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## ***Support for a sulfuric acid origin for caves in the Guadalupe Mountains, New Mexico***

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# SUPPORT FOR A SULFURIC ACID ORIGIN FOR CAVES IN THE GUADALUPE MOUNTAINS, NEW MEXICO

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**ABSTRACT.**—Most cave specialists consider the caves in the Guadalupe Mountains of New Mexico to have formed by sulfuric acid. The evidence is weighed in this paper. Support for the hypothesis includes (1) cave patterns that indicate *in situ* acid generation; (2) alteration minerals that form at low pH; (3) deep rills in carbonate rock formed by local acidic drips; (4) negative  $\delta^{34}\text{S}$  values in cave gypsum that contrast with positive values in nearby marine deposits; and (5) similarity to active  $\text{H}_2\text{S}$  caves elsewhere.

## INTRODUCTION

The Guadalupe Mountains contain some of the world's largest and best-known caves. What is not at all clear to most geologists, however, is the origin of the caves. Most cave specialists accept an origin by sulfuric acid, but many geoscientists in other fields are uncomfortable with this explanation. This paper was written at the request of those who would like the sulfuric acid hypothesis put to an impartial test.

## GEOLOGIC SETTING

The Guadalupe Mountains consist of a mainly sponge and algal Permian reef with fore-reef talus extending into the Delaware Basin to the southeast, and bedded back-reef carbonates extending as a high upland to the northwest (Fig. 1). The Delaware Basin is floored by thick evaporites, mainly sulfates, which are underlain by deep-water clastics and carbonates. Petroleum is located at depth in the basin. Carlsbad Cavern is the best-known cave in the Guadalupe Mountains (Figs. 1 and 2). There are many other caves in the Guadalupes, most notably Lechuguilla Cave,

5-6 km west of Carlsbad Cavern, and the fourth longest cave in the US with more than 170 km of surveyed passages. Carlsbad extends through all three of the carbonate facies (back-reef, reef, and reef talus), and Lechuguilla extends through at least the first two. Carlsbad Cavern is examined here as the type example, because of its public access.

## CONTROVERSIES ABOUT CAVE ORIGIN

Because all known caves in the Guadalupes are relict, any interpretation of their origin must rely on circumstantial evidence. Water that enters them today deposits carbonate speleothems but has little influence on solutional morphology.

Prior to the 1970s, there were few serious attempts to decipher the origin of caves in the Guadalupe Mountains region. In contrast to most caves in humid regions, which are fed by recharge from an overlying or neighboring karst surface, Guadalupe caves

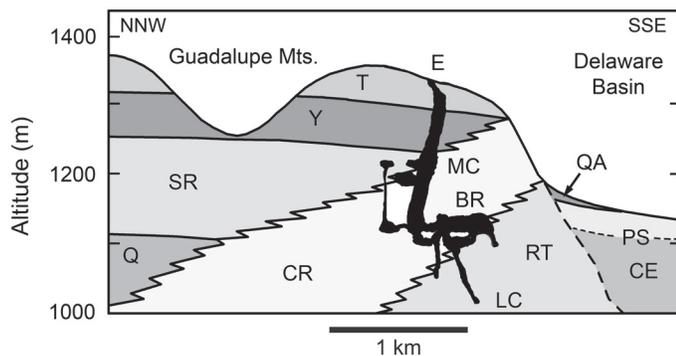


FIGURE 1. Geologic cross section through Carlsbad Cavern. E = entrance, MC = Main Corridor, BR = Big Room, LC = Lake of the Clouds (apparent local water table). CR = Capitan Reef, RT = reef talus, CE = Castile evaporites (and other lithologies), QA = Quaternary alluvium. Back-reef formations: T = Tansill, Y = Yates (silty), SR = Seven Rivers, Q = Queen. PS = potentiometric surface in the evaporite-alluvium aquifer. The border between the reef and the reef talus is highly irregular, so some of the passages shown in the talus are not entirely in that unit. See Jagnow (1977) for additional details.

