Geology

Chapter 26

Geologic Significance of Guadalupe Mountains National Park

LLOYD C. PRAY, Ph.D., is a professor of geology at the University of Wisconsin in Madison. Beginning in the 1950s, he led geology field trips in Carlsbad Caverns National Park. He began detailed research on Permian strata of the Guadalupe Mountains in the 1960s in association with other Marathon Oil geologists. Since joining the faculty of the University of Wisconsin in 1968, the major emphasis in his research, and that of his many graduate students, has been in the Southwest. He has supervised some 21 graduate students' theses in the Guadalupe Mountains working on interpretations of the Capitan reef and the older exposed Permian strata of the western escarpment. Specific topics include the origin of pisolites of the Capitan back reef, the Capitan reef and its contemporaneous fore reef and basin strata, submarine debris flows, erosion surfaces, and other strata relationships in the pre-Capitan units of Guadalupe Mountains National Park.

I wonder if any of you have been as lucky as I have been to have 21 darn good students want to come down and work their tails off out there in those hills called the Guadalupe Mountains. They have gone on to their own business of leading field trips and such—I am very proud of them—and it is one of the fun things of being in the university. You have coolies to do some of these things, but you have to know what you are doing with them and you have to have some overall projects. In that regard, I have been exceedingly fortunate to have concentrated, since about 1970, a lot of my graduate students doing doctoral and masters theses out here in the park and doing some regional work as well. It is a privilege to come down here, be part of this conference, and see what I consider a fine display of cooperation on the part of the National Park Service to put this kind of thing on. I learned some things this morning I didn't ever expect to learn and I am going to be here for the rest of the conference. I hope it will be really fun for me to get these perspectives, which are beyond my little niche of geology. But that is where I come from, and yes, to say that Guadalupe Mountains National Park is a geologic park—sure, that's my theme song. I know there are lovely things out there on the slopes. There are mosses, lizards, animals, and trees and all kinds of things that need work and research. But you know, they all are growing on rock, and they are there because of that magnificent pile of rocks, which is a national heritage, and which I am very concerned remains a national heritage. Of course, now it is in the hands of the National Park Service, which I am very pleased with.

The original 5,000 acres or so was given by Wallace Pratt, who was a real hero and first-class geologist. He said, "This area of McKittrick Canyon at the entrance is not only the prettiest place in Texas,"—you know, geologists can see pretty things, too—but he also said, "I want this place to be a place where geologists can come and poke and look around and learn from what's here"—a magnificent display of the Capitan reef that is now world famous. When that transferred back in 1972 to the "stewardship," in Jan's terms of the present park, it made a lot of us feel really good because out in some of this country you occasionally can't get into areas that you want to because of the trouble ranchers have had with some bad people. Now it is all in the park, and as I see it, with the stewardship that I am satisfied will go into it, those rocks are in good hands.

"I want this place to be a place where geologists can come and poke and look around and learn from what's here."
—Wallace Pratt

Now, there is one other introductory comment I want to make. How many of you are geologists? A little more than I'd hoped for. If there had only been a few I'd be able to get away with technological murder, and of course, professors do that all the time. But still, I am glad there are some friends of mine out there. Maybe they will be tolerant of what I want to put together for you. I wrote an abstract, and I want to call your attention to the facts in the abstract, because that is really what I want to say to you. I think what we put in there is important. It is important in terms of the National Park Service and the stewardship that is necessary with this magnificent pile of rocks that is out there in Guadalupe Mountains National Park. I have a feeling that if I were to ask you, "What is the most famous feature out there in the park?" the non-geologists would say, "Oh, it's the Capitan reef." Some of the geologists would say, "Oh, it's the Capitan reef." Well, I am going to tell you today that when the transfer was made from the McKittrick Canyon area to the entire area of the Hunter Ranch, there was a great taking-on of material older than the Capitan, which is of extreme importance, and where perhaps two-thirds of my students have worked. It has been fun working in an area where there is hardly anyone. Of course, there is nothing quite like being on a mountain range yourself, anyway. You have no one to control you and the clouds are always beautiful down here, and you can almost always find some interesting things you don't understand.

The Capitan is only the frosting on the cake.

In National Park Service circles, I hear the word "inventory" quite often. An inventory is important, but in geology, I have the feeling that some people think, "Well, it's been mapped." Or somebody wrote a whole book on it, and there are whole books written on the Guadalupe Mountains. It is not just what is where; it's how in the heck it got there. Those mysteries are the things that are exciting to scientists and should be to students—and are. When you can try to discern the reasons for it being there, then you are getting at meaningful research. That's what I would like to have the park focus on: the needs for continuing research under supervision. Sampling, yes—there's a lot of rock out there—but sampling so it doesn't hurt the side of the canyon and that people can actually bring the marvelous new techniques we have now in geology to bear on how that rock got there and what it is. That is the essence of the geological sciences. In the last two decades, we have been through great revolutions in geology with ocean floor spreading and all that stuff. There have been revolutions out here, too. One of the revolutions in geology is called sequence stratigraphy, where people try to make very detailed correlations of a rock that's here with a rock that's here; they are all time equivalent. It has gone into worldwide practice in search for petroleum, not just land areas but down under the sea; they are now capable of doing that and also in production technique. So this science, which evolved in part for carbonate rocks—and I'm a carbonate rocker, not a sandstoner—out here in the west face in the last two decades. It has been important in that way.

Well, enough generalizations. Let's get into some slides. I guess you know you're in Texas, and that the park is just the little tail-of-the-dog of the U-shaped Guadalupe Mountains. It is the high part, and it is a hunk of country in which rocks are beautifully exposed in canyons, most of them without water, but which involve research. Of course, the Capitan reef—the "caps" are right in here, and here is the Capitan reef escarpment. The Capitan gets a lot of the attention; in fact, the newspaper of the two parks is called *The Capitan Reef*. Well, I'm here to tell you in a somewhat facetious sense that the Capitan is only the frosting on the cake. It's wonderful frosting; it tastes good, and it's got all kinds of geological problems. But there is a heck of a lot of cake under it in the older rocks that are exposed out here, which are terribly important, and only in the last decade or so have been getting the attention they deserve.

This is the area; you know all about that. I only want to point out that going north there are exposures of rocks that are time equivalent of the rocks that are down here. This sequence stratigraphy involves rocks way up here and down here—I will say a little bit more about that later on. So, what do we say about it? Well, it is a big area in geology, and in this area we are dealing with a thousand feet of something. I have to tell you a story. One time we were coming off Nipple Hill with one of my partners, and we saw way down in a little gully; just before we got to the gully, there were a man and a woman. They were lying reclined as though they were having a good time down there on the side of the canyon, and we thought, well, out of decency we shouldn't come down there right on our line of traverse, we ought to go around them. Well, as we got a little bit nearer we thought, well, let's just make noises and go up there and see what's going on, and we did. The closer we got, the guy had a fishing pole, and what was he doing with a fishing pole? You know what they were doing? They were catching lizards. But do you know why? They had a thermometer and were taking the anal temperatures of lizards. That's valid research, too, but the contrast between worrying about 2,000 feet of cliffs and worrying about what temperature a lizard had, is impressive. So we all have our specialties, and they're fun.

Well, this is presumed to show something of a summary of the geologic significance of Guadalupe Mountains National Park. And it is the best North American exposure of the rocks of Permian age, 250 million years ago. The variety of types of rocks and the large scale of features enchants us to see what changes into what. It is simply phenomenal. The value of these features is global, because a lot of the studies done here by students are going out around the world to try to tie it in with petroleum exploration or just scientific understanding. On a regional scale, it's important for tourism, of course. And the more you can plug the Capitan reef as the frosting on the cake, the better. Because it is a very exciting thing, and I don't put it down. For study in the region, regional water resources tie into the Permian basin oil fields that are off here to the east a little further. There are a lot of other things that I could say of significance of the variety of features, but to me when you get to know it, you realize you don't understand it all. It is a very complex system of rocks, and that is fun for geologists, and that is part of what keeps us going on these hot days and traverses and the rest. Because we still don't understand it nearly as well as we should.

The fact is the Guadalupe Mountain Permian gets into textbooks and into research studies on carbonate rocks in all kinds of languages and all around the world.

How many of you have been walking on the west face of the Guadalupe Mountains? How many of you saw water over there? There are a couple of springs, and believe me, they're on maps, but the bulk of it is treeless, it is hot, and it is beautiful because of the geology. I guess the other thing I can make as a general comment—others have made the comment—this park is a magnet for geologists, literally from all over the world. It should continue. This is a [picture of a] textbook published some years ago, but the fact is the Guadalupe Mountain Permian gets into textbooks and into research studies on carbonate rocks in all kinds of languages and all around the world. The frosting on the cake is the big white upper cliff that goes about five miles up there on the magnificent top of the escarpment. Here is the cake; it's down here. It looks less dramatic but it is pretty darn exciting. There are three live people. This is the trip one year ago with a class from Wisconsin, but they were an international group. Toni Simo [professor at the Department of Geology and Geophysics, University of Wisconsin-Madison] is right in the middle and would like to be here today. I guess we conned somebody into taking a picture of the whole group. We have been doing this now for the last 30 years, and I suppose various people have brought thousands of geologists to come and see this thing. Because until you see it, you don't appreciate it.

It's important in my bias of this being a geologic park to realize what the enabling legislation was, and I recently had a chance to read it: "To preserve in public ownership in the area of the state of Texas possessing outstanding geological values". I could go on and say, "together with scenic and other natural values of great significance". The first and foremost, this should be kept as a national heritage for geologists. There will be a bunch of them coming on. A little bit of geology, for the non-geologists: you have heard about the Permian oceans that came into the area of the Guadalupe Mountains. There were three or four arms of the ocean that came in from somewhere, and Carol Hill has some idea that they didn't come here, but that is continued research. The Delaware Basin—the size of the Lake Michigan—ends and cuts obliquely right across the Capitan escarpment in a northwest trend, and the Capitan rims that entire area. But the only place we see it in decent outcrop, not chewed up or varied, is in the Guadalupe Mountains, so again, it is regionally significant. Then the basins are areas of one to two thousand feet deeper water during the time that shallow water sediments were going down on what we call platforms or shelves. Out here in the central basin shelf area—those are all the yellow areas—here's all kinds of oil fields, which are very juicy oil fields. Yates is right down there at the very tip of it. They are producing from rocks, not the Capitan. They are producing from rocks that are exposed up here in the Algerita escarpment.

Here's the frosting on the cake. Here are rocks, and you see ledges here which don't go here. Well, how come? Because that, too, was the edge of a shelf to a basin, and the changes in rocks as you go along in those layers are the fascinating things that are now being worked in detail. Just one thing: the frosting on the cake, the Capitan reef and the Goat Seep under-rim, make an upper lens on this sloping block of ground that we made the Guadalupe Mountains out of, both in Mexico and Texas, and water coming in, of course, goes down through the rocks that it can go through under gravity in the permeable layers, and of course we've got caves, Lechuguilla and Carlsbad Caverns, and we've got some springs down here in the Carlsbad region and the Carlsbad aquifer, which has something to do with good water out here. They go on out down to the central basin platform, and they provided some of the water drive for the oil fields that are out there. There is some value in knowing something about these rocks.

What they didn't notice for 75 years was that the sloping layers of rock were sloping from what had been a shelf area into a basin.

Here is our Capitan. Now, the interesting thing about it in terms of knowing what's there, and from 1855 until 1929 they knew there were rocks there, and El Capitan was very impressive and that's where the name Capitan comes from, but what they didn't notice for 75 years was that the sloping layers of rock were sloping from what had been a shelf area into a basin. If you go on top of Guadalupe Peak—here's looking down on El Capitan—while those layers look flat from out in the west, you can see here that they are actually not flat at all, they are sloping into, again, the basin and again, different rocks entirely here that would be up on the top of the peak. That was 75 years of not knowing why it was hard to correlate layers out there in the subsurface. It wasn't until they got into the oil fields that they began to realize, "We've got to understand this," and in 1929 three geologists came out and said, "There's a reef there." That's what makes these sloping layers. Seventy-five years. They say that geologists can't see things that are obvious, and that's true, and I hope mammalogists are the same way. Once it is pointed out, it's obvious. That was a case in point of just not recognizing what was there.

This slide is a little bit of Geology 101. What I want to use in this is that there are different ways you can go down a ski slope, for example, which might involve a reef like that from the shallow area in the basin, or you might just go down a gently declining thing like this. But the thing we know is that all the way along there are changes in rock, like from the Capitan reef out here at the edge, if that were the Capitan, into facies 5, 4, 3, 2, 1. These different type rocks are called facies. That's true whether you are on that profile or this, and that's true whether you're in shallow water or down in the deep. These changes are vital in understanding the localization of porosity. Porosity has something to do with big oil, because you've got to have the holes in the rock and making seals and all the rest. Here are two variations of the many I could show you, but just to make things complicated, we know as geologists that during Permian time the sea level changed just as it changed during our glacial ages. You put all the ice on the land and sea level goes down 300 feet; you melt it and it goes back up. Well, there were changes there. And every time you change sea level, you change the currents that are on these areas, you change the rock type, and so it is not a simple system. It could happen many times during the deposition of the Capitan.

I put these in this order, because in essence, this is the pile of rocks we have in the Guadalupes. We've got a ski slope reef, floor slope kind of thing up the frosting on the cake, and then in the older rocks we have this kind of gentle ramp, as it is referred to. The changes in the facies that we see take place in just 5 or 10 miles of the total width of this, but these might go 50 to 100 miles. You have to do regional studies. Studies that would be here in the Guadalupes are important to what is going on way up there in the Algeritas. Here's a cross section of the Capitan as such, in terms of scale, the basin is about half a kilometer deep, the red is where we were building reef at the time, and then here was stuff that sloughed off and formed on the slope, the foreslope, as we call it. Behind it all these changes in facies and wavy line evaporates. Within these bands there are again progressive changes, and progressive changes could involve porosity, but they don't have to have oil significance, it's just why the heck did it turn out the way it did?

Let's move on from the Capitan then. Here's a cross section of the west side of the entire area. This would be 1,500 meters or something like that, and here is the frosting on the cake, the Goat Seep and the Capitan reefs in diagrammatic form, but down below it there are rocks that are productive, age-equivalent rocks and can be seen in the surface of the Algerita escarpment and some 20 or 30 miles farther to the north. This is the study of the west side and should not be neglected by geologists or by preservationists. Again, the rocks we are showing you here change by the time they get up in here, and go all the way up. And as you go out from this lecture or the next lecture, on the board out there, there is a one yard high, three yard wide cross section that shows detailed work being done and summarizes all of the work on the escarpment and coming down into here—primarily by Charlie Kerans and Bill Fitchen, who was a Wisconsin student at one stage but a UT student much more recently, and he now works for Exxon. Let's take a look at those black rocks at the mouth of Shumard Canyon. People say, "Oh, they're black rocks, they're all black rocks," but you find out there are different kinds of black rocks. Why are they different, and how do they differ, and what's going on as we go through this thousand feet of stuff here into the next? Well, let's take a look at some of the people who are working it. This happens to be Peter Vale, who is the major guru of sequence stratigraphy in the world. He worked for Exxon his professional life, and he gets out in the field too. This is one of his students, named Rick Sarge, who is also one of my students. These two are primarily involved in talking about these facies out here, together with Charlie Harris and Bill and a number of other people. The real live people are trying to figure these things out. They are pretty smart people.

Here is a cross section of that. Now we have gorgeous color out there, but here is a diagram from the Algerita escarpment. South of that red line is the park. What you see is, gosh, the park geology is down in what I call the soap. It's the deep water area. It is very different in facies from this, and it is a very complicated history, but it has been fun seeing people work this out, including some students of mine. One of the things that has been done, sequence stratigraphy has evolved from taking of subsurface records by geophysical means, which send shock waves down and they are reflected back, and you can pick up records of the position, the depth, of different layers. Here is the typical cross section that might be gotten; in fact, it is the Delaware Basin line. All these squiggles mean something if you are trained in it. In the middle of this is the interpretation of what these squiggles mean, and it is highly significant. What it means is that now all over the world from the China seas to the Australian

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northwest shelf, Newfoundland, Gulf of Mexico deep water, they can go in deep water, they can get these signals and they can get the seismic waves. What we have out here is not only those changes in rock layers, but we have them on a scale that is comparable. It is not just a little laboratory model; we've got a thousand feet of rock out here that are showing these facies changes. So it is a marvelous training ground, as Rick Sarge recognized way back when, when he was working with that side.

One of the reasons for having a continuing flow of new eyes and new people working on new techniques in a thing like the Guadalupes is that the story is going to change and it is going to get better.

Let's go on from there. So there's the value. In this next little part, I want to introduce you to three people who I consider the major, dominant super- geologists working the Guadalupes of the 20th century. First is a man named Phil King, who worked with the U.S. Geological Survey all his life. He worked in west Texas and southern New Mexico for a lot of it. He was a superb mapper and superb field man. He died a few years ago, but his basic work here can't be beat. Yet despite the fact that this guy had won all the prizes of the Geological Society of America and the rest—you didn't have to salute Phil King, but you felt like it because you wondered, "Could we have just a little bit of his smarts?"—he made some mistakes. You know, good people make mistakes. One of the reasons for having a continuing flow of new eyes and new people working new techniques in a thing like the Guadalupes is that the story is going to change and it is going to get better. If we just inventory what we had, then it's dead, but we want to bring it to life. Let's look at Shumard Canyon, which is on the west face. Here's a cliff 110 feet high consisting of sandstone, which would make and does make, kind of nice reservoirs out there in the bottom of the Delaware Basin. If you look at the rock in detail and look right in that particular place at the base of it, there are spalls which show these features. Now, what are they? They are ripple marks. They are made by moving currents. You see them probably on the Pecos, when it runs. In any event, in Phil King's day, ripple marks were only known from shallow water. So his interpretations were subject to the concepts of the day. We now know through work that has been done all over the world, including our own Balma, who is a guru in this particular field, that there are deep water channels which formed that body of sand; there are ripple marks all in it, and there are currents that go down into the basins all around, and this is a major part of the exploration play of petroleum geology at the present time. So, King blew it. I would never really say he blew it. He was a terrific, terrific guy and geologist.

There is another gentleman. This is a picture I took a few years ago of Norman Newell, who is a Columbia professor at the American Museum, a paleontologist and paleoecologist. He was an expert when he came into the Guadalupes with some bright students of Pacific reefs. He said this is a reef? He interpreted the Capitan reef on the basis of the modern. Now geologists say the modern is where we learn; the key to the past is in the modern. He came in and he brought a whole book, a wonderful book, and he did a lot of good work, but the fact is that he brought the Pacific models of reef into the Capitan, and you know, that's not the Capitan. When we worked the Permian reef out here, we had to say the Permian reef is like the Permian reef, and it is not like stuff we've gotten recently, or at least we're not smart enough to recognize it all right now. You learn in different ways. This is one of the reasons it's fun looking in detail, in depth. This was Normal Newell. He blew it on a few things too. Another thing he did was particularly fun for me: out there on the west face in the middle of that black rock there is a lens that looks like just a scoop, a lens sticking out of the hillside. It was a different kind of rock. He found some fossils in it, and he said these are reef fossils, and he said these are little reefs. And he found some more out there. Like this knob right there. But you know, when we got to looking at it back in the early 1960s, we discovered it was a channel. The same kind of channel that the sandstone would have gone in, but in this case it was channelized debris with some blocks that could be the size of a house. Well, that turned out to be important, because now off the central basin platform, there are some [oil] fields producing from this age rock which consist of great big chunks, a mile or so across, of debris flows which moved off the shelf and into the basin. You never know where things are going to end when you get into this game. I have great respect for Normal Newell.

Here are another two people that I want to focus on, Death Valley Scotty here; this is a picture of Robert Gunn, who worked for Shell and was a very imaginative geologist. Again, high on my totem pole, right below Phil King, I think. He came in and wrote a book in 1962 which was published in 1972. It had remarkable insights into all the carbonate rock variations out here. Some of the things that he got into, he too didn't quite get right. There are these things, these little round balls that look like golf balls that are concentric, they are pearls, if you like, but he considered that they were formed in one way. We now have kind of upset that apple cart, even though it was paraded around the world where people believed it, he wanted them formed in a different way than we think now. It is just a little detail and it is not going to make an oil field, but it's a fun thing to get involved with and try and interpret. All these three guys didn't stop from sticking their necks out and interpreting things, and of course, they didn't have all that people have now.

The latest part—and this is what tickles me. The Capitan is called a sponge reef, full of sponges. For years they were little clusters and they would stand upright, and everybody, including sponge experts who made their living on sponges, believed they were upper end sponges. A young woman from Cambridge named Rachel Wood—I wish I had a picture of her, she is a lovely-looking young lady—came in on a field trip and said, "You know what? Those sponges aren't growing upright, they're growing downward." Only one person I know had ever recorded that the sponges, instead of growing up, were growing down. That's not all the sponges. Look at this. See the tip? That's where it attached and it grew this way, it came down, and this one and this one, and this one, and this one, and... I had seen these for years and so had every other geologist I know of until Rachel Wood came in. Now that's fun—when somebody can upset an apple cart that way with just her own knowledge and her own powers of observation. That is part of the fun of this whole game.

Then there is this guy [referring to himself], and you know he stuck his neck out a few times, and he almost hopes he'll die pretty quick before somebody just proves he was completely full of it in what he thought was out there. Geology is an evolutionary science. We can't afford to neglect the evolution of the future geologists and the future concepts because they're important. Out here in the park we've got one of the best possible sites with a whole variety of facies, to say they can go out and study this for another century. My bet is in another century someone's going to make the same qualifying comments I made just now about myself. They've got more of the picture, but you know we're still learning.

It's fun in this area. This is a view from the ridge trail and to be absolutely out in those things, usually alone, I get kind of thrilled. This is the reef trail of McKittrick Canyon, of course, and many of you have climbed that. You know, when the sun begins to go down is when it gets exciting here in the Guadalupes. When the heat is off usually, and the shadows are tremendous. The west face, now that's the face for late in the day. The cliffs get pink and here is the frosting up there, above where I hike down into here, and you get a moon up there, and it is just kind of like, "My God, I'm lucky I'm here." Well, I come from up north. Almost invariably in my pictures of the sunsets on the west face, I'm not down at the base yet. Almost invariably there is too much interest up the hill, so the last part of the traverse to the pickup truck or whatever is made in the last rays of that or, some nights, starlight. It just says, and many people have the same feeling, once they're out there they want to stay there

Now that's fun—when somebody can upset the apple cart that way with just her own knowledge and her own powers of observation.

and see what's going on. I encourage all of you to use the west side trails and to stay over late into a sunset. It's great.

The last one I've got, my last slide, what do you see here if you look hard? You really see El Capitan, but you may recognize a rather obscure rainbow. You know, that's kind of symbolic. There is a pot of gold at the end of the rainbow here in the Guadalupes, but it may be rather obscure. It is there for the taking and there for the study. I want to just report this one thing. Last April at this time we were down here with another field trip group—you gotta hear this—Hale-Bopp was in the sky. One night we were driving up the road to McKittrick. It was about nine in the evening and there was a full moon. The east face of El Capitan was brilliantly lit in the moon and off there on the right above where you see the rainbow coming down was Hale-Bopp comet. Pictures didn't work out but I will never forget it. It was quite a place up there. So, I will leave you with that.

Now, I have to tell you that there are two exhibits out there by big oil people and by the Bureau of Economic Geology. I put no signs on them. I want you to see the detail that has been done on this west face, Algerita escarpment and also some photographs made by Pat Laman, who's with Exxon, and who was also a Wisconsin student at one stage of the game. Take a look at them, as you will see how much work has been done, and don't believe there isn't room for more. To you park people, I wish you well in stewarding these marvelous resources. Thank you.

Chapter 27

Geology of the Guadalupe Mountains: An Overview of New Ideas

CAROL HILL, Ph.D., has studied the geologic resources of the Guadalupe Mountains for 30 years. She is a consulting geologist and the author of ***Cave Minerals of the World*, *The Geology of Carlsbad Caverns*, and *The Geology of the Delaware Basin*.**

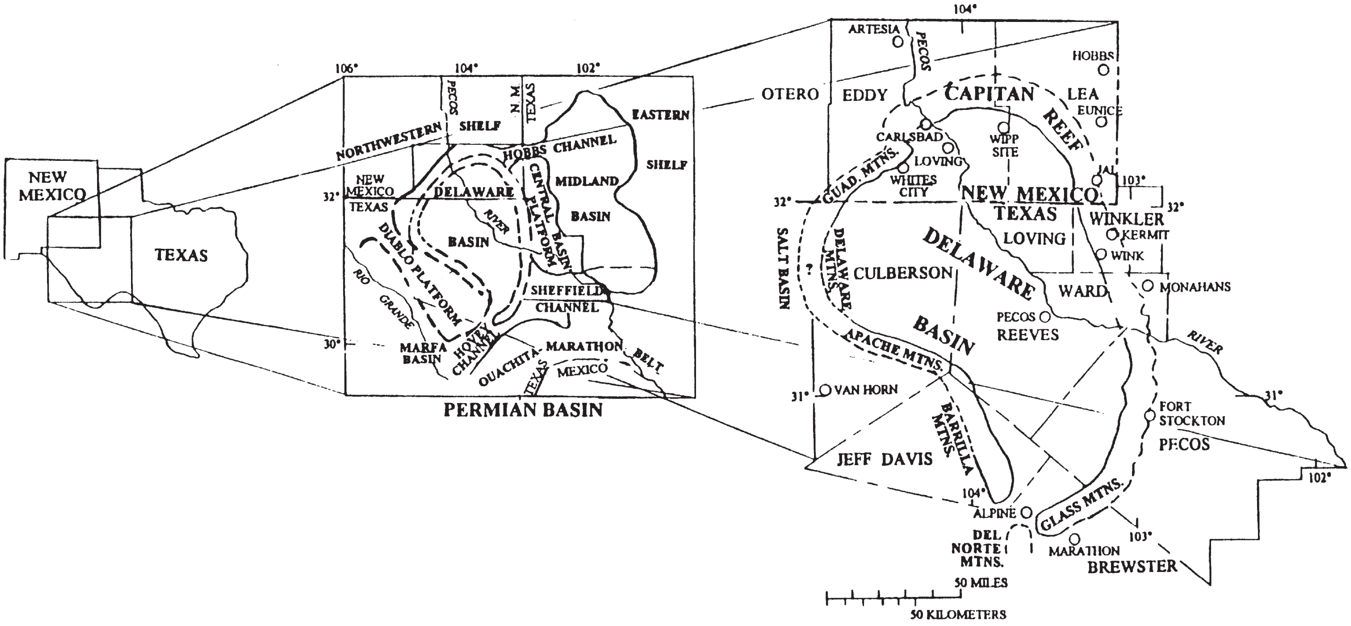
Introduction

This paper is a summary of new, and sometimes controversial, ideas on different aspects of the geology of the Guadalupe Mountains, from the Late Permian (Guadalupian) up to the present. Many of these issues were discussed in the "special topic" section of Hill (1996), but other issues are even more recent. Together, these ideas portray a somewhat different picture of the geologic history of the Guadalupe Mountains from that held only a decade or so ago.

Late Permian (Guadalupian)

Where was the inlet channel to the Delaware Basin in Permian time? In nearly every paper written on the Delaware Basin since the 1940s, the classic paleogeographic location map for the Permian of west Texas shows the Hovey Channel as being the inlet for sea water (Figure 1). But was it? Interpretations of new evidence suggests that the channel may have been on the west side of the basin rather than on the south side—in the area now known as the Salt Basin, between the Guadalupe and Apache mountains.

Figure 1. Location map, Permian Basin, southeastern New Mexico and west Texas. The Capitan reef is exposed in the Guadalupe, Apache, and Glass mountains, but it is located in the subsurface around the rest of the basin. The location of the Capitan reef in the vicinity of the Salt Basin is unknown. The Hovey Channel, supposed inlet to the Delaware Basin in Permian time, is also shown. From Hill 1996.



Four main lines of evidence support this interpretation. First, the location of the Capitan and Goat Seep formations in the area of the Salt Basin is unknown (the area marked "?" on Figure 1). The Capitan and Goat Seep reefs are known to turn from a southwestward direction at Guadalupe Peak to a southward direction through the Patterson Hills and Beacon Hill, but then these units become untraceable in the subsurface. The Capitan and Goat Seep are not encountered again (by well penetration) until exposed in the Apache Mountains near Seven Heart Gap. One possible reason why these rocks may be missing between the Guadalupe and Apache mountains is that they never formed there in the Permian because that was the location of the inlet channel to the Delaware Basin.

The second and third lines of evidence come from the Glass Mountains located near Alpine, Texas (Figure 1), where the Capitan reef is again exposed and where the inlet channel to the basin was supposed to have existed near the old railroad town of Hovey. The Hovey Channel was originally placed in the Glass Mountain area primarily because: (1) Leonardian and Guadalupian rocks in this vicinity were believed to be of deep-water, basin origin and (2) because the Tessey Limestone (equivalent in age to the Castile Formation in the rest of the basin) was believed to be a limestone facies that graded into anhydrite and then halite from south to north across the basin. Neither of these two interpretations has proven to be correct (Hill 1998).

The upper Cathedral Mountain, Road Canyon, and Word formations in the Glass Mountains—once considered to be deep-water facies—have been shown by Wardlaw and others (1990) to be shallow-marine, fan-delta to lagoonal deposits, as indicated by fossil leaves such as gigantoperoids. In addition, the Tessey Limestone turns out not to be a Late Permian marine limestone, but a bioepigenetic limestone of mid-Tertiary age formed by the replacement of anhydrite (Hill et al. 1996). In other words, the original depositional rock in the Hovey Channel area was gypsum-anhydrite, not limestone, and thus there was no facies change away from the assumed Hovey Channel inlet.

The fourth line of evidence strongly supports the other three. Heywood (1991), in his isostatic residual gravity anomaly map of New Mexico, clearly showed a circular "bull's-eye" negative anomaly in southeastern New Mexico which delineates the Permian Delaware Basin. On this map, the "entrance" to the basin appears to be on the southwestern, Salt Basin side of the Delaware Basin, rather than on the southern Hovey Channel side (Hill 1998).

Late Permian (Ochoan)

When did the Guadalupe Mountains first become emergent? The Castile Formation has been considered to be the classic textbook example of a deep-water evaporite deposit that formed within a barred and isolated basin. By "deep water" it is meant a brine-filled basin approximately 400–600 meters deep. This deep-water model has remained popular since it was first introduced in the 1940s, but recently it has been challenged by a new generation of workers such as Kendall and Harwood (1989), who presented evidence in favor of a shallow-water origin for the Castile. Hill (1996) listed eight reasons in support of a shallow-water model, and compared the Delaware Basin in Castile (Late Permian–Ochoan) time with the desiccated Mediterranean Sea basin in late Miocene time.

A shallow-water basin is also supported by a probable Ochoan-age karst episode in the Guadalupe Mountains. Hill (1987) described an early, Late Permian, "Stage 1 fissure karst" episode of cave development in the Guadalupe Mountains. Melim (1991) also identified an exposure episode in the Guadalupe Mountains that was Late Permian (Ochoan?) in age, during which time an initial stage of meteoric leaching occurred with the development of a large-scale, solution-enlarged fracture system. This solution-enlarged cave system in the Capitan Limestone implies at least a partial exposure of the reef in Late Permian (most probably Ochoan) time, and the descent of meteoric groundwater.

Mesozoic

At the close of Permian time the Delaware Basin was tilted eastward and uplifted slightly above sea level, and a marine environment was replaced by a deltaic, lacustrine (lake), and fluvial (stream) environment in the Triassic. During the Triassic and Jurassic, the area was low-lying with erosion and dissolution taking place both in the basin and the reef. During this time water slowly diffused through the Capitan reef forming Stage 2 spongework caves. Some of these caves became partially filled with montmorillonite clay, K-Ar dated by Hill (1987) at 188±7 million years (Jurassic). In the Early Cretaceous the Guadalupe Mountains area remained near sea level, with low-gradient streams and then a marine sea transgressing over the area.

What is the age of the Guadalupe Mountain summit gravels? Widespread siliceous lag gravels can be seen on the summit plain of the Guadalupe Mountains, immediately shelfward of the reef escarpment and overlying Tansill beds. The origin and age of these gravels has been a subject of debate for many years, but it now appears likely that they date from the Early Cretaceous (Hill 1996). In Early Cretaceous (Comanchean) time the Guadalupe Mountain area was traversed by low-gradient streams, which left behind their load of siliceous gravels. Then, later in the Comanchean, a marine sea transgressed over the area for a relatively brief period of time. According to S. Lucas (personal communication 1995), the Guadalupe Mountain summit gravels most nearly resemble Early Cretaceous Trinity clastics, which represent a fluvial regime just before the time of marine transgression.

Late Cretaceous–early Tertiary

How much uplift of the Guadalupe Mountain area was Laramide? The long interval of quiescence in the Mesozoic was terminated during the Late Cretaceous–early Tertiary by the Laramide orogeny, an event which elevated the entire Colorado Plateau and Rocky Mountains from New Mexico to Wyoming. A problem that has rarely been discussed by researchers working in the Guadalupe Mountains is: how much of the uplift of the Guadalupe Mountains occurred during the Laramide versus how much occurred later during the Basin and Range? Since very little work has been done on this problem in the Guadalupe Mountains, work from Colorado has been applied to this topic (Hill 1996).

Gregory and Chase (1992) showed that the entire uplift of the central Rocky Mountains in Colorado most probably happened during the Laramide, with very little of the elevation being due to Miocene-Pliocene Basin and Range uplift. This means that for the Colorado Rocky Mountains, and possibly also for the Guadalupe Mountains (part of the Southern Rocky Mountains), that the elevation of the land surface above sea level may have reached its full height (1.2 kilometers or more) in the Laramide (early Tertiary). Then, in the Miocene, Basin and Range extension and faulting uplifted the Guadalupe Mountain block between 1,000 and 2,000 meters (on its west face) relative to the downfaulted Salt Basin.

Oligocene

In the early Tertiary there was a transition from Laramide compression to Basin and Range regional extension. This transition phase was marked by an episode of volcanism in the Trans-Pecos region and to a lesser extent in the Delaware Basin (Horak 1985). Igneous dikes, with K-Ar ages of 32–35 million years, crosscut the basin just south of the Guadalupe Mountains, extending northeastward almost to Lovington, New Mexico (Hill 1996).

In the late Oligocene–early Miocene, beginning about 30 million years ago, faulting began to uplift the Guadalupe Mountain block relative to the downfaulted Salt Basin. This brought about a change in the hydrothermal regime: from one of melting and igneous intrusions to one of convective heat flow and an increased geothermal gradient. Hydrogen sulfide, produced in the reaction of hydrocarbons with anhydrite of the Castile Formation in the basin, moved into structural traps (anticlines) in the Capitan reef (Figure 2), and there, in the reduced zone, formed Mississippi Valley-type (MVT) sulfide deposits (e.g., Queen of the Guadalupes mine) (Hill 1993). The Oligocene was also a time when other MVT deposits formed in New Mexico (North and McLemore 1988).

Miocene

While the block faulting of the Guadalupe Mountains began at about 30 million years ago, the main uplift stage did not begin until about 15 million years ago. The Miocene was a time of especially high heat flow (~50°C/km) (Barker and Pawlewicz 1987), and this heat was responsible for the further maturation and migration of hydrocarbons in the basin and the convective circulation of hot fluids in the Capitan reef. As hot water rose and was cooled, the solubility of $CaCO_3$ gradually increased so that small (Stage 3 thermal) caves were dissolved in the deep-solutional zone. Higher in the depositional zone, the loss of CO_2 decreased the solubility of calcite so that the walls of these small caves progressively became lined with calcite spar (having fluid inclusion temperatures of 30–80°C and oxygen isotope values of $d^{18}O$ = -11 to -14‰) (Hill 1996). This same calcite thermal spar also filled Basin and Range fault zones, from the Guadalupe Mountains south to the Delaware, Apache, and Glass mountains (Hill 1996).

Are the large caves in the Guadalupe Mountains of sulfuric acid origin? As the Guadalupe Mountains uplifted in the Miocene, the water table–zone of oxidation progressively dropped in response to the lowering of regional base level. When hydrogen sulfide rose from the hydrocarbon basin and intersected this oxygenated zone, it formed sulfuric acid which dissolved the large cave passages in the Guadalupe Mountains (e.g., Carlsbad Cavern and Lechuguilla Cave). These large passages cut across all three of the former karst episodes (Stage 1 fissure karst, Stage 2 spongework karst, and Stage 3 thermal karst).

