STRATIGRAPHY, SEDIMENTOLOGY, AND STRUCTURAL GEOLOGY OF GYPSUM CAVES IN EAST CENTRAL NEW MEXICO

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ABSTRACT: Hundreds of solution caves have developed in evaporites and carbonates of the Permian San Andres Formation where it crops out between Vaughn and Roswell, New Mexico, USA. Several of the caves are over 3.2 km (2 miles) in length, and the deepest has a vertical extent of over 120 m (400 feet). These gypsum caves afford an extraordinary opportunity to examine the evaporite rocks in which they are developed. We have examined interbedded gypsum and dolostone strata exposed in the walls of 11 of these caves, and show stratigraphic sections on two geologic cross sections.

Gypsum textures exposed in the caves include massive, nodular, and laminar types. While we refer to them as "gypsum caves," gypsum is not the only lithology exposed. Some cave passages and rooms are developed in thick dolostone units intercalated with or overlain by gypsum beds. Correlation of beds exposed in two or more caves has allowed us to infer the local geologic structure.

The sedimentary sequence penetrated by a cave exerts a profound effect on the geometry and passage cross-section of the cave. Many cave passages have gypsum walls and a dolostone or limestone floor. Although many of the cave passages flood completely during major storm events, the stairstep profile of most of the caves is indicative of speleogenesis that has occurred predominantly within the vadose zone.

INTRODUCTION

Hundreds of caves in gypsum in east-central New Mexico provide an extraordinary opportunity to examine the evaporite rocks in which they are developed. The caves studied for this report are dissolved in the uppermost Fourmile Draw Member of the Permian San Andres Formation, which consists predominantly of interbedded gypsum and dolostone.

Individual beds of gypsum are exposed in the walls of the caves over distances of hundreds of meters. In contrast to surface exposures, the episodic floodwaters that continue to dissolve the caves, along with the humid cave environment, ensure that the rock surfaces of actively-forming caves are clean and well-exposed. In addition, slight differences in solubility accentuate subtle lithologic variations within and between beds. Gypsum caves therefore provide the geologist with unusually good exposures of evaporite rock textures.

In addition to the study of stratigraphy, per se, the sequence of rock layers often exerts a profound effect on cave passage development. This is perhaps more true for the caves described here than elsewhere, because the contrast in solubility and hardness between interbedded gypsum and dolostone beds is so marked. Thus, in addition to our use of the caves to study the rocks, it is imperative to examine the layering of the rocks to fully comprehend the speleogenesis of particular caves.

A third reason for studying the sedimentary sequence in the caves is that if we can identify a particularly distinctive marker bed or beds in several of the caves located some distance apart, we then have a means of defining the local geologic structure and dip of the beds.

With the above rationale in mind, we have measured stratigraphic sections in 11 caves, including: Burro Cave, Carcass Cave, Crowbar Cave, Crystal Cave, Double Barrel Shotgun Cave, Jansill Cave, Lobo Cave, Montecito Cave, Orange Feather Cave, Owl Cave, and Triple Engle Pit. The approximate relative locations of the caves are shown in Figure 1. Before discussing the stratigraphy of individual caves, we first briefly summarize the processes responsible for gypsum deposition and alteration (diagenesis).

SAN ANDRES FORMATION AND FOURMILE DRAW MEMBER

The San Andres Formation crops out in a broad belt along both sides of U.S. Highway 285 between the towns of Roswell and Vaughn, New Mexico. The outcrop area of the San Andres is the most extensive of any stratigraphic unit in the Pecos River basin, extending from the north end of the Guadalupe Mountains near Carlsbad, to as far north as Glorieta Mesa south of Santa Fe. The Permian age San Andres Formation was deposited approximately 200 million years ago in a shallow marine environment. In the study area, the regional dip is to the east or southeast, however, the local-scale dip may be in any direction, as a result of cave dissolution and subsequent collapse of the overlying beds (Fig. 2).

The San Andres Formation consists of three different members, as defined by Kelley (1971). The uppermost evaporitic member, the Fourmile Draw, is the most important cave-forming unit in the Pecos basin. The Fourmile Draw consists of varying proportions of evaporites (gypsum + anhydrite) and carbonates (dolostone + limestone). The caves studied here are located within the West Pecos Slope physiographic province (Kelley 1971), which has formerly been referred to as the Sacramento Plain. Petroleum geologists use the term Northwest Shelf to refer to this same area, in reference to its location with respect to the Permian Basin to the south.

