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POST-SPELEOGENETIC EROSION AND ITS EFFECT ON CAVES IN THE GUADALUPE MOUNTAINS, NEW MEXICO AND WEST TEXAS

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The Guadalupe Mountains of New Mexico and west Texas are a northeast-tilted fault block cut by canyons that increase in frequency and topographic relief from east to west. The processes of erosion and mass wasting have exposed more than 300 known caves, which range from systems like Lechuguilla Cave (>170 km) and Carlsbad Cavern (>49 km) in the east, to caves with less than 10 m of passage in the west. Erosion of the Capitan, Yates and Seven Rivers formations progressively removed more cave-bearing strata and destroyed more caves from east to west. It is likely that modern-day canyons in the central and western Guadalupe Mountains were once sites of long cave systems that have been truncated or destroyed by erosion and mass wasting.

The Guadalupe Mountains of New Mexico and west Texas are a northeast tilted fault block ranging in elevation from 2667 m at Guadalupe Peak to 960 m near the city of Carlsbad (Fig. 1). The mountains are an exhumed portion of the Capitan Reef Complex, a Permian (Guadalupian) shelf margin that nearly rings the Delaware Basin (DuChene & Hill 2000). Formations that crop out throughout the mountains are the Capitan, Seven Rivers, Yates and Tansill, with older rocks of the Goat Seep and Queen exposed to the west in deep canyons and along the Western Escarpment (King 1948; Hayes & Gale 1957; Hayes & Koogle 1958; Motts 1962; Hayes 1964; DuChene 2000). The Guadalupe Mountains contain an estimated 300 known caves (Jagnow 1979), some of which were formed by sulfuric acid derived from hydrocarbons in the Delaware Basin (Davis 1980; Hill 1987, 1990; Palmer & Palmer 2000). The two largest and longest caves, Lechuguilla (>170 km) and Carlsbad (>49 km), are in the relatively undissected area east of Rattlesnake Canyon, whereas smaller and shorter caves are concentrated in the more-deeply dissected area to the west. Ages of sulfuric acid caves range from 12.3 Ma in the higher elevations of the western Guadalupes to 3.9 Ma in the east at Carlsbad Cavern (Polyak *et al.* 1998; Polyak & Provencio 2000).

One of the great puzzles of the Guadalupes is why no long cave systems have been found in the western part of the mountains. It may be that none were formed, but it is also possible that they were once present but have been destroyed by erosion. In this paper, we investigate the rate and amount of erosion that has probably occurred in the Guadalupe Mountains since the horizontal cave passages formed about 12 - 4 Ma, and consider factors that may have controlled the locations of caves and canyons.

For this paper, we define a *long* cave as one with more than 8 km of passage, and a *short* cave as one with less than 8 km of passage. A *large* cave has great volume compared to its length and typically has passages or rooms more than 15 m wide and 10 m high. A *truncated* cave passage is one that was once part of a larger cave system that has been mostly destroyed by erosion.

The purposes of this paper are to show how much material has been eroded from the Guadalupe Mountains during the last 12 Ma, and to consider how erosion has impacted the caves. Subjects such as the possible causes for lowering of the water table, the timing of uplift, and the causes of faulting in and near the Guadalupe Mountains are not discussed. These controversial topics are beyond the scope of this paper and have been addressed elsewhere (e.g. Chapin & Cather 1994; Eaton 1987; Hill 1996; Lindsay 1998).

METHODS

The study area extends from the Western Escarpment of the mountains near Guadalupe Peak to a point 65 km east near the city of Carlsbad (Fig. 1). The southern boundary is the Capitan Reef Escarpment, which marks the basinward limit of the Capitan Reef Complex. The width of the area is approximately 7.5 km and includes the Capitan Formation as well as most of the cave-bearing carbonate beds of the Seven Rivers, Yates, and Tansill formations (DuChene 2000: his Fig. 3). The estimated aggregate thickness of the Capitan reef, backreef and forereef is 600 m.

