.		Unknown.		B4-C4
	Monzonites/Monzonites.	Moderate–Poor.		Unknown.		B4-C4
	*Cabullona Fm (Mex).	Poor.		Unknown.		C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Poor.		Unknown.		C4
	*Glance Conglomerate (Mex).	Poor.		Unknown.		C4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Moderate–Poor.		Unknown.		B4-C4
	Jurassic Granites/Jurassic Granites.	Moderate–Poor.		Unknown.		B4-C4
	Pinito Rhyolite/Jurassic Volcanic Rocks.	Moderate–Poor.		Unknown.		B4-C4
(25) Nogales–Rio Santa Cruz aq./Upper Santa Cruz Basin.	Qt Alluvium/Qt Alluvium.	Good.	K = 1–90 m/d	Good.	500	A1
	Qt Conglomerates/Qt Conglomerates.	Good.		Good.	500	A1
	Pliocene Conglomerates/Pliocene Conglomerates	Moderate		Good	500	A1
	Neogene Gravels and Conglomerates/Pantano Fm	Moderate.		Unknown.		B4
	Baucarit Fm/Nogales Fm.	Moderate.	K = 0.1–1 m/d	Good.	500	A1
	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.		Unknown.		C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Poor.		Unknown.		C4
	Jurassic Granites/Jurassic Granites.	Poor.		Unknown.		C4
	Pinito Rhyolite/Jurassic Volcanic Rocks.	Moderate.		Unknown.		B4
	*Permian Sedimentary Rocks (USA).	Poor.		Unknown.		C4
	*Paleozoic Rocks Undivided (USA).	Poor.		Unknown.		C4
	*Paleoproterozoic Plutonic Rocks (USA).	Poor.		Unknown.		C4
(26) Elenita-Huachuca Basin.	Neogene Gravels and Conglomerates/Pantano Fm	Moderate.		Unknown.		B4
	Monzonites/Monzonites.	Poor.		Unknown.		C4
	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Poor.		Unknown.		C4
	*Mesa Fm (Mex).	Unknown.		Unknown.		E4
	*Cabullona Fm (Mex).	Poor.		Unknown.		C4
	Jurassic Granites/Jurassic Granites.	Poor.		Unknown.		C4
	Pinito Rhyolite/Jurassic Volcanic Rocks.	Moderate.		Unknown.		B4
	Escabrosa–Horquilla Fm/Escabrosa–Horquilla Fm.	Poor.		Unknown.		C4
	*Abrigo Fm/Abrigo Limestone.	Unknown.		Unknown.		E4
	*Paleoproterozoic Plutonic Rocks (USA).	Poor.		Unknown.		C4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
(27) Rio San Pedro Aq./Upper San Pedro Basin.	Qt Alluvium/Qt Alluvium.	Good.	K = 12.5–7.5 m/d	Good.	229–751	A1
	Qt Conglomerates/Qt Conglomerates.	Good.	K = 12.5–7.5 m/d	Good.	229–751	A1
	Neogene Gravels and Conglomerates/Pantano Fm.	Moderate.	K = 3.5 m/d	Good.	229–751	B1
	Monzonites/Monzonites.	Poor.	K = 0.006 m/d	Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.	K = 0.018 m/d	Unknown.		C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Poor.	K = 0.039 m/d	Unknown.		C4
	*Paleozoic Rocks Undivided (USA).	Poor.	K = 0.039 m/d	Unknown.		C4
	*Permian Sedimentary Rocks (USA).	Poor.	K = 0.039 m/d	Unknown.		C4
	*Apache Gr (USA).	Poor.	K = 0.072 m/d	Unknown.		C4
	Las Mestenas Granite/Mesoproterozoic Granite.	Poor.	K = 0.006 m/d	Unknown.		C4
	*Pinal Schist/Metasedimentary Rocks.	Poor.	K = 0.006 m/d	Poor.		C3
	*Paleoproterozoic Plutonic Rocks (USA).	Poor.		Unknown.		C4
(28) Mule Mountains.	Neogene Gravels and Conglomerates/Pantano Fm.	Moderate–Poor.		Unknown.		B4-C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Poor.		Unknown.		C4
	*Bisbee Conglomerates (Mex)	Unknown.		Unknown.		E4
	Jurassic Granites/Jurassic Granites.	Poor.		Unknown.		C4
	*Permian Sedimentary Rocks (USA).	Poor.		Unknown.		C4
	*Pinal Schist/Metasedimentary Rocks.	Poor.		Poor.		C3
(29) Rio Agua Prieta Aq./Douglas Basin.	Qt Alluvium/Qt Alluvium.	Good.	T = 147 m^2/d K = 10 m/d	Good.	344–552	A1
	Neogene Gravels and Conglomerates/Pantano Fm.	Moderate–Poor.		Unknown.		B4-C4
	Washita Gr/Washita Gr.	Unknown.		Unknown.		E4
(30) Perilla Mountains.	Volcanic Rocks Undifferentiated/Rhyolitic Tuff.	Poor.		Unknown.		C4
