Tectonic Influences on Petroleum Migration and Speleogenesis in the Guadalupe Mountains, New Mexico and Texas*

Harvey R. DuChene[1]

Search and Discovery Article #120139 (2013)
Posted March 31, 2013

*Adapted from oral presentation given at the Department of Earth and Planetary Science, University of New Mexico, Albuquerque, NM, April 20, 2012, and a seminar at the Department of Earth and Environmental Science at New Mexico Tech, Socorro, NM, October 11, 2012

[1]Foreland Operating, LLC, Dallas, TX (hrduchene@gmail.com)

Abstract

Sulfuric acid speleogenesis in the Guadalupe Mountains is a consequence of the rise of the Alvarado Ridge and subsequent opening of the Rio Grande Rift during Cenozoic time. Uplands of the Late Laramide (~38-35 Ma) Alvarado Ridge provided an immense recharge area that supplied water to aquifers draining eastward to the Permian Basin. Evidence for east-directed hydrodynamic flow is the displacement, microbial degradation and subsequent recharging of hydrocarbons in large structural and stratigraphic traps in Artesia Group (Permian, Guadalupian) reservoirs in southeast New Mexico and adjacent West Texas. Prior to, or during the early stages of the development of the Rio Grande Rift, hydrostatic head in the Capitan aquifer caused water to flow eastward through Artesia Group strata toward the Permian Basin. Some of this water moved upward along fractures to artesian springs in the area of the Guadalupe Mountains. This resulted in solutional enlargement of fractures and development of early stage caves.

Extensional faulting since 29 Ma fragmented the east flank of the ridge, progressively reducing the size of the upland recharge area and reducing hydrostatic head. Fresh water influx introduced microbes into Artesia Group (Permian, Guadalupian) reservoirs causing biodegradation of petroleum and generating copious H_2S. The water table within the Guadalupe Mountains began to fall 14-12 Ma in response to erosion and tectonism. During this time, oxygen-rich meteoric water mixed with H_2S water to form sulfuric acid, which enlarged passages and galleries at the water table. Tectonic spasms related to the opening of the Rio Grande Rift caused abrupt drops in the water table, shifting the locus of sulfuric acid dissolution eastward and downward. Cave levels formed by sulfuric acid record the position of the water table at a given time, and the elevation difference between levels may correlate with episodes of Rio Grande Rift tectonism since 12 Ma.

References:

Bailey, N.J.L., H.R. Krouse, C.R. Evans, and M.A. Rogers, 1973, Alteration of crude oil by waters and bacteria – evidence from geochemical and isotope studies: American Association of Petroleum Geologists Bulletin, v. 57, p. 1276-1290.

Cunningham, K.I., H.R. DuChene, and C.S. Spirakis, 1993, Elemental sulfur in caves of the Guadalupe Mountains, New Mexico: New Mexico Geological Society Guidebook, 44th Field Conference, Carlsbad Region, New Mexico and West Texas, p. 129-136.

Dietrich, E.S, 1956, Robinson (Grayburg-San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 304-305.

Davis, D.G., 1973, Sulfur in Cottonwood Cave, Eddy County, New Mexico: National Speleological Society Bulletin, v. 35, no. 3, p. 89-95.

DuChene, H.R., and J.S. McLean, 1989, The role of hydrogen sulfide in the evolution of caves in the Guadalupe Mountains of southeastern New Mexico: *in* P.D. Harris and G.A. Grover (eds.), Subsurface and outcrop examination of the Capitan Shelf Margin, northern Delaware basin: SEPM Core Workshop No. 13, p. 475-481.

DuChene, H.R., and Ruben Martinez, 2000, Post-speleogenetic erosion and its effects on caves in the Guadalupe Mountains: National Speleological Society Bulletin, v. 62, p. 75-79.

DuChene, H.R., and Ruben Martinez, 2001, Post-speleogenetic erosion and its effects on caves in the Guadalupe Mountains: Reply: National Speleological Society Bulletin, v. 63, p. 77-78.

DuChene, H.R., and K.I. Cunningham, 2006, Tectonic influences on speleogenesis in the Guadalupe Mountains, New Mexico and Texas: New Mexico Geological Society Guidebook, 57th Field Conference, Caves and Karst of Southeastern New Mexico: p. 211-218.

DuChene, H.R., 2009, The relationship of oil field-derived hydrogen sulfide in the Permian (Guadalupian) Artesia Group to sulfuric acid speleogenesis in the Guadalupe Mountains, New Mexico and Texas, *in* K.W. Stafford, L.L. Land, and G. Veni (eds.), Advances in Hypogene Karst Studies: NCKRI Symposium 1, Carlsbad, NM: National Cave and Karst Research Institute, p. 111-120.

Eaton, G.P., 1986, A tectonic redefinition of the southern rocky Mountains: Tectonophysics, v. 132, p. 163-193.

Eaton, G.P., 1987, Topography and origin of the southern Rocky Mountains and Alvarado Ridge, *in* M. Coward, J.F. Dewey, and L. Hancock (eds.), Continental Extension Tectonics, Geological Society Special Publication 28, p. 355-369.

Egemeier, S.J., 1973, Cavern development by thermal waters with a possible bearing on ore deposition: Ph.D. dissertation, Stanford University, 88 p.

Egemeier, S.J., 1981, Cavern development by thermal waters: National Speleological Society Bulletin, v. 49, p. 73-76.

Fryman, A.A., 1956, Grayburg-Jackson (Grayburg-Sand Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 40-41.

Fryman, D., 1956, McMillan (Queen) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 275-276.

Gable, D.J., and T. Hatton, 1983, Maps of vertical crustal movements in the coterminous United States over the last 10 million years: U.S. Geological Survey Miscellaneous Investigations Series Map I-1315.

Goetz, L.K., 1980, Quaternary faulting in Salt Basin Graben, west Texas: New Mexico Geological Society, 31st Field Conference Guidebook, p. 83-92.

Goodger, J.M., 1956, Square Lake (Grayburg-San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 328-329.

Gregory, K.M., and C.G. Chase, 1992, Tectonic significance of paleobotanically estimated climate and altitude in the late Eocene erosion surface, Colorado: Geology, v. 20, p. 81-85.

Green, W.R., 1956, Penrose-Skelly (Queen-Grayburg) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 294-295.

Hayes, P.T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey Professional Paper 446, 69 p.

Hill, C.A., 1987, Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources Bulletin 117, 150 p.

Hill, C.A., 1990, Sulfuric acid speleogenesis of Carlsbad Cavern and its relationship to hydrocarbons, Delaware basin, New Mexico and Texas: American Association of Petroleum Geologists Bulletin, v. 74, p. 1685-1694.

Hill, C.A., 1996, Geology of the Delaware basin – Guadalupe, Apache and Glass Mountains, New Mexico and Texas: Society of Economic Paleontologists and Mineralogists, Permian basin Section, Publication 96-39, 480 p.

Hill, C.A., 2000, Overview of the geologic history of cave development in the Guadalupe Mountains, New Mexico: National Speleological Society Bulletin, v. 62, p 60-71.

Hinds, J.S., and R.R. Cunningham, 1970, Elemental sulfur in Eddy County, New Mexico: U.S. Geological Survey Circular 628, 13 p.

Hiss, W.L., 1975, Chloride-ion concentration in ground water in Permian Guadalupian rocks, southeast New Mexico and west Texas: New Mexico Bureau of Mines and Mineral Resources, Resource Map 4.

Hiss, W.L., 1980, Movement of ground water in Permian Guadalupian aquifer systems, southeastern New Mexico and western Texas: New Mexico Geological Society Guidebook, 31st Field Conference, Trans-Pecos region, southeastern New Mexico and west Texas, p. 289-294.

Hose, L.D., and J.L. Macalady, 2006, Observations from active sulfidic karst systems: is the present the key to understanding Guadalupe Mountain speleogenesis? New Mexico Geological Society, 57th Field Conference Guidebook, p. 185-194.

Jagnow, D.H., 1986, Current thoughts on cavern development in the Guadalupe Mountains, New Mexico, *in* D.H. Jagnow, and H.R. DuChene (eds.), Geology Fieldtrip Guidebook, 1986 National Speleological Society Convention, Tularosa, New Mexico, 102 p.

Jagnow, D.H., 1977, Geologic factors influencing speleogenesis in the Capitan Reef Complex, New Mexico and Texas: M.S. Thesis, Albuquerque, University of New Mexico, 197 p.

Jagnow, D.H., 1989, The geology of Lechuguilla Cave, New Mexico, *in* M. Harris and G.A. Grover (eds.), Subsurface and outcrop examination of the Capitan shelf margin, northern Delaware basin: Society of Economic Paleontologists and Mineralogists Core Workshop No. 13, p. 459-466.

Jagnow, D.H., C.A. Hill, D.G. Davis, H.R. DuChene, K.I. Cunningham, D.E. Northup, and J.M. Queen, 2000, History of the sulfuric acid theory of speleogenesis in the Guadalupe Mountains, New Mexico: National Speleological Society Bulletin, v. 62, p. 54-59.

Kinney, E.E., 1956a, Aid (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 40-41.

Kinney, E.E., 1956b, Tonto (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 342-343.

Kirkland, D.W., and R. Evans, 1976, Origin of limestone buttes, Gypsum Plain, Culberson County, Texas: American Association of Petroleum Geologists Bulletin, v. 60, p. 2005-2018.

Lindsay, R.F., 1998, Meteoric recharge, displacement of oil columns and the development of residual oil intervals in the Permian basin: West Texas Geological Society Publication 98-105, The Search Continues into the 21st Century, p. 271-274.

Matchus, E.J., and T.S. Jones (co-chairmen), 1984, East to west cross section through Permian basin west Texas: West Texas Geological Society Special Publication No. 84-79, 1 sheet.

McPeters, K.D., and J.M. Kelly, 1956, Hobbs (Grayburg-San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 206-207.

Mershon, P.M., Jr., 1960, East Millman (Queen-San Grayburg) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 152-153.

Meissner, F.F., 1972, Cyclic sedimentation in Middle Permian strata of the Permian basin, west Texas and New Mexico: West Texas Geological Society Publication 72-18, second edition, p. 203-232.

Milks, Roy, 1956, Vacuum (Grayburg-San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 352-353.

Molnar, Peter, and Phillip England, 1990, Late Cenozoic uplift of mountain ranges and global climate change: Chicken or egg?: Nature, v. 346, p. 29-34.

Motts, W.S., 1968, The control of ground water occurrence by lithofacies in the Guadalupian reef complex near Carlsbad, New Mexico: Geological Society of America Bulletin, v. 79, p. 283-298.

Muehlberger, W.R., R.C. Belcher, and L.K. Goetz, 1978, Quaternary faulting in Trans-Pecos, Texas: Geology, v. 6, p. 337-340.

Palmer, A.N., 1991, Origin and morphology of limestone caves: Geological Society of America Bulletin, v. 103, p. 1-21.

Palmer, A.N., and M.V. Palmer, 2000, Hydrochemical interpretation of cave patterns in the Guadalupe Mountains, New Mexico: Journal of Cave and Karst Studies, v. 62, p. 91-108.

Palmer, A.N., and M.V. Palmer, 2006, Support for a sulfuric acid origin for caves in the Guadalupe Mountains: New Mexico Geological Society, 57th Field Conference Guidebook, p. 195-202.

Polyak V.J., W.C. McIntosh, N. Güven, and P. Provencio, 1998, Age and origin of Carlsbad Cavern and related caves from 40Ar/39Ar of alunite: Science, v. 279, p. 1919-1922.

Puckett, H.W., 1960, Dos Hermanos Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 68-69.

Queen, J.M., 1973, Large-scale replacement of carbonate by gypsum in some New Mexico caves (abs): National Speleological Society Convention Abstracts, p. 12.

Reilinger, R.E., L.D. Brown, and J.E. Oliver, 1979, Recent vertical crustal movements from leveling observations in the vicinity of the Rio Grande Rift, *in* R.E. Riecker (ed.), Rio Grande Rift: Tectonics and Magmatism: American Geophysical Union, p. 223-236.

Roswell Geological Society, 1956, A symposium of oil and gas fields of southeastern New Mexico: Roswell Geological Society, Roswell, New Mexico, 376 p.

Roswell Geological Society, 1960, A symposium of oil and gas fields of southeastern New Mexico: Roswell Geological Society, Roswell, New Mexico, 229 p.

Roswell Geological Society Symposium Committee, 1956a, Arrowhead (Queen-Grayburg) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 52-53.

Roswell Geological Society Symposium Committee, 1956b, Atoka (San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 56-57.

Roswell Geological Society Symposium Committee, 1956c, Getty (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 180-181.

Roswell Geological Society Symposium Committee, 1956d, Jalmat (Yates-Seven Rivers) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 218-219.

Roswell Geological Society Symposium Committee, 1956e, P.C.A. (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 290-291.

Roswell Geological Society Symposium Committee, 1956f, Red Lake (Grayburg-San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 298-299.

Roswell Geological Society Symposium Committee, 1956g, Rhodes (Yates-Seven Rivers) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 300-301.

Sares, S.W., 1984, Hydrologic and geomorphic development of a low relief evaporitic karst drainage basin, southeast New Mexico: M.S. Thesis, University of New Mexico, Albuquerque, 123 p.

Sares, S.W., and S.G. Wells, 1986, Geomorphic and hydrogeologic development of the Gypsum Plain karst, Delaware basin, New Mexico, *in* D.H. Jagnow and H.R. DuChene (eds.), Geology Fieldtrip Guidebook, 1986 National Speleological Society Convention, Tularosa, New Mexico, p. 11-31.

Scholle, P.A., D.S. Ulmer, and L.A. Melim, 1992, Late stage calcites in the Permian Capitan Formation and its equivalents, Delaware basin margin, west Texas and New Mexico: Sedimentology, v. 39, p 207-234.

Schram, H.F., 1956a, Cedar Hills (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p.102-103.

Schram, H.F., 1956b, Russell (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 306-307.

Spirakis, C., and K.I. Cunningham, 1992, Genesis of sulfur deposits in Lechuguilla Cave, Carlsbad Caverns National Park, *in* G. Wessel and B. Wimberley (eds.), Native Sulfur – Developments in geology and exploration: American Institute of Mining, Metallurgical and Petroleum Engineers (AIME) Special Volume, p. 139-145.

Stringer, Bob, 1956, Langlie-Mattix (Yates-Seven Rivers-Queen) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 226-227.

