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HYDROCHEMICAL INTERPRETATION OF CAVE PATTERNS IN THE GUADALUPE MOUNTAINS, NEW MEXICO

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Most caves in the Guadalupe Mountains have ramifying patterns consisting of large rooms with narrow rifts extending downward, and with successive outlet passages arranged in crude levels. They were formed by sulfuric acid from the oxidation of hydrogen sulfide, a process that is now dormant. Episodic escape of H_2S-rich water from the adjacent Delaware Basin, and perhaps also from strata beneath the Guadalupes, followed different routes at different times. For this reason, major rooms and passages correlate poorly between caves, and within large individual caves. The largest cave volumes formed where H_2S emerged at the contemporary water table, where oxidation was most rapid. Steeply ascending passages formed where oxygenated meteoric water converged with deep-seated H_2S-rich water at depths as much as 200 m below the water table. Spongework and network mazes were formed by highly aggressive water in mixing zones, and they commonly rim, underlie, or connect rooms. Transport of H_2S in aqueous solution was the main mode of H_2S influx. Neither upwelling of gas bubbles nor molecular diffusion appears to have played a major role in cave development, although some H_2S could have been carried by less-soluble methane bubbles. Most cave origin was phreatic, although subaerial dissolution and gypsum-replacement of carbonate rock in acidic water films and drips account for considerable cave enlargement above the water table. Estimates of enlargement rates are complicated by gypsum replacement of carbonate rock because the gypsum continues to be dissolved by fresh vadose water long after the major carbonate dissolution has ceased. Volume-for-volume replacement of calcite by gypsum can take place at the moderate pH values typical of phreatic water in carbonates, preserving the original bedrock textures. At pHs less than about 6.4, this replacement usually takes place on a molar basis, with an approximately two-fold volume increase, forming blistered crusts.

Caves in the Guadalupe Mountains of southeastern New Mexico include some of the world's best-documented examples of sulfuric acid speleogenesis (Davis 1980; DuChene 1986; Hill 1987; Egemeier 1987; Jagnow 1989; Cunningham *et al*. 1995; Palmer *et al*. 1998; Polyak *et al*. 1998). Although the cave-forming process is now dormant, its overall picture seems clear: water rich in hydrogen sulfide (H_2S) rose from depth and, as it approached the water table, the H_2S reacted with oxygen to produce sulfuric acid, the main cave-forming agent. It is fortunate that the caves are now inactive, because the toxicity of H_2S would probably make them impossible to explore. Interpretations of cave origin must rely on indirect evidence.

This paper summarizes the geometry of these caves and examines the hydrologic and chemical conditions that formed them. Interpretations are based on geologic leveling surveys in about 10 km of cave passages, calculation of relevant geochemical equilibria, and comparison with caves elsewhere that are still forming by similar processes. Leveling surveys were conducted with a hand level or tripod-mounted Brunton compass, with mean closure errors of 0.05%. Chemical relationships were derived from free-energy data tabulated by Woods & Garrels (1987) and from calculations with the geochemical software program **SI** (Palmer 1996).

GEOLOGIC SETTING

The geologic setting for the Guadalupe caves is shown in figure 1. For more details see Jagnow (1979), Hill (1987, 1996), Harris & Grover (1989), and Jagnow & Jagnow (1992). The Guadalupe Mountains consist of an uplifted block of Permian limestones and dolomites. The southeastern border of the mountains, which drops off steeply as the Guadalupe Escarpment, consists of the massive Capitan Limestone, a reef that built upward and southeastward as the Permian sea level rose. It contains a loose framework of bryozoan, sponge, and algae fossils in a matrix of fine-grained limestone (DuChene 2000). The Capitan grades downward and laterally into the dolomitized reef rock of the Goat Seep Formation. To the northwest are prominently bedded back-reef dolomites and limestones. Of these, the Yates Formation is the only one with a large insoluble content, mainly quartz silt. To the southeast, the reef is bordered by an apron of talus formed by blocks broken off the steep reef front as it built upward. The talus, now dolomitic, merges diagonally downward with limestones and other strata deposited in deeper water within the Delaware Basin. The basinal rocks are overlain by Permian gypsum and other evaporites, mainly of the Castile Formation. These and other sediments once filled the entire Delaware Basin at least as high as the top of the Capitan reef, but much of this thickness has been removed by post-Permian erosion.

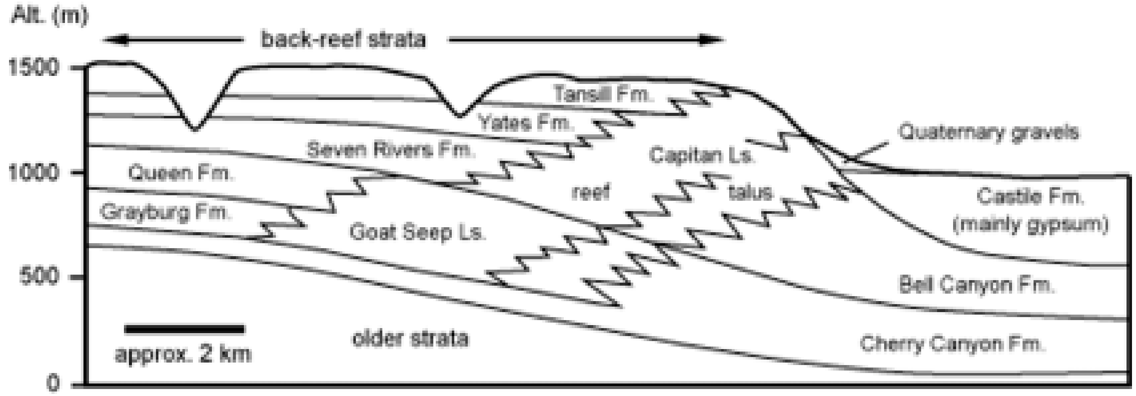


Figure 1. Geologic cross section through the Guadalupe Mountains, adapted from King (1948) and Hayes (1964). See text for brief description of rock types.

The Guadalupe Mountains owe their height to Late Permian, Mesozoic, and Cenozoic uplift, accompanied by faulting, minor folding, and broad southeastward tilting (Hill 2000). The main phase of uplift and cave development took place within the past 12-15 Ma (Hill 1996, 2000; Polyak *et al*. 1998). The carbonate rocks, which are considerably more resistant than the neighboring evaporites, now stand in high relief. The overall southeasterly dip of the back-reef beds is disrupted by broad folds parallel to the reef front (Hayes 1964; Jagnow 1979). The dip varies from bed to bed, even in the same vertical section, because of differences in formation thickness. In the cave area, the mean dip of the back-reef beds is <10° over large areas, but local dips can exceed 15°.

Normal faults along the western edge of the mountains have displacements as much as several hundred meters. Other faults within the mountains have only minor displacements. Prominent joints are oriented in at least two major sets roughly parallel and perpendicular to the reef front. Bedding-plane partings are conspicuous only in the back-reef strata. Paleokarst features include Permian breccias, breccia dikes, and solutional voids and small caves now lined with calcite spar, as well as clay-filled spongework representing Mesozoic enlargement of primary pores (Hill 2000). All of these structures and openings have helped to guide later cave development.

Most groundwater in the Guadalupe Mountains now flows parallel to the reef front and emerges in the Pecos River valley at Carlsbad Springs in the city of Carlsbad (Fig. 2). See Hiss (1980) for information on the regional hydrology.

CAVE PATTERNS

Cave patterns in the Guadalupe Mountains are of concern not only to geologists, but also to explorers and mappers who use their intuitive feel for the caves' layout to make new discoveries. Individual caves are scattered unevenly and it is difficult to verify their overall distribution. Most known caves have only a single entrance, and it is likely that many have no accessible entrance at all. Locations of caves used as examples in this paper are shown on figure 2, which includes most of the large Guadalupe caves.

The typical Guadalupe cave has a ramifying pattern consisting of irregular rooms and mazes with passages branching outward from them (Fig. 3). The map of a typical large Guadalupe cave resembles an ink blot, with many overlapping tiers. Branches do not converge as tributaries, but instead serve as distributary outlets at successively lower elevations. Many caves, or parts of caves, have a network or spongework pattern. Some involve simple widening of one or more fractures. Typical Guadalupe cave patterns are illustrated by the maps and profiles of Carlsbad Cavern and Hicks Cave (Figs. 4 & 5).

The overall layout of the caves is governed by the pattern of groundwater flow and sulfuric acid production. However, individual passages are guided in part by local geologic structures (Figs. 6 & &). Although caves tend to concentrate in the least dolomitized rocks, the main geologic control of individual cave patterns is evidently not lithologic, because many of

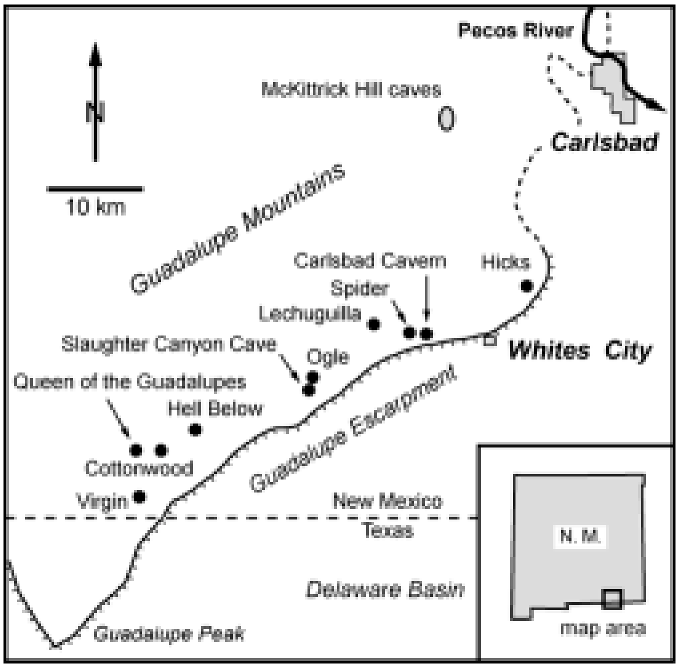


Figure 2. Location of caves and other features described in this paper.

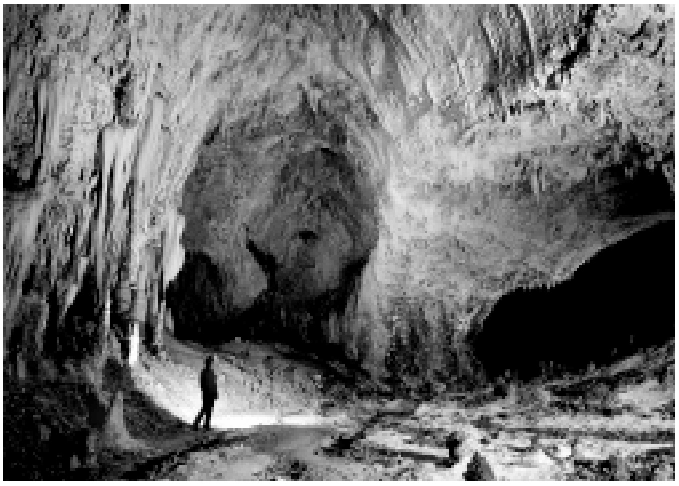


Figure 3. Lower Cave of Carlsbad Cavern, formed by dissolution at a former water table, with arched ceilings formed by gypsum replacement and condensation-corrosion. All photos by A.N. Palmer.

them cut discordantly across different rock types with only minor effects on passage morphology. The massive Capitan reef is structurally most competent, least dolomitized, and contains the largest cave rooms and passages. Many of these are guided by large fractures. Primary porosity fosters fine-textured spongework. The reef talus behaves similarly because the talus blocks are cemented into a single coherent unit. Back-reef strata produce passage cross sections that are elongate along the bedding, but discordant joints produce many fissures as well. Impure beds (e.g., the siltyYates Formation) can serve as confining units that limit the vertical range of passages.