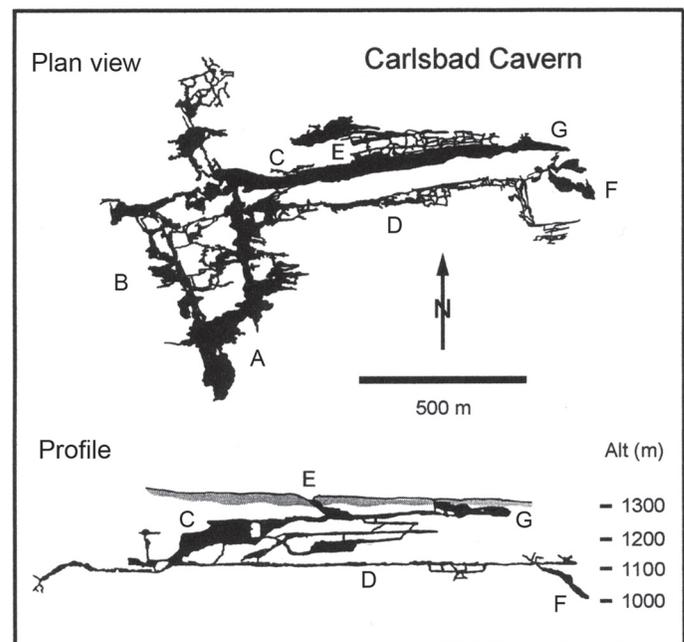


FIGURE 2. Map and profile of Carlsbad Cavern (from Cave Research Foundation, with permission). A = Big Room, B = Lower Cave, C = Main Corridor, D = Left Hand Tunnel, E = entrance, F = Lake of the Clouds, G = Bat Cave. The profile includes only the northern passages.

seem to have little relation to surface water sources. Bretz (1949) used Carlsbad Cavern as evidence to support his hypothesis that nearly all caves originate deep within the phreatic zone and undergo only minor vadose modification afterward. The field evidence seemed to support his view.

A substantially new hypothesis was proposed by Egemeier (1973, 1981, 1987) on the basis of his work in the Big Horn Basin of Wyoming, which centered on the role of sulfuric acid as the probable cave-forming agent. Contributions by Queen (1973), Jagnow (1977), and Davis (1980) elaborated on this theme. Application of the sulfuric acid hypothesis to Carlsbad Cavern culminated with the work of Hill (1981, 1987). See also the collection of papers on this topic edited by DuChene and Hill (2000). This hypothesis is scrutinized here to see how it stands up to recent field and laboratory evidence.

## EVIDENCE FOR THE ORIGIN OF GUADALUPE CAVES

### Cave morphology

The pattern of a solution cave is controlled most directly by the nature of its recharge (Palmer, 1991). The majority of caves are fed by discrete inputs through sinkholes and sinking streams. The most typical pattern is a branchwork in which the various passages join as tributaries and discharge at one spring, or a few related springs, in nearby valleys.

### Passage relationships

None of the Guadalupe caves have patterns remotely like that described above. The largest consist of rooms with short irregular galleries branching off at various levels, interspersed with labyrinthine sections having many closed loops. The map of Carlsbad Cavern is representative (Fig. 2). The labyrinths include networks, which consist of high, narrow fissures solutionally enlarged from fractures and which intersect in a roughly orthogonal pattern (Figs. 2 and 3); and spongework, which consists of interconnecting voids formed by the solutional enlargement of primary pores (Fig. 4). Many Guadalupe cave passages and rooms also have narrow fissures in their floors that descend several tens of meters along fractures and pinch out at depth (Figs. 1 and 3). Fissure bottoms are typically choked with carbonate sediment or secondary calcite, and it is likely that many have been completely obscured by this material.

A cave also reflects the chemical nature of the water that formed it. Where water derives its acidity from near-surface  $\text{CO}_2$ , dissolution is drawn out in a nearly uniform way along each major flow path. Cross-sectional areas of such cave passages are fairly uniform, except where they are influenced by collapse, sediment fill, or resistant stratigraphic units. In contrast, the Guadalupe caves have abrupt and large-scale changes in cross-sectional area. Passage junctions are ungraded, and blind terminations are common. Water inlets and outlets have an obscure and perhaps accidental relation to the overlying land surface. Carlsbad Cavern and Lechuguilla Cave, the two largest caves in the Guadalupe, have entrances near the tops



FIGURE 3. Left Hand Tunnel, Carlsbad Cavern, with floor fissure 20 m deep.

of ridges. These are unlikely places for cave-forming water to enter, because the catchment areas are too small (a few hectares today, and probably also in the past).

### Cave levels

Many of the largest rooms and passages in Guadalupe caves are arranged in nearly horizontal tiers with flat floors and irregular vaulted roofs. For example, the Big Room of Carlsbad Cavern has a nearly flat floor that coincides with that of most of the Left Hand Tunnel, which extends for about 800 m at a discrete level (Figs. 2D and 3). These rooms and passages are discordant to the geologic structure and intersect various carbonate facies with no interruption of their horizontal layout (Fig. 1). The only feasible explanation is that dissolution was concentrated along former positions of the water table. The water table in cavernous limestone has low gradients because of the high bedrock permeability. It is unlikely that any other hydrologic discontinuity (e.g., salinity boundaries) could be stable or discrete enough to produce such sharp levels. Some caves that form in seacoast mixing zones between fresh water and seawater have similar flat floors and are also concentrated at present or former water tables (Myroie and Carew, 1990).

