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TECTONIC INFLUENCES ON SPELEOGENESIS IN THE GUADALUPE MOUNTAINS, NEW MEXICO AND TEXAS

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Abstract.—Sulfuric acid speleogenesis in the Guadalupe Mountains of New Mexico and Texas 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 (~38-35Ma) Alvarado Ridge provided an immense recharge area that supplied water to aquifers draining eastward to the Permian basin. Prior to, or during the early stages of the opening of the Rio Grande Rift, hydrostatic head in the Capitan aquifer caused water to flow upward along fractures to artesian springs. This resulted in solutional enlargement of fractures and development of early stage caves that may not have involved H_2S. 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 also introduced microbes into Artesia Group (Guadalupian) oil 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.

INTRODUCTION

The Guadalupe Mountains of southeastern New Mexico and west Texas lie on the north margin of the Permian Delaware basin (Fig. 1). Within these mountains, Tertiary uplift and erosion caused exposure of Permian (Guadalupian) strata that contain caves formed by sulfuric acid (DuChene and Martinez, 2000). Understanding of the processes that form sulfuric acid caves in the Guadalupe Mountains has been a collaborative process that began in the 1970's (Egemeier, 1973; 1981; 1987; Jagnow, 1977; 1986; Jagnow et al., 2000; Ash and Wilson, 1985; Davis, 1973; 1980; Queen, 1973; Hill, 1987; 1990; 1996; 2000; DuChene and McLean 1989; Cunningham and Takahashi, 1992; Polyak et al., 1998; Polyak and Provencio, 2000; Palmer, 1991, 2006; Palmer and Palmer, 2000). The current model for the origin (speleogenesis) of these caves is a combination of ideas first proposed by Davis (1980) and Egemeier (1981, 1987), where H_2S derived from petroleum deposits was oxidized to sulfuric acid that dissolved limestone. Hill (1987, 1990) confirmed a petroleum source and modified Davis' conjectures by suggesting that speleogenesis was dependent on migration of H_2S from the basin to the reef. Palmer and Palmer (2000) showed that initial stages of cave development resulted from rising water that reached the surface through springs, emphasizing the need for oxygen to convert H_2S to H_2SO_4. Once primary conduits were formed, episodic lowering of the water table resulted in enlargement of passages and galleries at the water table where oxygenated meteoric water was available to mix with sulfidic water and form sulfuric acid. Polyak et al. (1998) used radiometric dating to show that caves were formed 12 – 4 Ma, with the oldest caves found at the highest elevations. The decrease in age with elevation reflects the progressive lowering of the water table over a span of 8 Ma (Polyak et al., 1998; Palmer and Palmer, 2000).

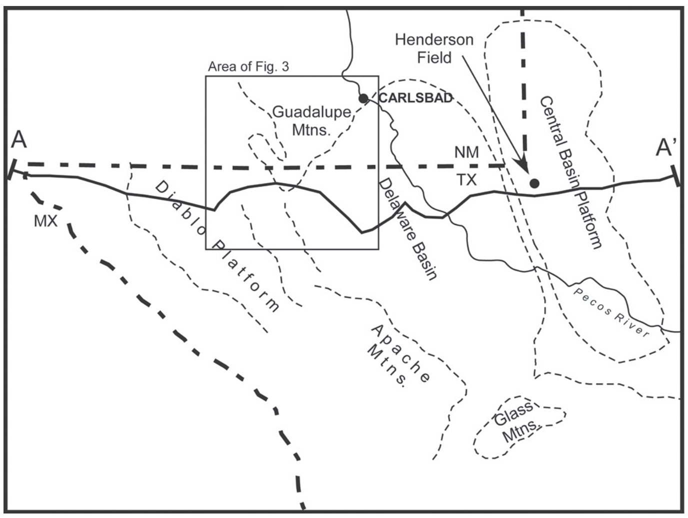

FIGURE 1. Index Map of the Guadalupe Mountains and vicinity. A – A' is the location of the cross section shown in Figure 4.

The development of sulfuric acid caves is a dynamic process influenced by regional structure, tectonism, climate and erosion, all of which contributed to the gradual lowering of the water table in the Guadalupe Mountains. Previous workers studying caves in the Guadalupes attributed the falling water table to Late Tertiary uplift during and after episodes of cave development (Hill, 1987, 1990; Polyak et al., 1998). We attribute this interpretation to a focus on the Guadalupe Mountains as a discrete block, rather than examining them in regional structural and tectonic context. We believe that the history of cave development in the Guadalupes is fundamentally tied to a regional paleohydrologic system, which developed in response to Laramide uplift of the Alvarado Ridge in New Mexico and Colorado. This paleohydrologic system was modified and reduced in area by Late Tertiary extensional faulting related to the opening of the Rio Grande Rift.

TECTONIC SETTING

The Guadalupe Mountains are located on the eastern flank of the Rio Grande Rift, an intermontane and intracratonic extensional feature superimposed on the Cenozoic Alvarado Ridge (Fig. 2) in southern New Mexico and west Texas (Eaton, 1986 and 1987; Chapin and Cather, 1994). The Guadalupes lie between the Salt Basin graben to the west and the Pecos River valley to the east (Fig. 3). The mountains rise southwestwardly from beneath Ochoan evaporites and Pecos valley Quaternary fill to an elevation of 2767 m at Guadalupe Peak in Texas (Fig. 3). The western margin is the Border Fault zone of King (1948). The upland surface of the Guadalupes slopes 1.2 degrees northeast (DuChene and Martinez, 2000) and may be continuous with the extensive upland of the Llano Estacado (Bretz and Horberg, 1949), a late Eocene surface capped by Ogallala gravels (Fig. 2). The Pecos River valley is incised into the Ochoan evaporite sequence between the Llano Estacado and the Guadalupe Mountains where it breached the Capitan Reef Complex (Fig. 2)(Bretz and Horberg, 1949; Motts, 1968; Hiss, 1980; Bachman, 1980).