The purely geologic factors described here cannot account for the great variety and unusual characteristics of Guadalupe caves. Flow patterns and water chemistry are the keys to understanding them.

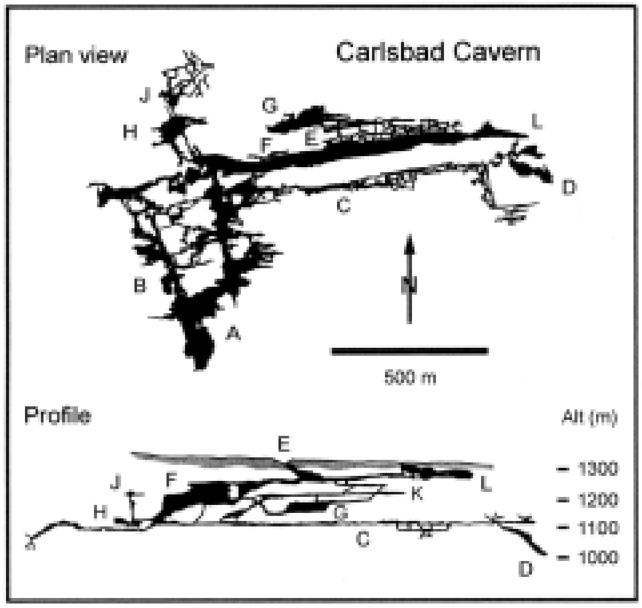


Figure 4. Map and profile of Carlsbad Cavern, based on surveys by the Cave Research Foundation (1992). A = Big Room; B = Lower Cave; C = Left Hand Tunnel; D = Lake of the Clouds; E = entrance; F = Main Corridor; G = Guadalupe Room; H = New Mexico Room; J = Chocolate High; K = New Section; L = Bat Cave.

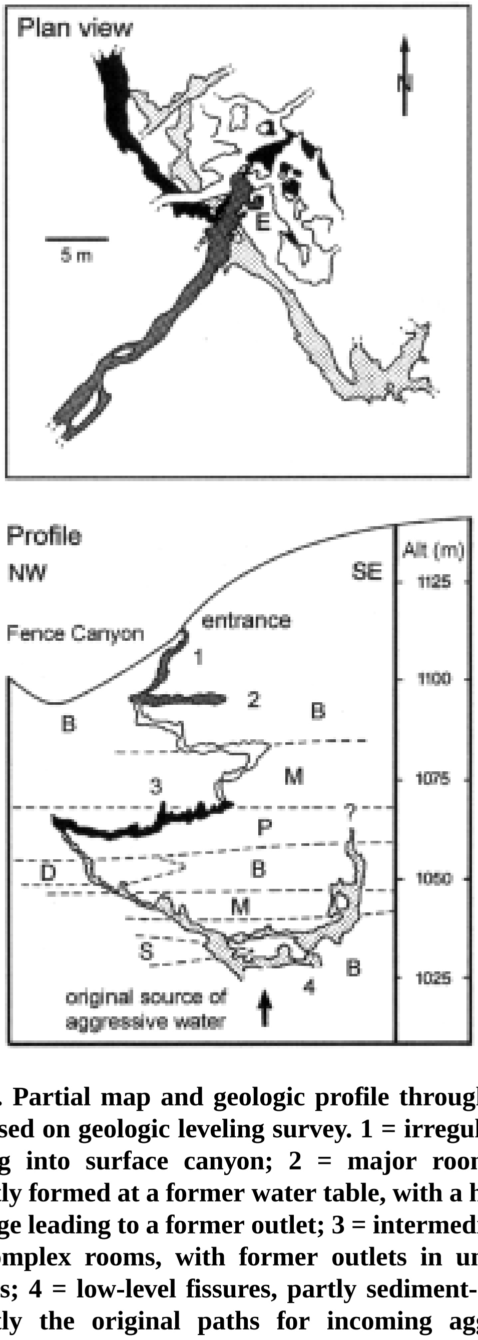


Figure 5. Partial map and geologic profile through Hicks Cave, based on geologic leveling survey. 1 = irregular tube ascending into surface canyon; 2 = major room level, apparently formed at a former water table, with a horizontal passage leading to a former outlet; 3 = intermediate levels of complex rooms, with former outlets in uncertain directions; 4 = low-level fissures, partly sediment-choked, apparently the original paths for incoming aggressive water. E = entrance; B = carbonate breccia; M = microcrystalline limestone and dolomite; P = pisolitic limestone; S = silty limestone and dolomite. Patterns show the relation between passages on map and on profile.

CAVE-FORMING PROCESSES IN THE GUADALUPE MOUNTAINS

The following sequence of steps is well accepted for the origin of Guadalupe caves (see Hill 1987): (1) reduction of sulfates (gypsum and anhydrite) at depth within the Delaware Basin to produce hydrogen sulfide (H_2S); (2) ascent of H_2S, either in solution or as a gas, into the carbonate rocks of the Guadalupe Mountains; (3) oxidation of H_2S to sulfuric acid, either where oxygen-rich groundwater mixes with the H_2S or at the water table; (4) dissolution of carbonate rock by sulfuric acid; and (5) removal of the dissolved solids to springs by groundwater flow. An idealized view of the geologic setting and flow patterns during cave origin is shown in figure 8. The chemical reactions involved are:

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

Reaction (1) often involves an intermediate sulfur phase, which is in turn oxidized. HSO_4^- is the dominant sulfate species only at pH less than about 2. Dissolution of limestone (calcite) and dolomite proceeds as follows:

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

$$4H^+ + 2SO_4^{2-} + CaMg(CO_3)_2 \Leftrightarrow Ca^{2+} + Mg^{2+} + 2SO_4^{2-} + 2CO_2 + 2H_2O \quad (3)$$

To explain specific cave patterns these processes must be examined in detail.

NATURE OF HYDROGEN SULFIDE SOURCE

Organic carbon compounds, such as those in oil fields, react readily with oxygen. Deep below the surface most groundwater has limited oxygen content, and where organic carbon is present nearly all oxygen is quickly consumed. In the absence of "free" oxygen, the most accessible remaining source is sulfate in zones of gypsum and anhydrite. Oxidation of organics, with simultaneous reduction of sulfate, produces H_2S and HCO_3^-, among other things. The most likely source for the H_2S-rich water is the Delaware Basin, which contains sulfate rocks as well as abundant hydrocarbons (Hill 1987, 1990). Water analyses from oil wells in the basin also show abundant hydrogen sulfide (Wiggins *et al*. 1993). The patterns of the largest Guadalupe caves are most compatible with this source.

However, several alternative H_2S sources may have contributed to cave origin, and their relative importance has yet to be determined. As in seacoast aquifers, H_2S may have been generated in sulfate-rich brines beneath a fresh-water lens, and speleogenesis could have been augmented by mixing between the fresh and saline water (Queen 1994). In the McKittrick Hill caves, some gypsum reduction may have taken place right in the cave-forming zone in the presence of hydrocarbons, which still impart an oily smell to the bedrock and calcite spar (M. J. Buck, pers. comm., 2000). H_2S could also have been carried by groundwater flow from the northwest, up the dip of the Capitan Formation, from low areas near the present city of

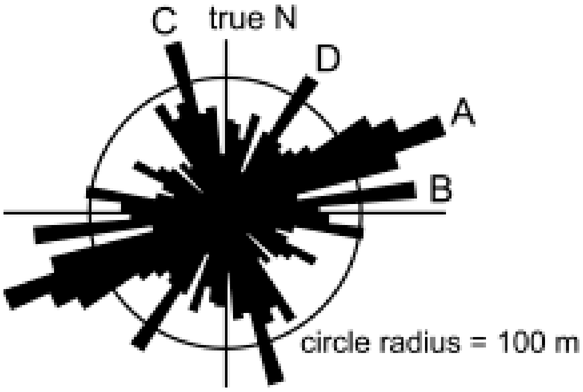


Figure 6. Rose diagram of compass azimuths from the geologic survey of Lechuguilla Cave (including Entrance series, Rift area, Southeastern Branch). A - D = major trends of fissure passages.

Figure 7. Main passage of Ogle Cave, oriented along trend C shown in figure 6.

Carlsbad (DuChene & McLean 1989).

Hydrogen sulfide in solution forms a mild acid as the result of its dissociation to H^+ and HS^-, especially at pH values above 7, but the build-up of HCO_3^-, in combination with Ca^{++} from the sulfate rocks, causes calcite supersaturation at the sites of sulfate reduction. The resulting solution is unable to dissolve further calcite, and in fact often precipitates it. Thus, the H_2S-rich water that rose into the Guadalupes during cave development was almost certainly near saturation with respect to calcite, and probably also dolomite.

The water also contained much sulfate that escaped reduction. When this water emerged into the cave-forming area, it was already well on its way toward gypsum saturation, which gave the water a head start in depositing subaqueous gypsum in the caves. The water also contained much carbon dioxide, but although it allowed high saturation concentrations of carbonate minerals, saturation had already been achieved, and so the CO_2 did not take an active role in cave development. These characteristics are typical of similar waters in other karst areas. For example, water rising into limestone from oil fields in Tabasco, Mexico, has been measured to be almost exactly at calcite saturation, only slightly undersaturated with dolomite, more than 60% saturated with gypsum, and having a PCO_2 of 0.1 atm (Palmer & Palmer 1998). A literature review shows that most sulfur springs throughout the world have similar chemistry.

Gases can rise through water as buoyant bubbles, following continuous fractures in an ever-ascending pattern. In contrast, gases in solution must be conveyed by water flow or molecular diffusion. The distinction between gaseous and aqueous transport is important, because it determines the paths by which H_2S entered and moved through the cave-forming zone. A dissolved gas forms bubbles only where its equilibrium partial pressure exceeds the static groundwater pressure. The partial pressure of H_2S in atmospheres is about 10 times its molar concentration. The relationship between H_2S concentration and maximum depth at which degassing can take place is shown in figure 9. At lesser depths, some H_2S forms bubbles, while the remainder stays in solution.