	*Cretaceous Granites/Volcanic Cretaceous Rocks.	Poor.		Unknown.		C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Poor.		Unknown.		C4
	*Permian Sedimentary Rocks (USA).	Poor.		Unknown.		C4
	*Abrigo Fm/Abrigo Limestone.	Unknown.		Unknown.		E4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
(31) Arroyo San Bernardino Aq./San Bernardino Valley.	Qt Alluvium/Qt Alluvium.	Good.	T = 100 m^2/d K = 43 m/d	Good.	<1000	A1
	Neogene Conglomerates/Neogene Conglomerates.	Moderate–Good.		Unknown.		A4-B4
	Qt Basalts/Qt Basalts.	Good.		Unknown.		A4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Moderate–Poor.		Unknown.		B4-C4
	*Cabullona Fm (Mex).	Moderate–Poor.		Unknown.		B4-C4
	*Permian Sedimentary Rocks (USA).	Poor.		Unknown.		C4
(32) Guadalupe Mountains.	*Gila Gr (USA).	Good.		Unknown.		A4
	Tertiary Lava Flows/Tertiary Lava Flows.	Poor.		Unknown.		C4
	Granite–Granodiorite/Granite–Granodiorite.	Poor.		Unknown.		C4
	*Andesite/Andesite.	Good.		Unknown.		A4
	*Paleogene Sedimentary Rocks (USA).	Unknown.		Unknown.		E4
	Rhyolitic Lavas–Tuffs/Rhyolitic Lavas–Tuffs.	Poor.		Unknown.		C4
	Bisbee Gr/Cretaceous Rocks Undifferentiated.	Moderate–Poor.		Unknown.		B4-C4
	*Paleozoic Rocks Undivided (USA).	Poor.		Unknown.		C4
	*Lake Valley Limestone (USA).	Unknown.		Unknown.		E4
	*Sostenes Fm/Montoya Limestone.	Unknown.		Unknown.		E4
(33) Animas Basin.	Qt Alluvium/Qt Alluvium.	Good.	T = 273–3055 m^2/d	Unknown.		A4
	Qt Lacustrine/Qt Lacustrine.	Poor.		Unknown.		C4
	*Quemado Gr (USA).	Unknown.		Unknown.		E4
	*Gila Gr (USA).	Good.		Unknown.		A4
	*Dacite (USA).	Unknown.		Unknown.		E4
	*Andesite/Andesite.	Poor.		Unknown.		C4
	Tertiary Lava Flows/Tertiary Lava Flows.	Poor.		Unknown.		C4
	Rhyolitic Lavas–Tuffs/Rhyolitic Lavas–Tuffs.	Poor.		Unknown.		C4
	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	*Cretaceous–Tertiary Intrusive Rocks (USA).	Unknown.		Unknown.		E4
	*Mancos Shale (USA).	Unknown.		Unknown.		E4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
(34) Janos Aq./Playas Basin.	Qt Alluvium/Qt Alluvium.	Good.	T = 345 m^2/d	Good.	250–500	A1
	Qt Lacustrine/Qt Lacustrine.	Poor.		Unknown.		C4
	*Quemado Gr (USA).	Unknown.		Unknown.		E4
	Pliocene Conglomerates (Mex)	Unknown.		Unknown.		E4
	Rhyolitic Lavas–Tuffs/Rhyolitic Lavas–Tuffs.	Poor.		Unknown.		C4
(35) Alamo Hueco Mountains.	Granite–Granodiorite/Granite–Granodiorite.	Poor.		Unknown.		C4
	Tertiary Lava Flows/Tertiary Lava Flows.	Poor.		Unknown.		C4
	Rhyolitic Lavas–Tuffs/Rhyolitic Lavas–Tuffs.	Poor.		Unknown.		C4
	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	*Cretaceous–Tertiary Intrusive Rocks (USA).	Unknown.		Unknown.		E4
	*Ringbone Fm (USA).	Unknown.		Unknown.		E4
	Lower Cretaceous Undivided/Mojado Sandstone.	Moderate–Poor.		Unknown.		B4-C4
	Horquilla Fm/Horquilla Fm	Poor.		Unknown.		C4
	*Lake Valley Limestone (USA).	Unknown.		Unknown.		E4
	*Paleoproterozoic Plutonic Rocks (USA).	Poor.		Unknown.		C4
(36) Ascension Aq./Hachita Moscos Basin.	Qt Alluvium/Qt Alluvium.	Good.	T = 346 m^2/d K = 0.17 m/d	Good.	500	A1
	Qt Lacustrine/Qt Lacustrine.	Moderate.		Unknown.		B4
	*Quemado Gr (USA).	Unknown.		Unknown.		E4
	Neogene Conglomerates/Upper Santa Fe Gr	Good.		Good.	250–1000	A1
	Lower Santa Fe Gr.	Moderate.		Unknown.		B4
	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Moderate.		Unknown.		B4
	*Cretaceous–Tertiary Intrusive Rocks (USA).	Unknown.		Unknown.		E4
	Lower Cretaceous Undivided/Mojado Sandstone.	Moderate–Poor.		Unknown.		B4-C4
	*Panther Seep Fm (USA).	Unknown.		Unknown.		E4
	*Sostenes Fm/Montoya Limestone.	Unknown.		Unknown.		E4

