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GEOLOGY OF THE GUADALUPE MOUNTAINS: AN OVERVIEW OF RECENT IDEAS

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Abstract.—A number of new ideas have been proposed over the last two decades regarding the geologic history of the Guadalupe Mountains from the Late Permian to the present. This paper will discuss six of these ideas. The classic model of P. B. King has the Hovey channel as being the inlet for the Permian basin, but new evidence suggests that the inlet was on the Salt Basin side of the Delaware basin rather than on the Glass Mountains side. The "Stage 1 fissure karst" in the Guadalupe Mountains has now been established as karst-modified syndepositional faults formed in Guadalupian (Late Permian) time. The "Stage 2 spongework karst" represents the slow diffuse circulation of Capitan aquifer water during limestone mesogenesis in the Mesozoic (Jurassic). The siliceous summit gravels of the Guadalupe Mountains are most likely Cox gravels of Comanchian (Early Cretaceous) age. The "Stage 2 spar-lined caves" in the Guadalupe Mountains date from the early Laramide (Late Cretaceous) and represent a time of deeply circulating, hydrothermal solutions. The large "Stage 4 cave passages" (e.g., Carlsbad, Lechuguilla) formed primarily from sulfuric acid rather than carbonic acid. The sulfuric acid derived from hydrocarbon reactions in the Delaware basin that generated hydrogen sulfide.

INTRODUCTION

This paper is an overview of recent, and sometimes controversial, ideas on different aspects of the geology of the Guadalupe Mountains, from Late Permian (Guadalupian) time up to the present. Many of these issues were discussed in the Special Topic sections of Hill (1996), and taken together they portray a significantly different picture of the geologic history of the Guadalupes than was held only a decade or two ago.

LATE PERMIAN (GUADALUPIAN)

Where Was the Inlet Channel to the Delaware Basin in Permian Time?

In nearly every paper written on the Delaware basin since the 1940s, the classic paleogeographic location map for the Permian of west Texas shows the Hovey Channel as being the inlet for sea water (Fig. 1). But was it? Evidence presented by Hill (1999b) suggests that the channel may have been on the west side of the basin rather than on the south side – in the area now known as the Salt Basin, between the Guadalupe and Apache Mountains (Figs. 2 and 3).

Three lines of evidence support Hill's interpretation. First, the location of the Capitan/Goat Seep Formations in the area of the Salt Basin is unknown (Fig. 2). The Capitan and Goat Seep reefs are known to turn from a southwestward direction at Guadalupe Peak to a southward direction through the Patterson Hills and Beacon Hill, but then these units become untraceable in the subsurface. The Capitan and Goat Seep are not encountered again until exposed in the Apache Mountains near Seven Heart Gap. One possible reason why these rocks may be missing between the Guadalupe and Apache Mountains is that they never formed there, since that was the inlet channel to the Delaware basin.

The second line of evidence comes from the Glass Mountains, where the Capitan reef is exposed and where the inlet channel to the basin was supposed to have existed near the old railroad town of Hovey. The Hovey Channel was originally placed in the Glass Mountain area by King (1930) primarily because: (1) Leonardian and Guadalupian rock in this vicinity was believed to be of deep-water, basinal origin, and (2) because the Tessey Limestone (equivalent in age to the Castile Formation in the rest of the basin) was believed to be a limestone facies that graded into anhydrite and then halite from south to north across the basin (Fig. 3). Neither of these two interpretations has proved to be correct (Hill, 1999b).