Sweeney, H.N., 1956a, Halfway (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 193.

Sweeney, H.N., 1956b, Littman (San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 238-239.

Sweeney, H.N., 1956c, Young (Queen) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 374-375.

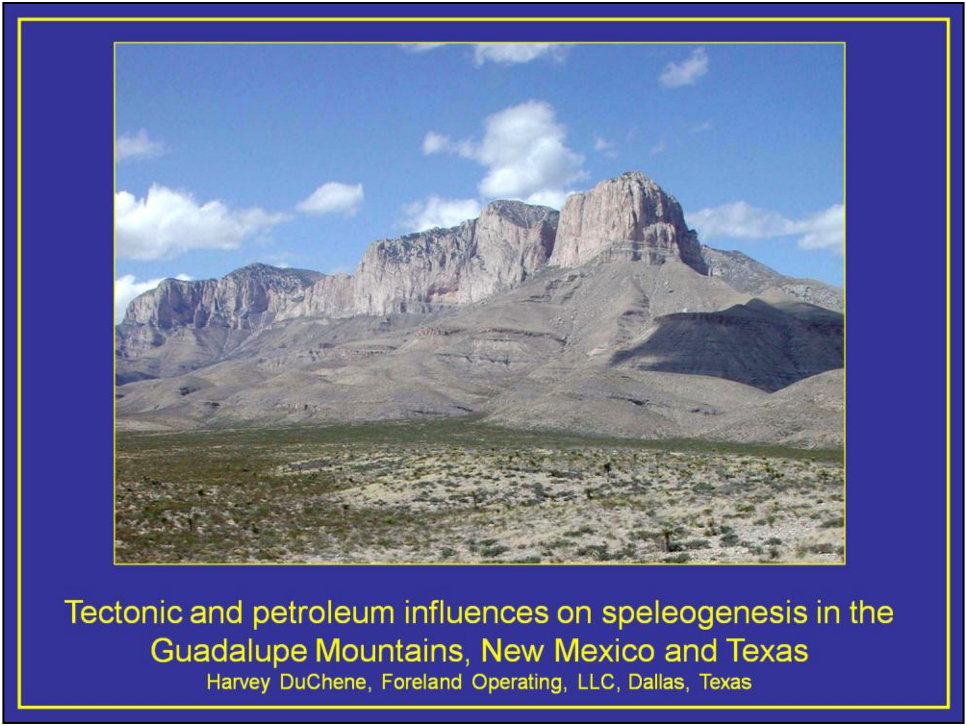
Veldhuis, J.H., and G.R. Keller, 1980, An integrated geological and geophysical study of the Salt Basin graben, west Texas: New Mexico Geological Society, 31st Field Conference Guidebook, p. 141-150.

Ward, R.F., St. C. Kendall, and M. Harris, 1986, Upper Permian (Guadalupian) facies and their association with hydrocarbons – Permian basin, west Texas and New Mexico: American Association of Petroleum Geologists Bulletin, v. 70, p. 239-262.

Wiggins, W.D., P.M. Harris, and R.C. Burruss, 1993, Geochemistry of post-uplift calcite in the Permian Basin of Texas and New Mexico: Geological Society of America Bulletin, v. 105, p. 779-790.

Wilson, D., 1956, Gem (Yates) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 179.

Zoller, M.L., 1956, House (San Andres) Field: Roswell Geological Society Symposium, Oil and Gas Fields of Southeastern New Mexico, p. 214-215.

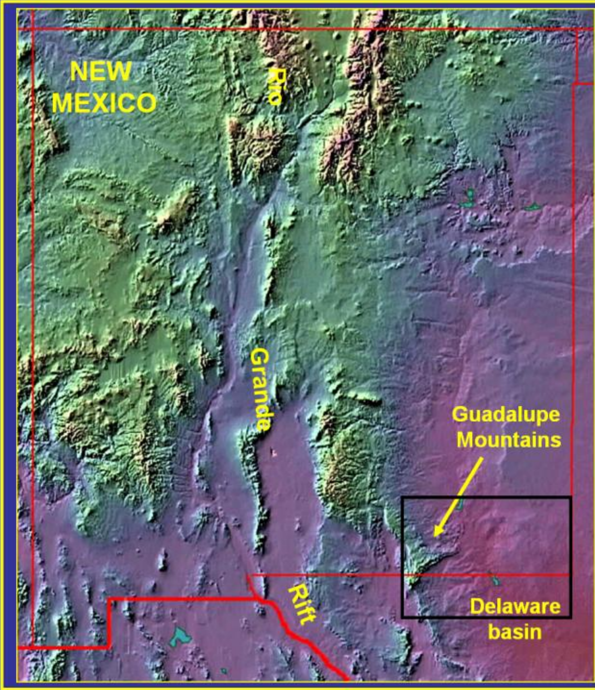


Presenter's notes: During the last 35 years, our understanding two seemingly unconnected geological features of New Mexico has greatly advanced. These features are the Rio Grande rift and the great caverns of the Guadalupe Mountains. We now know that the Rio Grande rift is a complex structural feature of continental proportions, comparable to great rift systems around the world. We have also learned that the caves of the Guadalupe Mountains were modified and significantly increased in volume by sulfuric acid. At first glance, these features seem unconnected and unrelated. However, evidence I will present today shows that the origin of Guadalupe Mountain caves is a consequence of the evolution of the Rio Grande rift.

GEOLOGIC SETTING

Western escarpment, Guadalupe Mountains.
Salt Basin graben in foreground and Border fault zone in middle distance.

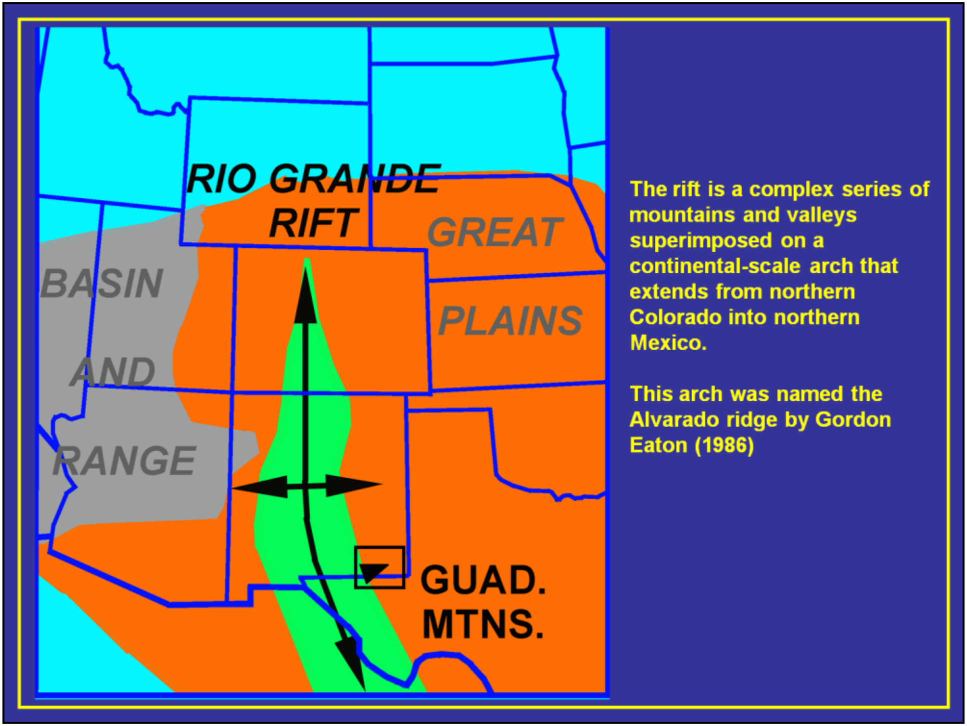
Presenter’s notes: This view of the western escarpment of the Guadalupe Mountains if from the floor of the Salt Basin graben at the west end of the range. The western escarpment is bounded by down-to-the-west faults that formed as a result of extension caused by the opening of the Rio Grande rift.



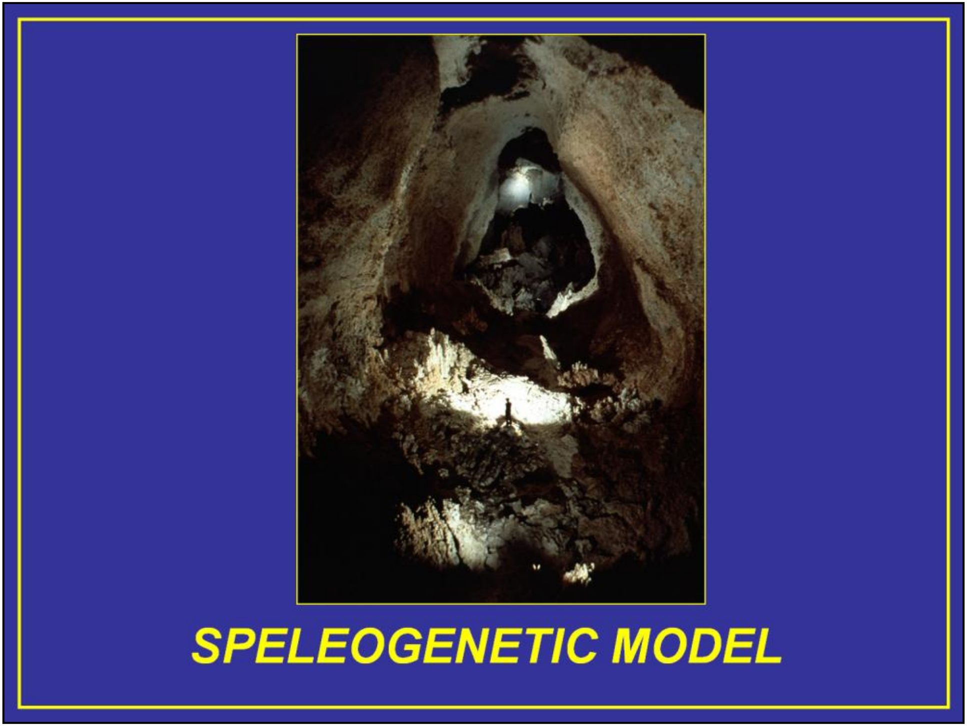
The Guadalupe Mountains
Are located in southeastern
New Mexico and west Texas

The mountains are part of a
east-dipping tilted fault block
uplift on the eastern flank of
the Rio Grande rift.

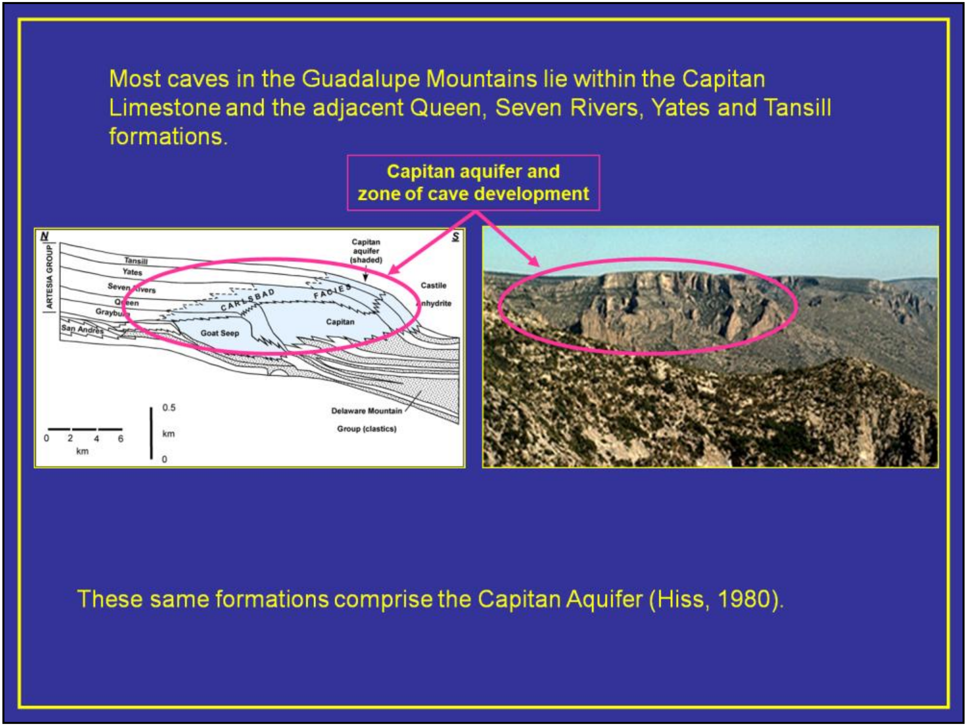
Presenter's notes: The Guadalupe Mountains are located in southeast new Mexico and west Texas, on the east side of the Rio Grande rift. The mountains are part of an east-tilted fault block that includes the Delaware Mountains of west Texas, and extends northward to the southern part of the Sacramento Mountain block.



Presenter's notes: The Rio Grande rift is a complex series of mountains and valley superimposed on a continental-scale arch that extends from northern Colorado into northern Mexico. It was named the Alvarado Ridge by Gordon Eaton (1986).



Presenter's notes: Speleogenesis is the process of cave formation. Most caves are epigenic, formed by near-surface processes related to the movement of water through soluble rock. In the Guadalupe Mountains, however, caves were dissolved by sulfuric acid that was formed beneath the surface and is related to the microbial metabolic degradation of hydrocarbons in the presence of sulfate. Such caves are referred to as hypogenic, formed by processes within the earth rather than at the surface.

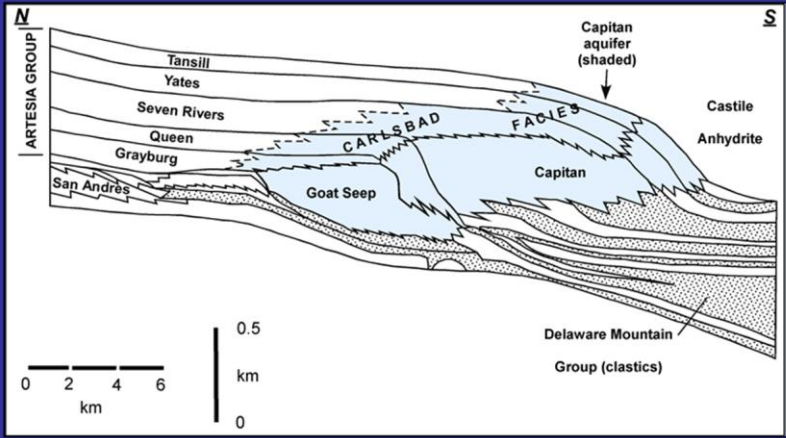


Presenter’s notes: This slide is a geologic profile through the Guadalupe Mountains from north to south. It shows the geologic formations that make up the mountains, including the Capitan Limestone, which has been described as an exhumed reef.