Table 3. *Cont.*

HGU/Aquifer	Boundary (*) and Transboundary Formations	Aquifer Potential	Hydrogeologic Features	Water Quality	TDS (ppm)	ID
(37) Josefa Ortiz de Dominguez Aq.	Qt Basalts/Qt Basalts.	Poor.		Unknown.		C4
	*Quemado Gr (USA).	Unknown.		Unknown.		E4
	*Trachyte (Mex).	Poor.		Unknown.		C4
	*Andesite/Andesite.	Poor.		Unknown.		C4
	Tertiary Lava Flows/Tertiary Lava Flows.	Poor.		Unknown.		C4
	Rhyolitic Lavas–Tuffs/Rhyolitic Lavas–Tuffs	Poor.		Unknown.		C4
	Tertiary Basalt–Andesite/Tertiary Basalt–Andesite.	Poor.		Unknown.		C4
	Aurora Fm/Glen Rose Fm.	Moderate–Poor.		Unknown.		B4-C4
	Horquilla Fm/Horquilla Fm.	Poor.		Unknown.		C4
(38) Las Palmas Aq./Mimbres Basin.	Qt Conglomerates/Qt Conglomerates.	Good.	T = 35–330 m^2/d K = 0.7 m/d	Fresh.	340	A1
	Qt Lacustrine/Qt Lacustrine.	Poor.	K = 0.4 m/d	Fresh.	340	C1
	Qt Basalts/Qt Basalts.	Good.	K = 0.24–0.36 m/d	Fresh.	340	A1
	*Quemado Gr (USA).	Unknown.		Unknown.		E4
	Neogene Conglomerates/Upper Santa Fe Gr	Moderate.		Fresh to slightly saline.	120–1400	B1-B2
	*Gila Gr (USA).	Good.		Fresh.	200–380	A1
	*Tertiary Igneous Rocks (USA).	Good.		Unknown.		A4
	Granite–Granodiorite/Granite–Granodiorite.	Good.		Unknown.		A4
	*Andesite/Andesite.	Good.	n = 18%–25%	Unknown.		A4
	Tertiary Lava Flows/Tertiary Lava Flows.	Good.		Fresh.	260–560	A1
	*Paleogene Sedimentary Rocks (USA).	Unknown.		Unknown.		E4
	*Mancos Shale (USA).	Unknown.		Unknown.		E4
	Horquilla Fm/Horquilla Fm.	Poor.		Slightly saline.		C2
	*Panther Seep Fm (USA).	Unknown.		Unknown.		E4
	*Cambrian–Ordovician Plutonic Rocks (USA).	Good.		Unknown.		A4
	*Paleoproterozoic Plutonic Rocks (USA).	Good.		Fresh.	500	A1
(39) Potrillo Mountains.	Qt Basalts/Qt Basalts.	Good.	n = 18%–25%	Unknown.		A4
	Tertiary Lava Flows/Tertiary Lava Flows.	Good.	n = 18%–25%	Unknown.		A4
	*Tertiary Igneous Rocks (USA).	Good.	n = 18%–25%	Unknown.		A4