It is now the concensus of most karst geologists that the large caves in the Guadalupe Mountains were formed primarily by sulfuric acid and not by carbonic acid. A number of different lines of evidence attest to this sulfuric acid/hydrocarbon origin for the Stage 4 caves (Hill 1987, 1990, 1996):

1. Massive gypsum blocks (up to 10 meters high) and native sulfur deposits (up to thousands of kilograms) in these caves formed as byproducts of a sulfuric-acid mode of dissolution. Epigenic, carbonic-acid caves do not contain these types of deposits.
2. The low pH, sulfuric acid indicator minerals: endellite, alunite, and natroalunite occur in these caves.
3. High uranium, radon, and the minerals tyuyamunite and metatyuyamunite in these caves are all indicative of a H_2S system where uranium (and vanadium) precipitated along a redox boundary interface (Hill 1995).
4. Other sulfuric acid caves are known worldwide, and these are also associated with hydrocarbons. Some of these caves are actively forming today by a sulfuric acid mechanism (e.g., La Cueva de Villa Luz in Tobasco, Mexico, is a sulfuric acid cave related to hydrocarbons in the Gulf of Campeche) (Pisarowicz 1994). A milky-white river, with dissolved gypsum and sulfur, flows from the cave, and sulfur crystals are growing in areas where drip water has a measured pH of 1. Sulfur isotope values for the sulfur and gypsum in La Cueva de Villa Luz ($d^{34}S$ = -26 to -22‰) are in the same range as for the sulfur and gypsum in Guadalupe Mountain caves.
5. The isotopically light composition of the massive gypsum, sulfur, and alunite/natroalunite deposits in Stage 4 caves is the most convincing evidence for a sulfuric acid origin related to hydrocarbons. Only biologically aided reactions such as occur with hydrocarbons could have produced the large isotopic fractionations found in these deposits. Gypsum and native sulfur deposits in Guadalupe Mountain caves are sig-

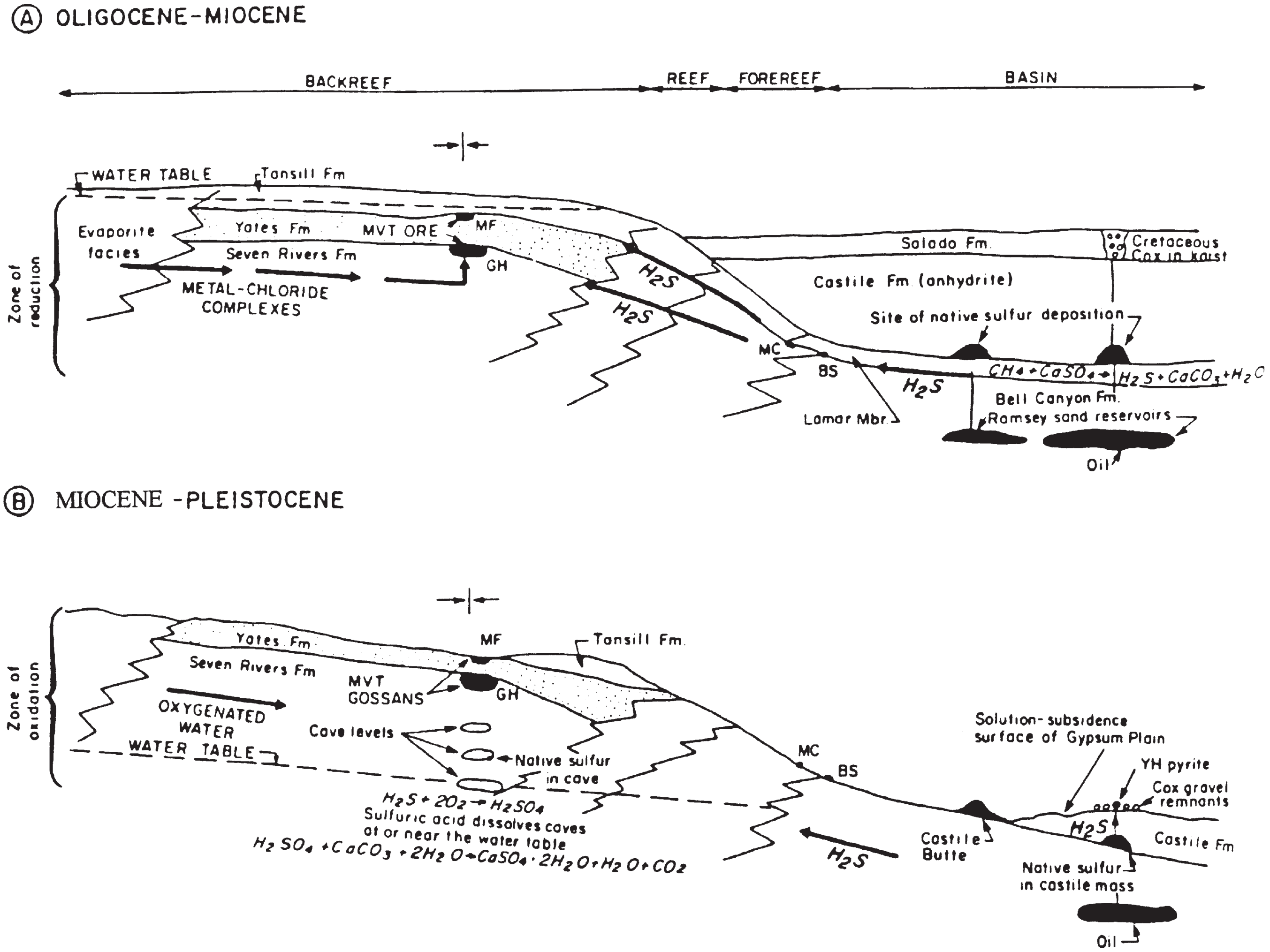


Figure 2. The idealized model for the origin of caves and for Mississippi Valley-type (MVT) sulfides in the Guadalupe Mountains proposes a genetic connection between hydrocarbons and native sulfur in the basin, and MVT deposits and sulfuric acid caves in the carbonate-reef margin. (A) In the late Oligocene–early Miocene during the Tertiary tilting of the Delaware Basin, H_2S was generated in the basin by reactions involving hydrocarbons and Castile anhydrite solutions. The H_2S oxidized to native sulfur in the basin and also migrated from basin to reef to accumulate there in structural (anticlinal) and stratigraphic (base of Yates) traps. Metals moved downdip as chloride complexes from back reef–evaporite facies; where these metals met with ascending H_2S below the water table in the zone of reduction, they formed MVT deposits. (B) Later in the Miocene and also in the Pliocene to Pleistocene, continued uplift and tilting of the Guadalupe Mountain block and Delaware Basin area caused increased H_2S generation and migration of gas from basin to reef. Cave dissolution occurred in the same structural and stratigraphic position as earlier MVT deposits, and cave passages formed where H_2S oxidized to sulfuric acid at or near the water table in the zone of oxidation. Cave levels correspond to a descending base level caused by the regional lowering of the Pecos River. From Hill 1996.

> nificantly enriched in ^{32}S; depletions as great as -25.6‰ for gypsum and -25.8‰ for sulfur have been measured (Hill 1990). The same isotopically light signatures also characterize alunite and natroalunite in these caves d^{34}S = -28.9 for alunite and -28.6 for natroalunite (Polyak and Güven 1996).

Hydrogen sulfide, generated from hydrocarbon reactions in the basin, migrated into the surrounding Capitan reef and accumulated in structural and stratigraphic traps (Figure 2). Where it met with oxygenated meteoric groundwater descending to the water table along dipping back-reef beds or joints in the overlying land surface, it formed sulfuric acid.

(Equation 1)

$$H_2S + 2O_2 = HSO_4^- + H^+$$

(Equation 2)

$$HSO_4^- + H^+ + CaCO_3 + 2H_2O = Ca^{2+} + SO_4^{2-} + 3H_2O + CO_2$$

The sulfuric acid produced (Equation 1) dissolved the Capitan reef limestone to produce the cave void, gypsum, and CO_2 (Equation 2). Sulfuric acid was neutralized by the limestone away from gas injection points and, therefore, horizontal cave passages in the Guadalupe Mountains end abruptly (Figure 3). The sulfuric acid reaction did not occur below the zone of oxygenation of the groundwater and hence vertical passages thin and end

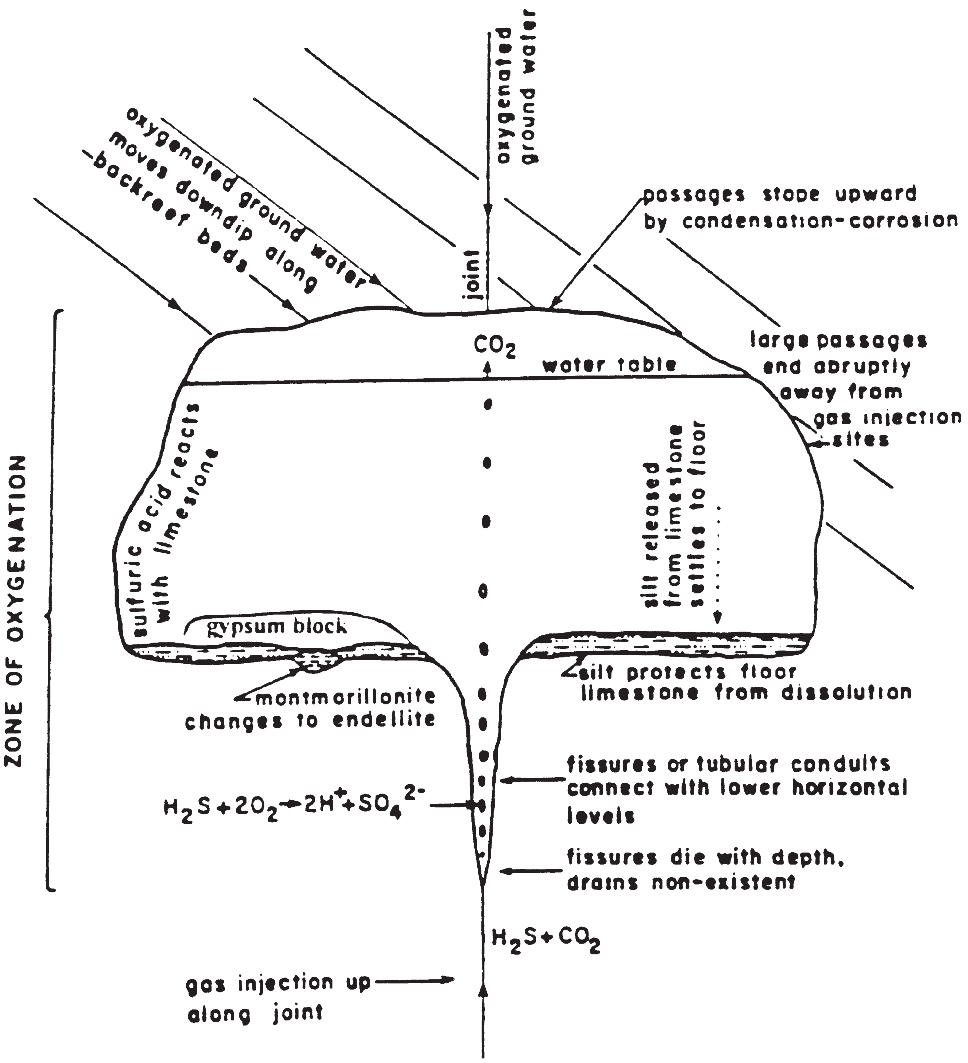


Figure 3. Model of hydrogen sulfide reaction with dissolved oxygen near the water table to form the large, Stage 4, sulfuric acid cave passages. Hydrogen sulfide from the basin ascends into the reef along injection points and reacts with oxygen in the zone of oxygenation to form sulfuric acid. The acid is neutralized by limestone away from the injection points and therefore horizontal rooms end abruptly. The sulfuric acid reaction does not occur below the zone of oxygenation and hence vertical passages thin and end with depth below large, horizontal rooms. With successive lowering of base level, new horizontal levels become connected with older horizontal levels by spring shafts and joint chimneys. The sulfuric acid dissolving the limestone forms the cave void, and insoluble residue in the limestone settles to the floor as silt. Later, dissolved sulfate created in the sulfuric acid–limestone reaction precipitates over the silt as gypsum. From Hill 1987, 1996.

with depth below large, horizontal rooms. With successive lowering of base level, new horizontal levels became connected with older horizontal levels by spring shafts and joint chimneys. Silt residue from the limestone settled to the floor; gypsum in solution (Equation 2) precipitated over the silt in slack places to form massive gypsum blocks, or directly replaced the limestone bedrock; and the CO_2 produced (Equation 2) caused further dissolution beneath the water table or condensation-corrosion of cave passages in the air zone. According to this model vertical tubes, fissures, and pits in Guadalupe caves are interpreted as having formed along injection points for hydrogen sulfide gas (bathyphreatic dissolution), and horizontal levels are interpreted as forming at the water table where dissolved oxygen was the most concentrated (water-table dissolution). H_2S degassing created the native sulfur deposits and also (ultimately) the precipitation of the secondary, later-stage uranium-vanadium minerals: tyuyamunite and metatyuyamunite. A low pH, sulfuric acid environment also caused clay minerals to reconstitute to endellite, alunite, and natroalunite.

What is the age of the large cave passages in the Guadalupe Mountains? It now appears that Stage 4 sulfuric acid caves may be older than the Pliocene-Pleistocene age ascribed by Hill (1987). Maximum uplift and tilting of the Guadalupe block is now believed to have occurred in the Miocene (15–5 million years ago). This means that hydrogen sulfide could have been migrating throughout the middle to late Tertiary with the potential for cave formation (Hill 1996). This suspicion has been confirmed by Polyak and others (1997) who ^{40}Ar/^{39}Ar dated alunite from four Guadalupe caves. These dates establish that the large cave passages formed from about 14 million years ago in the southwestern part of the reef (Virgin Cave) to about 4 million years in the northeastern part of the reef (Carlsbad Cavern and Lechuguilla Cave). These absolute dates are very important because they correlate with the time of major uplift of the Guadalupe Mountains and the migration of hydrogen sulfide from the basin into the Capitan reef.

Pliocene-Pleistocene

As the Delaware Basin and Guadalupe Mountains continued to uplift and tilt towards the northeast in the Pliocene-Pleistocene, evaporites were progressively eroded from west to east across the basin, and caves developed from southwest to northeast in the Capitan reef. The last lowering of the water table out of Carlsbad Cavern and Lechuguilla Cave may have taken place at about 600,000 years ago when the Capitan aquifer was breached by the Ancestral Pecos River at Carlsbad (Bachman 1980). This is about the time that speleothem growth began in Lower Cave and when clouds were forming at the Lake of the Clouds, Carlsbad Cavern, and Lake of the White Roses in Lechuguilla Cave (Hill 1996). Climate in the Holocene has become increasingly arid so that most speleothems in the caves of the Guadalupe Mountains are no longer active.

Conclusions

The geologic history of the Guadalupe Mountains is now known with some certainty. Over the last decade an explosion of new ideas has emerged as new analytical techniques have been developed. For the first time, the sequence of geologic events from the Late Permian to the present can be estimated for the Guadalupe Mountains.

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Note: Because the boundaries of the Middle Permian and Guadalupian have been defined and adopted (see Glenister et al. and Lambert et al. in this volume), the editors treat them as formal units. Therefore, the initial letters of the names and modifying words of both the period/system (e.g., Middle Permian) and epoch/series (e.g., Upper Guadalupian) have been capitalized in this context. Other geologic units in this paper follow the guidelines provided in Hansen, W. R., editor. 1991. Suggestions to authors of the reports of the United States Geological Survey. 7th edition. U.S. Geological Survey, Washington, D.C.

Chapter 28

History of the Sulfuric Acid Theory of Speleogenesis in the Guadalupe Mountains

DAVID H. JAGNOW has been a consulting geologist in Los Alamos, New Mexico, for the past 15 years. He began exploring and studying the caves of the Guadalupe Mountains in 1971. He completed his M.S. thesis in geology at the University of New Mexico. His thesis proposed the theory that the Guadalupe caves were dissolved by sulfuric acid.

The caves of the Guadalupe Mountains in New Mexico and Texas, are among only a few caves in the world that are known to have been dissolved by sulfuric acid, rather than a carbonic acid. Research in the early 1970s led to this controversial discovery and helped explain the uniqueness of the Guadalupe caves. The theory, as currently understood, is that hydrogen sulfide (either brine or gas or both) leaked upward along fractures from underlying sour oil and gas deposits. Upon reaching the oxygenated meteoric groundwater in the Capitan aquifer, sulfuric acid formed, dissolving large voids in the Capitan reef complex at or immediately below the water table. With the uplifting of the Guadalupe block over the past 12 to 20 million years, caves formed at subsequently lower elevations as the water table continued to lower. Deposits of gypsum, sulfur, chert, and other minerals in the Guadalupe caves have helped unravel the story of these caves. After 25 years of research, the caves of the Guadalupe Mountains are still revealing the secrets of their origin.

Early history

In a 1971 (lost) report to Carlsbad Caverns National Park, Steven J. Egemeier first suggested very briefly that the large rooms of Carlsbad Cavern may be the result of solution by sulfuric acid. Egemeier's thesis, published in 1973 at Stanford University, again mentioned the possibility that the caves in the Guadalupe Mountains are of sulfuric acid origin. This was based on his replacement solution, sulfuric acid theory for the Kane Caves, Wyoming.

Based on field work during 1972 and 1973, and completely independent of Egemeier, David Jagnow completed his M.S. thesis in 1977 at the University of New Mexico, proposing a sulfuric acid origin for the Guadalupe caves. Jagnow attributed the source of the sulfuric acid to oxidation of pyrite in the Yates Formation during uplift of the Guadalupe block.

The caves of the Guadalupe Mountains in New Mexico and Texas, are among only a few caves in the world that are known to have been dissolved by sulfuric acid.

Early clues

Morphology. Egemeier had not visited many Guadalupe caves but based his hypothesis largely on the morphology of the caves: the large rooms, deep blind pits, and joint-controlled passages that abruptly terminate, which characterize Carlsbad Cavern and many other Guadalupe caves. This morphology is unusual, even for most phreatic caves. (Phreatic caves form by dissolution below the water table.)

Limonite. Jagnow first observed the thousands of limonite pseudomorphs-after-pyrite along the Guadalupe Ridge road while doing field work on October 30, 1972. These 3-to-8-centimeter-diameter cubes of limonite within the Yates Formation had originally been pyrite. With the uplift of the Guadalupe fault block, which started 12–20 million years ago (and continues today), the pyrite was exposed to oxygen-rich fresh water and slowly altered to limonite, releasing sulfuric acid during this process. Jagnow first theorized that the pyrite was the primary source for the sulfuric acid solution reaction. While the current theory indicates that hydrogen sulfide was the source for the sulfuric acid, the pyrite may have played a role in the abundance of caves found directly below the Yates Formation in the more soluble Seven Rivers Formation.

David F. Morehouse (1968) discussed cavern development via the sulfuric acid reaction as applied to the caves in the Galena Limestone around Dubuque, Iowa. Jagnow assisted Morehouse in the collection of water chemistry data in 1965 and was familiar with this relatively new theory of cavern development.

Slowly, it became accepted that the sour gas and oil deposits beneath the Capitan reef complex provided the primary source for the sulfuric acid reaction that dissolved the Guadalupe caves.

Gypsum. The massive deposits of gypsum (up to 10 meters thick) in the Big Room of Carlsbad Cavern had always puzzled geologists. In 1972, Jagnow recognized that the gypsum was the end product of the sulfuric acid reaction. During 1972 Jagnow documented remnants of massive gypsum at many locations within Carlsbad Cavern, New Cave [also known as Slaughter Canyon Cave], Cottonwood Cave, Black Cave, Hell Below Cave, Pink Panther Cave, and the McKittrick Hill caves.

In December 1972, Jagnow discovered finely laminated (varved) gypsum exposed in the gypsum tunnel, near the “jumping off point” in the Big Room of Carlsbad Cavern. Later, finely laminated gypsum was also discovered along the Texas trail in the Big Room. Most of the gypsum in Guadalupe caves has been recrystallized, destroying the original texture. But the few exposures of the original texture indicated that the beds of massive gypsum precipitated out of solution during the final stages of solution at any one base level. (Base level solution in the Guadalupe caves is solution at or immediately below the essentially horizontal water table.) As the Big Room in Carlsbad Cavern began to drain of water and fill with air, evaporation increased, causing the gypsum-saturated water to precipitate gypsum onto the floor of the water-filled room. Thus, massive beds of gypsum floored the rooms of all Guadalupe caves as each base level slowly drained, and solution continued at lower levels. In most caves, the gypsum has been dissolved by dripping vadose water (meteoric water that drips or flows above the water table); only remnants of these massive beds remain today.

Donald G. Davis (1973) and Michael Queen (1973) described sulfur and gypsum deposits in Cottonwood Cave and concluded that the gypsum was derived at least in part by replacement of the carbonate bedrock. The exact replacement mechanism was uncertain.

Sulfur. Bright yellow, native sulfur has been found in several Guadalupe caves. To date, perhaps 50 metric tons of sulfur have been discovered at various locations within Lechuguilla Cave. But in 1972 and 1973, the sulfur studied in Cottonwood Cave, at the crest of the Guadalupe Ridge anticline, provided the strongest argument for hydrogen sulfide leaking as gas or brines from the underlying sour hydrocarbons. Slowly, it became accepted that the sour gas and oil deposits beneath the Capitan reef complex provided the primary source for the sulfuric acid reaction that dissolved the Guadalupe caves. In 1973, Davis published the first detailed description of the sulfur deposits in Cottonwood Cave.

Later history

In 1977, Art and Peg Palmer and Michael Queen discussed gypsum-replacement mechanisms at the International Congress of Speleology. In 1978, Jagnow, Carol Hill, and others published in National Speleological Society Bulletin Symposium on Ogle Cave. Jagnow’s discussion of the geology and speleogenesis again attributed the sulfuric acid origin to the overlying pyrite in the Yates Formation. This paper stimulated Davis to comment on other possible sources for the sulfuric acid, and began a renewed focus on hydrogen sulfide from the underlying hydrocarbons within the Delaware Basin. Davis proposed an ascending-water theory.

Sulfur isotope analysis. Hill (1979) did the first sulfur isotope determinations on gypsum blocks in the Big Room of Carlsbad Cavern. The presence of isotopically light sulfur proved that the gypsum was not derived from the Castile gypsum in the Permian basin.

Endellite. Hill (1979) also suggested that endellite, a sulfuric acid indicator mineral, was additional supporting evidence for sulfuric acid-related speleogenesis.

Gypsum and sulfur. In 1980, Davis wrote a review of the sulfuric-acid theory of speleogenesis, and was the first to propose a hydrocarbon source for the hydrogen sulfide–sulfuric acid origin for gypsum and sulfur present in Guadalupe caves. In 1981, Hill first published her isotope results in the Proceedings of the International Congress of Speleology at Bowling Green, Kentucky. In 1982, Doug Kirkland published (in New Mexico Geology) more sulfur stable isotope values on the gypsum blocks in the Big Room of Carlsbad Cavern. In 1985, Egemeier died after a long illness. Dr. Egemeier was a pioneer in the subject of hydrogen sulfide speleogenesis. Shortly before his death, he wrote the paper "A Theory for the Origin of Carlsbad Caverns" that was posthumously published in the National Speleological Society Bulletin in 1987. He concluded that Carlsbad Cavern was formed by ascending hydrogen sulfide waters that outgassed hydrogen sulfide into the cave air. He proposed that the limestone was replaced by gypsum.

Corrosion. In 1985, Van Everdinger and others published, "Role of Corrosion by H_2SO_4 Fallout in Cave Development in a Travertine Deposit: Evidence from Sulfur and Oxygen Isotopes."

Chert. In 1987, Hill published *Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico and Texas*. Hill relates the chert deposits, beneath the massive gypsum in the Big Room of Carlsbad Cavern, to sulfuric acid speleogenesis. Hill also is the first to discuss in detail the sulfuric acid origin of the Guadalupe caves in relation to the underlying hydrocarbon deposits and Mississippi Valley-type (MVT) sulfide ore deposits.

Recent clues

Since the early 1980s, the theory of sulfuric acid solution for the Guadalupe caves has been largely accepted by those researching the caves. Additional studies of endellite, silica deposits, isotopically light gypsum and sulfur, the presence of alunite, natroalunite, tyuyamunite, and other unique minerals all point to basinal degassing of hydrogen sulfide as the most likely source of the sulfuric acid solution.

In 1990, Hill published in the American Association of Petroleum Geologists Bulletin a summary of "Sulfuric Acid Speleogenesis of Carlsbad Cavern and its Relationship to Hydrocarbons, Delaware Basin, New Mexico and Texas." She proposed that during uplift of the Guadalupe Mountains, oil and gas moved up dip within the Delaware Basin. The gas reacted with the Castile anhydrite to form H, S, CO, and "castile" limestone. She proposed that the hydrogen sulfide rose into the Capital reef along joints, fore-reef carbonate beds, or the Bell Canyon siliciclastic beds.

In 1991, Art Palmer published a classic paper on the origin of caves and offered important information on the morphology of hypogene caves (formed by warm ascending waters). Caves of the Guadalupe Mountains were used as an example of sulfuric acid–type hypogene caves.

Alunite and natroalunite. In 1992, Art and Peg Palmer reported alunite in Lechuguilla Cave; soon after Victor Polyak identified alunite and natroalunite in Carlsbad Cavern. The sulfur isotope analysis of these two minerals by Polyak and Guven indicate that they are isotopically light, are comparable to the gypsum from cave to cave, and further support the theory of sulfuric acid-related speleogenesis. Since 1992, Polyak has identified alunite and natroalunite in Carlsbad Cavern, Cottonwood Cave, Endless Cave, Lechuguilia Cave, and Virgin Cave.

Gypsum. In 1994, Marcus Buck and others provided a detailed characterization of H_2S gypsum in caves. Their work, while not yet published in full, produced a genetic classification of these gypsum deposits. Further work in this area will show whether a cave passage formed above or below the water table.

Since the early 1980s, the theory of sulfuric acid solution for the Guadalupe caves has been largely accepted by those researching the caves.

Canaa: yellow cave precipitates. Since 1994, Polyak and Cyndi Mosch have teamed up to identify many yellow cave deposits that had previously been mistaken for sulfur. Metatyuyamunite was first identified in Spider Cave. Tyuyamunite has been identified in Carlsbad Cavern and Lechuguilla Cave. The uranium minerals metatyuyamunite and tyuyamunite were precipitated after the origin of the caves, however, the redox boundaries when the caves were forming are probably the reason why uranium and vanadium became concentrated enough to allow precipitation of these minerals.

Sulfur redox reactions. In 1995, Hill published "Sulfur Redox Reactions: Hydrocarbons, Native Sulfur, Mississippi Valley-type Deposits, and Sulfuric Acid Karst in the Delaware Basin, New Mexico and Texas." This was the first detailed review of data surrounding the entire Delaware Basin relative to sulfuric acid speleogenesis.

Also in 1995, R. H. Worden and others published "Gas Souring by Thermochemical Sulfate Reduction at 140°C." They attribute the high concentrations of hydrogen sulfide encountered in deep carbonate gas reservoirs to the in situ heating and thermochemical sulfate reduction of anhydrite. This paper helps clarify the origin of hydrogen sulfide–rich gas deposits.

In 1996 Hill, Jagnow, and Mosch found gypsum in a Glass Mountain Cave with an isotope value the same as the Guadalupe caves. This was an extremely important find since it showed that the entire Delaware Basin is degassing hydrogen sulfide. Hill subsequently (1996) published *Geology of the Delaware Basin: Guadalupe, Apache, and Glass Mountains, West Texas and New Mexico*. Hill presents the story of hydrogen sulfide basinal degassing with convincing evidence from all the mountain ranges surrounding the Delaware Basin. Her publication provides an excellent summary of all the relationships previously discussed.

Research is now shifting emphasis to the unique microbes living off the sulfur compounds found in these caves.

Sulfur deposits have been recognized in at least two active caves of sulfuric acid origin: Egemeier found sulfur in the Lower Kane Cave which is developed in the Madison Limestone in the Big Horn Basin of Wyoming; Pisarowicz and others found and described sulfur in Cueva de Villa Luz in Cretaceous limestone in the southern part of the state of Tabasco in Mexico. While these occurrences do not directly relate to the Guadalupe caves, they do demonstrate that the mechanism is valid and operative today at these locations.

Latest developments

Victor Polyak and others (1997) published, "Age of formation of Carlsbad Cavern, Lechuguilla Cave and other caves of the Guadalupe Mountains based on $^{40}Ar/^{39}Ar$-dating of Alunite." Because the alunite deposits are byproducts of H_2S-H_2SO speleogenesis, these ages date the formation of the caves. Using the fine-grained alunite crystals that formed at the time of speleogenesis, Polyak and others have reported radioisotope ages of formation for Cottonwood Cave (12.3 million years), Virgin Cave (11.3 million years), Endless Cave (6 million years), and the New Mexico Room of Carlsbad Cavern (4 million years). Ages are strongly correlated with elevation of the alunite cave deposit, confirming a relationship described by Jagnow (1992). It appears that the Guadalupe block began its eastward tilting at least 12 million years ago. The oldest Guadalupe caves formed high in the block, toward the western end, and younger caves formed eastward as the water table subsequently dropped, accompanying the continued structural uplift of the Guadalupe Mountains.

Summary

The past 25 years of research have established the sulfuric acid theory of speleogenesis for the caves of the Guadalupe Mountains. Debate continues over the migration routes of the gases or brines derived from the underlying formations. Research is now shifting emphasis to the unique microbes living off the sulfur compounds found in these caves. Twenty-five years from now, the caves of the Guadalupe Mountains will still be revealing the secrets of their origin.

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Chapter 29

Recording of Earth Movements in Karst: Results of a Short Trip in Southwestern U.S.A.

ROBERTA SERFACE is a speleologist in Carlsbad, New Mexico. She has been doing cave-related research since 1991. She has worked for the National Park Service and U.S.D.A. Forest Service, as well as private consultants. She is currently employed by Celtech in Carlsbad. Her experiences with speleological investigations include the Grand Canyon, southern Texas, the Navajo Nation, and New Mexico. Her plans for a summer expedition into Lechugilla Cave are currently in process to collect microbial samples for studies and research into cures for cancer.
Other author: ERIC GILLI is a geologist in Nice, France.

Description of the method

A great number of countries are affected by earthquakes (or "seisms") that cause thousands of lost lives and countless damages. Even if some experiences have been positive (e.g., VAN system, Chinese methods), a large majority of examples prove that no technique permits us to predict the occurrence of a seism. The only possibility is to search in old records to see if great seisms have already affected a country (historical seismicity). In Earth sciences it is thought that if a seism has occurred in the past, one is likely to occur again in the future at a particular location. Therefore it is very important to locate the places where many old seisms have occurred and to know the intensity of the damages. Such studies help specialists define the probability of a future seism in an area and to draw risk maps. It is common in Europe to study old writings and it is sometimes possible to discover very old earthquakes in antiquity descriptions, but in most cases it is very difficult to get usable information that is older than 500 years. In cases when written history does not exist or has been destroyed (French Revolution) those studies are impossible. Some seismologists work on old ruins when they exist or lake deposits and Quaternary alluvium to find information which may be helpful.

The study of caves is an interesting new approach to see whether great seisms have affected an area and to find whether fractures are active. As a matter of fact, caves are very good recorders for natural phenomena. In the same way the underground environment has preserved prehistoric human traces (e.g., paintings, bones, and tools) for thousands of years, they also have preserved many traces of Earth movements. As caves may be a few million years old, it is possible to discover whether many great seisms have occurred over very long periods of time.

We search two kinds of information:

1. Old seisms: which can cause collapse of soda straws, stalactites, stalagmites, or parts of the roof.
2. Active faults: seisms are caused by fault movements (tectonic). In some cases the movements are visible (e.g., El Asnam, San Andreas), but in most cases the movements are smaller and their effects are hidden by soil or vegetation. Inside caves, which are always excavated along natural fractures, even a millimeter-scale movement is observable as it causes breaks on speleothems. Larger movements may displace whole gallery sections.

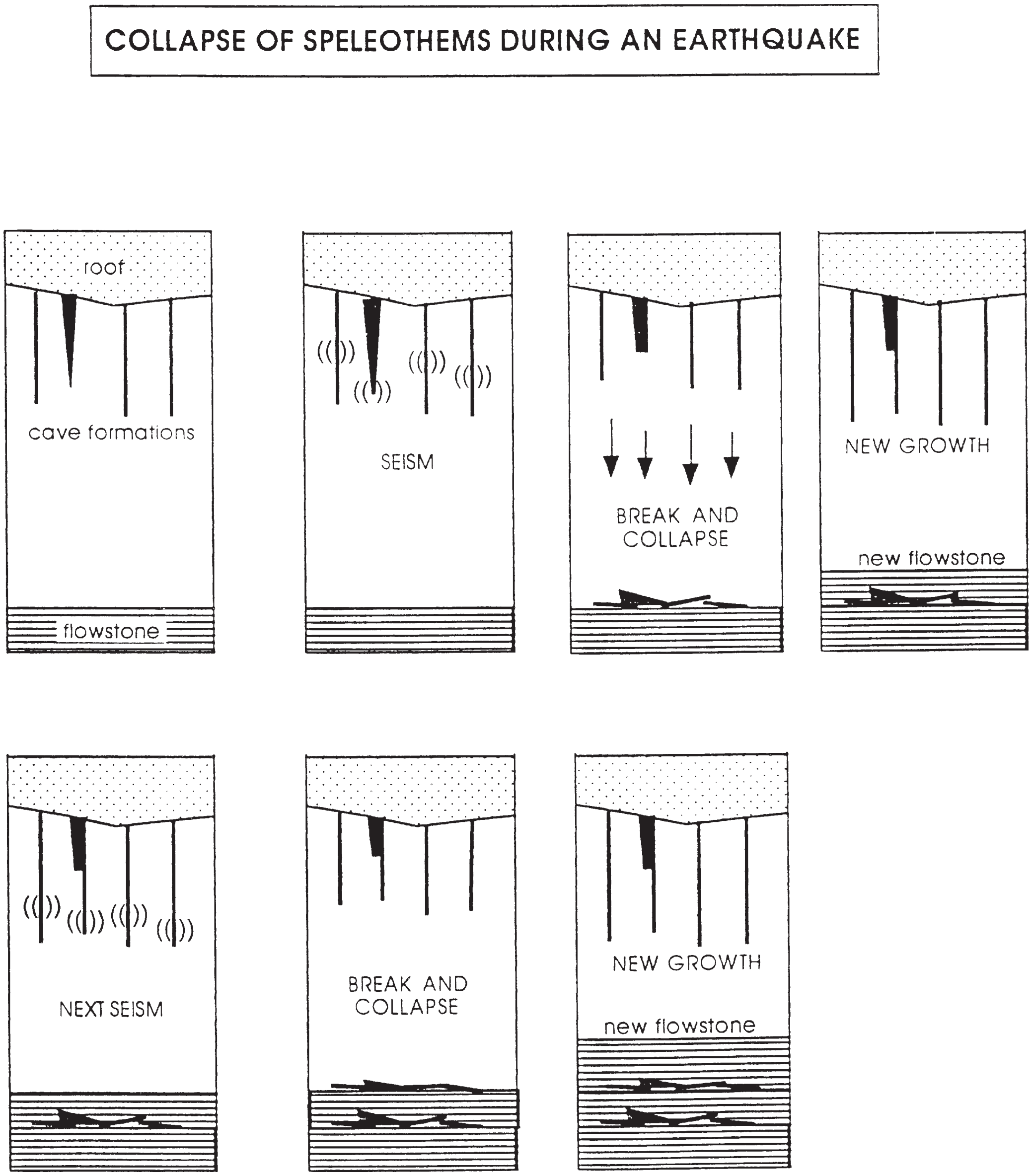
As it is possible to give an age to the speleothems, the study of the breaks is very interesting for seismic investigations. Carbon 14, uranium/thorium 180, photo luminescence, or paleomagnetism methods may be used with good results.

Since 1981 we have made observations in southern France, which is an active zone (several important seisms known since A.D. 1328). We are continuing this research to find known seisms recorded in caves and search for unknown ones. These studies will provide a new tool for many countries with historical seismicity. Karstic zones cover more than 10% of the emerged land in the world.

Significant previous results
1980: Method definition in southern France. Study of Cassaire Cave (Var) and Peneta Cave (Alpes Maritimes).

1986: Evidence of neotechtonics in Deux Gourdes' Cave (Vesubie Valley, Alpes Maritimes, France).

Figure 1. Collapses of speleothems during an earthquake.



1995: Turkey (Tilkiler Cave, Manavgat) where broken stalactites prove that a seism occurred in Manavgat several centuries ago. Located here is one of the largest hydroelectric dams and this dam site is considered as a non-seismic zone!

1995: Study of a slope movement for a 30,000-year period in Chemin du Castellaras Cave where formations are affected by the movement (Le Tignet, Alpes Maritimes, France).

1995: Field trip to Costa Rica to verify if the data in French caves could be attributed to tectonic events and to make a comparison between different seismotectonic areas. We have been able to see differences between the caves that are located in seismic zones (Cueva Corredores, Ciudad Neilly) and the caves in quiet places (Venado) and to realize the seismic zonation of Costa Rica.

1995: Evidence of fault movements in caves near Durance Fault (France). Dating of speleothems attributed to the 1887 seism.

1996: Study of the caves around Saint Paul de Fenouillet (Pyrenees Orientales, France) after 1996 earthquake (magnitude 5.3). Evidence of underground damage.

1996: Study of a dating method using growth laminae in 30 stalagmites (Alpes Maritimes, France).

1996: Drill sample taken in Monaco Cave flowstone producing a description of seismic history of Monaco for more than 38,000 years.

1997: Southwestern United States evidence of paleoearthquakes in Carlsbad Caverns and McKittrick Hill caves (Guadalupe Mountains, New Mexico). Present report.

1997: Study of underground damage in Barrenc du Paradet Cave (Pyrenees Orientales, France). Evidence of an east–west shock direction and a very large old seism.

Results in U.S.A (May 1997): itinerary

California

1. Mercer Caverns (May 7)
2. Mitchell Caverns (May 9)

Arizona

3. Boulder hills with petroglyphs near Tucson (May 11)
4. Sutherland Peak Cave (May 13)
5. Tectonic cracks near (northern) Flagstaff (May 15)
6. Lava River Cave near Flagstaff (May 15)

New Mexico

7. Endless Cave near Carlsbad (May 19)
8. Carlsbad Caverns (May 21)
9. Sand Cave and McKittrick Cave (May 22)
10. Hidden Cave in the Guadalupe Mountains (May 23)

Caves in California

Mercer Caverns. We spent a few days with Bruce Rogers (U.S. Geological Survey, San Francisco) looking for caves near the San Andres Fault. In fact, very few caves are known in this part of California. We only visited Mercer Caverns in the Sierra Nevada, located in the Mother Lode area near the small town of Murphys in Calaveras County. It is a small cave in a banded marble lens (Permian?) of the Calaveras Group and is the result of rocks collapsing between vertical tectonic joints. It is well decorated and has a wall of aragonite crystals at the bottom. There are several places where the columns and flowstones have been fractured, but these features seem to have been caused by subsidence.

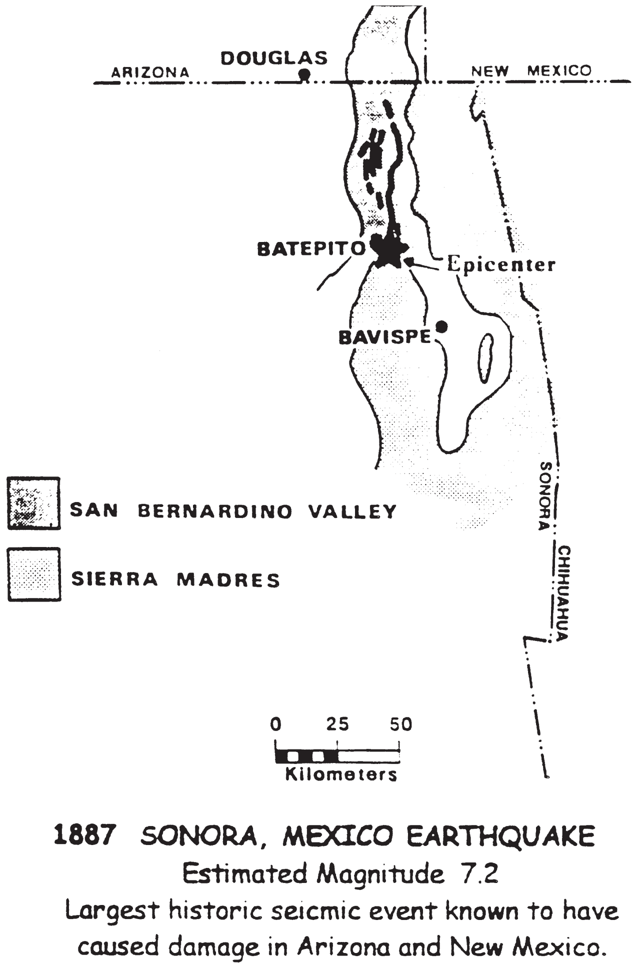
Mitchell Caverns. It is a small cave in Providence Mountains State Park in the Mojave Desert, very close to the border of Nevada and Arizona. The cave is a subvertical series of limestone beds covered with rhyolite. There are two main rooms, one of which is well decorated. It is possible to observe many breaks in the rock wall and in the flowstone, but as the cave is very close to the outside, most of the features may have been caused by decompression. The passage between the two rooms contains many broken stalactites and some are vertically cleaved. Such an unusual shape may have been caused by seismic vibrations.