The study area is divided into three segments based on geomorphic characteristics and topographic slope (Fig. 1 & Table 1). The western segment extends from the Western Escarpment to Double Canyon and has an area of 296 km². It has an average slope of 21 m/km to the northeast, is characterized by deep, steep-walled, mostly northwest-trending canyons, and contains numerous short, truncated caves. There are a number of large passages in caves such as Cottonwood, Virgin and

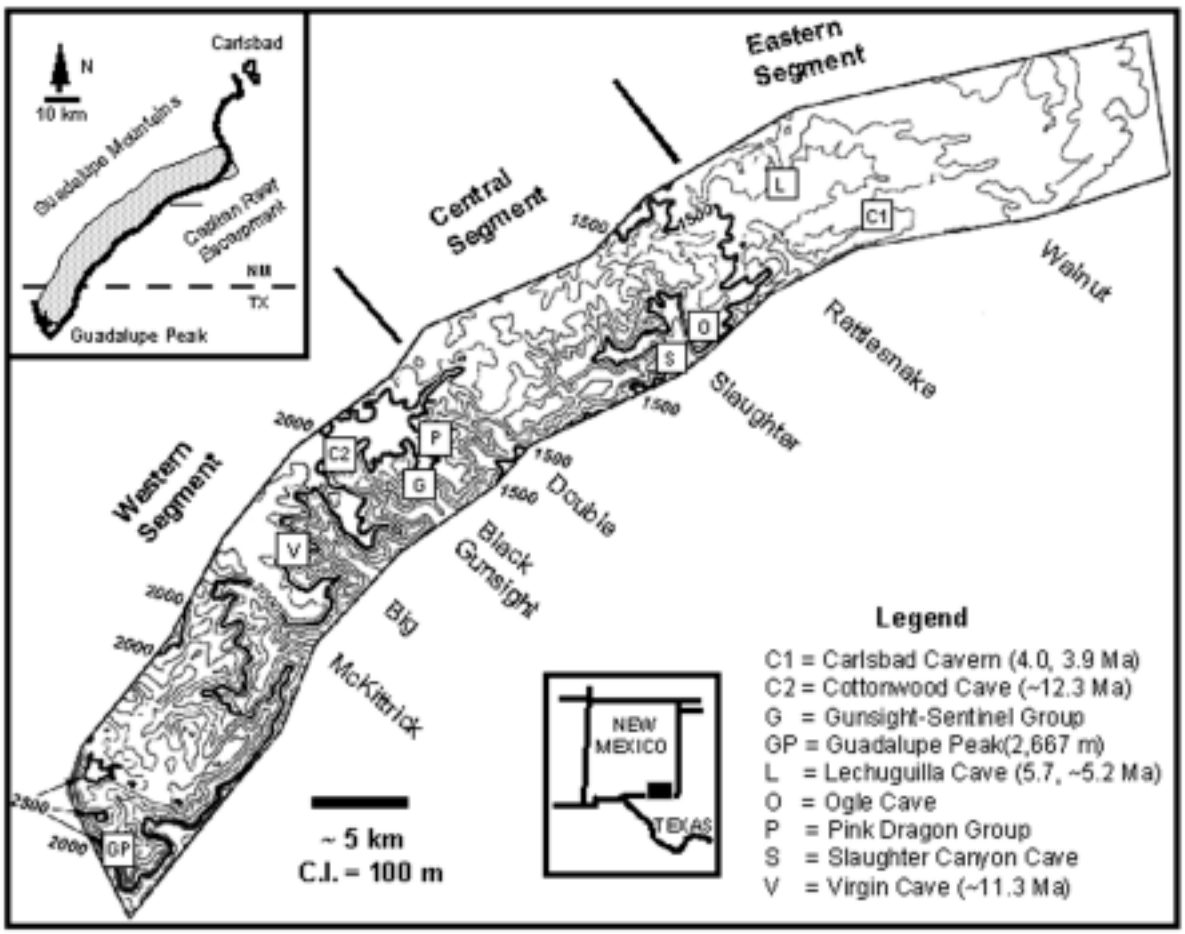

Figure 1. Topographic map of the Guadalupe Mountains showing the locations of caves and canyons discussed in the text. The key to symbols and the ages of significant caves (Polyak *et al.* 1998) are listed in the legend.