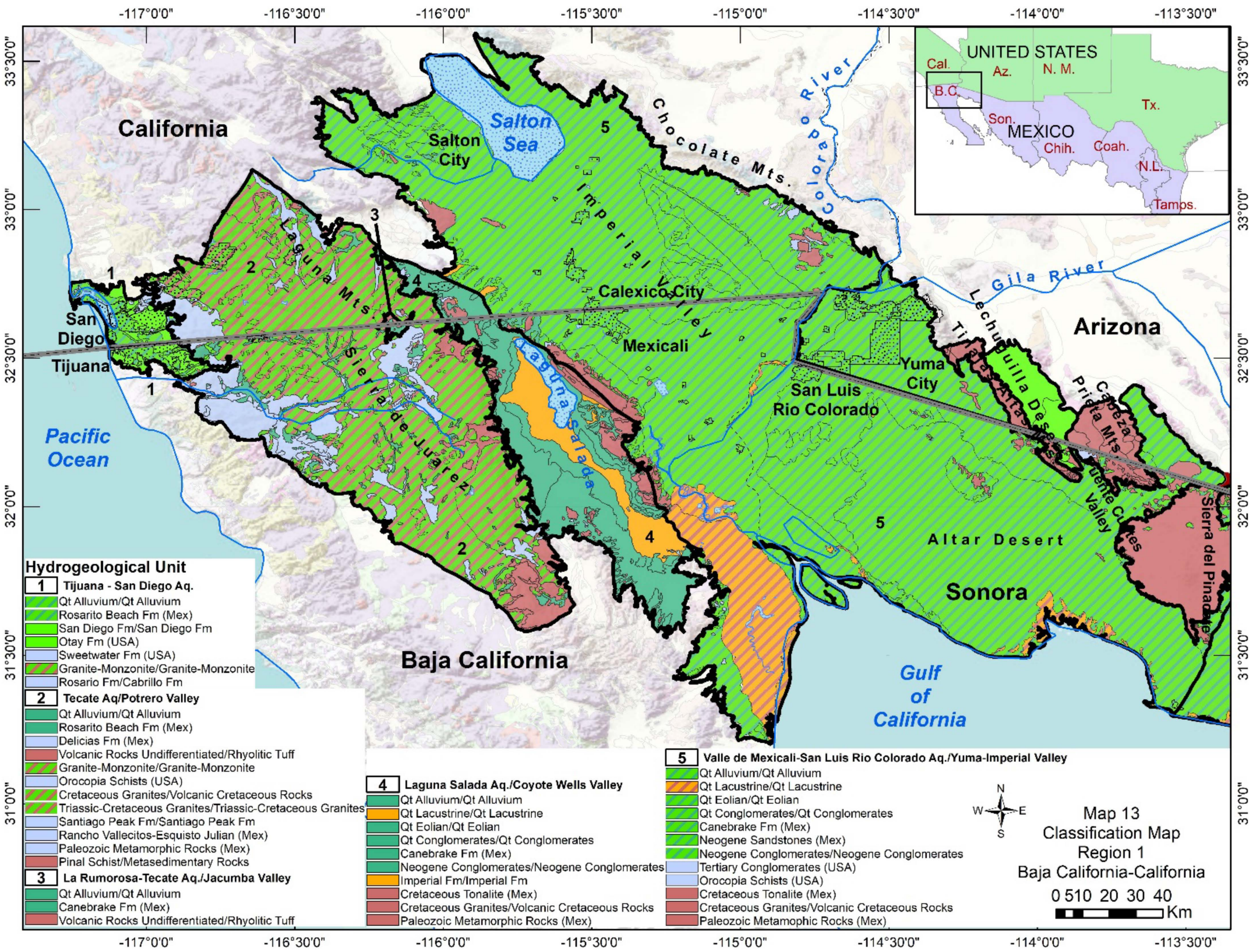

Figure 13. Classification map, Baja California—California.

Figure 14 shows the classification of the formations within their corresponding HGUs across the remaining western side of Arizona and Sonora. This region is also characteristic of good aquifer potential formations but with moderate to poor or unknown water quality conditions. There is an important presence of aquitard conditions in several of the identified HGUs that characterize the area such as the cases of Tinajas Altas Mountains, Cabeza Prieta Mountains, Los Vidrios Aq., Agua Dulce Mountains, Senita Basin, and Los Chirriones Aq. These HGUs are conformed primarily by Quaternary Basalts, Granite-Monzonites, Jurassic Granites, and Volcanic Cretaceous Rocks. Some of these geologic characteristics are also present but to a lesser extent in San Simon Wash and Sonoyta-Puerto Peñasco Aq., where moderate water quality conditions can be found. Puerto Cuates Valley/Lechugilla Desert, Lukeville-Sonoyta Valley, and The Great Plain report good aquifer conditions, but there is limited information related to water quality. As in the Baja California–California region, this region relies heavily on groundwater for agriculture and domestic use considering the limited availability of surface water. Figure 15 shows the eastern part of the border between Arizona and Sonora. Good aquifer potential and good levels of water quality are present to a greater extent in this region as compared to the westernmost side. The Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin, the Rio San Pedro Aq./Upper San Pedro Basin, and the Rio Agua Prieta Aq./Douglas Basin, all recognized transboundary aquifers at binational level, show good aquifer potential and good water quality. These aquifers have been categorized as high priority given the level of groundwater dependence for domestic use and population growth and therefore the vulnerability of the aquifer to overexploitation and contamination. The Pajarito Mountains, Arroyo Seco Aq., and Arroyo San Bernardino Aq./San Bernardino Valley also show good aquifer potential, but there is limited information on water quality.