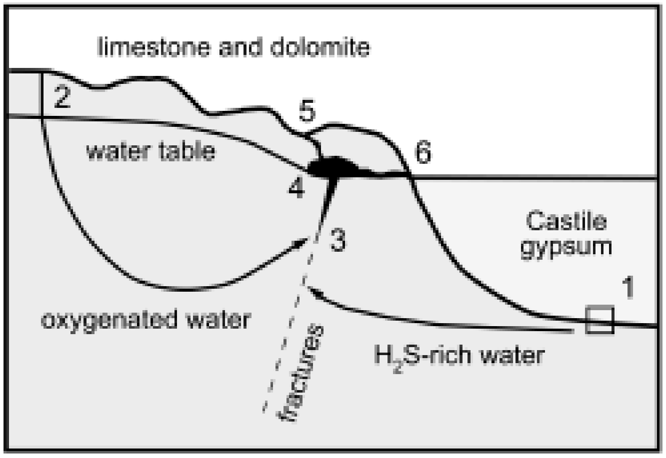


Figure 8. Idealized diagram of flow patterns and processes during cave origin. 1 = possible sites of gypsum reduction (after Hill 1987); 2 = infiltration of fresh water from high mountains; 3 = rifts formed by mixing of the two water sources below the water table; 4 = large rooms and passages formed at sites of rapid H_2S oxidation at the water table; 5 = passages ascending to former spring outlets, later enlarged by corrosion where H_2S was absorbed by vadose moisture; 6 = passages to progressively lower spring outlets. The level of water-table cave development was not necessarily at the elevation of the top of the Castile gypsum.

Wiggins *et al.* (1993) reported an H_2S concentration of 600 mg/L in the Henderson oil field in the Delaware Basin, 120 km east of the Guadalupe Escarpment. A maximum of 394 mg/L was measured in sulfur springs in Tabasco, Mexico, and 103 mg/L in the well-known sulfur spa at Sharon Springs, New York (Palmer & Palmer 1998). Egemeier (1981) measured 6 mg/L in Lower Kane Cave, Wyoming, and 15 mg/L at nearby Hellespont Cave. Movile Cave in Romania contains 10 mg/L (Sarbu *et al*. 1996). Even in these well-known examples of active H_2S systems, the concentrations are not enough to form gas bubbles more than a couple of meters below the water surface (Fig. 9). Thus, the vast majority of H_2S involved in Guadalupe cave development probably arrived in aqueous form.

On a molar basis, methane (CH_4), the most common natural gas, is only ~1.3% as soluble in water as H_2S. Carbon dioxide (CO_2) is ~35% as soluble as H_2S. It is possible that some H_2S was carried by bubbles of these gases, although the depth of degassing is still rather limited (Fig. 9), and the process is not often observed at H_2S springs.

H_2S can also migrate toward oxidizing zones by molecular diffusion. As H_2S is consumed by oxidation, a concentration gradient develops in that direction and H_2S diffuses toward lower concentrations. Fissures extending downward to deep

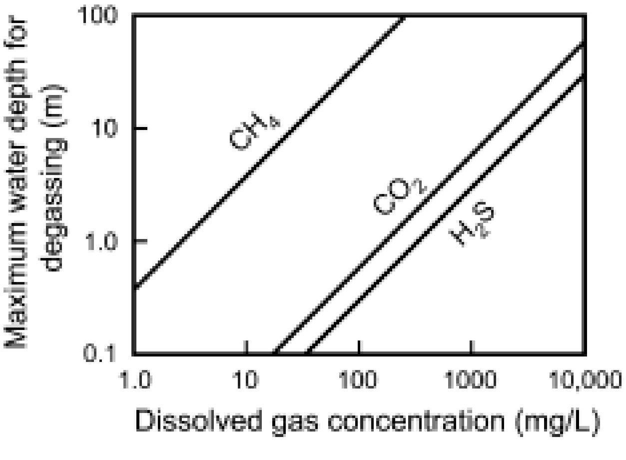


Figure 9. Maximum depth at which degassing of H_2S, CO_2, and CH_4 can take place below the water table. Partial degassing of a gas takes place at depths below its respective line, but no degassing can take place above the line.

anoxic water could potentially serve as paths for diffusion. The steady-state diffusion equation is

$$q = -D \frac{dC}{dx} A \qquad (4)$$

where q = transfer rate of dissolved components (g/sec), D = diffusion coefficient (cm²/sec), dC/dx = local concentration gradient (g/cm³ per cm), and A = cross-sectional area across which the diffusion takes place (cm²). The minus sign adjusts for the negative gradient. D varies with temperature, chemical species, porosity pattern, and very slightly with concentration; a typical value is 1.5×10^{-5} cm²/sec. Eddies or convection, if present, can greatly increase the transfer rate but are not covered by Eq. (4).

As a feasible example, consider a vertical fissure 100 m deep, with a horizontal cross section 10 cm x 10 m, and with constant H_2S concentrations of 500 mg/L at its base and 10 mg/L at its top. Eq. (4) shows that diffusion alone could deliver only 0.23 gram of H_2S per year. If the entire amount is converted to sulfuric acid (rarely true), and all the acid is expended in dissolving limestone, the dissolved calcite would total only about 0.25 cm³/yr. Apparently H_2S diffusion alone cannot produce caves unless unusually steep concentration gradients persist through large openings for very long times.

Nature of the Oxygen Source

To produce the Guadalupe caves, the rising H_2S-rich water had to mix with oxygen. This is abundant at the water table, and much sulfuric-acid production appears to have taken place there. However, long ascending passages (discussed later) show that some mixing must have taken place as much as hundreds of meters below the water table.

The only feasible source for oxygen at such depth was fresh water that infiltrated at higher elevations in the Guadalupes and followed deep flow paths on its way to springs (Fig. 8). Guadalupe caves enlarge upward toward former water tables, indicating that the oxygen was not generated at depth. Oxygen levels are low in most groundwater, but less so in mountainous areas because the soil is thin and poor in organics, which easily consume oxygen. Measurements of dissolved oxygen in well water in the Basin and Range province in Nevada and Arizona show rather consistent oxygen levels of 2-8 mg/L (Winograd & Robertson 1982). The Guadalupe Mountains are part of this geomorphic province, and although today's measurements tell nothing of the conditions that may have prevailed while the caves originated in the late Tertiary Period, the presence of oxygen in groundwater today is a promising indicator of past conditions under similar climates.

Water wells are scarce in the Guadalupes, since the area is mainly federal land. The chemistry of the water supply at the Dark Canyon Lookout (near Cottonwood Cave) has been measured by state agencies (reported by Hill 1987: 20). From this information, equilibrium calculations show that the water is essentially at saturation with calcite and dolomite and highly undersaturated with gypsum. By itself, this water is not capable of producing deep caves in limestone or dolomite.

Groundwater Flow Patterns During speleogenesis

Guadalupe caves extend into some of the highest topography of the region. For example, the entrance passages of Carlsbad Cavern and Lechuguilla Cave are nearly at the tops of their local ridges. Yet the cave morphology indicates that these passages were originally outlets for rising groundwater. Only those parts of the Guadalupe Mountains to the southwest of the main cave areas rise to substantially higher elevations, and they were the likely sources for oxygenated groundwater (Fig. 8). At that time (probably in the Miocene; see Hill 2000), sediments in the Delaware Basin extended nearly to the top of the Guadalupe Escarpment, and nearby surface rivers were essentially at the same elevation.

The great vertical range of passages in many of the caves shows that rising water must have been chemically aggressive to depths as much as 200 m below the surface. H_2S-rich water could easily have come from still deeper sources, but oxygenated water was an equally important part of the aggressive mixture and probably its major flow component. Considerable meteoric groundwater must have followed deep flow paths along joints and faults, which are especially prominent in the vicinity of the Guadalupe Escarpment, where the majority of cave development has taken place. A depth of several hundred meters is only a small percentage of the maximum possible horizontal distance between infiltration sources and springs.

Hill (1987, 2000) considered that the H_2S was generated at or near the base of the Castile gypsum and migrated upward through underlying non-evaporite strata, since the plastic nature of the gypsum gives it a very low permeability by sealing joints. She concluded that the sandstone beds of the directly underlying Bell Canyon Formation were among the favored paths. But how did the H_2S-rich water rise from reducing zones at lower elevations? This is no problem if the water table above the source was higher than at the outlet. Even today, the water table in parts of the Gypsum Plain at the foot of the mountains lies as much as 100 m higher than that in the cavernous Capitan reef (Sares & Wells 1987). The high permeability of the cavernous carbonate rock allows efficient groundwater drainage toward the northeast.

Another mechanism may have helped move the H_2S water. It is common in sedimentary basins for accumulation of sediments and tectonic forces to raise the hydrostatic pressure to values greater than could be achieved by water depth alone. Such "overpressured" water is able to escape along paths of weakness, typically around the margins of the basin, and can rise to elevations higher than that of the water table above its source area. Such flow tends to be episodic, driven by occasional tectonic stresses and released to the surface by fracturing. It alternates with lengthy dormant periods. This scenario fits the Guadalupes better than steady-state flow in the direction of a sloping water table, as shown later. Yet it is not certain that overpressuring was the only mode of H_2S expulsion, or even the dominant one.

Mylroie *et al.* (1995) noted that the morphology of Guadalupe caves and their origin by mixing of oxygenated and

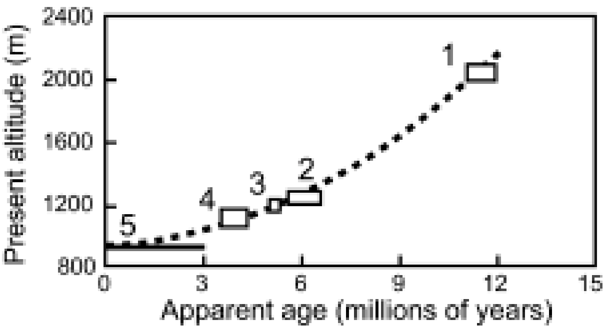


Figure 10. Age vs. elevation for several cave levels in the Guadalupe Mountains (from Polyak *et al.* 1998). 1 = Cottonwood Cave and Virgin Cave; 2 = Endless Cave and Glacier Bay (Lechuguilla Cave); 3 = Lake Lebarge (Lechuguilla Cave); 4 = New Mexico Room, Big Room, and Green Clay Room (Carlsbad Cavern); 5 = present water table.

H_2S-rich water resembles the morphology of seacoast caves in porous limestone and their origin by mixing between fresh water and saltwater. Diffuse flow through a seacoast aquifer produces caves in mixing zones and exits as diffuse flow once again, producing isolated chambers. This is a reasonable comparison, although most flow in the Guadalupes is focused along major fissures, and the exiting water usually follows discrete passages. This model may help to explain the origin of rooms that seem to lack outflow passages at the level of maximum cave development.

The temperature of the cave-forming water was probably not much above the ambient groundwater temperature of today (16-20°C). In aqueous solutions warmer than about 35°C at atmospheric pressure, anhydrite is the stable calcium sulfate, rather than gypsum. The equilibrium temperature drops with increasing pressure. Microscopic examination by M.V. Palmer has so far shown no evidence for anhydrite or pseudomorphs of former anhydrite in the gypsum wall crusts in Guadalupe caves, including replacement crusts of phreatic origin.