Gunsight, but no known long caves. The central segment extends from Double Canyon to Rattlesnake Canyon and has an area of 127 km². It has an average slope of 38.4 m/km and has steep-walled, northwest- and northeast-trending canyons. Caves in this segment are also short, but a few, such as Ogle and Slaughter Canyon (formerly called New Cave), are large.

The eastern segment covers 159 km² and extends from Rattlesnake Canyon to the eastern limit of the study area near Carlsbad. It has an east-northeast slope averaging 18 m/km and low relief compared to the other two segments. This segment has fewer entrances, but contains Carlsbad Cavern and Lechuguilla Cave, the two longest and largest caves in the Guadalupe Mountains.

Table 1. Summary of volume calculations and statistics for Guadalupe Mountains.

Table 1

Calculation of volume of material eroded from Guadalupe Mountains during last 12.3 Ma						East-northeast plunge		Vertical relief (ridge top to canyon bottom) in m			Downcutting in m/Ma		
Segments	Maximum age of caves in block in Ma (from Polyak et al, 1998)	Area in km2	Original volume (pre-erosion) in km3	Volume removed by erosion in km3	% of volume removed by erosion	m/km	degrees	minimum	maximum	median	minimum	maximum	median
1 (West)	12.3	296.15	177.7	40.9	32.0%	21	1.2	650	1140	895	53	93	73
2 (Central)	9 (est)	127.43	76.5	16.1	21.1%	38	2.2	200	650	425	22	72	47
3 (East)	5.7	159.42	95.7	7.2	7.5%	19	1.1	0	200	100	0	35	18
Totals		583.00	349.8	64.2	18.3%								