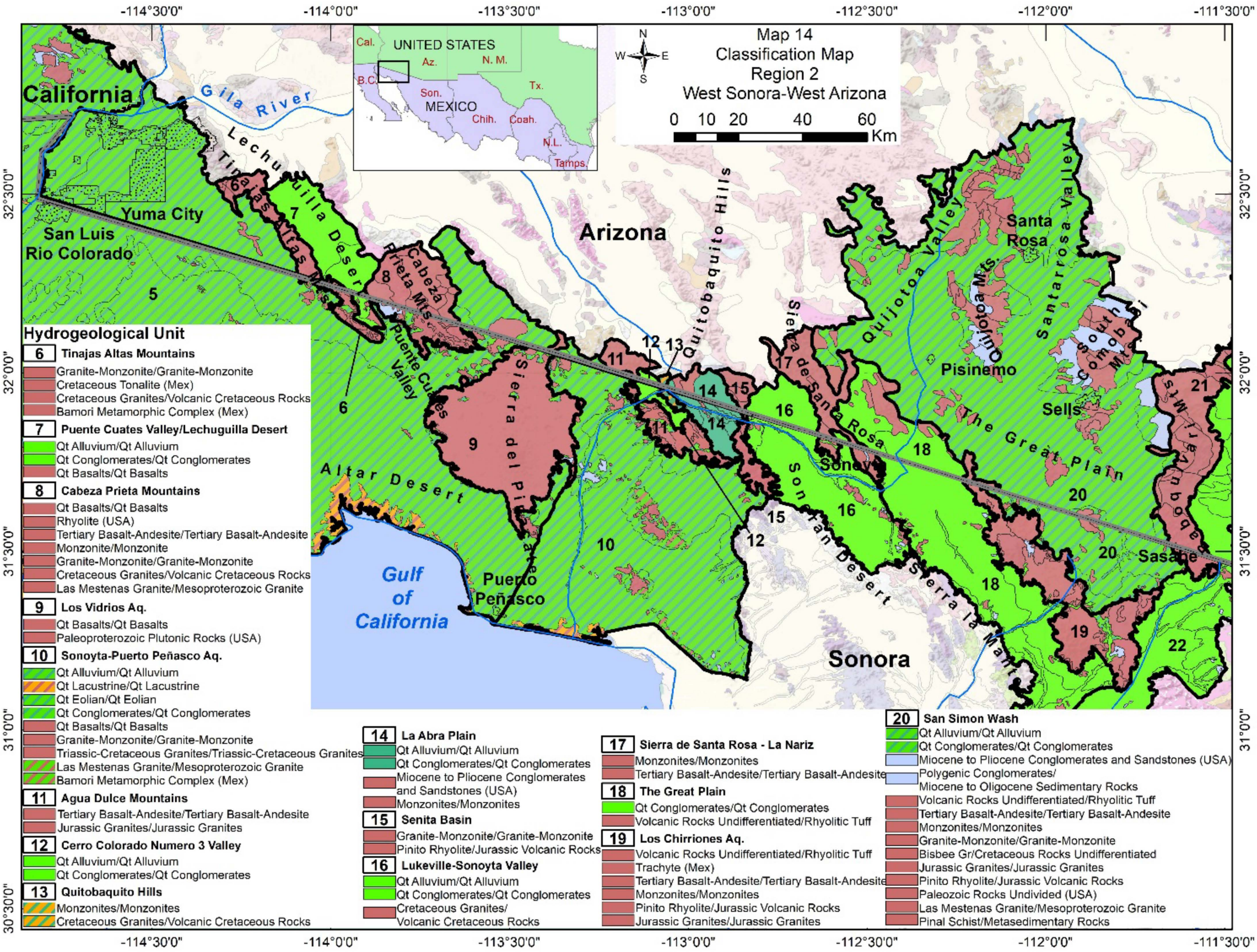

Figure 14. Classification map, West Sonora—West Arizona.