Constraints on Cave-Forming Processes

Although it is difficult to reconstruct the exact conditions during cave development, it is still possible to establish some limits on the processes and their rates. The ultimate time limit for cave origin in the Guadalupes is given by radiometric dating of the clay mineral alunite, which is a by-product of sulfuric acid speleogenesis (Polyak *et al*. 1998; Polyak & Provencio 2000). The highest sampled sites appear to be about 12 Ma old (Fig. 10). The age decreases downward at a decelerating rate, which indicates a slowing of tectonic uplift and water-table decline with time. The size of the sampled rooms and passages, plus the presence of massive gypsum (or clues of its former presence), show that these sites were probably produced by high dissolution rates at former water tables. Figure 10 suggests at least half a million years for any of the sampled levels to form.

During large H_2S influxes, the delivery rate of oxygen was the limiting factor in cave development, and enlargement rates varied with the production rate of sulfuric acid. Whenever H_2S was absent, as it is today, phreatic dissolution of carbonate rock virtually ceased, although vadose condensation-corrosion may have continued. On a molar basis, the production of sulfuric acid requires twice as much O_2 as H_2S (reaction 1), and at the low oxygen concentrations in groundwater, the optimum rate of phreatic cave enlargement would be achieved by a flow of meteoric water considerably larger than that of H_2S-rich water. Bacterial mediation can greatly speed the oxidation rate, and conversion of H_2S to sulfuric acid in a single step (reaction 1) may require the intervention of certain species of sulfur-oxidizing bacteria (Ehrlich 1996: 514).

In most sulfur springs, contact with oxygen is very limited until the water emerges at the surface. The Guadalupe caves owe their unusual character to the abundance of oxygenated groundwater, which allowed cave development to begin far upflow from the springs. As the caves enlarged, air exchange with the surface allowed still greater enlargement rates. Where dissolved H_2S or O_2 concentrations were small, the cave enlargement rate could be kept high by a large discharge, although oxidation would have been spread over longer distances, causing more H_2S to escape at the springs.

It is difficult to separate the effect of sulfuric acid from that of carbonic acid, because not only does most groundwater have a fairly high CO_2 content, but CO_2 is also generated by dissolution of carbonate rocks by sulfuric acid. If some of the generated CO_2 is retained within the caves, dissolution is greatly enhanced (Fig. 11). Very high CO_2 concentrations can retard dissolution of carbonate rocks by sulfuric acid, since CO_2 is a by-product (reactions 2 and 3), but sufficiently high CO_2 levels are rarely, if ever, achieved in carbonate aquifers.

It is logical to think of sulfuric acid as a far more potent cave-former than carbonic acid. This is not necessarily so. Although sulfuric acid is diprotic (supplying two H^+ ions), in general only one reacts with limestone, while the other combines with HCO_3^- to produce CO_2. In a moderately closed environment the CO_2 builds up, increasing the amount of dissolved limestone that can be held in solution. However, under totally closed conditions oxygen is unable to enter the system to produce sulfuric acid. Under typical field conditions, sulfuric acid generated from H_2S can increase the amount of dissolved limestone by only about 30-50% (see Fig. 11). But if oxygen is available deep within an aquifer, as in the Guadalupes, most of the solvent capacity of sulfuric acid is expended on cave development. In contrast, the carbonic acid dissolution typical of most karst areas is dispersed over long flow distances, and most of it is consumed at and near the bedrock surface, leaving relatively little for cave enlargement at depth.

With a few assumptions, it is not difficult to estimate the mass of H_2S needed to produce the Guadalupe caves, or at least a representative volume of cave. If all the H_2S is consumed in reactions (1) and (2), one mole of H_2S (34 g/mole) would dissolve one mole of calcite (100 g/mole), regardless of whether an intermediate sulfur phase is involved, or whether gypsum is a temporary by-product. If the limestone is nearly pure calcite (density = 2.7 g/cm³), the dissolution of 1 m³ of calcite would require 9.18×10^5 grams of H_2S. Conversion to volume of H_2S-bearing water within the source area could be misleading, because H_2S continued to be generated over a long time within the source area while it migrated out elsewhere, and was not simply depleted from static storage. To produce this amount of H_2S by reduction of sulfate (a 1:1 molar conversion) would require 2.0 m³ of gypsum or 1.2 m³ of anhydrite. In the simple model assumed here, the required volume of gypsum would be twice as great as the volume of cave dissolution.

To maintain the mass balance, the rate of cave enlargement (volume/time) must equate to $Q\Delta C/\rho$, where Q = groundwater discharge, ΔC = increase in dissolved solids between the incoming and outflowing water, and ρ = density of the soluble bedrock. Consider that the discharge through a given cave passage is 10 L/sec, and that H_2S is carried in at 100 mg/L (0.003 mole/L) in a solution saturated with calcite and containing 0.001 mole/L CO_2. These conditions fall within the range of observed H_2S systems elsewhere. If the ambient CO_2 in the cave air is 0.01 atm and there is sufficient oxygen to convert all the H_2S to sulfuric acid, figure 11 shows that ~200 mg/L of additional $CaCO_3$ could be dissolved. At a discharge of 10 L/sec, this amounts to ~23 m³ of limestone per year. At that rate, even the largest cave rooms in the Guadalupes could form in less than 100,000 years. Not all of this potential is achieved, because some H_2S may not convert to sulfuric acid. Much of the reaction with limestone produces gypsum, which complicates the volume estimate. Despite the many uncertain variables, this plausible example shows how potent this mode of speleogenesis can be.

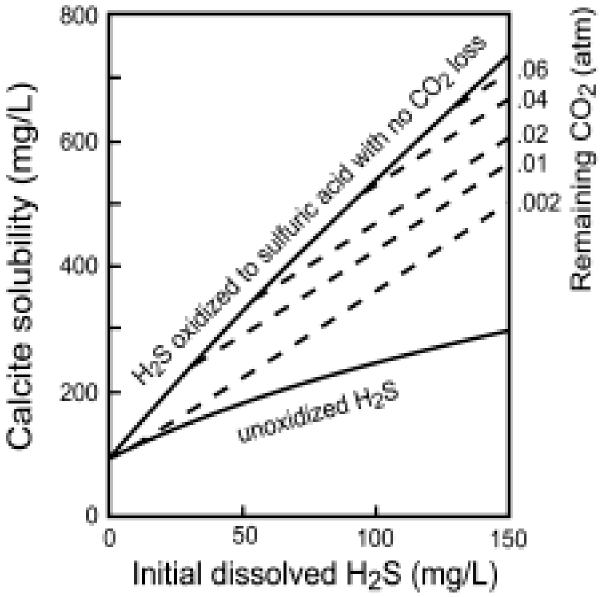


Figure 11. Increase in calcite dissolution caused by oxidation of H_2S to sulfuric acid. Initial CO_2 concentration is 0.001 mole/liter. Lower line = calcite saturation in the initial H_2S–CO_2 solution. Upper line = calcite saturation after complete oxidation of H_2S to sulfuric acid, with no degassing of CO_2. Dashed lines show diminished dissolution if CO_2 degassing takes place. After Palmer (1991).

GYPSUM DEPOSITION AND BEDROCK REPLACEMENT

Sulfuric acid cave origin is not a simple matter of dissolution of carbonate rock. Incoming H_2S-rich water contains at least a moderate concentration of dissolved gypsum, and oxidation of H_2S raises the sulfate content still farther. As carbonate rock dissolves, the release of calcium can force gypsum to precipitate if the influx of fresh water is not too large. Much gypsum has precipitated in such a delicate balance with carbonate dissolution that the net result resembles a direct replacement of the carbonate bedrock. Gypsum deposition can diminish the rate of cave growth by filling some of the void space in the carbonate rock. Fresh groundwater or infiltrating seepage can later carry away the gypsum, continuing to enlarge the caves long after the H_2S source has become inactive.

The texture of gypsum remnants can shed light on their origin, and therefore on the origin of the host passage or cave room. Buck *et al*. (1994) described the origin and petrology of five types of gypsum in Guadalupe caves: (1) subaerial gypsum crust that has replaced bedrock by the sulfuric acid reaction; (2) subaqueous gypsum crust of the same origin; (3) subaqueous gypsum sediment; (4) breccias of fallen gypsum blocks; and (5) evaporitic gypsum.

Gypsum replacement of calcite can take place by the following reaction:

$$2H^+ + SO_4^{2-} + CaCO_3 + 2H_2O$$
$$\Leftrightarrow \quad CaSO_4 \cdot 2H_2O + H_2O + CO_2 \qquad (5)$$

Dolomite reacts in a similar way. Where sulfuric acid is generated in contact with carbonate rock, it is difficult to achieve pH values less than about 6 because the acid is almost immediately neutralized by the carbonate. Very low pH can be reached if the acid is shielded from the carbonate rock by a rather non-reactive material such as gypsum, chert, clay, or organic material. Some water droplets isolated from the carbonate bedrock by gypsum crusts in Cueva de Villa Luz, Mexico, have pH values below 0.1 (Palmer & Palmer 1998).

Subaerial gypsum crusts form by reaction (5), which involves an approximate mole-for-mole replacement of carbonate rock (the reaction is often not perfectly balanced). The gypsum occupies a larger molar volume, so the crust expands to a greater volume than the rock it replaces. As a result the crust tends to be blistered and poorly bonded to the host rock, so it easily falls as fragments to the cave floor. In contrast, subaqueous crusts appear to have replaced the bedrock on a volumetric basis, in which each volume of carbonate rock is replaced by a roughly equal volume of gypsum. This is shown by the inheritance of textures from the original bedrock, such as bedding, pisoliths, and fossils (Fig. 12). These features are preserved almost intact, as verified by comparison with adjacent bedrock exposures (Queen 1973; Queen *et al*. 1977; Buck *et al*. 1994), although later recrystallization of the gypsum can disrupt the textures. The reaction probably involves ionic diffusion through the porous gypsum crust. Endless and Cottonwood Caves contain excellent exposures of this type of crust, which in places lines entire passages. Later dissolution along the bedrock-gypsum contact by vadose seepage often causes the gypsum crust to slump into the passage, forming a gypsum-lined tube within a larger bedrock tube.

By an odd coincidence, an almost perfect volume-for-volume replacement of limestone by gypsum can be achieved if one gypsum molecule replaces two calcite molecules, because the molar volume of gypsum is almost exactly twice that of calcite (precisely 2.02 times). This exchange can occur in the following way:

$$2H^+ + SO_4^{2-} + 2CaCO_3 + 2H_2O \Leftrightarrow CaSO_4 \cdot 2H_2O + Ca^{2+} + 2HCO_3^- \qquad (6)$$

This reaction is balanced if the solution remains supersaturated with gypsum and undersaturated with calcite. The pH must remain high enough (greater than about 6.4) to suppress the tendency for H^+ to react with bicarbonate to form H_2CO_3 and CO_2. These conditions are most common in phreatic water that is close to equilibrium with carbonate rock. Typical groundwater in active sulfuric acid caves has sufficiently high pH values, 0.001-0.01 M bicarbonate, and molar Ca/SO_4 ratio about 1.0. Under these conditions, the phase relationships between gypsum and calcite, according to reaction (6), are shown in figure 13. As pH rises, the reaction can proceed to the left of the equation, allowing calcite to replace gypsum; meteoric groundwater in karst normally satisfies these conditions. Dolomite can react in a similar manner, except with a 1:1 ratio of dolomite to gypsum. Because the molar volume of gypsum is 1.15 times greater than that of well-ordered dolomite, the volume expansion during replacement tends to disrupt initial bedrock textures more than in the case of limestone.