Most of the caves in the Guadalupe Mountains are developed in the Capitan Formation or the carbonates of the Artesia Group. The Artesia Group is the name for several geologic formations that are equivalent in age to the Capitan Formation.

The Capitan Formation is composed of massive limestone “reef” deposits, whereas the Artesia Group formations are layered and were deposited in a lagoon that existed between the reef and the land. Together, the limestone deposits of the Capitan and the Artesia Group comprise a hydrologic unit known as the Capitan Aquifer. This aquifer is a highly permeable conduit through which meteoric water moves from outcrop into the Permian basin.

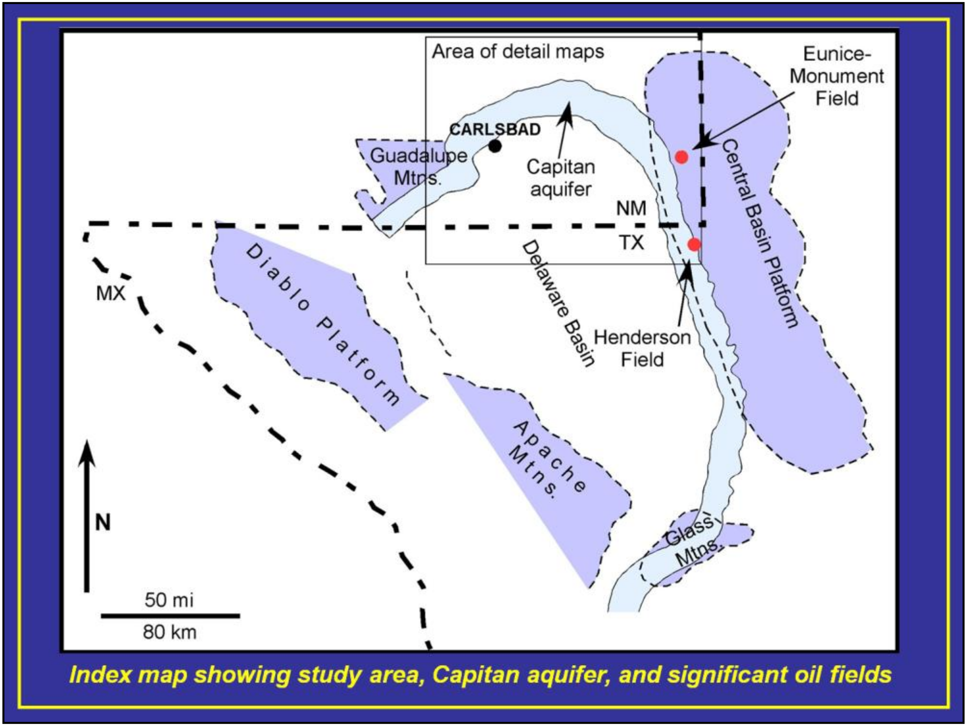
CAPITAN AQUIFER



The Capitan aquifer is comprised of the fractured carbonate and sandstone facies of the Goat Seep and Capitan formations and the Carlsbad facies of the Artesia Group

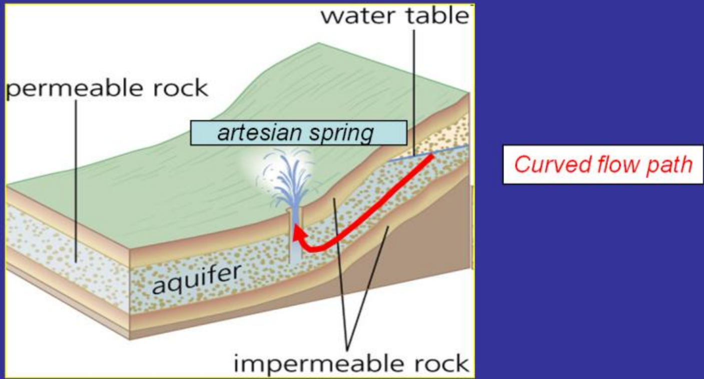
The rocks of the Guadalupes are cut by numerous vertical and near-vertical fractures, which provide flow paths for water moving through the aquifer.

Presenter's notes: The Capitan aquifer is comprised of the fractured carbonate and sandstone facies of the Goat Seep and Capitan formations and the Carlsbad facies of the Artesia Group. The rocks of the Guadalupes are cut by numerous vertical and near-vertical fractures, some that are contemporaneous with reef formation and others that resulted from later tectonic events.



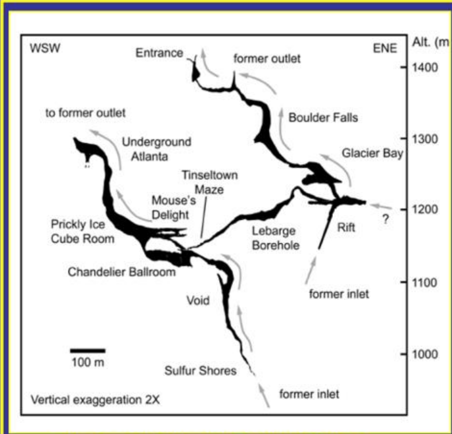
Presenter's notes: This map shows the surface and subsurface extent of the Capitan aquiver in relation to major features that surround the Delaware basin. The location of the Henderson and Eunice-Monument oil fields, which will be discussed later, are shown in red.

Almost 30 years ago, it was recognized that caves in the Guadalupes are in part a result of dissolution by waters moving along deep-seated, curved flow paths in the Capitan aquifer (Davis, 1979) .



What was not explained is how these deep flow paths could have existed in the current structural configuration of the Guadalupe Mountains.

Presenter’s notes: Almost 35 years ago, it was recognized that caves in the Guadalupe Mountains are, in part, a result of dissolution by waters moving along deep-seated, curve flow paths in the Capitan aquifer (Davis, 1979). What was not explained by Davis is how these deep flow paths could have existed in the current structural and erosional configuration of the Guadalupe Mountains. The implication of Davis’ work is that the structural configuration of the region must have been significantly different in the past when the caves were being formed.



Cross section through Lechuguilla Cave

Early stage solution-enlarged fractures are sub-vertical to vertical.

Palmer and Palmer (2000) showed that solution enlarged sub-vertical fissures in Guadalupe caves were conduits for rising water, following up on Davis' (1979) observation.

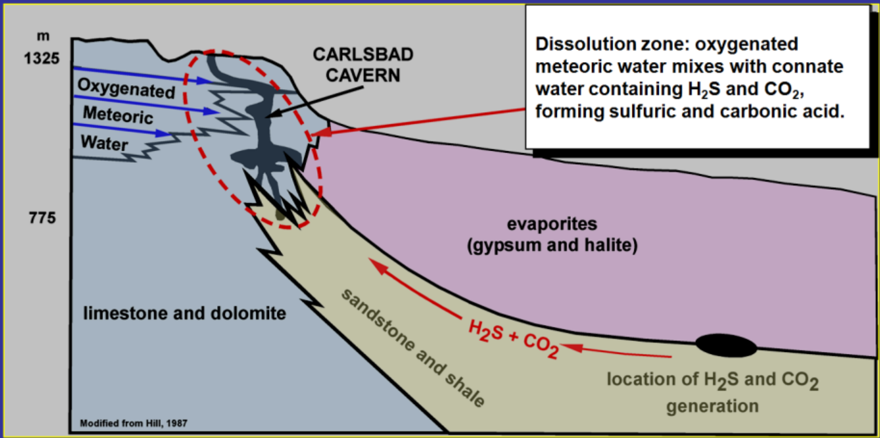
In contrast, typical water table-controlled passages formed by sulfuric acid are horizontal.

Presenter's notes: In the 1990's Art and Peg Palmer conducted detailed investigations in numerous Guadalupe Caves, especially Lechuguilla and Carlsbad Cavern, where the caves have not been dissected and fragmented by canyon-cutting erosion. They observed that Guadalupe caves actually consist of two distinct types of passage – vertical conduits that can have as much as 500 meters of relief, and near-horizontal passages and galleries that intersect the vertical conduits.

Based on geometric and morphologic characteristics, the Palmers concluded that the vertical conduits were feeders for artesian springs. Water flowed upward along fractures in the limestone of the Guadalupes, enlarging them and forming mostly vertical cave passages. Cave entrances like Carlsbad and Lechuguilla were once spring outlets, as were other caves in the Guadalupes. An example of this geometry is found in Hell Below cave in the western part of the mountains.

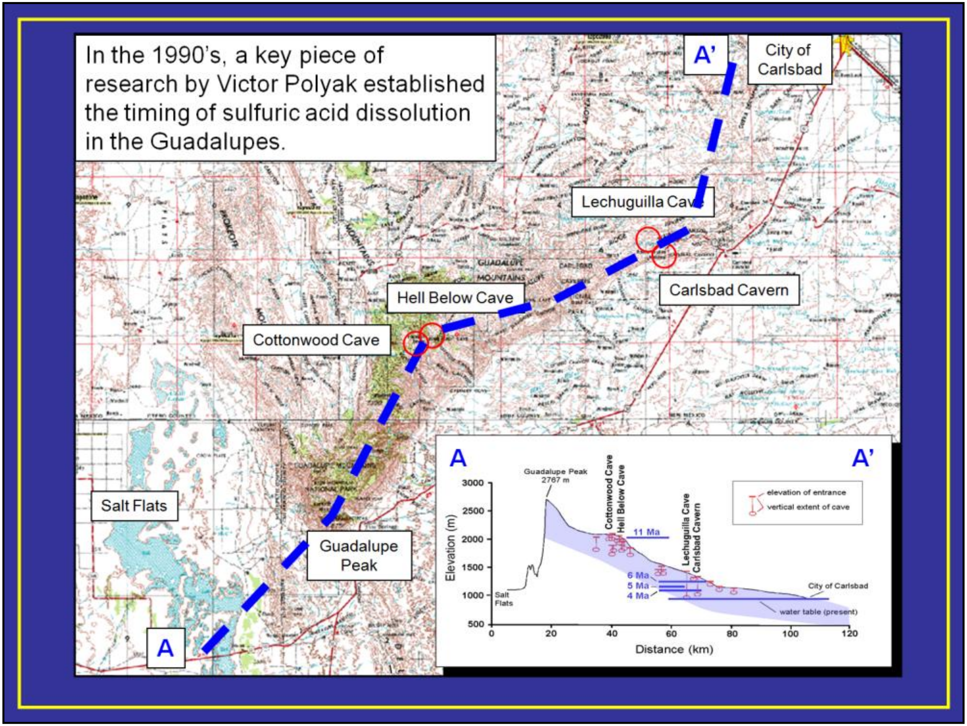
Flowing (artesian) springs require hydrodynamic conditions that will support water flow – conditions that do not exist in the Guadalupe Mountains today. The water table currently is at the elevation of the Pecos River in Carlsbad.

The work of the Palmers also show that hydrologic conditions, and by extension, geologic conditions, had to be different in the past.



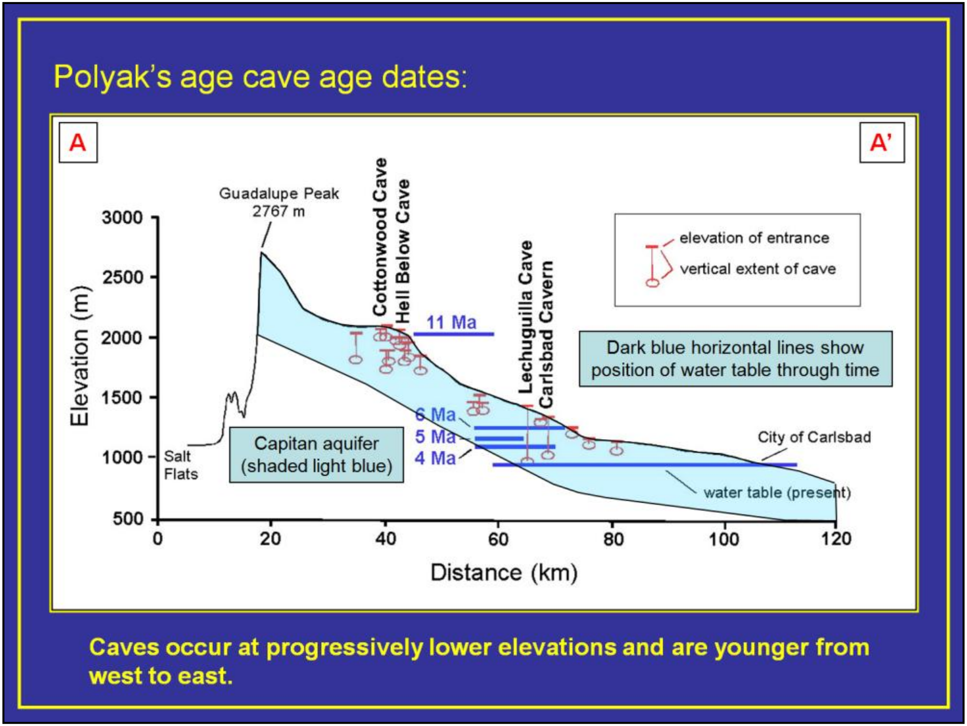
In 1987, a model where H_2S generated in the Delaware basin migrated up dip into the Permian limestone where it mixed with O_2-rich meteoric water forming sulfuric acid was proposed (Hill, 1987).

Presenter's notes: Based on her extensive studies of Carlsbad Cavern and other Guadalupe Mountain Caves, Carol Hill developed a model for sulfuric acid speleogenesis in the Guadalupe Mountains. In this model, hydrogen sulfide was generated at the contact between the Bell Canyon Formation and the overlying Castile evaporites. The hydrogen sulfide was formed when anaerobic bacteria metabolized hydrocarbons and sulfate. This reaction converted calcium sulfate to calcium carbonate and released hydrogen sulfide as a byproduct. In her model, hydrogen sulfide migrated up-dip into carbonates of the Capitan Shelf Margin. Here, the hydrogen sulfide mixed with oxygenated meteoric water to form the sulfuric acid that dissolved the immense chambers and galleries that typify Guadalupe Mountain caves.