Caves in southern Arizona

Seismic history. An important earthquake in the San Bernadino Valley of northern Sonora, Mexico, had caused damages in 1887 near the border of Arizona and New Mexico. A fault displacement was visible eight kilometers south to Douglas on a 50-kilometers-long main fault. The supposed magnitude was 7.2. In Sierra Vista the damage intensity (actual standardized scale didn't exist at the time) was VII to VIII. Damage included: (1) VIII in Box Canyon with rocks and trees collapsing on Ramsey Peak, (2) VII in Miller Canyon with some rock collapse, (3) VII at Fort Huachuca which opened fissures in buildings, (4) VII in Cave Canyon with large rocks collapsing, and (5) VII in Ash Canyon also with large rocks collapsing.

S.P. Cave. On Sutherland Peak in the Huachuca Mountains near Sierra Vista is a very small, well-decorated cave known as S.P. Cave. It has many stalactites, soda straws, disks, and helectites. A limestone lens in a volcanic environment acts as a natural drain for surrounding fractured rhyolite and the area has been intensively karstified. The contact between rhyolite is a faulted one with many cracks. Several fractures that affect speleothems may be observed in the entrance. This could be attributed to fault movement. In the deep parts of the cave, fractures are also visible; however, most were caused by subsidence. Large flowstone columns have been deposited on clay substratum. The clay, washed away by water, caused the collapse of these speleothems. Meanwhile in several places it is possible to see soda straws and small stalactites in the clay. Some of them are stuck vertically in the soil. The

Figure 2. The earthquake that occurred in 1887 near Sonora, Mexico, had an estimated magnitude of 7.2. This is the largest historic seismic event known to have caused damage in Arizona and New Mexico.



collapse was probably caused by the 1887 earthquake. It would be interesting to drill a segment from the soil to see if older levels of collapsed formations exist.

Hidden Cave. Located in the Santa Rita Mountains, this very small cave (where a main fault is observable) does not contain any evidence of movement or speleothem collapse.

Non-karstic signs. Close to Tucson there are several small diorite hills with large boulders covered with Native American rock art called petroglyphs. It is possible to observe collapse and displacement. Some boulders are broken and displaced without patina and a good number of petroglyphs are damaged. The movements have been attributed to the 1887 Sonoran earthquake (J. Holmlund, personal communication).

Caves in northern Arizona (Flagstaff)
Geologic environment. The area around Flagstaff is volcanic with many different basalt flows since Miocene time. The main volcano, San Fransisco Peak, is Quaternary in age. The last volcanic event has a K-Ar age of 0.60 ± 0.08 million years (R. Holm, Northern Arizona University, personal communication). Two types of cave features exist in this area: (1) lava tubes that form in lava flows when lava at the surface cools and hardens while hot lava in the interior continues to flow and eventually evacuates, leaving a void and (2) earthcracks caused by distension.

Lava River Cave. Eighteen miles northwest of Flagstaff in the Coconino National Forest is Lava River Cave, the longest lava tube in Arizona. Such caves contain no true formations, and we did not see any unusual features. This cave is around 650,000 to 700,000 years old.

Earthcracks. In the Coconino National Forest near Wupatki National Monument, some distension features affect the limestone making it possible to climb down very deep into one-meter-wide open fractures. These are in fact small grabens and it is possible that this distension phase is still going on as parts of these cracks are collapsing at the present time. Most of these cracks contain earth and small rock fill, while others drain large, urban areas and contain things such as garden hoses and barbeque grills. The same phenomena exist near Meteor Crater in Diablo Canyon located 40 miles east of Flagstaff.

Caves in southern New Mexico
Geology of the Guadalupe Mountains, Carlsbad area. The main element of the geologic environment is the Guadalupe block whose highest point is Guadalupe Peak (8,749 ft). The block that contains limestone formations (Capitan Limestone) dips towards the northeast where it disappears beneath the plains of Carlsbad. It is bordered on the west by an escarpment over salt lakes and on the south by another escarpment (the reef escarpment) over the Delaware gypsum basin.

Capitan Limestone was a Permian reef, bordered by a large evaporitic basin. It was probably covered with Mesozoic rocks. In the Miocene Epoch this place began to arch. In early Pliocene time a main fault line broke the block and the eastern part began to rise up until the present time. This movement has been extending several miles for the past six million years.

There is little evidence of faulting in the reef escarpment area that was caused by a difference of solubility between the gypsum of the Delaware Basin and the Capitan Limestone. The western part rose up forming a graben that filled in with clay and salt deposits.

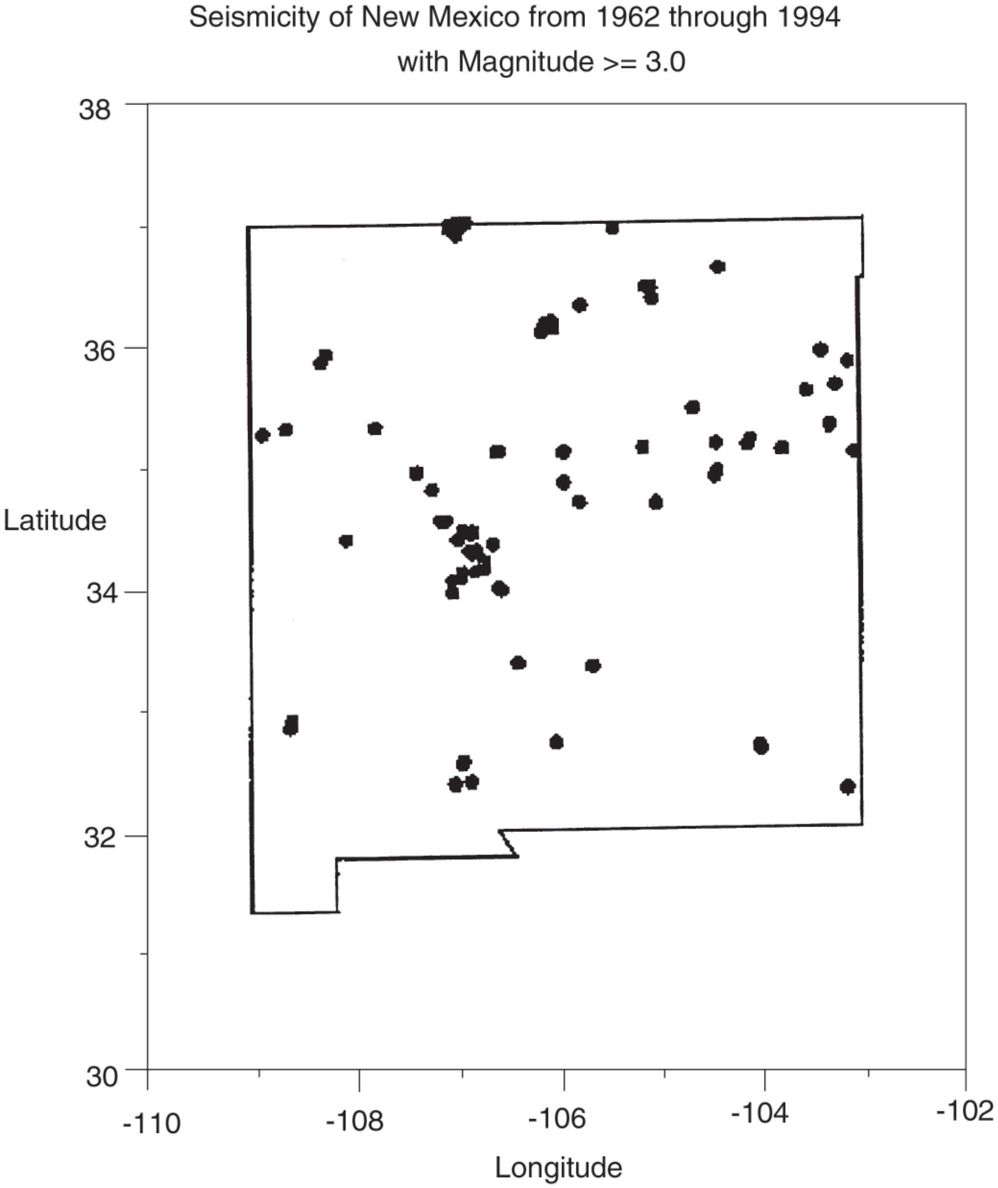
The area around Carlsbad contains many limestone caves. Most of the caves are mazes with different levels, and Lechuguilla Cave is now considered the deepest cave in the United States with more than 80 miles mapped so far. It is probable that the Guadalupe Mountain caves began to form during the late Miocene or early Pliocene when the Capitan reef began to arch and rise up. The Mesozoic cover eroded away allowing the action of water on the limestone to form the large voids. Most contain gypsum that may come from the Delaware Basin, but may also result from the action of a sulfuric acid solution on limestone in a thermal process.

The functioning of water flow and cave formation inside the Capitan Limestone is very difficult to understand as several phenomena are involved: (1) uplift speed, (2) sea level position, (3) connections between the Delaware Basin aquifer and the karstic aquifer, and (4) the presence of sulfuric acid. The water now flows towards springs in the Pecos River near Carlsbad.

The different levels of the caves show different steps in the rise of the Guadalupe block, and there is evidence that uplift of the block is continuing today. Recent active faults are visible and seismographs have recorded many small earthquakes.

Endless Cave. This cave is a maze with three different levels. It seems to be a hydrothermal cave as it is located at the top of a hill which was probably covered, at one time, by an impervious layer. There are many signs of speleothem collapse.

Figure 3. Seismicity of New Mexico from 1962 through 1994 with Magnitude = 3.0.



In some places it is possible to see ancient broken soda straws that are now soldered with calcite onto the flowstone, as well as more recent breakage loose on the soil which is a result of human contact. In several places it is also possible to observe the collapse of the limestone beds between the upper level and the entrance level. The collapse has crashed down onto flowstone causing damage to these formations.

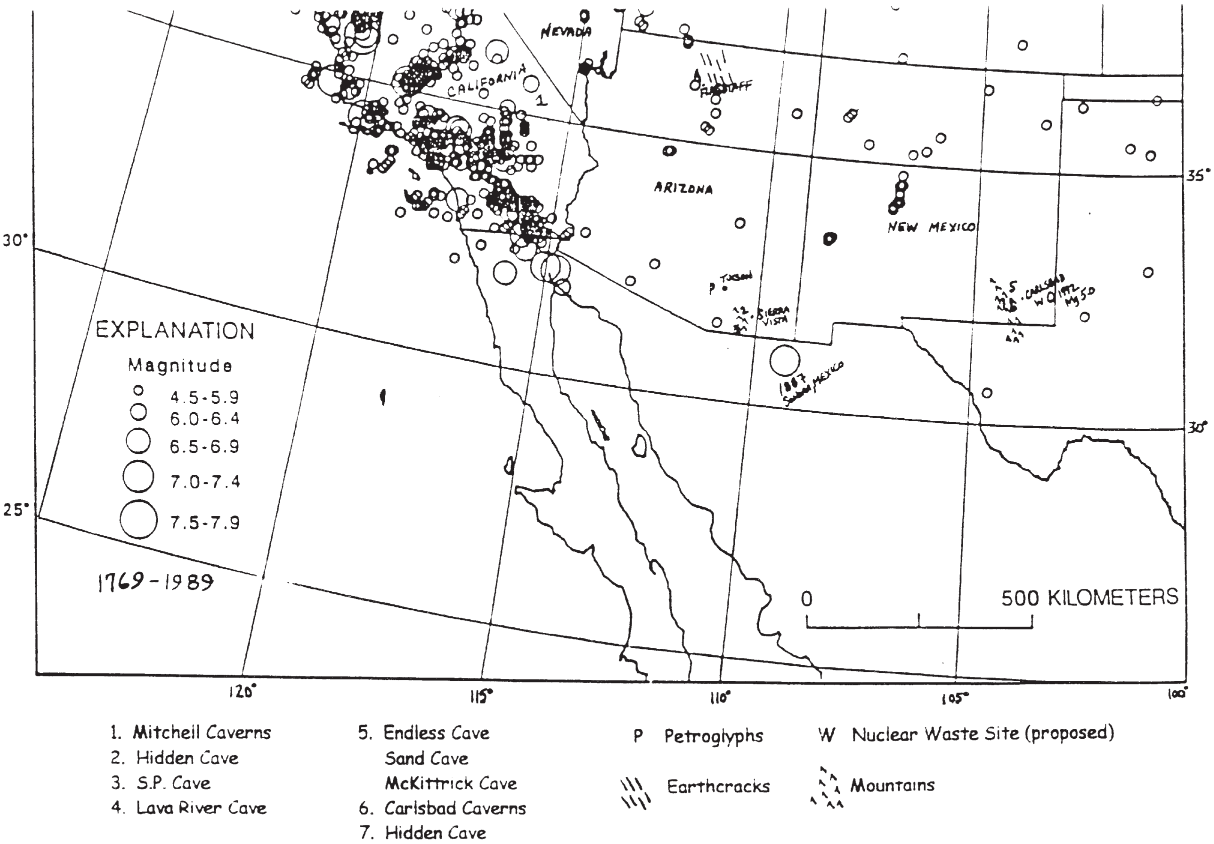
Sand Cave. This is a maze, like Endless Cave, and is also located at the top of a hill. Unfortunately in the early part of the 20th century, the cave was totally destroyed for the selling of speleothems, but the two different ages of broken formations are visible. A signature with a date of 1917 is located on flowstone in which an older collapse of soda straws is included and indicates that calcite formation is very slow and the age of collapse is older than human contact. It is possible to see many collapses in niches or difficult places to reach which excludes a human cause.

McKittrick Cave. It is also a maze cave located at the top of a hill in which we have observed two ages of speleothem collapse: a recent one free on the soil, and an older one soldered with calcite.

Carlsbad Cavern. Inside the whole cave we observed, on the soil, broken soda straws. Many large collapses are visible in many places inside this cave. One of the most important is Iceberg Rock, but this movement seems to have been a slow slip as the formations that were on the rock before the collapse are not broken. It could be possible to know the age of this collapse by dating the broken formations under Iceberg Rock.

The Big Room area shows two ages of rock collapse. The rocks of the oldest collapse have smooth edges; the more recent ones have many angles. Between Crystal Spring Dome and Rock of Ages, a little basin is full of ancient broken stalactites. In Lower Cave many broken soda straws are now covered with cal-

Figure 4. Recorded and estimated earthquake magnitudes from 1769 to 1989.



cite, forming cave pearls. In the Colonel Boles Formation a large crack in the soil was caused by subsidence.

Hidden Cave. This small shaft is located on top of the Guadalupe Mountains. The entrance is a vertical pit that goes into two separate galleries. It is aligned on a fault line but we did not observe any fault movement. In both parts many collapses are visible, and like the previous examples, two different ages may be observed. For the oldest collapse, several pieces are located behind unbroken formations proving that the breaks did not have a human cause. The soda straws of Hidden Cave are short ones and stalactites have broken extremities with new calcite growth. It is most certain that this cave has been affected by an important earthquake.

This succinct study of caves in the Carlsbad area indicates the existence of ancient seismic activity in the whole area between the Guadalupe Mountains and the City of Carlsbad. The western fault that caused the uplift of the Guadalupe block was probably responsible for some earthquakes in the past. Unfortunately, some of the caves have been partially destroyed by human activity. It would be very interesting to check preserved caves, like Lechuguilla Cave, to see if broken soda straws of the two different ages are visible.

General conclusion

In comparison to Europe where caving is free, we have been very discouraged to see the difficulties in obtaining permits for cave research. It would be interesting, for our research, to be able to visit preserved caves like Lechuguilla or Kartchner Caverns. But we have also been very disheartened to see how some caves have been destroyed by human actions and, of course, one thing explains the other.

Concerning our method, caves in Arizona and New Mexico are very dry and dusty. Calcite growth speed is much slower here than it is in Europe; however, it is possible to make good observations. The collapses are probably older than what we are used to evaluating.

Concerning the results, the California area does not contain enough caves for our purpose, which was the study of the San Andres Fault activity on cave development. In Arizona some evidence in S.P. Cave may be attributed to the 1887 Sonoran earthquake. It would be worthwhile to check for the same evidence in other caves nearby. In New Mexico this short trip revealed how caves in the Carlsbad area were affected by past seismotectonic activity. An accurate study could give much information on the seismic history of the Guadalupe Mountains. We have discovered that a project of nuclear waste disposal is in progress near Carlsbad. The knowledge of the recurrence and intensity of ancient seisms could be beneficial.

As the known seismic history of the United States is very recent, cave studies could be a very good geologic tool for seismic prevention. Such work could be done in places where active faults have been detected, to see if these faults have caused ancient earthquakes.

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Note: Formatting of geologic units in this paper follows the guidelines provided in Hansen, W. R., editor. 1991. Suggestions to authors of the reports of the United States Geological Survey. 7th edition. U.S. Geological Survey, Washington, D.C.

Chapter 30

Guadalupian Series: International Standard for Middle Permian Time

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Looking around, I feel as if I am preaching to the choir, but it is a pleasure to talk with many old friends. The joint authors here, of course, are Bruce Wardlaw and Lance Lambert, and I might say in starting that we have a poster station and encourage you to observe this, and of course on Saturday we are running the field trip to Stratotype Canyon. There are many reasons that the three of us are glad to be here, but at the head of the list probably is the opportunity to celebrate a couple of anniversaries. The first one you know about: the 25th anniversary of the founding of the park. The second, perhaps, you are not so familiar with; it is coming up very soon, and that is the first anniversary of the international ratification of the Guadalupe Mountains section as the standard for part of a very exciting interval of geological time; that is, the Permian and the succeeding Permian-Triassic boundary. The Permian, of course, is an interval of geologic time that ranges from about 200 million years back to 250 million, in round terms. It is named for the city of Perm in the northern Urals of Russia, and it is a very old term. It was proposed in 1841 by Sir Roderick Murchison. He was invited to Russia by the czar to observe the geological successions in Russia and compare them with those that were being named, particularly in Great Britain. Many of the systems were proposed in the early 1800s. I just mentioned the first of these, which was the Carboniferous, which was proposed in 1811. The reason for the early proposal of the Carboniferous, I think, is obvious to you, because of its economic value. The Carboniferous, of course, is carbon-bearing and yields the coal measures of western Europe that allowed the Industrial Revolution, and our own Carboniferous age resource. Murchison went to Russia at the invitation of the czar and about all he was able to say was that yes, I can recognize these other systems that we have named in Britain, but you seem to have something different here at the top of the stack. It looks to be more advanced—he was looking at a few fossils—that seemed to be more advanced than those of the Carboniferous of Britain. And so he named the Permian System. As with the preceding systems, that had been named, the objective was to develop an international language so that people of Asia or Australia could recognize the same age of rocks and utilize the same terminology. In other words, the original objective was to develop an international language for geologic time. However, as many of us experience almost daily, correlation from one area to another, correlation in facies from Lloyd Pray's back reef to the slope facies, for example, is always difficult. So there was a temptation for people in different geographic areas to propose their own time scales, and the result of this was the development of what I like to call a "Tower of Babel." People were utilizing local terms, and as a result of this were really unable to communicate the correlation of geologic events.

In the last 50 years, however, a very active group, the International Commission on Stratigraphy, has been developing or choosing an international language for geologic time. I am going to restrict my comments to the Permian here and simply state that at the moment, the international commission after something like 50 years is about to achieve this international nomenclature for Permian time. The Lower Permian has its objective reference section in the southern Urals. I will show you photographs of this area and others shortly. It serves very well for this interval of geologic time. However, near the end of the Lower Permian, Earth was confronted with the collision of Europe and Asia and the in-filling of the intermediate Urals Mountain basin. The result of this is that these excellent sections, these Lower Permian sections, lower in the succession, very fossiliferous, very adept for correlation to other parts of the world, were replaced by evaporites. So the Urals, the original type section of the Permian, is no longer suitable as an international reference for the rest of the period. We need to look someplace else for an international reference for the Middle Permian, and a year ago we were delighted to have the consensus of the International Commission on Stratigraphy. This was not a quick decision, and it was not an easy decision. It was a very painful decision for the Russians, in particular, to have the reference section for the rest of the Permian transferred to other areas. There were three candidates: one was middle Asia in the high mountain country there, the second was in south China, and the third in the southwestern United States. Now without going into detail, I would like to say that the first two have serious problems. First of all, the state of knowledge—they have not been studied for as long or as intensively as the Guadalupe Mountain area, and secondly, there tend to be noncomformities there, i.e., gaps in the record more than in other areas. Also, there are other problems, particularly the matter of access. In middle Asia, some of the type sections are at 4,000 meters elevation, and most of us get nosebleeds, of course, even below that. Also, in south China, for example, there is a problem of accessibility. So almost a year ago a formal vote, or a series of formal votes by the Subcommission on Permian Stratigraphy, of which Bruce Wardlaw is now the chair and I am a past-chair, voted formally in favor of the Guadalupian as the international standard for Middle Permian time. I won't go into details, but it was ratified successively by other international groups, and the final vote a year ago stabilizes the Guadalupian name as the international standard reference for Middle Permian time.

You might well ask what is the reason for selection of the Guadalupian as the international standard? There are a number of reasons for this. First of all, the state of knowledge—and this goes back almost a century to intensive study by G. H. Girty and descriptions of fossils, and so on—and an Iowa City boy by the name of P. B. King made major contributions on the physical stratigraphy. Other people like Miller and Furnish contributed important information on the biostratigraphy, particularly the ammonoids of the area. I am still amused and occasionally rib my colleague, Bill Furnish, about the title of the Miller and Furnish 1940 monograph. It is a classic, titled *Permian Ammonoids of the Guadalupe Mountain Region and Adjacent Areas*. Of course, the adjacent areas are Mexico and China and Australia and so on! I should mention the oil companies, Exxon, Amoco, and many of the others who have made intensive investigations on the stratigraphy and sequence relationships in the Guadalupes. In terms of stratigraphy and lithology, the Guadalupe Mountains are probably better known than any other sequence of those sedimentary rocks.

A second factor is that the Guadalupian has abundant fossils. These have been studied for almost a century. I think Girty's monograph of 1902 consisted of—perhaps we'll miss a page or two—but I think it was 561 pages and 30 or 40 plates of the fossils. Others have followed, as I mentioned, Miller and Furnish on the ammonoids. The fusulines have been studied in very intense detail by Garner Wilde and others, and more recently the conodonts have received very intensive investigation. Bruce Wardlaw and Lance Lambert, for example, are collecting specimens centimeter by centimeter near the base of the Middle Permian to document in great detail the evolution of that group. Stratigraphically as well as biostratigraphically, the Guadalupian appears very attractive.

A third consideration here would be accessibility, and I can't emphasize this matter too much. This is a very, very sensitive area that we explored three or four years ago, and the request was that the park guarantee access forever to qualified scientists interested in studying the Guadalupian type section. Again, access is essential. Fortunately, the park managers agreed to this, and staff has been very, very cooperative. It is a difficult situation for the park staff, as well as some of the international researchers who tend to think that they can come in here and blast the canyons. The compromise that we have reached is a very fine one. Now, qualified scientists do have free access to the resources here.

Another matter that is important is priority. Here, I think we have the situation "by the throat" because Girty in 1902 actually proposed the Guadalupian as a time interval, corresponding to the Mississippian and the Pennsylvanian. It had the status of a series as far back as 1902. The components, or the subdivisions, of the Guadalupian again have outstanding priority. The terms Wordian and Capitanian—these are the Middle Guadalupian and the Upper Guadalupian—were proposed in 1904. I think they were used in a time sense for the first time by me and Furnish in 1961. The Roadian, named for the Road Canyon, which is the basal stage of the Guadalupian, is sort of a newcomer. It was not proposed until 1973, and this may pose a problem for us. So although we have the series agreed upon by the International Commission on Stratigraphy and the international community, we still have to document very carefully the three subdivisions: the Roadian, the Wordian, and the Capitanian.

I could go on for a long time, but there are other advantages here. A very significant one is the low thermal history of the area. The studies indicate that the temperatures have never been more than 80°C. The importance of this is that we are able to conduct paleomagnetic studies on these rocks. The paleomagnetic signatures are still there, and very importantly, we are able to trace a magnetic marker—this is the Illawarra reversal—named for Australia. We can recognize it here and we can recognize it in the northern Urals. Paleomagnetics are a very important feature. Also, absolute dating is possible because of the low temperatures here; in recent years we have had quite a few dates and there is potential for further dating. Finally, because of the low temperatures, we have the potential here for recognition of geochemical anomalies. I won't go into the details of these.

One problem to which I referred is the present day Tower of Babel. It simply indicates that in the southern Urals they like local terms. In Armenia, Iran, and the Pamirs they have other choices as in south China and Japan. The worst is Australia. They even proposed a new period there because they could not differentiate the Carboniferous from the Permian. This is the situation we are trying to avoid by development of an international standard for geologic time.

Let me show you just a couple of slides, first of all the sections in the lower Urals, then on to the Guadalupian, and then to China for the upper part of the succession. These are the standards that have been accepted. This is at Aidaralash in the southern Urals. This is the base of the Permian, and again, this has been formally ratified. It is a long, painful process, which involves both personal and national interactions, but most importantly these generate a great deal of good science. American groups together with our Russian colleagues and many, many other groups have collaborated to select and define the base of the Permian. Here is the general location. It is important to note that this is the basin between Asia and Europe. This is the European-Russian platform here. This is the depression in which the type Permian or type Early Permian developed, and it was the collision of Asia and Europe in the Middle Permian that made that an undesirable and unacceptable reference for geological time. We have evaporites there in the Middle Permian just the same as we have evaporites here in North America in the Upper Permian. This is the kind of detail that we require for such a definition. These are meters: this is zero, -30, +60, and an idea of how these boundaries are defined. In this case, there is a plethora of fossils. There are fusulinacean foraminifera; there are ammonoids, and also there are conodonts. The collective judgement of the group has been that conodonts are the best reference for definition of the base of the Permian, and the coincident top of the Carboniferous.

I will go into a little detail here. Conodonts were eventually approved for definition. This is an evolutionary morphocline—a succession of evolving forms. There is no natural break in this succession, and that is a desirable feature, because it confirms or demonstrates that there is no time break in this particular succession of rocks in the boundary succession. There is no physical evidence, but as you are all aware, sometimes there is a nonconformity where no physical evidence exists. The definition is on the conodonts, and the fusuline workers fear that their preferred boundary is 6.3 meters above, but what the hell! For practical purposes, the fusuline boundary is coincident with the conodont boundary. The ammonoid workers are a little more difficult to get along with, but their preferred boundary is 26.8 meters above the conodont boundary. For practical purposes then, this is an excellent boundary definition that can be recognized throughout the world by reference to other groups of organisms, or geochemical anomalies, or geomagnetic anomalies, or absolute dates and so on.

This is the morphocline. The succession of conodonts—small phosphatic organisms—and the first appearance of a particular species here has been selected for definition of the boundary. Russian colleagues, here is the boundary. There is a nice pavilion there at the present time. However, with the collision of Asia and Europe, shoaling upward and evaporites, we need to go somewhere else for a reference for the higher Permian. As I indicated earlier, the favored place is Guadalupe Mountains National Park. You are all aware of the general relationships here. I will just point out that the complex facies relationship that Lloyd Pray has dealt with already, the back reef, the reef, the slope and the basin, and the fact that the interfingering here allows you to correlate on physical grounds any of these facies. We can look for data, whether it is paleomagnetic data or biological data, we can look for these data in any of these facies and we can relate them to other facies. The selection of the position for the base of the Guadalupian is in the western mountain face here, at the feature that we plan to term Stratotype Canyon. This will be the international reference for the Middle Permian interval of geologic time.

The other subdivisions of the Permian—remember there will be three: the Roadian, the Wordian, and the Capitanian—will be on the eastern boundary of the park on Nipple Hill. There is a fantastic exposure there which has bentonites where we can get an absolute date. It has magnificent evolutionary continua, particularly the transitions in the conodonts, which we can trace around the world. These will be excellent references, international references, for this interval of geologic time. To come back to the point, as was made already, it is possible, of course, to trace the back reef facies into the reef itself and into the slope facies, and we can accumulate the data from each of these facies and integrate it into a single body of data because of the interfingering relationship of these facies.

The back reef is very interesting. From a biological point of view it is a bit of a disappointment; there aren't many fossils there. Again, we have geomagnetic reversals and so on, so this is a valuable part of the section. It is also a very interesting one. I think Lloyd Pray and I must have been looking at the same face here. He didn't tell you why—this is a centimeter rule here—the graded beds are reversed. But maybe I will be here some time and we can talk about that. From the reef into the slope into the basin, and one of the very attractive features of these is the increase in the diversity in the abundance of fossils such as these fusulinaceans. Again, there is some provincialism; they are not exactly the same species as elsewhere, but it is possible to correlate on forams as well as conodonts and other groups of organisms.

In the slope facies near the top of the Guadalupian, it is not very exciting in terms of paleontology, at least from a camera view, but fortunately these uppermost beds of the Lamar Limestone and post Lamar do retain important groups of fossils, particularly the conodonts. These enable us to make precise correlations to China, in particular, and the base for the international standard for the Upper Permian.

Above that, of course, are the evaporites. This was the problem in the Urals, the shoaling upwards. It is the problem here, so that we have to go elsewhere for the Upper Permian standard. Stratotype Canyon displays the arbitrarily chosen point in the conodont evolutionary continuum that forms the base of the Guadalupian. We will talk about these. Here is the ancestral form; here is the descendent form—and Lance or Bruce can discuss this at length; there is a display outside. Of course, we must mention the ammonoids. I have emphasized the conodonts—I love them—but my favorites are the ammonoids. They are some of the most useful. Again, this was a critical time for the evolution for the ammonoids. The oldest of the ceratites, one group of ammonoids, was in the Roadian at the base of the Guadalupian. These are actually characteristic of the Mesozoic, the dominant Mesozoic forms. They originated back in the basal Guadalupian. You can see the diversification. I apologize for even putting this one in, but that is the distribution of ammonoid groups in the Carboniferous and Permian. I would make the point that the extinction of the Paleozoic ammonoids was not a catastrophic event; it was a sequential event that actually began in the Guadalupian. Again, [this picture shows] the nasty evaporites that make that sequence unsatisfactory.

We have to go elsewhere, and of course the fewer the standard references, the easier and more useful these references are. We finish up with three, and remember that this involves the top of the Carboniferous, defined by the base of the Permian; the Middle Permian, the base of the Middle Permian defines the top of the Lower Permian. This is the Permian-Triassic boundary that we are looking at here. This is in south China halfway between Shanghai and Nanjing. There is the boundary with three characters up there collecting the boundary beds. Here is the actual boundary itself; it is that point there. I collected that slab and it is on display, you might want to look at this. Again, this is becoming monotonous. It is an evolutionary cline of conodonts and the first appearance of a specific conodont in the middle of this bed [number] 27 represents the base of the Triassic, and therefore, by definition, the top of the Permian. I would also like you to note that there are other lithologies here: this white shale, the black shale, and other black shales here. There are all kinds of useful exciting characteristics of this boundary succession: paleomagnetic, geochronologic, and also isotope anomalies, carbon anomalies and so on.

This is the boundary in the wall we are looking at. This bed is 16 centimeters in thickness, and this interval is the one on display out there. Again, the first appearance of the designated conodont at this level in the middle of this bed is the international reference for the base of the Triassic.

We are very grateful and thankful that the Tower of Babel has collapsed, or at least it is in rubble, and we are in the process then of developing this international language! The delightful thing is that the Guadalupian will play a very important role in these definitions.

Notes: Because the boundaries of the Middle Permian and Guadalupian have been defined and adopted (see Glenister et al. and Lambert et al. in this volume), the editors treat them as formal units. Therefore, the initial letters of the names and modifying words of both the period/system (e.g., Middle Permian) and epoch/series (e.g., Upper Guadalupian) have been capitalized in this context.

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Chapter 31

Defining the Base of the Guadalupian Series—The World Standard Middle Permian—In Its Type Area, Guadalupe Mountains National Park

LANCE L. LAMBERT, Ph.D., is an instructor of geology at Southwest Texas State University. His dissertation research resolved long-standing problems associated with the basal Guadalupian boundary, which ultimately helped lead to the formal proposal of the Guadalupian Series as the world standard reference for Middle Permian time. His other projects within Guadalupe Mountains National Park are related in theme, primarily the upper and interior boundaries of the Guadalupian Series. He annually uses the park resource for teaching the southwest Texas field geology course.
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BRIAN F. GLENISTER, Ph.D., is an A. K. Miller Professor of Geology Emeritus with the University of Iowa, Iowa City. He is an active member of the International Commission on Stratigraphy and the past chair of the Subcommission on Permian Stratigraphy.

Introduction

The geologic time scale provides the major ordering framework for understanding Earth history. It may thus come as a surprise to some that the nomenclature of the time scale is still evolving. This is in part because different names have been applied to rocks of the same age in different countries. Because geology is a global science, a single international language for the units of the geologic time scale is desirable to ease communication and to encourage stratigraphic precision. The International Union of Geological Sciences (IUGS) serves to coordinate international committees of recognized specialists from varied countries to formally ratify component units of the proposed world standard. They have erected a set of criteria and established procedures for selecting reference standards (Cowie et al. 1986, Remane et al. 1996; refer also to Glenister et al. 1992, Lambert et al. 1995, and Remane 1996 regarding the Guadalupian). Meeting those criteria and following the established international procedures, the Guadalupian Series has been selected as the world standard reference for the Middle Permian Series (Spinosa 1996, Jin et al. 1997).

The basal boundary of the Guadalupian, a clear definition of which is essential for precise international correlations, is designated by the evolutionary first occurrence of the conodont, *Jinogondolella nankingensis*. The ancestor, *Mesogondolella idahoensis*, evolved into *J. nankingensis* through a short-lived mosaic paedomorphocline. A paedomorphocline is a temporal series of populations through which juvenile characteristics of an ancestral species become progressively expressed in increasingly adult stages of the descendant species. Because of the complex evolutionary interplay between individual characters, a precise point within the transition can be selected to clearly define the first occurrence of *J. nankingensis sensu stricto*—and thus the basal Guadalupian Series boundary as proposed by Glenister and others (1992). This point is selected at the first specimens retaining serrations beyond juvenile growth stages. In preliminary sam-

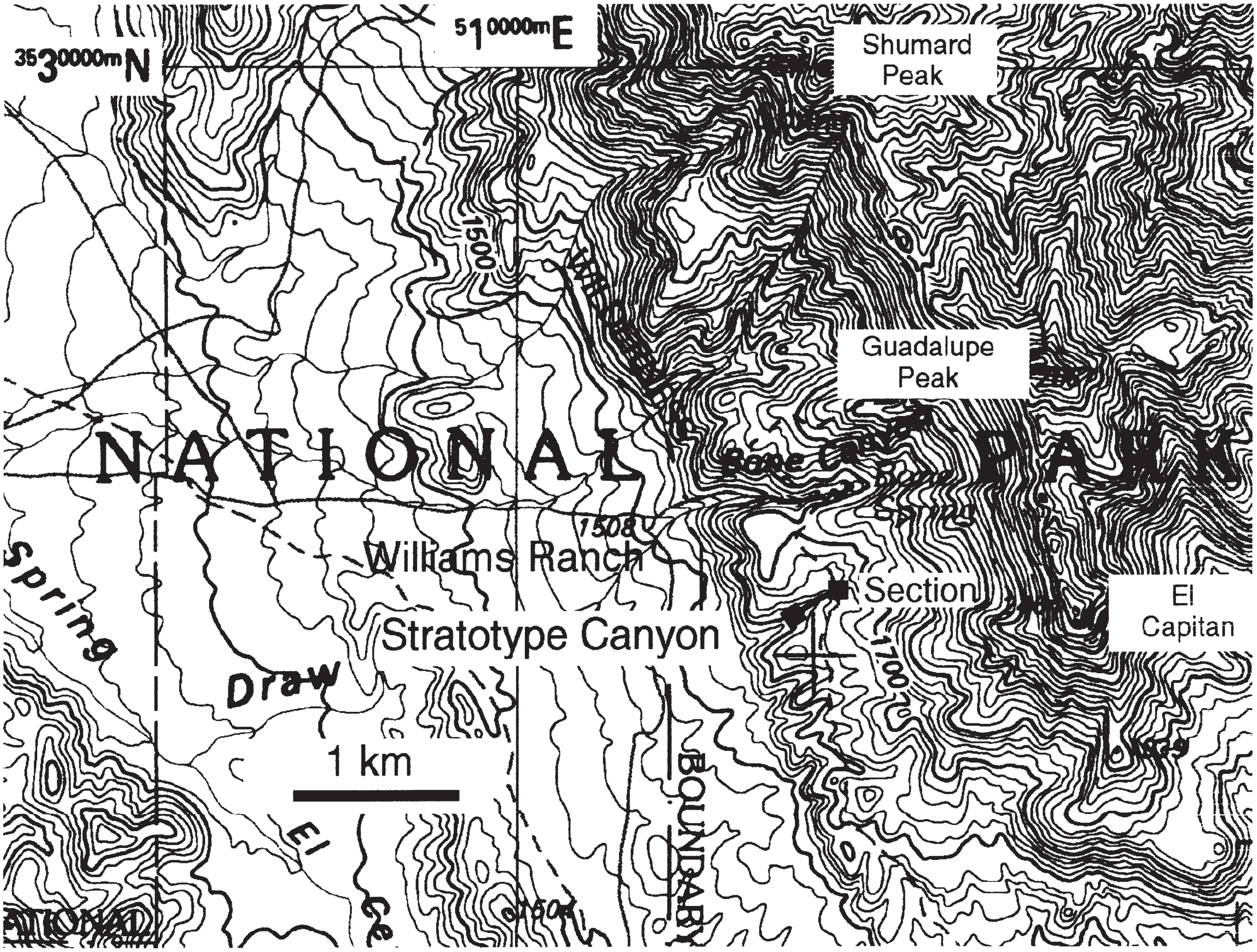

Figure 1. Location of Stratotype Canyon in Guadalupe Mountains National Park.

pling of Stratotype Canyon (set aside by the National Park Service for preservation and study of the boundary stratotype that marks the base of the Guadalupian) (Figure 1), such specimens occur in sample W92-8, at 140 feet (42.7 m) above the base of the Cutoff Formation (Table 1). The sampled horizon lies within monotonous pelagic calcilutites, 11.25 inches (28.6 cm) below a prominent shale band in the middle part of the El Centro Member (Figure 2.).