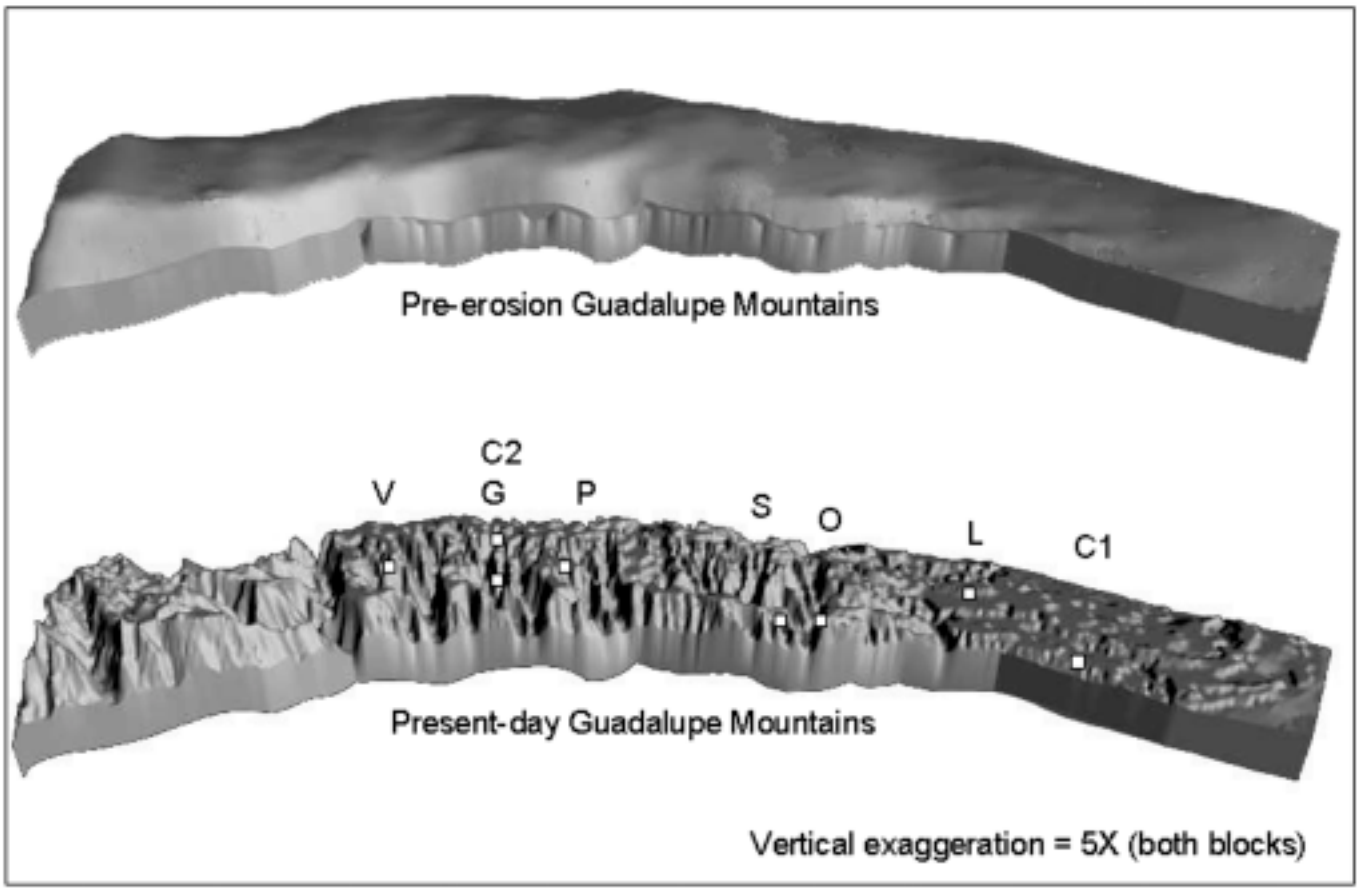

Figure 2. Block diagrams showing the pre-erosion and post-erosion topography of the Guadalupe Mountains. Symbols are the same as in figure 1.

Volume calculations for the Guadalupe Mountains were derived from U.S. Geological Survey digital topographic data for the Carlsbad East and Van Horn East 1° quadrangles and are computer-generated. The 3 arc-second Digital Elevation Model data depicting the present topography of the Guadalupe Mountains was imported into AutoCad and converted into a UTM Zone 13 projection, with a grid density of 100 m. Two surfaces were created to calculate the eroded and original volumes of the mountains. The pre-erosion surface was hand contoured and electronically converted to a grid that matches the present-day topographic surface. The surface representing the base of the Capitan Reef Complex was determined by subtracting 600 m from the top of the pre-erosion surface. The volume of eroded material was calculated by subtracting the present topographic surface from the pre-erosion surface, and the total volume was calculated by subtracting the bottom surface from the top of the pre-erosion surface (i.e., the pre-erosion volume of the study area is the area multiplied by the thickness). To simplify the calculations, it was assumed that the Guadalupe Mountain block had no significant erosion prior to the onset of sulfuric acid speleogenesis in the Middle to Late Miocene, although it is likely that some erosion of the block occurred earlier (Hill 1996, 2000). Pre- and post-erosion volumes and rates of downcutting were calculated for the eastern, central and western segments; the results are summarized in table 1. Downcutting is reported as maximum, minimum and median rates for each segment.

RESULTS

The western segment has pre- and post-erosion volumes of 127.7 km³ and 86.8 km³, respectively. Canyons range in depth from 1,140-650 m from west to east, and ~32% of the original volume has been removed by erosion. The rate of downcutting ranges from 93 m/Ma in the west to 53 m/Ma on the east with a median rate of 73 m/Ma. The central segment has pre- and post-erosion volumes of 76.5 km³ and 60.4 km³, respectively. Depth of erosion ranges from 650-200 m from west to east and ~21% of the original volume has been removed. The rate of downcutting is based on an estimated cave age of 9 Ma because no alunite age dates have been determined for this segment (Polyak *et al.* 1998; Polyak & Provencio 2000). The rate of downcutting ranges from ~72 m/Ma on the west to 22 m/Ma on the east, with a median rate of 47 m/Ma. The eastern seg-

ment has pre- and post-erosion volumes of 95.7 km³ and 88.5 km³, respectively, and topographic relief is a maximum of 200 m, decreasing to the east. The amount of material removed by erosion is about 7.5% of the original volume. The rate of downcutting in this segment ranges from 0-35 m/Ma, with a median rate of 18 m/Ma.