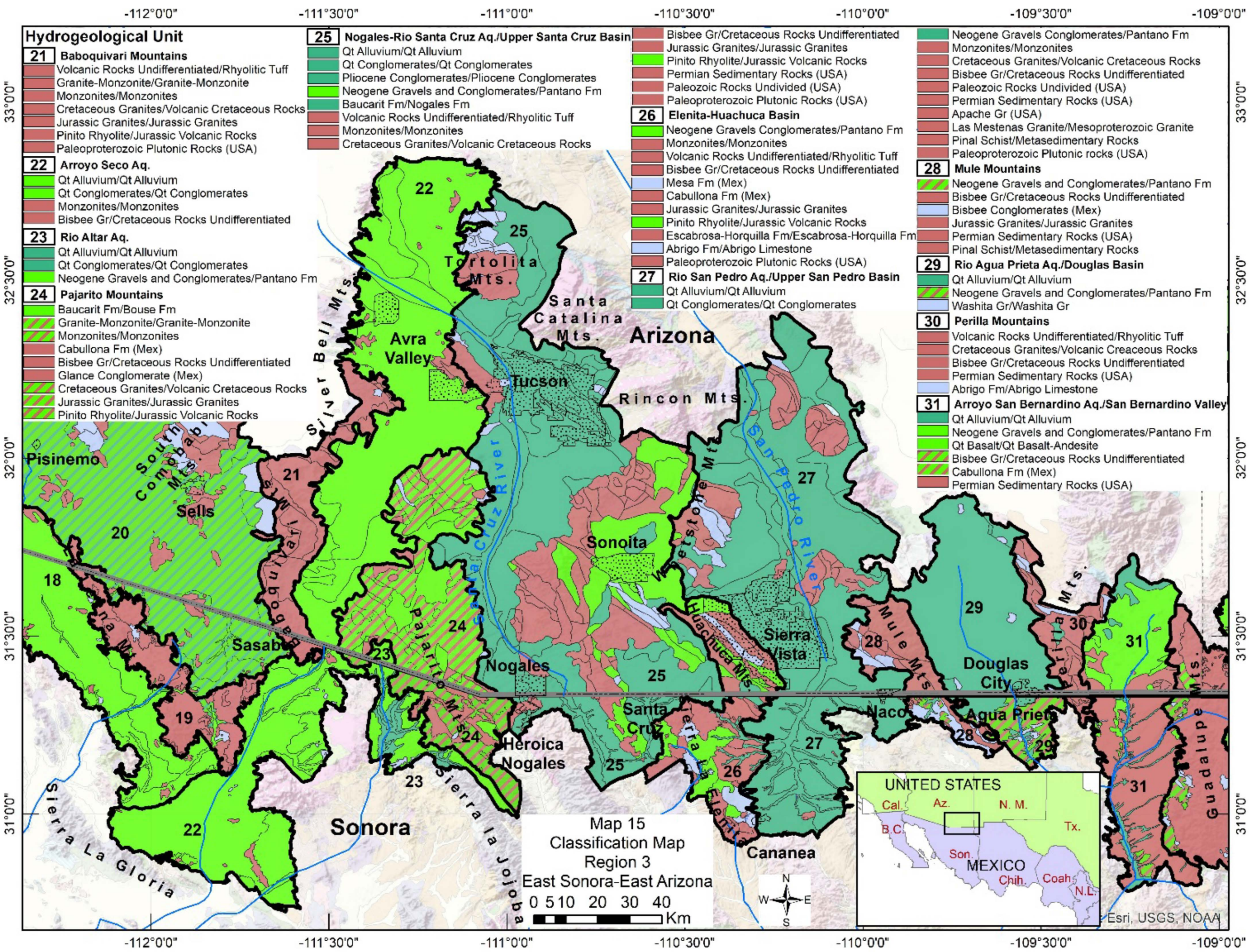

Figure 15. Classification map, East Sonora—East Arizona.

Figure 16 shows the classification of units between Nuevo Mexico and Chihuahua. Janos Aq./Playas Basin, Ascension Aq./Hachita Moscos Basin, and Las Palmas Aq./Mimbres Basin show the highest levels of aquifer potential and water quality, followed by Conejos-Medanos Aq./Mesilla Bolson, and Animas Basin, which report poor to moderate water quality. The Mimbres Basin is an officially recognized transboundary aquifer according to ISARM databases; however, the delineation officially reported is an undefined line in the area, meaning more research is required to confirm the delineation of this aquifer at transboundary level [101]. Over-pumping has been reported around the Columbus-Palomas region as well as high levels of salinity associated with mining activities [1]. It is worth mentioning that, from the total shareable land in this region, approximately 85 percent reports good aquifer potential and water quality. Small communities in the border region rely on these aquifers for potable and local agricultural use, and therefore, the strategic value for this area for future sources of water in the region is one of the highest in the U.S.–Mexico border region.