Figure 12. Gypsum replacement of dolomite, with preservation of original bedrock textures (dolomite above, gypsum below), in the upper level of Endless Cave. Only close examination can verify the inheritance of textures by the gypsum. Width of photo is 0.5 m.

INTERPRETATION OF CAVE PATTERNS

In humid karst, caves are best interpreted in relation to the history of the river valleys into which they drain. This approach has merit in the Guadalupes, too, but the relationships are obscure. It is more appropriate to examine separately the origin of the features that make up a typical Guadalupe cave. Each cave can then be deciphered according to its individual layout and character.

CAVE ROOMS

The most impressive aspect of Guadalupe caves is the great size of their largest rooms. In humid karst, most cave rooms are formed by the intersection of two or more passages, often accompanied by breakdown. In contrast, cave rooms in the Guadalupe Mountains were formed by intense dissolution in local areas of sulfuric acid production. It is common for such a room to connect only to minor passages that seem unsuited to the task of conveying aggressive water to such a grand site. The Guadalupe Room of Carlsbad Cavern, for example, is reached by a network of narrow fissures, none of which gives the impression of large spaces beyond. The room was formed by local aggressiveness from rising H_2S, and the passages that connect it to the Main Corridor are only peripheral enlargements.

Irregular outlines, dead-end galleries, and blind alcoves are typical of Guadalupe cave rooms. Some rooms and adjacent passages have nearly horizontal floors. For example, the Big Room and adjacent Left Hand Tunnel of Carlsbad Cavern have a remarkably consistent floor elevation of 1110 m over much of their area. Some rooms have distinct notches in their walls at the level of maximum dissolution (Buck *et al*. 1994). Persistent elevations of this type, and their disregard for stratigraphic boundaries, almost certainly indicate water-table control, with aggressiveness produced at an air-water interface. Fissures are common in the floors of many cave rooms, and they are the likely sources for rising hydrogen sulfide (Fig. 14).

The oxygen demand in producing a large room cannot easily be met without plentiful air exchange with the surface, so it is not surprising that most of the largest cave rooms connect to the surface via older ascending phreatic passages. The rooms postdate the initial ascending passages, but the relict passages contribute to their enlargement by serving as conduits for oxygen exchange. In the absence of an open cave passage, air can also be exchanged in limited quantities through narrow fissures

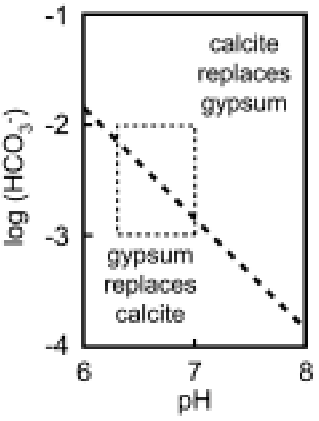


Figure 13. Stability fields for volumetric gypsum replacement of calcite (lower left) and calcite replacement of gypsum (upper right) as a function of pH and bicarbonate activity, according to reaction (6), at 25° C with molar Ca/SO$_4$ ratio of 1.0. For gypsum to replace calcite, (Ca^{2+})(SO_4^{2-}) must exceed 3.2 x 10^{-5}. For calcite to replace gypsum, (Ca^{2-})(CO_3^{2-}) must exceed 3.3 x 10^{-9}. The equilibrium line shifts slightly to the right as temperature decreases. The dashed rectangle shows typical conditions in present karst sulfur springs.

in the overlying bedrock. Despite the need for an oxygen supply, however, the greatest dissolution rates must have been limited to rather closed environments where high CO_2 levels could be sustained (as suggested by Fig. 11). The Main Corridor and Entrance Passage of Carlsbad Cavern provide an example of the open but indirect communication with the surface that favors the origin of large rooms. Some rooms and galleries, such as the entrance section of Cottonwood Cave, are open directly to the surface now, but probably were connected by less-direct routes before they were intersected by the present canyons.

Some rooms have uneven floors simply as the result of breakdown or gypsum accumulation. Others with irregular or sloping floors may have been generated by local mixing between H_2S-rich and oxygenated water below the water table (e.g., Prickly Ice Cube Room, Lechuguilla Cave). The presence of thick gypsum in some of them indicates either that sulfuric acid production can be very intense even below the water table, or that these rooms were formed at a dropping or fluctuating water table.

Gypsum precipitation and bedrock replacement can take place with little net increase in room volume unless the gypsum is later removed by fresh groundwater. The ceilings of major cave rooms are typically smooth and arched, and they almost invariably show evidence of gypsum replacement (Fig. 3). In some rooms large gypsum blocks still remain on the floor (e.g., the Big Room in Carlsbad). Many blocks contain smaller fragments of gypsum that have fallen from the ceiling (Hill 1987). Upward enlargement of rooms by vadose gypsum replacement has been documented in active H_2S caves such as Lower Kane Cave in Wyoming (Egemeier 1981) and Cueva de Villa Luz in Mexico (Hose & Pisarowicz 1999).

ASCENDING PASSAGES

Certain passages have remarkably steep profiles. They include inclined and vertical fissures that extend along joints and faults, as well as tubular passages controlled mainly by bedding in the back-reef strata. Both show strong evidence for having been formed (or at least initiated) by rising aggressive water.

Some fissures, also known locally as “rifts,” extend downward from the floors of large rooms or passages and simply pinch downward with bottoms that are clogged with calcite crust or carbonate sediment. Examples include the route to Sulfur Shores in Lechuguilla Cave (Fig. 15) and the Four O’Clock Staircase, a 100-meter-deep vertical fissure in Virgin Cave. These fissures extend below the level of major cave enlargement and appear to be the inflow routes along which oxygenated and H_2S-rich water first began to mix. Active examples occur in Lower Kane Cave, Wyoming (Egemeier 1981), but they are narrower than the typical Guadalupe rifts. If H_2S oxidation is limited to the points where water emerges into air-filled passages or at the surface, significant enlargement does not take place deep inside the ascending fissures. Mixing between oxygen-rich and H_2S-rich flow paths below

Figure 14. Rift in the floor of the main passage of Hell Below Cave, through which an aggressive mixture of H_2S-rich water and oxygenated water rose.

the water table must have been responsible for the deep rifts in Guadalupe caves.

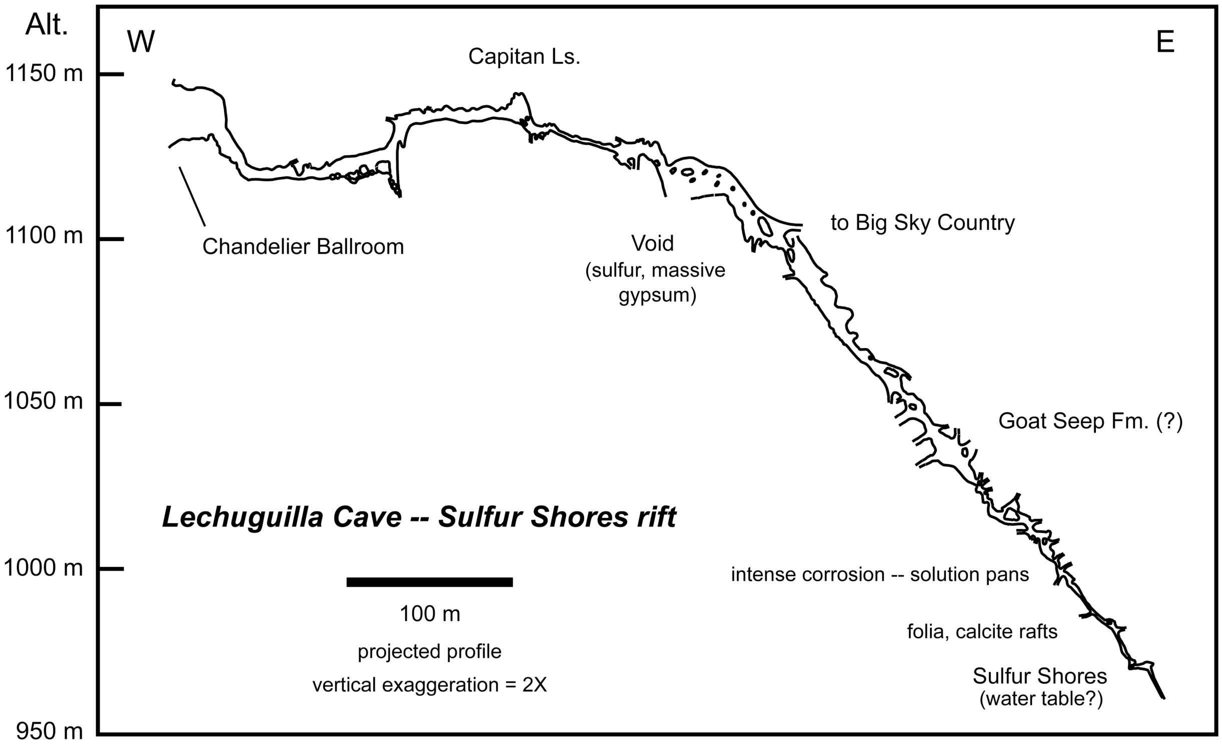
Many ascending passages connect different levels or serve as entrance passages to the caves (Fig. 16). Some are fissures, such as the Great White Way and the rift above Lebarge Borehole in Lechuguilla Cave (Fig. 17), while others are mainly tubular with only local fracture control. The entrance series of Carlsbad Cavern (Fig. 4), Hicks Cave (Fig. 5), and Lechuguilla Cave (Fig. 18) are all ascending passages with mainly tubular shapes. Such entrances give the superficial impression that they were once surface-water inlets, because they descend steeply from surface gullies or from the walls of canyons. The Carlsbad entrance even swallows a sinking stream during heavy rainfall. However, there is no evidence that they were vadose inputs while the caves were forming. They contain no stream entrenchment or fluting, and virtually no truly vertical shafts or coarse clastic sediment. Instead, the passage ceilings rise in a series of smooth convex-upward arcs quite distinct from the abrupt stair-step pattern typical of vadose passages. Local confinement by resistant beds can force rising passages to follow an up-dip course, accounting for the northwesterly trend of the entrance passages shown in Figures 4, 5, and 18. Abrupt discordance of such passages to the strata is common only along prominent fractures or cross-cutting structures. For example, Boulder Falls, shown in figure 18, follows a vertical breccia dike.