The Alvarado Ridge (Fig. 2) is a regional topographic feature extending from southern Wyoming to westernmost Texas (Eaton, 1986, 1987), and into Mexico. The feature was caused by distributed subcrustal thinning and related extensional strain, a mechanism similar to the cause of known marine and continental rift zones. The ridge is characterized by youthful mountains enclosing axial rift valleys, and by eastward and westward concave-upward slopes where elevation decreases asymptotically away from mountain crests. Sedimentary cover on the slope is composed of Miocene and Pliocene fluvial sediments interbedded with rhyolitic tuffs, with the youngest undisturbed lithologies belonging mostly to the Ogallala Formation (Fig. 2). These sediments were derived from upland areas of the Alvarado Ridge (Eaton, 1987) and transported downslope to sites of deposition on a regional Eocene planation surface (Gregory and Chase, 1992). The distribution of Miocene-Pliocene sediments is a consequence of the tectonic history of the Alvarado Ridge, a feature that has persisted against supracrustal and subcrustal degradation since at least 38-35Ma (Gregory and Chase, 1992). The age of sediments derived from the crest of the ridge correlates with periods of tectonic maxima in the southern Rocky Mountains with rift initiation at 29-27 Ma, a maximum phase of extension at 17-14 Ma, and rift culmination at 7-4 Ma (Seager and Morgan, 1979; Eaton, 1987; Chapin and Cather, 1994). Little or no uplift is indicated during latest Pliocene to Pleistocene time (Muehlberger et al., 1978; Reilinger et al., 1979; Goetz, 1980; Gable and Hatton, 1983).

Eaton's (1986, 1987) model was reinterpreted by analysis of late Eocene Florissant flora in Colorado by Gregory and Chase (1992) and a similar study of paleoflora from the southern Rio Grande Rift in New Mexico by Meyer (1986). These studies indicate that the present elevations of the southern Rocky Mountains have been approximately maintained over the past 38-35Ma, that Pliocene uplift is not required to explain the present elevations, and that Pliocene fluvial incision of the Front Range must have been climatically, rather than tectonically, controlled (Gregory and Chase, 1992). If correct, these data show that late Pliocene uplift is not required to explain the present elevations of the late Eocene regional planation surface on the east rise of the Alvarado Ridge (Molnar and England, 1990), including the Guadalupe Mountains.

The Alvarado Ridge zone of maximum structural thinning is estimated to be 150-200 km wide and encompasses the Guadalupe Mountains, whose western rim is only 120 km from the axial center of the Rio Grande Rift valley. The upland, peneplained surface of the Guadalupes was tentatively correlated by Bretz and Horberg (1949) with the east-dipping surface of the Llano Estacado. The absence of any post-Leonardian flexure or hinge at or east of the Pecos River strengthens the idea that the Guadalupe Mountains and Llano Estacado share a common tectonic history.

HYDROGEN SULFIDE

Hydrogen sulfide is common in subsurface formations in southeastern New Mexico (Bjorklund and Motts, 1959; Hinds and Cunningham, 1970). In the central Delaware basin, H_2S is a byproduct of microbially assisted degradation of hydrocarbons associated with alteration of anhydrite to calcite above the contact between