The Paedomorphocline

Qualitatively the evolution of *J. nankingensis* involved numerous taxonomically important characters, including: the acquisition of anterior serrations, alteration of cusp size and placement, isolation of carina denticles (from an initially fused state), and the narrowing and protrusion of the lower attachment surface (Lambert and Wardlaw 1992).

The most conspicuous change in character was the acquisition of serrations along the anterior platform margins. When first developed, serrations were indistinct and restricted to juvenile specimens. In successive populations, the juvenile serrations became more distinct, but subadult and adult forms masked those serrations beneath subsequent histological laminae. The smoothed serrations were masked initially at the element margin, leaving faint relict serrations adjacent to adcarinal furrows on subadult forms. In slightly younger populations, adult specimens display the faint serrations, whereas those on preceding growth stages became better defined. This pattern of incrementally increasing serration was carried progressively later through ontogeny in successive populations until the pronounced serrations characteristic of *J. nankingensis* at all growth stages were attained. Such serrations are distinctly visible in lateral view as notches along the anterior platform margins. Notches are not discernible from this perspective on earlier transitional forms.

Concomitant in lateral view, the cusp became less pronounced in both relative height and width, while migrating subtly to a more posterolateral position. The fused anterior carina denticles of adult *Mesogondolella idahoensis* became increasingly discrete through the transition, a character state common to both *J. nankingensis* and juvenile *M. idahoensis*.

Similarly in lower view, the broad, flat, and commonly recessed basal attachment surface of adult *M. idahoensis* became narrower through the transition, simultaneously developing a consistently protruding keel. This trend in adult morphologies represents a reverse pattern of the ontogenetic development patterns for individuals of typical *M. idahoensis*.

Emphasizing practical biostratigraphic utility, morphotypes from this clinal transition are assigned to taxonomic categories on the following criteria: (1) Initiation of the transition (earliest transitional morphotype) is recognized among populations in which serrations first appear and are restricted to juvenile growth stages. These specimens remain assigned to *M. idahoensis* with regard to formal taxonomy. (2) *J. nankingensis s.s.* first occurs in specimens that display prominent serrations in subadult growth stages. Prominent is here defined as the distinct expression of serrations, which in lateral view form conspicuous notches along the anterior platform margin. (3) The extinction of *M. idahoensis* is denoted by populations that no longer include unserrated juvenile specimens. (4) The last occurrence of the transitional morphotype is denoted by populations that no longer include adult specimens without prominent serrations. These criteria explicitly lead to some range overlap of morphotypes from complete sections, as would be expected for evolutionary transitions. More importantly, these criteria unambiguously characterize the chronostratigraphic boundary interval.

Quantitative analysis of characters through the transition was briefly discussed by Lambert (1994) and illustrated graphically by Lambert and Wardlaw (1996). Because the transition is expressed along a paedomorphocline, characters were examined both independently from size, and as function of size and stratigraphic level.

Size (as a proxy for relative maturity) was standardized by reference to a character that exhibits growth in a linear relationship to the remainder of the element. Selection of a standardized reference character is complicated for Permian gondolellids because of inconsistent allometric fields resulting from variable bowing and arching of individual elements. However, a reliable approximation can be achieved by using carina length as a measure of allometric size. To minimize error introduced by warping of the allometric field from bowing, carina length was measured from denticle apex to denticle apex, extending from the anteriormost denticle to the tip of the cusp. These distances were integrated then standardized to a value of 100 for each element. All landmark distances were scaled to this standard parameter, producing results measured as a percentage of carina length, independent of size (Lambert 1994).

The above method also provides a precise definition of juvenile, subadult, and adult forms; and allows for rigorous comparisons between juvenile and adult growth stages with similar character states. Actual carina length was recorded for subdivision of the three taxon groups into ontogenetically-based components for separate analysis as a function of size.

The complete results of this complex morphometric analysis will be presented in Lambert and Wardlaw (in prepara-

Sample		Meters	Feet	Unit
37	MHB-690-13	61.7	202.5	Williams Ranch Member, Cutoff Formation
36	MHB-690-12	50.9	167.0	Williams Ranch Member, Cutoff Formation
35	W92-12	50.5	165.5	Williams Ranch Member, Cutoff Formation
34	MHB-690-11	50.2	164.5	Williams Ranch Member, Cutoff Formation
33	MHB-690-10	45.9	150.5	Williams Ranch Member, Cutoff Formation
32	MHB-690-9	45.7	150.0	Williams Ranch Member, Cutoff Formation
31	W92-11	45.6	149.6	Williams Ranch Member, Cutoff Formation
30	MHB-690-8	45.6	149.6	Williams Ranch Member, Cutoff Formation
29	W92-10	45.1	147.8	Williams Ranch Member, Cutoff Formation
28	W92-9	43.8	143.7	Williams Ranch Member, Cutoff Formation
27	MHB-690-7	43.0	141.0	Williams Ranch Member, Cutoff Formation
26	W92-8	42.7	140.0	**Proposed Basal Guadalupian Boundary**
25	W92-7	41.8	137.2	El Centro Member, Cutoff Formation
24	W91-23	40.0	131.2	El Centro Member, Cutoff Formation
23	W91-22	38.1	125.0	El Centro Member, Cutoff Formation
22	W92-6	36.9	120.9	El Centro Member, Cutoff Formation
21	W91-21	36.3	119.0	El Centro Member, Cutoff Formation
20	W92-5	35.9	117.9	El Centro Member, Cutoff Formation
19	MHB-690-6	35.2	115.5	El Centro Member, Cutoff Formation
18	W91-20	35.1	115.0	El Centro Member, Cutoff Formation
17	W91-19	34.9	114.6	El Centro Member, Cutoff Formation
16	W91-18	34.5	113.1	El Centro Member, Cutoff Formation
15	W91-17	34.0	111.5	El Centro Member, Cutoff Formation
14	W91-16	33.5	110.0	El Centro Member, Cutoff Formation
13	W91-15	32.9	108.0	El Centro Member, Cutoff Formation
12	W91-14	32.0	105.0	El Centro Member, Cutoff Formation
11	W91-13	31.4	103.0	El Centro Member, Cutoff Formation
10	MHB-690-5	31.4	103.0	El Centro Member, Cutoff Formation
9	MHB-690-4	30.9	101.5	Shumard Member, Cutoff Formation
8	W91-12	30.2	99.0	Shumard Member, Cutoff Formation
7	W91-11	29.6	97.0	Shumard Member, Cutoff Formation
6	W91-10	28.0	92.0	Shumard Member, Cutoff Formation
5	W91-9	26.2	86.0	Shumard Member, Cutoff Formation
4	W91-8	24.4	80.0	Shumard Member, Cutoff Formation
3	MHB-690-3	1.5	5.0	Shumard Member, Cutoff Formation
2	MHB-690-2	0.6	2.0	Shumard Member, Cutoff Formation
1	MHB-690-1	-0.3	-1.0	Top of Bone Spring Limestone

Table 1. Conodont samples from the Guadalupian stratotype. The table is a list of coarser initial sampling.

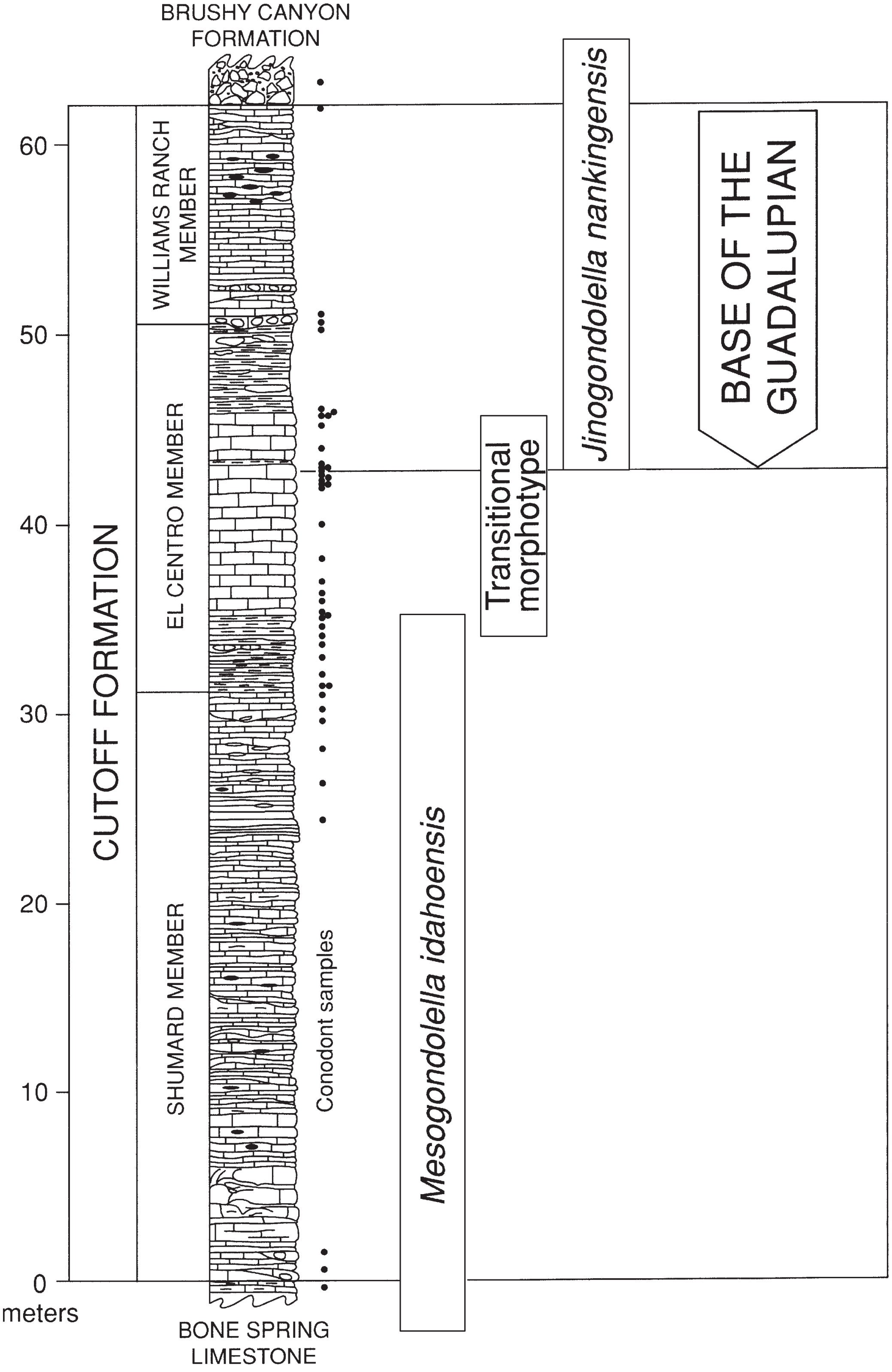

Figure 2. Columnar section of the Cutoff Formation in Stratotype Canyon with position of biostratigraphic samples and ranges of pertinent conodont species. The first occurrence of *J. nankingensis sensu stricto* defines the base of the Guadalupian Series. Note: as illustrated by the dots on the figure, which are immediately below the proposed boundary, the El Centro Member has been sampled more finely (bed by bed) for ongoing detailed morphometric analysis than the initial sampling listed in Table 1.

tion). The initial results confirm that the transitional form observed qualitatively can be characterized quantitatively (Lambert 1994). These preliminary results can be summarized as follows:

1. A direct linear relationship demonstrates an increasing degree of serration through the transition. Overall, small specimens in mid-transition fall nearer the mean for *J. nankingensis*, whereas large specimens from the same sample fall nearer the mean for *M. idahoensis*.
2. Both cusp height and width (elongation) show a decrease through the transition. Once scaled for size (relative maturity), the mean of the transitional form lies approximately half way between those of *M. idahoensis* and *J. nankingensis* for both measures.
3. Platform width is consistent for all three taxon groups when standardized for size.
4. The transitional form and *J. nankingensis* have identical measures that indicate less bowing (lateral displacement) than occurs in *M. idahoensis*.
5. *M. idahoensis* is significantly less arched (vertical displacement) than either the transitional form or *J. nankingensis*, again the latter two sharing an essentially identical mean arch ratio.
6. There is a decreasing relative width of the lower attachment surface through the evolutionary morphocline.
7. The keel forms a more significant component of the lower attachment surface in *M. idahoensis* than it does in either the transitional form or *J. nankingensis*, but it protrudes more in the latter.
8. Comparison of length measurements for the discrete portion of the penultimate anterior carina denticle to the fused portion of the same denticle show that the discrete portion of the transitional form is essentially the same as that of *J. nankingensis*, and both are larger than that mean length for *M. idahoensis*. Conversely, the mean fused portion of that denticle in the transitional form is approximately the same as that for *M. idahoensis*, both of which are significantly larger than for *J. nankingensis*. The overall evolutionary pattern for this character is from predominantly fused (*M. idahoensis*) to relatively discrete (*J. nankingensis*).

Stratigraphy

The Cutoff Formation is comprised predominantly of lime mudstone and shale from pelagic suspension deposits (Harris 1987, 1992). Coarser grained lithologies, usually confined to channeliform beds, are localized in shelf-margin paleosettings and interpreted as various flow deposits. Discontinuities in shelf and shelf-margin strata die out basinward. Thus, a section located within the proximal basin paleosetting would be complete and include some fossil constituents transported in from shallower paleoenvironments.

The National Park Service, steward of Guadalupe Mountains National Park, has agreed to extend collecting permits to the international scientific community following the same guidelines used to evaluate applications submitted by U.S. citizens (Glenister 1993). Stratotype Canyon has been set aside as a geological preserve where international sampling activities will be both monitored and allowed to take place. Stratotype Canyon boasts nearly complete exposure of strata ranging from the Bone Spring Formation (Artinskian Stage) through the Capitan Formation (Capitanian Stage). The paleosetting of the Cutoff Formation in Stratotype Canyon is a proximal basin milieu.

At Stratotype Canyon the Cutoff Formation consists primarily of lime mudstone (calcilutite) and shale, with localized skeletal debris beds, scattered chert, and one thick chert marker bed. The Cutoff is subdivided into three members (Harris in press). The lower member, the Shumard, is predominantly composed of lime mudstone, with several coarser-grained shallow channeliform beds at the base. The middle El Centro Member is composed of a characteristic shale-limestone-shale triplet. That middle limestone is a medium-bedded, argillaceous lime mudstone, with a prominent shale band in its upper part in Stratotype Canyon (Figure 2). The upper member, the Williams Ranch, is lithologically similar to the Shumard Member: composed mostly of lime mudstone with several coarser-grained channeliform beds. All of these units reflect the interplay of basin and toe-of-slope deposition. Contemporaneous skeletal debris washed in from shelf paleosettings range from individual fossil particles to the larger channeliform beds, which are intercalated into the complete pelagic calcilutites.

All samples from Stratotype Canyon have yielded conodonts in varying degrees of abundance. The Permian Subcommission of the IUGS must vote, and then the International Commission on Stratigraphy must ratify exactly which sample will formally denote the basal Guadalupian (Middle Permian) boundary. The material analyzed as of now indicates that current sampling is tight enough in the critical intervals to present first and last occurrences that should not change significantly with the subcommission's vote or with additional sampling (Figure 2).

The first occurrence of the transitional morphotype, as defined above, is sample W91-16 (110 ft, 33.5 m; see Table 1) near the base of the El Centro Member of the Cutoff Formation. The last occurrence of *M. idahoensis* is sample W91-19 (114.6 ft, 34.9 m), from the very top of the lower shale in the El Centro triplet. The first occurrence of *J. nankingensis* is sample W92-8 (140 ft, 42.7 m) high in the medial part of the El Centro middle limestone. The last occurrence of the transitional morphotype is sample MHB-690-9 (150 ft, 45.7 m) from the uppermost El Centro middle limestone. Although last occurrences in this section appear to coincide with relatively minor lithofacies changes within the El Centro Member, the biostratigraphic record is robust: all evolutionary initiations (first occurrences) are recorded within monotonous lithologic successions distinctly inside the lower shale and middle limestone lithofacies of the El Centro Member of the Cutoff Formation.

Conclusion

The base of the Guadalupian Series, world standard reference for the Middle Permian, occurs in the El Centro Member of the Cutoff Formation within the evolutionary paedomorphocline from *Mesogondolella idahoensis* to *Jinogondolella nankingensis*. That basal boundary is defined on the initial evolutionary appearance of *J. nankingensis sensu stricto* in Stratotype Canyon (Guadalupe Mountains National Park, west Texas), which occurs at 140 feet (42.7 m) above the base of the Cutoff Formation, in the middle of the El Centro Member.

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Notes: Because the boundaries of the Middle Permian and Guadalupian have been defined and adopted (see Glenister et al. and Lambert et al. in this volume), the editors treat them as formal units. Therefore, the initial letters of the names and modifying words of both the period/system (e.g., Middle Permian) and epoch/series (e.g., Upper Guadalupian) have been capitalized in this context.

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Chapter 32

Permian Extinctions: A Fusilinacean's Way of Life and Death

GARNER L. WILDE, Ph.D., is an international geological consultant in Midland, Texas. He has studied for over 40 years in the Guadalupe Mountains and Permian basin with emphases in biostratigraphy and facies analysis, fusulinid foraminifera, and calcareous algae.

Introduction

In recent years much effort has been concentrated upon reaching closer consensus in definition of the major periods of Earth history. Whenever such work is undertaken it is natural to assume that occasional startling results will be achieved. One is reminded of the great controversy that developed over what finally constituted the breakthrough for definition of the Cretaceous-Tertiary (K/T) boundary. Today, hindsight shows us that a thin iridium layer marks, for many, a "golden spike" position for this boundary, and all would seem to be well among the world's Cretaceous-Tertiary pundits. This iridium layer is thought to represent fallout from one or more giant meteorite impacts on Earth.

But even here, all might not be so well according to a recent report of studies from Israel's Negev Desert, reviewed in *Geotimes* by Bartlett and Wexler (1998) and Collins (1998). The K/T boundary impact has previously been blamed for the near total extinction of Mesozoic oceanic plankton; however, these recent studies suggest that Late Cretaceous marine environments in the Negev underwent many periods of stress during a four-million-year period leading up to the K/T boundary time.

Similar controversy has raged about the great dinosaur extinctions that took place at K/T boundary time. How did it all happen? And now there are good reasons to suspect that, indeed, an extremely large extra-terrestrial impact site in the general area of the southern Gulf of Mexico, just off Yucatan, played a major role in providing the global spread of the iridium clay layer and the subsequent demise of the dinosaurs. These relatively new data have electrified the field of paleontology and excited the fertile minds of young and old alike. "Make no bones about it," dinosaur bones are big business today.

Again, in a manner similar to the arguments dealing with the extinction of so many oceanic plankton species, there are those workers in the field of dinosaur studies who would suggest that a single event might have done nothing more than deplete many, but not all, of the large dinosaur species. G. S. Paul (1988) pointed out that giant meteorites were crashing into Earth throughout the Mesozoic. Indeed, he plotted six "possible ones," and suggested that "the best documented of these, the Late Triassic impact, did little or nothing to the world dinosaur population."

To the many less initiated, so awed by the sheer size of some individual dinosaurs, the catastrophe must have been the greatest event in Earth's history. But to those who spend their lives studying Permian life, the real truth presents an entirely different story. "End-Permian" time was by far the greatest extinction period in the entire history of Earth.

Even for the End-Permian, some would suggest a singular cause and effect. There are reasons, however, to suggest that a single catastrophe was probably not the cause of the great Permian extinctions. Most likely there were a series of events, occurring over a 5-to-10-million-year period, culminating in a final knockout blow. Not all of the suggested causes for the extinctions can be considered herein; however, volcanism and the late history of the fusulinacean foraminifers offer insights that ought to be considered seriously to help explain the demise of much of Permian life.

Extinctions and some possible causes
Numerous paleocontinental reconstructions of Earth have been offered for Late Permian time. For the present purposes, however, the one shown here (Figure 1) by Lin and others (1985) and recently utilized by Erwin (1992) is preferred because of its simplicity and its assumptions of an early opening of the Atlantic Ocean. This reconstruction is helpful in understanding how a Tethys-connected superocean, Panthalassa, and the early-rifted Atlantic Ocean provided ample conditions for comingling of some Tethyan and North American faunas. On the other hand, the comingling was not complete because of other, restrictive factors.

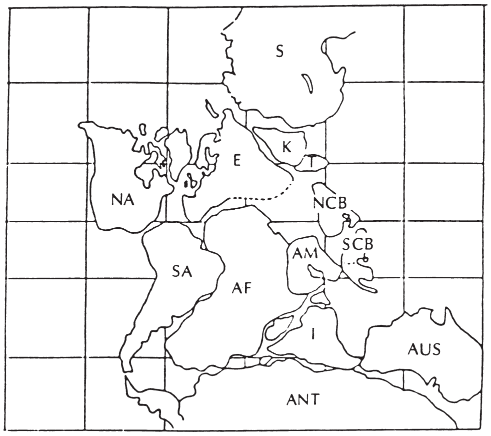


Figure 1. Paleocontinental reconstruction for Late Permian time. AF = Africa, AM = Asia Minor, ANT = Antarctica, AUS = Australia, E = Europe, I = India, K = Kazakhstan, NA = North America, NCB = North China Block, S = Siberia, SCB = South China Block, T = Tarim. From Lin et al. 1985. Reprinted by permission from *Nature* 313:444–449. Copyright 1985 Macmillan Magazines Ltd.

Nevertheless, enough is now known to provide workers with a chronostratigraphic road map for correlation of the entire Permian (Figure 2). Inasmuch as the present paper considers only the Middle (Guadalupian Series) and Late (Lopingian Series) Permian, the full history of fusulinacean life will not be considered nor will other groups of Permian life, except briefly to emphasize some important observations about life and extinction rates in general.

SYSTEM/SERIES		STAGES
TRIASSIC		GRIESBACHIAN
PERMIAN	LOPINGIAN	CHANGHSINGIAN
		WUCHIAPINGIAN
	GUADALUPIAN	CAPITANIAN
		WORDIAN
		ROADIAN
	CISURALIAN	KUNGURIAN
		ARTINSKIAN
		SAKMARIAN
		ASSELIAN
CARBONIFEROUS		GZHELIAN

Figure 2. Permian chronostratigraphic subdivisions. After Jin, Wardlaw, Glenister, and Kotlyar 1997.

Sepkoski (1982) developed a compendium of marine family life, from which Erwin (1992) plotted extinction percentages for 17 major groups during the Asselian, Sakmarian, Leonardian, Guadalupuian, and Dzulfian series of the Permian (Figure 3). For the present purposes, in order to follow the generally accepted subdivisions of the Upper Permian (Figure 2), the Dzulfian becomes the Wuchiapingian, or Lower Lopingian. The Leonardian is retained in this chart to represent the Artinskian and Kungurian, combined. These data are utilized later (Figure 5) to express composite extinction rates.

Still utilizing data from Sepkoski (1986), Erwin (1992) plotted Permian and Triassic extinctions in marine genera as percentage extinctions, and total number of generic extinctions (Figure 4). From these plots, there is no question that the greatest extinctions in the Permian actually took place during the Guadalupian, and diminished dramatically thereafter.

The data from Figure 3 is shown in a different manner in Figure 5 as composite extinction rates for each of the Permian series. Estimates for the latest Permian Changhsingian stage have been added to

Marine family	Percentage extinction A	S	L	G	D
Foraminifera	0	0	3	6	38
Porifera	0	0	18	24	10
Tabulata	0	14	15	42	100
Rugosa	0	6	38	62	100
Gastropoda	0	0	15	25	11
Bivalvia	0	3	2	12	11
Cephalopoda	17	0	20	43	47
Other Mollusca	0	17	40	33	0
Other Arthropoda	0	0	21	33	25
Ostracodes	4	8	8	35	29
Bryozoa	10	4	4	23	65
Brachiopoda	0	3	12	34	71
Crinoidea	0	16	5	93	0
Other Echinodermata	5	5	5	37	8
Conodonta	0	20	0	20	25
Other taxa	0	0	0	9	3
Marine vertebrates	0	0	0	39	0

Figure 3. Extinction percentages for 17 major groups of marine families during each series of the Permian. Families not resolved to series were not used in the analysis. A = Asselian, S = Sakmarian, L = Leonardian, G = Guadalupian, D = Dzulfian. Data from Sepkoski 1982. After Erwin 1992.

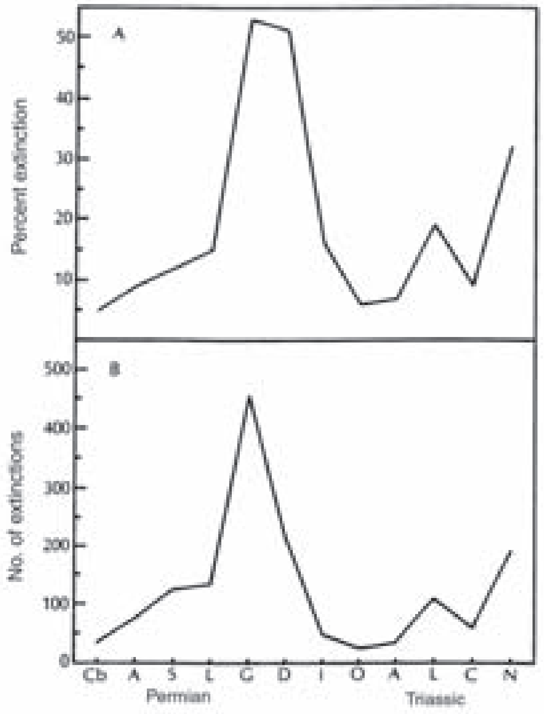


Figure 4. Permian and Triassic extinctions in marine genera. A: Percentage extinction. B: Total number of generic extinctions. Data from Sepkoski 1986. After Erwin 1992.

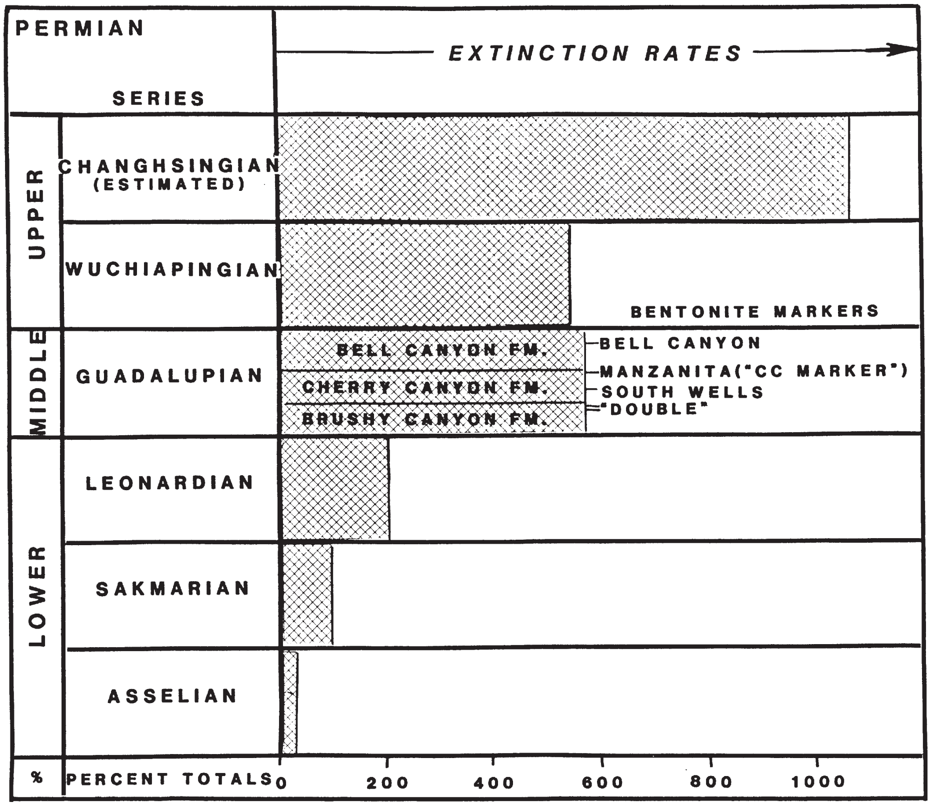


Figure 5. Composite extinction rates for each of the Permian series based on data from 17 major marine family groups. After Erwin 1992 (except for the Changsingian). Bentonite marker names after Wilde 1975.

these data. This has been done only to complete the Permian picture. While the data might not be shown as precisely as that of Sepkoski, the point is made: of those major marine family groups that were still living near End-Permian, the extinction rate was greater than the Guadalupian only because the numbers were already so greatly diminished that the composite rates are skewed proportionately.

Bentonites. Four important bentonite levels that were named originally by Wilde (1975) from Guadalupian rocks at the surface or in the subsurface accompany the composite extinction rates in Figure 5. These bentonites were referred to by initials at the time, and more recently interchangeably as follows (youngest to oldest):

1. Bell Canyon (BC bentonite), upper part of the Bell Canyon Formation
2. Cherry Canyon, or Manzanita (CC marker bentonite), near top of Cherry Canyon Formation, beneath the Manzanita Limestone
3. South Wells (SW bentonite), about the middle of the Cherry Canyon Formation
4. Double (Double bentonite), near top of Brushy Canyon Formation

Recognition that a given claystone or shale is of bentonitic origin is often difficult. Certain criteria, however, have been shown to be helpful in identifying bentonites, especially the ones found in the Guadalupian of the Permian basin:

1. “Bentonite” is defined as “rock composed essentially of a crystalline clay-like mineral formed by devitrification and chemical alteration of a glassy igneous material, usually a tuff or volcanic ash” (Ross and Shannon 1926 after Todd 1976). Newell and others (1953) referred to most of the bentonites of the Guadalupe Mountains as “metabentonites” and emphasized that they were commonly associated with apple-green cherts.
2. Apple-green color, waxy texture, often floculent, or fluffy, when brought into contact with water (King 1948, Newell et al. 1953)
3. Most Guadalupian bentonites are considered to have been altered, consisting of authigenic crystalline clay minerals such as kaolinite, illite, chlorite, and smectite. Often present is authigenic pyrite, detrital quartz, feldspar silt grains, and occasionally, glass shards are still recognizable (Garber, Grover, and Harris 1989)
4. Presence of euhedral biotite and sanidine, characteristic of volcanic rocks, and a lack of nonvolcanic minerals, such as garnet and tourmaline (Todd 1976).
5. Highly radioactive character, due to high concentrations of thorium that produces a strong incursion on gamma-ray logs. Some of the Guadalupian bentonites produce a characteristic signature on the gama-ray log, which allows for rather precise identification in the subsurface. This is particularly true for the Cherry Canyon marker, which displays a “double kick” and can be followed over wide areas of the Permian basin.

Permian-age volcanic terranes have not been identified specifically in the immediate proximity to the Delaware Basin, which at the time consisted of a deep marine basin, bordered by a shallow shelf with broad evaporite flats extending landward for many miles (Figure 6). This fact would call for the volcanoes to have been located far into the interior of Mexico, and perhaps beyond, to the virtual edge of the North American continent, where they have since been lost under younger sediments and zones of plate subduction.

The normal history of sedimentation during the Permian was deposition along shelf margins of reefs or broader carbonate ramps that were succeeded over and over again. The lateral positions of these platforms varied with rise and fall of sea level, and were interrupted from time to time by siliciclastic bypass, thus filling the basin with deeper-water carbonate muds, shales, or sandstones (Figure 7).

This pattern of sedimentation was only occasionally intruded upon by the volcanic fallout alluded to earlier. Thus, each layer of bentonite, as it were, now exists as a perfect time line by which rather close correlations are possible. Such bentonites were unable to withstand the unstable conditions along shelf margins, however, due to strong wave activity. Because of this caveat, considerable problems often exist in trying to correlate given bentonites preserved in the basin with those preserved back on the shelf.

Fortunately, fusulinacean foraminifers were living prolific lives during the same time that the volcanic fallouts were occurring, thus providing another excellent tool for constraining the great pile of sediments in terms of age (Dunbar and Skinner 1937, Wilde 1975, 1990).

Bentonite-fusulinacean correlation examples

A 34-well cross section constructed 25 years ago in the northern Delaware Basin was generalized by Wilde (1975) to

Figure 6. Late Permian (Upper Guadalupian). From Garber, Grover, and Harris 1989. After Ward et al. 1986.

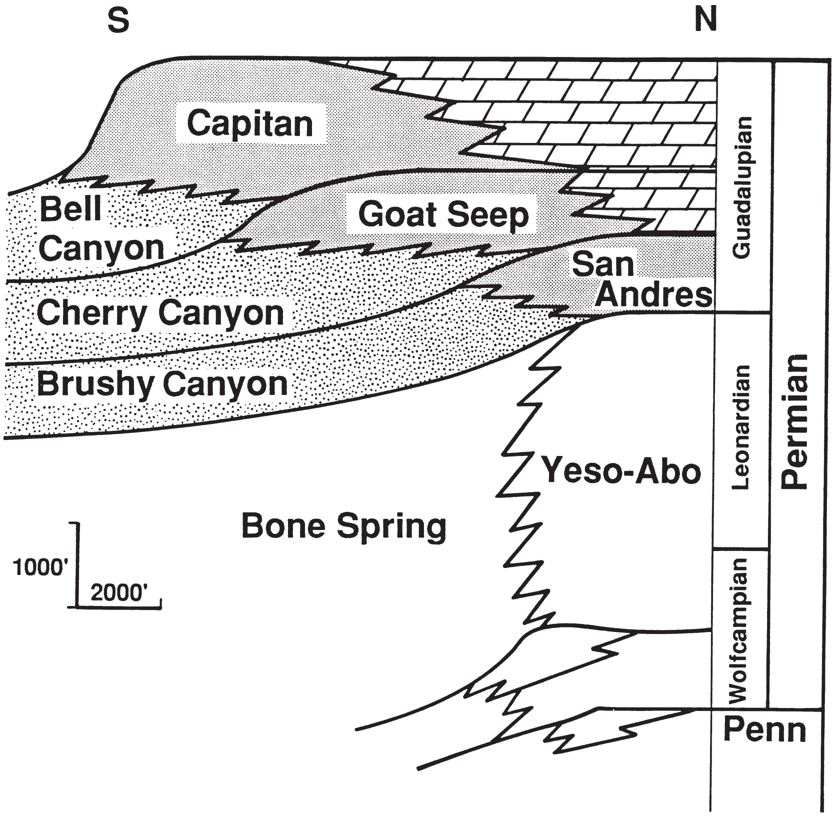


Figure 7. Summary cross section of the northwest shelf, Delaware Basin. After Garber, Grover, and Harris 1989.

demonstrate the utility of combining bentonite correlations with fusulinacean biostratigraphy. As can be seen in Figure 8, the fusulinaceans serve best in the areas (shelf margins) where the bentonites are absent or overlooked in samples; and, in turn, the bentonites serve best on the shelves and out in the basin, where the fusulinaceans are either absent or rare.

On the outcrop, numerous examples of combining bentonites with fusulinaceans for correlative purposes can be documented. One excellent example that has been documented, yet never published, is located in the southern Delaware Mountains (Figure 9). The location is in a complexly faulted area of Trew Canyon (Section 22, Block 94, PSL Survey, Culberson County, Texas) at the head of a small tributary to Scott Canyon, less than two miles north of the Trew Ranch house. The section is 500 feet (152 m) thick, and straddles the Cherry Canyon–Bell Canyon boundary (Figure 10).

In the area, the Cherry Canyon Formation is represented by 200 feet (61 m) of basinal, dark gray-colored shales, interrupted by only occasional thin, basinal limestones with fusulinaceans in the lower half. Siliciclastics are conspicuously absent. About the middle of this section is an algal mound that is prominently displayed in the slope. The mound, less than 35 feet (about 10 m) thick, is an algal boundstone, which appears to grade rather abruptly on the

Figure 8. Generalized cross section from northwest shelf showing fusulinid-bentonite control. After Wilde 1975.

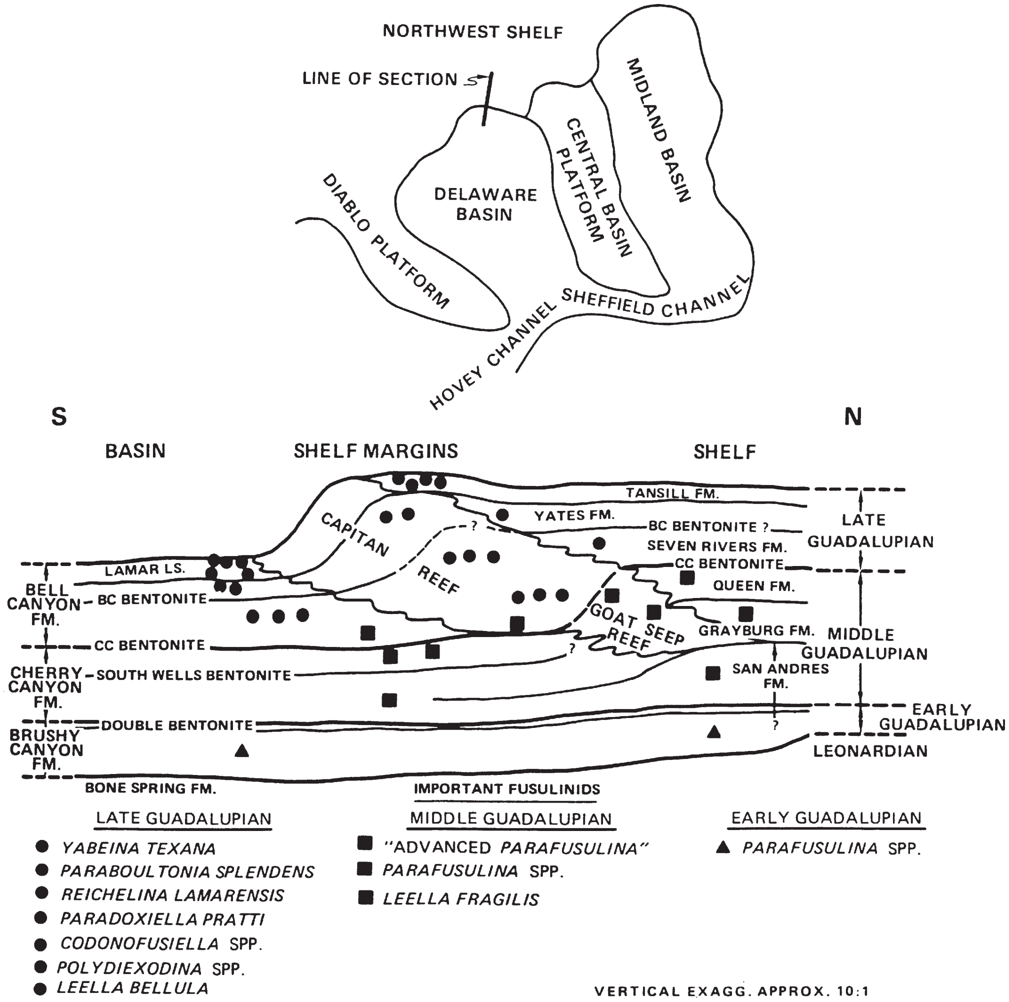


Figure 9. Geologic map of portion of south Delaware Mountains, Culberson County, Texas (Block 94). PSL survey showing location of measured section. After King 1948, 1960.