Like the narrow rifts described above, ascending tubes appear to have formed in one stage by aggressive solutions in which mixing of the two major water sources had already taken place. Some have enormous cross-sectional areas and vertical ranges. The descent through the entrance and Main Corridor of Carlsbad Cavern is breathtaking. The entrance series of Lechuguilla Cave (Fig. 18) rises from the Rift to the cave entrance over a vertical range of at least 200 m. The Wooden Lettuce Passage is a possible precursor to the entrance passage that extends even higher, and it is possible that the Rift itself was the original feeder, extending the vertical range still farther. There seem to be no alternate flow routes, which suggests that the entire passage formed simultaneously below the water table, although enlargement of its rooms probably took place at a later time at or near the water table.

Alternatively, some of the ascending passages may have started as narrow channels that were greatly enlarged by dissolution from their upper ends downward as the water table and zone of maximum oxidation dropped with time. This would require outflow of the water at many different levels, and large rooms that interrupt the passage profiles would correlate in elevation from one passage to another. Neither characteristic is present. Guadalupe cave development was intermittent, controlled by episodes in which H_2S-rich water was released from lower strata (as discussed later), and it is likely that the inception of a typical ascending passage took place over its entire length in a single stage, rather than in small descending increments over a long time period.

Some ascending passages are interrupted by large rooms that appear to post-date the passages. Their size and the presence of massive gypsum suggests discrete episodes in which H_2S entered and was oxidized at the water table. Examples in the entrance series of Lechuguilla Cave (Fig. 18) include Glacier Bay and the room at the base of Boulder Falls. No tra-

Figure 15. Profile through the Sulfur Shores rift, Lechuguilla Cave, from geologic leveling survey by the authors. The contact between the Capitan Limestone and Goat Seep Formation is unclear.



versable passages are known to lead laterally from them to the surface. Their origin apparently involved little discharge, perhaps allowing outflow to be diffuse. Much of their volume increase has taken place by later removal of gypsum by vadose seepage, a process that continues even today.

Ascending tubes must also have enlarged above the water table by sulfuric acid generated where H_2S was absorbed by moisture on walls and ceilings. This process would be enhanced when H_2S was drawn upward along wide fissures during periods of low atmospheric pressure at the surface. It may have been possible for short passages to form entirely in this way. Replacement gypsum, a likely by-product of this process, would have been easily removed by fresh infiltrating water. Rills and other gravitational dissolution features are generally absent, because (as with condensation-corrosion) the moisture rarely forms more than a capillary film. The resulting surfaces would bear many characteristics of phreatic dissolution, complicating the speleogenetic interpretation. This mechanism should be investigated more thoroughly, because it could affect the estimates of depth and percentage of phreatic dissolution in the origin of the Guadalupe caves.

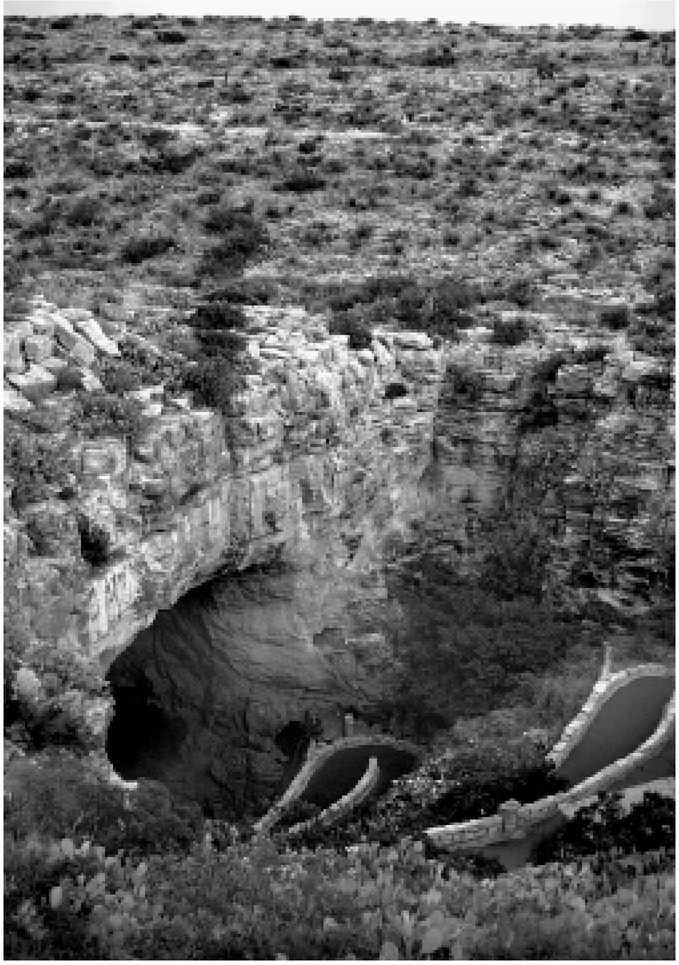


Figure 16. Entrance to Carlsbad Cavern, a former spring outlet fed by an ascending tube.

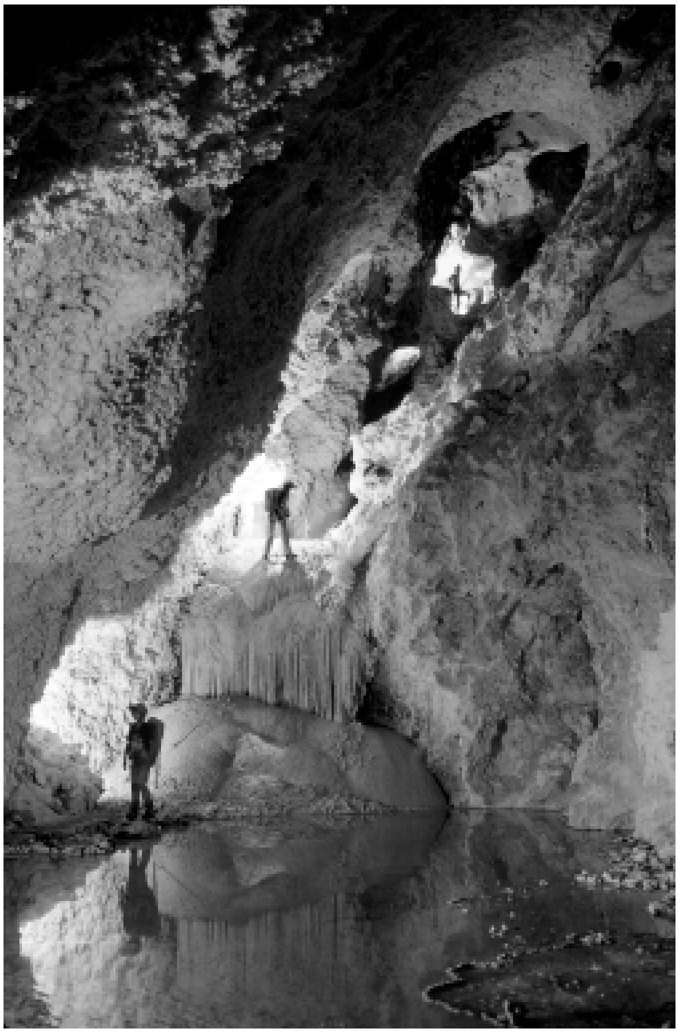
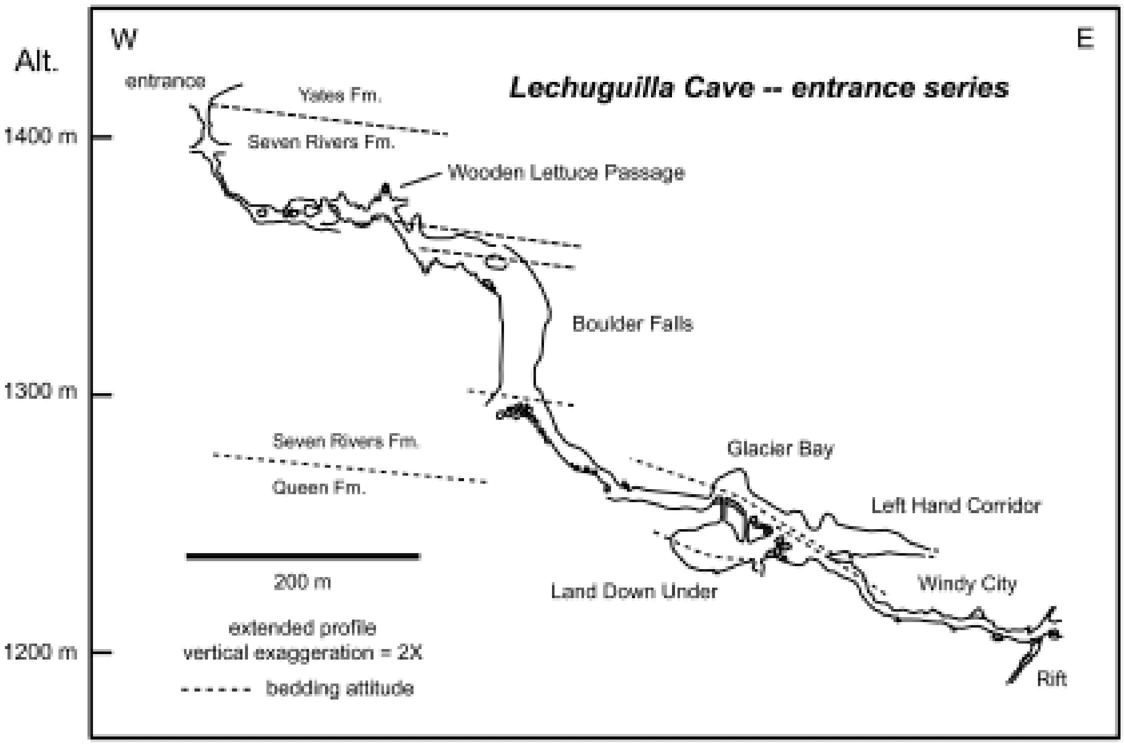


Figure 17. Lake Lebarge and the sloping fracture-controlled fissure ascending from it to higher-level passages, Lechuguilla Cave.

HORIZONTAL PASSAGES

Despite the rambling three-dimensional nature of most Guadalupe caves, certain distinct, nearly horizontal passage levels represent former water-table levels. The best documented is the Left Hand Tunnel in Carlsbad, whose floor coincides closely with that of the Big Room. Other slightly less horizontal examples, of many, include the Western Borehole in Lechuguilla Cave and the main passage of Ogle Cave (Fig. 7). Some of these tunnels once served as outlets for water from the zones of maximum cave origin, such as the outward-branching passages shown on the map of Hicks Cave (Fig. 5). They tend to diminish in size in the direction of flow because of decreasing aggressiveness. Most pinch down to fissures and spongework too narrow to traverse before reaching the surface. Cave entrances along former horizontal outflow routes at successively lower elevations, although expected, are actually quite rare.

Figure 18. Profile through the entrance passage of Lechuguilla Cave, from geologic leveling survey.



