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THE PECOS RIVER HYPOGENE SPELEOGENETIC PROVINCE: A BASIN-SCALE KARST PARADIGM FOR EASTERN NEW MEXICO AND WEST TEXAS, USA

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Abstract

Since the mid-Tertiary, lateral migration and entrenchment of the Pecos River Valley in eastern New Mexico and west Texas, USA, has significantly influenced regional groundwater flow paths, providing a focus for ascending flow in multi-storey artesian systems and a powerful potentiometric driving force for hypogene speleogenesis. Individual occurrences of hypogene karst phenomena associated with the central Pecos River Valley are widespread throughout the greater Delaware Basin region, including development in a wide range of Permian carbonate and evaporite fades. Hypogene occurrences are well-documented as far north as Santa Rosa, New Mexico and as far south as Lake Amistad, Texas. Throughout the northern shelf, intrastratal dissolution and brecciation of the San Andres formation is widespread as a result of eastward migration of the Pecos River. Proximal to the current river, hypogene dissolution in interbedded carbonate/evaporite facies of the Seven Rivers Formation has produced three-dimensional network caves and vertical collapse structures. In the carbonate reef facies of the Guadalupe Mountains, complex three-dimensional caves are common, as well as stepped terraces associated with eastward migration of the Pecos River. Although these caves have been attributed to sulfuric acid dissolution, they are the result of hypogene speleogenesis in which solutional aggressivity was increased by the addition of both thermal and sulfuric-acid components. Within the interior of the Delaware Basin, hypogene karst in basin-filling evaporite facies of the Castile and Salado Formations is widespread, including development of large solution subsidence troughs associated with the lateral migration of the Pecos River. On the far eastern margin of the Delaware Basin, at the southeastern tip of the Central Basin Platform, persistent downcutting of the Pecos River Valley contributed to the development of hypogene karst within the Yates Petroleum Field, providing cavernous reservoir porosity for the largest individual oil field known within the Permian Basin region. Immediately below the confluence of the Pecos River and the Rio Grande, the large first order magnitude spring, Goodenough Spring, flows from a deep phreatic cave under extreme artesian conditions, even as 45 meters of pressure head has been added over the spring from Amistad Reservoir.

Introduction

Hypogene processes have been recognized throughout far west Texas and southeastern New Mexico, USA, for many decades, but these processes have generally been associated with unusual fluid chemistries in Permian age carbonate units of the Guadalupe Mountains (Figure 1), specifically sulfuric acid speleogenesis. While sulfuric-acid karst is often hypogene, the two are not interchangeable terms. Instead, what has been defined as sulfuric acid karst in the Guadalupe Mountains is porosity produced by hypogene processes that has simply been enhanced by solutionally aggressive fluids enriched with a sulfuric acid component. This phenomenon is not limited to the reef and forereef facies of the Capitan Formation in the Guadalupe Mountains, but also extends into the carbonate backreef facies as seen in the upper portions of some of the Guadalupe Mountains caves (Hose and Pis¬arowicz, 2000) and in strata deposited farther shelfward, such as found associated with the caves of McKittrick Hill (Kunath, 1978).

The voluminous carbonate caves of the Guadalupe Mountains are usually invoked as typical examples of hypogenic speleogenesis in the Delaware Basin region; however, there is extensive and even more widespread karst development within the associated evaporite facies of southeastern New Mexico and west Texas (Stafford and Nance, 2009). Breccia pipes in evaporite strata, several hundred meters in vertical
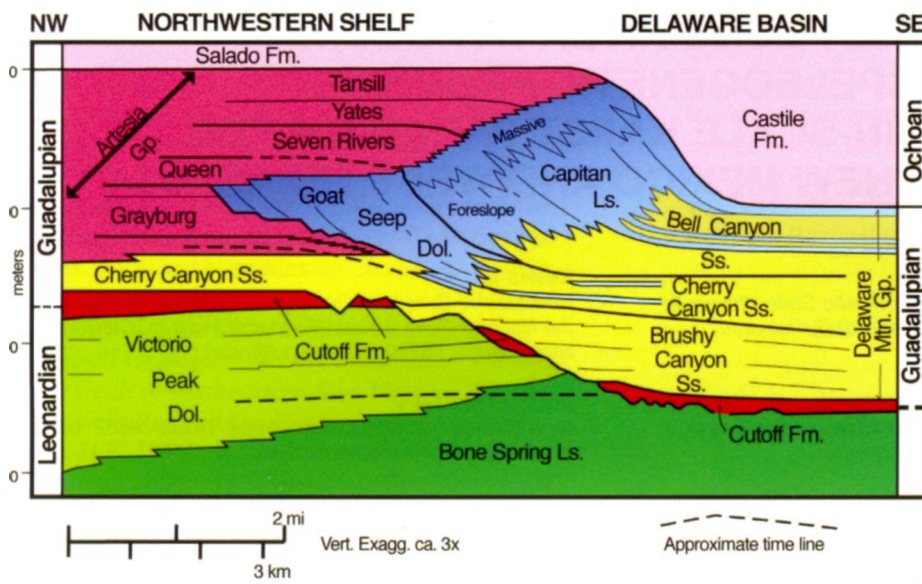
Figure 1. Late Permian stratigraphic nomenclature showing relationship to deposits on the Northwestern Shelf, Capitan Reef and Delaware Basin (from Scholle, 2004).

fluids with a thermal component. Similarly, various caves beyond the Pecos River Valley in Cretaceous strata west of San Antonio (Kunath, 1995) exhibit morphologies that are suggestive of formation by hypogene processes.

Previously known evidence of hypogene karst occurs throughout the lower Pecos region of eastern New Mexico and west Texas, but most of these features have been regarded as unique, isolated occurrences. This paper is a first attempt to view these speleogenetic phenomena in the context of related, basin-scale processes dominated by a unifying potentiometric driving force, the Pecos River.
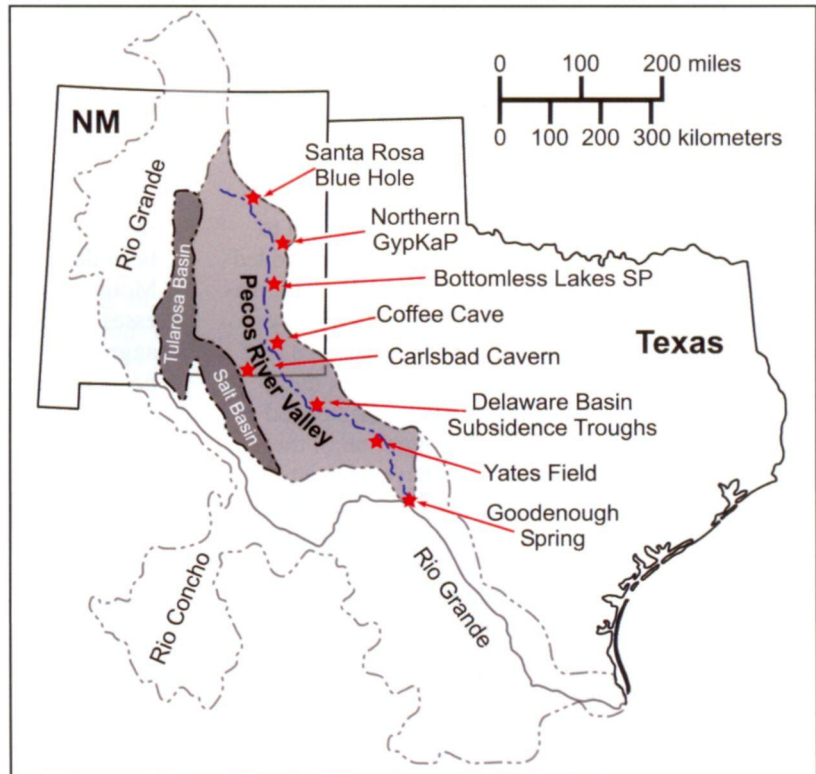
extent, have been associated with brine density convection, where hypogene processes are driven by variations in the solute concentrations of intrastratal fluids (Anderson and Kirkland, 1980). Recent research has shown that evaporite calcitization, native sulfur deposits, and speleogenesis within the Castile Formation are largely the result of hypogene processes (Stafford et al., 2008d, e), an association similar to that recognized in the western Ukraine (K.limchouk,l997). However, all of these features show varying degrees of epigenic overprinting, as do the carbonate caves of the region. The very nature of these caves, breached, drained and thus available for human exploration, has removed them from the hypogenic environment in which they formed.