In the Guadalupe these levels show only faint correlation with each other from cave to cave (Jagnow, 1977, 1989; Palmer and Palmer, 2000). The most likely interpretation is that the passages and rooms did not form simultaneously when the water table was stable for lengthy periods of time, but instead formed whenever and wherever rising hydrogen sulfide emerged in large quantity at specific locations.

### Network and spongework patterns

Network and spongework patterns, so common in the Guadalupe, are formed in several ways (Palmer, 1991): (1) by uniform recharge through a permeable but insoluble cap-rock, e.g., thin quartzarenite; (2) by steep hydraulic gradients during floods; or (3) by short flow distances, as measured from the point where the aggressive water first encounters soluble rock. In the Guadalupe the first process is untenable, as there is no feasible source of uniform recharge. The second is also not possible in this area of limited groundwater recharge and velocity. There are also no solutional scallops (asymmetrical solution hollows in bedrock formed by turbulent flow) and only very limited detrital sediment, both of which are extensive in floodwater caves. Process (3) applies best to the Guadalupe, not just by default, but because the local setting is ideal. The most popular view is that  $H_2S$  was generated by sulfate reduction at depth, rose along the fissures now seen in the cave floors, and mixed with oxygen to form sulfuric acid. The caves formed where the sulfuric acid generation was most active.

Over short flow distances in such caves, the aggressiveness is distributed fairly uniformly among all flow routes. Only after a considerable flow distance is there discrimination between favorable and unfavorable zones of enlargement (Palmer, 1991). Network and spongework mazes are produced where the aggressiveness is great and all openings enlarge at roughly similar rates. Where dissolution is most intense, the fissures quickly enlarge and coalesce to form large rooms, with maze remnants located between them and around their perimeters (e.g., The Boneyard in Carlsbad Cavern, Fig. 4). Large discrete passages form along the major flow routes that emanate from those areas. Besides the horizontal passages described above, some passages rise in steep, irregular paths toward the surface (e.g., the Main Corridor of Carlsbad Cavern, Fig. 2C). One opening leads to the main entrance, and others nearby are skylights in the passage ceiling. This pattern suggests development along deep phreatic paths, rather than along the water table, but this idea deserves a closer look.

By itself, the cave pattern reflects the local production of solutional aggressiveness but gives no solid proof of an origin by sulfuric acid. Could the mixing of two waters of differing chemical character have been responsible? Mixing between fresh water and seawater, or between high- $CO_2$  and low- $CO_2$  water are examples (Bögli, 1964; Plummer, 1975). This uncertainty will be resolved below.

### Vadose dissolution

Most caves in soluble rock are exposed to dissolution by descending vadose water. The resulting features have a strong gravitational orientation. These can include steeply descending shafts and passages, or simply rills etched in the walls of preexisting caves. But steep passages in the Guadalupe, such as the Main Corridor, contain none of the features typical of vadose flow, such as scallops, rills, and coarse detrital sediment. Instead the major effect of infiltrating water is simply the deposition of

calcite speleothems, such as those so prominently displayed in Carlsbad Cavern.

Vadose dissolution is visible mainly in gypsum blocks, through which holes have been drilled by dripping water (e.g., in the Big Room). This water is generally supersaturated with calcite but greatly undersaturated with gypsum. But in some areas vadose water has cut deep rills in carbonate rock (Fig. 5). Examples are visible in the Left Hand Tunnel and at the north end of the Big Room. In places they are jacketed by gypsum. The intensity of grooving gives the impression of water having been poured over blocks of salt. Many rills line the walls of pits in the floor that lead to lower levels. Oddly, the ceilings overhead show no evidence for inflow of any kind, and in places they are flat and featureless.

The most likely interpretation for the rills is that rising  $H_2S$  gas was absorbed by water droplets from infiltration or condensation, which adhered to former gypsum surfaces. The  $H_2S$  reacted with dissolved oxygen in the water to form sulfuric acid, as observed in active  $H_2S$  caves elsewhere (Egemeier, 1981; Hose et al., 2000). Where the drops are suspended from non-carbonate rock, their acid does not react with the rock and retains its low pH. Production of sulfuric acid consumes both oxygen and  $H_2S$ , which allows more of the gases to be absorbed and to produce more