Presenter's notes: In the mid-1990s, Victor Polyak studied endellite clay in caves of the Guadalupe Mountains. In this clay, he found microscopic crystals of alunite and natroalunite, two potassium sulfate minerals. The presences of these minerals proved to be one of the most important discoveries made in Guadalupe Mountain caves. Polyak was able to use Potassium/Argon rations to age-date the minerals, thus establishing the timing of sulfuric acid speleogenesis in the Guadalupes.

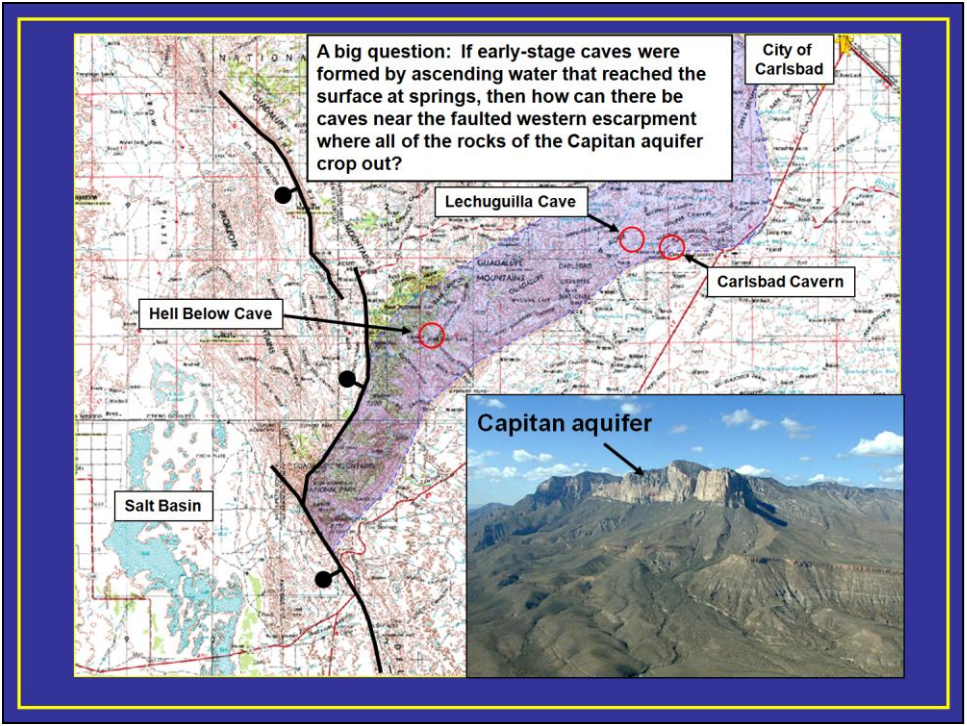
This topographic map shows the location of several key sites in and near the Guadalupes, including the city of Carlsbad, where the present-day water table in the Capitan aquifer intersects the surface also shown are several key cave locations. Also shown are Guadalupe Peak, the highest topographic point in the Guadalupe Mountains and the Salt Flats graben west of the Guadalupe Mountain block. The cross section is a vertically exaggerated profile that will be discussed in the next slide.



Presenter's notes: This profile extends along the line shown on the previous slide and illustrates what Polyak discovered. He found that the oldest alunite and natroalunite crystal occur in the western Guadalupes at the highest elevations, and that the age of these minerals is progressively younger to the east.

Work by Hill, Kim Cunningham, Chuck Spirakis and others has shown that the generation of sulfuric acid occurred in a mixing zone at or near the water table. This implies that the relative position of the water table within the Guadalupe Mountain block was at least 1000 meters higher 12 million years ago than it is today.

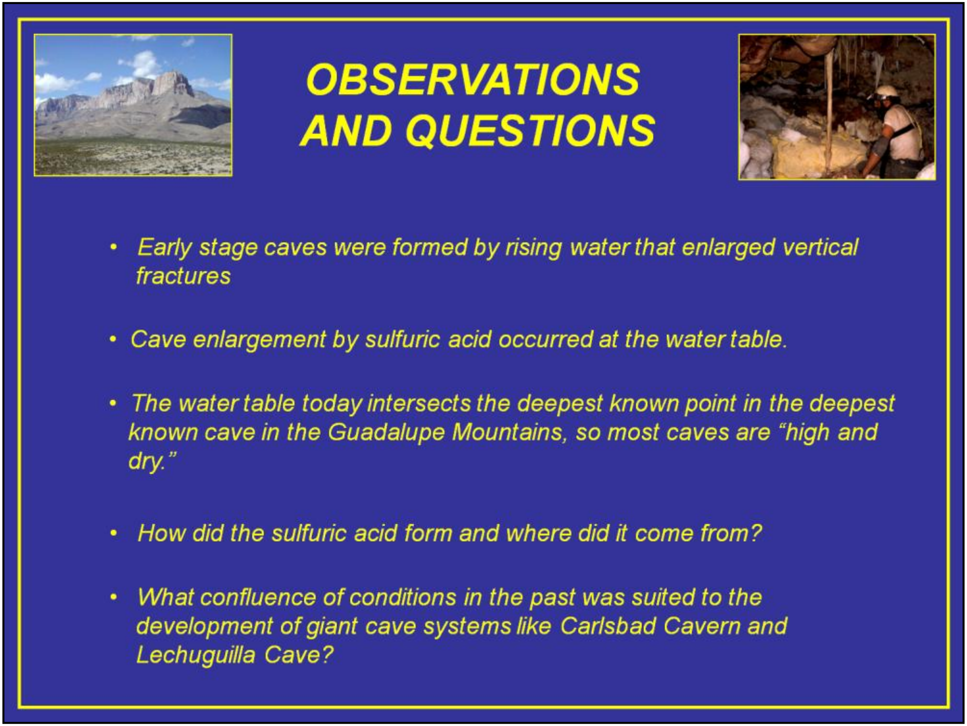
However, as this cross-section through the Guadalupe Mountains shows, the present configuration of the Guadalupe block, particularly on its west side, could not possibly support a water table that is higher that the one that exists today. The structural geometry of the region had to be much different in the past in order for the water table to have been high enough to form caves in the western Guadalupes.



Presenter's notes: The work of Art and Peg Palmer shows that Guadalupe Mountain caves began to form when water under pressure flowed upward along fractures in the rocks of the Capitan aquifer. This water dissolved limestone and dolomite adjacent to the fractures, enlarging them and forming predominately vertical cave systems that probably did not involve sulfuric acid.

Hell Below cave, shown in the center of the map, has an entrance at 2043 meters above sea level. It is located about 11 km (6.3 mi) from the steep western escarpment of the Guadalupes, near the contact between the Yates and Seven Rivers formations. In the Salt Basin, the Yates-Seven Rivers contact is at least 1400 meters lower due to down-to-the-west faults.

The present geometry of the Guadalupe Mountain block could not have supported a water table at the elevation of Hell Below cave, showing that the structural configuration of the area had to be significantly different at the time the cave was formed.



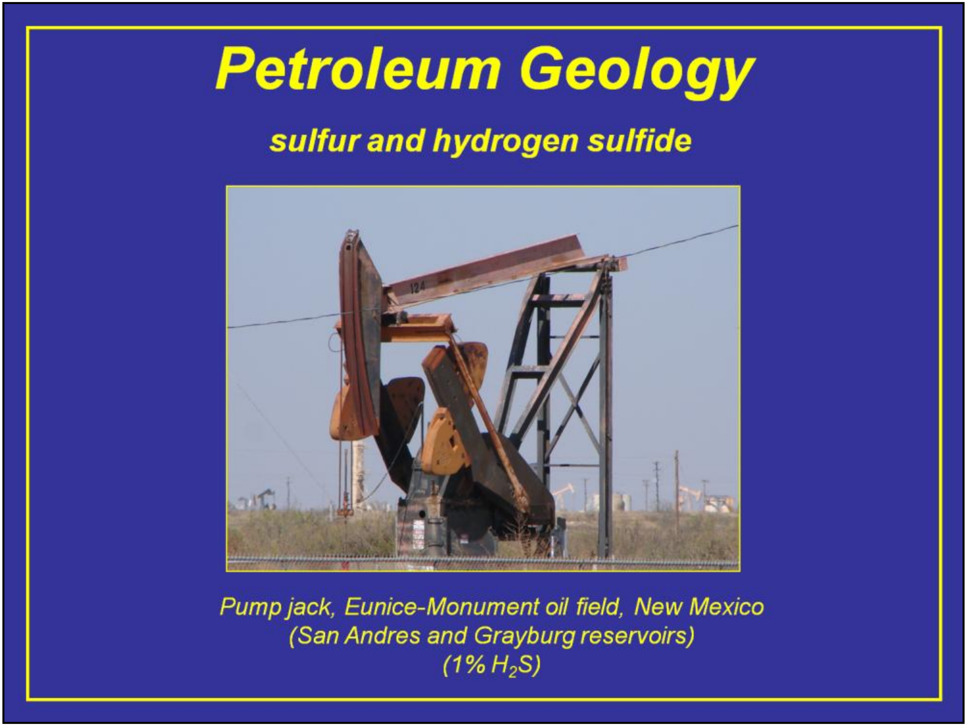
Presenter's notes: Here are some observations and questions about the origin of Guadalupe Mountains caves.

Observations:

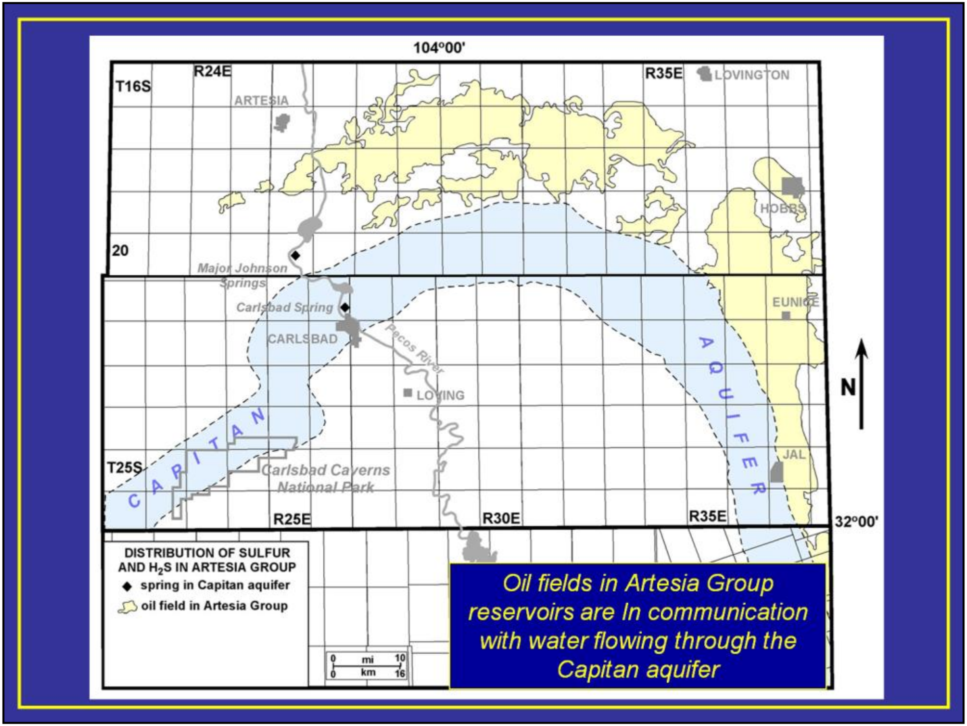
1. Early-stage cavers were formed by rising water that enlarge pre-existing vertical fractures.
2. Cave enlargement by sulfuric acid occurred at the water table.
3. The water table today intersects the deepest known point in the deepest known cave in the Guadalupe Mountains, so most of the caves are "high and dry."

Questions:

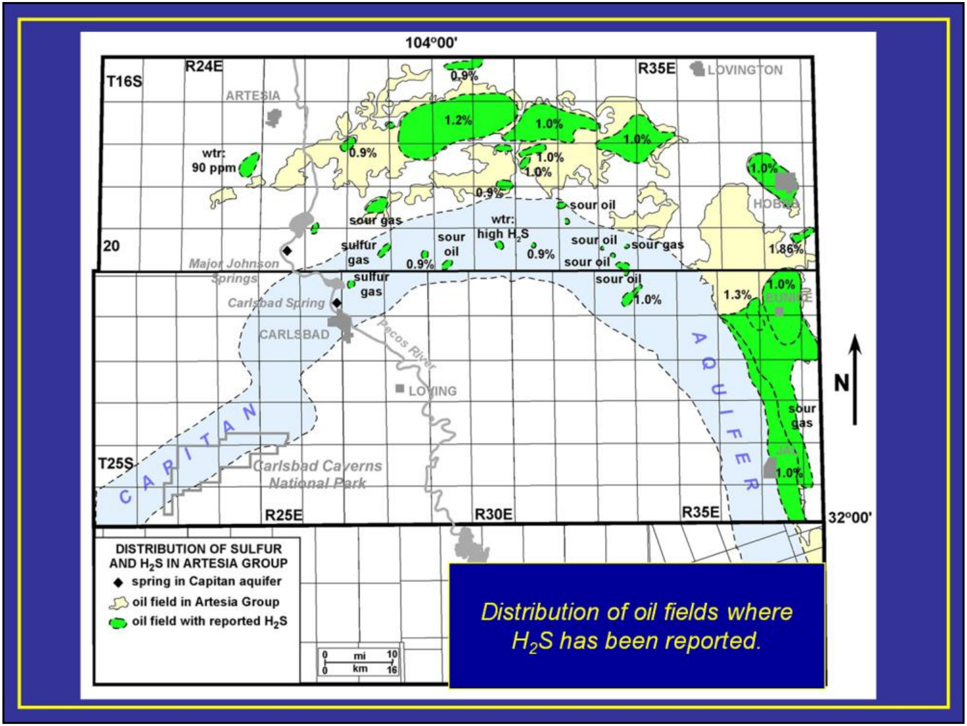
1. How did the sulfuric acid form and where did it come from?
2. What confluence of conditions in the past was suited to the development of giant cave systems like Carlsbad Cavern (27 mi) and Lechuguilla Cave (135 mi)?