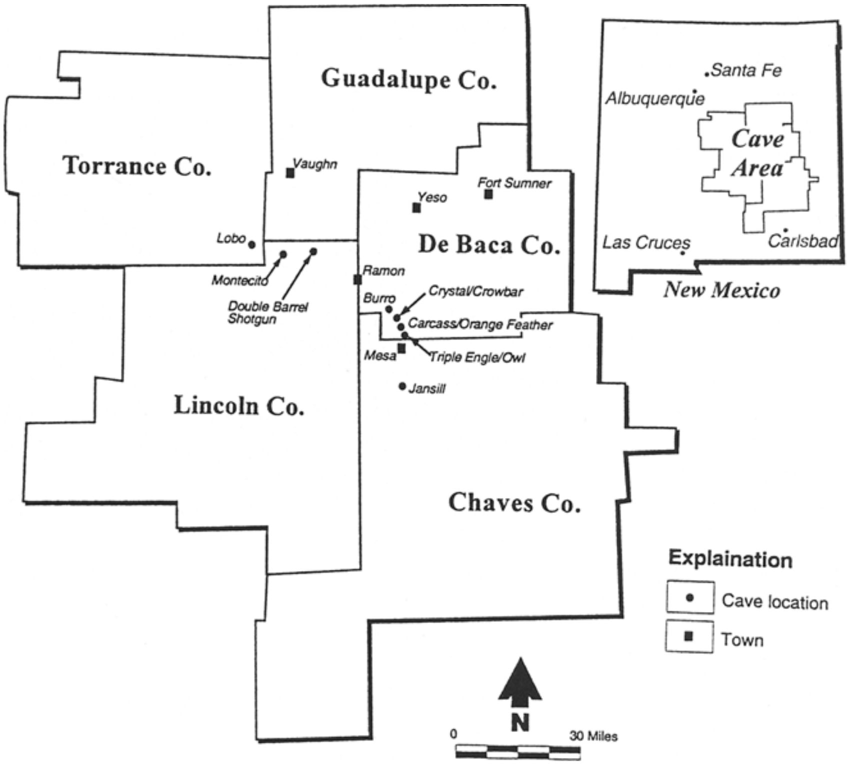

Figure 1. Locations of caves studied.

Figure 2. Small fold in dolostone beds of the Fourmile Draw Member, San Andres Formation (Permian). The fold developed as a result of solutional subsidence and collapse of the underlying gypsum beds.

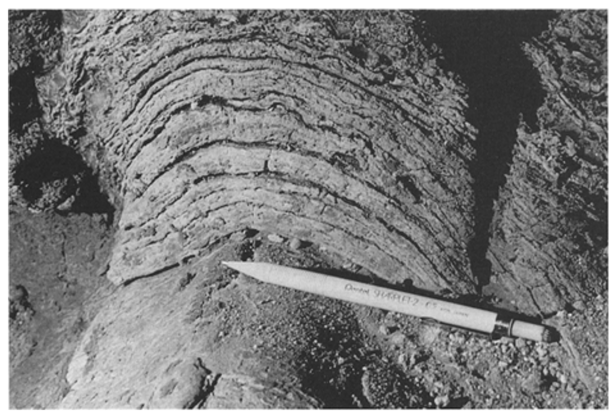

Figure 3. Laminated dolostone of possible stromatolitic origin in Montecito Cave.

Most, if not all, of the evaporite beds were deposited in very shallow water, probably at most a few meters deep. According to Warren (1989), during times of widespread evaporite deposition of the Permian Period, "one could have traveled 50 to 150 km south and seaward from the (shoreline) and never crossed through water which was much more than a meter or two deep." Modern examples of such low relief "evaporitic ramps" do not exist, and tidal effects were negligible. Probably only during storms or hurricanes did water depths vary appreciably (Warren 1989).

The carbonate beds we observed within the stratigraphic section presumably represent somewhat deeper water conditions, though still relatively shallow. Based on acid tests performed in the field, dolostone is the predominant carbonate lithology in the Fourmile Draw Member within the study area. In addition, laboratory analyses using XRD and carbon dioxide evolution methods have confirmed that dolomite is much more abundant than calcite in the carbonate units.

Noteworthy features of most of the dolostones in the study caves include chocolate brown color, micritic texture, and almost complete lack of macrofossils and chert. Given the saline environment during which most of these sediments were deposited, it is not too surprising that macrofossils are lacking, as algae are among the few organisms that can tolerate saline conditions. However, several examples of what may be algal stromatolites have been observed in a few of the caves, most notably Carcass, Crystal, and Montecito Caves (Fig. 3). Many of the dolostone beds in the study area are highly fractured; crystal wedging by gypsum recrystallization along joints appears to be a significant disintegration process.

GYPSUM-ANHYDRITE CYCLE

The well-known process of recrystallization of gypsum to anhydrite upon deep burial, and the reverse process upon uplift and erosion is referred to as the gypsum-anhydrite cycle (Boggs 1992). It is likely that the gypsum beds exposed in the caves studied here have experienced several such cycles. With each cycle, some or all of the original sedimentary structure is destroyed through the recrystallization process. Because of their low yield strengths, evaporites can undergo plastic deformation (Boggs 1992). Both recrystallization and plastic deformation obscure the primary sedimentary features, which in turn makes it difficult to interpret the original depositional environment of these rocks.

The depths at which anhydrite rehydrates to gypsum can vary, depending on the availability of water and the temperature. It has been reported that in some situations ancient anhydrite may actually be present in outcrop (Blatt et al. 1980). However, the transition back to gypsum commonly takes place at depths of at least a hundred meters below the surface (Murray 1964).