The upper Cathedral Mountain, Road Canyon, and Word Formations in the Glass Mountains – once considered to be deep-water facies – have been shown by Wardlaw et al. (1990) to be shallow-marine, fan-delta to lagoonal deposits, as indicated by

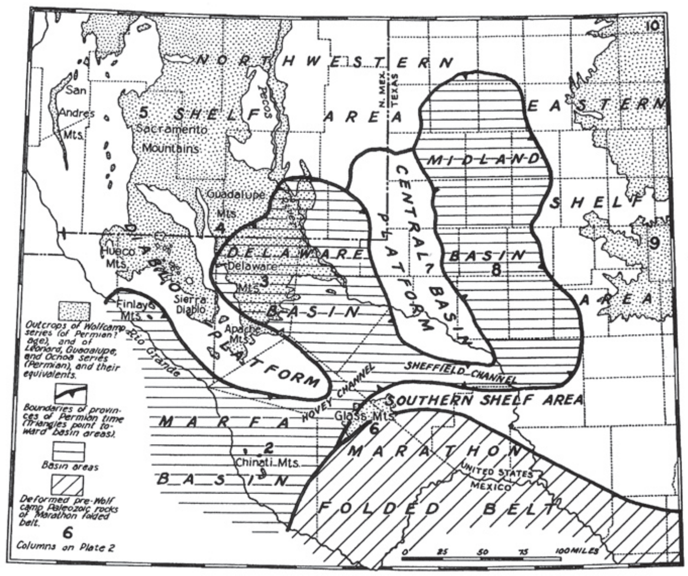

FIGURE 1. P. B. King's (1942) classic paleogeographic map of the west Texas region showing the Midland basin, Central Basin Platform, and Delaware basin. Note that the entrance to the Delaware basin and Midland basin was considered by King to be the Hovey Channel.

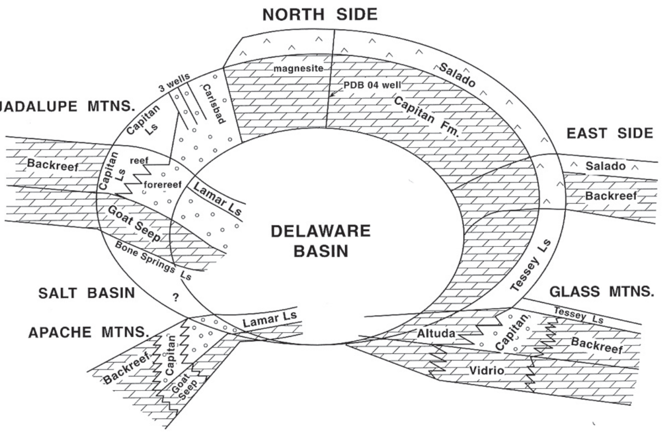

FIGURE 2. Idealized schematic diagram showing the distribution of dolomite in upper Permian units around the Delaware basin. The upper Capitan reef in the Guadalupe Mountains is the only area that consists of substantial amounts of undolomitized limestone. Diagonal lines show dolomitized rock, circles show rock with patchy or partial dolomitization, white areas show limestone. The location of the Capitan and Goat Seep Formations in the Salt Basin is unknown (?). From Hill (1999a).

fossil leaves such as gigantopterids. In addition, the Tessey Limestone turns out not to be a Late Permian marine limestone, but a bioepigenetic limestone of mid- to late-Tertiary age formed by the replacement of anhydrite (Hill et al., 1996). In other words, the original depositional rock in the Hovey Channel area was gypsum-anhydrite, not limestone, and thus there was no facies change away from the assumed Hovey Channel inlet.

The third line of evidence strongly supports the other three. Heywood (1991), in his isostatic residual gravity anomaly map of New Mexico, clearly showed a circular "bulls-eye" negative anomaly in southeastern New Mexico that delineates the Permian Delaware basin. On this map, the "entrance" to the basin appears to be on the southwestern, Salt Basin side of the basin, rather than on the southern Hovey Channel side (see Hill, 1999b, fig. 12).

LATE PERMIAN (GUADALUPIAN)

What is the age and significance of Stage 1 fissure karst in the Guadalupe Mountains?

The world-renowned caves in the Guadalupe Mountains, such as Carlsbad and Lechuguilla, represent just the final stage in a long history of karsting in the Capitan reef. Dunham (1972) was the first to describe the early solution-enlarged fractures in the Guadalupes, which Hill (1996) later called "Stage 1 fissure karst". Stage 1 fissure caves are often located at or near the contact of reef-backreef sediments, a location which suggests a response to a lithologic zone of instability between the Capitan reef core and backreef shelf members when the shelf facies lithified, compacted, faulted, and pulled away from the already lithified reef core. Stage 1 fissure karst is typically filled with breccia or siliciclastic material.