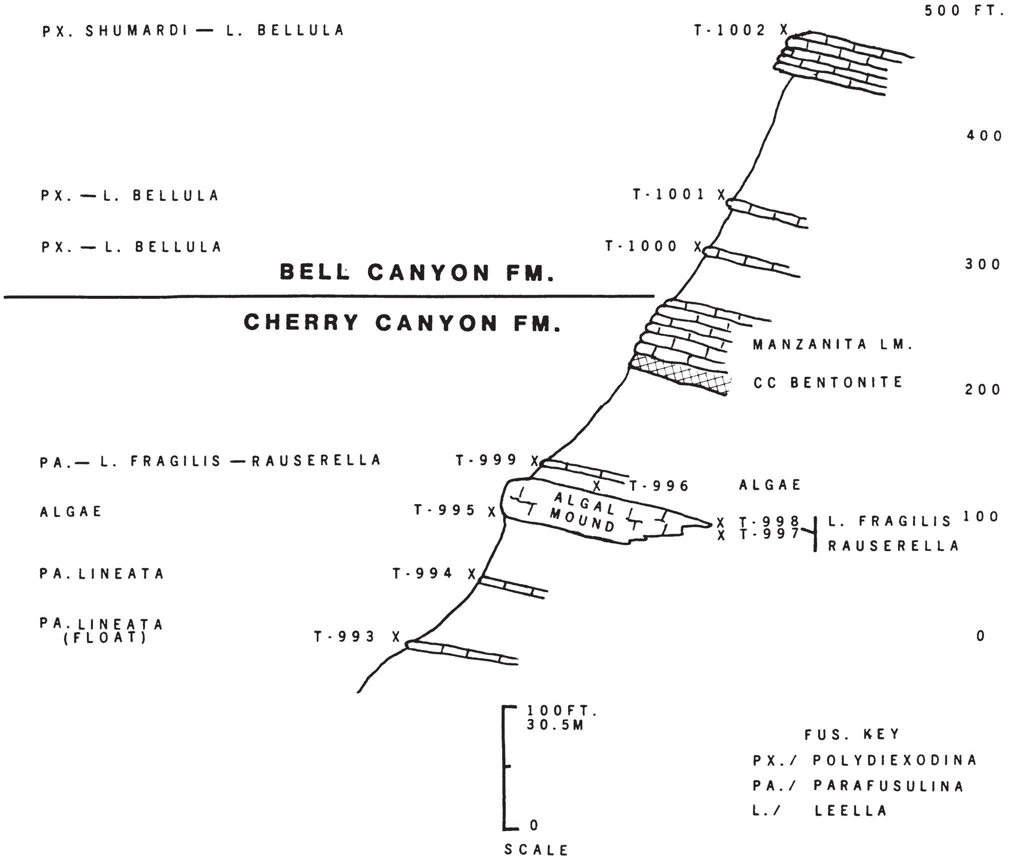


Figure 10. Stratigraphic section, south Delaware Mountains, Culberson County, Texas, showing faunal control and CC bentonite. See Figure 9 for location. From Wilde 1998.

back side into basinal sediments. At the time of discovery this feature was not believed to be any kind of slide block. Thus, if the interpretation is correct, water depths at the time of deposition could not have been great, certainly not below the euphotic zone of light penetration.

Approximately 10 feet (3 m) above the top of the algal mound is a thin limestone carrying the highest, Middle Guadalupian fusulinacean fauna discovered in the section. Here occurs *Parafusulina* sp., *Leella fragilis,* and *Rauserella* sp.

The Manzanita Limestone is easily identified 100 feet (30.5 m) above this highest fusulinacean level, holding up the slope and immediately overlying the Cherry Canyon bentonite. Here, the Manzanita Limestone is something over 40 feet (12 m) thick, and by definition, marks the top of the Cherry Canyon Formation (King 1942, 1948).

Late Guadalupian fusulinaceans were collected at three levels in the overlying Bell Canyon Formation at 40 feet (12 m), 80 feet (24 m), and 180 feet (54.9 m) above the Manzanita top. Similarly, the highest Middle Guadalupian fauna occurs 180 feet (55 m) below the lowest Late Guadalupian faunal level, which contains *Polydiexodina* and *Leella bellula*. Thus, the faunas constrain the age of the bentonite very closely.

More than 75 miles (120 km) northeast of the outcrop discussed previously, near the county line separating southeastern Loving and northwestern Ward counties, Texas, is a well that is chosen to show the top of the Cherry Canyon overlying the Cherry Canyon bentonite marker by 180 to 190 feet. Such intervals vary widely around the basin, depending on individual choice of tops for the Cherry Canyon and its possible disconformable relations to the overlying Bell Canyon Formation. Even so, one cannot miss the Cherry Canyon marker signature below this top. This well—the Exxon, Keith Camp Trustees et al., No. 1—is located 1,980' FSWL and 1,320' FSEL, Section 33, Block 1, W&NW RR Survey, Loving County, Texas. The well, displayed as a borehole compensated sonic log, illustrates the double kick referred to earlier.

Todd (1976) published an interesting study of an oolite-bar progradation in the San Andres Formation across an area of central Upton and Reagan counties, in the Midland Basin. In that study, Todd's examination of one well, in particular, exhibited an upward shallowing facies succession above an easily recognizable, green bentonite bed (Figure 11). This well—the Pure, Hanks No. 1-A, Upton County—when placed in cross section context with other wells (Figure 12) demonstrated the diachronous nature of the oolitic sequence with relation to the bentonite. The bentonite could represent the South Wells bentonite (Figure 5) (Wilde 1975) because of its position. It is not the Cherry Canyon marker.

Gulf, PDB-04 well, Eddy County, New Mexico

In 1989 in an SEPM core workshop publication, Garber, Grover, and Harris published the detailed results of a continuously cored research well in Eddy County, New Mexico, at the north end of the Delaware Basin (Figure 13). The well is the Gulf, PDB-04, 247' FSL, 1,288' FEL, Section 32, Township 20S, Range 32E. The importance of reviewing this well is that practically all of the parameters discussed previously are brought into play in this unique borehole.

The PDB-04 well was cored continuously from the Rustler-Salado section into the shelf equivalents of the Capitan (Tansill, Yates, and Seven Rivers formations) prior to entering the reef itself. Finally, the well cored out of the reef into basin sediments of the lower Bell Canyon and upper Cherry Canyon formations.

The upper portion of the core (Figure 14) encountered bentonite in the lower part of the Yates Formation (1,931–1,932 ft) which the authors believe represents the BC (Bell Canyon) bentonite originally identified by Wilde (1975) (Garner

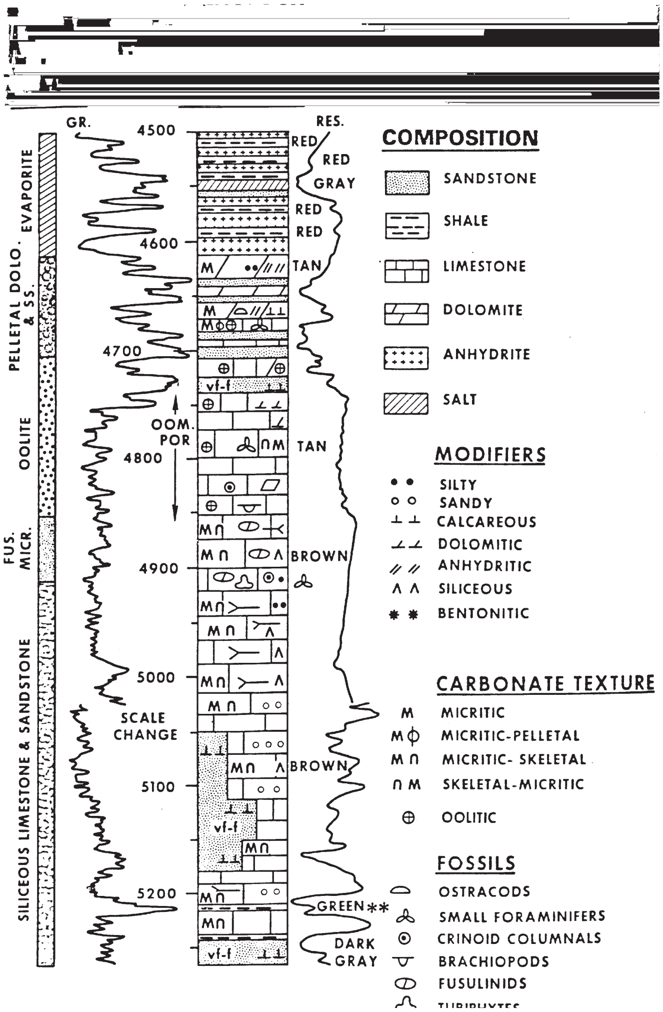


Figure 11. Facies succession, bentonite marker. Pure No. 1-A Hanks well, Upton County, Texas.

et al. 1998). This writer agrees with that conclusion. Garber and others (1989) also identified the CC (Cherry Canyon marker) bentonite (Figure 15) in the lower portion of the core, at 4,021 feet (4,023 ft on wireline log). The easily recognizable double kick signature is once again on the gamma ray/sonic.

Chevron engaged the author at the time of the study to identify the fusulinid faunas in the core (Figure 16). In that study, however, fusulinaceans were not studied below 3,827 feet, where *Polydiexodina*, a Capitanian genus, was still present. Thus, no Middle Guadalupian fusulinacean forms were found, but the Cherry Canyon bentonite marker at 4,023 feet constrained the basal part of the core, as noted earlier.

By utilizing data from the PDB-04 well and data from King (1948), Wilde (1975), Tyrrell (1962), and Garber and others (1989) constructed a profile based upon the fusulinacean-bentonite controls discussed herein, expressing the depositional history with time slices (Figure 17).

Evolution of Late Guadalupian fusulinaceans Polydiexodininae. Coincidentally, or so it would seem, certain very strange things began happening to the fusulinaceans, shortly after (geologically speaking) volcanic ash began falling across the Permian basin. And there is some evidence that Earth's plate boundaries were in states of tension and subduction, indicative of an early beginning of the breakup of the supercontinent, Pangaea.

Large Permian fusulinacean genera with cuniculi, such as *Parafusulina*, had become giants by the close of the Middle Guadalupian (Dunbar and Skinner 1931; Dunbar, Skinner, and King 1936; Dunbar 1953). From Late to Middle Guadalupian rocks (but probably pre-Cherry Canyon marker time) in western Sonora, Mexico, for example, Dunbar (1953) has described *Parafusulina antimonioensis*, whose megalospheric shells attained lenghts of 25 to 30 millimeters or more, and widths up to 5 millimeters. Microspheric shells attained lengths up to 62 millimeters. This writer can testify

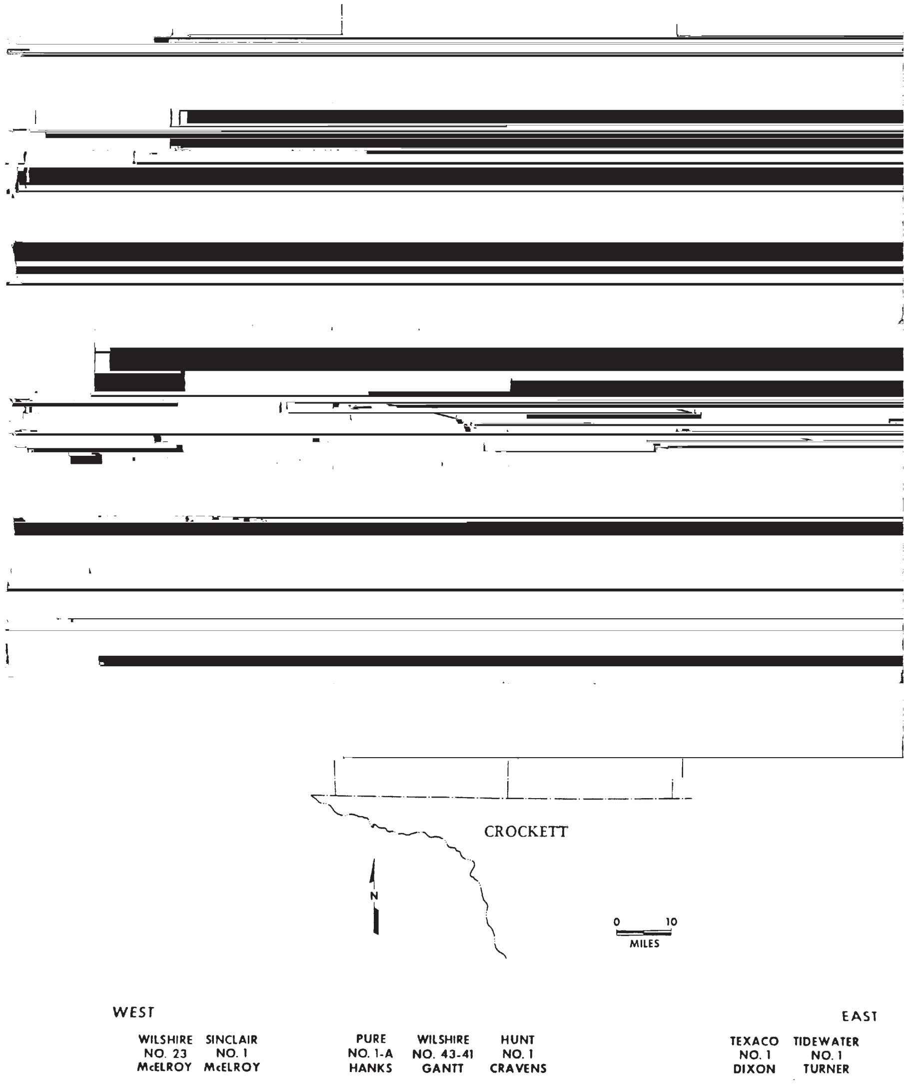


Figure 12. Oolite bar progradation, San Andres Formation, Midland Basin, showing bentonite time line.

to these gigantic sizes from having collected at the same locality. Specimens are truly of pencil size!

But even for these giants, a single, central tunnel remained characteristic, except for the rare microspheric shells, which characteristically have no central tunnel. In Early Guadalupian (Roadian) time, however, an interesting genus, *Skinnerina*, had already come on the scene without the well-defined central or median tunnel common to most fusulinid genera. *Skinnerina*, instead, displays sporadic multiple tunnels (Figure 18, Figure 19). Arguments persist as to whether such forms constitute a dead-end lineage, as thought by Skinner (1971), or whether *Skinnerina* represents the beginnings of a lineage culminating in *Polydiexodina* (Figure 18, Figure 19).

During the Middle Guadalupian, particularly in Eurasia, *Eopolydiexodina* appeared with the same lack of any well-defined median tunnel but with sporadic, multiple, secondary tunnels. The septal folds are intense and squared off with secondary material in both *Skinnerina* and *Eopolydiexodina*, which is also characteristically *Polydiexodina*-like. The writer suggests that the three genera are parts of an evolutionary continuum.

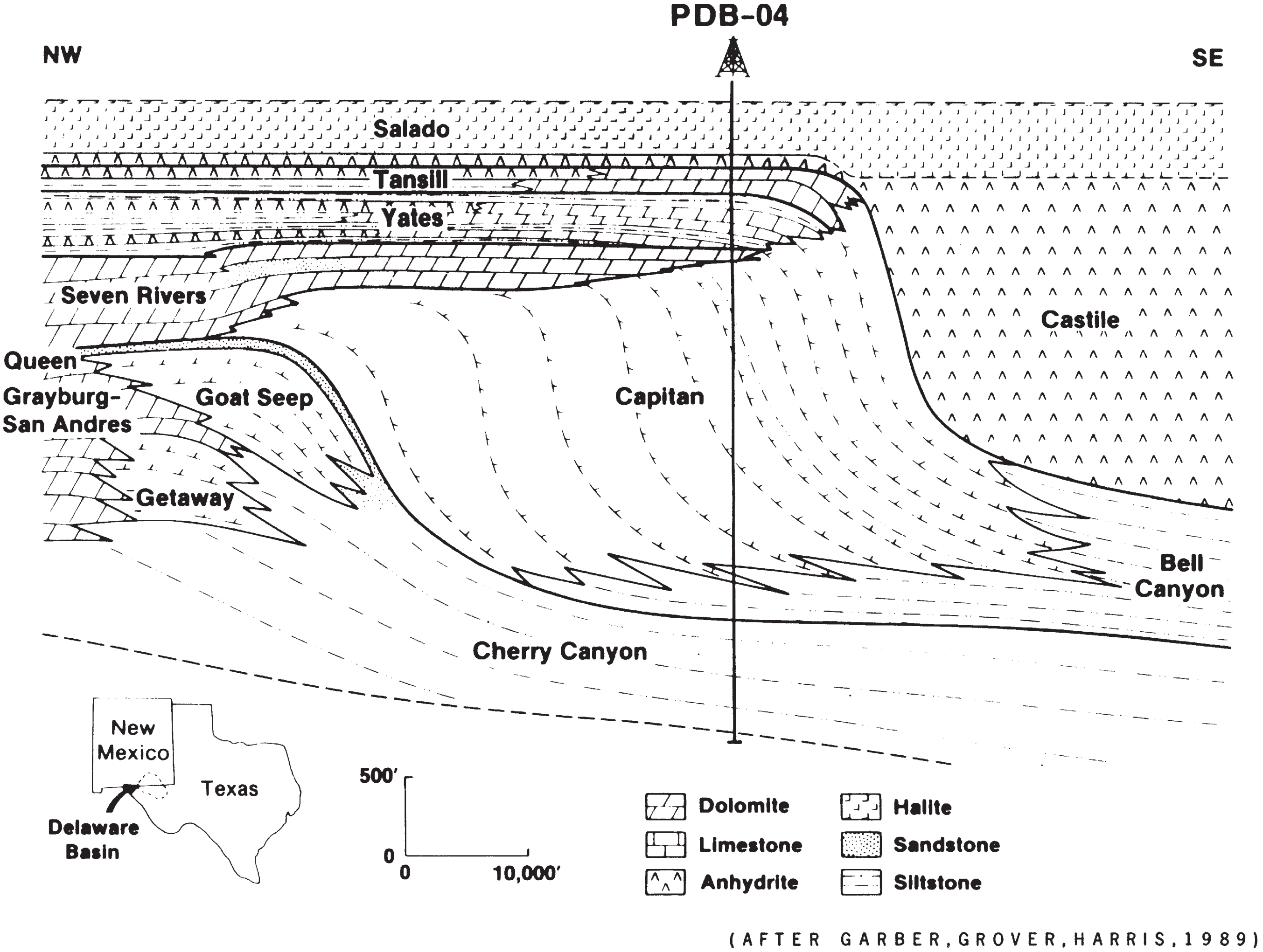
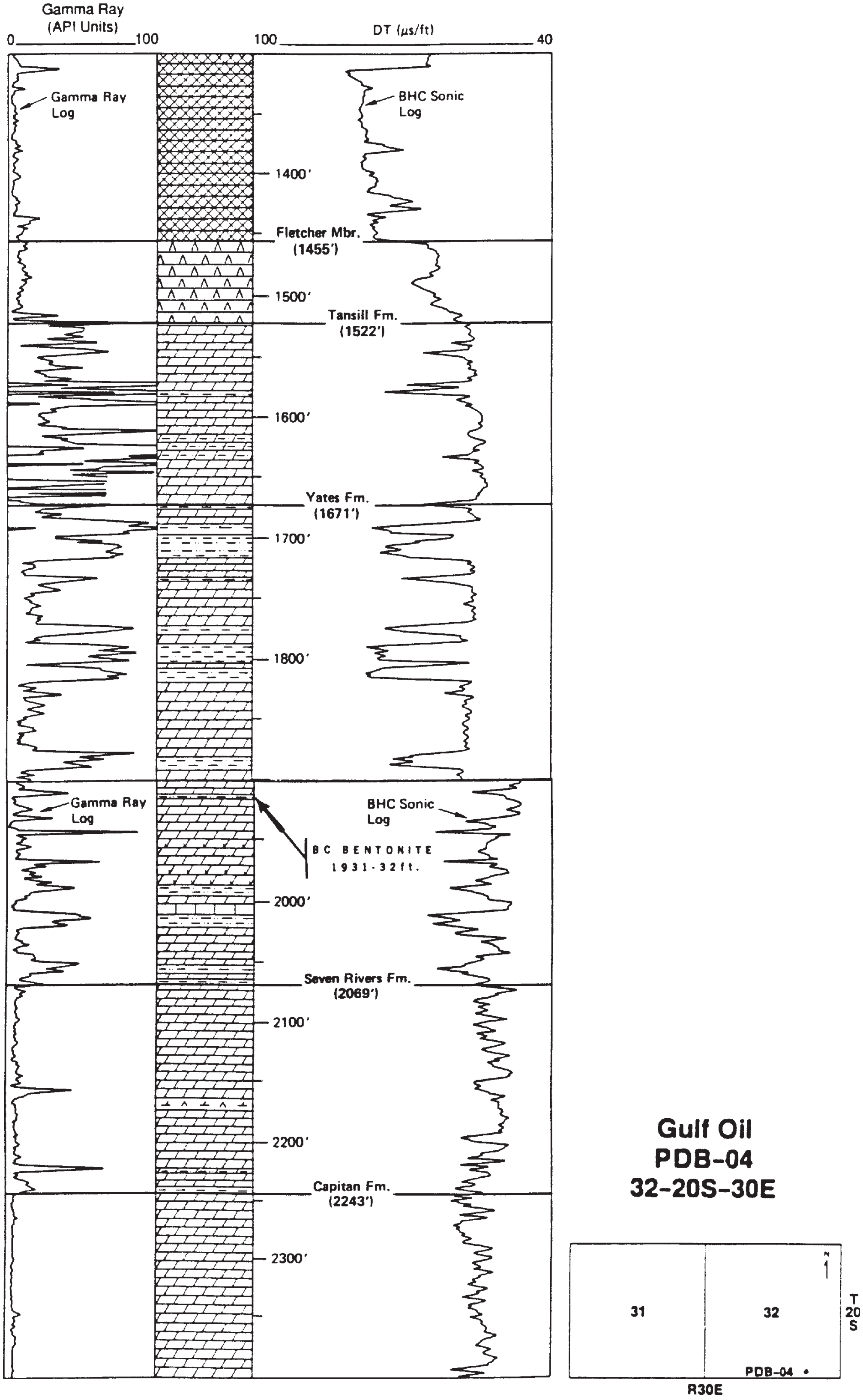


Figure 13. Cross section showing stratigraphy and lithology in area of Gulf PDB-04 well. After Garber, Grover, and Harris 1989.

Something very strange began to occur at the close of the Middle Guadalupian. Consider the fact that the giant *Parafusulina* species seemingly had no need, merely because of size, to develop multiple tunnels. Consider the fact that *Polydiexodina* apparently "needed" to attain not only well-developed multiple tunnels but also a well-developed central or median tunnel. Apparently, continued existence of these large forms depended upon the attainment of a more highly developed tunnel system. Perhaps something was happening to the sea water, accompanied by extensive volcanic ash blanketing the ocean waters. We shall return to these ideas later.

What we do know, however, is that *Polydiexodina,* with all its size and beautifully developed tunnel system, did not hang around much longer than about a million years. Apparently the Late Guadalupian seaways were becoming very stressful for these foraminifers.

The highest occurrence of *Polydiexodina* in the Guadalupe Mountains is the McCombs Limestone, and its Yates-Capitan equivalent, on the shelf and shelf margin, respectively. This correlation is to the top of Yates "B" on the shelf (Newell et al. 1953, Mruk and Bebout 1993, Garber et al. 1989).



(AFTER GARBER, GROVER, HARRIS, 1989)

Figure 14. Sonic log, lithostratigraphy of upper portion of PDB-04 well, showing position of BC bentonite marker in shelf Yates Formation. After Garber, Grover, and Harris 1989.

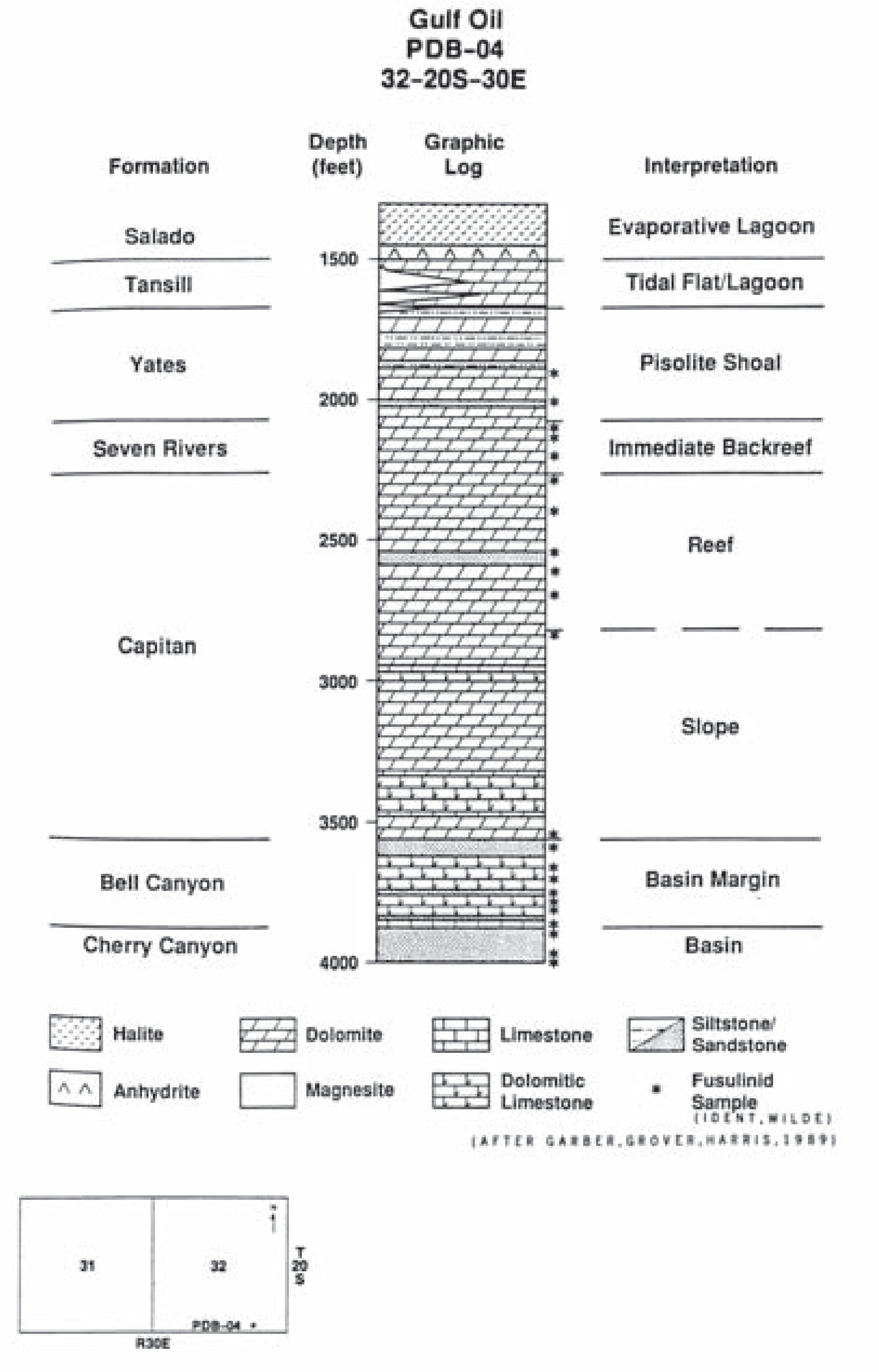
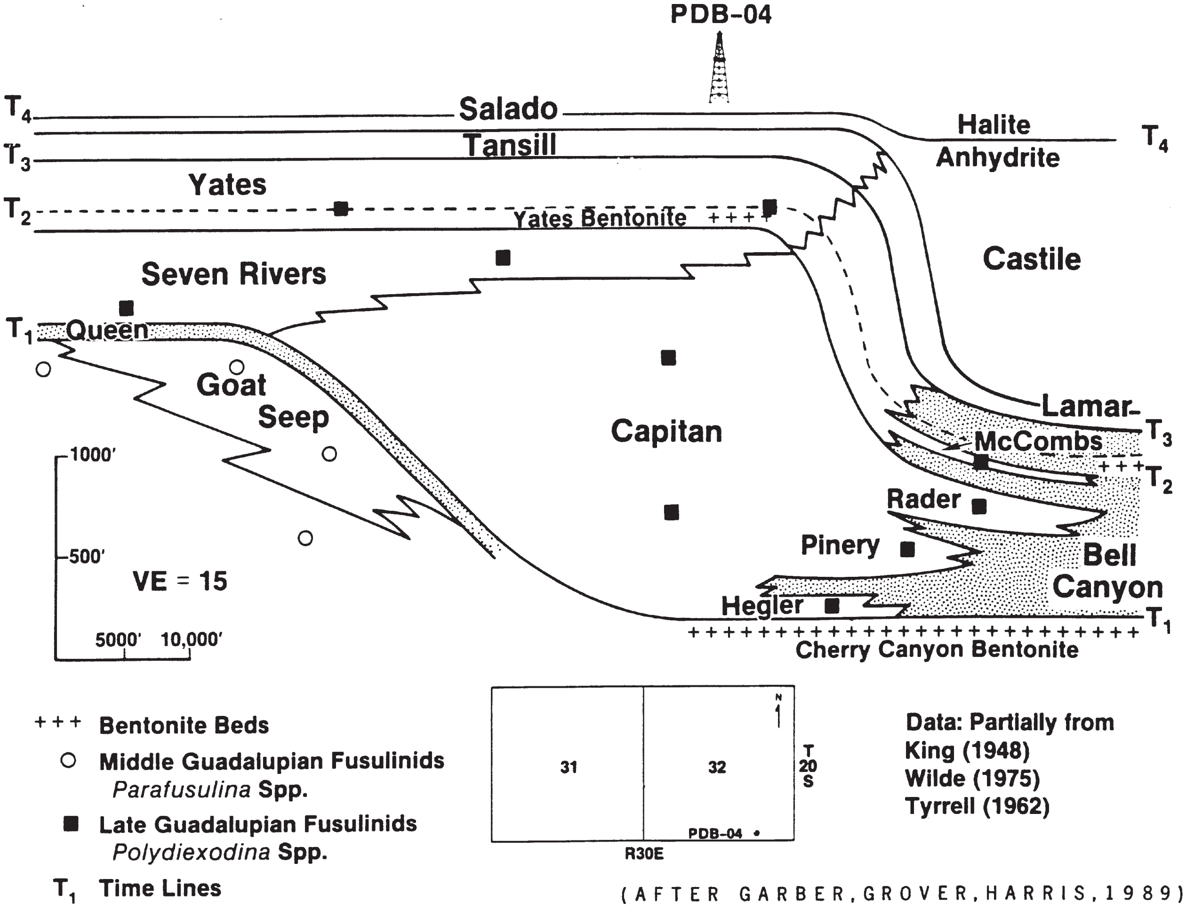


Figure 15. Sonic log, lithostratigraphy of lower portion of PDB-04 well, showing position of CC bentonite marker. After Garber, Grover, and Harris 1989.



(AFTER GARBER, GROVER, HARRIS, 1989)

Figure 17. Summary cross section showing time lines based on lithostratigraphy, fusulinid biostratigraphy, and bentonite markers in area of PDB-04 well.

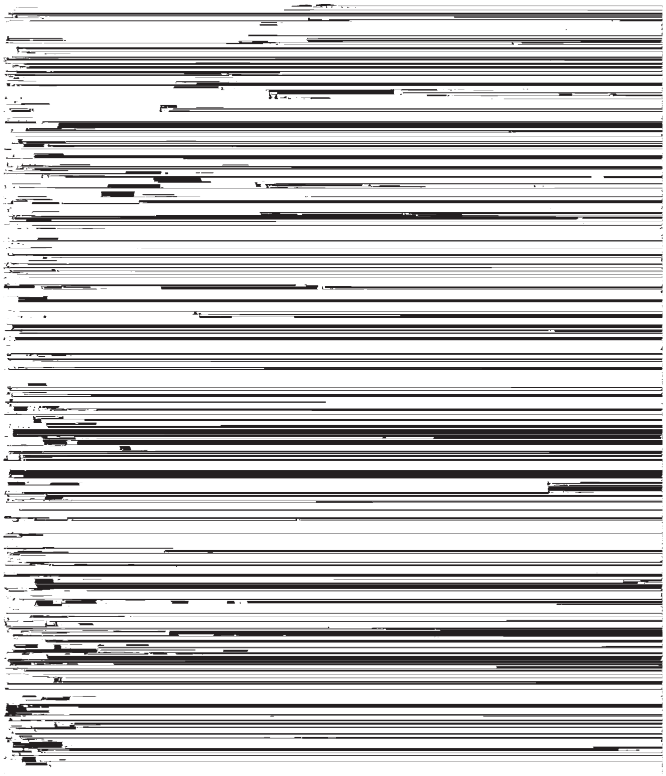


Figure 18. Evolution of the Polydiexodinids.

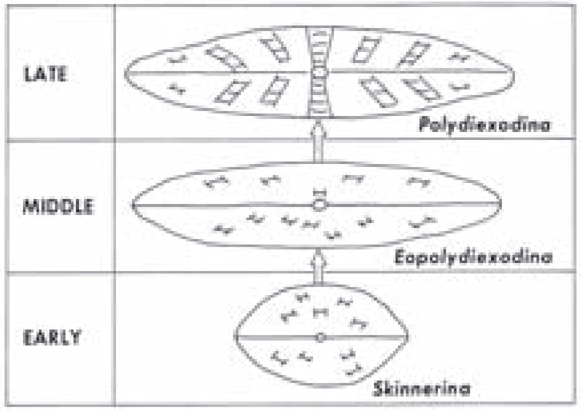


Figure 19. Evolution of the Polydiexodininae during Guadalupian time. After Wilde 1975.

Yabeina. Approximately 56 feet (17 m) above the McCombs is the basal Lamar Limestone. Here occurs one of the phenomena of fusulinacean biostratigraphy for the Delaware Basin: a tiny example of the Tethyan fusulinacean genus *Yabeina* (*Y. texana*) (Skinner and Wilde 1955) made its appearance. This form represents an intrusion from the outside, so to speak, as the first known occurrence of a "typical" Tethyan fusulinacean in the entire Permian basin history. Some workers would prefer that *Y. texana* not be considered a member of that genus because of its tiny size; however, it has all of the characteristics of *Yabeina*. And whether or not it is called by that name, the fact remains that it is a representative of the subfamily Neoschwagerininae, whose members are Tethyan.

Almost as quickly as *Yabeina* arrived in the Delaware Basin it was gone for good, and no later member of the Neoschwagerininae ever entered the Basin again. The picture is, as if to say, that the basin environment was not right in terms of size development for individual species, and definitely unsuited for continued development of progeny. What was happening to the sea water?

Boultoniinae. All members of the subfamily Boultoniinae are minute, yet complex fusulinaceans, with a type of preservation that is difficult to describe. When the subfamily was erected, Skinner and Wilde (1954) recognized this problem of description: "In thin section the spirotheca of even the best preserved specimens has a translucent to transparent quality which produces a glassy or resinous appearance." This quality is clearly not one of poor preservation; most members are beautifully preserved. Indeed, minute septal pores that are plugged with secondary material are seen in most of the genera, and in fine detail. This feature is also present in *Schubertella,* the probable ancestor to the group. The boultonids got their start in the Early Permian in genera such as *Boultonia* and *Minojapanella,* but a sudden outburst occurred about the time that *Yabeina* left the Delaware Basin. This outburst continued through Lamar Limestone and Reef Trail (post-Lamar beds, King 1948) deposition.

One member of the group, *Codonofusiella,* with an uncoiling habit, had already gotten its start in Early Capitanian time; however, by Lamar time some unusual changes were occurring within the lineage (Figure 20). From a codonofusiellid species, such as *C. extensa* (Figure 20, 1–3), arose an entirely new genus, *Paradoxiella* (Figure 20, 4–12), with features more akin to later Mesozoic and modern forms. The following stages spell out the transition:

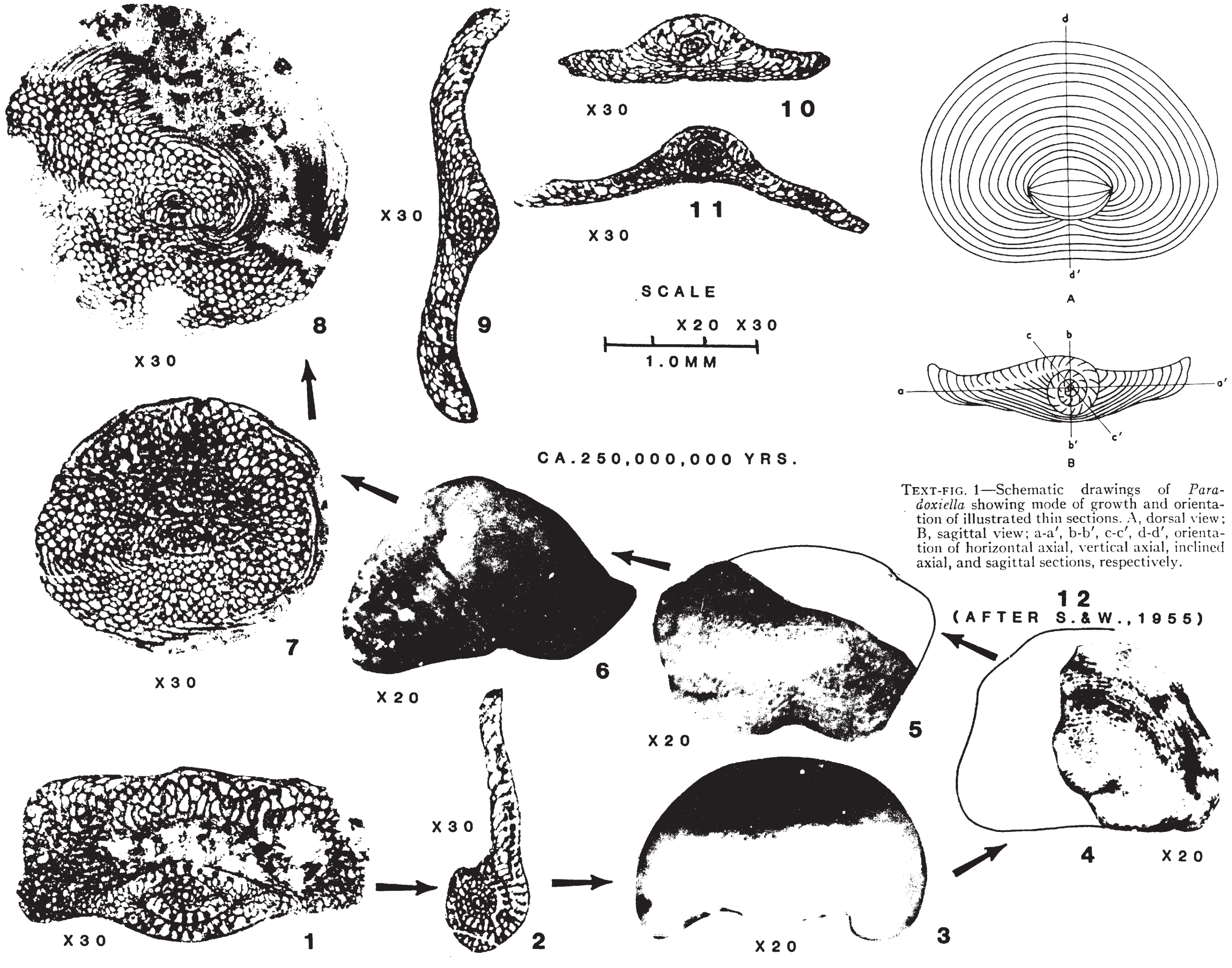
Stage 1. A *Boultonia*-like form began to uncoil in Early Capitanian time, producing *Codonofusiella*.