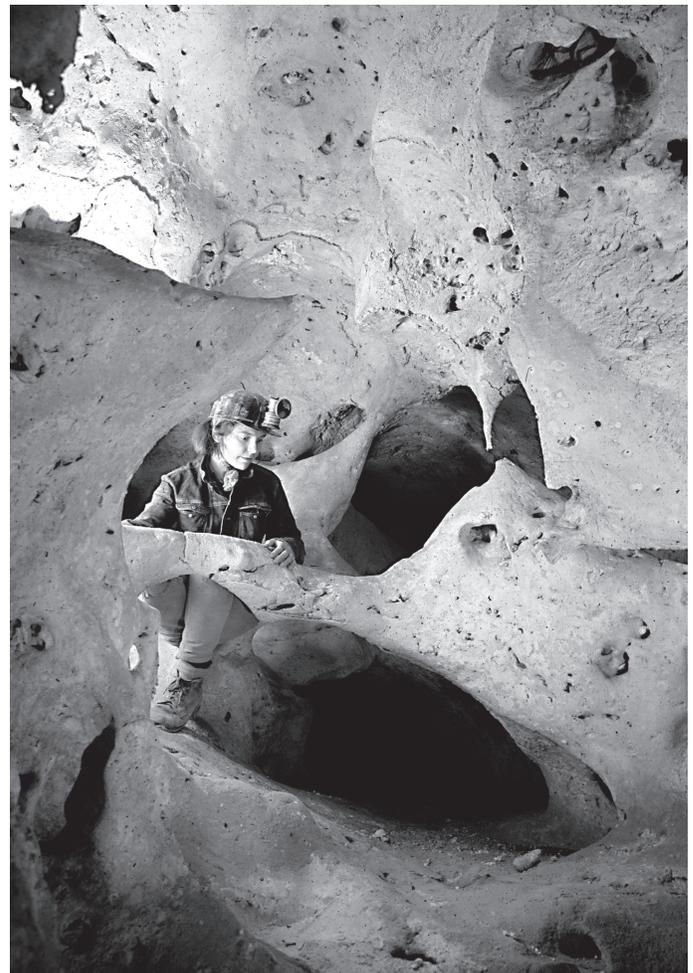


FIGURE 4. Spongework pattern in the Boneyard, bordering the Big Room, Carlsbad Cavern.

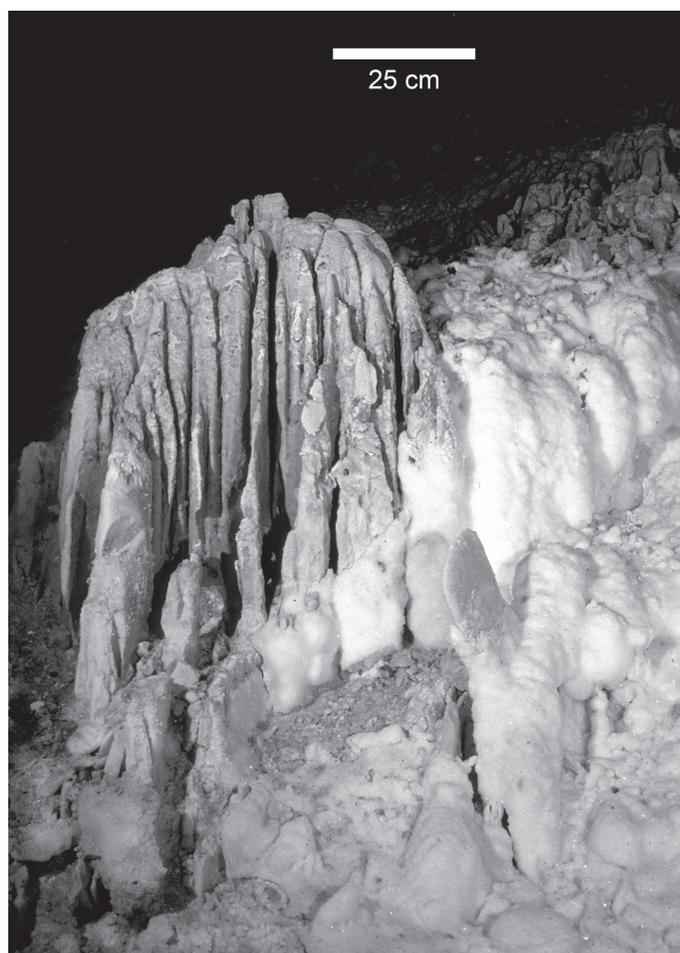


FIGURE 5. Rills formed by acid drips, overlain by what is now a flat limestone ceiling, Far East, Lechuguilla Cave. Note secondary gypsum (white material at right).

sulfuric acid. The longer the drops remain in contact with the atmosphere, the more acidic they become. When they eventually drop off, they are very corrosive to carbonate rock and form deep, narrow grooves and rills. In the Guadalupe most of the gypsum has been removed by fresh vadose water, leaving a puzzle as to how the acid drips formed.