Most of the course of the Pecos River is across Permian age carbonate and evaporite facies with associated karst development in these strata. However, throughout the southeastern portion of the Pecos River Valley near-surface strata are primarily Cretaceous carbonate rocks of the Edwards Plateau. Klimchouk (2007) argues that maze caves (e.g., Amazing Maze Cave) in this region are the result of hypogene processes involving sulfuric acid-rich

Figure 2. Location of karst features throughout the current Pecos River Valley, with comparison to the modern Rio Grande and Rio Concho basins (adapted from Thomas, 1972).
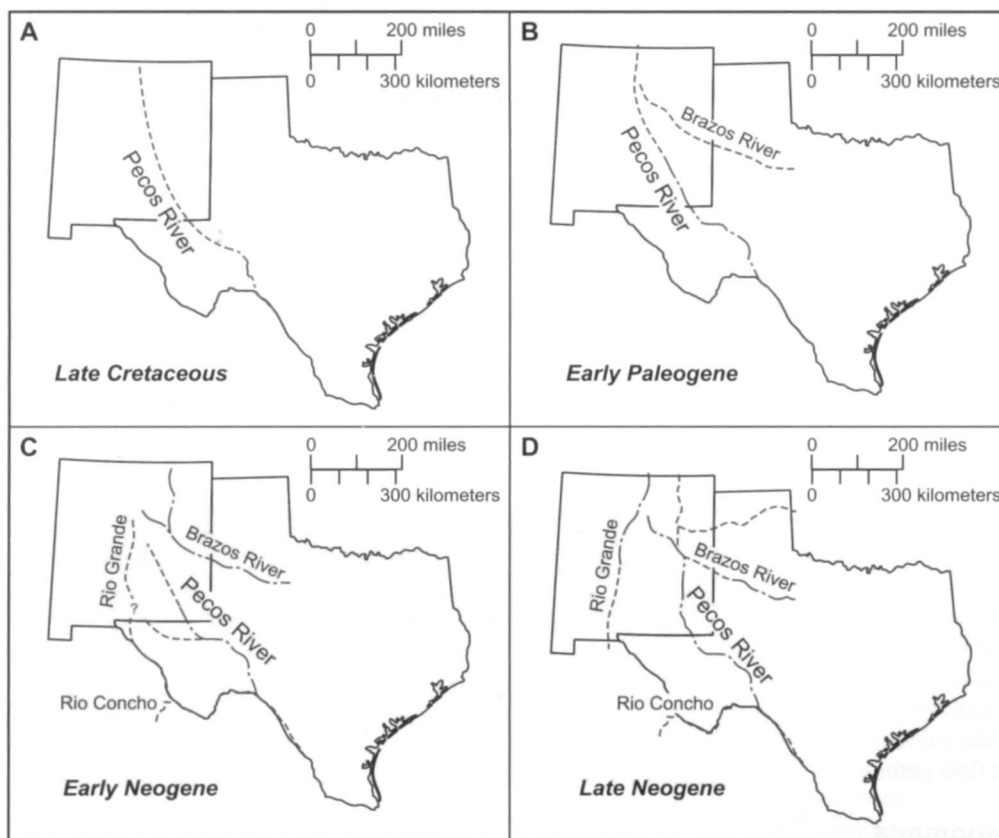
Pecos River

The headwaters of the Pecos River are located in the Sangre de Cristo Mountains of northern New Mexico (Figure 2). After exiting the mountains in western San Miguel County, the Pecos flows southward across eastern New Mexico into west Texas. The course of the river then turns southeast and ultimately flows into the Rio Grande west of Lake Amistad on the international border. The river's length is 1,320 km. Over this distance the Pecos crosses portions of the Southern Rockies, High Plains and Edwards Plateau physiographic provinces. Most of the river's route is across Permian age strata, including: 1) evaporites, mudstone and carbonates representing far backreef facies on the Northwest Shelf of the Delaware Basin ; 2) carbonates of near backreef, reef, and forereef facies deposited on the Basin margin; and 3) evaporites that filled the Permian inland basins and extended beyond the basin margin onto the Northwest Shelf by the end of the Permian. These sediments were deposited in equatorial conditions along the western edge of Pangaea with a limited connection to the Panthalassa Ocean (Scholle et al., 2004). Today, these strata not only host groundwater resources and numerous caves, but also a plethora of oil fields, both large and small.

As the Pecos River passes out of the Delaware Basin and onto the Central Basin Platform, the Permian strata are progressively buried in subsurface and surficial units dominated by Triassic conglomerates and sandstones, and by overlying carbonate strata. The carbonate strata were deposited during a Cretaceous-age continental transgression, which covered the western interior of North America with a shallow epicontinental sea (Richey et al., 1985). Through much of the flowpath across these carbonate strata, the Pecos River has entrenched into the Cretaceous units of the Edwards Plateau (Thomas, 1972). Today, the Pecos River is a major tributary of the Rio Grande, and is deeply-entrenched, near the rivers' junction west of Lake Amistad.

Thomas (1972) states that by the end of the Cretaceous or earliest Paleogene, the ancestral Pecos River had already developed in eastern New Mexico and west Texas as a result of Laramide Orogeny and uplift of the San Juan Mountains in southwestern Colorado (Figure 3). This early Pecos River was likely the dominant fluvial system at this time as it flowed across northern New Mexico, down through west Texas and discharged into the Gulf of Mexico possibly by joining with an ancestral Conchos River. This early phase began its incision into the Edwards Plateau (Thomas, 1972). During the late Paleogene and throughout much of the Neogene, most of the northern reaches of the ancestral Pecos River were diverted toward eastern New Mexico and northwest Texas where vast accumulations of clastic sediments were deposited to produce the Ogallala Formation (Bretz and Horberg, 1949). This northern piracy, resulting from increased sediment production from the Rocky Mountains, reduced the area of

Figure 3. Reconstructions of the ancestral Pecos River in the A) Late Cretaceous, B) Early Paleogene, C) Early Neogene and D) Late Neogene (adapted from Thomas, 1972).

the Pecos River Valley; however its general course persisted throughout southeastern New Mexico and west Texas, with continued entrenchment into the Edwards Plateau (Thomas, 1972).

By the end of the Neogene (Figure 3), uplift of the Sacramento and Sangre de Cristo Mountains had begun, shaping the current route of the Pecos River. At the same time, the ancestral Rio Grande was forming and at this time probably flowed across the Delaware Basin of west Texas as a tributary of the Pecos, or it may have continued farther south as a tributary of the ancestral Conchos River (Thomas, 1972). Contemporaneously, the ancestral Brazos River was draining most of northeastern New Mexico, continuing to supply alluvium to north Texas. During the Pleistocene the lower Pecos Valley extended farther to the north by karstification and headward erosion, culminating in capture of the ancestral Brazos near Fort Sumner, and thereby established the modern configuration of the Pecos River valley (Galloway, 1956; Reeves, 1972).