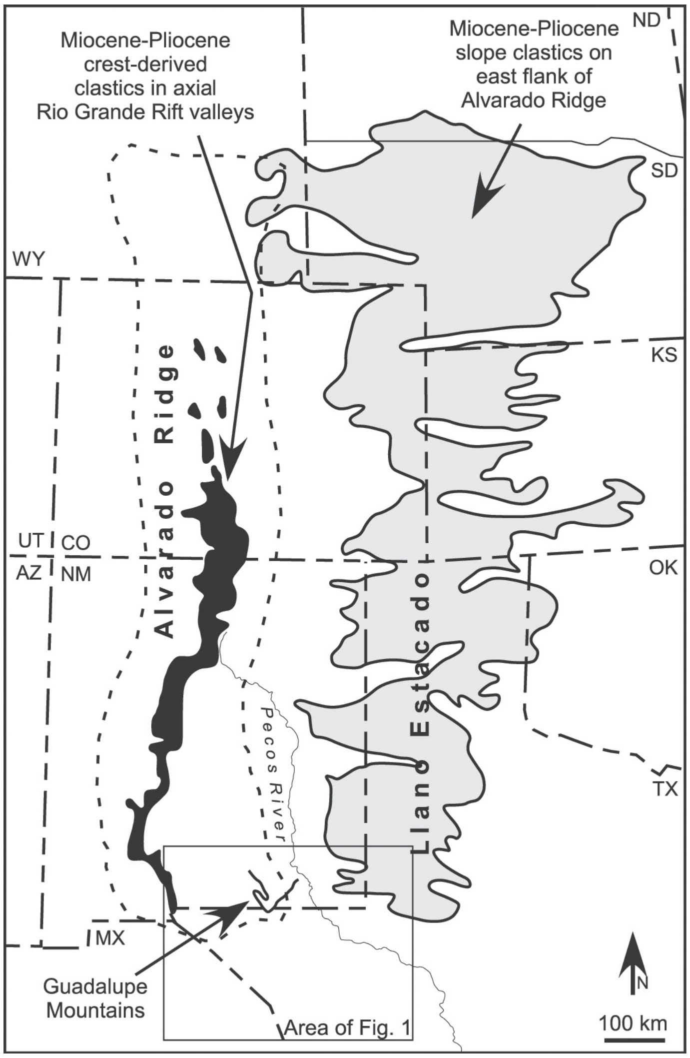

FIGURE 2. Distribution of Ogallala-age sedimentary cover on the east-sloping regional Eocene erosion surface on the east flank of the Alvarado Ridge. Modified from Eaton, (1987, fig. 4).

the Bell Canyon and overlying Castile formation. The process has created at least 70 isolated masses of replacement limestone that range up to several hectares in the Gypsum Plain of the western Delaware basin (Kirkland and Evans, 1976). Hill (1987) developed a model for speleogenesis in the Guadalupe Mountains wherein H_2S generated near the Bell Canyon-Castile evaporite contact migrated into the Capitan Formation to sites of sulfuric acid dissolution. In this model, H_2S was confined beneath Castile evaporites and migrated into the Capitan aquifer until progressive, down-dip dissolution breached the halite seal and allowed H_2S to degas to the atmosphere. Sites of speleogenesis within the Guadalupe Mountains migrated down-dip along with the retreating halite. Several workers (Motts, 1968; Bachman, 1980; Hiss, 1980; Sares, 1984; Sares and Wells, 1986) point out that basin and reef aquifers are poorly connected, and that it is therefore difficult to move significant amounts of water directly from the basin to the Capitan. However, Palmer and Palmer (2000) note that this is not a problem where the basin water table is higher than in the Capitan aquifer water table, as it is today (Hiss, 1980).

Another source of H_2S is associated with petroleum accumulations in the Artesia Group of the northwest shelf of the Delaware basin. Wiggins et al. (1993) describe late-stage calcite cement at Henderson field on the northwest side of the Central Basin Platform in Texas (Fig. 1). This calcite was deposited when meteoric water flowing through a confined aquifer introduced microbes into accumulations of oil. The microbes degraded the oil, converting calcium sulfate to calcite while generating H_2S. Oil and gas accumulations in the Artesia Group east of the Pecos River become progressively more degraded to the west (DuChene and McLean, 1989), and are rare west of the Pecos River. Many of these oil accumulations contain H_2S (DuChene and McLean, 1989; Schram, 1956a, 1956b; Wilson, 1956; Roswell Geological Society Symposium Committee, 1956a, 1956b), which was probably generated by the processes described by Wiggins et al. (1993).

Much of the oil production from the Delaware basin east of the Pecos River is from Permian (Guadalupian) Artesia Group reservoirs located along a linear trend 30 to 33 km in width and 5 to 8.5 km behind the Capitan Reef (Ward et al., 1986). Although little has been written on the fate of Artesia Group hydrocarbon accumulations west of the Pecos River, we believe that prior to epeirogenic tilting associated with the rising Alvarado Ridge, the distribution of petroleum was similar to the area east of the Pecos River. Breaching of reservoirs occurred due to climatically controlled erosion and rift-related tectonism from west to east since at least the mid-Oligocene. H_2S is abundant today in back-reef petroleum accumulations and groundwater due to large quantities of formerly sweet, basinal oil being in contact with evaporite strata at appropriate temperatures for biochemical sulfate reduction.

The amount of oil produced from Artesia Group strata surrounding the Delaware basin (7.4 billion barrels) is greater than the amount from Permian reservoirs in the central part of the basin (351 million barrels) by a factor of twenty (Ward et al., 1986). The amount of produced oil suggests that there was more hydrocarbon available for microbial degradation and H_2S generation in shelf deposits than in the central Delaware basin.

SULFUR

Elemental sulfur occurs in the Gypsum Passage of Cottonwood Cave, in the Big Room of Carlsbad Cavern, and four sites in Lechuguilla Cave. Sulfur occurs as individual crystals and in massive deposits ranging from a few grams to many tons (Davis, 1973; Spirakis and Cunningham, 1992). In these deposits, and in associated cave gypsum deposits, sulfur is isotopically light compared to the Canyon Diablo Troilite (CDT) standard (Hill, 1987). Hill (1987, 1990) and Egemeier (1980, 1987) invoked the subaerial sulfur deposition model proposed by Egemeier (1973) for Kane Cave in the Big Horn basin of Wyoming to account for these deposits. However, limited fluid inclusion data and modeling of the water chemistry in Lechuguilla Cave suggest that some sulfur formed subaqueously at a geochemical interface that was probably controlled by the availability of dissolved oxygen. Water composition was a complex mixture of fresh water, salty water, and various gases including CO_2, CH_4, H_2S and light (C1 – C6) aliphatic hydrocarbons (Spirakis and Cunningham, 1992).