#### Cave deposits

##### Carbonate minerals

Calcite speleothems are the dominant secondary deposits in Carlsbad Cavern. Their abundance suggests, perhaps incorrectly, that vadose infiltration also played a part in the cave origin. Other carbonate deposits are mainly evaporative and include aragonite and hydromagnesite, as well as small amounts of huntite, dolomite, and magnesite.

##### Sulfur and sulfate minerals

Gypsum is the second most abundant secondary deposit in Carlsbad Cavern, and in some dry caves elsewhere in the Guada-

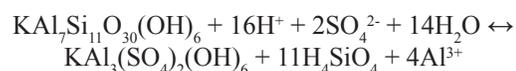
lupes it is far more abundant than calcite. Gypsum is common in many caves throughout the world and is usually related to pyrite oxidation, but in the Guadalupe there is little evidence for this process. The proximity of vast plains of gypsum in the neighboring Delaware Basin suggests that the cave gypsum might be part of the same depositional episode. But many of the gypsum cave deposits include large crystals growing from cave ceilings and walls and appear to have been transported in solution from higher gypsum deposits by infiltrating water. Queen (1973) showed that much of the gypsum in contact with carbonate bedrock is replacive, as it has inherited local bedrock textures such as pisoids, fossils, and distinctive bedding.

That the gypsum deposits in the caves do not correlate with those of the Permian Castile Formation of the Delaware Basin is shown by a significant contrast in sulfur isotopes. Hill (1981, 1987, 2000) showed that the  $\delta^{34}\text{S}$  values of gypsum and anhydrite in the basin have a range of +10 to +15‰ (28 samples), whereas those of cave gypsum in the Guadalupe and nearby Glass Mountains are mainly negative (-25 to +5‰, 17 samples). Values for  $\text{H}_2\text{S}$  from oil and gas wells of the Delaware Basin are -12 to -22 (33 samples). The negative values indicate fractionation that is commonly attributed to biogenic processes. The implication is that the marine gypsum is reduced in the presence of hydrocarbons to  $\text{H}_2\text{S}$ , and that the sulfide is later oxidized to sulfur and sulfuric acid. At temperatures below about 85 °C, sulfate reduction takes place almost exclusively through microbial processes, which can account for the isotopic fractionation (Machel, 2001). Other possible mechanisms could be invoked for the disparity in isotopic signature, but the results are compatible with those measured in active  $\text{H}_2\text{S}$  caves elsewhere (see Hose and Macalady, 2006).

Sulfur is locally abundant in some Guadalupe caves but in Carlsbad it is limited to a few scattered deposits. It also has negative  $\delta^{34}\text{S}$  signatures (-15 to -25‰, 6 samples; Hill, 2000). The stability field for sulfur forms a thin wedge on pe-pH diagrams at low pH and at pe values just above those for the stability field of  $\text{H}_2\text{S}$  (Faure, 1998, p.245). The sulfur deposits are mainly incorporated in gypsum or sandstone, which shields them from carbonate bedrock. The low pH and pe needed for sulfur deposition are most compatible with oxidation of sulfides, although not exclusively so.

##### Clay alteration minerals

Rare minerals are also present in Guadalupe caves from the alteration of clay. These include alunite, natroalunite, dickite, and hydrated halloysite (endellite). Alunite (Fig. 6) is examined here because of its importance in radiometric dating (see later). It forms from K-montmorillonite by the following reaction:



where alunite =  $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$  and K-montmorillonite =  $\text{KAl}_7\text{Si}_{11}\text{O}_{30}(\text{OH})_6$ . From the free-energy values listed by Faure

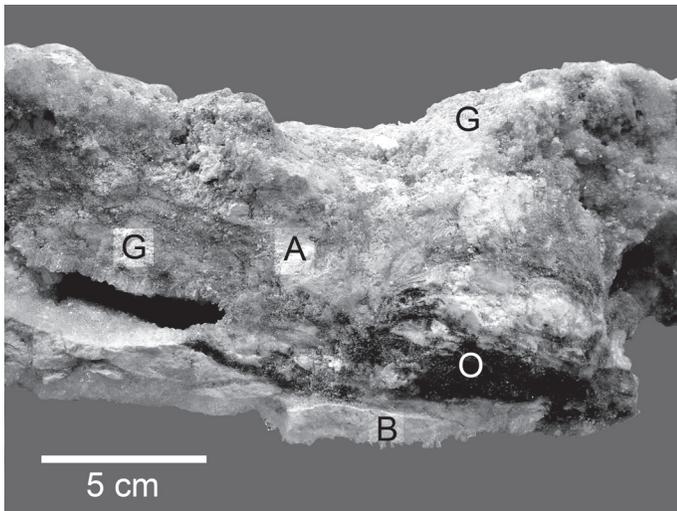


FIGURE 6. Alteration products in a fragment from the ceiling of Lechuquilla Cave (Lebarga Borehole). B = dolomite bedrock, O = manganese and iron oxides, A = alunite, G = gypsum.