Throughout its history of the Pecos River, it has had a profound influence on the geomorphology and hydrology of west Texas and eastern New Mexico. Since the late Cretaceous or early Paleogene, the Pecos River has incised into the Edwards Plateau of southwest Texas, providing a consistent, major potentiometric low across this region that focused groundwater migration and discharge. Throughout west Texas and southeastern New Mexico the Pecos River has persisted since its inception, but in this region there have been greater lateral shifts as the river has migrated across a large alluvial floodplain (Thomas, 1972), again acting as a regional potentiometric low. The northern reaches of the Pecos River have seen the most change during its history. While the northernmost reaches of the ancestral Pecos are now part of the Rio Grande, its current headwaters are positioned in a region that has been occupied by either the ancestral Pecos River or the ancestral Brazos River for at least several million years (Thomas, 1972). This long presence of a river in a relatively persistent location must have had a significant influence on the evolution of regional groundwater flow paths.

Selected Karst Phenomena

In the following sections, eight specific areas are discussed that

demonstrate the dominance of hypogene speleogenesis throughout the greater Pecos River basin. While many more individual examples occur throughout the region, these eight show that hypogene karst development associated with the Pecos River exists from the northern reaches of the Pecos River Valley of north-central New Mexico, through the entire length of the river as it passes through eastern New Mexico and west Texas, and even at its confluence with the Rio Grande in south Texas. These eight occurrences likely represent only a small fraction of the total hypogene karst that is associated with the evolution of the Pecos River (Figure 2).

Santa Rosa Blue Hole

Santa Rosa, known as the "City of Natural Lakes" (McLemore, 1989), is located on the Pecos River in Guadalupe County, New Mexico (Figure 2). The city is known for its many spring-fed lakes and marshes, including the well known Blue Hole. Blue Hole is a collapse feature more than 25 meters deep, with an entrance approximately 24 meters in diameter that bells out to approximately 40 meters in diameter at the bottom (Kelley, 1972). Blue Hole is developed in the Triassic Santa Rosa Sandstone, which crops out throughout the Santa Rosa area. While the surficial sandstones are largely insoluble, the underlying Permian San Andres carbonates contain abundant solutional voids that stope upward to create cenote-like features that pierce the overlying strata (McLemore, 1989). Blue Hole, the largest of 16 small natural lakes in the Santa Rosa area, discharges more than 16.3 million liters of potable spring water per day (Kelley, 1972).
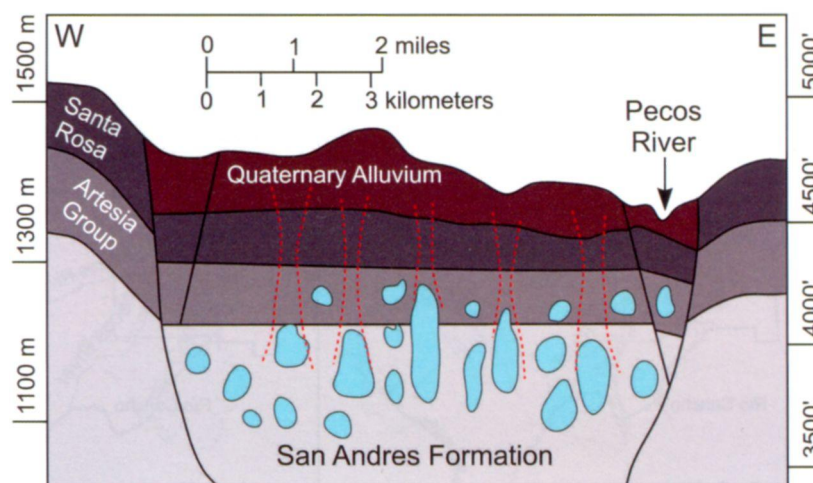
Figure 4. *Simplified cross-section through the Santa Rosa Sink, showing intense dissolution in the San Andres and massive stoping to produce this immense collapse structure. Dashed red lines indicate zones of stoping (adapted from Kelley, 1972).*

Blue Hole and the other flooded sinkholes of Santa Rosa are only a small part of speleogenesis in the area. These features and the town of Santa Rosa are all positioned inside a broad karst subsidence depression 10 kilometers in diameter and more than 120 meters deep (Figure 4) (Kelley, 1972). The depression consists of a series of convex-outward fractures, suggesting that the feature has expanded outward from a central collapse area. According to Kelley (1972), collapse of the massive sink began in the early Pleistocene, based on sediment fill and the deep gorges that the Pecos River cut through the northern and southern edges of the sink as a result of incision related to Pleistocene regional uplift. Most of the interior of the sink is mantled with Pleistocene gravels as the Pecos River deposited more than 75 meters of sediment into this expanding collapse structure (McLemore, 1989). Today, more than 190 individual collapse features in and around the periphery of the Santa Rosa depression attest to extensive vertical stoping of voids throughout the region. The large size of the subsidence basin and the abundance of springs and sinkhole lakes suggest that significant cavernous porosity exists at depth, probably related to deep circulation flow paths, which are focusing artesian discharge locally along the potentiometric low created by the Pecos River.

Northern   GypKaP

The San Andres Formation crops out extensively from Roswell to Vaughn, New Mexico on both the east and west sides of the Pecos River valley. Here interbedded gypsum and dolomite host a plethora of simple and complex caves in what is commonly termed "Northern GypKaP," the northern extent of the Gypsum Karst Project of the National Speleological Society (Figure 2) (Eaton, 1987). While karst regions to the north and south currently exhibit abundant features that actively discharge artesian waters, attesting to hypogene influences, the caves in this region have a more complex history, with sections that clearly exhibit morphologies similar to those observed in hypogenic caves, and other sections that are dominated by epigenic, vadose features.