Stage 2. Some time between the deposition of McCombs and Lamar limestones a Codonofusiellid began to extend its uncoiled flare along the axis of coiling and tangentially. Thus, the portion of the flare in the axial area is curved back upon the axial extremities, causing a pronounced bulge of the shell at each end (Figure 20, 3). This advanced form is typified by *Codonofusiella extensa* (Skinner and Wilde 1954, 1955) whose type locality is the "middle" limestone of Brown (1996) at the mouth of McKittrick Canyon.

Stage 3. In the middle of the Lamar Limestone one sees the zone of *Paradoxiella*, a genus in which the uncoiling has been taken to the utmost extremes (Figure 20, 4–12). In *Paradoxiella*, the uncoiled flare is also extended laterally as before and recurved around the poles of the coiled body of the shell terminating against the posterior side of the shell. This mode continued until opposite ends of the recurved flare reached the shell's center. Then the flared septa, as it were, bridged across the middle to become annular. Because of this most unusual growth pattern, new terminology was needed to describe the various orientation patterns (Figure 20, 12) (Skinner and Wilde 1955). In finality, the shells have a sort of coolie-cap appearance and commonly fell onto the lime mud floor with the posterior side protruding upward.

Once again, occurring in a single evolutionary group is what might be interpreted as stressed conditions. Whether stressful or not, *Paradoxiella* had a relatively short life, occurring only during the middle of Lamar Limestone deposition. But its occurrence was widespread; species were described from Japan (Sada and Skinner 1977, Ishii and Takahashi

Figure 20. Evolution of Codonfusiella to Paradoxiella.



TEXT-FIG. 1—Schematic drawings of *Paradoxiella* showing mode of growth and orientation of illustrated thin sections. A, dorsal view; B, sagittal view; a-a′, b-b′, c-c′, d-d′, orientation of horizontal axial, vertical axial, inclined axial, and sagittal sections, respectively.

1960) and China (Sheng and Sun 1975). In the latter instance, this writer believes that the species described as *Codonofusiella orthonios* by Sheng and Sun, is in reality a *Paradoxiella*. These Asian forms occur with huge *Yabeina* in the upper part of the *Yabeina* zone.

***Paraboultonia* and *Lantschichites*.** It is beyond the scope of the present paper to consider the entire story of *Paraboultonia* and *Lantschichites*. This has been discussed in detail in Wilde and Rudine (1997). Both forms have been found to occur together from the top of the Lamar Limestone through the Reef Trail Member (post-Lamar beds, King 1948) to the base of the Castile Formation. *Paraboultonia* is elongate, with strongly folded septa and exhibits cuniculi, openings at the base of opposed folds of septa, as is seen in the older large genera, *Parafusulina* and *Polydiexodina*. The final whorl of *Paraboultonia* is inflated, but the septa do not rise off the floor to uncoil as in *Codonofusiella*. However, in *Lantschichites* uncoiling does occur, and indeed, *Lantschichites* is considered to be an elongated subgenus of *Codonofusiella*.

The point to be made here, however, is that these two forms appear to represent end members of a line of boultonids that developed very quickly during the Late Guadalupian–Early Lopingian and then died out, following a pattern experienced by other fusulinacean genera ahead of them.

End-Permian

By the close of the Permian all of the fusulinaceans had died out, but numerous species of boultonids, represented by such genera as *Palaeofusulina*, not present in the Delaware Basin because of the onslaught of evaporitic conditions, continued to the end. Numerous other minute genera hung on to the end with them.

Some major changes had obviously occurred in the chemistry of the sea water. There is no good reason to argue, as this author did many years ago (1955), that the arrival of evaporites and salts signaled the ultimate demise of *Polydiexodina*, for example. Perhaps this could constitute a reasonable argument in the case of the Delaware Basin history, but such an argument fails to consider the worldwide aspect of fusulinacean evolution. *Polydiexodina* and *Paradoxiella* did live at approximately the same time elsewhere. *Yabeina* coexisted elsewhere with *Paradoxiella* in healthy abundance and size. But in the Delaware Basin *Yabeina* arrived, did not enjoy a healthy existence, and either left or died out.

Conclusions

Two lines of evidence, one well-documented, the other speculative but plausible, suggest an explanation for what happened to the fusulinaceans during the Guadalupian and at End-Permian time.

There seems little doubt that volcanism played a commanding role in the demise of the larger fusulinaceans in the Delaware Basin. Not mentioned earlier, but true, the Manzanita Limestone, which overlies the Cherry Canyon marker bentonite, is rather light-colored with a pale-green aspect, and, according to Newell and others (1953), the depth of water during Manzanita deposition was much shallower than for most of the other limestone deposits of the basin margin two miles from the basin rim. Also, and most telling, the Manzanita Limestone lacks many of the faunal groups with the exception of ammonoids and rare brachiopods and gastropods (Newell et al. 1953). The Manzanita had no shelf margin reef equivalent either. It is very compelling to suggest that the volcanism that was associated with the Manzanita deposition also played a role in the demise of large *Parafusulina* and subsequent proliferation of *Polydiexodina*, with its well-developed tunnel structures.

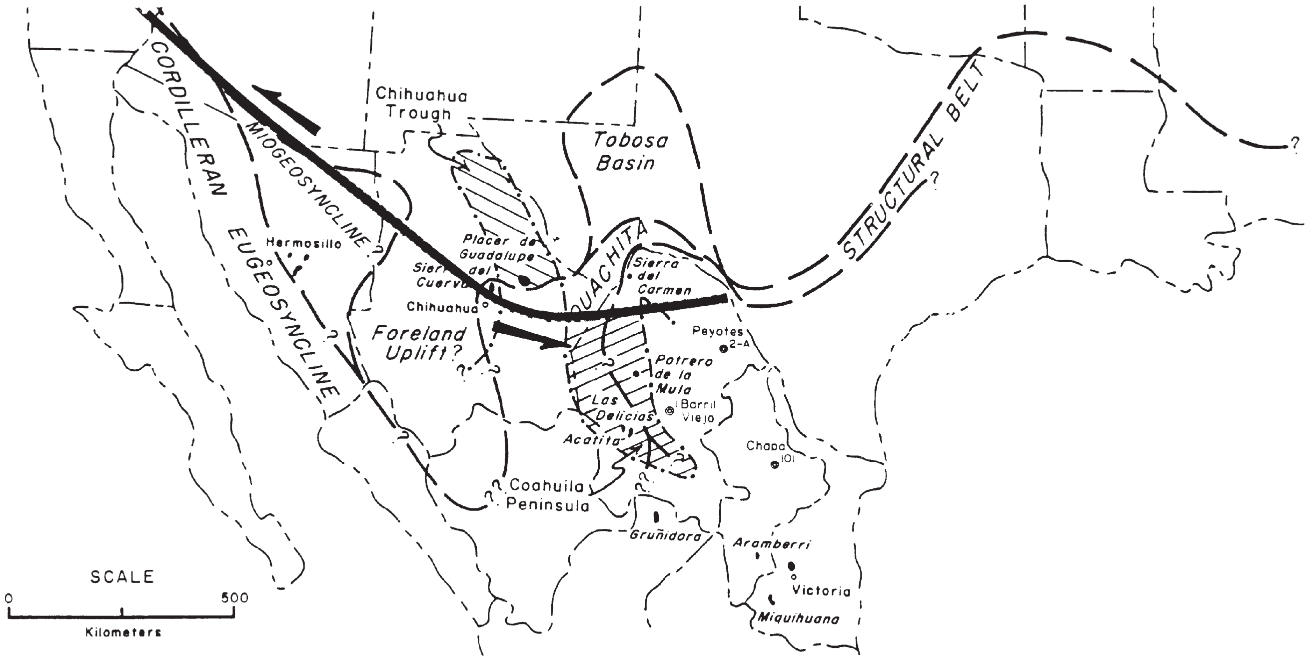
But a new element was conspiring with the volcanism to limit *Polydiexodina*, and later *Yabeina*, to a short life in the Delaware Basin. To be sure, the continuing volcanism did not help. A restrictive inflow of sea water, possibly coupled with altered sea water content, was occurring. The earlier high $CaCO_3$ production of the basin margin was now being shut down. Although $CaCO_3$ production during Lamar deposition was strong, many changes were about to occur. The prolific Capitan reef was dying and became subaerially exposed because of relative sea level fall at the close of Lamar–lower Tansill deposition. By the time a rising sea level had reestablished itself in upper Tansill–Reef Trail time, only scattered patch reefs were being developed (Noe 1996). With increasing aridity and the closing of the Hovey Channel (Figure 6, Figure 8), evaporative conditions proved to be devastating for reef development.

By the close of Lamar deposition, the minutely complex fusulinaceans had completely taken over in the Delaware Basin, matching worldwide changes. Thus, the Hovey Channel could not have sealed off the Basin completely, at least prior to Castile deposition. There was not only continued freshening, but continued evolution of the tiny fusulinaceans. Sea water over the entire Earth seemed to be undergoing major change due to ocean-floor spreading brought about by the central fissures of the Pacific (Panthalassa) and the Atlantic ridges juxtaposed to major plate boundaries.

The structural speculations of Bridges (1964) have been modified to express simply the idea that large left-lateral movements of Late Permian plate boundaries could have been involved in moving Panthalassic waters in and out of the Delaware Basin while volcanoes were spewing ash over the landscape (Figure 21). Close of the Permian was not far away, but its end was already in sight during the Guadalupian.

All kinds of causes have been offered for the End-Permian extinctions, including salinity changes, global cooling, tectonics, extra-terrestrial impact, marine regression, and others, in no particular order. Erwin (1992) argued that the most likely cause of these extinctions "was tectonically-induced climatic instability and marine regression which brought

Figure 21. Structural speculations in northern Mexico. Modified after Bridges 1964.



about trophic instability." Wilde (1975) offered similar arguments based on observed mineralogical changes in fusulinaceans as a possible result of continental plate displacements.

Finally, it is suggested that plate tectonics might offer a single cause and effect scenario for lumping most of the suggested causes of End-Permian extinctions. Plate tectonic activity and ocean-floor spreading moved continents, rerouted sea water flow, caused volcanic eruptions, and elevated mountains of carbonates, which added CO$_2$ to the water column with water and ice runoff. Adding large amounts of CO$_2$ to the world's oceans offers one of the best opportunities for anoxic conditions to develop. A number of workers have recently argued for a "superanoxic, stratified superocean" at the Permian-Triassic boundary as the defining cause for Permian extinctions (Sepkoski 1986, Erwin 1992, Knoll et al. 1996, Isozaki 1997). This "cause," however, is only an end result of all that had begun a few million years earlier in the Guadalupian.

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Note: Because the boundaries of the Middle Permian and Guadalupian have been defined and adopted (see Glenister et al. and Lambert et al. in this volume), the editors treat them as formal units. Therefore, the initial letters of the names and modifying words of the period/system (e.g., Middle Permian), epoch/series (e.g., Upper Guadalupian), and stage/age (e.g., Early Capitanian) have been capitalized in this context. Other geologic units in this paper follow the guidelines provided in Hansen, W. R., editor. 1991. Suggestions to authors of the reports of the United States Geological Survey. 7th edition. U.S. Geological Survey, Washington, D.C.

Chapter 33

Sponge Diversity Patterns in the Middle Capitan Reef of the Guadalupe Mountains, Texas, and Their Environmental Implications

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Introduction

The Guadalupe Mountains of Texas and New Mexico provide unparalleled exposures of the marvelously preserved Capitan reef system (Figure 1). Considered a classic teaching example, the reef is visited by hundreds of geologists annually. Despite its very different biological composition, the middle Capitan reef is remarkably similar in morphology and dimensions to modern reefs and to other ancient reefs. Because of fortuitous conditions of burial and erosion, part of the original depositional profile of the Capitan is intact. Its profile, in fact, is hauntingly similar to the steep front of modern reefs.

One feature common to almost all shallow-water reefs today is a significant change in faunal diversity and community composition with depth. Such

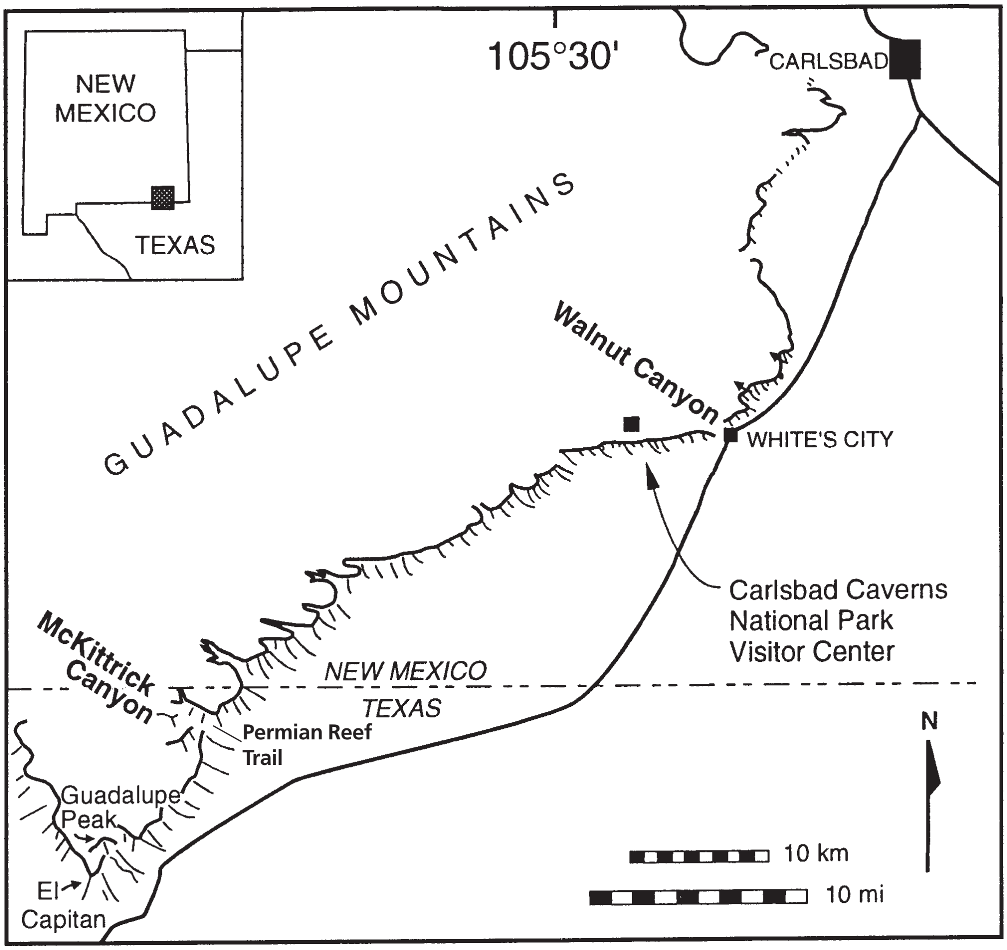


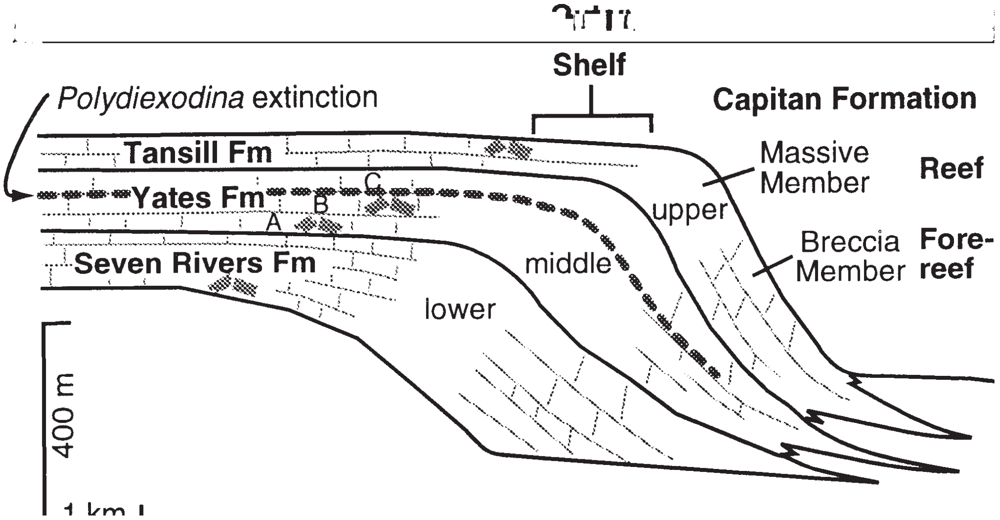
Figure 1. Map indicates the locations of the Guadalupe Mountains and the Permian reef geology trail in McKittrick Canyon from which the samples in this study were collected.

changes are well-documented for corals (e.g., James, 1983, Bianchi et al. 1997, and many others), and similar changes have been observed in many other groups as well, including sponges (Alcolado 1990, 1994; Alvarez et al. 1990; Diaz et al. 1990; Schmahl 1990; Liddell et al. 1997; Reed and Pomponi 1997). Unfortunately, it is difficult to recognize faunal changes with depth in the fossil record because burrowing, sorting by waves, and other processes alter and destroy the original community composition.

Fortunately, the Capitan reef does contain well-preserved assemblages. In contrast to modern reefs, the Capitan community, like other Permian communities, contained few organisms that could damage the reef itself (Wood et al. 1996, Fagerstrom and Wiedlich in press). Preservation of the reef in situ was also enhanced by the contemporaneous encrustation, largely by the presumed red alga Archaeolithoporella (Wiedlich and Fagerstrom 1998), and by the binding of reef organisms through the precipitation of lime mud, or micrite, by bacteria (Kirkland et al. 1998). Furthermore, and most remarkably, the excellent exposures and lack of structural deformation allow us to determine the water depth at the time of deposition along the front of the reef.

The Capitan Formation itself consists of two members: a Massive Member, which comprises the reef, and a Breccia Member, consisting of the fore-reef debris (Figure 2). The Capitan has been divided into lower, middle, and upper units by correlation to the interfingering Seven Rivers, Yates, and Tansill formations on the shelf to the northwest. Time lines have been drawn through these rock units using index fossils, most commonly fusulinids (e.g., Newell et al. 1953). These rice-shaped protozoans sometimes grew to surprisingly large sizes. The large fusulinid *Polydiexodina* is one of the most prominent and distinctive, and being commonly about two-centimeters long, it is easily seen in outcrop. Its extinction marks a prominent time line that can be carried through the Capitan Formation, and it defines the profile of the reef as it appeared during deposition of the middle Capitan. During this phase of its deposition, the reef had a nearly vertical profile (Kirkland et al. 1993). In some places the ancient reef profile runs almost parallel

Figure 2. Diagram shows the spatial relationships and stratigraphy of the outer shelf, reef, and fore-reef facies of the Permian reef complex in the Guadalupe Mountains. The Seven Rivers, Yates, and Tansill formations correlate to the lower, middle, and upper Capitan reef facies, respectively. The *Polydiexodina* extinction provides a time line illustrating the original, nearly vertical profile of the reef and shelf margin. The samples in this study were collected from the middle Capitan Formation parallel to this time line.



to the modern erosional surface (Figure 2, Figure 3). The time line defined by *Polydiexodina* is so prominent and the nearly vertical depositional profile it defines so striking that tracing it in outcrop is a common field exercise for geology students.

The goal of this study is thus to document the contemporaneous faunal changes within the reef along the *Polydiexodina* time line and to correlate these changes with the original water depth. In this way faunal patterns can be tied directly to bathymetry, allowing inferences to be made about oceanographic conditions in the Delaware Basin and the environmental controls on the organisms that lived there.

Methodology

One of the places where the ancient reef profile parallels the modern erosion surface is along parts of the Permian reef geology trail in McKittrick Canyon (Figure 1). In the parts of the trail that we studied, walking down the trail is analogous to diving deeper and deeper down the face of the reef. Because of this fortuitous configuration, we were able to plot the location of each sample with respect to the shallowest part of the reef, the outer shelf–reef transition (Figure 3), and thus deduce water depth (±10 m) at the time of deposition.

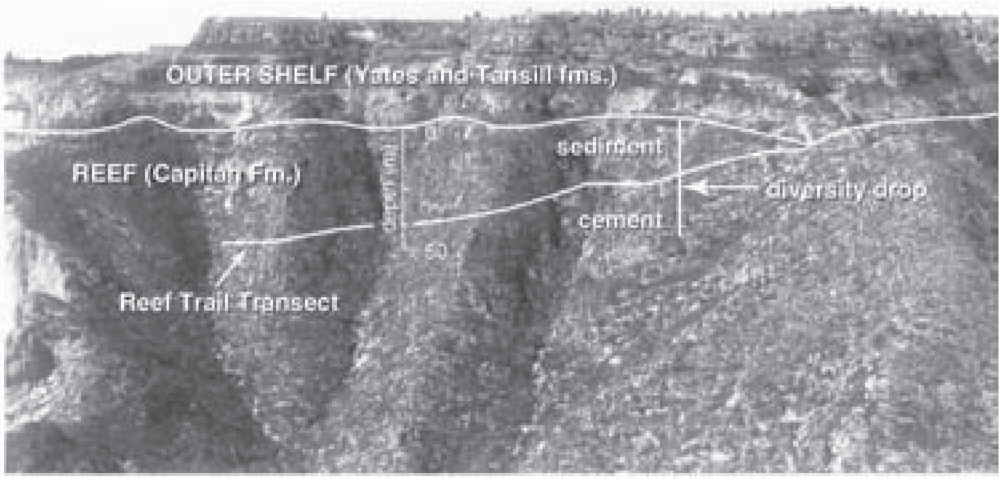
Samples used in this study were collected from the Capitan Massive at approximately five-meter intervals, beginning at the outer shelf–reef transition, and continuing downward along the trail to an elevation (and paleodepth) about 50 meters below the transition (Kirkland et al. 1993) (Figure 3). In order to determine relative elevations, the sample sites were marked on a photograph of the exposure then measured off the photograph in relation to elevation markers surveyed by the Texas Bureau of Economic Geology. The fusulinid *Polydiexodina* is common throughout this part of the reef, and the time line defined by its extinction is easy to trace.

Results

The Massive Member of the middle Capitan Formation exposed in McKittrick Canyon contains numerous sphinctozoan and inozoid sponges. These sponges have a solid, basal skeleton of calcium carbonate, which in the case of sphinctozoans, forms distinct chambers.

Between the outer shelf–reef transition and a position 15 to 20 meters below, samples exhibit a high overall diversity, with at least 13 species and 10 genera of sphinctozoans, as well as one species of inozoid, being present (Figure 4, Table

Figure 3. Photograph of the Permian reef geology trail in McKittrick Canyon. The outcrop here nearly parallels the original depositional surface as indicated by the *Polydiexodina* time line. Samples were collected along the reef trail transect from the outer shelf–reef transition down to a paleodepth of about 50 meters below. The drop in faunal diversity is about five meters below the transition from grainy sediment to cement-dominated fabric.



	Depth below reef–outer shelf transition (m)												
	0	3	12	15	17	18	24	27	35	37	40	43	46
Sphinctozoans													
Lemonea	x	x	x	x		x	x	x	x	x	x	x	x
Colospongia	x	x											
Ambithalamia		x					x	x	x				
Girtyocoelia		x		x			x						
Guadalupia				x									
Cystothalamia		x		x									
Amblysiphonella		x		x	x	x	x			x	x	x	
Parauvanella		x		x	x								
Discosiphonella			x	x									
new genus				x									
Inozoids				x					x				x
Hexactinellids?	x												
Bryozoans	x					x					x		
Acanthocladia			x	x	x		x					x	x
sheet		x											
encrusting		x					x						
stick-like			x										
Coral				x									
Algae													
Green Algae									x				
Phylloidal			x										
Dasyclad	x												
Mizzia		x											
Collenella	x												
Pseudovermiporella		x				x							
Archaeolithoporella	x	x	x	x	x	x	x	x			x	x	x
Problematica													
Shamovella (=Tubiphytes)	x	x	x	x		x	x	x					x
Lercarituba							x						
Articulate Brachiopods	x	x	x					x	x	x			x
Foramanifera			x			x			x				
Encrusting Forams	x	x		x			x						x
Unidentified Fusulinids								x	x				
Polydiexodina	x	x	x	x									
Mollusks									x				
Gastropods	x	x	x										x
Bivalves	x	x											
Arthropods	x	x											x
Echinoderms	x	x				x						x	
"Worms"						x							

Table 1. The genera present within samples taken from 0 to 50 meters elevation below the outer shelf–reef transition along the Permian reef geology trail in Guadalupe Mountains National Park, Texas. The sediments change character with increasing water depth below this transition. The unit was extensively dolomitized along a fracture between 5 and 10 meters depth, preventing any meaningful analysis of samples from that interval.

1). In addition to the indeterminate inozoid, these taxa include: *Ambithalamia*, *Amblysiphonella* (3 spp.), *Colospongia*, *Cystothalamia*, *Discosiphonella*, *Girtyocoelia*, *Guadalupia*, *Lemonea* (2 spp.), *Parauvanella*, and a new porate genus distinguished by having exaules and reticular filling tissue. Each species was usually represented by just one individual per sample. Unfortunately, replacement of the original reef rock by dolomite along fractures (Melim 1991) prevented meaningful sampling between 5 and 10 meters below the outer shelf–reef transition. The original total diversity within this zone may therefore have been even higher. However, the same rock type and species abundances were found above and below this zone, so there does not appear to have been any significant lithologic or faunal change across the dolomitized interval.

At a point 15–20 meters below the outer shelf–reef transition, sponge diversity plummets (Figures 5, Figure 6, Table 1). Samples collected at this point and at points below are dominated by just one genus of sphinctozoan sponge, *Lemonea*

Figure 4. Photograph shows the sphinctozoan *Lemonea*, one of the more common genera in the Capitan Formation. This taxon dominates faunas of the upper Capitan (Rigby et al. 1998) and those samples from the middle Capitan occurring more than 20 meters below the outer shelf–reef transition. Note that successive generations attach to and hang from older individuals. Photograph by Rachel Wood.

(Figure 4). Although *Ambithalamia*, *Amblysiphonella* (4 spp.), *Girtyocoelia*, *Parauvanella*, and one inozoid are also present, their occurrence is sporadic and their abundance is low. *Lemonea*, on the other hand, is represented by two, three, or even more individuals in almost every sample.

A similar but less pronounced drop in diversity is seen among the other fauna within the reef (Table 1). Once again, the greatest diversity of organisms is found in samples taken 0–15 meters below the outer shelf–reef transition. Green algae, mollusks, brachiopods, encrusting foraminifera, and corals are more common in samples from shallower depths (Table 1). Sponges, bryozoans, and the presumed red alga *Archaeolithoporella* are more common than other organisms at depths greater than 15 meters below the outer shelf–reef transition. The unusual organism *Shamovella* Rauser-Cernousova (formerly *Tubiphytes*, see Riding 1993) is also present at these depths but only occurs in local concentrations.

The character of the rock also varies with depth below the outer shelf–reef transition. Samples collected less than 12 meters below the reef to outer shelf transition were dominated by grains. These grains are poorly sorted, subrounded to rounded, and include fragments of dasyclad algae, bryozoans, *Shamovella*, bivalves, ostracods, and what are probably sponges (Kirkland and Moore 1996). The mud content in these grainstones to packstones varies from sample to sample and even on a microscopic scale. Very little lime mud (micrite) is present and cement and similar crystalline material comprises no more than 10% of the samples. However at depths greater than 12 meters below the outer shelf–reef transition, the rocks are characterized by cement-filled voids that make up 15–70% of each sample (Table 1).

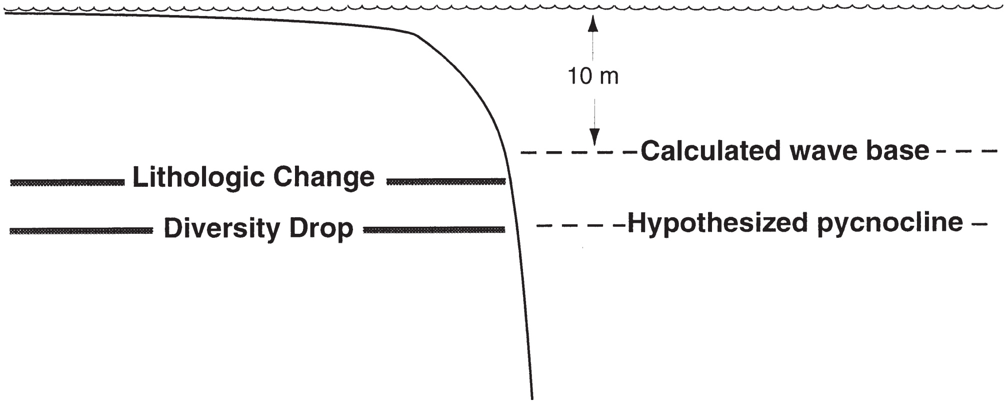


Figure 5. Diagram illustrates the positions of calculated wavebase and the interpreted pycnocline relative to the observed lithologic change and drop in biological diversity.

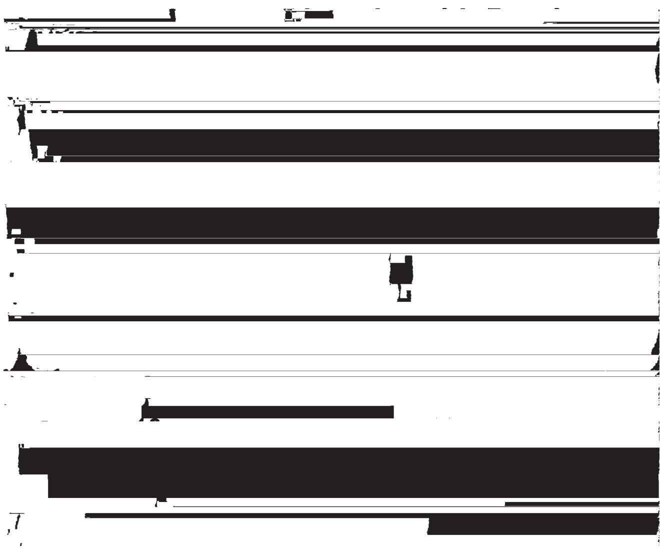


Figure 6. Plot shows changes in sphinctozoan generic diversity with depth below the outer shelf–reef transition along the Permian reef geology trail in Guadalupe Mountains National Park, Texas. Whereas the taxa in the shallower assemblages are about equally abundant, *Lemonea* dominates the assemblages below about 17 meters.

Subtle variations also occur in the composition of the frame-building community and in the nature of the binding elements. In samples taken 0–10 meters below the transition from reef to outer shelf, organisms that could fill the role of frame builders are present. These include sphinctozoan sponges, the green alga *Collenella*, and bryozoans. These organisms are commonly encrusted by one or more layers of micrite, the innermost being very thin (0.05 mm) and having distinct, ovoid holes. Successive encrustations may be as much as 10 millimeters thick.

Approximately 15 meters below the contact between the reef and outer shelf, *Collenella* is absent. Relationships between the organisms are easier to recognize. Bryozoans and sponges clearly form cavity walls and act as frame builders. Accumulations of fine-grained micrite, probably precipitated by microbes, are much thicker (1–3 cm) than they are higher in the reef.

Figure 5 illustrates the sedimentary and faunal changes with respect to the outcrop. Interestingly, the drop in biological diversity occurs about 5 meters below the change from grainy sediments to cement-rich boundstone.

Interpretation

We interpret the change in rock type and the distinct drop in diversity seen below the outer shelf–reef transition to be the results of changes in the physical environment and water mass below wave base. The reduced diversity in the deeper samples suggests some kind of environmental stress, but of what sort?

In terms of modes of life, the closest ecological analogues to the Capitan sphinctozoans in modern open marine environments would be heterotrophic demosponges. The diversity of such sponges is usually greatest at depths of 10–30 meters or more, with much greater diversity in deep waters than in shallow ones (Hartman 1977; Alcolado, 1990, 1994; Wilkinson and Evans 1989; Schmahl 1990; Liddell et al. 1997; Reed and Pomponi 1997). Based on a comprehensive, global study of sphinctozoans, the optimum water depth for Permian and Triassic sphinctozoans in reefs was 15–40 meters (Senowbari-Daryan 1990).

Some of the environmental conditions known to influence modern sponge distributions include: turbulence and turbidity (Pouliquen 1972, Sarà and Vacelet 1973, Sarà 1978, Wilkinson and Evans 1989, Alcolado 1990, Diaz et al. 1990, Liddell et al. 1997), the frequency of environmental disturbance (Alcolado 1990, Diaz et al. 1990), light levels (Pouliquen 1972, Sarà and Vacelet 1973, Wilkinson and Evans 1989), the character and availability of the growing surface (de Laubenfels 1955, Pouliquen 1972, Sarà and Vacelet 1973, Bergquist 1978, Diaz et al. 1990, Bakus and Ormsby 1994, Liddell et al. 1997), salinity (Pouliquen 1972, Sarà and Vacelet 1973, Alcolado 1990, Bakus and Ormsby 1994), oxygen levels (Sarà and Vacelet 1973), and temperature (Hartman 1958, Wells et al. 1960, Pouliquen 1972, Sarà and Vacelet 1973, Bakus and Ormsby 1994). Predation (Sarà and Vacelet 1973, Bergquist 1978, Bakus and Ormsby 1994) can also affect the distribution of some sponge taxa.

In modern reefs, turbulence and turbidity are important controls on sponge distributions (Pouliquen 1972, Sarà and Vacelet 1973, Sarà et al. 1978, Wilkinson and Evans 1989, Alcolado 1990, Diaz et al. 1990, Bakus and Ormsby 1994, Liddell et al. 1997), but produce a markedly different diversity curve than that seen in the middle Capitan. Because sponges are filter feeders, their diversity is greatest where the water is neither stagnant nor excessively turbulent (Sarà and Vacelet 1973). In stagnant waters, the current is too weak to bring food to the sponge, and oxygen levels may also be too low. In modern settings, though, sponge diversity at less than 30 meters is limited because turbulence fills the water with fine sediment and interferes with filter feeding (Alcolado 1990, 1994). In addition, the high wave-energy at these shallow depths results in high levels of environmental disturbance and stress that can reduce diversity (Alcolado 1994, Bakus and Ormsby 1994).

Our samples, however, showed diversity peaking at a water depth of less than 20 meters. Below this diversity plummets (Figure 6, Table 1), suggesting that controls on diversity in the middle Capitan were very different from those in modern reef settings, and that high levels of turbulence, turbidity, and rates of environmental disturbance were thus less important than other factors in controlling the distribution of Capitan sponges.

Changes in light levels affect distribution of modern coral and some sponge species (Pouliquen 1972, Sarà and Vacelet 1973, Wilkinson and Evans 1989) because these organisms contain photosymbionts. However, no morphological evidence exists to suggest that these Permian sphinctozoans had such symbionts. In addition, most ancient and all modern sphinctozoans inhabit caves, crevices, and the undersides of reef cavities, so the likelihood of their having had photosymbionts is very low. While light levels could have affected planktonic abundance and food supply, light and high levels of planktonic productivity in clear waters continue to 30 meters or more, rather than the inferred depth of 15–20 meters for the sudden drop in diversity in our samples. Furthermore, high levels of light may result in high levels of ultraviolet radiation (Wilkinson 1982). The deleterious effect of such radiation would result in higher diversity in deeper waters—the pattern seen in many modern reefs—but the exact opposite of what is seen in the middle Capitan reef.

The nature of the sediment can also influence sponge species distribution (Pouliquen 1972, Sarà and Vacelet 1973, Diaz et al. 1990, Bakus and Ormsby 1994, Liddell et al. 1997). However, the shift from grainy to cement-rich sediments occurs 10–15 meters below the outer shelf–reef transition and about five meters above the drop in sponge diversity. There is thus no direct correlation between the type of substrate and faunal diversity. While many modern species distributions are also affected by competition for limited substrate, the frequent lack of contact between the sphinctozoan sponges in the upper Capitan has been interpreted to suggest that little, if any, spatial competition occurred between them (Wiedlich and Fagerstrom 1998).

Predation by spongivores can influence species distribution today (Sarà and Vacelet 1973) but probably had almost no effect on the diversity patterns of Permian sphinctozoans. Those groups of fish and turtles that eat sponges today did not evolve until much later. Furthermore, the demosponges preyed upon in modern oceans have proteinaceous skeletons much softer and more nutritious than the hard, calcareous skeletons of the Permian sphinctozoans.

The most plausible explanation of the observed diversity pattern in the middle Capitan is a rapid change in water conditions with depth. The Capitan reef fringed the Delaware Basin, a nearly enclosed embayment. As such, its circulation would have been very restricted, and many authors have suggested that at least during some intervals of Permian time, this basin experienced hypersaline conditions (e.g., Harms 1974). Evidence of high salinity includes ghosts of gypsum crystals in the basinal sediments of the Lamar Formation. The inner shelf at this time was about 120 kilometers across and very shallow (Adams and Rhodes 1960), and dense, saline waters could have formed on the shallow shelf and then flowed into the basin.

Oxygen levels might also have changed with depth within the Delaware Basin. Being a nearly enclosed embayment at equatorial latitudes (Darke 1989), the waters within the basin would not have experienced seasonal overturn. Most of the strata within the basin are characterized by large amounts of organic matter, fine laminations, and a very low or no faunal diversity (L. C. Babcock 1974). These observations suggest that the deepest basinal waters were usually poorly oxygenated, stagnant, and that the water mass within the Delaware Basin was probably intermittently stratified with respect to oxygen and possibly with respect to temperature and salinity (Harm 1974, Given and Lohmann 1985, Kirkland George 1992).