When gypsum dehydrates to anhydrite, a large volume of water is produced. If the water cannot escape readily through the rock matrix, then overpressuring may cause lubrication along the crystal boundaries, and the dewatering gypsum bed may convert to a quicksand-like consistency (Warren 1989). In addition, the relatively high water pressures that develop can cause intense disruption and deformation of the rock beds (autobrecciation). This process is probably responsible for some of the intense fracturing and plastic deformation that we observe in a few of the caves, such as Triple Engle Pit. In some instances, the hydrostatic pressure may lead to contorted folds or ropy bedding called enterolithic structure (Boggs 1992).

In most cases, however, the evaporite beds in the caves studied show no such disruption. If hydrologic conditions are such that the water of dehydration can escape easily, then the compaction of gypsum beds may occur with little or no deformation. In this case, there may be little evidence that the thickness of the beds have been reduced to only 62% of their original thickness during the conversion to anhydrite, as Warren (1989) suggests. This is probably what has occurred to most of the evaporite rocks in the study area.

We have not done detailed laboratory mineralogic studies of the rocks exposed in these caves, and it is not easy to visually distinguish between gypsum and anhydrite in the field. This is particularly true in cases where recrystallization has preserved pseudomorphs (crystal shapes) of an earlier crystal habit. However, anhydrite is slightly harder (3 vs. 2 on Mohs Scale) and denser (2.9 vs 2.3) than gypsum, and these properties are more useful than appearance in differentiating between the two minerals. Our experience to date indicates that most, if not all, of the "gypsum" beds exposed in the cave walls can be scratched with a fingernail. Because anhydrite is harder than a fingernail (2.5), in principle this demonstrates that the caves are developed in gypsum, rather than anhydrite. Preliminary laboratory X-ray diffraction analyses confirm this, with gypsum being the only prominent evaporite phase detected in the samples analyzed.

Gypsum is approximately 10 times more soluble in water than limestone. Also, in contrast to limestone, gypsum solubility is not dependent on the pH of the solution. Because of its greater solubility, and the fact that carbonic acid is not required for dissolution of gypsum, caves developed in gypsum tend to develop much more rapidly than limestone caves. For this reason, gypsum caves are probably more short-lived than caves developed in carbonate rocks.

CLASSIFICATION OF GYPSUM AND ANHYDRITE

A classification system for anhydrite textures has been proposed by Maiklem et al. (1969) and summarized by Boggs (1992). Three basic anhydrite (or gypsum) types are defined: massive, nodular, and laminated. All three textures have been observed in the walls of the caves studied here, although nodular gypsum appears to be the most common. The three basic gypsum textures are briefly described below.

Massive gypsum lacks perceptible internal structure within a bed. Presumably, the massive (homogeneous) texture results from sustained, uniform conditions during deposition (Boggs 1992). Massive gypsum in these caves is often a relatively uniform white or gray color, and may have a granular, sugary (sucrosic) appearance as a result of the uniformity of crystal size. Impurities, such as carbonate and clay minerals, are generally lacking from this type of gypsum. Some massive varieties have a grayish or brownish translucent, almost transparent appearance, probably as a result of recrystallization that obscures intercrystal boundaries.

Nodular gypsum is very common in the caves discussed here. The overall color may range from white to nearly black, and the rock has a spotted or mottled appearance. The nodules consist of irregularly shaped lumps of gypsum separated from each other by a carbonate or clay matrix (Fig. 4). The nodules are generally thought to represent remnants of individual selenite crystals that originally precipitated in a soft, muddy matrix at the bottom of a shallow, saline, inland sea. Such primary gypsum crystals grow by displacement of the surrounding insoluble sediment (Boggs 1992). Subsequently, the displacement gypsum crystals may recrystallize to anhydrite during diagenesis, and the resulting anhydrite crystals may continue to grow by addition of calcium and sulfate ions derived from the pore waters. If the original

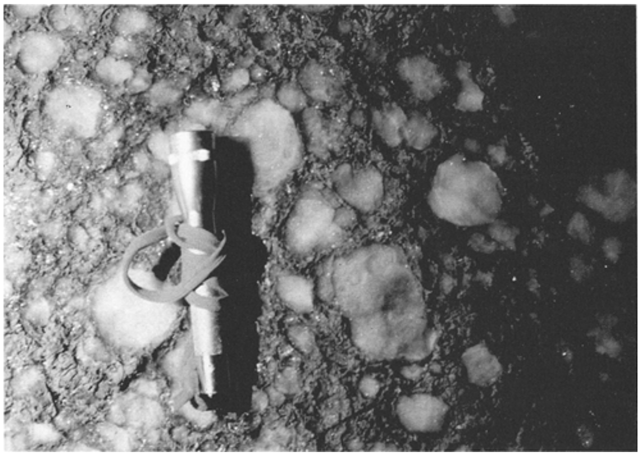

Figure 4. Example of nodular gypsum exposed in Triple Engle Pit. Note relatively pure gypsum nodules encased in muddy carbonate matrix.