CAVE ELEVATIONS AND WATER TABLE

There are numerous caves in the western part of the Guadalupe Mountains with entrances at high elevations. A typical example is Hell Below Cave, located 8.9 km from the western escarpment (Fig. 3). Hell Below is about 150 m deep and has morphologic and mineralogical characteristics typical of sulfuric acid caves (Palmer and Palmer, 2000). The entrance is at 2043 m, near the top of the Seven Rivers Formation and lies 945 m above the salt pan near Dell City, Texas (Fig. 3). Veldhuis and Keller, (1980) estimate 500 m of bolson fill in the Salt Basin, so the Yates-Seven Rivers contact is at least 1400 m lower in the downthrown block than at Hell Below Cave.

Most of the stratigraphic units that comprise the Capitan aquifer of Hiss (1980) crop out on the western escarpment of the Guadalupes (King, 1948). Today, the water table within the aquifer is at an elevation of 945 m at Carlsbad Springs (Fig. 3), and is estimated at 963 m at deep points within Lechuguilla Cave (Jagnow, 1989). Extrapolating the gradient westward to Hell Below Cave gives an estimated potentiometric surface of 991 m, which is 1052 m below the entrance. This estimate compares favorably with Polyak's estimate of an 1100 m decline in the water table since 12 Ma (Polyak, et al., 1998; Polyak and Provencio, 2000).

If Hell Below Cave was the site of a flowing spring early in its development, then the entrance had to be at or below the water table at that time. The present structural position and topography of the Guadalupe Mountains precludes a water table at the level of the entrance to Hell Below. There had to be aquifer continuity and sufficient elevation gain to the west to support the hydrostatic head required for a flowing spring. This means that the Salt Basin graben had not yet subsided when speleogenesis was active at Hell Below Cave. Polyak et al. (1998) did not report an age for Hell Below Cave, but did report that nearby Cottonwood Cave, which has an entrance at 2073 m, formed 12.3 Ma.

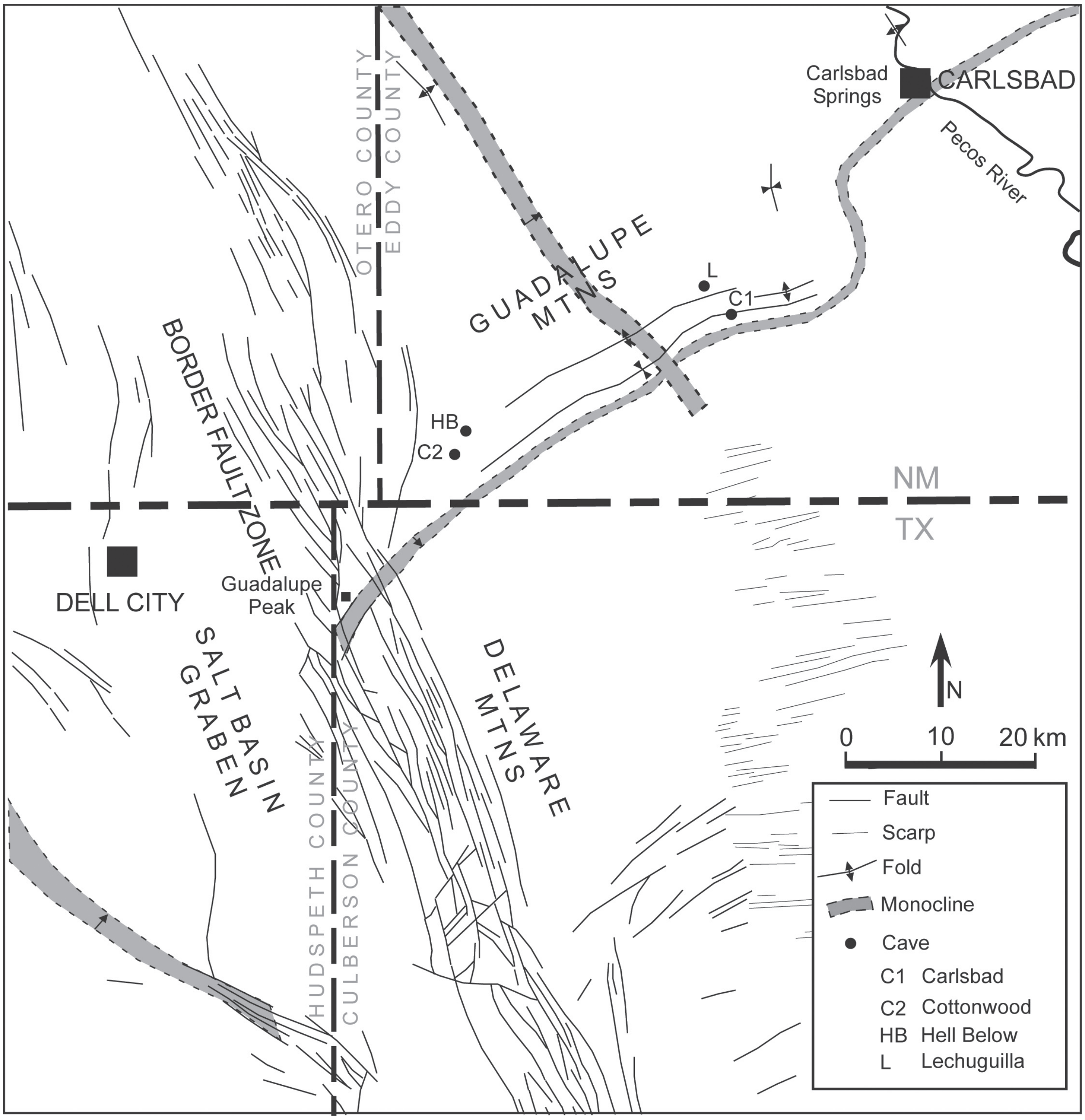

FIGURE 3. Tectonic map of the Guadalupe Mountains and vicinity showing the location of caves and key landmarks. Modified from Hayes, (1964, fig. 24)