Many caves in Northern GypKaP exhibit sections of rectilinear maze and/or large isolated chambers that have been intersected by entrenched vadose canyons (Figure 5). Scrooge Cave contains a large section of rectilinear maze developed along northeast and northwest trending fracture sets, while Montecito Cave contains long sections of narrow vadose canyons that occasionally intercept large isolated chambers, generally at significant lithology changes (Stafford and Nance, 2009). Most of the longer surveyed caves exhibit passage lengths that are disproportionately long compared to the size of the watersheds that feed the entrances, especially for caves developed in gypsum fades. Individual morphometric features suggestive of hypogene dissolution, or at the very least sluggish flow regimes, are common throughout both the small and large caves of the region. However, scallops are also commonly observed, indicating that in recent times high velocity, unconfined flow conditions have existed in many of these caves.
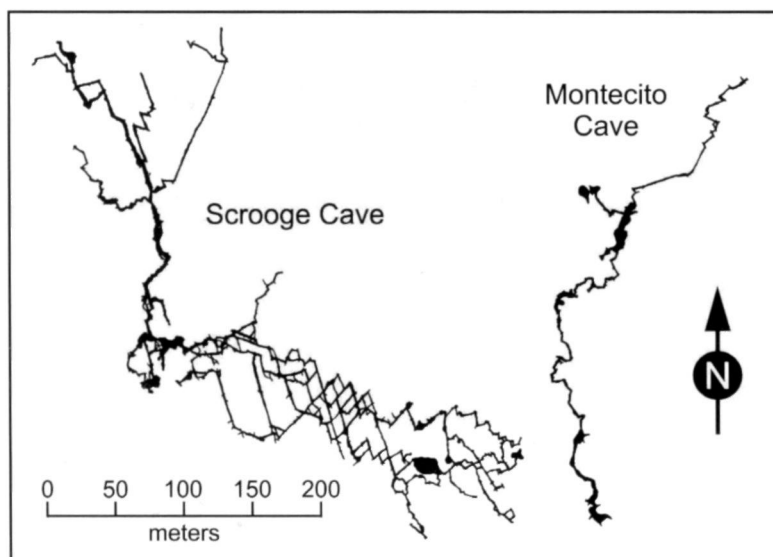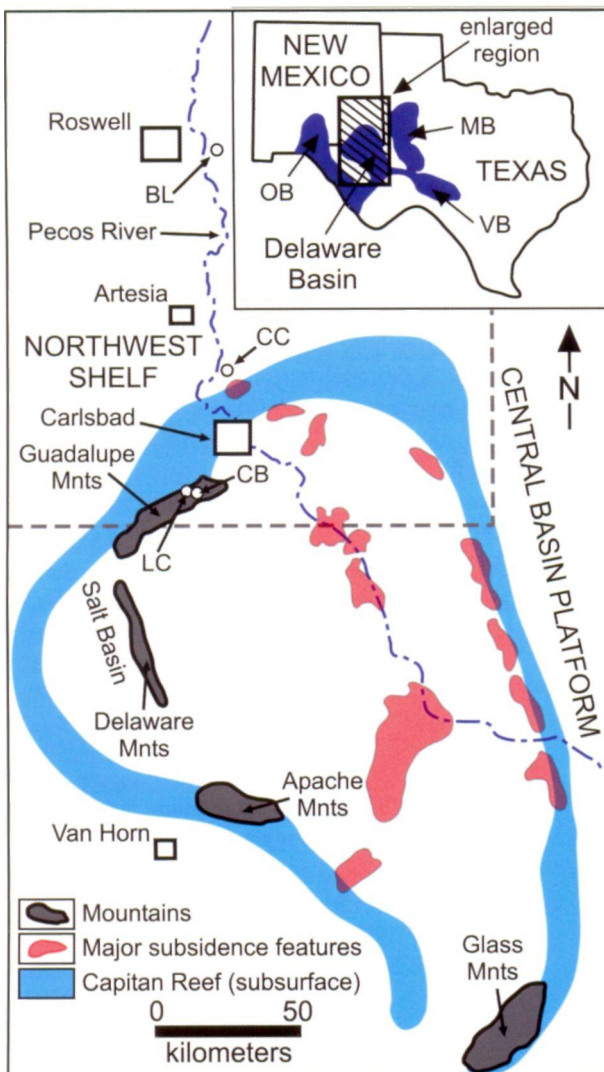

Figure 5. *Plan view map outlines of Scrooge and Motecito Caves, which illustrate the complex cave patterns documented in Northern GypKaP. Note that caves are depicted at the same scale but not spatially projected in relation to each other (adapted from Lee, 1996).*

Many of the caves within the Northern GypKaP region have complex speleogenetic histories that reflect epigenic over-printing onto originally hypogenic features. Complex maze patterns and extensive cave networks in gypsum facies likely formed when these units were buried more deeply and the Pecos River was migrating across them, possibly tens of millions of years ago at the same time intense dissolution was actively proceeding near Santa Rosa to the north (Kelley, 1972). As surface denudation and down cutting of the Pecos River continued, these caves systems became unconfined and exposed to epigene processes. Surface breaching introduced focused recharge into the cave networks, which was followed by significant epigenic over-printing, including the development of incised canyons connecting zones of more intense hypogene porosity.

Bottomless Lakes State Park

Bottomless Lakes State Park is located on the eastern margin of the Pecos River Valley southeast of Roswell, New Mexico (Figures 2, 6). The park includes a series of eight cenote-like features, formed in gypsum and mudstone of the Permian Seven Rivers Formation, that extend for several kilometers along the Seven Rivers Escarpment (Kelley, 1971; Martinez et al., 1998; Land, 2003). These steep-walled, vertical collapse structures occur at the downstream end of the Roswell Artesian Basin, a regional artesian aquifer system formed in the San Andres limestone (Welder, 1983; Land and Newton, 2007; 2008). Meteoric

Figure 6. *Map of Delaware Basin showing the geographic relationships between the Capitan Reef, major subsidence features and the Pecos River. BL = Bottomless Lakes State Park, CC = Coffee Cave, CB = Carlsbad Cavern, LC = Lechuguilla Cave, OB = Orogrande Basin, MB - Midland Basin, VB = Val Verde Basin (adapted from Klimchouk, 2007).*

waters recharge the aquifer where the San Andres Formation crops out on the Pecos Slope west of Roswell, and migrate down gradient to the south and east. The San Andres aquifer is under water table conditions on the Pecos Slope, but becomes confined ~10 km west of Roswell where it dips beneath gypsum and mudstones of the Seven Rivers Formation (Figure 7.). In the vicinity of Bottomless Lakes, the potentiometric surface within the San Andres aquifer is above ground level. Forced convection drives lateral and upward migration of groundwater toward the Pecos River, and focused solution occurs along fractures in the overlying gypsum and mudstone. As artesian water migrates upward through the leaky confining beds of the Seven Rivers Formation, it is saturated with calcite but undersaturated with respect to gypsum. The result is the development of large hypogene voids that collapse and stope upward to discharge high salinity, artesian waters into the Bottomless Lakes cenotes. Some of these cenotes overflow into wetlands west of the park, which are hydraulically connected to the Pecos River (Land, 2003; 2006).

Historically, high volume springs that fed extensive wetlands were common in the Roswell area. Decades of intensive pumping for irrigated farming caused substantial declines in hydraulic head in the artesian aquifer, and most of these springs are now dry (Welder, 1983; Land and Newton, 2007; 2008). However, substantial discharge still occurs into springs and cenotes along the Pecos River, indicating that hypogene processes remain active along this reach of the Pecos River valley. This natural artesian discharge amounts to -37 million m³/yr, but was much greater prior to pumping (Barroll and Shomaker, 2003).