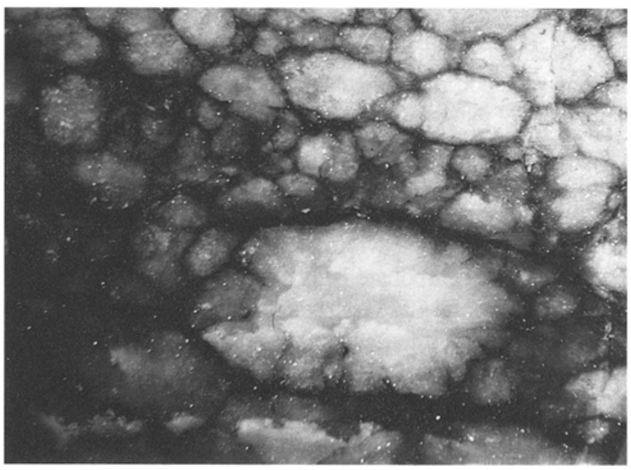

Figure 5. Example of "chickenwire" structure in nodular gypsum exposed in Triple Engle Pit. Largest nodule is approximately 10 cm across.

displacement gypsum crystals were small, the resulting anhydrite nodules will be small as well, and vice versa.

The nodules may remain isolated from one another, or may be compressed together, so that only a thin rim of the darker-colored clay matrix surrounds the almost interlocking anhydrite nodules. The latter evaporite texture is commonly called mosaic or chickenwire structure, and often is responsible for the striking appearance of some of the gypsum beds we observe in the caves (Fig. 5).

Laminated gypsum often consists of thin alternating layers of white gypsum and dark gray or black carbonate (calcite or dolomite). This texture is less common than the others in the Fourmile Draw Member within the study area. This is probably attributable to the fact that laminated gypsum is generally deposited in deeper water than the shallow seas which existed during San Andres time. Nevertheless, very thinly laminated gypsum beds can be seen in the walls of some of the caves. Some of the wavy laminae have the appearance of ripple marks (e.g. Double Barrel Shotgun Cave). These laminated gypsum beds are quite different in appearance from the deep-water laminae that typify other laminated gypsums of New Mexico, such as the Permian deep water Castile Formation exposed at the surface south of Carlsbad. We believe that the laminated beds within the Fourmile Draw Member of the San Andres Formation are exclusively shallow water deposits, as are the nodular and massive textured varieties. In some cases, we observed gradational change through each of the three textural types within a single gypsum stratigraphic unit.

We also include a fourth classification of gypsum, namely "*gypsite*," the earthy, soft, impure gypsum crust which blankets most of the gypsum surface outcrops, and surrounds most of the cave entrances. Gypsite forms in the soil horizon of semiarid regions by evaporation of calcium-sulfate waters drawn to the surface through capillary, or wicking action (Weber and Kottlowski 1959). Gypsite is essentially recrystallized gypsum, containing variable amounts of clay, silt, and carbonate minerals. In some cases, dissolution of bedded gypsum outcrops by rainwater results in a crust of spongy, "honeycomb" gypsite, which is partly a residue of the original gypsum bed, and partly reprecipitated gypsum mixed with mud. Gypsite has a characteristic hollow sound when struck (Weber and Kottlowski 1959), which probably accounts for the "hollow ground" noted by ranchers who have ridden over the land on horseback.

STRATIGRAPHY OF SELECTED GYPSUM CAVES

To date, we have measured stratigraphic sections in 11 caves. Detailed stratigraphic sections and maps of these caves, as well as information regarding their lengths and depths, can be found in Forbes et al. (1996). Generalized stratigraphic sections were constructed for each cave by noting the positions and thicknesses of the major geologic units visible in the cave walls, floor, and ceiling of 11 caves. The thicknesses of the sedimentary units were measured to the nearest 0.3 meters (1 foot), and the units were numbered sequentially from bottom to top. While the placement of contacts between successive sedimentary units is by nature somewhat arbitrary, in most cases the contrast in adjacent lithologies was dramatic and obvious. For example, the contact between adjacent gypsum and dolostone beds was usually quite distinct and sharp, and this was defined as the contact between two different sedimentary units. In most cases, a single sedimentary unit as defined here consists almost entirely of either gypsum or dolostone/limestone, but not both.

While generally referred to as "gypsum caves," gypsum is by no means the only rock type exposed in these caves. In fact, some of the caves are partially developed in thick sections of dolostone intercalated with or overlain by gypsum beds, as shown in the stratigraphic sections that follow. In general, the rocks exposed in the caves studied thus far are relatively undeformed sequences of evaporites and carbonates.

However, dips of up to 10 or 20 degrees are not uncommon, and dip reversals and folds can be seen in some of the caves, such as Jansill Cave. In addition, a few well-exposed faults have been mapped in several caves, and fault breccias and collapse breccias are also present, though not common.