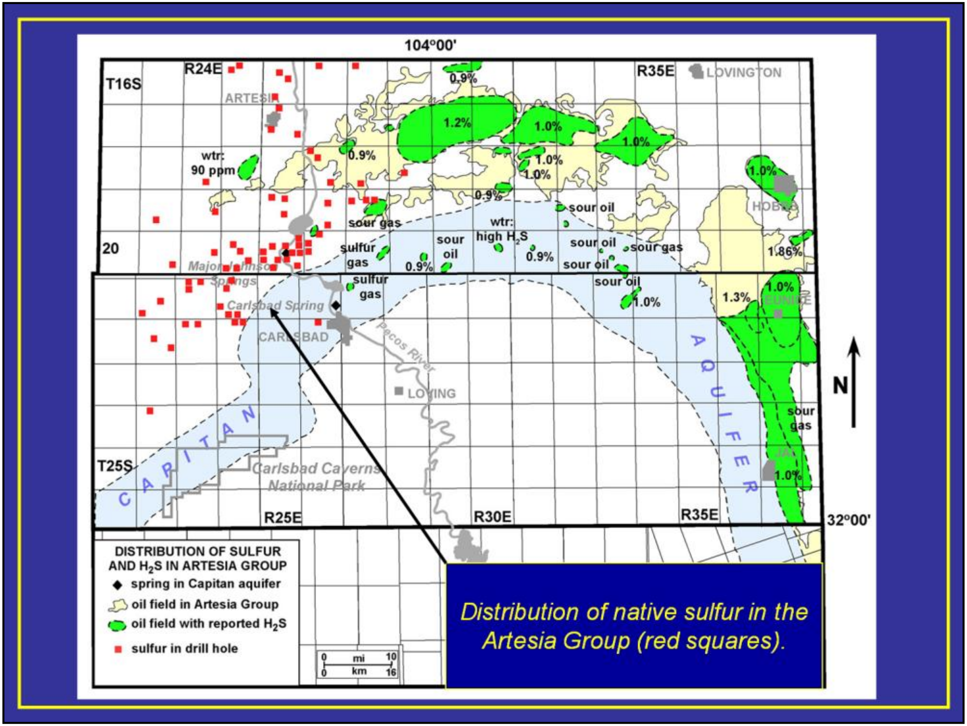
Presenter's notes: The development of caves in the Guadalupe Mountains is intimately connected to the petroleum geology of the Delaware basin. The generation, expulsion, trapping and ultimately, the microbial degradation of hydrocarbons provided hydrogen sulfide. In the presence of oxygen, the some of the hydrogen sulfide was converted to sulfuric acid that dissolved limestone. Tectonic uplift changed the geometry of the Delaware basin in Tertiary time, resulting in erosion of upland areas that exposed aquifers and allowed influx of fresh water deep into the basin. These waters were strongly hydrodynamic and were agents for the displacement and degradation of hydrocarbons.



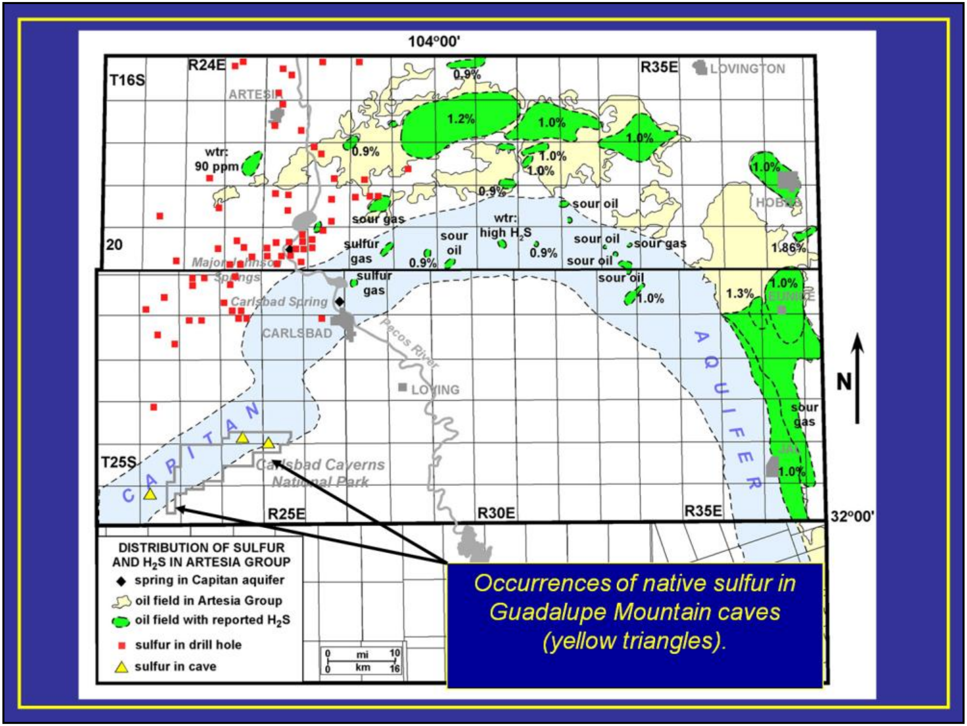
Presenter's notes: Oil fields in reservoirs of the Guadalupian Artesia Group and adjacent units (shown in yellow) are in communication with water in the Capitan aquifer (shown in blue). Up-dip is to the west. Note that there are few oil fields in Artesia Group strata west of the Pecos River.



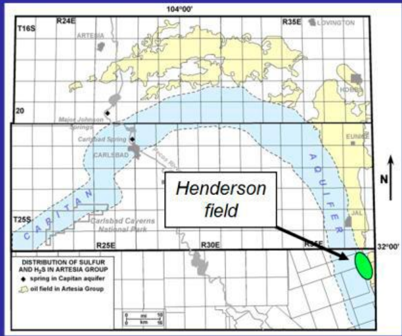
Presenter's notes: In addition to oil and gas, these reservoirs contain sulfur and hydrogen sulfide. Oil and gas in the fields shown in green contain as much as 1.3% hydrogen sulfide, based on reports published by the Roswell Geological Society. East of the Pecos River, water in the Capitan aquifer also contains dissolved hydrogen sulfide.



Presenter's notes: Free sulfur is common in cores and samples (red squares) taken from Artesia Group strata up-dip from the oil fields.



Presenter’s notes: Free sulfur, commonly associated with speleogenetic gypsum, has been found in several caves in the Guadalupe Mountains.



Henderson Field (Yates-Seven Rivers) fluid inclusion data

(Wiggins et al., 1993)

Observations:

Diagenetic calcite and H_2S have been generated in the reservoir by microbial metabolic alteration of petroleum and sulfate.

Fluid inclusions in diagenetic calcite contain biodegraded oil.

Oil in the fluid inclusions is more degraded that oil currently in the reservoir.

Conclusions:

Early stage oil was biodegraded and swept out of the reservoir by strong hydrodynamic flow.

Oil currently in the reservoir migrated into the reservoir after hydrodynamic flow diminished.

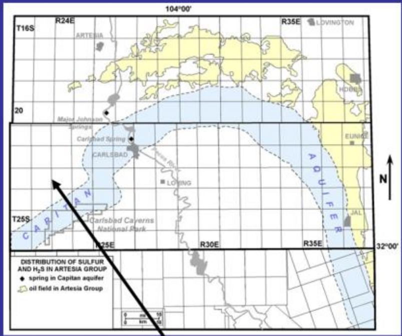
Presenter's notes: Oil has been found in fluid inclusions in diagenetic calcite in oil reservoirs in Artesia Group and adjacent strata at Henderson field near the Texas-New Mexico border. This oil is more degraded than oil currently produced from the reservoir (Wiggins et al., 1993; Robert Lindsay, personal communication).

Observations:

1. Diagenetic calcite and hydrogen sulfed have been generated in the reservoir by microbial metabolic alterate of petroleum and sulfate.
2. Fluid inclusions in diagenetic calcite contain biodegraded oil.
3. Oil in the fluid inclusions is more degraded than the oil currently in the reservoir.

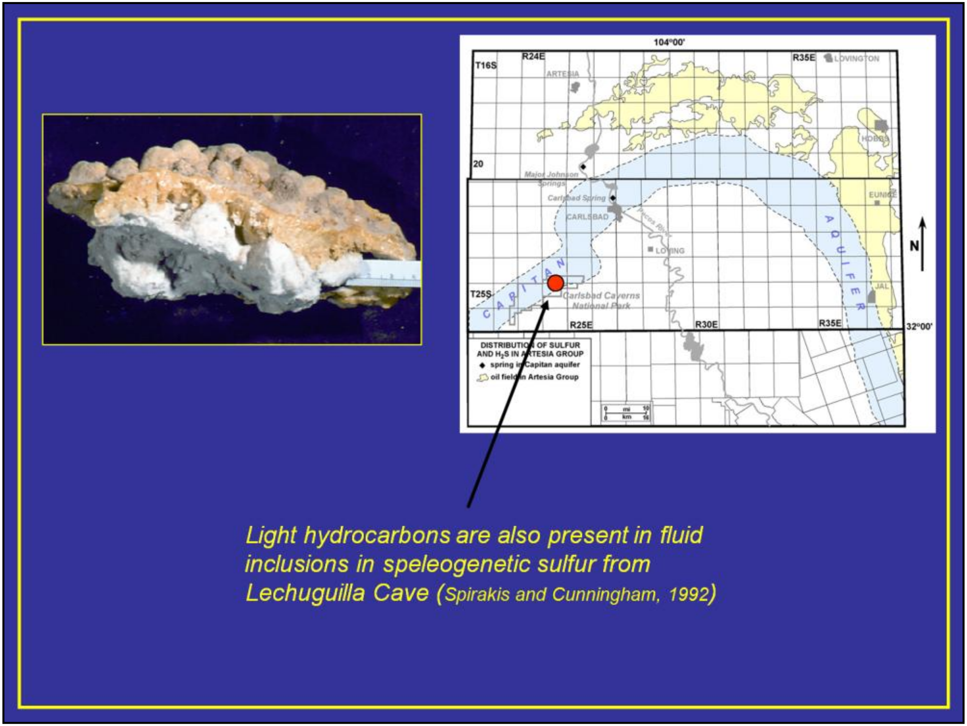
Conclusions:

1. Early-stage oil was biodegraded and swept out of the reservoir by strong hydrodynamic flow.
2. Oil currently in the reservoir migrated into the reservoir after hydrodynamic flow diminished.



Hydrocarbons have been found in fluid inclusions in late-stage diagenetic calcite in the Artesia Group on the north side of the Guadalupe Mountains
(Scholle, Ulmer and Melim, 1992).

Presenter's notes: Hydrocarbons have also been found in fluid inclusions in late-stage diagenetic calcite in Artesia Group strata on the north side of the Guadalupe Mountains (Scholle, et al., 1992).



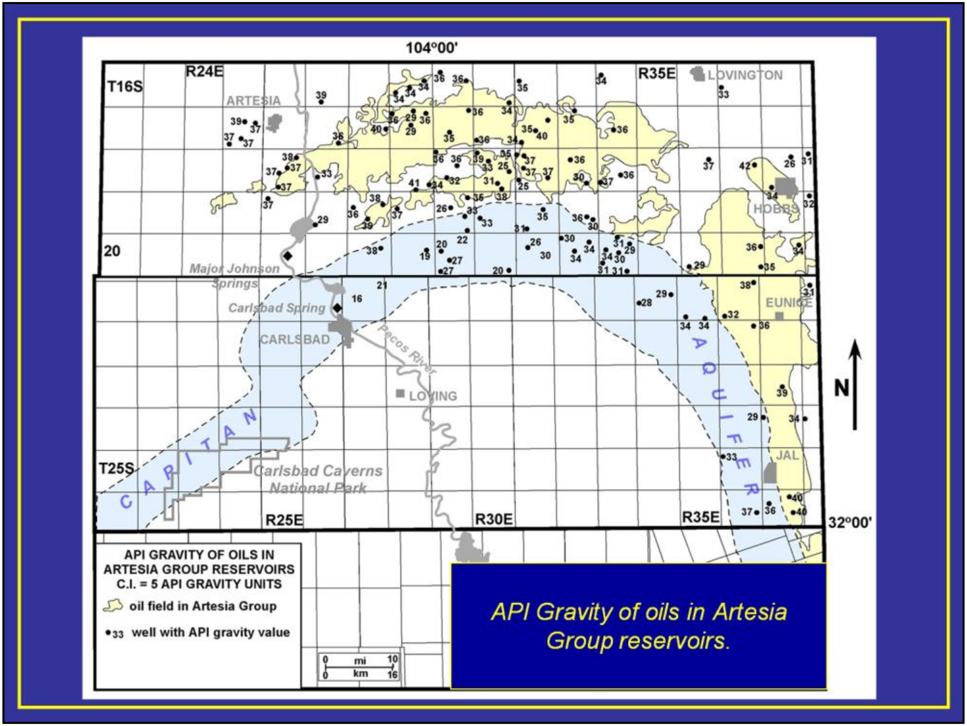
Presenter's notes: Light hydrocarbons are also present in fluid inclusions in speleogenetic sulfur from Lechuguilla Cave (Spirakis and Cunningham, 1992).