DISCUSSION

Evidence for sulfuric acid speleogenesis in the Guadalupe Mountains is summarized by Palmer (2006), and examples of active caves elsewhere in the world are described by Hose and Macalady (2006). The model for the Guadalupe Mountains is different from many active sulfuric acid caves in that H_2S is derived from microbial alteration of petroleum. Any model for sulfuric acid speleogenesis must account for the presence of light chain aliphatic hydrocarbons in sulfur fluid inclusions from Lechuguilla Cave (Spirakis and Cunningham, 1992). Petroleum is part of the generation model for both basin-derived and shelf-derived H_2S, so it is possible that the hydrocarbons in the fluid inclusions could have come from either source. We favor a shelf source because of the abundance of oil accumulations north of the Capitan margin and because Artesia Group reservoirs are directly tied to the Capitan aquifer. We also believe that petroleum deposits that once existed in Artesia Group reservoirs west of the Pecos River were partly swept by the hydrodynamic flow described by Lindsay (1998), but that residual hydrocarbons remained in the system at least as late as 5.2 Ma when lower levels of Lechuguilla cave were enlarged (Polyak et al., 1998).

Sulfuric acid enlargement of caves occurred 12-4 Ma in the Guadalupe Mountains. However, the caves that were modified by sulfuric acid speleogenesis were formed earlier (Palmer and Palmer, 2000). These caves formed by solution enlargement of fractures below the water table that may not have involved H_2S. Age dates reported by Polyak et al. (1998) record the time of sulfuric acid dissolution at the water table, not the onset of cave development, so the absolute ages of Guadalupe sulfuric acid caves are unknown (Palmer, 2006). The Cenozoic tectonic history of the region provides some constraints on timing of speleogenetic events. The Alvarado Ridge began to rise in early Tertiary time, and by 38-35Ma, an elevated regional erosion surface extending across Colorado and New Mexico had developed (Meyer, 1986: Gregory and Chase, 1992). Prior to opening of the Rio Grande Rift, the ridge was an immense upland recharge area for aquifers that drained eastward into basins in eastern New Mexico and western Texas. As pointed out by Lindsay (1998), the hydrostatic head needed to sweep oil from Central Basin Platform fields was greater than exists today, so the aquifer system had to extend farther west than the Border Fault Zone (Fig. 3). The presence of sulfuric acid caves in the high western part of the Guadalupes also indicates that the aquifer had to extend farther west. Prior to the onset of extensional faulting 29-27 Ma, the east flank of the Alvarado Ridge supported hydrodynamic flow through the Capitan aquifer, and therefore, solution-enlarged fracture caves could predate the opening of the Rio Grande Rift.

As the Rio Grande Rift developed, the immense recharge on the east flank of the Alvarado Ridge was progressively reduced in area by extensional faulting (Fig 4). Evidence of the two early pulses of rift tectonism 29-27 Ma and 17-14 Ma are not recog-