Stage 1 fissure caves are significant because they relate to a time when the Guadalupe Mountains first became emergent and flushed with fresh water. Melim (1991) and Melim and Scholle (1989, 2002) argued that the influx of fresh water had occurred concurrently with deposition of the Capitan Platform during periods of sea-level lowstand. Kendell and Harwood (1989) and Hill (1996), however, thought that fresh-water flushing had occurred in the Ochoan, when the reef was exposed above a shallow-water Castile basin. Most recently, Hunt et al. (2002) and Koša and Hunt (2005) have established that these fissures are karst-modified syndepositional growth faults, some of which are filled with sediment containing Capitanian fossils. It thus appears that the reef became at least periodically emergent in the Guadalupian during differential compaction as the reef pulled away from the backreef.

MESOZOIC (JURASSIC?)

What is the age and significance of Stage 2 spongework karst in the Guadalupe Mountains?

At the close of Permian time the Delaware basin was tilted eastward and uplifted slightly above sea level, so that the marine environment was replaced by a Triassic deltaic-fluvial environment. During the Triassic and Jurassic the area was low-lying, and water probably slowly diffused through the Capitan reef. In the early stages of a cave system there develops a complex, three-dimensional array of pores and joints of minimal cross-sectional area in the rock. These pores and joints are not necessarily integrated, so that flow under these conditions is diffuse, with phreatic water under pressure creating a spongework array of solutional openings (Ford and Ewers, 1978). Such was the environment for Stage 2 spongework cave dissolution. ("Spongework" refers to interconnected solution cavities of varied size in a seemingly

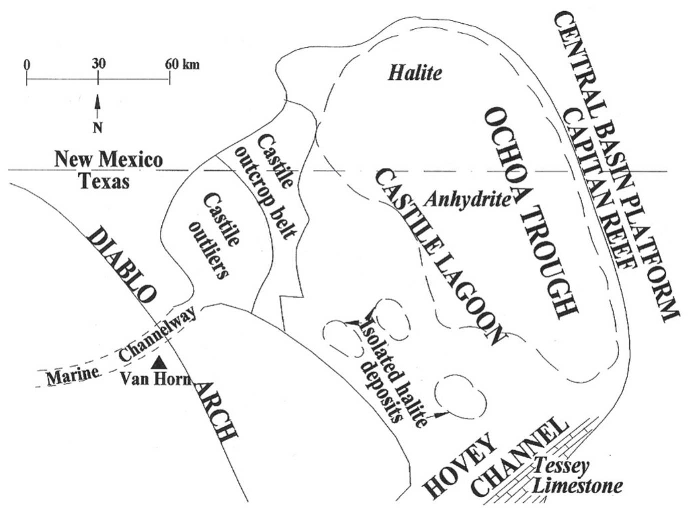

Figure 3. The marine channel of Adams (1972), placed in the area of Van Horn, Texas. Adams considered this channel to have been operative during Castile deposition only, and King's (1942) channel to have been operative earlier in the Permian. Note the distribution of Castile anhydrite in the Delaware basin, with the thickest deposits being in the eastern "Ochoa trough", and a supposed facies change from limestone to anhydrite to halite northward across the basin. The Tessey Limestone is actually a mid- to late Tertiary bioepigenetic limestone containing sulfur (Hill et al., 1996). From Hill (1999b).

random, three-dimensional pattern like the pores of a sponge; Palmer, 1991.) These cavities/caves dissolved under conditions of complete waterfill created by the slow-flow, diffuse circulation of aquifer water during limestone mesogenesis. Some of these cavities became partially filled with montmorillonite clay, which was K-Ar dated by Hill (1987) at 188±7 Ma (Jurassic).

EARLY CRETACEOUS (COMANCHEAN)

What is the Age and Source of the Summit Gravels in the Guadalupe Mountains?