Petroleum Geology

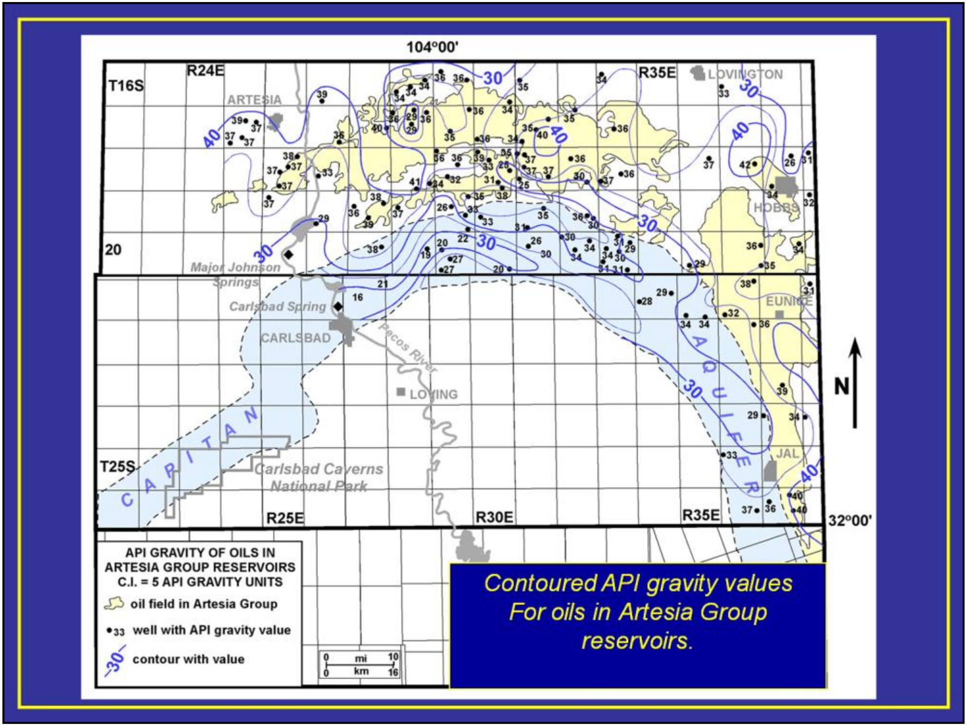
hydrodynamics

Pump jack, Eunice-Monument oil field, New Mexico
(San Andres and Grayburg reservoirs)

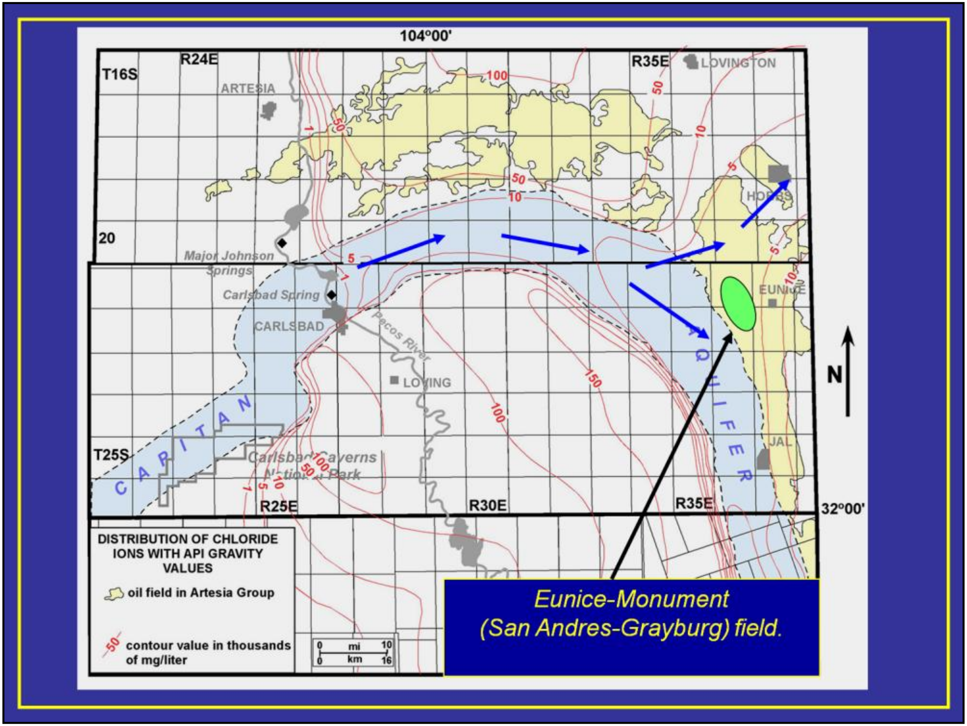
Presenter's notes: The hydrodynamic conditions in the Capitan aquifer have changed over time. Prior to regional eastward tilting, which began during the Laramide orogeny and continued into the Miocene, conditions were probably static.



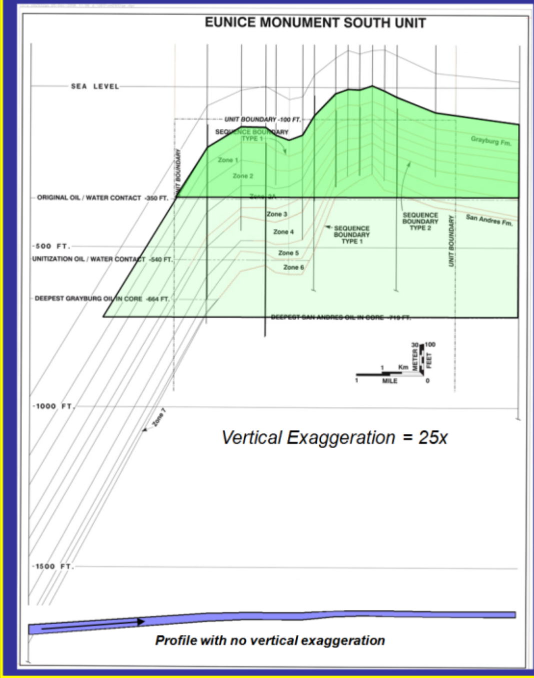
Presenter's notes: This map shows the distribution of the API gravity of oils found in the Capitan aquifer and equivalent strata in southeastern New Mexico. API gravity information was extracted from reports published by the Roswell Geological Society.



Presenter's notes: A contour map of the API gravity data shows a prominent plume of lower gravity oil associated with the Capitan aquifer. The API gravity of oil in Artesia Group and adjacent reservoirs systematically increases with distance north of the aquifer on the Northwest Shelf of the Delaware basin.



Presenter's notes: A map of the distribution of chloride ions (iso-salinity) in the vicinity of the Capitan aquifer shows that the water within the aquifer is significantly fresher than the water in equivalent, adjacent strata. There is an apparent correlation between the fresher water in the water and the amount of degradation of hydrocarbons, based on API gravity. This may be due to water washing, loss of the more volatile fractions of the hydrocarbons, microbial alteration, or a combination of all three processes.



Eunice-Monument field was studied by Bob Lindsey, who was then at Chevron.

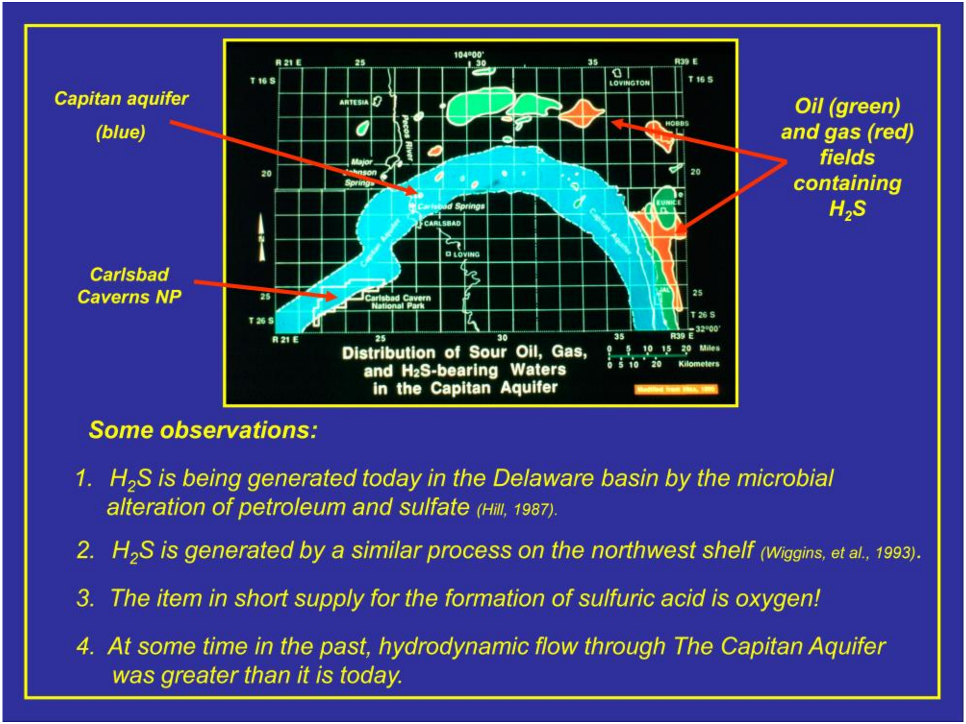
He observed that the oil-water contact at the time the field was discovered was >300 ft above the *original* OWC.

He concluded that the oil originally in the trap had been pushed out by strong hydrodynamic flow.

He also concluded that oil currently being produced remigrated into the trap after hydrodynamic flow decreased.

Cross section by R.F. Lindsay. Used with permission.

Presenter's notes: Robert Lindsay, formerly of Chevron, graciously provide this cross section across Eunice Monument South Unit. He observed that the oil-water contact in the field at the time it was discovered was 300 ft above the original oil-water contact, based on core and borehole geophysical log data, including fluid inclusions similar to those in Henderson field, a few miles to the south . He concluded that oil that was originally in the trap had been pushed out by strong hydrodynamic flow. He also observed that oil in the fluid inclusions was more degraded than oil currently in the reservoir. His conclusion was that oil currently being produced from the reservoir had migrated into the reservoir *after* the original accumulation had been swept out.



Presenter's notes: Some observations:

1. Hydrogen sulfide is being generated today in the Delaware basin by the microbial alteration of petroleum and sulfate (Hill, 1987)
2. Hydrogen sulfide is also generated by a similar process on the Northwest Shelf (Wiggins, et al., 1993).
3. In the vicinity of the Capitan aquifer, the item in short supply for the generation of sulfuric acid is not hydrogen sulfide, which is ubiquitous. The critical ingredient is oxygen!
4. At some time in the geologic past, hydrodynamic flow through the Capitan aquifer was substantially greater than it is today.

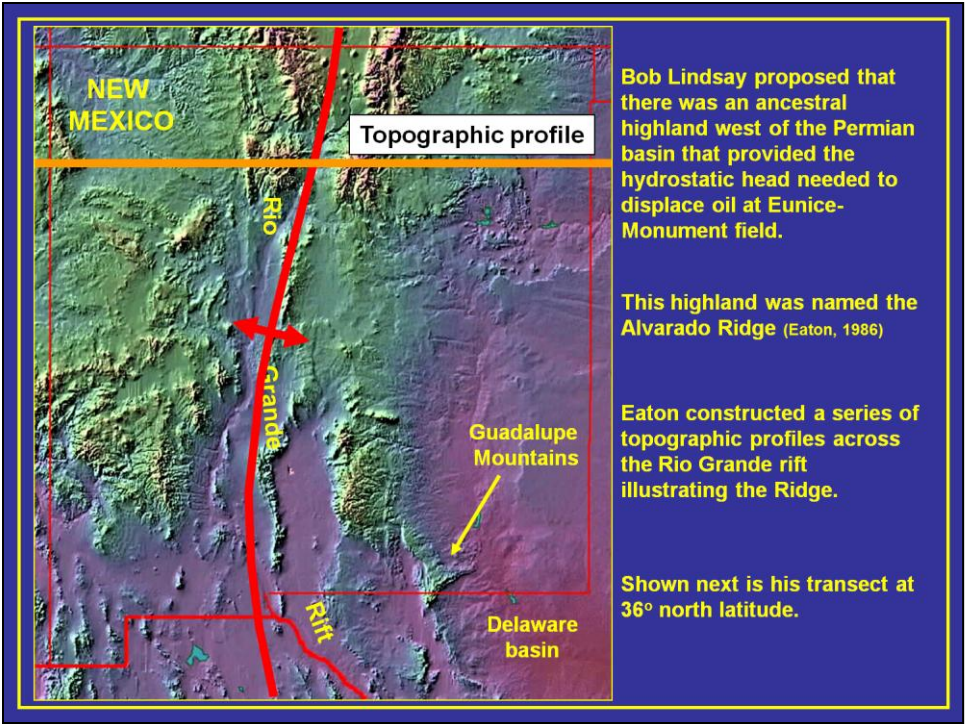
An implication that can be drawn from the presence of sulfur, diagenetic calcite and hydrocarbons in fluid inclusions north of the Guadalupe Mountains and west of Artesia Group oil fields is that there were accumulations of oil and gas west of the Pecos River at some time in the geologic past. These accumulations are now gone because the trapping geometries were altered by eastward tilting of the region during Tertiary time. If these hydrocarbon accumulations did exist, then the amount of hydrogen sulfide in the system would have been even greater in the vicinity of Guadalupe Mountain caves when they were being enlarged by sulfuric acid.

Tertiary Tectonic History

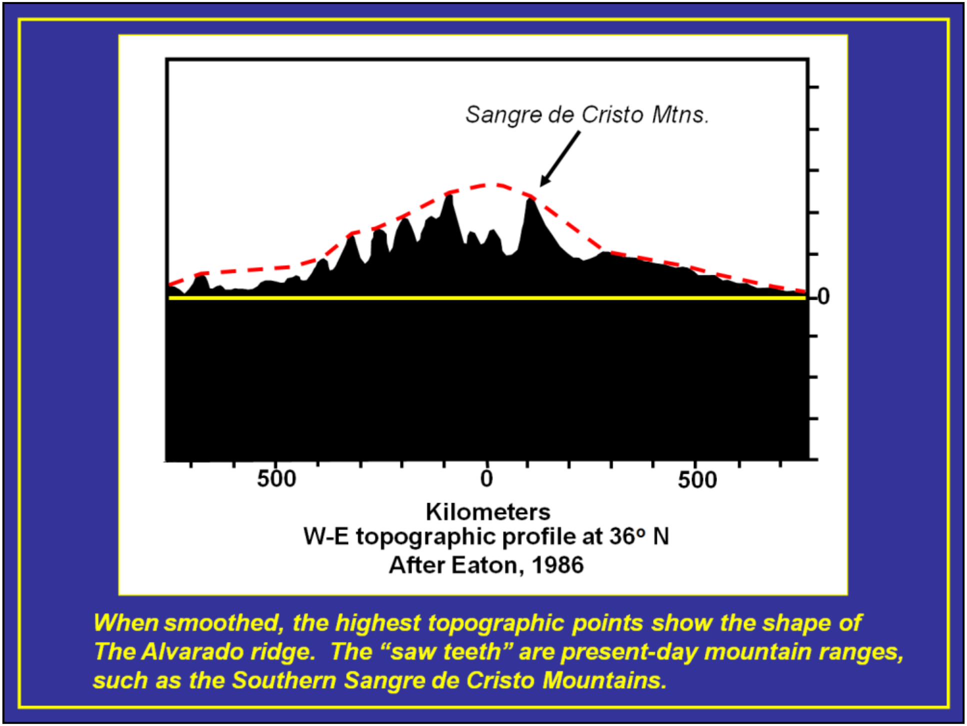
View SW from Guadalupe Peak with Salt Basin graben in middle distance and Sierra Diablo Mountains on the horizon