Temperature, however, could also have been important in producing the sponge distributions observed in the middle Capitan. Temperature is the main factor controlling the geographic and bathymetric distributions of many sponge species today (Hartman 1958, Wells et al. 1960, Pouliquen 1972, Sarà and Vacelet 1973). Species are adapted to certain temperature ranges and are largely limited to water depths in those temperature ranges (Sarà and Vacelet 1973). Changes in temperature can also have a dramatic influence on filtration rate in some marine sponges, with a temperature increase of 6°–12°C as much as quadrupling the filtration rate (Riisgard et al. 1993). Although the sphinctozoans of the Capitan lacked spicules, temperature could have affected their ability to precipitate a calcareous basal skeleton.

The outer shelf deposits just above the part of the reef that we studied in detail contain coated grains, stromatolites, and oriented, articulated crinoids (Kerans and Harris 1993). We interpret this as evidence of current activity, rapid sedimentation, and abundant light. We suggest that these outer-shelf units were deposited above normal wave base. Modern wave base on continental shelves is typically 10 meters (Dietz 1963), and based on calculations involving the size of the basin and the prevailing winds, normal wave base within the Delaware Basin at this time would also have been about 10 meters. This is in close agreement with inferences that outer-shelf sediments were deposited in 12 to 15 meters of water (Hurley 1989, Kerans and Harris 1993). Given this, the outer shelf–reef transition would have to have been at about 15 meters depth or less.

The transition between grains surrounding a few thinly encrusted organisms and true boundstone may mark approximate wave base. The delicate organisms that formed the framework for much of the Capitan reef may only have been sturdy enough to survive in the quiet water below wave base. In our samples, grainy sediments change to boundstones 10–15 meters below the outer shelf–reef transition. Interestingly, the sudden drop in sponge diversity observed in this study occurs approximately 5 meters below this change in rock type.

The depths postulated for major changes in salinity and oxygen levels are much deeper than the observed drop in sponge diversity seen in our samples. L. C. Babcock (1974) documented a gradual drop in oxygen with depth in the Delaware Basin during deposition of the Lamar Member of the Bell Canyon Formation. Salinity might have increased gradually with depth or the change may have been abrupt (Harms 1974).

The depth to the pycnocline is difficult to establish. In modern, open-ocean reef settings, the pycnocline is 30–40 meters depth, but with the restricted circulation of the equatorial Delaware Basin, a change in water composition could have occurred just below the zone of well-mixed water, that is, normal wave base.

In the absence of good circulation, the evaporation and heating of surface water might have produced a layer of warmer, slightly more saline water below the pycnocline. Climatic models suggest that surface water temperatures within the Delaware Basin may have been as high as 40°C during the Late Permian (Moore 1990). Elevated temperature and salinity both reduce the amount of oxygen dissolved in water, so this water mass might also have had somewhat lower levels of dissolved oxygen. Some combination of slightly higher temperature, slightly higher salinity, and slightly lower oxygen could have made the water mass below wave base less suitable for the growth of sponges and many other organisms, resulting in the low diversity we observed.

Below wave base, the water would only rarely be mixed with the surface layer, and would therefore tend to be less oxygenated and stratified. If the change from grainy sediments to boundstones is also related to wave base, then one would expect the faunal change to occur at a depth slightly below the shift in rock type. This is, in fact, what is seen. The drop in faunal diversity is approximately five meters below the depth at which the grainy sediments largely disappear. The pattern of microbial layers also fits this scenario, for layers of microbial micrite were probably related to layers of gelatinous mucilage that would not have withstood wave action. Thick layers of microbial micrite are present below the change in lithology and below the drop in diversity. Although such a relationship between rock type, diversity, and wave base remains speculative, it fits the pattern of sedimentological and faunal changes observed within the middle Capitan.

The genus *Lemonea* dominates our middle Capitan, deep-water samples. The low sponge diversity of these samples suggests that this assemblage represents a community living under stressed conditions. *Lemonea* was apparently able to thrive in conditions that many other Capitan reef sphinctozoans and inozoids could not tolerate.

In this context, it is significant that *Lemonea* becomes the dominant sponge towards what would have been the shallowest part of the Capitan reef, where sponge diversity appears to decrease (Rigby et al. 1998). The last stages of the uppermost Capitan consist of only a few scattered patch reefs (Noé and Mazzullo 1992, Noé 1996, Senowbari-Daryan and Rigby 1996, Rigby et al. 1998). Although the causes of the demise of the Capitan reef are not yet known, it clearly was beginning to wane near the end.

Many of the factors believed to have caused the Permian–Triassic mass extinctions would also have stressed the Capitan reef complex. Possible causes of the mass extinctions include global warming and climatic instability (Parrish et al. 1986), changes in oceanic salinity (Fisher 1964), widespread anoxia (Wignall and Hallam 1992, 1993), increased volcanism (Yin et al. 1992, Holser and Maragritz 1987), and many others. Unfortunately, the relative timing and magnitude of each of these factors is still far from clear. Sphinctozoan sponges had increased in diversity throughout the Permian, but about 70% of Upper Permian genera had gone extinct by the beginning of the Triassic (Rigby and Senowbari-Daryan 1995). Environmental conditions were undoubtedly deteriorating within the Delaware Basin towards the end of the Guadalupian, stressing the organisms that lived there.

Thus, one can envision for the middle Capitan reef an upper, well-oxygenated, normal salinity water layer populated by a variety of different sponges and other organisms, with a deeper, slightly warmer, slightly more saline, and less oxygenated water mass dominated by *Lemonea*. We suggest that the abundance of *Lemonea* in both low diversity situations and the deeper water in the middle Capitan and in the late Capitan reef, indicate that it thrived in stressed conditions that other sponges could not

Species	LC	MC	UC
Ambithalamia n. sp.	x	x	
Amblysiphonella guadalupensis (Girty 1908a)	x		•
Amblysiphonella cf. *A. Merlai* (Parona 1933)	x		
Amblysiphonella sp. 1		x	
Amblysiphonella sp. 2		x	
Amblysiphonella sp. 3	x		
Amblysiphonella sp. 4		x	
Amblysiphonella sp. 5		x	
Amblysiphonella sp. 6		x	
Amblysiphonella sp. 7		x	
Colospongia americana (Girty 1908b)		•	
Colospongia sp. (Senowbari-Daryan and Rigby 1988)		x	•
Corymbospongia permica (Senowbari-Daryan 1990)			•
Cystothalamia nodulifera (Girty 1908a)		x	•
Cystothalamia ramosa (Senowbari-Daryan and Rigby 1988)			
Cystothalamia sp. (Girty 1908a)		•	
Discosiphonella mammilosa (King 1943)	x	x	•
Girtyocoelia beedei (Girty 1908b)		x	•
Girtyocoelia sp. (Yurewicz 1976)	•		
Guadalupia zitteliana (Girty 1908a)		x	•
Guadalupia explanata (King 1943)	x	•	•
Guadalupia? favosa (Girty 1908a)		•	
Lemonea cylindrica (Girty 1908a)		•	•
Lemonea conica (Senowbari-Daryan 1990)		x	•
Lemonea cf. *L. conica* (Senowbari-Daryan 1990)	x		
Lemonea polysiphonata (Senowbari-Daryan 1990)		x	•
Parauvanella minima (Senowbari-Daryan 1990)		x	•
Parauvanella sp.		x?	
Sollosia ostiolata (Parona 1933)			•
Sollasia? sp. (Girty 1908a)			•
Uvothalamia? sp.		x	

• = found in previous studies; x = found in our study to date

Table 2. Sphinctozoan sponge taxa recognized from the Capitan Formation. *Amblysiphonella, Discosiphonella,* and *Girtyocoelia* were previously recognized from the middle Capitan by Kirkland et al. (1993) but were not identified to the species level. These authors also first described *Guadalupia zitteliana* from the middle Capitan. *Amblysiphonella, Cytosthalamia, Girtyocoelia,* and *Guadalupia* were previously recognized from the lower, middle and upper Capitan by Yurewicz (1976) but were not identified to the species level.

tolerate. This, in turn, may explain why it is one of the most abundant sponges in Late Permian reefs worldwide.

Conclusions

Our data demonstrate a dramatic drop in sponge diversity within the middle Capitan reef, 15–25 meters below the outer shelf–reef transition, and a fundamental change in rock type from grainy to cement-rich sediments 10–15 meters below this transition. These represent inferred water depths of no more than 25 to 35 meters and 20 to 25 meters, respectively. In contrast to modern reefs, sponge diversity was highest at water depths of less than 25 meters and lowest at depths greater than 25 meters. The sharpness of this change in sponge diversity, occurring over an interval of less than 2 meters, suggests a significant change in the character of the water mass. This change occurs about 5 meters below the shift in depositional character from grainy to cement-rich sediments, indicating that the faunal turnover may not be directly related to changes in the nature of the substrate. Because the Delaware Basin was equatorial, we suspect that a pycnocline (thermocline?) existed, effectively separating the water masses above and below. The water mass below the thermocline could have been slightly warmer, slightly saltier, and/or contained less dissolved oxygen than the surface waters. Given the environmental sensitivity of most reef organisms, any combination of these factors could have been less conducive to the growth of sponges and many other organisms. Such a subtle change in the character of the water masses across the pycnocline could explain the observed drop in sponge diversity. Unfortunately, whatever the cause of the drop in diversity, it was too subtle to leave a direct record in the rocks. As a result, we are forced to make our best guess.

The abundance of *Lemonea* in low diversity settings, both in the deeper (> 25 m) waters of the middle Capitan reef and in the presumably stressed upper Capitan reef, indicates that it could tolerate conditions that other sponges could not. This ability to survive environmental stress gave *Lemonea* an advantage as the reef system began to wane towards the close of Guadalupian time.

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Note: Because the boundaries of the Middle Permian and Guadalupian have been defined and adopted (see Glenister et al. and Lambert et al. in this volume), the editors treat them as formal units. Therefore, the initial letters of the names and modifying words of the period/system (e.g., Middle Permian), epoch/series (e.g., Upper Guadalupian), and stage/age (e.g., Early Capitanian) have been capitalized in this context. Other geologic units in this paper follow the guidelines provided in Hansen, W. R., editor. 1991. Suggestions to authors of the reports of the United States Geological Survey. 7th edition. U.S. Geological Survey, Washington, D.C.

Chapter 34

Application of the Permian Brushy Canyon Formation in Guadalupe Mountains National Park as an Outcrop Analog for Deep-marine Petroleum Reservoirs

MICHAEL H. GARDNER, Ph.D., is a research assistant professor with the Colorado School of Mines. His studies in sequence stratigraphy, sedimentology, and reservoir characterization have seen him as a frequent visitor to the west and south faces of the Guadalupe Mountains.

It's a pleasure to be here, particularly given all of the wonderful resources that the park has provided for the research that we have been doing over the last four years. I must confess to a bit of embarrassment over the clunky title of my talk, and despite the bad grammar I could have just named this talk, "Why Parks Are." Most of us, particularly those of us who are geologists, understand the geologic heritage that many of our national parks have in terms of scenic splendor and the biological and cultural overlays on that geologic framework that results in our recognition of them as special places. Certainly Guadalupe Mountains National Park fits that, and I think of all the parks we have in the National Park System, Guadalupe Mountains National Park best reflects its geologic heritage. The research that has gone on over the last century in the park is recognition that geologists have understood that we are looking at a very special landscape. In fact, it's a very rare circumstance to preserve a landscape that is 250 million years old and to be able to see it essentially in its undeformed state. That is why we see the special attributes that this park has. That is what has led to the voluminous research, particularly with respect to the carbonate reef. This paper will discuss a feature associated with the reef that is sort of its orphaned cousin. Those are the basin deposits that occur below the reef. I'll present not only the results of the research we're doing, but how we're using that information.

Geologists have long come to the Permian reef. In fact, many of our modern carbonate models owe some lineage back to an understanding of the Permian reef system and how carbonate reefs evolve. The use of that information gets lost in the literature in terms of what was the "crystallizing thought" that led to that concept. Was it an outcrop in west Texas that made me realize the stratigraphic relationship in Abu Dhabi? Or alternatively, just an understanding of the reef itself focuses the emphasis on that geographic position of Earth.

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I'm in the fourth year of a research consortium at Colorado School of Mines that is funded by a variety of oil companies. What is interesting about our research is that none of it is geared toward exploration and development in the Permian basin. I shouldn't say "none of it"—that's a pretty absolute statement—but I would say the majority of people that are interested in our work are interested in its application as an analog to other outcrops and formations around the world. That provides us with an opportunity, and in fact, is an attribute of parks that is commonly not expressed or appreciated as such. Because of the unique geologic circumstance that created this undeformed 250-million-year-old landscape, we now have an opportunity to go out and look at relationships that we will never see in the subsurface. Petroleum geology is essentially a subterranean endeavor and we are only looking at analog data. There was a

Our emphasis is not so much on finding more oil in the Delaware Basin, but trying to understand why the oil that's there is where it is.

gentleman in the audience at a previous talk who asked, "What are those squiggly lines?" Well, that's rock in the subsurface. That is how we have to translate the information we see on the surface to make predictions and to try to understand relationships where we have limited data. People come to outcrops to try to acquire visual images of how rocks are arranged and how the architecture produces different kinds of petroleum systems. In our consortium, as I mentioned, the people—I would like to think—are interested in our research. But in reality, the reason why they fund our work is because these rocks arguably represent the most continuous exposure of deep-water deposits in the world. It is because of that this that people come to this park—to look at the geology of these deep-water deposits.

What I would like to share with you—and this is a pilot run on some new technology—is how we're taking the results from [our studies in] the park and making that information more accessible to geoscientists around the world who are trying to use our information. The reason why there are so many people interested in these types of deep-water deposits is [because] that is where the petroleum industry has shifted the bulk of their exploration effort today. Just an example to emphasize why we need outcrop information: the last lease sale in the Gulf of Mexico—this is offshore—drilled through 1,500 feet of water to hit earth. Just the right to do that cost $20 million. It costs another $20–$30 million to drill a hole. So these people are making $50 million decisions based on those squiggly little lines. People need to have information about how those rocks are arranged. That is probably the most important aspect of an outcrop.

What we are trying to develop here is not only to study these rocks but come up with methodologies of how to portray the data. What we are trying to develop is what I'm calling this "analog catalog." What we are really interested in is how these 250-million-year old rocks relate to all the other deep-water rocks that we have around the world. So here you can see superimposed on the modern and ancient submarine fans of the world, the Permian Delaware Basin shown in here. This represents our study area relative to the size and morphology of all the deep marine fans. For example, this dark blue essentially outlines the Bengal and the Indus fans, and then you can see the Amazon and the Mississippi fans. These are the submarine channels that were mapped by Paul Weimer in the Mississippi fan, which our exploration targets for petroleum geologists. What you can see is that relative to the size of submarine fans, the rocks that we have that compose those geomorphic features is a relatively small volume.

What we want to do then is put that into some kind of geographic and geologic context. So here we're looking at a map. Carlsbad would be at about this position; here's the Guadalupe Mountains, and this is the outcrop belt of the deep-water deposits, which include the Brushy Canyon, Cherry Canyon, and Bell Canyon formations. They are dipping in this direction, reflecting structural dip into the basin. You can see over here, this green is a position of a stratigraphic cross section taken from the outcrop. Now, in addition to this sort of geomorphology, you can see these splotches of colors out in here. The rocks are dipping to the east into the basin, and these same colors are what are producing oil out here in the basin. These rocks are color coded to these oil fields. That is where the oil that is producing out of these rocks occurs in the basin. As I mentioned, our emphasis is not so much on finding more oil in the Delaware Basin, but trying to understand why the oil that's there is where it is. The idea is that a geologist would be able to come in, look at an image of a map showing a particular area, and then be able to come in and look at any other kind of visual image of that particular data set. After all, geology is visualization. It's a visualization science. It's how we visualize geometric arrangements of rock. So I can look at that in a map, or I might want to come over here and look at that in a cross-section view, and I could come in that cross-section view and look at that cross section. So now, this is a cross section taken from the outcrop. What I can see here is where those oil fields are actually occurring within a volume of rock. Each one of those green boxes represents the main hydrocarbon pools of oil that are trapped within these rocks. We basically then take an essentially 3,000-feet section and hydrate it to those key areas that are controlling the distribution of hydrocarbons within the basin fill. We can then go back to the outcrop and try to understand why these different pools are here, why some of them produce more oil than others, and what controls and strategies as a geologist that I would want to use to try to exploit and maximize that particular resource base.

I might want to come back and just compare that cross section to what I saw on the map. The geologist who is working in the North Sea off the coast of Norway may have an idea and want to see if there is anywhere else in the world where that particular geometry or arrangement or attribute may be expressed. If so, what are the issues I need to be concerned with in terms of verifying or testing that particular hypothesis? This is a way in which we can then visualize the information.

We have been working the entire outcrop belt over this area but this presentation is going to be restricted to the work we have been doing in the national park. If we look at the geologic map of the west face, the different colors show the different layers of rock that basically compose the western escarpment of the Guadalupe Mountains. You can see there are some very different changes, some different color patterns that are occurring on that map that I need to understand. For example, why is there this sudden loss of yellow package at this point here? Or why is the brown package pinching out up here in A? What are those relationships and how am I to try to understand that? I can look at that stratigraphy in map view, and I can look at that information in cross-section view. Here is that same rock looked at in a cross-section slice through Earth's surface. What I can see is that some of those pinch-outs are related to these terminations of the strata against this big edge of the reef, the shelf margin of the Victorio Peak. Furthermore, I can look at that relationship and I can see that the geometry is such that there is a lot of relief on that. These orange patterns are not ubiquitous across the cross section. The yellow patterns, which represent sandstones, appear to be somewhat randomly distributed in space through that. What does all that mean? Well, now I have to come back and I have to interpret this information. This is just based on, if we all go out and we look at the west face—and I will focus on this area right in here—and if I come over to that area, that's what I see. For example, that lower sandstone that was pinching out is replaced by another sandstone that steps up higher, and there is another one offset to the right. What this is or what that cross section is, is just basically an interpretation or a way of visualizing this rock architecture. Now I have to understand this. To do that, let's go back to the geologic map. I have to think about: what does this represent in terms of the depositional patterns that occurred 250 million years ago and also the more recent things that have modified to produce this landscape? The first thing I am concerned about is these pinch-outs and what is controlling the orientation of that pinch-out. We would interpret that to represent a series of submarine canyons that basically are overlaid on that outcrop, so if we superimpose those submarine canyons onto the orientation of the outcrop belt, we now have some kind of understanding of those very strange geometric arrangements. For example, in this particular submarine canyon here's the reef trail, the old shelf margin 250 million years ago. Here are a series of submarine canyons that are incised into that reef. And you can see as we move into the basin, they expand as we move away from the canyon head. Well, this is really important, because what it tells me as a geologist is that as I go along the outcrop in [one] orientation, as [if] I was a Permian grain 250 million years [ago], I'm going basinward. I'm moving into the basin, but I'm doing that in an oblique fashion. The sediment is basically coming one way, and I'm going another way. So I need to understand how that geometric change is going to

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What we were interested in, was if we charged this outcrop with hydrocarbons, how much of it are we going to recover? How is it going to flow? Where are we leaving it behind?

affect my interpretation. For example, the body of knowledge we have on sediment body geometry says that bodies will be oriented in this direction and will be shorter in length in this direction. Well, I can use that as a strategy in how I correlate rocks in the subsurface in my subterranean world. I can take this to another level, because what this tells me is I'm never going to be able to go within the same canyon from the canyon head out into the basin floor. I'm going to be able to go into the basin floor along this outcrop, but I'm going to do it in an oblique way. So as I walk along the outcrop, I am going to be going progressively further into the basin, but I'm going to be doing that in a very nonlinear way. So there is the actual outcrop, there is the Permian overlay onto it, and now we can go back to our cross section and now start to look at these geometric arrangements and try to understand them a little better, in terms of why there is this random distribution. I can go so far as to take those different submarine canyons, which show up here, and now compress them into one to give me a visual image of what it would have looked like if I was a Permian sand grain going from the canyon into the basin. I have taken the information from various locations along the western escarpment of the Guadalupe Mountains, and I have collapsed them into a single canyon slope system to try to get a visual image of what this deep-water environment looked like 250 million years ago. I can go into an area and look at a cross section of what that stratigraphy may have looked like. We can see then, an interpretation for that geometric offset in the types of sandstone piles that apparently were chaotic and random in distribution but now, incorporating a little bit of knowledge based on the geology, I can see that there is actually a pattern. There is a pattern whereby older and lower rocks are replaced by younger and higher rocks in a progressive fashion as they step out into the basin. Well, what does that mean? Again, I can come back to my actual rock data, look at my submarine canyons, get back to my geology, look at it in map view or look at it in cross-section view.

The people who are coming out here may be intrigued by these relationships, but what they're really after is how this relates to the subsurface. One of the things we have been doing at the School of Mines is starting to make outcrop seismic models. This is basically the same image that you have looked at here, but converted to how it looks to a petroleum geologist in the subsurface. If you look at this package of the cross section up in this area, we can come over and query the seismic expression of that, and see that there's this dark zone which is basically amplitude reflection packages that are recording the lithologic change between the sandstone and its encasing deposits. So now a geologist can look at this and say that this was the shelf edge of the Gulf of Mexico, and they're looking at seismic data, because that's all we have in a subsurface, this analog data, with the exception of the core hole. They can look at this geometric arrangement and try to understand how that might occur and to also compare to my own data in terms of whether I am seeing a geologically reasonable relationship. So now I want to go in and I want to study what the architecture of that particular reflection package is. So I can go in, back to my cross section, and now I can come in and look at the details of that sand, which is labeled UB3. Now I am at a different scale. I'm now at a scale where this entire body is only 30 meters thick, as opposed to the last scale, where we were looking at approximately 350 meters of rock. What we can look at here is an example of a three-dimensional architecture of a submarine channel complex. You can see the flow. This is a wrap-around cross section, such that this part of the cross section is this segment; this part of the cross section is this segment, and this part of the cross section is this segment. Flow came in one side and out the other, so it's a true three-dimensional depiction of what the architecture of that body looked like. You can see that we have broken out a variety of units in there that basically we call the building blocks. They are the sediment bodies that are stacking to form that larger architecture. Now, we have studied this at a variety of scales. At that scale we are recognizing and resolving bodies on the order of 5–10 meters. In this scale we're resolving beds that are on the order of 50 centimeters. This is an 896 layer reservoir model that we built for this particular outcrop. What we were interested in, was if we charged this outcrop with hydrocarbons, how much of it are we going to recover? How is it going to flow? Where are we leaving it behind? Those are the decisions that a petroleum geologist has to face with only analog data. This would be an example of what that looked like. You might want to say, well, gee, I don't believe you, Gardner. I want to see your interpretation of that. Okay. We can scroll on and look at the outcrop as we go back along this face. As we scroll along the top here, we are basically going to be moving through the outcrop. There's my first view of what we call the distal strike wall. I can then come over to here. This is how the architecture changes as I move across the face. You can see that there are some fairly dramatic changes. Finally, I end up with this very nice cross-section view of a channel-formed geometry pinching out from right to left across the outcrop, and I want to understand exactly what is controlling that particular relationship. I can come in and I can look at an interpretation of that outcrop. There was the photo, and here's the geologist's interpretation of that relationship; I can go back and actually look at that information in a variety of different ways in addition to the photo. There's the interpretation. Now I can come back and look at the details. Now I've gotten down to the scale of architecture.

Here are those squiggly lines someone was asking about. What we're doing is actually collecting squiggly lines on the outcrop so that they can be translated to the subsurface in addition to the architectural information that exists within this overall package of rocks. Now I mentioned that this was part of a bigger model, and that bigger model is this one. So there's the entire 896 layer model. One of my graduate students, Kyle Johnson, went to work for Shell for the summer and digitized this, built this into a reservoir model from which we did fluid flow models. The main goal was to try to understand how those different colors are affecting the movement of fluids through that rock. Our fluid just happens to be one of economic interest.

The point is that in the outcrop in this case, we have collected this tremendous flow of information. I would like to think that the body of work we have done has contributed to the knowledge of the geology in Guadalupe Mountains National Park. What really makes this useful—because after all, no one wants to do science that no one's going to use—is its application to other places. And that's the uniqueness that geologic parks provide us. They are opportunities to look at snapshots of Earth where we only have a limited number of examples where we can see these kinds of relationships. In this particular body, we interpret this—and you can see these gray mudstones—to represent a channel body that was confined by a slump scar on the slope. We think the slumping was very important in terms of forming this master container that produced this very highly connected architecture. It is important because of when we go to places like the Gulf of Mexico where we have these types of images. We now have to understand how the architecture is controlled. What you're looking at here is a diagram taken from some work that Shell did off of a very recent deep-water deposit in the Gulf of Mexico. What you're looking at is the base of that surface and the top of that surface. This information, which is not very well reproduced here, is the actual seismic that was shot over this site. This is the same kind of geophysical information I was showing you in our outcrop seismic model. What's important about this particular system is that what you see here is this mounded topography. That's what geologists would call a channel levy system. With these mounds being the levies that are confining that channelized depression. This is one of the key phrases that deep-water geologists use in terms of trying to convince their manager to drill a $30-million well. "Oh, I've found the channel levee complex." What's important about that is the present surface morphology of that particular fan. You can see even the effect of the Coriolis,

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the rotation of the water in your toilet in terms of the asymmetry of the levee height, due to the Coriolis force of Earth's rotation.

What's important is that, although that's the surface expression of it, here is the control. This is why the sand occurs here and not here. There's a container, and that container is a slump scar, and that slump scar is acting to confine that sandstone body, and furthermore, it's focusing sand to sites farther in the basin where I may want to go to find even better and higher volumes of reservoir quality rock. So it's going back to the outcrop: where we can start to see the importance of these types of features, such as slump scars, to help verify these kinds of images. To help validate, to help hypothesize, and to help test the concepts that were coming up from views based entirely on analog data.

I would like to emphasize that although the national parks provide a variety of opportunities for individuals in terms of their enjoyment of the natural environment, and the cultural and biological diversity that is preserved in these unique places, they also provide geologists—and in some cases such as in this park, perhaps the only place in the world where we can look at these kinds of relationships in three dimensions—an opportunity to get a better understanding and to increase our accuracy and our precision in the pursuit of hydrocarbons in other places in the world. That's a value of national parks that geologists certainly appreciate, but I think the general community also needs to appreciate in terms of what these types of areas offer as benefit to all of us.

Chapter 35

Orientation of Synsedimentary Folds in Carbonate Basin and Slope Deposits, Permian Guadalupian Mountains, West Texas

ALTON BROWN, Ph.D., is a research geologist for ARCO Exploration and Production Technology Company. He has worked for ARCO for the past 18 years. He is the author of sections about toe-of-slope carbonate sedimentation near McKittrick Canyon in Permian Reef Geology Trail Guidebook for Guadalupe Mountains National Park. He has recently studied the middle-lower Bell Canyon toe-of-slope deposition.

What we are going to try to do is look at a park that is under utilized. It's strange for me coming from the oil industry, following Mike Gardner. Here he is predominantly doing all this stuff, or to a certain extent, not only for its academic interest but also for application to petroleum geology. What I'll be presenting actually has very little application to petroleum geology. This is true sedimentology. We have talked a little bit about the paleoecological stuff, the stratigraphic value of the national park. What I would like to emphasize is this other aspect, the pure process of sedimentology, how rocks actually get deposited on a very small scale.

What we are going to do today is look at another type of gravity flow deposit in a deep-water basin. These are referred to as slides. What we are going to be looking at predominantly is the Bell Canyon Formation, but we will look at some of the older areas too. What we are going to do is look at the different types of slide deposits that are there, determine the controls on the different types of slides, and finally look specifically toward the tidal area, which is looking at these basal shear zones in these synsedimentary folds. Here we are again with a cross section, which we have seen a number of times before. This is the one I have assembled, and the reason this one is different from the others is because these are actually measured out: elevation is done and corrected for structural deformation, so these are actual real measured surfaces instead of cartoons. Here is the vertical reef face that we heard about a little bit earlier today on sponge growing. Right here is this little inflection. It's probably going to be something close to sea level, somewhere up there, but we are going to be way down here. Now, notice that I put down here that this is the zone of slides we are looking at. All this other area here, which is called a slope, is dominated by other sorts of mechanisms or serves as a bypass for various sorts of sediments as it is careening outward. What we are going to be looking at is what happens here with this change of flow. Now, as a sedimentologist speaking, whenever we see an inflection, like from topset going to slow, that's a major change in geological process. Likewise, we have this other major change here in which we are going from the slope to flat area. So this is another one of these critical interfaces, very much like the reef up here; we really need to understand why this whole pile of sediments is moving in a seaward direction.

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Well, the main point we are going to talk about is up here at the Lamar, which is the upper part of the Bell Canyon group. The little red dots here indicate other parts of intervals in which we have seen these soft sediment folds. In addition to these, we also have some type of slide deposits. There are three types: Type 1, 2, and 3. Geologists always like to number things before they actually get to naming them.

What we are going to talk about are various technical terms. I am not going to describe these now; we are just going to take a look at the pictures so we can see them. They have slightly different distribution on the slope. Type 1 is higher up on the slope. These are paleoslope angles, starting from as high as 12 degrees down to maybe three degrees. Type 2 picks up somewhere in the three-to-four-degree range, going down to about a one-degree paleoslope. Type 3 gets out here where it's very gentle, less than half a degree. I have not been able to follow it up any shallower than about one-degree paleoslope. We can talk about where the paleoslopes come from.

Type 1. Well, again, as I said, these are steeper dips. Generally, we have throws around 30 to maybe 100 meters or so. There are various types of rocks here, which we will talk about by looking at the photos. Here is an example of one. This is a cliff that occurs on the south side of McKittrick Canyon—everybody has looked at it at various times. This one is actually obliquely done; it's a little bit of a close-up. The interval I like to point out is this very prominent surface, which comes up more or less like so. Notice that beds at the top appear to onlap this. But if you look closely, you will also see that beds below it are truncated at the surface. Now, two things could have happened here. We could have had erosion followed by an onlap-type deposition. But in fact, if you look carefully, you can see that one interval here, the base of this thick bedded unit here, actually corresponds to approximately the surface right there. This is actually behaving like a normal fault. Beds have been offset along this particular surface. Let's take a closer look at the next one up in the section. This is in the cliff at the north side. I didn't climb up the cliff myself; it would be quite an undertaking. Here we see an interval which is about the middle of the Lamar equivalent. Here are turbidites, mostly thin bedded turbidites. Overlying this is a waxy stone, which is equivalent to a carbonate mud, whereas these turbidites are predominantly carbonate sand size material. Up here you can see this very characteristic pinch and swell. This is something that indicates that what's happening is that we are getting thin layers of incipient slumping and sloughing of material down a slope. Because mud slopes generally tend to fail at steeper dips; they tend not to hang around very much.

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Now, the surface in which we are really interested in this type is this surface which comes right down through here. Here is a turbidite bed with a classic sequence. This is a sequence of sedimentary structures geologists recognize, and the whole thing is being cut very nicely at this surface. You can get within an inch of this thing and see no evidence of deformation whatsoever. The reason is because these are sand-sized grains; they don't deform like mud. Also in this surface it's harder to see. Right down here you actually see the exact same thing, in which another bed has been cut and is actually onlapping this surface. So that was our Type 1: no deformation, very plain and flat. This occurs mainly in grain stones.

Type 2. This type is what we refer to as rotational slumps. Instead of having a flat surface, these will have a concave up surface. Now, these occur a little bit lower in paleoslopes, and they occur in mud-rich sediments. In addition to this, we start to see our first evidence of soft sediment deformation; we are going down the slope. Now, this is a little bit hard to see, but this is the exact same cliff on the south side of McKittrick Canyon again. The area we are looking at is where the dips are a little bit steeper. Where we are now is this more gently dipping stuff down toward the base of Lamar, right down through here. This is the underbedded siltstone and limestone through here and this is a very mud-rich interval, which is the lower part of this particular formation. Notice here, you see "funny beds" which are sort of concave upward. If you look at this particular turbidity current deposit right here—I'm sort of tracing it out correctly—you see it actually truncates things. What happened is that this particular interval was an area of rotational slumping, very much like a series of landslides or avalanches, but here it occurred on a mud surface on the bottom of an ocean under about a half a kilometer or so of water. After it happened, turbidites came along and shaved off a little bit of the topography and smoothed it out. This same sort of irregular area extends on beyond the visitor center; it is an area which is sometimes called the mound area on the little cliff in front of the visitor's area and a little bit along the road farther down. Now, if we can't look there, again, we have to go to the other side of the canyon to look in more detail. You can look at this same stratigraphic interval, through which we have measured sections, and see that near the base of these features we are starting to see soft sediment deformation. There is a little recumbent fold. A recumbent fold is a folded rock which is sort of on its side; it's recumbent, it's lying down. Just for a little nomenclature, this is called the fold axial plane, where we sort of connect the bits at the highest kinkiness, and the fold axis is actually the line which goes along the folds parallel to that little bit there that is most kinked. This again is a laminated mud-rich rock, and that's the reason it deforms like this.

Type 3. We see abundant evidence of soft sediment deformation, and these occur predominantly in mud-rich sediments. Type 3 also has a plainer translational glide. It is a very, very flat surface. But here, let's take a look at an example of one of these. Again, this is from a road cut somewhere outside the park, so we are not supposed to talk about it very much. This is the old road cut. But this is just too great to miss. Look down here. Here's the fold; everybody can see this fold, right? Now, this is recumbent again because the axial plane is nearly flat, right? There's the fold axis right there, and we will talk about more of that later. But notice that the rocks that are overlying it are flat. I didn't go quite far enough to show that. This little fold here bends up, but the bed immediately above it just keeps going on and on. Look down here. I think you can see it again. Here beds are flat lying; here they are folded. There's a fold there, and a fold there. Now, the only way geologically you can do this is if you have a surface of dislocation, which we call a décollement surface. It's a French term. And that décollement surface runs right down here and the upper one runs right like so. So we have a zone between two layers in which we have something like a fault that's almost flat, and in between all the sediment is smooshed up and screwed around. What's happening here is we are getting at a very low degree dip, less than a degree dip, very far down on the slope, in which we are getting this messed deformation through here in an otherwise flat bedded unit.

Now, let's talk a little bit about what exactly is causing the different types of deformation fabrics and types of slides. The easiest way to see this is by comparing the paleoslope vs. the sediment type. Paleoslope go from steep-to-intermediate-to very-gentle, and sediments go from muddy-to-grainy. Now, if we start off at the steep dips, where we have muddy sediments, we see this pinch and swell boudinage type fabric, remember? Because we are starting to get these little tiny sloughs coming down the hill. On the other hand, where we have grain deposits, we get these big, flat translational surfaces. Why is this? Grainy bodies tend to be a lot more stable on steep slopes, so they don't deform the same way, but every once in a while they do fail, but as a big, flat surface.

Grainy bodies tend to be a lot more stable on steep slopes, so they don't deform the same way, but every once in a while they do fail, but as a big, flat surface.

Now, on the intermediate slopes, we also have muddy deposits, and here we tend to get rotational slumps. Why is this? This slope is so steep that instead of forming a big, long continuous area, it just wants to slough out on top of itself, and as a result we get a lot of deformation associated with this rotational behavior. Notice in this intermediate area in the grainy strata, we see no apparent slumps. The reason is because at these slope angles, the grainy deposits are perfectly happy to stay where they are. They are not moving by these grainy deposits. Now, whenever we get to the very gentle part that's out in the basin, we have again these flat surfaces, the Type 3, but again, we are getting a lot of sediment deformation and likewise as before, with the thin grainy beds out there we see no evidence of deformation. Now, let's talk a little bit about deformation types and then we will get to the orientation part, which I think is very interesting.

First, at the rotational slumps, we have various sorts of mud and remolded sediments. These are all deformed and redone. We have some disorganized soft sediment folding but also we see that concentration of deformation occurs mainly on the low angle part, so for example, if we are going out again to look at the steep dipping part along the drive to the visitor center, we don't see deformation there, we see it at the bottom part, where it tends to flatten out. Now, a translational glide is what we saw up on the slope. We had the grainy fabrics with almost no deformation at all. That would be very hard to identify unless we have a really excellent outcrop, as we do here in McKittrick Canyon. Where we do see these things, they are referred to as a basal shear zones. This develops in muddy fabrics. This particular fabric is predominantly dominated by recumbent folds and very commonly we have at least one, and usually two, décollement surfaces and sometimes even more than this within it.

Basically, we have a very unique situation. That is the fact that we have an extremely well-constrained paleoslope.

So, now let's talk a little bit about orientation of these folds. I will finally give you the title of it, and this is what I spent most of my time on, on the poster and the other presentation. Basically, we have a very unique situation. That is the fact that we have an extremely well-constrained paleoslope. This reef was exposed a long distance. We have a slope strata through here, so we know which way is down dip during deposition, and that's toward the base and all those arrows pointing through there. Well, it turns out that this allows us to do very accurate comparisons between various paleoslope indicators, which we can see on an outcrop scale, compared to the real paleoslope we know is there. So we can double check and make sure that the things we think are playing downslope really do indeed point downslope.

Okay, the other thing I should point out here is that here I think we really do tend to have a slope apron at the time of Lamar deposition rather than the channel system, so we really do have a constant slope of this area. And, of course, relatively undefined sections we all know. Now I'm pointing out this other soft sediment recumbent fold from down the outcrop, only this one is messed up just a bit more, and you can think about this for your amusement and entertainment, but let me just show you what's happening through here. You have folds that come around like so; here's another one that comes around like so, bend up like so and comes back down like this. These are refolded recumbent folds, but they are called coaxially deformed, meaning they are folded around the same fold axis. Now, if we were to go through here and measure all these orientations, all the fold axes are still pointing the same direction. And what direction is that? Well, here we see it. This particular old bar diagrams is called a rose diagram; what this shows is the orientation of the various fold axes. Now, north is that way, of course, and south is down here. This dashed line here is basically the strike of the Tansill shelf edge as defined by the outcropping reef. Here is the orientation of the axis. It's symmetric because we don't know whether it's pointing up or down. Notice that the axis is almost perpendicular to the shelf edge.

Now many people imagine a landslide or things like this as being some big bulldozer pushing down, and as a result of this, you expect sediments to sort of pile up in front and form an axis that's more or less parallel to the strike instead of parallel to the dips. The question is: how do we get these things pointed in a down-dip direction? The answer required coming back to look at these sediment fabrics. This is something that is called progressive deformation. This is where a rock has not just a single period of folding but continues to be folded through some geologic period of time that may be short or may be long, but as a result it has a strained history. What happens in this case is one initially forms what is referred to a buckle fold, which is the bulldozer-type effect in which we get things parallel to the strike, but as we continue to deform, various parts move down the slope faster than others, because of these décollement surfaces, and as a result, the fold gets rotated into a down-dip direction, and the fold axis goes from a more vertical position to a flat position. This is called progressive deformation, and as a result of this, we rotate the axes around so that they are now pointed in a downslope direction at the same time that the axial planes go from almost vertical to flat. So, basically this is something that is different from things that have happened in the past. In the past, structural geologists have gone to these hugely deformed areas at continental margins, trying to guess which way the fold axes are telling them the paleoslope is. They don't have an independent way of telling it, so as a result there is quite a bit of literature, but most commonly we think about this bulldozing argument up through here. However, here we clearly have this paleo dip orientation. And the answer actually was already worked out some time back—I didn't realize this until after I got fairly far along here. These guys didn't know the exact slope, either, but they recognized the fact that we had progressive deformation. Basically, here we have the same argument again, and this basically proves it. Here we have a case where we can actually document this process occurring.