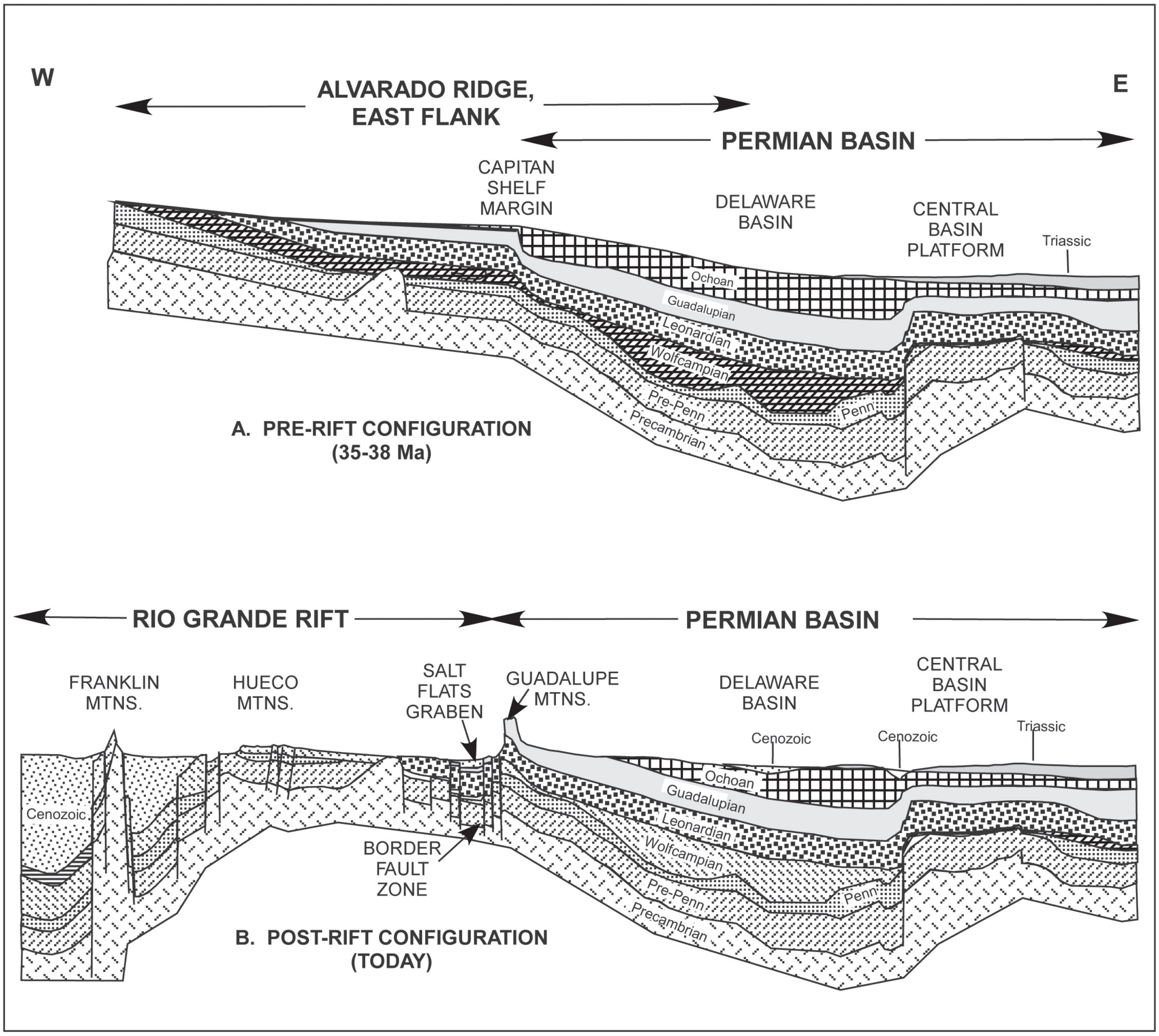

FIGURE 4. Cross section A shows the structural configuration of the Guadalupe Mountains region prior to development of the Rio Grande Rift. Cross section B shows the today's structural configuration of the region, illustrating how the Alvarado Ridge upland recharge area has been fragmented by Rio Grande Rift tectonism. Modified from Matchus and Jones, (1984), and Lindsay, (1998, fig. 3).

nized in Guadalupe caves. However, the interval from 14-4 Ma, between the end of the middle and late pulses of tectonism, fits well with the 12-4 Ma cave age dates reported by Polyak et al. (1998). During this time, the elevation of the water table in the Capitan aquifer fell at least 1100 m between the westernmost caves in the Guadalupe Mountains and the deepest points in Carlsbad Cavern and Lechuguilla Cave. However, if the Salt Basin graben and other rift structures to the west existed in their present form (Fig. 4B), there would not have been support for the water table. The locations of cave passages and galleries mark the position of the water table at each episode of sulfuric acid speleogenesis. Progressively lower levels of passage enlargement from west to east are each records of times when the water table was stable, but the vertical difference between levels reflects times when either there was no speleogenetic activity, or the water table dropped more rapidly.

The proximity of caves in the Guadalupes to the Rio Grande Rift in both time and space suggests that relatively rapid drops in the water table could be caused by episodes of tectonism. Subsidence of the Salt Basin graben on the western margin of the Guadalupes began sometime between 12-4 Ma and probably contributed to the lowering of the water table in the Guadalupes. Once the graben subsided below the elevation of the lowest major passages in Carlsbad Cavern, active sulfuric acid speleogenesis in the Guadalupes ceased. This implies that the Salt Basin graben reached essentially its present configuration 3.8 Ma, the youngest age date for Carlsbad Cavern (Polyak et al., 1998), and this event brought the era of sulfuric acid speleogenesis in the Guadalupe Mountains to an end.

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Stop 1 (2)
Day 2
2005
Jordan