The sedimentary sequence in a particular cave was found to exert a profound influence on cave geometry and passage shape. Perhaps not unexpectedly, many passages were found to have gypsum walls and a dolostone or limestone floor. Often, cave passages remain confined to a single stratigraphic unit for tens to hundreds of meters, before the flood waters that dissolved it breach the resistant carbonate floor to reach the next gypsum bed below. The breach point often takes the form of a vertical shaft or climbdown (Fig. 6). Therefore, dolostone or limestone beds, sometimes only a foot or so thick, often form the lips of major vertical drops in these caves. Thus, carbonate beds in gypsum caves occupy a similar position with respect to cave development as do chert beds found in limestone caves of the eastern U.S. Although many of the cave passages flood completely during major storm events, the stairstep profile is indicative of speleogenesis predominantly within the vadose zone. Most of the caves contain no flowing water, except immediately following storm events. Descriptions of the rocks exposed in selected caves are given below.

Stratigraphy of Montecito Cave

The stratigraphic section described in Montecito Cave includes 16 stratigraphic units spanning an interval of approximately 30 meters (100 feet). Some of the best exposures occur in the walls of "Classic Dome," a vertical solution shaft at least 25 meters (80 feet) tall (Fig. 6). The upper portion of the section resembles that in nearby Lobo Cave, and the two can be correlated. Several thin carbonate beds form prominent ledges that protrude into the narrow canyon passages near the entrance. An interesting 60-cm (2-foot) thick dolostone bed (Unit M10) forms the resistant lip of the rope drop into Classic Dome (Fig. 3). This dolostone bed contains fine wavy laminations, possibly stromatolites, and is also exposed in Lobo Cave. Secondary gypsum "popcorn" is abundant along some vertical joints in this cave (Fig. 7). The generalized stratigraphy of rocks exposed in this and the other caves is shown in Figure 8.

Stratigraphy of Lobo Cave

Approximately 30 meters (100 feet) of stratigraphic section was described in Lobo Cave and on the surface surrounding the entrance. These rocks include 11 stratigraphic units consisting predominantly of thick gypsum units intercalated with thin dolostone beds (Fig. 8). An unusual wavy laminated carbonate bed (Unit L09; stromatolites?) has been correlated with a similar bed in Montecito Cave.

Stratigraphy of Double Barrel Shotgun Cave

Thirteen stratigraphic units totalling 30 meters (100 feet) in thickness were mapped in this cave (Fig. 8). Additional rocks in the lower portion of the cave remain to be described. The upper part of the section includes several thick dolostone units that are visible in the Dragon's Breath Room. The lower part of the section consists mostly of gypsum. Cave development within thick dolostone units appears to occur primarily by collapse into solution cavities in the underlying gypsum beds. Several thinner carbonate beds exert profound influence on passage shape, and these resistant units invariably form ledges upon which intermittent waterfalls are perched. The rocks in Double Barrel Shotgun Cave have been tentatively correlated with those exposed in Lobo and Montecito Caves to the west.

Stratigraphy of Burro Cave

Sixteen stratigraphic units totaling 65 meters (210 feet) thick were defined and measured in Burro Cave, also known as "El Burro Grande." The best exposures are in the walls of Trash-A-Dome, a huge collapse chamber at the downstream end of

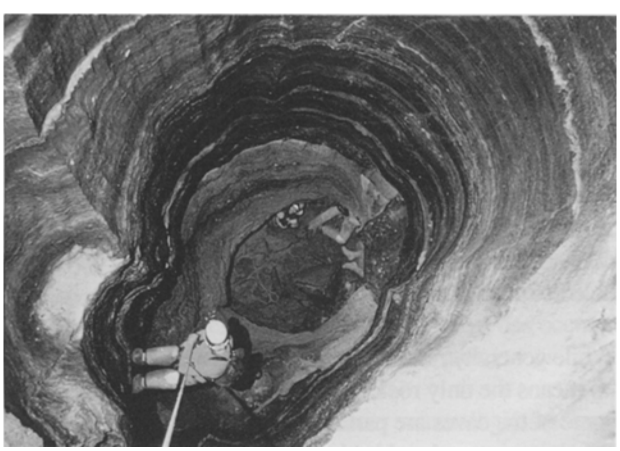

Figure 6. Vertical solution shaft in Montecito Cave. The shaft is 42 feet deep and developed as a result of dissolution along vertical joints in flat-lying gypsum beds.

Figure 7. Secondary gypsum "popcorn" precipitating where gypsum-supersaturated water flows vertically downward along joints in the bedded gypsum cave wall.