So to conclude, basically the study here demonstrates this particular model, a Ferrell and Eaton 1987 model. It really does work. We see progressive deformation; we can prove it here because we know the paleoslope orientation. We also can demonstrate here that the slide type is controlled by both paleoslope and sediment type. There has been a lot of discussion about what actually controls different deformation mechanisms. The other thing we can say here is that basically the slide type also controls the type of deformation we see associated with these soft sediment things; in particular, the concept of the basal décollement developing with an upper and lower décollement surface, so we can have this sort of rotation of slides into downslope directions.

Finally, of course, I would like to finish by acknowledging the National Park Service for allowing me to look at their rocks. I should say that no rocks were harmed during the purpose of this particular operation. This is one which doesn't appear on your records because no samples were collected.

Chapter 36

Lacustrine Paleoenvironments in the Trans-Pecos Closed Basin

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Introduction

The last glacial maximum (LGM) in the intermountain western North America was a period of cooler temperatures and increased effective moisture and runoff; these cooler, mesic (so-called pluvial) conditions were accompanied by the formation of lakes in what Currey (1994a) terms "hemiarid lake basins." He defines these lake basins as being both topographically and hydrographically closed, with tributary areas being in a water-surplus state in the basin highlands and in a water-deficit state in the basin lowlands. Within each basin, the boundary between zones of water surplus and zones of water deficit is what Currey (1994b) calls the hydroclimate equilibrium line altitude (HELA). For lakes to form and persist in these basins, the cumulative annual water budget must be positive, such that precipitation must be greater than or equal to potential evapotranspiration.

This paper presents and examines the geomorphic and sedimentary evidence of late Pleistocene paleolakes in the Trans-Pecos closed basin and the implications of the timing and duration of these lakes during the LGM.

Paleolake studies: western North America

Reconstructions of late Quaternary climates in the intermountain region of western North America are based on the interpretation of a spatial and temporal aggregation of proxy evidence and morphometric (e.g., hydrometric, limnometric, glaciometric) data. Evidence for the presence of contemporaneous permanent or persistent (102 to 103 year duration) lakes over a wide range of latitudes and elevations (e.g., paleolakes Bonneville and Lahontan) (Benson et al. 1990) and under different basin configurations with respect to tributary characteristics or catchment geometry (Currey 1991, Enzel et al. 1992), allows for a generalization of climate conditions at a broad spatial and temporal resolution. However, this same evidence shows that late Quaternary climates in the region were not homogeneous, but demonstrated a spatial heterogeneity influenced by local responses to broad climate forcing (Mock and Bartlein 1995); this spatial heterogeneity reflects the geographic factors (e.g., latitudinal extent and topographic range) that influence the temporal and spatial variability in a palaeolake basin's response to climate change.

Hemiarid basins that are situated along a climate boundary zone or threshold, separating states of hydroclimatic equilibria, exhibit more dramatic response to changes in hydroclimatic variables than basins situated away from the climate boundary. It is the capability of these basins to change rapidly between equilibrium states, in response to changes in basin conditions that favor their utility as potential high-resolution records of abrupt climate change.

Trans-Pecos closed basin: environmental setting

The Trans-Pecos closed basin is an internally drained, hydrographically closed region bounded by the Guadalupe and Delaware mountains to the east and the

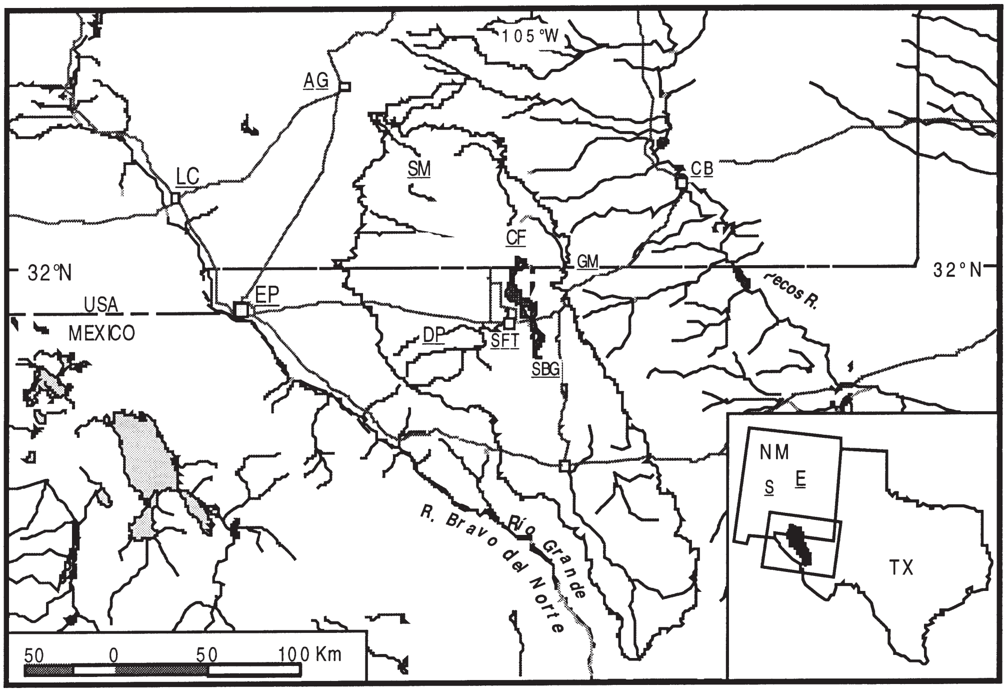

Figure 1. Trans-Pecos closed basin regional setting. Underlined abbreviations refer to toponyms: EP = El Paso, SM = Sacramento Mountains, AG = Alamogordo, LC = Las Cruces, CF = Crow Flats, GM = Guadalupe Mountains, DP = Diablo Plateau, SFT = Salt Flat, SBG = Salt Basin Graben, CB = Carlsbad, S = Lake San Agustin, E =Lake Estancia. From Wilkins 1997.

Diablo Plateau to the west in far west Texas and south central New Mexico (Figure 1). It encloses over 22,000 square kilometers in Texas and New Mexico and includes the western portion of Guadalupe Mountains National Park. Elevations range from 2,918 meters on Sacramento Peak, New Mexico, to 1,087 meters at the deepest point in Salt Basin, a northwest-southeast trending half-graben located approximately 160 kilometers east of El Paso.

Modern climates and biomes in the study area vary from arid upper Chihuahuan desertscrub at lower elevations to humid, mixed conifer forests (*Pinus-Picea-Abies* sp.) at higher elevations (Tuan et al. 1973, Van Devender et al. 1984). Temperatures at Salt Flat, Texas, located near the floor of Salt Basin (elevation 1,100 m), range from warmest-month mean of 27°C in June and July to a coolest-month mean of 6°C in January, with a mean annual temperature of 17°C (Griffiths and Bryan 1987). Mean annual temperatures at higher elevations in the Sacramento Mountains are estimated to be approximately 5°C based on local climate data applied to a mean annual environmental temperature lapse rate of 7.2°C/1,000 meters (Van Devender et al. 1984).

Average annual precipitation totals range from 280 millimeters at Salt Flat to more than 760 millimeters at Sacramento Peak in a summer maximum precipitation regime (Tuan et al. 1973). Mayer and Sharp (1998) show precipitation has a strong dependence on elevation in the basin. High magnitude storms sometimes result in shallow flooding of portions of the floor of Salt Basin; these inundations seldom persist for more than a few weeks under the high modern evaporation rates, estimated to average between 175 and 200 centimeters per year on the basin floor (Bjorklund 1957, Kohler et al. 1959).

Four major (i.e., > about 1,500 km^2) and numerous minor catchments direct runoff into what was the inundated area of Salt Basin (Figure 2). Analysis of catchment parameters by Wilkins (1997) reveals that the five largest catchments are very similar, and mean elevation is the characteristic best used to distinguish between catchments. Using this param-

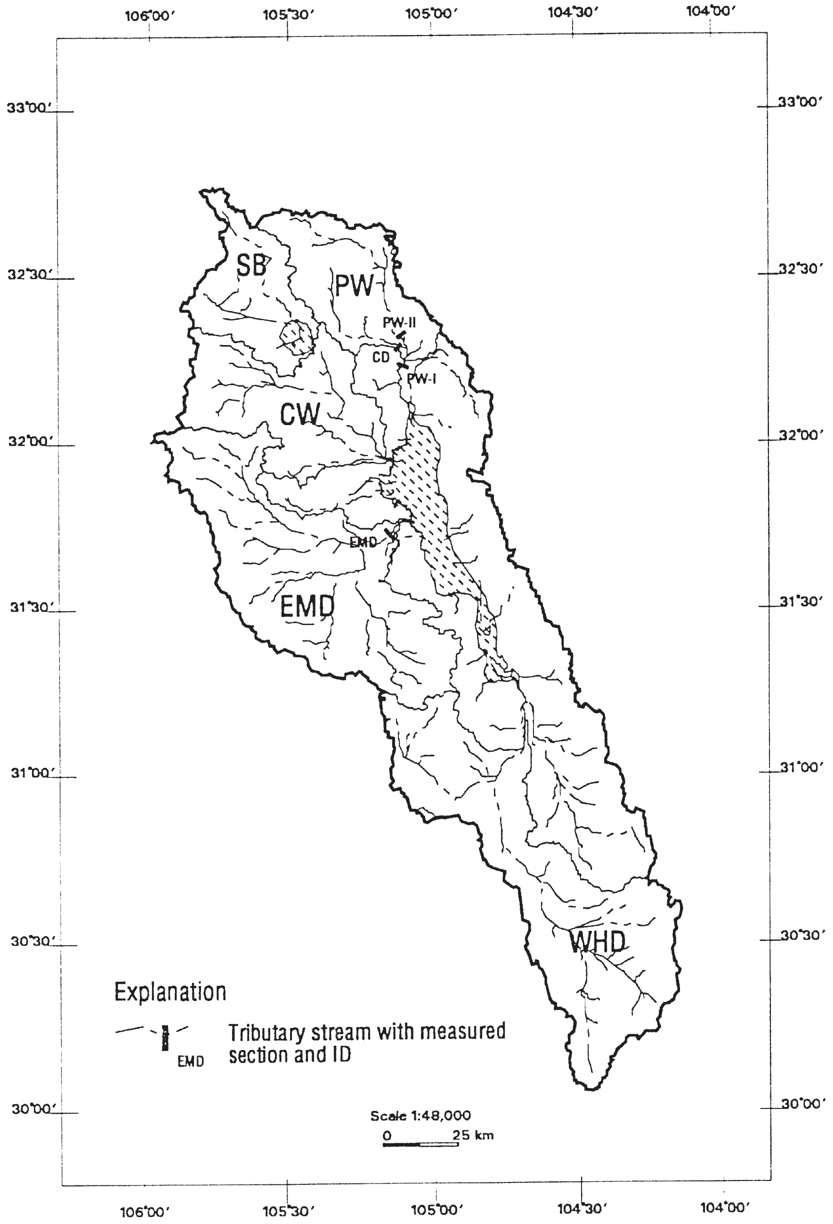

Figure 2. Catchment boundaries for the five largest catchments in the Trans-Pecos closed basin. Catchments are identified by their initials: EMD = Eight Mile Draw, CW = Cornudas Wash, SB = Sacramento River Basin, PW = Piñon Wash, WHD = Wild Horse Draw. Hachured polygons represent the maximum extent of paleolakes in the basin. Produced from USGS 1:250,000 digital elevation model data.

eter, the catchments are categorized as belonging to one of two hydroclimatic regions: a northern highland catchment region (mean elevation > 1,600 meters) or a southern lowland catchment region (mean elevation < 1,600 m) (Wilkins 1997).

The Sacramento River system terminates in a nested closed basin with a local base level elevation 200 meters above the floor of Salt Basin. There is no evidence of channel incision, indicating overflow, at the subbasin threshold, so any runoff generated by this catchment is contained within its boundaries and either lost to evapotranspiration or transferred through the groundwater system into the floor of Salt Basin (Wilkins 1997).

No perennial surface water reaches the floor of Salt Basin graben, but the graben does receive significant groundwater contributions from the Permian Bone Spring Limestone underlying the Sacramento and Guadalupe mountains

(Bjorklund 1957, Boyd and Kreitler 1986, Mayer and Sharp 1998). Sediment sequences filling the graben culminate in modern playa evaporites, indicating hydrographic closure. Groundwater levels in the Crow Flats area (Figure 1), near the northern end of the graben, are very close to or at the surface of the playas and include contributions from both valley fill alluvium and Bone Spring Limestone (Bjorklund 1957). Expressions of surface water interception are visible as depressions and sinks on the Diablo Plateau to the west and the Sacramento Uplands and the Crow Flats areas to the north. Modern groundwater discharge from the Bone Spring Limestone into the Salt Basin alluvium is probably less than 100,000 acre feet (2,800 m^3) per year, roughly equal to the modern recharge (Bjorklund 1957).

Trans-Pecos closed basin: LGM paleolake record

The Trans-Pecos closed basin contained deep lakes at various times during the LGM, much like other hemiarid basins in western North America. The basin terminus, Salt Basin, was the site of Lake King, the name given to the succession of lakes that formed during the late Pleistocene (Miller 1981). The descriptor "deep" (i.e., depth > 2 m) is used here relative to the long-term range of lake depths in this particular lake basin.

Paleochannels, shorelines, and laminated sediments are evidence of periods of increased effective moisture in the region. The laminated sediments are visible in erosional remnants of breached lake floor sediments (locally known as "islands") interspersed between the evaporite-encrusted playas that occupy the modern Salt Basin. Fragments of shorelines from Lake King are preserved around the periphery of Salt Basin positioned 8 to 14 meters above the modern basin floor (average elevation 1,100 m). Depositional shorelines have been identified for both Lake King (i.e., Salt Basin) and Lake Sacramento (Figure 2) (Wilkins and Currey 1997).

Wilkins and Currey (1997) develop a model limnograph for Lake King (Figure 3), inferring changes in lake surface elevations from changes observed in the sedimentary record. Maximum elevations of the model hydrograph lake cycles are reconstructed from the paleolake geomorphic record taking into consideration the elevation, superposition, and relative preservation of depositional shoreline segments (Currey 1994, Sack 1995).

In the Lake King model, transgressive and regressive phases of paleolakes are reconstructed from sequences of contrasting sedimentary environments ob-

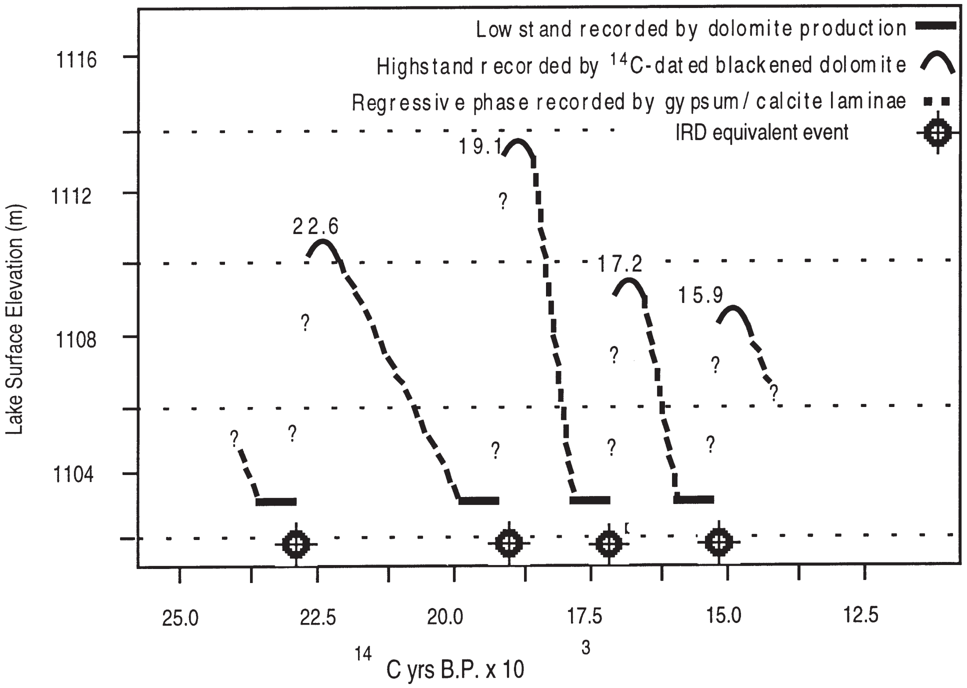

Figure 3. Lake King model hydrograph denoting shifts between states of basin hydroclimatic equilibria, with respect to time and North Atlantic IRD events (Bond and Lotti 1995, Wilkins and Currey 1997).

served in the lacustrine stratigraphy. Lacustrine lowstands, represented by "troughs" in the model limnograph, were accompanied by higher rates of evaporation and an increasing magnesium:calcium ratio in lake waters that resulted in the deposition of dolomitic sediment layers (Friedman 1966). Climate changes marking the onset of mesic LGM conditions were accompanied by increased inflows of fresh water and rapidly rising lake levels. Stratification of the limnia through rapid freshening and deepening of the water column was accompanied by formation of anoxic bottom conditions. Subsequent anaerobic bacterial decomposition of iron oxides within the dolomitic layers resulted in Fe_2S darkening of the dolomite, creating the characteristic "black mats" (Wilkins and Currey 1997). Samples of the organic material found in these sediments have been radiocarbon-dated (Figure 3) (Wilkins and Currey 1997), providing ages for four abrupt climate changes during the LGM. Locally, an apparent uncomformity between the oldest and the youngest black mat is evidenced by their close stratigraphic proximity (4 cm). This suggests Lake King underwent at least one phase of complete desiccation or subaerial exposure accompanied by erosion of lacustrine sediments.

The sharp contacts between the dolomite layers and the overlying sediments suggest that the onset of mesic conditions were abrupt. After conditions supporting lacustrine environments were reestablished, lakes are thought to have reached their maximum elevation early in their cycles, as indicated by the "peaks" in the limnograph. During these cycles, lakes were maintained in a quasi-steady state of annually fluctuating water levels and chemistry that are represented by varve-like evaporite couplets of organic-rich calcite layers alternating with gypsum-dominated sediment layers. The calcite layers are interpreted as annual cycles of seasonal increases in calcium, total alkalinity ($HCO_3^- + CO_3^{2-}$), organic matter, and pH driven by early season runoff. Late season lake evaporation resulted in depletion of total alkalinity levels (with respect to SO_4^{2-}) and precipitation and deposition dominated by gypsum (Wilkins and Currey 1997).

Examination of playa floor exposures revealed packages of more than 100 of these couplets, giving an indication of the duration of these lakes. The absence of codepositional disturbance in the couplets indicates that they were deposited and buried in deep water, low energy conditions; absence of in situ postdepositional disturbance of the couplets through displacive transformation of evaporites implies that the couplets were buried sufficiently deep as to preclude this. The number of seasonal cycles in the packages of sediments suggests that the return to moisture-deficit conditions was gradual, culminating in high rates of evaporation from shallow bodies of water that resulted in the formation of the dolomite.

Trans-Pecos hydroclimates: factors and responses

Mifflin and Wheat (1979) infer dual hydroclimates for hemiarid basins in Nevada, similar to the one reconstructed here for the Trans-Pecos basin, basing their results on mean annual temperature and precipitation trends at several climate stations. Their data indicate that stations at higher elevations (with correspondingly cooler temperatures) have significantly greater precipitation than the intermediate and lower elevation sites; the analogy is the upper elevation sites represent tributary conditions and the lower sites represent lake conditions. Isohyetographs of New Mexico and Texas support a similar relationship in the Trans-Pecos region (e.g., Tuan et al. 1973).

The patterns in the model limnograph for Lake King suggest that runoff from the catchments to the inundated area were HELA-controlled; that is, a catchment's ability to contribute to the inundated area of the basin varied with the position of the HELA. Highstands occurred only when conditions improved such that the HELA lowered sufficiently in order to include the larger, but lower elevation, catchments, resulting in increased runoff and higher magnitude stream discharge to the terminus. This model is supported in part by the absence of well-developed channels terminating at the level of the modern playa. The channel systems for Eight Mile Draw and Cornudas Wash both terminate near the elevation of the Lake King maximum highstand, suggesting a correlation between improved hydroclimatic conditions in those catchments and increases in lake surface elevation.

Climatic conditions in the Trans-Pecos closed basin during the LGM are reconstructed for this study by extending the findings of other researchers in the region. A study of periglacial features (Blagbrough 1991) in the Capitan Mountains of New Mexico (33.75°N, 105°W) places the LGM elevation limit of permafrost (MAT 0°C) at approximately 2,440 meters. Taking this as the permafrost isotherm surface altitude (PISA), and applying Péwé's (1983) temperature gradient (80 m/1° latitude) places the PISA at approximately 2,520 meters in the Sacramento Mountains (summit 2,918 m) and 2,580 meters in the Guadalupe Mountains (summit 2,667 m) 45 minutes latitudinally south of the Sacramento Mountains; using these parameters, the Guadalupe Mountains would have been the southern limit of alpine permafrost in western North America. Assuming the mean annual environmental lapse rate of 7.2°C/1,000 meters in the adjacent Otero basin to the northwest (Van Devender et al. 1984), the mean annual temperature at Salt Flat, Texas, (elevation 1,185 m) would have been lowered to approximately 10°C, roughly equivalent to modern conditions in the Sacramento highlands to the north.

Temperature, among other variables, is a major factor influencing rates of evaporation from open water surfaces (e.g., Tuan et al. 1973, Mather 1985). Other studies on climate factors affecting lake level variations (e.g., Mifflin and Wheat 1979, Benson 1981, Hostetler and Benson 1990) also recognize the importance of this relationship, using it to minimize the importance of increased precipitation as a factor in the persistence, if not formation, of lakes in the Great Basin during the LGM. Street-Perrott and others (1989) present a similar argument that even without a significant increase in precipitation, higher lake levels could have been favored by increased cloud cover and cooler temperatures in the summer season (i.e., period of greatest evaporation).

The impact that cooler LGM climates had on precipitation and runoff is uncertain. It is probable that snow cover in the basin highlands would have persisted into, and possibly through, the summer at the highest elevations, thereby extending runoff from those areas. Another result of lower temperatures would have been to reduce the importance of evaporation as a limiting factor, or hydroclimatic threshold, in generating runoff: with lower background evaporation rates, the position of the HELA surface would then have become precipitation limited. Increases in cloud cover and accompanying precipitation would have been dependent on timing, sources, and direction of flow of atmospheric moisture.

LGM teleconnections

Climate simulations of North America during the LGM show that the areal extent and height of the Laurentide Ice Sheet split the 500-mb polar jet stream into a northern, polar branch and a southern branch (Kutzbach et al. 1993). A high pressure cell and the accompanying anticyclonic flow originating from the ice sheet displaced the southerly branch of the jet by as much as 6° to 20° equatorward; modern mean winter position of the polar jet along the west coast is 42°N and summer position is 58°N (Street-Perrott et al. 1989, Hostetler and Benson 1990). This displacement brought increased winter precipitation, with estimates ranging from +5 to +35 percent (Dawson 1992), to intermountain western and southwestern North America. This increased winter precipitation, coupled with increased summer cloud cover, reducing local evaporation while increasing effective moisture (Hostetler and Benson 1990), corresponds well with the LGM high lake levels in the Great Basin (Mifflin and Wheat 1979).

The position of the LGM subpolar winter storm track, with the accompanying moisture enhancing and energy-reducing cloud cover it provided, was critical as it provided the increased moisture required to initiate lake cycles in western North American hemiarid basins.

Locations of prevailing LGM winter storm tracks (i.e., CCM January) at the longitude of the Trans-Pecos region are poorly constrained, a result of the coarse resolution of the climate models. Evidence presented in this paper, however, indicates that the tracks remained to the north of the region. Allen and Anderson (1993) invoke an equatorward shift to place the storm track over the Lake Estancia basin (35°N, 106°W) at 19,770±160 radiocarbon-years-before-present (^{14}C yr BP), and again at 13,700±105 ^{14}C yr BP, to explain the high lake levels that formed abruptly in that basin. Rapid freshening events similar in amplitude and corresponding to the Lake King highstands (within the 1-sigma error of the black mat ^{14}C dates) also have been identified by Phillips and others (1992) in the Lake San Agustin basin (34°N, 108°W).

The mechanism most likely to have driven these changes in the position of the storm track was a periodic strengthening of the Laurentide high pressure cell. Under this model synoptic pattern, the resulting increase in anticyclonic wind flow would have displaced the storm tracks equatorward from their intraglacial mean positions as far south as the New Mexico and Texas (low latitude) lake basins.

The timing of these episodes of latitudinal shifts in the storm tracks corresponds to periods of cooling in the North Atlantic marine and Greenland ice records (Bond and Lotti 1995). Mikoljewicz and others (1997) report similar conditions have been modeled for the North Pacific Ocean, suggesting that the effects of the North Atlantic–North Pacific teleconnections may extend into western North America. Most studies of these northern-hemisphere cooling events focus on the marine or Greenland ice records. Ongoing studies are searching terrestrial records for indications of these events as evidence of their global impact (Broecker 1995). Phillips and others (1994) raise the question as to a causal relationship between fluctuating Greenland ice temperatures and expansion and contraction of Searles Lake (36°N, 117°W), suggesting that six lowstands between 33,600 and 26,100 ^{14}C yr BP were synchronous with Greenland interstadial episodes. Oviatt (1997) notes a similar relationship between the onset of North Atlantic warming and five regressive oscillations in Lake Bonneville (41°N, 113°W) between 21,000 and 13,000 ^{14}C yr BP. In both cases, a teleconnection is implied between changing paleolake levels and changes in temperatures over the continental ice sheets; this suggests that the mean positions of the winter storm tracks over western North America ranged between more southern positions during cooling events to more northern positions as temperatures over the continental ice sheets rose.

The timing of the onset of lake cycles in Lake King corresponds well, but not perfectly, to those cooling events and highstands identified in paleolakes San Agustin (fig. 35 in Phillips et al. 1992) and Estancia (Allen and Anderson 1995); discrepancies between the reported timing of these events in Lake King and New Mexican hemiarid basins result from the expected lag effects produced by differences in latitude as the mean storm track shifted. That the onset of transgressive events corresponds with the latter stages of the North Atlantic cooling events, coupled with the short tenure of these lake cycles, implies that full pluvial conditions in the basin were restricted to only the most extreme equatorward shift in the storm track.

Summary and discussion

The record of lake cycles in the Trans-Pecos closed basin indicates that conditions favoring formation of deep-water lakes varied with time. The formation of Lake King seems to have been a result of the basin to generate sufficient runoff;

persistence of lake cycles benefited from, first, lower temperatures and evaporation rates and second the ability of the Sacramento Mountains (northern basin highlands) to generate runoff for the Sacramento River–Lake Sacramento and Piñon Wash systems, which operated as groundwater transfer nodes to Salt Basin.

Water transferred in this fashion is protected from the evapotranspiration that limits catchment contribution to the inundated area of the terminal basin (Langbein 1949). Analogous to a leaky toilet, the superelevated (with respect to the terminal basin floor) piezometric surface resulting from groundwater discharging into Salt Basin (the bowl) sustained in large part by the influent discharge from the Sacramento subbasin (the tank), reduced lake area variability for Lake King and, benefiting from lower evaporation rates, was able to support small, shallow lakes between highstands.

Hydrologic analysis of the five largest tributaries, including the Sacramento River and Piñon Wash systems, reveal no major differences in catchment parameters save for area and range of elevations. Absence of continuous lacustrine sedimentary records indicates that the tributaries were ineffectual in generating prolonged and sustained runoff and discharge into the inundated area. This implies that the mean lower position of the HELA was limited by precipitation to an elevation somewhere above the runoff generating hydroclimatic threshold area; as hydroclimatic conditions improved (i.e., as available moisture increased), the HELA descended until the area contributing runoff (that area above the HELA) reached that threshold.

The term "quasi-pluvial" is used here to describe hydroclimatic conditions in hemiarid basins—where background evaporation rates were low as a result of lower LGM temperatures yet long-sustained surface-water runoff contributions persisting on a time scale of 100 to 1,000 years (Currey 1994b), were absent or discharge volumes were insignificant in terms of impacting palaeolake volume. Background LGM rates of evapotranspiration were low and relatively time invariant, but availability of moisture at levels great enough to generate runoff was a function of extrinsic hydroclimatic factors other than temperature. Only when those factors were favorable did moisture availability in the basin increase to a level that resulted in rising lake events; this episodic modulation of moisture availability in hemiarid basins provides the rationale behind the description of quasi-pluvial.

During the LGM, moisture was supplied to western North American hemiarid basins by winter storm tracks that were positioned several degrees south of modern position. The variability of available moisture in those basins was a function of latitude; basins farther north benefited from a more reliable source and amount of moisture, a factor reflected in higher pluvial hydrologic index values (e.g., Mifflin and Wheat 1979). Basins such as the Trans-Pecos closed basin at the extreme southern range of the storm track lacked this constancy, and the lacustrine sedimentary record reflects this.

Much like the polar ice record in Greenland that provides a record of rapid climate shifts—acting as what Taylor et al. (1993) term a "flickering switch"—the lacustrine sedimentary record provided by these storm-track margin basins may reveal the effects of what have been largely described as high latitude climatic events. Abrupt climate changes that led to equatorward shifts in the storm tracks are recorded in the lacustrine sedimentary records along meridional alignments of quasi-pluvial paleolake basins. As data on lake cycles are refined, these wide-ranging arrays of lake basins may prove useful as long transects of paleoclimate-change records, with distance of the basin from mean storm track positions and persistence of lake cycles interpreted as measures of global climate change intensity.

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Chapter 37

Fossil Assemblages of Mollusks as Indicators of Past Communities in the Guadalupe Mountains, Culberson County, Texas

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Introduction

Environmental changes in North America from the Pleistocene to the present have affected the extent and composition of communities. Within the Guadalupe Mountains, evidence of environmental change has come from studies of mammal remains from cave deposits, pollen profiles, and plant macrofossils from packrat middens (Van Devender, Spaulding, and Phillips 1979). Perhaps the most useful or direct evidence of plant community change has come from studies of packrat middens. The middens are created by the activities of woodrats (*Neotoma* sp.) and contain plant remains from the immediate vicinity of the nest, which are cemented together by urine and preserved in arid environments by drying. Such deposits are easily dated by radiocarbon methods. Packrat midden studies may be limited by scarcity or absence of rock outcrops with dry fissures conducive to midden preservation. Such outcrops are lacking on lower mountain slopes in the Guadalupe Mountains. Reconstruction of past plant community changes on such slopes have to be inferred using models of life zone depressions or from other indirect lines of evidence. Assemblages of fossil mollusks offer one such line of evidence that can be used to interpret past changes.

Mollusk shells preserve well in sediments, especially those derived from limestone substrates. In the Franklin Mountains fossil assemblages have been recovered from buried talus or colluvium that has been exposed by arroyo cutting as well as from soil accumulations (Metcalf and Johnson 1971, Worthington and Metcalf 1998). Metcalf and Fullington (1976) listed species in a fossil assemblage occurring in Pine Spring Canyon as the type locality of *Ashmunella nana*. Shells have generally been destroyed in fluviatile sediments deposited by currents of sufficient strength to transport gravel. Herein we report on two mollusk assemblages from shallow soil accumulations on the bajada on the east side of the Guadalupe Mountains where studies of middens, pollen, and faunal remains have not been done.

Methods

Two assemblages of mollusks were collected near Frijole Ranch in Guadalupe Mountains National Park at 1,667 meters elevation. The first was collected about 100 meters southwest of the ranch house from a road cut near the parking area. From 11 to 12 kilograms of soil substrate at one-meter depth, 466 shells of 11 species were collected (Table 1, Site 1). The second assemblage was recovered from drift deposited on the hiking trail 75 meters north of the ranch house. From two business envelopes full of drift material, more than 200 shells comprising 19 species were obtained (Table 1, Site 2). The small arroyo was explored to locate the source of the shells. It was determined that the shells came from within 100 meters of the trail where the arroyo had cut 1.0–1.5 meters into soil substrate. The arroyo was found not to originate from the roughland higher elevations of the mountains some distance farther to the west, so that drift shells clearly seem to be of very local provenance. Shells were separated and identified in the laboratory and organized into collections of the Laboratory for Environmental Biology at the University of Texas at El Paso and of Guadalupe Mountains National Park.

Discussion

The present habitat around Frijole Ranch is an open juniper woodland and grassland (Genoways et al. 1979). This is in the upper Sonoran zone, which is known to be relatively depauperate of snails (Metcalf and Smartt 1997). Only *Gastrocopta pellucida* is known for certain to live in the area today, but other species are expected including *Hawaiia minuscula*, *Glyphyalinia indentata*, *Helicodiscus singleyanus* and *Thysanophora hornii*. The fossil assemblages are rich in species, many of which seemingly cannot survive in the area today. Assemblages of mollusks contain species with different ecological amplitudes.

Information about the present distributions of the species in the Guadalupe Mountains that were also found in the fossil assemblages is included in Table 1, and is from the work of Fullington (1979). It is clear that many of the species found as fossils survive today only at considerably higher elevations. Others are more generally distributed, reaching lower elevations. Interpretations of such fossil assemblages generally focus on where one would have to go today to find the most species shared with a fossil assemblage of interest. One can then infer from the extant habitat what the past environment might have been like. Problems that hamper such interpretations include the lack of radiocarbon datable organic matter, possibility of import from other habitats, and confounding effects of suitable microhabitats. The age of the fossil assemblages treated here is not known. Sediments at Site 1 represent a shorter interval of time than those at Site 2, the latter spanning up to 1.5 meters of soil accumulation, and obviously including some Holocene material along with that from older, Pleistocene sediments. The fauna seems to have lived at a time when the environment was cooler and wetter. This strongly suggests a time in the late Pleistocene, although Site 2 also seems to include shells from Holocene sediments. Evidence that the assemblages are not of greater

Table 1. Gastropods recovered from two sites near Frijole Ranch (1,667 meters), Guadalupe Mountains National Park, with notes on their present distribution in the mountains from the work of Fullington (1979).

Species	Site 1	Site 2	Notes
Cionella lubrica	x	x	General over mountains where leaf litter occurs
Discus whitneyi		x	No living populations known
Euconulus fulvus		x	1,920 meters
Gastrocopta armifera armifera	x	x	McKittrick Canyon
Gastrocopta contracta		x	1,920 meters
Gastrocopta pellucida		x	Found near the sites
Gastrocopta pentodon	x		1,890 meters
Gastrocopta pilsbryana		x	1,981 meters
Gastrocopta procera	x	x	Upper Dog Canyon at 1,890 meters
Glyphyalinia indentata		x	General over mountains
Hawaiia minuscule	x	x	General over mountains
Helicodiscus eigenmanni		x	1,981 meters
Helicodiscus singleyanus	x	x	South McKittrick Canyon at 1,615 meters
Holospira montivaga	x	x	1,524 meters
Nesovitrea hammonis		x	1,920 meters
Punctum minutissimum		x	2,011 meters
Pupilla blandi	x	x	McKittrick Canyon drift
Succinia sp.	x		No information; elsewhere occurs at lower elevations
Vallonia gracilicosta	x	x	2,011 meters
Vallonia perspective	x	x	McKittrick Canyon at 1,615 meters
Vertigo gouldii		x	2,286 meters

age is provided by the fact that the shells are from shallow sediments and lack encrustations so that they wash clean.

A model that has been proposed for a late Pleistocene [(11,590 ± 230 years before present (BP)] community structure in the Guadalupe Mountains at 2,000 meters on a xeric west-facing slope is that of a mixed conifer community of Douglas-fir (*Pseudotsuga menziesii*), limber pine (*Pinus strobiformis*), Colorado piñon (*Pinus edulis*), and Gambel oak (*Quercus gambelii*) (Van Devender and Wiseman 1977; Van Devender, Spaulding, and Phillips 1979). At the south end of the Guadalupe Mountains packrat middens from Williams Cave at 1,500 meters elevation and dating from 12,010 ± 210 BP indicate a rich piñon-juniper community including New Mexico locust (*Robinia neomexicana*), black cherry (*Prunus serotina*), netleaf hackberry (*Celtis reticulata*), and oak (*Quercus* sp.). The mollusk assemblages (Table 1) are from the more mesic east side of the mountains and from an elevation intermediate to that for the two communities noted above.

The altitudinal distributions of land snails in several nearby mountain ranges in New Mexico have been reported (Metcalf 1984, Dillon and Metcalf 1997). In these mountains the greatest numbers of species and specimens are found today in the mid-transition to mid- to-upper Canadian zones (2,286–3,048 m) (Dillon and Metcalf 1997). In the Organ Mountains the gastropod fauna triples to quadruples at 1,920–2,040 meters elevation (Metcalf 1984). In the Sierra Blanca (Lincoln County) transect, the gastropod fauna increased from 5 to 21 species between 1,700 and 2,073 meters (Dillon and Metcalf 1997). This pattern is similar in the calcareous Sacramento Mountains with the greatest densities of gastropods occurring within the general range of 2,195–2,834 meters (Dillon and Metcalf 1997).

Table 2. Late Pleistocene plant communities (Van Devender et al. 1979).

2,000 meters—west-facing slope (about 13,000 before present)	**Subalpine forest**
	Picea sp.
	Juniperus communis
	Pseudotsuga menziesii
	Pinus strobiformis
	Pinus edulis
	Ostrya knowltonii
	Quercus gambelii
	Arctostaphylos sp.
	Robinia neomexicana
	Rubus strigosus
2,000 meters—west-facing slope (11,590 ± 230 before present)	**Mixed conifer forest**
	Pseudotsuga menziesii
	Pinus strobiformis
	Pinus edulis
	Juniperus sp.
	Ostrya knowltonii
	Quercus gambelii
	Robinia neomexicana
	Celtis reticulate
1,667 meters—east slope (Frijole Ranch)	?????
1,500 meters—south facing bajada (12,010 ± 210 before present)	**Piñon-juniper community**
	Pinus edulis
	Juniperus sp.
	Robinia neomexicana
	Prunus serotina
	Celtis reticulate
	Quercus sp.

We believe the diversity of the gastropod fauna reported here is consistent with the model postulated by Van Devender, Spaulding, and Phillips (1979) of a mixed conifer woodland (transition zone) existing in the Guadalupe Mountains during late Pleistocene time. We suppose that this zone was lower on the more mesic east side of the mountains in accordance with patterns reported in these mountains today (Gehlbach 1979). Diverse gastropod assemblages of this type are not found today in the open grassland and juniper community at the site or from piñon-juniper communities elsewhere in southern New Mexico or western Texas.

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