PLATE 2: LANDSAT ETM+ IMAGE SOUTHEAST NEW MEXICO AND NORTHWEST TEXAS

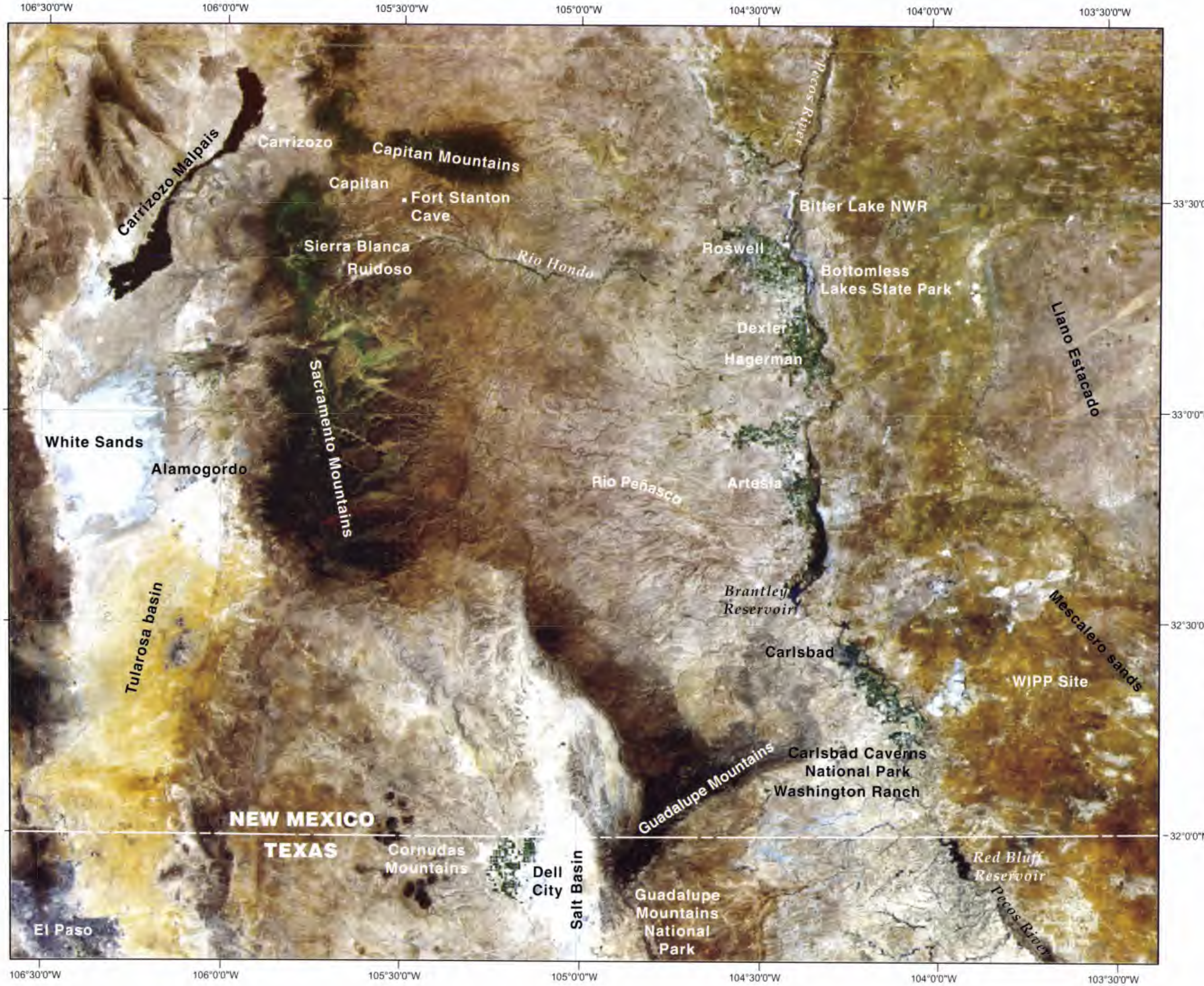

PLATE 3: GEOLOGIC MAP OF SOUTHEAST NEW MEXICO

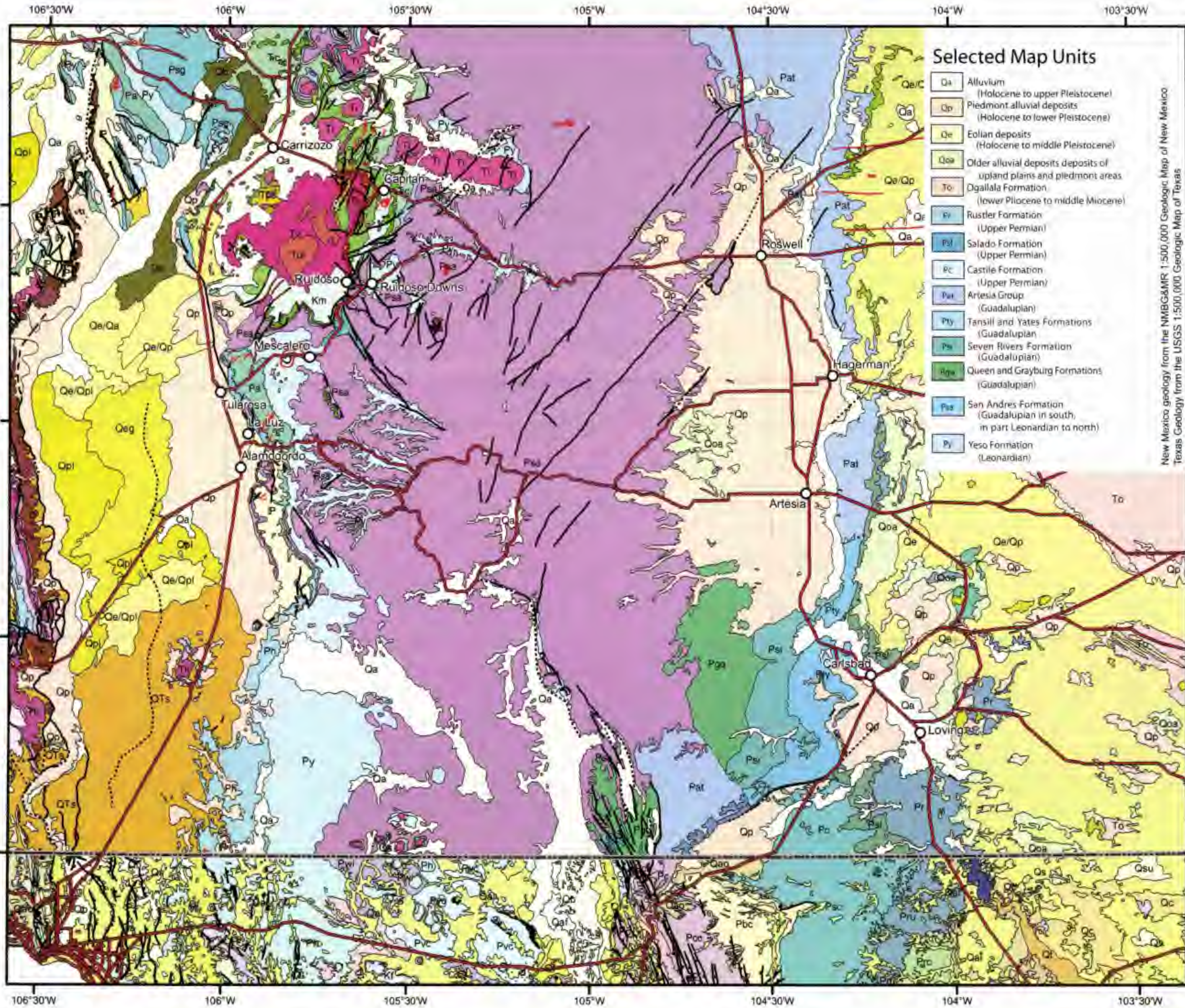

PLATE 4: PHOTOSTRATIGRAPHY OF SOUTHEASTERN NEW MEXICO AND WEST TEXAS