(1998), the change in free energy for the reaction at 25 °C ( $\Delta G_r^\circ$ ) is  $\sim -31.1$  kcal/mole. The equilibrium constant for the reaction is  $\sim 10^{22.8}$ , so the equilibrium equation is  $11 \log(H_4SiO_4) + 4 \log(Al^{3+}) - 2 \log(SO_4^{2-}) + 16 \text{ pH} = 22.8$ .

The stability fields for alunite vs. K-montmorillonite are shown in Figure 7 at various  $H_4SiO_4$  and  $SO_4^{2-}$  activities. Silica released by the reaction is likely to drive quartz to well beyond supersaturation ( $H_4SiO_4 > 10^{-4}$ ). Crystalline quartz is slow to precipitate at low temperatures, so the  $H_4SiO_4$  activity is likely to rise enough to force amorphous silica to precipitate instead ( $H_4SiO_4 > \sim 10^{-2.7}$ ). Polyak and Provencio (2001) describe the presence of both crystalline quartz and amorphous silica in weathered zones in Guadalupe caves. The shift in stability fields caused by  $SO_4^{2-}$  activity is also shown in Figure 7, but the effect is small. The line for  $SO_4^{2-} = 10^{-2}$  is most appropriate in a sulfuric acid environment, because it represents the solubility of gypsum. The activity range for  $Al^{3+}$  is shown for typical karst groundwater (low values in shallow caves, high values in thermal springs). In the environment of clay decomposition, activities of  $Al^{3+}$  and aluminum ion complexes are likely to be much higher than either of these, although of uncertain value. The alunite field is therefore constrained to the light-gray triangle in Figure 7. The pH must be less than about 4. The requirement for high acidity and for a source of sulfate indicates that the reaction is almost certainly driven by sulfuric acid.

This acidity is virtually impossible to achieve if the water has intimate contact with carbonate rock. Sulfuric acid is neutralized quickly, and it reaches calcite equilibrium at a high pH (Fig. 8). As the initial sulfuric acid concentration increases, calcite solubility increases almost linearly, but the pH does not drop substantially. Carbon dioxide is liberated during the reaction, and the equilibrium pH is controlled more by the ambient  $CO_2$  partial pressure than by the initial sulfuric acid concentration.

When  $H_2S$  enters the incipient cavernous zone, the solution is already saturated with calcite. Oxidation of the  $H_2S$  to sulfuric

acid generally allows more calcite to dissolve, but the amount depends strongly on the ambient  $CO_2$  partial pressure (Palmer, 1991). At low  $CO_2$  partial pressures there may be virtually no increase in calcite solubility. Sulfuric acid has the greatest cave-forming potential in somewhat confined settings, where  $CO_2$  has a high concentration. At the same time, there must be sufficient oxygen to oxidize the sulfide. Connections with the surface, or input of oxygen-rich water, are essential, but if aeration becomes too great the sulfuric acid loses much of its cave-forming potency. While sulfuric acid caves are forming, they are likely to have modest exchange of air with the surface. This may account for the fact that in nearly all Guadalupe caves the entrances are few and small in relation to the size of the caves.

Carbon dioxide is liberated by the dissolution of carbonate rock by sulfuric acid. Although calcite solubility increases greatly with the amount of hydrogen sulfide present, the final pH depends mainly on how much  $CO_2$  is retained (Fig. 8). Even at very high  $CO_2$  values, the pH at calcite equilibrium is far too high to produce the alteration minerals observed in the caves. In typical  $H_2S$  caves (see Hose and others, 2000), the  $CO_2$  in the inflowing water is about 0.01 atm and pH is about 6.5-7.0, which is outside the stability field of alunite. To achieve sufficiently low pH values it is necessary for the sulfuric acid to be shielded from the carbonate rock. The presence of a gypsum rind or clay beds is sufficient. Otherwise, as sulfuric acid is produced by oxidation of  $H_2S$ , the continuous reaction with carbonate rock would prevent low pH from ever occurring.