Coffee Cave, Lake McMillan

Coffee Cave is located along the eastern edge of old Lake McMillan in northern Eddy County, New Mexico (Figure 2, 6). Coffee Cave, along with several smaller caves in the area, is developed in interbedded dolomites and gypsum of the Seven Rivers Formation. Coffee Cave is a rectilinear maze cave developed along northeast and northwest trending fracture sets (Figure 8) (Stafford et al., 2008b). The cave consists of at least 4 levels of passage development in gypsum facies, each separated by a significant dolomite bed. The uppermost two levels tend to be small and often not humanly navigable, while the lowest level, and potentially additional lower levels, is currently flooded. Throughout the cave, abundant hypogene morphometric features are found, including individual occurrences of well-developed cupolas, risers, half-
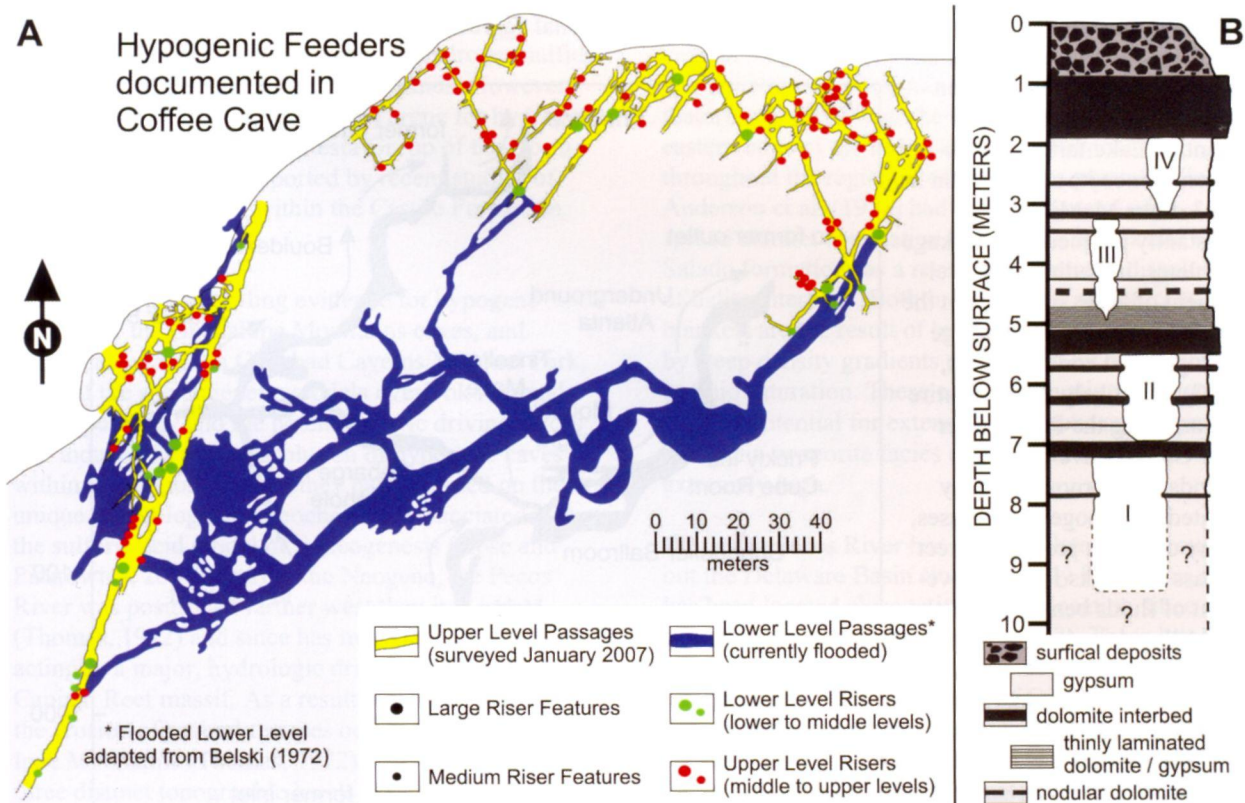
Figure 7. Stratigraphic cross-section showing the groundwater circulation flow paths associated with Bottomless Lakes State Park, where meteoric water is recharged on the Pecos Slope and discharge as artesian springs along the Pecos River (from Land, 2006).
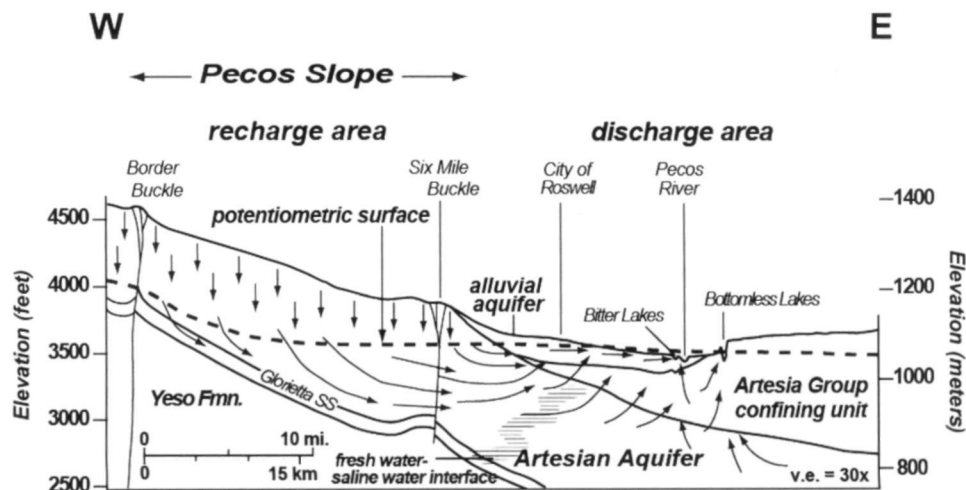
tubes and ceiling channels (Stafford et al., 2008b). Most importantly, these morphometric features are commonly found in related suites where fluid flow paths can be visually traced from lower riser inlets, up wall half-tubes, along ceiling channels, and out ceiling cupolas. The presence of these features provides diagnostic evidence of dissolution in confined, hypogene conditions (Klimchouk, 2007). The morphol-

ogy of Coffee Cave shows considerable similarities to the classic hypogene maze caves of the Western Ukraine.

Stafford et al. (2008b) conclude that speleogenesis within Coffee Cave is largely the result of hypogene processes. The cave is located at the southern end of the Roswell Artesian Basin. Groundwater discharge

Figure 8. Coffee Cave, A) plan view map showing distribution of cave passages, levels and hypogene features and B) stratigraphic section through Coffee Cave showing relationship between the four documented cave levels and dolomite interbeds (from Stafford et al., 2008b).

from the underlying San Andres artesian aquifer has been focused upward along the Pecos River, similar to the hydrologic system described above at Bottomless Lakes State Park (Land, 2003; 2006) (Figure 7). Meteoric recharge on the Pecos Slope to the west infiltrates down through the Permian San Andres and Grayburg formations and moves laterally, down-gradient to the east and south (Land and Newton, 2007; 2008). Proximal to the Pecos River, these fluids migrate upward though the Seven Rivers Formation as forced convection is induced by the potentiometric low of the river (Stafford et al., 2008b). As surface denudation and eastward migration of the modern Pecos River occurred, Coffee Cave was breached and the semi-confined conditions that formed the bulk of the cavernous porosity were replaced by unconfined, epigene conditions. While early models for the formation of Coffee Cave suggest the cave resulted from dissolution associated with back-flooding along the Pecos River, gypsum solution kinetics do not support this theory. Average cave passage cross sectional area increases with depth and distance from the numerous collapse entrances into Coffee Cave (Stafford et al., 2008b), suggesting that solutionally aggressive fluids were delivered from below instead of laterally or above as a result of back flooding.

Lake McMillan is no longer an active reservoir, but has been drained and replaced by Brantley Lake farther downstream. Since its construction in 1893, Lake McMillan was constantly plagued with leakage problems, including the development of large sinkholes in the lake bed and massive leakage through karst conduits (Cox, 1967). It is likely that the entire region along the Pecos River near Coffee Cave contains abundant cavernous porosity created by hypogene processes, many of which provided direct bypass networks for the movement of fluids beneath the Lake McMillan dam.

In the early 20' century, many irrigation wells in the vicinity of Coffee Cave displayed strong artesian flow (Fiedler and Nye, 1933; Welder, 1983). Today, flowing artesian wells are less common in this area because of reductions in hydraulic head due to decades of agricultural groundwater pumping. However, in 2007 water levels in Coffee Cave rose more than 2 meters between the summer irrigation season when groundwater pumping is most intense and mid-winter when most irrigation pumping has ceased (Stafford et al., 2008b). This rise in water levels suggests that hypogene processes are still active in interbedded evaporites and carbonates of the Seven Rivers Formation near the Pecos River.