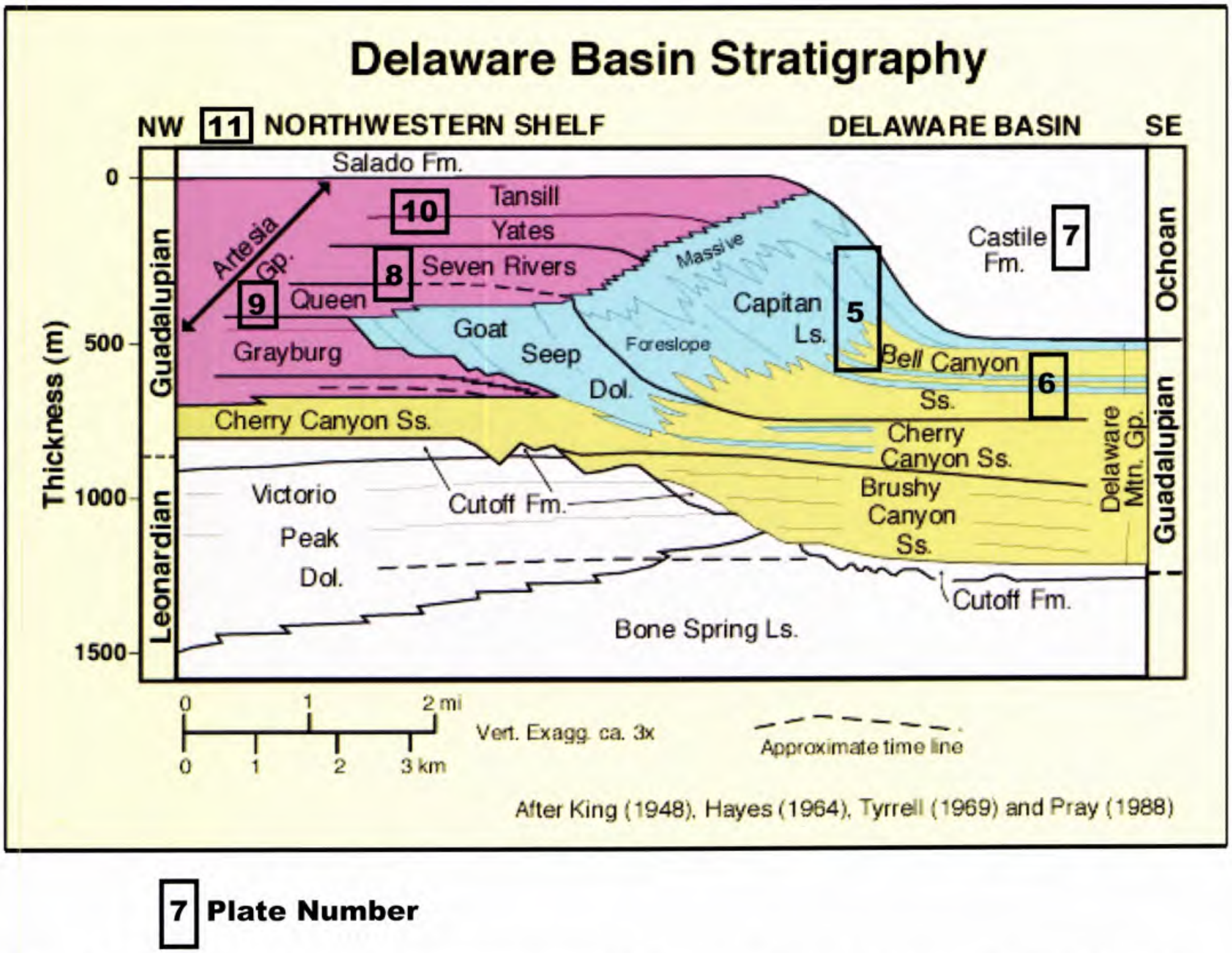

PLATE 4. Stratigraphic nomenclature of the Permian strata exposed in the Guadalupe Mountains. Boxed areas with numbers represent approximate stratigraphic locations for the various photostratigraphic plates .