Widespread siliceous lag gravels can be seen on the summit plain of the Guadalupe Mountains, immediately shelfward of the Reef Escarpment and overlying Tansill beds. They are also the main constituent of Type 2 dikes (Hill, 1996; Koša and Hunt, 2005). The origin and age of these gravels has been a subject of debate for many years, but it now appears probable that they date from the Early Cretaceous. In Early Cretaceous (Comanchean) time the Guadalupe Mountain area was traversed by low-gradient streams, which left behind their load of siliceous gravels (S. Lucas, personal communication in Hill, 1996). Then, later in the Comanchean, a marine sea transgressed over the area for a relatively brief period of time. According to Lucas, the Guadalupe Mountain summit gravels most nearly resemble Early Cretaceous Trinity (Cox) clastics that represent a fluvial regime just before marine transgression.

LATE CRETACEOUS (LARAMIDE)

What is the age and significance of Stage 3 spar-lined caves in the Guadalupe Mountains?

The age of calcite spar crystals lining small "geode" caves in the Capitan Limestone has long been a matter of conjecture. Hill (1996) speculated that this spar might be Miocene in age because large calcite spar crystals form from hydrothermal water and the Miocene was a time of high heat flow (~50°C/km; Barker and Pawlewicz, 1987). In addition, the calcite spar was reported by Hill (1996) to have fluid inclusion temperatures of 30-80°C and oxygen isotope values of $\delta^{18}O$ = -11 to -14‰, which values also suggest that the spar precipitated out of low-temperature hydrothermal solutions.

However, Hill's Miocene presumption turns out *not* to be correct. U-Pb dating of a football-sized, dogtooth-spar, calcite crystal collected from a cave in Big Canyon (Fig. 4) gave an age estimate of 87-98 Ma for calcite deposition (Lundberg et al., 2000). This Upper Cretaceous (Laramide) date is important because there is very little geologic evidence of any kind for what was happening in the Guadalupe Mountains in the Laramide. This date not only implies that there may have been a karsting episode in the Guadalupe Mountains at the beginning of the Laramide (because the spar lines small caves probably formed during the same solution-deposition cycle; Fig. 5), but also that the Laramide must have been a time of high heat flow and deeply circulating, hydrothermal, groundwater solutions.

This U-Pb date also relates to how much overburden may have existed over the Capitan Limestone in the Laramide because the dissolution of cave passages having spar linings typically occurs in the phreatic zone rather than near the water table (Fig. 5). As convective water rises and cools, the solubility of calcite gradually increases so that small caves dissolve in the deep "solutional zone", usually somewhere between ~250-500 m below the water table (Dublyansky, 2000). As the water table descends, caves formed in the solutional zone are shifted into the "depositional zone". When this happens the solubility of calcite drops sharply due to the loss of CO_2, so that solutions change from aggressive to precipitative. Since the loss of CO_2 is very slow, large spar crystals line the previously formed cave passages. Thus, in the early Laramide circulating cells of hydrothermal water must have descended deep into the reef in order for Stage 3 cave dissolution and then spar precipitation to have occurred.

LATE MIOCENE-PLEISTOCENE

What is the age and significance of Stage 4 sulfuric acid caves in the Guadalupe Mountains?

The large, Stage 4 cave passages in the Guadalupe Mountains cut across all three of the earlier cave episodes (Stage 1 fissure karst, Stage 2 spongework karst, and Stage 3 spar-lined