Carlsbad Caverns National Park

The caves of Carlsbad Caverns National Park in the Guadalupe Mountains of southernmost New Mexico (Figure 2, 6) are the most studied karst features within the western United States (Hose and Pisarowicz, 2000). The caves contain large isolated chambers, maze sections and multiple levels, all characteristics of dissolution involving sluggish waters in a confined or semi-confined setting. Cavernous porosity is developed largely in the Permian age Capitan Formation (Figure 1), including the reef and fore reef sections, and extends into the equivalent near back reef facies (Hill, 2000). Massive accumulations of secondary gypsum in caves attest to the role of sulfuric acid (Palmer and Palmer, 2000), which increased solutional aggressivity. Regional tectonic studies indicate
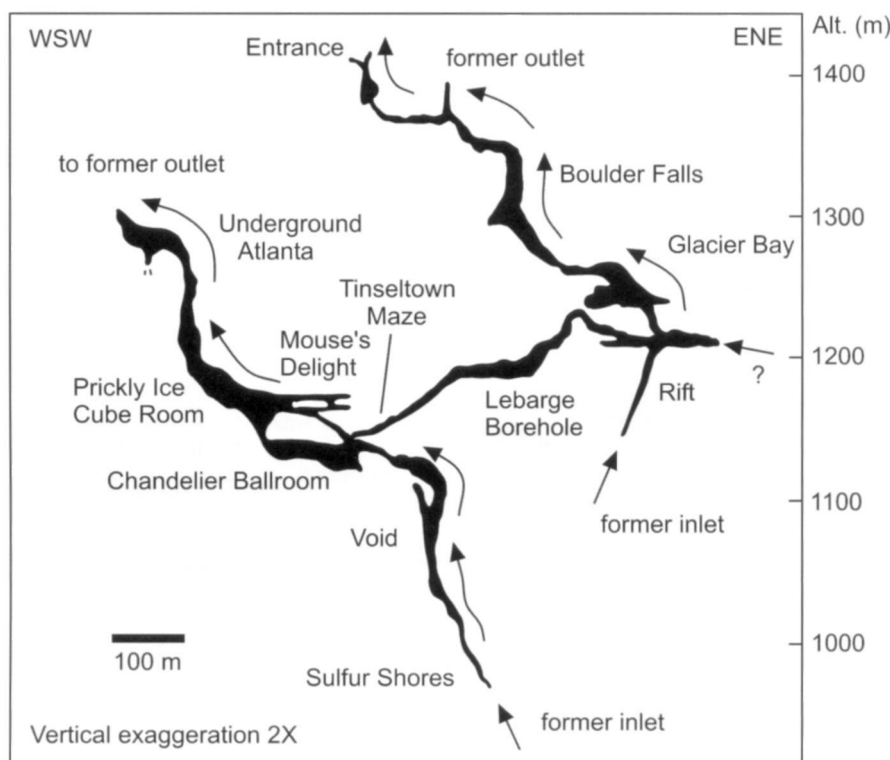
Figure 9. *Simplified profile view through part of Lechuguilla Cave shows the flow paths of ascending fluids (from Palmer and Palmer, 2000).*

that geothermal gradients were as high as 40-50°C/km (Barker and Pawlewicz, 1987), which must have added a thermal component to the hypogene speleogenesis of the Guadalupe Mountains.

Klimchouk (2007) and Palmer and Palmer (2000) suggest that most of the volume of major caves in the Guadalupe Mountains (e.g., Carlsbad Cavern, Lechuguilla Cave) is the result of speleogenesis in deep-seated conditions wherein rising solutional fluids are delivered from depth. Palmer and Palmer (2000) trace distinct flow paths through the caves that show fluids migrating from the deepest portions (e.g. Sulfur Shores in Lechuguilla Cave; Lake of the Clouds in Carlsbad Cavern), through intermediate passages, to the uppermost levels of the caves and even to the current cave entrances, which they interpret as outlets for ascending fluids (Figure 9). Klimchouk (2007) further shows abundant morphometric evidence throughout the caves of Carlsbad Caverns National Park that attests to dissolution within semi-confined, hypogene conditions. The intense hypogene dissolution was driven by steep density gradients established by thermal convection (Hill, 1996) and high solute loads resulting from increased dissolution by sulfuric acid-rich fluids. Hill (2000) concluded that sulfate reduction within the Castile Formation of the Delaware Basin interior was the source of hydrogen sulfide that produced the sulfuric acid-rich fluids. However, DuChene and Cunningham (2006) argue for hydrogen sulfide originating in the Artesia Group of the Northwest Shelf, which is supported by recent studies of evaporite calcitization within the Castile Formation (Stafford et al., 2008e).

While there is compelling evidence for hypogene origins for the Guadalupe Mountains caves, and specifically caves in Carlsbad Caverns National Park, most of the speleogenetic models overlook regional paleohydrology and the potentiometric driving forces that induced focused dissolution of hypogene caves within this region. Instead they have focused on the unique mineralogy and geochemistry associated with the sulfuric acid model of speleogenesis (Hose and Pisarowicz, 2000). During the Neogene, the Pecos River was positioned farther west than it is today (Thomas, 1972) and since has migrated eastward, acting as a major, hydrologic driving force across the Capitan Reef massif. As a result, entrenchment and the erosion of several terraces occurred in the Guadalupe Mountains (Thomas, 1972), as is well marked by three distinct topographic levels that decrease in elevation from west to east over the length of the mountain ridge (DuChene and Martinez, 2000). While thermal and sulfuric acid components drove increased

dissolution rates, locally focused forced flow was likely induced by the ancestral Pecos River as it migrated eastward. This model is supported by age dates from alunite deposits in caves that show increasing age to the west with increasing elevation (Polyak and Provencio, 2000).

Delaware Basin Subsidence Troughs

Within the interior of the Delaware Basin, caves and solution subsidence features are common in Ochoan evaporites (Hill, 1996) (Figures 2, 6). Along the western edge of the Delaware Basin large subsidence troughs have been identified, associated with hypogenic fluids ascending from the subsurface Capitan Reef (Anderson and Kirkland, 1980). In the eastern Delaware Basin, extensive caves, evaporite calcitization and native sulfur accumulations are associated with hypogene processes primarily in the Castile Formation, but also extending into the overlying Rustler and Salado Formations (Stafford et al., 2008 c,d,e). In the middle of the Delaware Basin, several large subsidence features filled with Quaternary sediments occur along the direct flowpath of the Pecos River (Figure 6) (Malley and Huffington, 1953).

Anderson and Kirkland (1980) show that vertical breccia pipes occur throughout the Delaware Basin as a result of brine density convection combined with upward stoping. Their model was developed for features observed over the buried Capitan Reef on the eastern edge of the basin, and was extrapolated throughout the region to other breccia pipes. Earlier, Anderson et al. (1978) had also recognized widespread blanket brecciation throughout the Castile and Salado formations as a result of intrastratal dissolution of halite interbeds. Both breccia pipes and breccia blankets are the result of hypogene dissolution driven by steep density gradients established by differences in fluid saturation. These early observations indicate that the potential for extensive hypogene speleogenesis within evaporite facies of the basin interior is extremely high.

While the Pecos River has migrated laterally throughout the Delaware Basin since the early Paleogene, it has been located close to its current location since at least the late Neogene (Thomas, 1972). These large subsidence features appear to be the result of locally intense, intrastratal dissolution of Castile and Salado evaporites, resulting in intrastratal collapse and upward stoping to create large closed depressions that were subsequently filled by Quaternary sediments delivered by the Pecos River (Malley and Huffington, 1953). This intrastratal dissolution was driven by brine density free convection and forced convection,

with flow directed toward the potentiometric low of the Pecos River. Because of the high solubility of evaporites and the lack of upper Permian carbonate or clastic interbeds within the interior of the Delaware Basin, the development of large hypogene voids is possible.