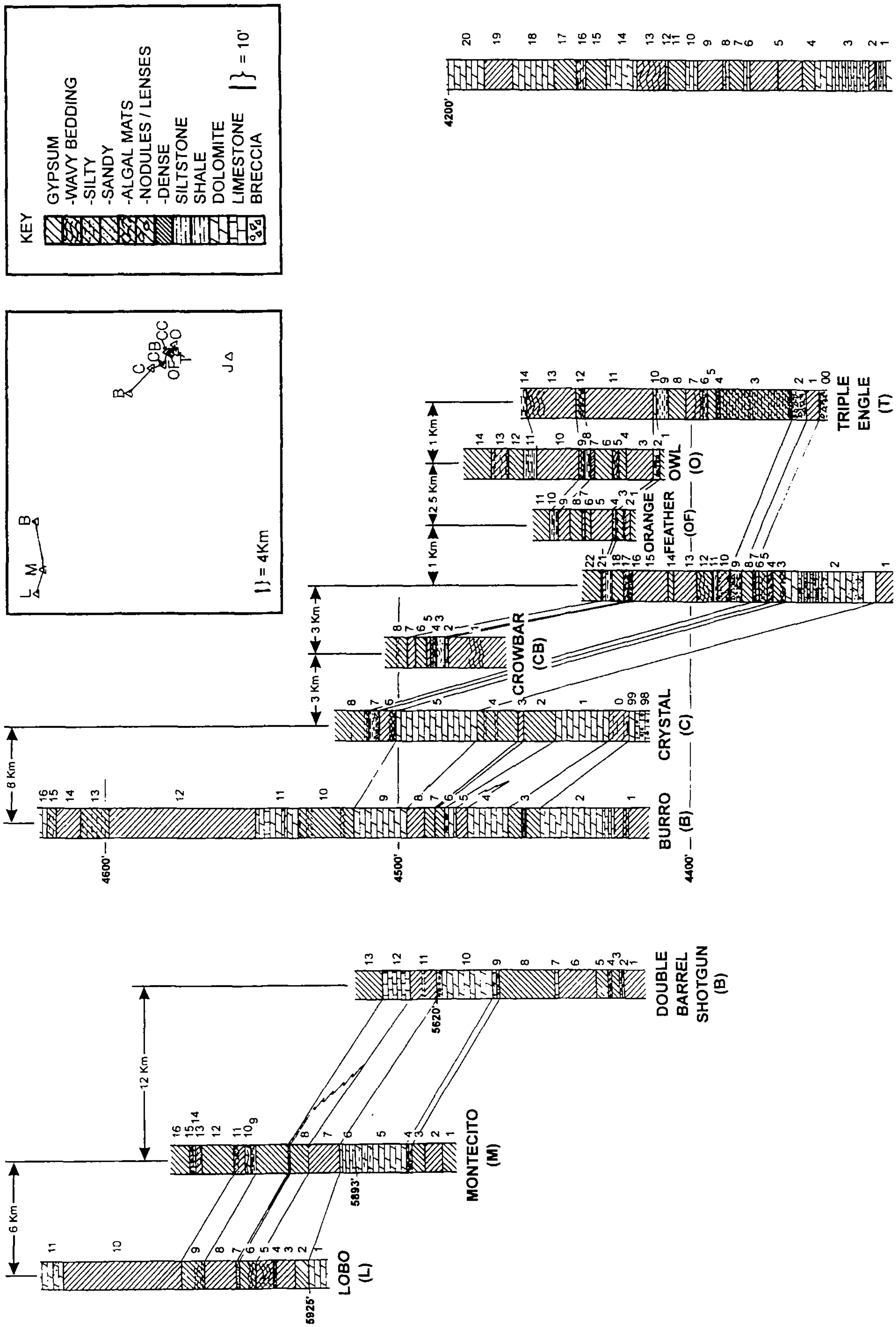

Figure 8. Stratigraphic cross section showing correlation of beds observed in gypsum caves.

the cave. We estimate that the ceiling of Trash-A-Dome is approximately 40 meters (140 feet) above the floor as determined from the highest point atop the talus cone.

Burro Cave penetrates approximately equal thicknesses of gypsum and dolostone beds (Fig. 8). The lower part of the section consists of thick dolostone and dolomitic limestone units separated by somewhat thinner evaporites. The main stream passage intersects Trash-A-Dome about half way up, and the lip of the rope drop is at the top of an 5.5 meter (18-foot) thick carbonate unit consisting of hard, micritic dolostone. Another dolostone unit approximately 5 meters (15-feet) thick is exposed immediately inside the cave entrance (Unit B11). Nearly 20 meters (70 feet) of continuous gypsum section is visible in the upper walls of Trash-A-Dome.

An unusual set of satin spar gypsum beds is exposed in the walls of Trash-A-Dome. Three prominent white satin spar gypsum beds 2 to 20 cm thick are separated from one another by a black gypsum matrix. This striking unit (Unit B03), dubbed the "Tiger Stripe Bed", encircles the entire circumference of the nearly 60 meter (200-foot) diameter chamber. The satin spar beds appear to be secondary gypsum that precipitated along voids that opened along bedding planes. The origin of these is unknown, however Gustavson (1994) suggests that such satin spar deposits often form when dissolution of underlying halite beds causes extensional opening of overlying bedding planes. This mechanism seems plausible in this setting, even though no halite beds remain in the section.