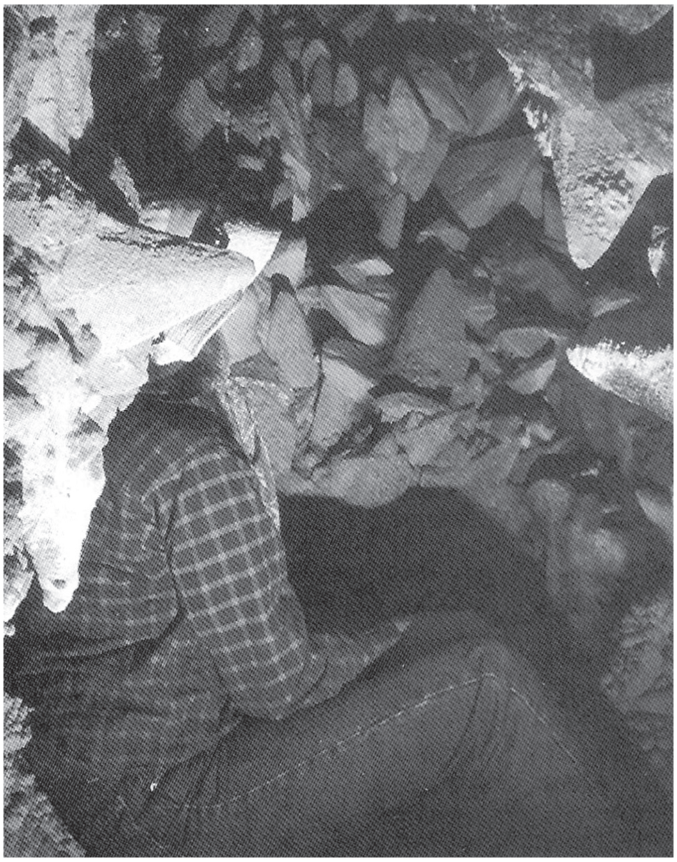

FIGURE 4. Dogtooth spar crystals lining a small "geode" cave in the area of Big Canyon, Guadalupe Mountains. Some of the spar crystals are as large as footballs. Photo by Alan Hill.

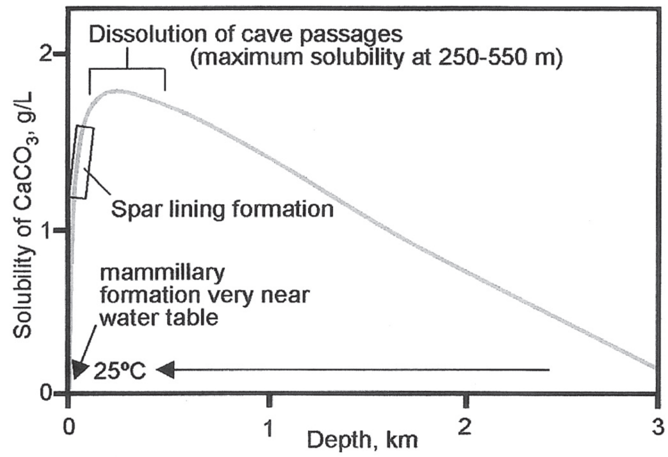

FIGURE 5. Solubility curve for calcite showing (1) the depth of cave dissolution in the "solutional zone", where maximum solubility occurs ~250-500 m beneath the water table, and (2) the depth of formation of large calcite spar crystals that lined these caves in the "depositional zone". Very fine-grained mammillary coatings form near the water table because in this regime the loss of CO_2 and rate of precipitation is rapid. After Dublyansky (2000).

karst). These large caves (e.g., Carlsbad and Lechuguilla) are world famous – not only for their amazing and beautiful array of speleothems, but also for their unusual method of speleogenesis (refer to the symposium of DuChene and Hill, 2000). It is now the consensus of most karst geologists that the large caves in the Guadalupe Mountains formed primarily by sulfuric acid and not by carbonic acid. A number of different lines of evidence attest to a sulfuric acid/hydrocarbon origin for Stage 4 Guadalupe caves (Hill, 1987, 1990):

(1) Massive gypsum deposits (up to 10 m thick) and native sulfur deposits (up to thousands of kilograms) in these caves formed as by-products of a sulfuric acid mode of dissolution. Epigenic, carbonic-acid caves do *not* contain these types of deposits.

(2) The low-pH, sulfuric acid minerals endellite, alunite, and natroalunite occur in these caves.

(3) High uranium, radon, and the minerals tyuyamunite/metatyuyamunite in these caves all indicate an H_2S-rich system where uranium (and vanadium) originally precipitated along a redox boundary interface (Hill, 1995).