Photo credit: Phil Gavenda, 14ers.com

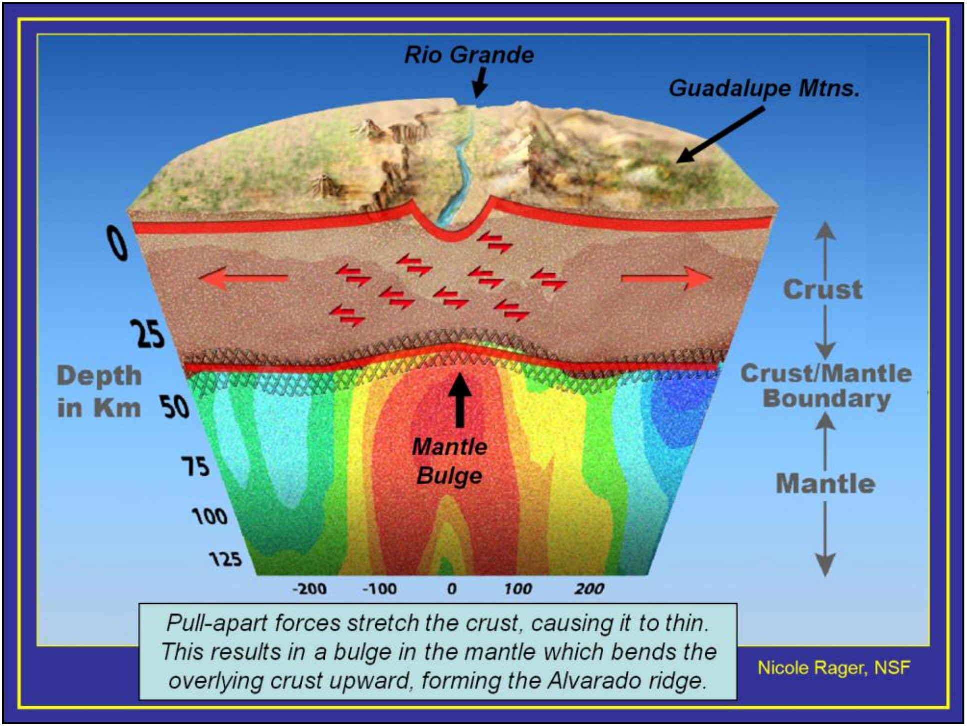
Presenter’s notes: This photo is taken from Guadalupe Peak lookong southwest across the Salt Basin graben to the Sierra Diablo uplift. The structural geometry of eastern New Mexico and west Texas was profoundly changed by regional uplift and subsequent rifting in Laramide and Tertiary time. Uplift tilted the region to the east, resulting in major erosion and eventual exposure of reservoir strata and aquifers at the surface. Faulting fragmented the east-dipping homocline, reducing recharge areas and diminishing hydrostatic head. The geologic history of the western Delaware basin is one of constant, but also episodic, change throughout Tertiary time. Photo by Phil Gavenda.



Presenter's notes: This shaded relief map of New Mexico shows the location of the Guadalupe Mountains with relation to the Rio Grande Rift. The Guadalupes are an east-tilted fault block that are part of a much larger east tilted slope that extends from Colorado to Mexico.

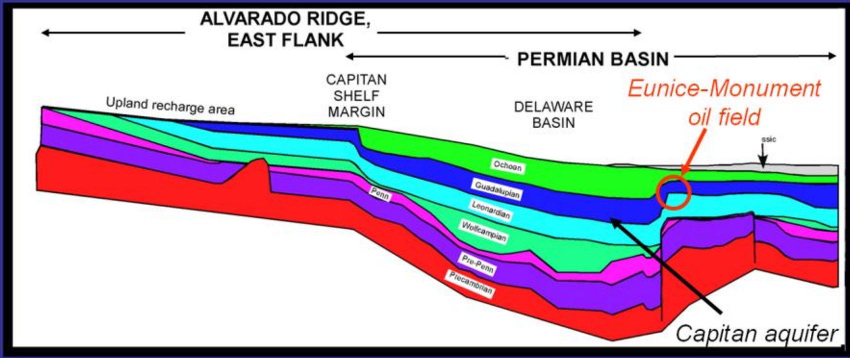


Presenter's notes: In the 1980's Gordon Eaton observed that modern day west to east topographic profiles across Colorado and New Mexico show a broad, continental scale arch, which he called the Alvarado Ridge. This ridge has been fragmented by faulting associated with the opening of the Rio Grande rift since about 35 million years ago.



Presenter's notes: Eaton attributed the arch to crustal thinning over a bulge in the earth's mantle, As the bulge developed, and crustal extension continued, the crust failed along the faults that bound the mountain blocks of the Rio Grande valley.

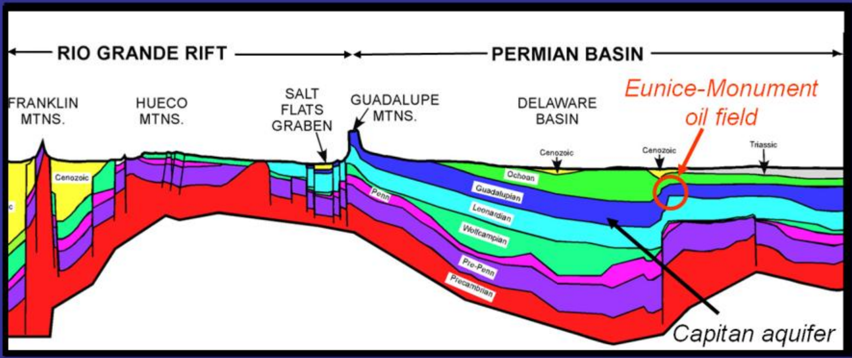
West to east cross section across Delaware basin



He also suggested that the western limit of the aquifer migrated eastward as the Rio Grande rift opened, reducing the height of the water column and reducing the hydrodynamic head.

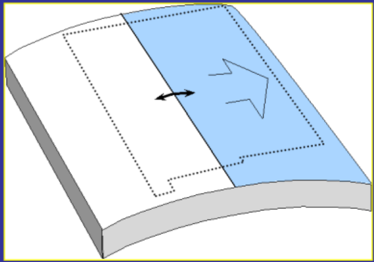
Presenter's notes: Bob Lindsay proposed that displacement of the oil in Eunice Monument field resulted from hydrodynamic flow conditions resulting from uplift of a broad arch that developed prior to the opening of the Rio Grande rift.

West to east cross section across Delaware basin



He also suggested that the western limit of the aquifer migrated eastward as the Rio Grande rift opened, reducing the height of the water column and reducing the hydrodynamic head.

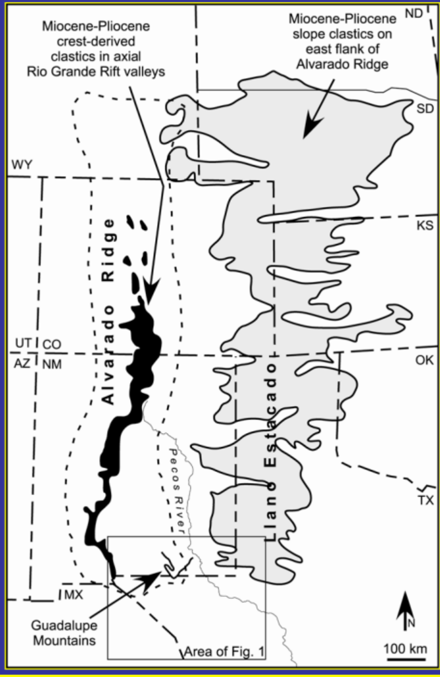
Presenter’s notes: Lindsay also suggested that the western limit of the aquifer migrated eastward as the Rio Grande rift opened, reducing the height of the water column and reducing the hydrodynamic head.



Schematic block diagram of pre-rift Alvarado ridge in New Mexico.

As the arch developed, material was eroded from the uplands and transported down the flanks. These deposits are recognized today as the Ogallala Formation of the high plains.

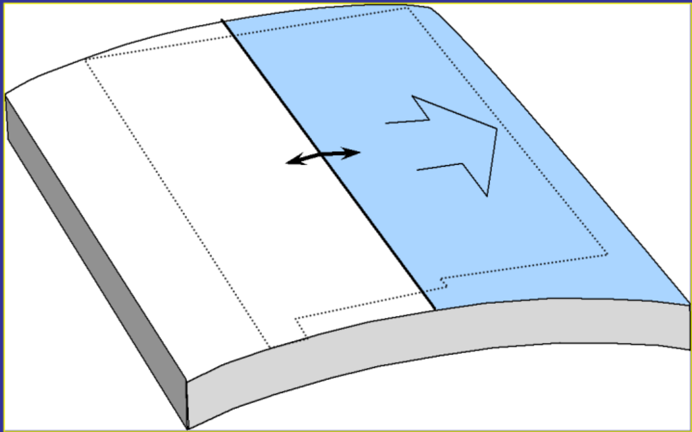
Although most precipitation flowed away from the ridge as surface runoff, part of it percolated into the subsurface and recharged aquifers, including the Capitan aquifer in SE New Mexico.



Presenter's notes: Based on the observation presented above, a model for conditions in the Capitan aquifer is presented in the following series of illustrations.

On the east flank of the Alvarado ridge are gravel deposits of the Miocene Ogallala Formation. These are fluvial deposits, transported down-slope by water. While much of the precipitation that fell on the Alvarado ridge drained away on the surface, as it does today, some of it percolated into the subsurface and charged the Capitan aquifer. This water provided the hydrodynamic push that moved oil out of Eunice-Monument and other oil fields, as described by Bob Lindsay. Some of the water in the Capitan aquifer reached the surface at springs in the Guadalupe Mountains. These springs occurred where a sufficient amount of the overlying confining beds were removed by erosion, allowing water to break through to the surface above fractures in the Capitan aquifer carbonates. Solution of bedrock bounding the fractures resulted in development of mostly vertical caves that were later significantly enlarged by sulfuric acid.

Schematic block diagram of pre-rift Alvarado ridge in New Mexico.



~35 ma: Alvarado ridge is at its maximum pre-rifting development.

Surface erosion and subsurface flow are at their greatest.

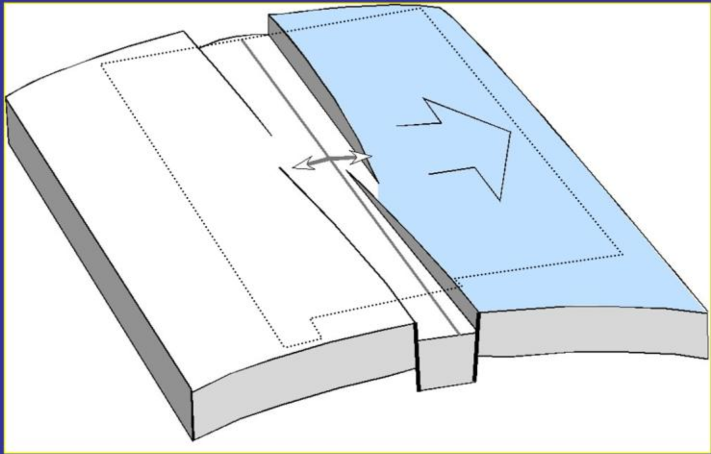
East-directed hydrostatic head is maximum.

Oil accumulations in Guadalupian reservoirs in eastern New Mexico and west Texas are displaced by strong hydrodynamic flow (Lindsey, 1998)

Artesian karst springs begin to develop in the Capitan Aquifer

Presenter’s notes: Prior to 35 million years ago, the arch was unbroken by faulting and aquifer recharge was at its maximum.

Schematic block diagram of early-rift Alvarado ridge in New Mexico.

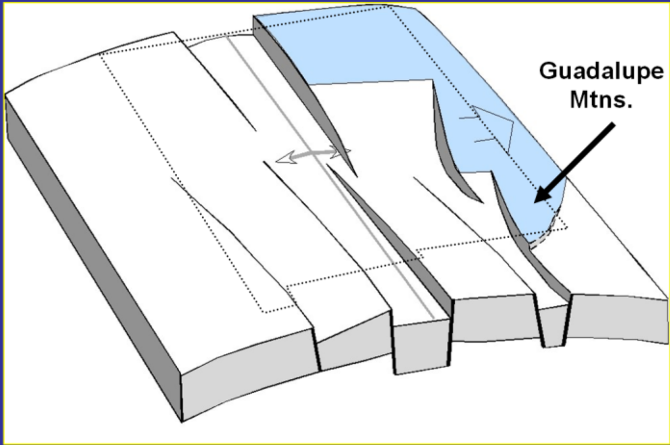


+/- 29 million years ago:

- Onset of extensional faulting (rifting)
- Size of regional aquifer recharge area on east flank of ridge begins to shrink.
- Hydrostatic head progressively diminishes as rifting progresses.

Presenter's notes: Then, about 35 million years ago, the crust began to fail by faulting, and the size of the recharge area began to shrink.

Schematic block diagram of late-rift Alvarado ridge in New Mexico.