The near-horizontal trends of these passages are unaffected by stratigraphic boundaries or variations in rock texture. An example is the passage along the top of the Rift in Lechuguilla Cave, which continues southward as the E and F surveys (Fig. 19). This passage system cuts discordantly across back-reef strata, which locally have a mean dip of 7.5° SW. Water-table control is evident. Note the contrast with the entrance series, formed by ascending phreatic water, which contains sloping, stratally concordant sections (Fig. 18). The profile in figure 19 deviates from the horizontal at the southernmost extent of the F Survey. It is almost unnoticeable in the cave but is clearly shown on the expanded vertical scale of the profile. It may be the result of a mild headward steepening of the water table. Egemeier (1981) noted similar characteristics in the profile of Lower Kane Cave, Wyoming.

HORIZONTAL PARTITIONS WITHIN ROOMS AND PASSAGES

An odd characteristic of Guadalupe caves is that many of their rooms and passages are divided horizontally by thin bedrock partitions. Explorers are occasionally alarmed to find that a seemingly substantial floor is actually a frail and discontinuous shelf over a large void. In the most distinct examples, the floor of the upper level is covered with a thick deposit or replacement crust of gypsum, or there is evidence that gypsum once occupied the site.

Glacier Bay in Lechuguilla Cave is an unusual example in which a horizontal room (Land Down Under) cuts across an older sloping room (Fig. 18). The horizontal partition is about 6-8 m thick and covered with an additional 4 m of brecciated gypsum derived mostly from blocks of replaced bedrock that fell from the ceiling during cave development. The bedrock consists of silty and partly brecciated limestone and dolomite no different from that in adjacent passages, and there is no evidence that the partition consists of relatively resistant rock, nor is the partition recrystallized or dolomitized. Fluted vadose drip holes up to 2 m in diameter extend through the gypsum. Most of the holes terminate at the gypsum-bedrock contact, but a few extend all the way through the bedrock partition. Above the drip holes the ceiling shows no apparent vadose inlets such as fissures, and the drips are now inactive or nearly so.

These partitions rely on intense acidity generated at successive water-table levels. In most examples, the ceilings of both levels were enlarged upward by gypsum replacement of carbonate bedrock. During the later stage, the partition was perforated or removed entirely. While the lower level enlarged, some of the H_2S degassing from the water surface must have been absorbed by moisture on the ceiling of the upper level and prolonged the gypsum replacement of carbonate rock. Where acid drips were not entirely saturated with gypsum they could core through both the gypsum and the carbonate partition between levels.

Not every cave level relates to a former water table. Endless Cave in McKittrick Hill contains up to three superimposed labyrinths separated by bedrock partitions only a few meters thick. The resulting complexity makes a plan-view map almost indecipherable unless the overlapping tiers are depicted separately (Fig. 20). All the tiers appear to have formed simultaneously near the water table. A gypsum crust has replaced the bedrock, inheriting the bedrock textures, indicating phreatic dissolution (Fig. 12). A sequence of favorable beds and bedding-plane partings was enlarged, leaving the intervening bed remnants as partitions.

MAZES

Network and spongework mazes form parts of many Guadalupe caves, and some entire caves (e.g. Fig. 20). Mazes develop where many interconnected openings enlarge at comparable rates. This is not the way most caves form, because slight differences in flow rate or hydraulic efficiency cause larger openings to outpace the lesser ones, so that only a few reach traversable size. An effective way to form a maze is to combine high aggressiveness with short distances of flow from where the aggressiveness is produced (Palmer 1991). This criterion is amply met in the Guadalupe caves. The only major genetic difference between network and spongework mazes is the nature of the initial openings; i.e., intersecting fractures vs. intergranular pores. An impressive network maze surrounds the Left Hand Tunnel of Carlsbad Cavern (Fig. 4). Spongework is most abundant in the massive reef, which is noted for its large primary pores, and is common around the periphery of large rooms. The local term for spongework is "boneyard," in reference to the Boneyard of Carlsbad Cavern, which contains such thin remnants that it resembles a pile of bones (Fig. 21). Hill (2000) describes early spongework of Mesozoic age, which is generally of less than traversable size. Most traversable spongework mazes were produced during the major stages of Cenozoic cave development, which in many places simply enlarged the Mesozoic pockets.

Mazes originated in mixing zones where the aggressiveness was high. In the downflow direction from these sites, where aggressiveness weakened, the passages tend to unite into single conduits, except where additional H_2S inputs boosted the local acidity. Ascending high-level tubes are least likely to have maze-like characteristics, because they represent long phreatic flow paths with rather low aggressiveness. Many mazes connect large rooms or passages, some at different levels. If the mazes were part of the main flow routes, their passages would have been enlarged to a size comparable to that of the rooms. Diffuse flow into or out of the rooms was necessary to form them.

Those caves that consist almost entirely of mazes, such as Spider Cave and the caves of McKittrick Hill (Fig. 20), were themselves the sites of greatest aggressiveness. Most are in the bedded back-reef strata, particularly the Yates Formation, and have limited vertical extent. Diffuse infiltration through silty beds may have supplied the necessary oxygen. Stratigraphic trapping of rising H_2S-rich water at and near the crest of an anticline accounts for the dense concentration of McKittrick Hill caves.

Some large rooms contain spongework in their floors and lower walls, but not in their upper walls and ceilings (for example, the New Mexico Room, Carlsbad Cavern). Ash & Wilson (1985) attributed the spongework to downward migration of H^+ ions through aggressive solutions. A simpler explanation is that the growing rooms were only partly filled with water, limiting the upward extent of spongework, and upward ceiling migration by falling of replacement rinds tended to remove incipient spongework.

VADOSE DISSOLUTION FEATURES

Although much cave enlargement in the Guadalupes took place within the vadose zone where H_2S was oxidized to sulfuric acid in moisture films, traditional vadose dissolution by descending meteoric water has been almost nil. A few forms of fresh-water vadose dissolution, though accounting for only minor cave enlargement, shed light on the local cave-forming processes:

(1) Gypsum deposits are readily dissolved by vadose water, even if the water is saturated with dissolved limestone. Rills and boreholes are produced in the gypsum by high-volume drips.

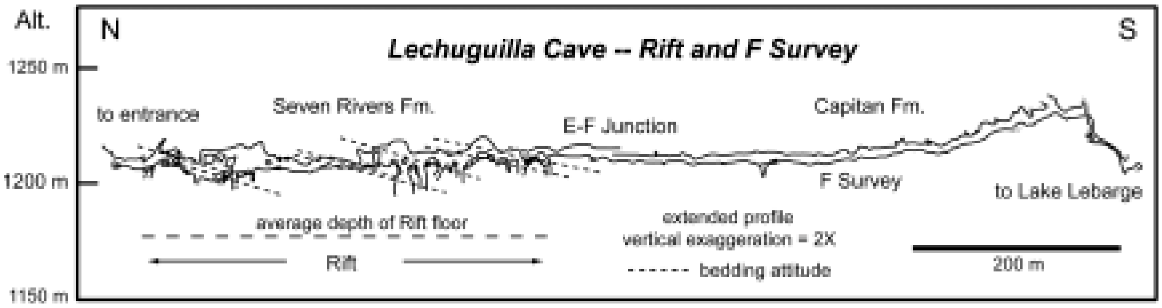
(2) Oxidation of pyrite to sulfuric acid can produce local shafts and rills in carbonate rock. An example is the Queen of the Guadalupes, a fluted shaft system that formed below a concentrated zone of pyrite weathering (Jagnow 1979).

(3) In the past, aggressive drips of sulfuric acid formed deep, narrow rills (rillenkarren) in carbonate rock (Fig. 22). The acidity of the drips is explained in the section on gypsum replacement.

(4) Condensation-corrosion occurs where warm, moist air ascends from lower levels, allowing water to condense on the walls of cooler upper levels (Queen 1981; Davis 2000). Dissolution of bedrock and speleothems is common at these condensation sites, and the dissolved minerals are drawn to zones of evaporation by capillary potential, where they precipitate as speleothems and crusts.

(5) Features that superficially resemble potholes are common in certain places, for example in the Near East and Sulfur

Figure 19. Profile through the Rift and related passages, Lechuguilla Cave, from geologic leveling survey.



Shores areas of Lechuguilla Cave (Fig. 15). These are not true potholes (i.e. erosional features formed by turbulent water), but simply the underground equivalent of the solution pans that form on limestone surfaces where rainwater collects in hollows. In the caves they were fed by local drips charged with sulfuric acid.

CORRELATION BETWEEN CAVES

Passages in many Guadalupe caves can be grouped into crude levels. As implied in the graph of cave age vs. elevation (Fig. 10), regional geomorphic history has played a significant role in determining the vertical layout of Guadalupe caves. One would expect the vertical arrangement of major passages and rooms to reflect the history of base-level lowering.

The real picture is not as simple as expected. Figure 23 compares the altitudes of the major rooms and passages in Carlsbad Cavern with most of those in Lechuguilla Cave. Aside from a few apparent correlations, the general picture is chaotic. Differential uplift rates are not sufficient to explain the muddle, because the two caves are close neighbors and the intervals between levels are just as mis-matched as the elevations. Portraying the vertical extent of a passage or room can be subjective because many of them taper upward and downward into smaller voids. Arbitrary decisions also had to be made as to which parts of Lechuguilla to omit, since the cave is such a complex tangle.

The Main Corridor of Carlsbad overlaps with almost every major passage and room in Lechuguilla. Distinct horizontal levels, such as the Left Hand Tunnel, floors of the Big Room and Lower Cave, Outback area, top of the Rift, Lebarge Borehole, and Western Borehole, are scattered inconsistently at many different elevations. The floor of the Big Room in Carlsbad overlaps in elevation with the Western Borehole, but the latter includes several different levels and its floor is quite irregular. A tentative correlation can also be made between the Chocolate High and the New Section in Carlsbad and the top of the Rift in Lechuguilla, but they do not include much cave volume. The Lebarge Borehole, main level of the Far East, and the Guadalupe Room match if a slight eastward slope is tolerated. But, in general, the anticipated precise matching between levels is elusive.

Because of the absence of widespread cave correlations, the confidence with which cave development can be related to regional geomorphic events is limited. However, an alternative and more dynamic view of cave evolution emerges. As the water table dropped, bursts of cave enlargement occurred at those times and places where H_2S was rising to the water table in significant quantity (Jagnow 1989). As the water table declined, episodic release of H_2S (probably during uplift and deformation) produced major rooms and passages. When these releases coincided with rather static water tables, distinct horizontal levels resulted. The greatest volumes and durations of gas escape were along the Guadalupe Escarpment, producing huge rooms and corridors such as those in Carlsbad, Ogle, and Lechuguilla Caves.