The conclusion is that fairly concentrated sulfuric acid is required for alunite to form. The required initial  $H_2SO_4$  was at

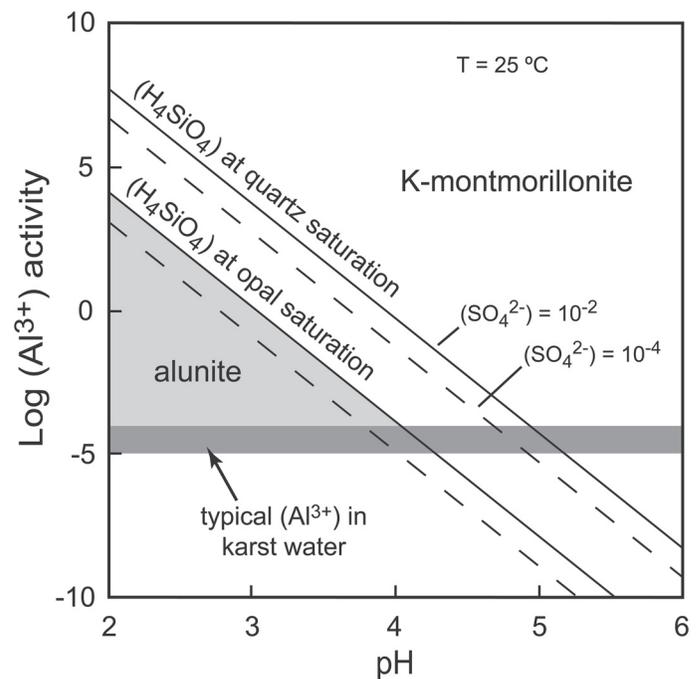


FIGURE 7. Stability fields for alunite and K-montmorillonite.

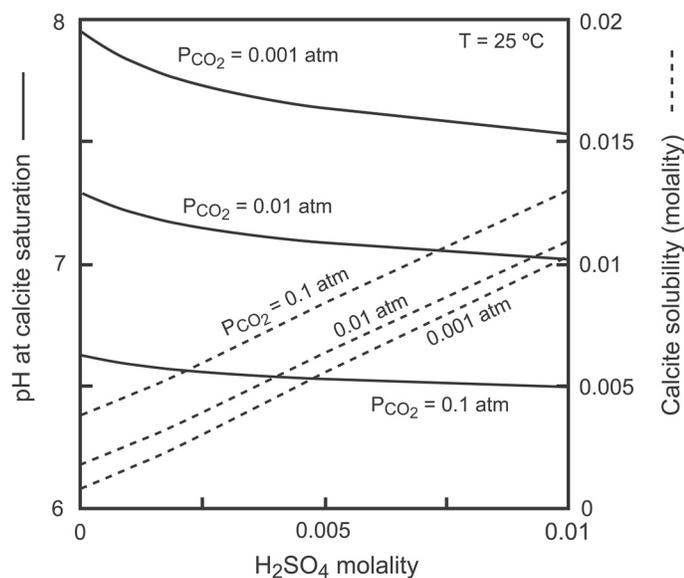


FIGURE 8. Calcite solubility and equilibrium pH vs. sulfuric acid molarity and  $\text{CO}_2$  partial pressure.

least  $10^{-4}$  moles/L. Sulfuric acid from the oxidation of sulfides is the only likely source.

Could the acid have been produced by oxidation of iron sulfides? This process can also produce negative  $\delta^{34}\text{S}$  values, and pyrite is abundant in certain beds of the Yates Formation high in the back-reef stratigraphic section. But oxidation of iron sulfides produces sulfuric acid *in situ*, resulting in intense but local dissolution in the form of solution pockets. The Yates appears only in a few limited areas in Carlsbad Cavern. Caves in the Yates, such as nearby Spider Cave, are rich in red and yellow oxides from this reaction, but they are rare in Carlsbad. Even in Spider Cave, the dissolution is widespread and not just from the pyrite-rich beds.

### Radiometric dating

U/Th dating of speleothems indicates mainly a Pleistocene age (Hill, 1987), but this gives little information about the actual cave origin. U/Pb dating of spar linings on older Guadalupe caves (Lundberg et al., 2000) give dates as early as Mesozoic, but these represent the linings of an earlier and more limited phase of cave origin than that of Carlsbad.

Analyses of  $^{40}\text{K}/^{40}\text{Ar}$  and  $^{40}\text{Ar}/^{39}\text{Ar}$  in alunite have been used by Polyak et al. (1998) to date the alteration of the clay minerals by sulfuric acid, and thus presumably the origin of the Guadalupe caves. Dates increase from low to high cave levels, as expected for caves formed at or near a water table. The curve of age vs. altitude describes a smooth curve that steepens with time. The highest levels, as old as 12 Ma, appear to represent the earliest phases of cave development, when the Guadalupe block first began its uplift. With time, the uplift appears to have slowed. The lowest levels, including the Lower Cave of Carlsbad Cavern, have ages of about 4 Ma. Thus the cave ages also seem to reveal the tectonic history as well. The close relation between age and altitude shows

that the caves developed in conjunction with a dropping water table relative to the mountain block.