The rate of downcutting and volume of eroded material reported for each segment of the Guadalupe Mountains assumes that erosion occurred at a constant rate during the last 12 Ma. Certainly, the rates have varied in response to changes in the amount of precipitation and recharge over time. However, since these variables are unknown, and for simplicity, we have assumed a constant rate.

DISCUSSION

Most of the major cave passages in the Guadalupe Mountains are developed along joints that are either parallel or perpendicular to the Reef Escarpment. Most of these caves are developed near the reef-forereef contact in the Capitan Formation, or the reef-backreef contact between the Capitan and Seven Rivers and Yates formations (Jagnow 1979; Hill 1996, 1999, 2000; DuChene 2000). Guadalupe Mountain canyons also either parallel the Reef Escarpment or are perpendicular to it (Fig. 1). These canyons, especially those that parallel the Reef Escarpment, are excavated into those parts of the Capitan, Seven Rivers and Yates formations that are most likely to contain caves. The processes of erosion and mass wasting that are excavating the canyons are also destroying many of the caves.

In the eastern segment of the Guadalupe Mountains, erosion has not reached the parts of the Seven Rivers and Capitan where most known cave passages occur (DuChene 2000). Since only ~7.5% of the rock has been removed, this segment has the highest chance of containing long, undissected cave systems, and the smallest chance of having cave entrances.

In the central segment, ~21% of the bedrock has been removed. Topographic relief ranges from 200-650 m and erosion has cut deeply into the cave-bearing rocks of the Seven Rivers and Capitan, especially in West Slaughter Canyon. Canyons in this area have many entrances in their walls including those for Ogle and Slaughter Canyon caves, which are located on opposite sides of Slaughter Canyon and horizontally separated by only 1125 m (Figs. 1 & 2). It is possible that these two caves were once part of a longer system, but downcutting of Slaughter Canyon has destroyed most of the original cave. This hypothetical cave system is located approximately at the same stratigraphic position as Carlsbad Cavern and would have been comparable in size. A prominent set of northwest-trending joints probably controlled both speleogenesis and erosion near the mouth of Slaughter Canyon. Surface erosion and mass wasting deepened and widened the canyon, eventually destroying most of this cave system, but with Ogle, Slaughter Canyon and a few smaller remnant cave passages remaining "stranded" high on the walls of the canyon.

In the western segment, ~32% of the original bedrock has been removed, and topographic relief ranges from 650-1140 m. Erosion has cut completely through the prime cave-bearing parts of the Yates, Seven Rivers and Capitan formations, and many truncated caves are exposed, especially in Double, Black and Gunsight canyons. If surface erosion and mass wasting followed the joint systems that controlled speleogenesis, then the largest parts of many of these caves have been destroyed. Two examples of areas where there are clusters of truncated caves are Black Canyon near Gunsight and Sentinel caves, and Double Canyon at the Pink Dragon group of caves (Figs. 1 & 2). The caves in both of these areas were probably once parts of larger systems, but erosion has destroyed all but these remnant passages.

CONCLUSIONS

The Guadalupe Mountains can be divided into western, central and eastern segments based on their elevation, slope and topography. From east to west, the depth and magnitude of erosion increases, and the number of exposed caves increases. The longest known caves are in the eastern segment of the mountains where erosion has not cut deeply enough to expose cave-bearing strata of the Capitan and Seven Rivers formations.

Downcutting progressed at an average rate of 73 m/Ma in the western segment of the Guadalupe Mountains. In the central segment, the average rate is 47 m/Ma, and in the eastern segment, it is 18 m/Ma. Erosion has removed ~7.5% of the original volume of rock from the eastern segment, ~21% from the central segment, and ~32% from western segment of the mountains.

Most caves in the Guadalupe Mountains are located near the reef-backreef contact between the Capitan formation and the Seven Rivers and Yates formations. In the central and western segments, canyons are deeply incised into cave-bearing strata and a large amount of the limestone most likely to contain caves has been removed by erosion. Long cave systems probably once existed throughout the Guadalupe Mountains, but west of Rattlesnake Canyon erosion has mostly destroyed them, leaving only truncated remnants stranded high on canyon walls.

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