Also noteworthy are numerous thin wavy-laminated carbonate stringers that may be stromatolites (algal mats) in Unit B10. These were noted previously by DuChene (1987), and are well exposed near the lip of the Trash-A-Dome rope drop. The stromatolites are about four feet above the base of the chickenwire gypsum unit, and resemble thin varves with wavy, contorted cross-sections. They are similar to those observed at the top of "Classic Dome" in Montecito Cave, however there is no indication that the two beds are correlative.

Stratigraphy of Crystal Caverns

A 30-meter (100-foot) stratigraphic section including eight lithologic units was mapped in Crystal Caverns between the Main Entrance and the Big Room (Fig. 8). Additional rocks remain to be described above the measured section and below the Big Room in the lower portion of the cave. The measured section includes roughly equal proportions of dolostone and gypsum.

The rocks exposed in Crystal Caverns dip more steeply and more consistently throughout the cave than in many others. An obvious case of stratigraphic control of passage development can be seen along the passage leading to the Big Room. Here, the stream passage developed in gypsum follows down the dip for approximately 300 meters (1000 feet), with the floor perched on the top of a dolostone bed. The strike/dip measured in this passage was 310°/12°NE. At the lip of the climbdown into the Big Room, the stream passage breaches the resistant dolostone and penetrates through to another gypsum unit below.

At least two faults are exposed in this cave. One appears to be a vertical fault visible near the entrance where gypsum is exposed on one wall of the canyon passage, and dolostone on the opposite wall. The displacement and sense of movement could not be determined. Another fault is visible in the passage leading due north out of the Big Room. This appears to be a reverse fault with the east side upthrown. Drag folds and impressive fault breccia are also visible here.

Stratigraphy of Carcass Cave

A total of 22 stratigraphic units measuring slightly over 30 meters (100 feet) were described in Carcass Cave between the entrance and the New Year's Day Room. The upper portion of the section consists mostly of gypsum, whereas a thick dolostone unit occurs near the base (Fig. 8). Particularly noteworthy is a spectacular breccia bed (Unit CC09) that contains gypsum and dolostone clasts up to 1/2 meter in diameter embedded in a red muddy matrix. This unit is probably a collapse breccia that long predates the dissolutional development of the present cave. A 15-cm thick bed that may display stromatolites is visible in the main entrance passage of Carcass Cave, and has been tentatively correlated with a similar unit in Crystal Caverns three miles away.

Stratigraphy of Triple Engle Pit

Triple Engle is the deepest gypsum cave in the United States, and provides an excellent opportunity to examine the Fourmile Draw Member of the San Andres Formation. A total of 15 stratigraphic units totaling about 30 meters (100 feet) have been described in the upper portion of the cave thus far. This section consists almost entirely of gypsum (Fig. 8). Small-scale rupturing and enterolithic structures can be seen in the walls near the entrance. These may be related to volume changes that accompany dehydration of gypsum and subsequent rehydration of anhydrite. It is also possible, however, that some of these features may represent sedimentary structures that existed at the time of deposition.

Several observations suggest that Triple Engle Pit is in a key location with respect to regional structure. Three vertical faults and a spectacular breccia are exposed in this cave. The faults have resulted in deformation of the nearby rocks, however there is little evidence of vertical displacement. In addition, a thick shaley gypsum unit visible in and beyond the Stinkey and Horrendously Icky Tunnel displays numerous small reverse fault-type offsets of individual beds, creating a mosaic of tightly interlocking angular blocks. This unit contains numerous gypsum nodules flattened normal to bedding, and the base of the unit is highly contorted above the contact with the underlying breccia unit, suggesting that this unit suffered considerable compressional shear. Measured dips in Triple Engle ranged from 3° to 30°, and the dip changes rapidly within a short horizontal distance.

Stratigraphy of Jansill Cave

Jansill Cave provides some excellent exposures for geologists willing to crawl to work. A total of 20 stratigraphic units totaling over 40 meters (140 feet) of section were measured in the lower portion of Jansill Cave (Fig. 8). Rocks exposed near the entrance and large breakdown collapse area have not yet been described.

The best exposures occur in the walls of 12:30 Pit, a huge collapse chamber at the downstream end of the cave. The measured section includes approximately equal proportions of gypsum and dolostone. Spectacular chicken-wire gypsum is visible near the bottom of 12:30 Pit. A 4 meter (14-foot) thick dolostone (Unit J11) forms the floor of the 550 meter (1800 foot) long crawlway leading to the pit, as well as the lip of the rope drop into the chamber. Large collapsed slabs of this unit are scattered about on the floor of the chamber.

The floor of the long bedding-plane crawlway consistently dips at about 3° toward the southeast. However, at 12:30 Pit the dip reverses to 12° to the northwest, as visible in the walls of the large chamber. Therefore, it appears that 12:30 Pit lies at the axis of a synclinal fold. Perhaps this accounts for the location of this large collapse chamber, which may have developed as a result of increased fracture density along the fold axis, which allowed the stream to breach the resistant dolostone at this point.