It is possible that some subsidence features may have also developed along the ancestral Rio Grande, which is postulated to have flowed across the Delaware Basin during the Neogene as a tributary of the Pecos River (Thomas, 1972). It is likely that intrastratal dissolution is still occurring today throughout the Delaware Basin in association with the Pecos River and other natural hydrologic phenomena. However, modern catastrophic collapse features within this region are often attributed to anthropogenic causes such as leaky casing and improper well installation (e.g. Johnson et al., 2003; Powers, 2003), even though natural subsidence features and collapse structures permeate these evaporite units.

Yates Field

The Yates Unit Oil Field is located in eastern Pecos County, Texas (Figure 2) on the southeastern tip of the Central Basin Platform. It is the largest oil field in the Permian Basin and has been characterized as a karstic reservoir since the first well was drilled in 1926 (Hennen and Metcalf, 1929). Production is from middle Permian strata, primarily the upper San Andres

Formation but extending into the overlying Grayburg and Queen formations, at depths of approximately 300 meters (Stafford et al., 2008a). The field is subdivided into low permeability Westside Yates and high permeability Eastside Yates units (Figure 10). Structurally, the Yates Field is dominated by a horseshoe-shaped anticline, with an axial ridge centered in Eastside Yates and extending into the northern and southern edges of Westside Yates (Craig, 1988). Stratigraphically overlying the Yates Field along the northeastern edge, the Toborg Field is developed in uppermost Triassic and Cretaceous strata (Franklin, 1966). Both fields are located on the southwest side of the Pecos River and were initially discovered because of oil seeps along the river.

Cavernous porosity within the Yates Field includes open caves, solution enhanced fractures and extensive brecciation, as well as secondary mineralization including clastic sediment fill, calcite and dolomite spar, and more rarely native sulfur, albite, galena and sphalerite (Stafford et al., 2008a). Cave distribution within the field, based on petrophysical analyses and documentation of 1,566 individual cave occurrences, is highly clustered and tends to be focused along the structural axis of the field at the upper San Andres contact (Figure 10) (Stafford et al., 2008a). Isotope analyses of secondary calcite spar indicate deposition in thermal fluids associated with methane oxidation (Stafford et al., 2008a). While no Permian strata are
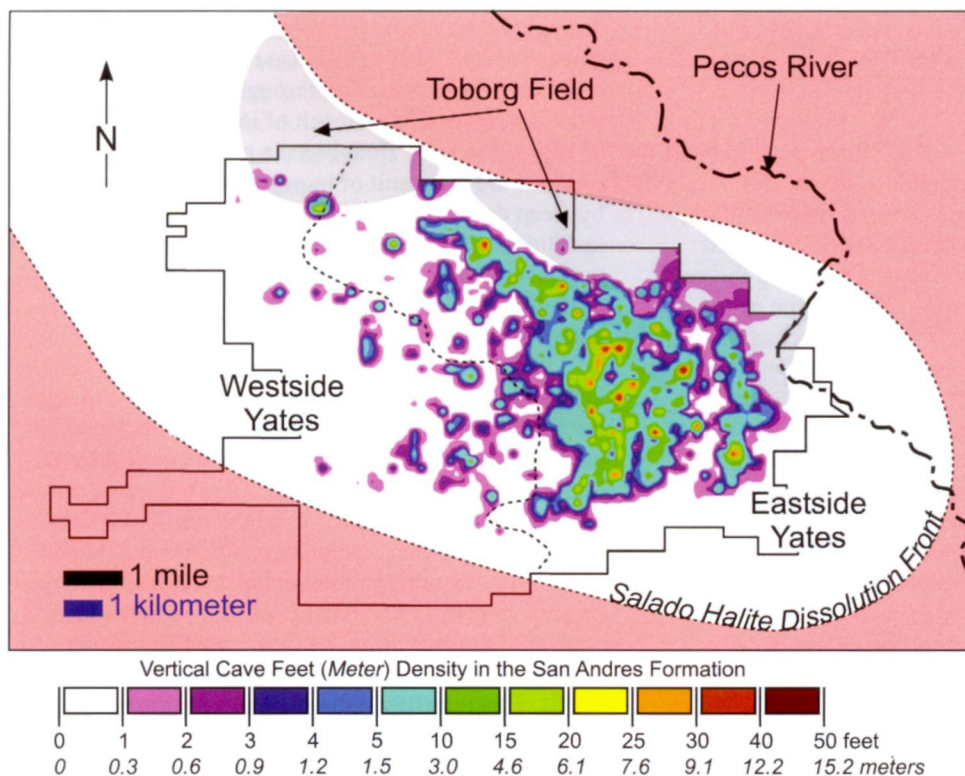
Figure 10. *Distribution of caves within the San Andres Formation of the Yates Field in comparison to the overlying Salado Halite Dissolution Front, Toborg Field and Pecos River. Note that the most intense karst development forms an arch through Eastside Yates, which is the structural axis of the anticlinorium that dominates the region (adapted from Stafford etal., 2008a).*

Vertical Cave Feet (*Meter*) Density in the San Andres Formation

0	1	2	3	4	5	10	15	20	25	30	40	50 feet
0	0.3	0.6	0.9	1.2	1.5	3.0	4.6	6.1	7.6	9.1	12.2	15.2 meters

exposed at the surface in this region, in the overlying Cretaceous carbonates morphometric features observed in Ess Cave within the Yates Unit Oil Field indicate that hypogene processes have been locally active (Stafford et al., 2008a).

Early models for the karst porosity of the Yates Field invoked eogenetic, island karst processes for cave origins (Craig, 1988; Tinker and Mruk, 1995; Tinker et al., 1995). These models suggest that subaerial exposure at the end of San Andres deposition created a series of islands on the southern end of the Central Basin Platform in which freshwater horizons developed where caves formed as a result of mixing of fresh and saline waters. However, current studies (Stafford et al., 2008a) suggest that most of the cavernous porosity within the Yates Field is probably attributable to hypogene processes. The distribution of cavernous zones from petrophysical analyses shows karst development centered along the crest of the anticlinal structure that dominates Yates Field (Figure 10), not as an elliptical band of intense karst as would be expected from island karst dissolution along a coastal margin. It is significant that cavernous porosity is not limited to the San Andres Formation but extends upward into the Grayburg and Queen Formations (Tinker and Mruk, 1995; Tinker et al., 1995). Clastic sediments filling San Andres vugs are the same composition as the insoluble residue of the overlying strata (Tinker and Mruk, 1995), suggesting an autochthonous origin, in contrast to allogenic sediments derived from surface environments in an epigenic system. Secondary minerals filling vugs and lining fractures indicate thermal and sulfuric-acid components to the fluid history of the field (Stafford et al., 2008a). Associated with the Yates Field, overlying halite in the Salado Formation has been removed through intrastratal dissolution (Wessel, 2000), which is likely associated with upward fluid migration from Yates Field units. Finally, overlying Cretaceous rocks contain caves resulting from hypogene speleogenesis.

We contend that Yates Field developed though hypogene speleogenesis with dissolution focused along structural and lithologic boundaries. As fluids migrated upward toward the Pecos River, which has been persistently downcutting in this region since the early Paleogene, they passed through San Andres carbonates, overlying Permian strata and through Cretaceous carbonates in which hypogene caves have been locally documented. As solutionally aggressive fluids were replaced with hydrocarbons within the Yates Field during the Neogene, it is probable that solutional pathways created through the overlying interbedded evaporites and carbonates of the Seven Rivers Formation began to close and provide a leaky seal for hydrocarbon entrapment. The Yates Field has a complex diagenetic history, but it appears that much of the cavernous porosity and the location of the field are related to proximity of the Pecos River.