(4) The isotopically light composition of massive gypsum, sulfur, and alunite/natroalunite deposits in Stage 4 caves is the most convincing evidence for a sulfuric acid origin related to hydrocarbons. Only biologically aided reactions such as occur with hydrocarbons could have produced the large isotopic fractionations found in these deposits. Gypsum and native sulfur deposits in Guadalupe Mountain caves are significantly enriched in the light isotope of sulfur; depletions as great as -25.6‰ for gypsum and -25.8‰ for sulfur have been measured (Hill, 1990). The same isotopically light signatures also characterize alunite and natroalunite in these caves ($\delta^{34}S$ = -28.9‰ for alunite, -28.6‰ for natroalunite; Polyak and Güven, 1996).

(5) Other sulfuric acid caves are known worldwide, and these are also associated with hydrocarbons. Some of these caves are actively forming today by a sulfuric acid mechanism; e.g., La Cueva de Villa Luz, Tobasco, Mexico (Hose and Pisarowicz, 1999). A milky-white river, with dissolved gypsum and sulfur, flows from Villa Luz, and sulfur crystals are growing in areas where drip water has a measured pH of 1. Sulfur isotope values for the sulfur and gypsum in Villa Luz ($\delta^{34}S$ = -26 to -22‰) are comparable to those in Guadalupe Mountain caves. (Refer to Palmer, 2006, for the description of active sulfuric acid caves and how they relate to the speleogenesis of "fossil" sulfuric acid caves such as Carlsbad and Lechuguilla.)

The method by which Stage 4 Guadalupe caves formed is as follows. Hydrogen sulfide, generated from hydrocarbon reactions in the Delaware basin, migrated into the surrounding Capitan reef and accumulated in structural and stratigraphic traps. Where H_2S-rich waters met with oxygenated meteoric groundwater descending to the water table along dipping backreef beds or joints in the overlying land surface (Fig. 6), it formed sulfuric acid according to (Palmer and Palmer, 2000):

$$H_2S + 2O_2 \leftrightarrow HSO_4^- + H^+ \leftrightarrow 2H^+ + SO_4^{2-} \quad (1)$$

$$2H^+ + SO_4^{2-} + CaCO_3 \leftrightarrow Ca^{2+} + SO_4^{-2} + CO_2 + H_2O \quad (2)$$

The sulfuric acid produced in (1) dissolved the Capitan reef limestone to produce the cave void, gypsum, and CO_2 (2). Sulfuric acid was neutralized by the limestone away from H_2S injection points and therefore horizontal cave passages in the Guadalupe Mountains end abruptly (Fig. 7). The sulfuric acid reaction did not occur below the zone of oxygenation of the groundwater;

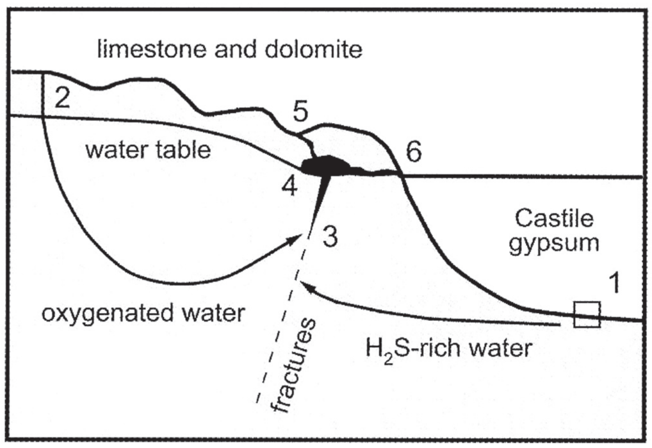

FIGURE 6. Idealized diagram of flow patterns and processes during the origin of sulfuric acid caves in the Guadalupe Mountains. 1 = site of gypsum reduction in the Castile Formation with the liberation of H_2S; 2 = infiltration of fresh water from the Guadalupe Mountains; 3 = ascension of H_2S-rich water into the Capitan reef along fractures; 4 = large rooms and passages formed at sites of rapid H_2S oxidation at the water table; 5 = passages formed by ascending water to former spring outlets; and 6 = passage connection to lower spring outlets. From Palmer and Palmer (2000).