4 Million years ago:

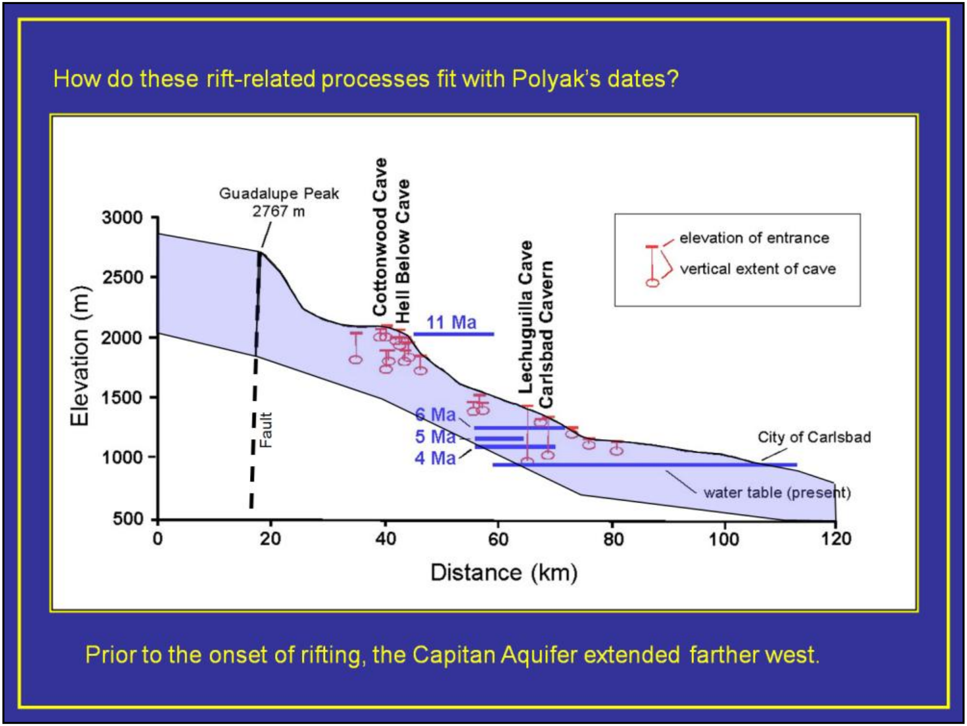
- Rifting has spread to the western side of the Guadalupe Mountains.
- Upland recharge areas are drastically reduced in size.
- Hydrostatic head within the Capitan Aquifer is greatly diminished.

Presenter's notes: This process continued for the next 30 million years, gradually expanding outward from the center of the rift and progressively fragmenting the slopes of the Alvarado Ridge. As the ridge became more fragmented, the size of the recharge area became progressively smaller, and hydrostatic head decreased.

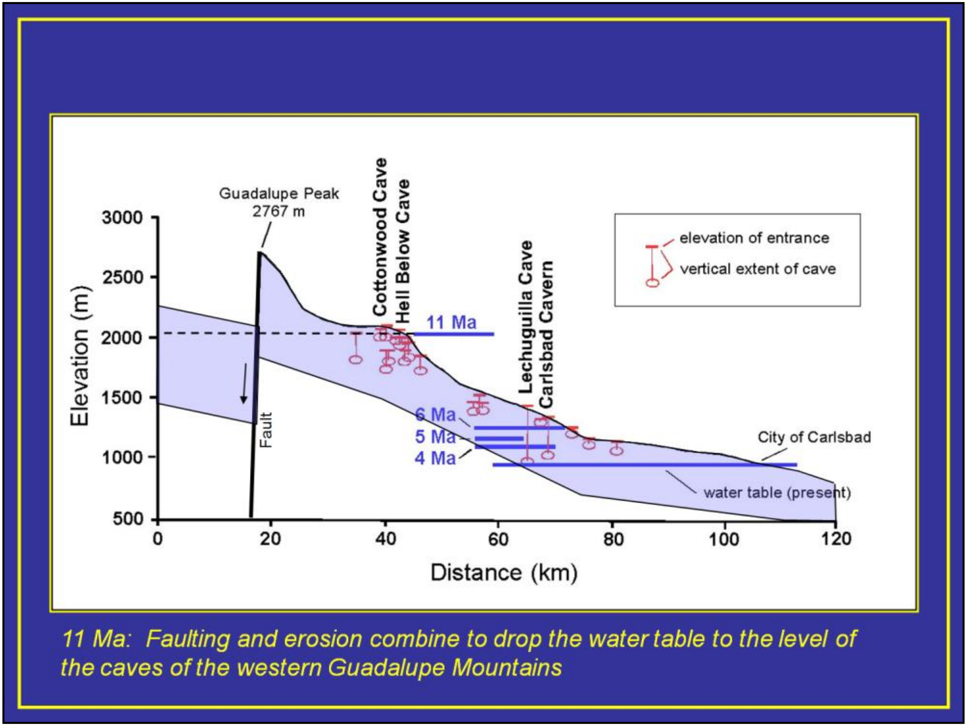
Between 14 – 4 million years ago: Extensional faulting spread eastward to the Border fault zone. As the Salt basin subsided, the water table also dropped in the east-tilted Guadalupe Mountain block. Sulfuric acid cave enlargement occurred at the water table, greatly enlarging previously formed fissure caves. As the water table drops, the locus of sulfuric acid dissolution within rocks of the Capitan aquifer shifted eastward. The youngest dated speleogenetic event is at Carlsbad Cavern (3.8 ma) (Polyak et al, 1998). Once the water table fell to near its current level, sulfuric acid enlargement of cave passages in the Guadalupes ceased.

IMPLICATIONS FOR SULFURIC ACID SPELEOGENESIS

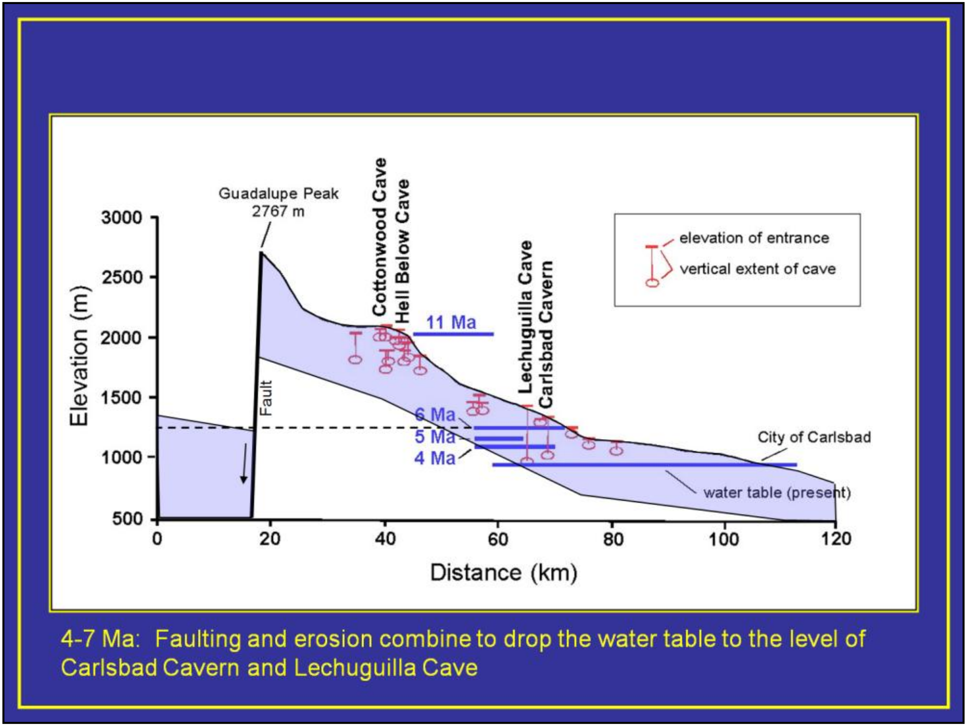
Rillenkarren and spitzkarren, Lechuguilla Cave (sulfuric and carbonic acid dissolution features)



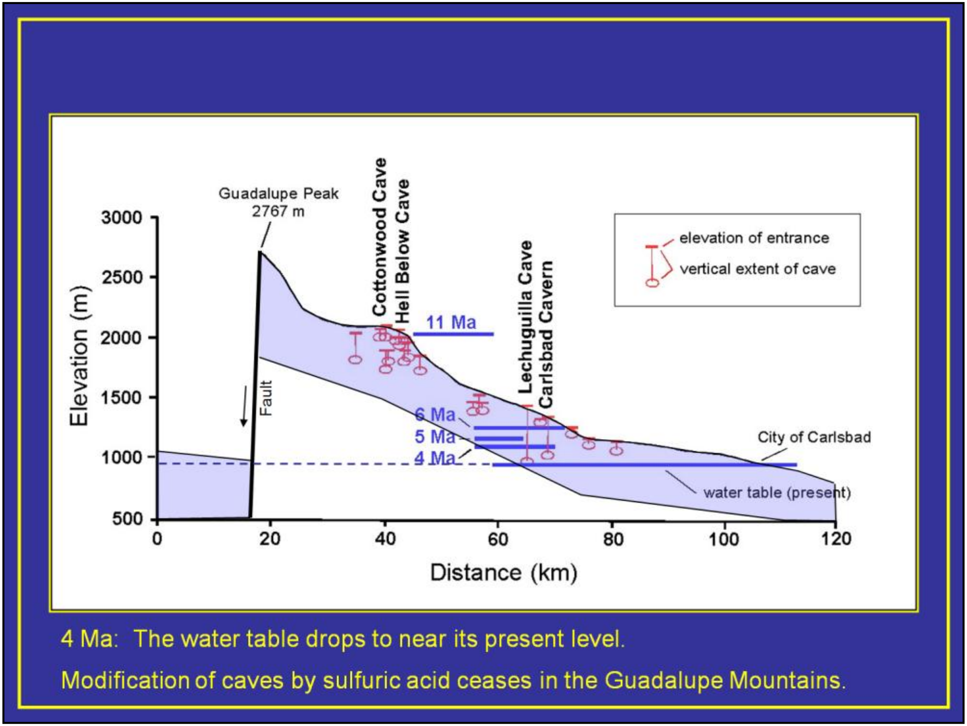
Presenter's notes: In this cross section, the Capitan aquifer is shown in light blue. The position of the water table, as determined by Victor Polyak's age dating of alunite and natroalunite from cave deposits, is shown by dark blue horizontal lines. Note that prior to the onset of rifting, the Capitan aquifer extended farther west and was unbroken by faults.



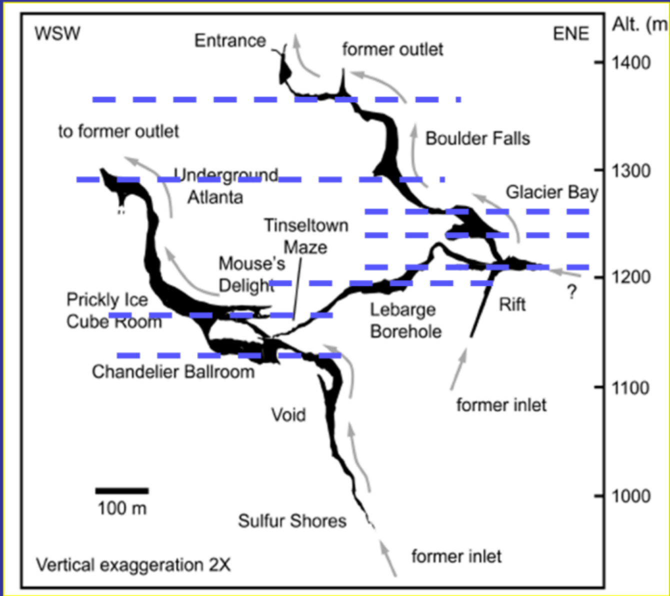
Presenter's notes: Around 11 Ma, progressive faulting related to opening of the Rio Grande rift caused the water table to fall to the level of Cottonwood and Hell Below caves in the western part of the Guadalupe Mountains.



Presenter's notes: By about 6 Ma, faulting and erosion combined to cause the water table to fall to the upper level of Carlsbad Cavern and Lechuguilla Cave in the east-central part of the Guadalupes.



Presenter's notes: At 4 Ma, the water table had reached the approximate level of the City of Carlsbad on the Pecos River, and was below the maximum depth of most Guadalupe caves. The era of extensive enlargement of caves by sulfuric acid in the Guadalupe Mountains ended although it is possible that some dissolution is occurring today, near the Pecos River.



Schematic cross section through part of Lechuguilla Cave illustrating how horizontal levels record a falling water table during a span of 2 My.

Presenter's notes: This diagrammatic cross section through Lechuguilla Cave is taken from a publication by Art and Peg Palmer. It shows two subvertical, solution-enlarged fracture systems that have been modified by sulfuric acid dissolution at the water table. The dashed blue lines show horizontal cave levels where the water table was stable long enough for significant sulfuric acid dissolution to occur. Horizontal levels in Guadalupe caves reflect the position of the water table at times in the geologic past. The keys to understanding these dynamic processes were the dating of cave deposits resulting from sulfuric acid dissolution by Victor Polyak, and unraveling the history of oil fields adjacent to the Capitan aquifer by Bob Lindsay and the geoscientists at ChevronTexaco.

Summary

1. Most Guadalupe caves were formed in at least two stages:

    A. Enlargement of sub-vertical fractures by upward flowing water before the opening of the Rio Grande Rift.

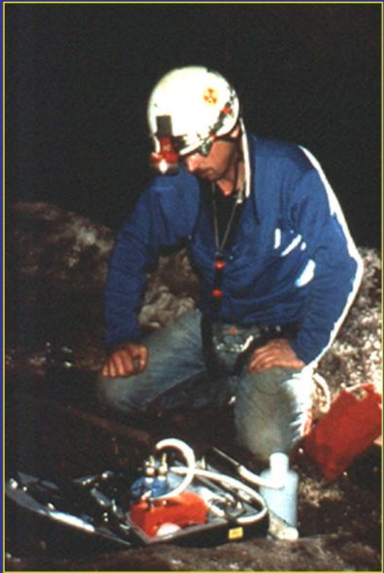
    B. Enlargement of horizontal passages at or near the water table by sulfuric acid concurrent with the opening of the Rio Grande Rift from 11 to 4 million years ago.

2. Hydrodynamic flow that enlarged vertical fractures in the Guadalupe Mountains also displaced oil in Artesia Group oil fields occurred prior the opening of the Rio Grande Rift.

3. Sulfuric acid dissolution occurred where the water table intersected vertical caves. At these sites, the supply of oxygenated fresh water was greatest and the maximum amount of sulfuric acid was generated.

4. The position of the water table was controlled by faulting and erosion associated with the tectonic development of the Alvarado Ridge and the Rio Grande Rift.

5. Guadalupe Mountain caves are intimately related to the petroleum geology of the Delaware basin and the development of the Rio Grande rift.



I thank the late Kim Cunningham for his friendship and for many stimulating discussions, and more than a few arguments, about the geology of the Guadalupe Mountains. It was Kim who first recognized the connection between speleogenesis in the Guadalupes and the development of the Rio Grande Rift.

Harvey DuChene

Kimberley I. ("Kim") Cunningham
1954-2000

Presenter's notes: I would be remiss if I did not pay special tribute to my friend, Kim Cunningham. Kim passed away several years ago, but the contributions he made to understanding the geologic history of caves in the Guadalupes were huge. His work in the Guadalupes included geology, geochemistry, mineralogy, atmospheric studies, and the biology of extremophile life.