### *Goodenough Spring - Amistad Reservoir*

The distal end of the Pecos River reaches the Rio Grande in Val Verde County, Texas, at the International Amistad Reservoir, which was constructed in the 1960's impounding the Rio Grande, including the lowest reach of the Pecos River. The geology of Val Verde County is dominated by early-mid Cretaceous limestone of the Edwards Plateau, associated with the Maverick Basin. This large, closed marine basin developed as the Devils River Formation formed a reef bank surrounding basinal facies of the West Nueces, McKnight, and Salmon Peak Formations (Figure 11) during Fredericksburgian through Washitan time. The Salmon Peak and Devils River Formations are significantly karstified through this region of Texas and Mexico (Boghici, 2004; Barker et al., 1994).

The impoundment of Amistad Reservoir flooded numerous caves and springs along the Pecos and Rio Grande rivers. The most significant feature inundated was Goodenough Spring, 21 kilometers south-southeast of the confluence of the Pecos and Rio Grande (Figure 11). This spring was the third largest in Texas prior to inundation in 1968 with an average annual discharge of 3.9 meters^3/second and a maximum recorded flow of 18.4 meters'/second (Brune, 1981). The water flowing from Goodenough Spring is 28° C, which is over 7 degrees above average surface temperatures and has low total dissolved solids of 208 mg/1 (Kamps et al, 2009).

In the 1990's underwater cave exploration began at Goodenough Spring by cave divers using SCUBA. A tight restriction was encountered over 100 meters into the cave with very high water velocity hindering further exploration (Milhollin and Laird, 1996). This restriction was passed in 2004, and passage continued down at a steep angle. The passage was extended in 2008 to a water depth of 157 meters (GSEP, 2008). The reservoir water level was 45 meters over the spring cave entrance at this time, pushing the total explored depth within the cave to 112 meters (Figure 11), making it the third deepest cave in Texas, either air or water-filled (Elliott and Veni, 1994).

Goodenough Spring continues to flow significant volumes despite additional head above the cave. In 2005, over 2 metersVsecond of flow was measured
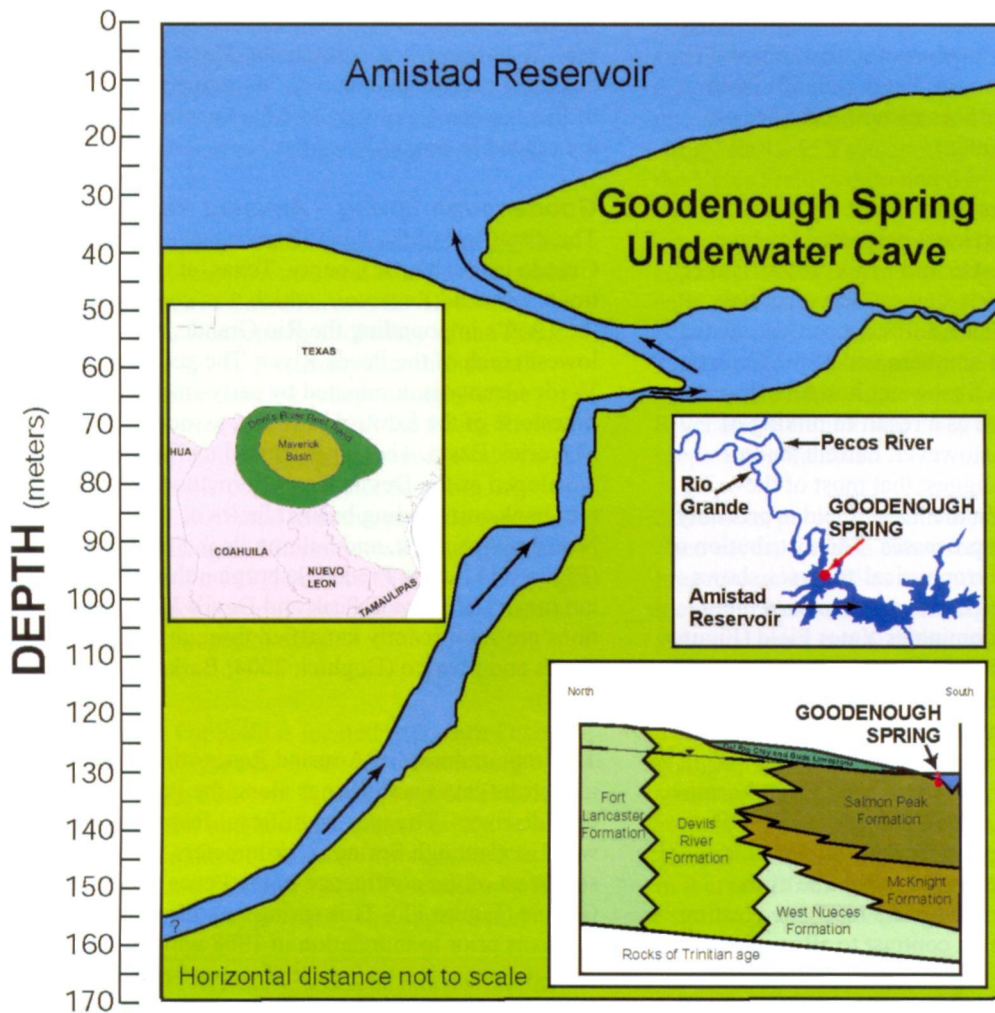
Figure 11. *Profile cave map of Goodenough Spring underwater cave (main image) shows vertical extent of the artesian spring extending to water depths beyond 160 m. The water depth above the spring cave entrance is 45 m due to impounded water from Amistad Reservoir (upper right inset). The cave has formed in the Salmon Peak Formation (lower right inset), which is the top unit of the Maverick Basin (upper left inset).*

from the spring (Kamps et al., 2009). Geologists active in the area prior to inundation of Goodenough Spring noticed responses in spring flow to precipitation events occurring to the south in Mexico, when no event occurred to the north in Texas (T.A. Small, 2000, personal communication). Uplifted limestone with extrusive igneous rocks 30 kilometers south of Goodenough Spring is hypothesized as a possible recharge zone. The extreme artesian conditions and elevated water temperatures indicate a deep groundwater flow route through conduits likely formed from hypogene karst processes, possibly influenced by subsurface volcanic activity. Entrenchment by the Pecos and Rio Grande rivers exposed the deep flow path of Goodenough Spring, creating the modern karst system.

Conclusions

The Pecos River has played a dominant role in shaping the geomorphology of eastern New Mexico and west Texas, but it has also had a profound impact on the hydrologic and speleogenetic evolution of the region since the late Cretaceous. Karst features located in the Pecos River Valley suggest that the continuous potentiometric low this fluvial system created has been a major driving force for basin-scale groundwater movement throughout the Cenozoic Era. Modern artesian springs in eastern New Mexico attest to continued hypogene processes acting today in many areas of the Pecos River Basin. Relict caves in the Guadalupe Mountains signify intense periods of hypogene karst development associated with the ancestral Pecos River. Cavernous porosity in the Yates Field is probably only a small fraction of the cavernous porosity associated with Cenozoic entrenchment of the Pecos River in southwest Texas. It is likely that future research will demonstrate an even greater dominance of the Pecos River on speleogenetic processes throughout eastern New Mexico and west Texas.

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