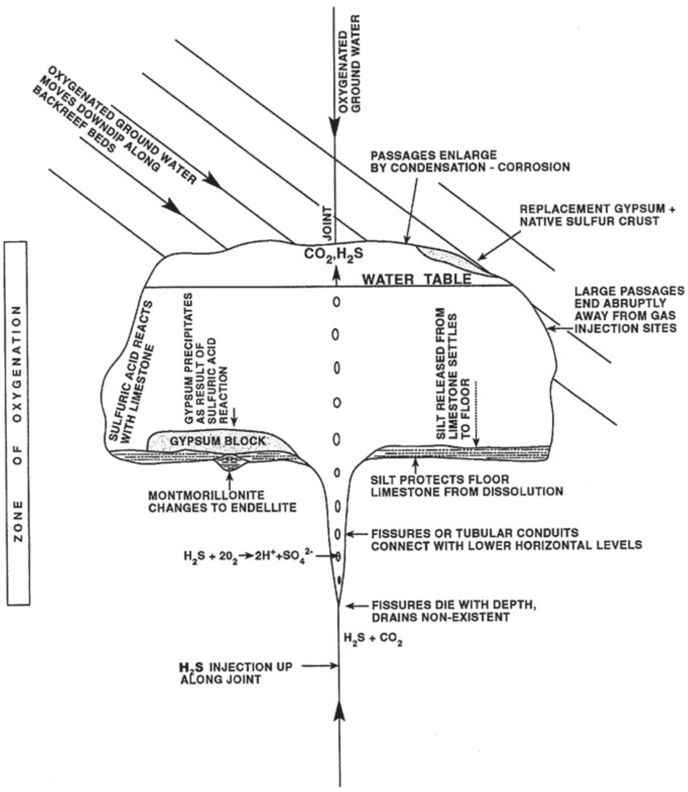

FIGURE 7. Model of hydrogen sulfide reaction with dissolved oxygen near the water table to form the large, Stage 4, sulfuric acid cave passages. See text for explanation. From Hill (1999a).

hence vertical passages narrow and "die" with depth below large, horizontal rooms. With successive lowering of base level, new horizontal levels became connected with older horizontal levels by spring shafts and joint chimneys. Silt residue from the limestone settled to the floor; gypsum in solution derived from equation (2) precipitated over the silt in slack places to form massive gypsum deposits or directly replaced the limestone bedrock; and the CO_2 produced in equation (2) caused further dissolution beneath the water table and condensation-corrosion of cave passages above the water table in the air zone. According to this model, vertical tubes, fissures and pits in Guadalupe caves are interpreted as having formed along injection points for H_2S-rich solutions (bathyphreatic dissolution), and horizontal levels are interpreted as forming at the water table where dissolved oxygen was the most concentrated (water-table dissolution). A low-pH, sulfuric acid, water-table environment also caused clay minerals to reconstitute to endellite, alunite, and natroalunite. In the air zone, H_2S dissolved in wet films on cave walls oxidized to native sulfur, which later were converted to gypsum in the presence of dripping and seeping water (Hill, 1995).

It now appears that Stage 4 sulfuric acid caves may be somewhat older than the Pliocene-Pleistocene age ascribed to them by Hill (1987). Polyak et al. (1998) $^{40}Ar/^{39}Ar$ dated the mineral alunite from four Guadalupe caves, establishing that the large cave passages formed from ~14-12 Ma in the southwestern part of the reef (e.g., Virgin Cave) to about 4 Ma in the northeastern part of the reef (e.g., Carlsbad Cavern and Lechuguilla Cave). These absolute dates are very important because they correlate with the time of major Basin and Range uplift of the Guadalupe Mountains relative to the Salt Basin, and also with the time of maturation and migration of hydrocarbons and generation of H_2S in the Delaware basin.

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