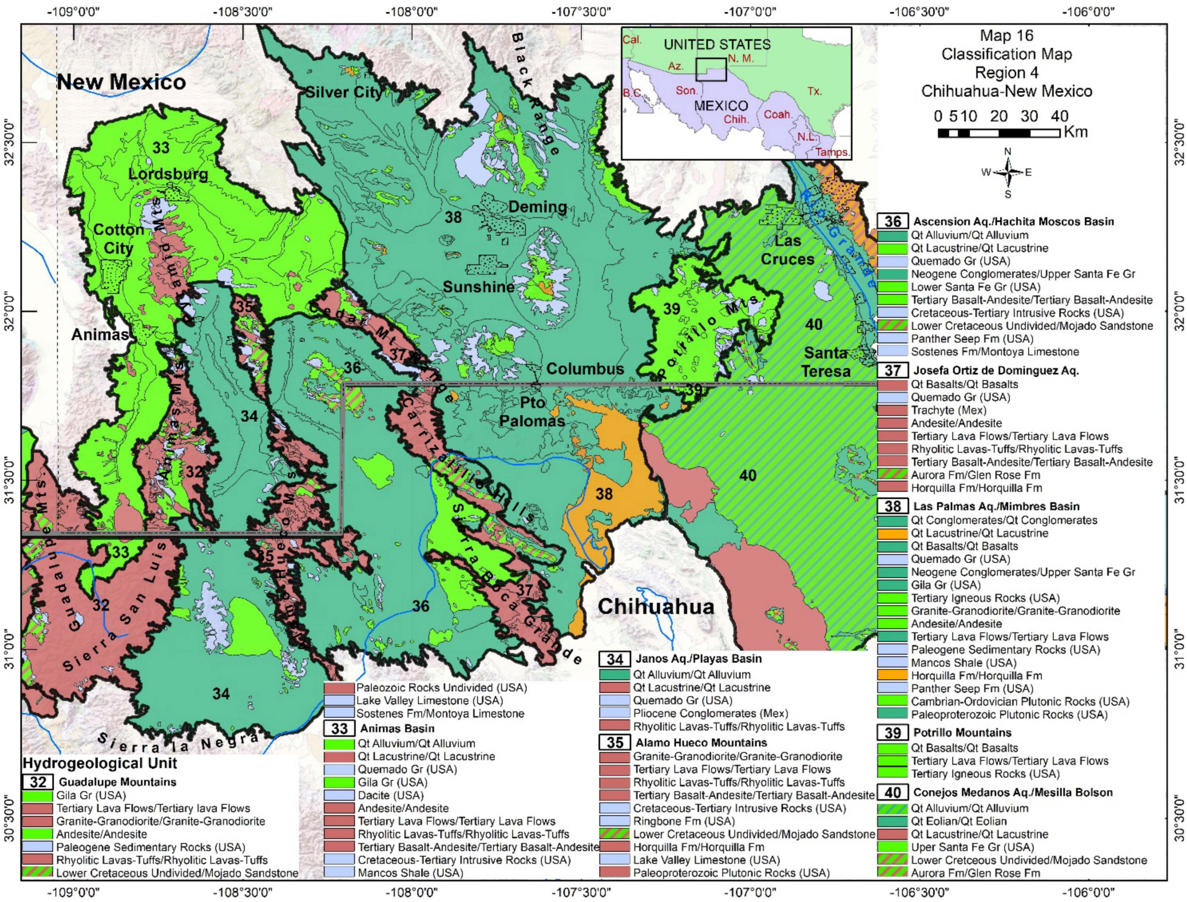

Figure 16. Classification map, Chihuahua—New Mexico.

4. Conclusions

Results indicate that a total of 39 HGUs have been identified in the border between California, Arizona, and New Mexico on the U.S. side and Baja California, Sonora, and Chihuahua on the Mexico side. This region accounts for an approximate shareable area of 135,000 km^2 where both countries share half of the area (65,000 km^2 Mexico and 69,000 km^2 the U.S). From the total shareable area, around 40% reports good to moderate aquifer potential and water quality, of which 65% is in the U.S. and 35% on the Mexico side. It should be noted that approximately 15% of the shareable land that reports good aquifer conditions also reports unknown or limited data on water quality conditions; therefore, this could mean that estimations of good aquifer conditions and water quality along the region might be underestimated.

Border-wide and adding the HGUs previously reported by Sanchez et al. [1] between Texas and Mexico, the total number of HGUs in the border region between Mexico and the United States is 72, covering an approximate area of 315,000 km^2 (180,000 km^2 in the U.S. and 135,000 km^2 on the Mexico side). The total area considered to have good to moderate aquifer potential as well as good to regular water quality ranges between 50 and 55% (of which approximately 60% is in the U.S. and the rest in Mexico).

From a statewide perspective, the border between Baja California and California reports a total of 5 HGUs, from which 3 (Tijuana-San Diego Aq., Valle de Mexicali-San Luis Rio Colorado/Yuma-Imperial Valley, and a great portion of the Quaternary deposits of Laguna Salada Aq./Coyote Wells Valley) report good to moderate aquifer potential and generally good to moderate water quality. Available data on water quality vary across the Valle de Mexicali-San Luis Rio Colorado/Yuma-Imperial Valley from good to poor (included limited information), particularly in the southern portions where saline intrusion has been reported. In the case of Sonora and Arizona, 25 HGUs have been identified, with at least 7 HGUs (Nogales-Rio Santa Cruz Aq./Upper Santa Cruz Basin, Rio San Pedro Aq./Upper San Pedro Basin, Rio Agua Prieta Aq./Douglas Basin, Rio Altar Aq., San Simon Wash, Sonoyta-Puerto Peñasco Aq., and La Abra Plain) with generally good to moderate aquifer potential and good to moderate water quality. Variability in water quality for Sonoyta-Puerto Peñasco Aq. and San Simon Wash is also reported. Additional 4 HGUs reported good to moderate aquifer potential but poor water quality with also uncertainty considering the data limitations. Those include Cerro Colorado Numero 3 Valley, Lukeville-Sonoyta Valley, The Great Plain, and Arroyo Seco Aq. In the border region between Chihuahua and New Mexico, good aquifer potential and good water quality were identified in at least 3 out of the 8 HGUs reported. These HGUs are Janos Aq./Playas Basin, Ascension Aq./Hachita-Moscos Basin, and Las Palmas Aq./Mimbres Basin. Potrillo Mountains also report good aquifer potential but limited data on water quality.