### A second look at vadose processes

Do the alunite ages represent the actual dates of cave origin? Recall from Figure 7 that the production of alunite requires low pH, and from Figure 8 that this pH cannot be maintained by water in contact with carbonate rock. Rills in the limestone (Fig. 5) indicate very low pH in vadose dripwater. Much of the production of sulfuric acid appears to have been subaerial, in droplets and water films on non-carbonate surfaces, such as clay, gypsum, and silica. The localized nature of minerals from clay alteration and of sulfur supports this hypothesis.

$\text{H}_2\text{S}$  that escapes from the water table or cave streams can be very intense in cave air. Hose et al. (2000) report concentrations up to 210 ppm in Cueva de Villa Luz, Mexico. The gas is denser than average air, but it is mixed by diffusion, as well as by convection driven by the rise of warm moist air, and especially by barometric winds. Absorption of hydrogen sulfide by water drips and films, with subsequent oxidation to sulfuric acid, dissolves the carbonate rock and may produce gypsum, but where moisture is most abundant the gypsum will lose its grip on the walls and fall off, or will be dissolved off, leaving little evidence except for irregular corrosion pits.

$\text{H}_2\text{S}$  in cave air moves by air currents caused by convection or by barometric winds, both of which are considerable in large Guadalupe caves.  $\text{H}_2\text{SO}_4$  dissolution is most intense in the immediate vicinity of water sources, but it can also be drawn upward along fractures and narrow fissures toward the surface and enlarge them into incipient passages. It is possible that this mechanism accounts for the passages that ascend to entrances, although this premise needs further investigation. Much, if not most, of the cave volume has been produced subaerially by this mechanism. This is shown by the presence of high arched ceilings overlying flat floors controlled by former water tables. The process can be observed in presently active caves elsewhere (e.g., those described by Hose and Macalady, 2006).

Alunite can form anywhere above the water table, but not below it. In active caves the most intense  $\text{H}_2\text{S}$  concentrations are located just above the points where rising water enters the caves (Hose and Macalady, fig. 2, 2006). Thus the alunite in the Guadalupe caves is likely to have formed close to the contemporary water table. The presently visible alunite represents one of the latest events of cave enlargement, because it partly lines the walls of passages and rooms that acquired their shape beforehand. The alunite dates therefore give minimum ages for cave origin at any given level.

### SOURCE OF HYDROGEN SULFIDE

There are a few inevitable loose ends to the discussion of sulfuric acid cave origin that are beyond the scope of this paper. For example, the source of the hydrogen sulfide is still debated. Most researchers agree with Hill (1987) that the gas migrates from the

Delaware Basin, which is rich in sulfates and in organic compounds to serve as reducing agents. In contrast, DuChene and McLean (1989) present a case for southwesterly migration of H<sub>2</sub>S up the dip of the Capitan Formation. In addition, Queen (1994) interprets the H<sub>2</sub>S source to be reduction in sulfate-rich brines beneath the Guadalupe Mountains. The diversity of these opinions does not compromise the argument for a sulfuric acid origin of the Guadalupe caves. Any of these sources, or a combination, could maintain the cave-forming process.

### COMPARISON WITH ACTIVE H<sub>2</sub>S CAVES ELSEWHERE

So far the evidence for a sulfuric acid origin in the caves of the Guadalupe Mountains is based on interpreting processes that are now largely inactive. Active H<sub>2</sub>S caves are much less abundant than H<sub>2</sub>S springs, but those caves that are accessible show evidence for the same processes that have been inferred for Guadalupe caves. The caves described in the paper by Hose and Macalady (2006) are among the best known examples. These include Lower Kane Cave in Wyoming, Cueva de Villa Luz in Mexico, and the Frasassi Cave System of Italy. In Hose and Macalady's paper, note the following features: complex passage pattern in their figures 2, 6a, and 6b; flat floors with arched ceilings (fig. 4a); rills in carbonate bedrock (fig. 4b), and secondary gypsum (fig. 7).

Bacterial filaments are present in many caves that are exposed to redox reactions but are most notable in active H<sub>2</sub>S caves, where sulfur-fixing bacteria form the base of an extensive food chain (Hose and Macalady, fig. 3, 2006). Filaments of sulfur-fixing bacteria have not been positively identified in the Guadalupe caves, but many finger-like calcite speleothems are cored by filaments that are likely of this origin (Davis et al., 1990).

### CONCLUSIONS

Only a few major lines of evidence have been presented here, but they are the most salient. The hypothesis of sulfuric acid cave origin in the Guadalupe Mountains is not proved by any of the individual pieces of evidence described in this paper, but their combined weight is overwhelming. Most telling is the comparison with active H<sub>2</sub>S caves elsewhere. Any argument against a sulfuric acid origin for the Guadalupe caves must address all of the positive evidence described here.

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