Under this scheme of cave enlargement, it was possible for neighboring caves to develop almost independently. Yet in places there was overlap between speleogenetic zones, resulting in erratic and rather unpredictable connections between

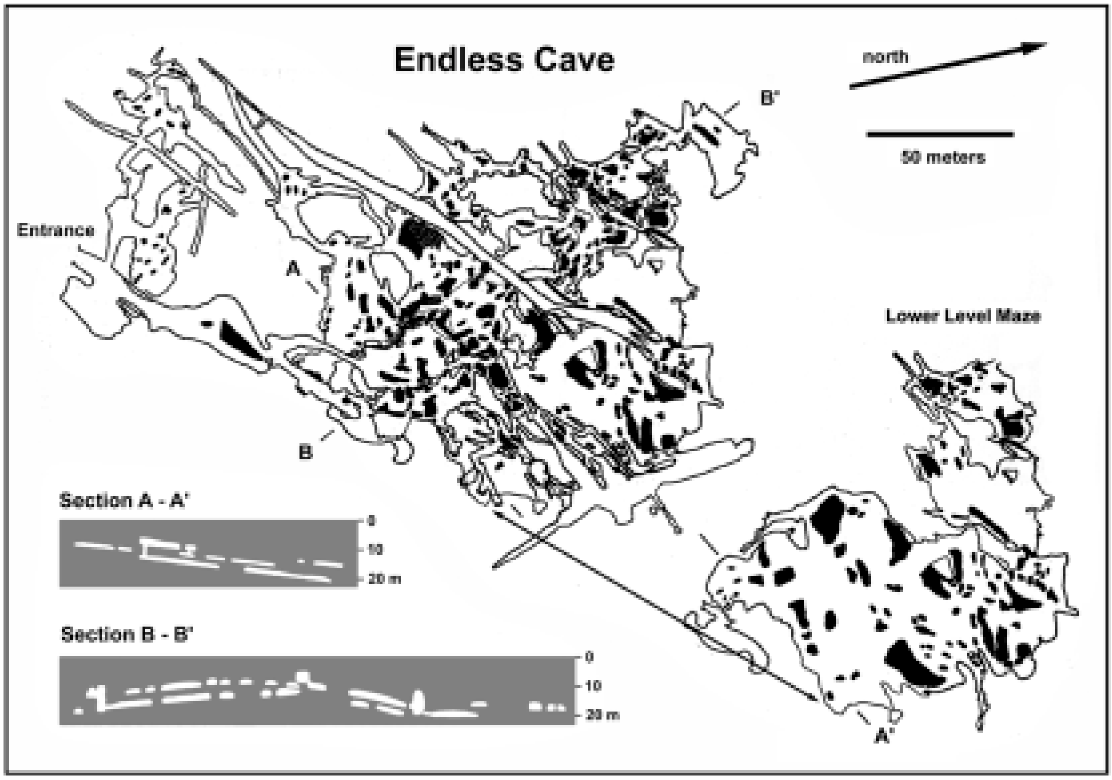


Figure 20. Map of Endless Cave, McKittrick Hill, simplified from Kunath (1978). Shaded areas on map are bedrock pillars.

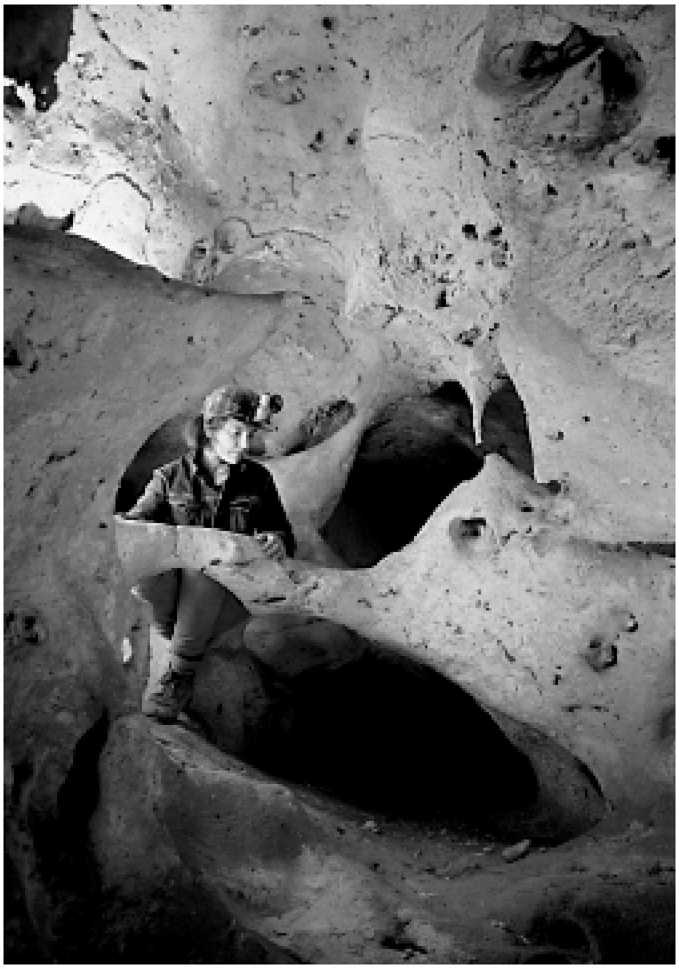


Figure 21. Spongework maze development in the Boneyard of Carlsbad Cavern.

otherwise independent caves. These connections are not necessarily traversable. Some caves, such as Spider Cave, seem isolated despite close proximity to the much larger surrounding caves (Fig. 2). Attempts by explorers to follow air movement in such caves have sometimes been frustrating. The huge air flow from several Guadalupe caves can be misleading if translated into units of cave volume, because much of it consists of passages of non-traversable size, including many fissures and pores that have undergone little if any solutional enlargement.

Certain complex Guadalupe caves were fed simultaneously by different H_2S sources. For example, the entrance series of Lechuguilla Cave was fed by water rising from the Rift area, while simultaneously (since their passages overlap in elevation) the Prickly Ice Cube Room, Underground Atlanta, and Tower Place were formed by water rising from the Sulfur Shores rift (Fig. 24). Connections between these two large areas are nearly impenetrable chutes and mazes, such as Tinseltown Maze, which were formed by minor exchange of aggressive water between the two sections as the head configuration in the aquifer changed with time.

During H_2S influxes, a given pathway would be active for a time, only to become inactive as the site of H_2S escape shifted. Some sites were active for long times, others only briefly. Some paths were occupied repeatedly, others abandoned after a single wave of activity. Although they must have varied in duration, the main episodes probably lasted at least 10^5 years to achieve such large passage and room sizes. The capricious nature of this cave development contradicts one's first impression of the Guadalupe caves as being sites of immensely stable groundwater conditions that prevailed over long periods of geologic time.

CONCLUSIONS

This paper raises as many questions as it answers. The morphology of Guadalupe caves, though well known in a general sense, could use far more quantitative evaluation. In particular, the methods for distinguishing between phreatic and vadose cave enlargement are still hazy. Further comparison with active caves of similar origin would be useful, along with a more penetrating geochemical analysis. Advances in understanding the Guadalupe caves has required a remarkable variety of researchers using tools that extend across all the sciences. And here, perhaps more than in any other cave area, the value of exploration is absolutely clear, for every new cave discovery helps to reveal more about the conditions that formed these enigmatic caves.

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Figure 22. Rills formed by ceiling drips enriched in sulfuric acid, in Far East Series, Lechuguilla Cave. Note gypsum deposition around the drip site, apparently including mole-for-mole replacement of limestone at low pH, which involves a volume increase. Height of photo = 1.5 m.

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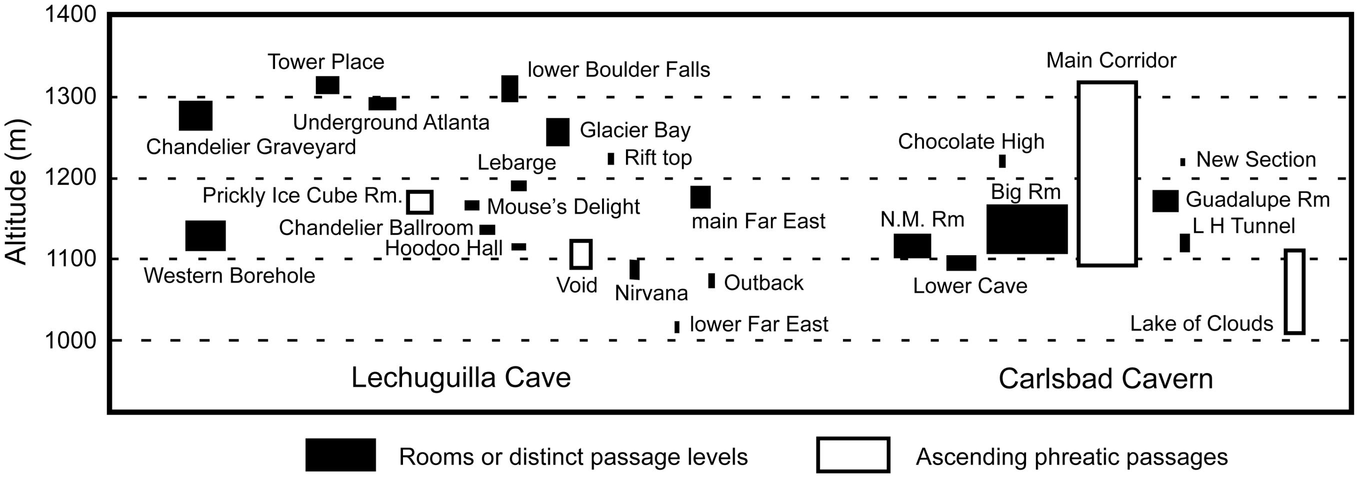

Figure 23. Elevation of major rooms and passages in Carlsbad Cavern and Lechuguilla Cave. The width of each block is proportional to the width of the room or passage. Carlsbad levels are based on data from the Cave Research Foundation (1992). Lechuguilla levels are based on geologic leveling survey, and on maps by the Lechuguilla Cave Project and Lechuguilla Exploration and Research Network.

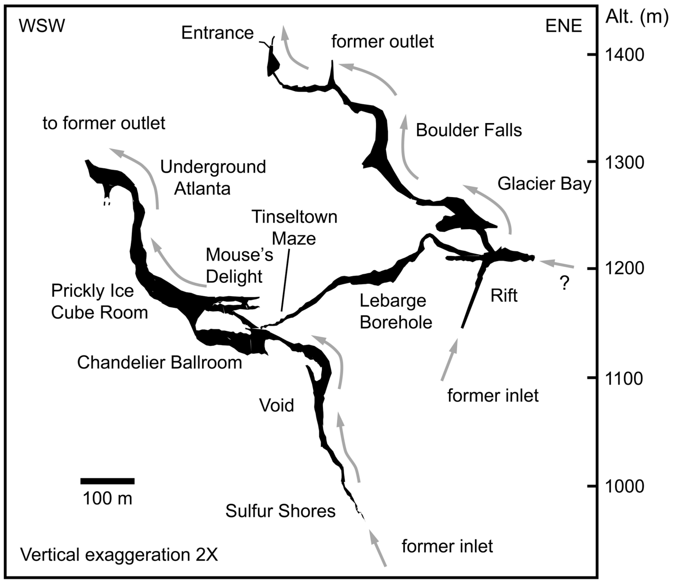

Figure 24. Projected vertical profile through part of Lechuguilla Cave (viewed from 165° with respect to true north), showing the nearly independent flow systems through the entrance series and through the Sulfur Shores - Underground Atlanta system. Based on geologic leveling survey by the authors.

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