CORRELATION OF BEDS BETWEEN CAVES

One of the objectives of this study was to attempt to find one or more distinctive marker beds that could be traced from one cave to another. This effort has been at least partially successful, although it appears that no single bed is exposed in all eleven caves. This is not too surprising, given that the Fourmile Draw Member is approximately 150 meters (500 feet) thick, and that individual caves may only penetrate a portion of the total thickness. It therefore appears that different caves have developed within different stratigraphic intervals of the Fourmile Draw Member.

Stratigraphic correlations were made by examining the measured sections in those caves located closest together, then working progressively farther away. Dolostone beds seemed to serve as better marker beds that the intervening gypsum units, which tend to thicken and thin more abruptly. This is to be expected, because the carbonate rocks are generally deposited in somewhat deeper water than the evaporite facies. Depositional environments would be more uniform over wider areas during sea level high stands during times of carbonate deposition.

Beginning in the west (Fig. 1), the rocks exposed in Lobo Cave were found to correlate rather well with those in Montecito Cave located about three miles to the east. Figure 8 shows our proposed correlation between rock units. Dolostone unit L1 in Lobo Cave is probably the same as unit M5 in Montecito Cave, and the wavy-bedded gypsum at the base of Lobo unit L9 probably correlates with units M9 and M10 in Montecito.

Double Barrel Shotgun Cave is located approximately 8 miles east of Montecito. The correlation of rocks between these caves is less certain. Dolostone unit B10 in Double Barrel Shotgun appears to correlate with units M5 and M6 in Montecito. Although it cannot be confirmed at present, the thin limestone/dolostone bed visible in Montecito (middle Unit M8) and Lobo (Unit L7) may thicken substantially to the east to correlate with unit B12 in Double Barrel Shotgun. At present, we are unable to correlate the three westernmost caves with those further southeast.

A reasonably good stratigraphic correlation has been established between Burro Cave, Crystal Cave, and Carcass Cave. The stromatolite bed in Burro (Unit B10) appears to correlate with a similar bed in Crystal (Unit C6), and both are underlain by thick dolostone units. Furthermore, Burro Units B4 through B6 may correlate with Crystal Caverns Unit C1.

We believe Crystal Caverns Unit C5 corresponds with Carcass Cave Unit CC2. Furthermore, immediately above in both caves are algal stromatolite beds (C6 and CC3). Although they are located only about a mile apart, the correlation of units between Carcass Cave and Triple Engle is presently tenuous. A possible correlation exists between the breccia units observed in both caves (Units CC9 and T2/T0), although this remains to be established with any degree of certainty. Another dubious correlation exists between dolostone units CC21 and T10. If this is correct, it demonstrates considerable lithologic changes over short distances within the approximately 15 meter (50 foot) interval of evaporite facies between the dolostone bed and the breccia beds below.

The rocks exposed in Jansill Cave cannot be positively correlated with those in the other caves at present. A possible correlation may exist between Jansill Unit J16 and Crystal Caverns Unit C7, both of which are mudstones or shales. Also, Jansill gypsum units J4 and J5 may correspond to Units C2 through C4 in Crystal Caverns. However, Jansill Cave contains numerous thin carbonate beds that have not been seen in Crystal Caverns or elsewhere.

INFERRED GEOLOGIC STRUCTURE

Earlier studies have evaluated geologic structures in the study area. Kelley (1971) described the Bogle Dome and the Downing Buckle, which expose the lower members of the San Andres Formation and are located to the southwest of the study area. Additionally, Kelley (1971) documented minor faulting and folds and igneous intrusions along the southern and western boundaries of the study area. However, very little mapping of geologic structures has been done within the study area.

A prior report indicated the possibility that the larger caves may have developed along the crests of regional-scale anticlines (DuChene 1987; DuChene and Belski 1992). The present study did not find support for the presence of such large anticlines. However, it was determined that an anticline does extend from Triple Engle Pit under Poquito Mesa to the east-southeast. This is consistent with the eastern end of the anticline proposed by DuChene and Belski (1992). The only caves currently known to occur on the crest of this anticline are in the vicinity of Triple Engle Pit and Carcass Cave. Crystal Caverns, Burro Cave, and others in the vicinity do not appear to have formed on the crests of an anticline.

The data gathered in this study do not negate the presence of smaller scale folds or faults that may influence the orientation and location of the caves. However, these folds, if they exist, must be small and of local scale relative to the entire study area. Locating and defining these smaller structures may be difficult and will require examination of more outcrops on the surface and in the caves. Further analysis will be necessary to determine the exact relationship between these small-scale structures and the development and morphology of the caves.

Localized structures have been observed in or near several caves. The dip of beds in Triple Engle Pit ranges from 3 to 30 degrees and changes rapidly within a short distance. Additionally, three vertical faults have been observed in this cave, and two faults have been observed in Crystal Caverns (Forbes et. al. 1996). The offset on these faults appears at most to be only a few feet. In several caves, including Burro Cave and Jansill Cave, rock dips increase markedly toward large shafts or collapse domes. This is believed to be related to subsidence which occurs in the area of these shafts as dissolution of underlying beds undermines support for beds above.

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