Figure 17 shows the complete map of the HGUs/aquifers identified in this paper from California through New Mexico and their corresponding southern border states in Mexico. This is the first ever recorded map that shows the geological continuity across the border between both countries in the complete study area and, along with that reported by Sanchez et al. [2], that covers the border between Texas and Mexico, constituting the first geological assessment on this scale for the complete border region between Mexico and the United States. Further research must incorporate new data particularly on vertical geology, water quality, three-dimensional distribution of HGUs, evidence of groundwater flow systems, isotope assessments for residence times and so on. This new scientific information will support the potential discussions of transboundary groundwater management possibilities towards a more sustainable groundwater use in the border region.

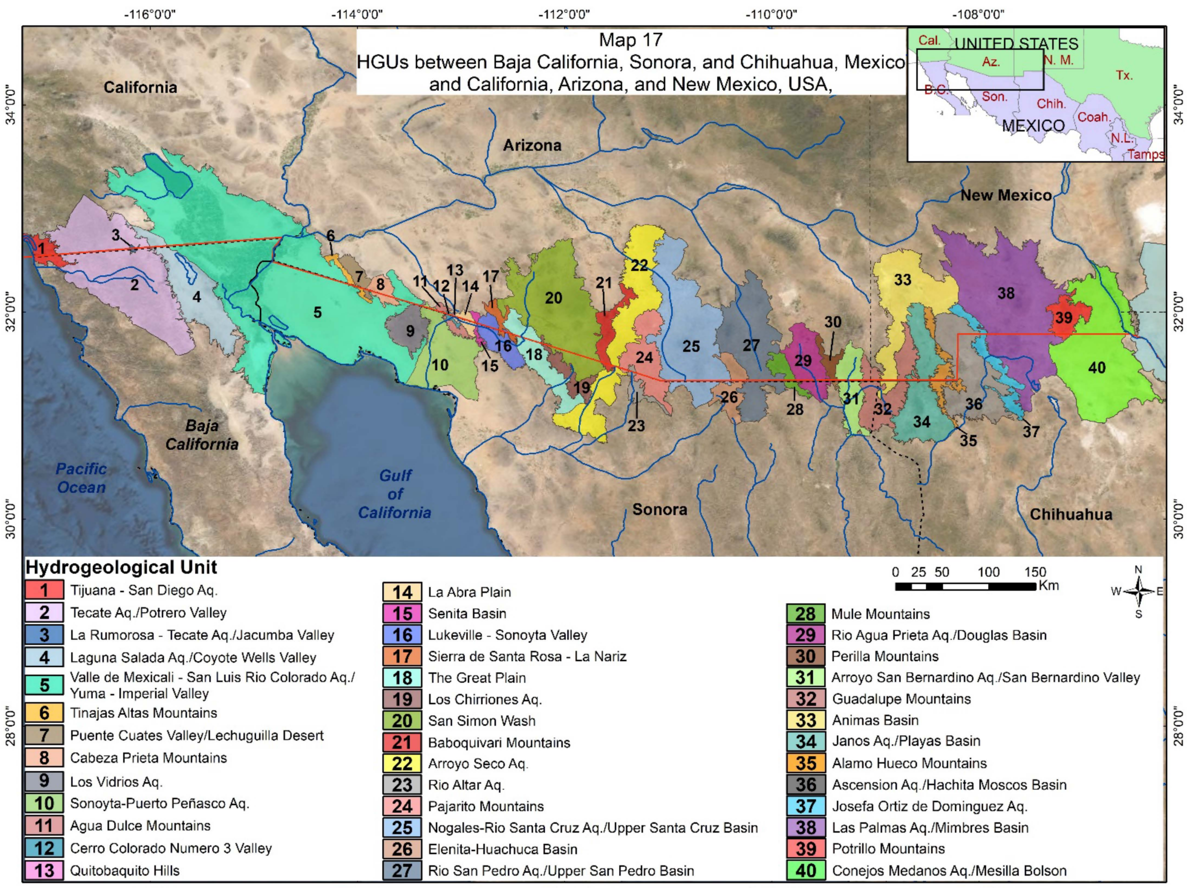

Figure 17. HGUs between Baja California, Sonora, and Chihuahua, Mexico and California, Arizona, and New Mexico, USA.

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Data Availability Statement: Data are available in a publicly accessible repository that does not issue DOIs. Publicly available datasets were analyzed in this study. This data will be found here after publication: Home | Transboundary Water Portal (tamu.edu).

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