The Capitan Margin of the Guadalupe Mountains – A Field Trip Guide*

Paul M. (Mitch) Harris[1]

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[1]ChevronTexaco Energy Technology Company; currently ETC, Chevron, San Ramon, CA, USA. (MitchHarris@chevron.com)

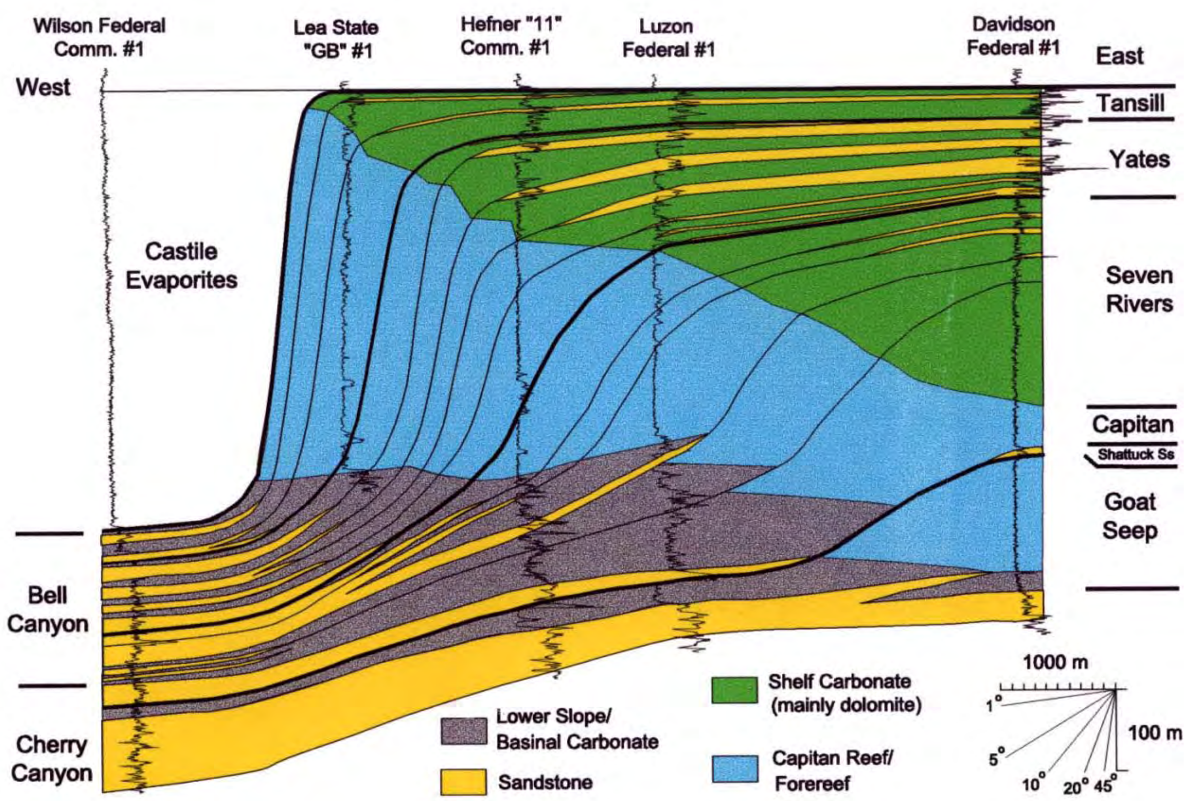
Introductory Statement

The Guadalupe Mountains are an exquisite natural laboratory for studying the stratigraphy, depositional facies, and diagenetic overprint of the world famous Capitan Reef Margin. Well studied outcrops serve as important analogs for other areas where the data is more limited and have had immediate application to subsurface hydrocarbon exploration and exploitation efforts in the immediately adjacent Permian Basin.

Our emphasis is on the Capitan margin, as well as the related shelf and basin deposits. Large-scale outcrops like that of McKittrick Canyon offer an unparalleled view into the inside of a progradational platform, and we hope you will agree that the hike up the Permian Reef Geology Trail presents an extremely valuable opportunity to examine close-up the facies, biota, and diagenesis. We will briefly examine the outer shelf equivalents to the Capitan in Walnut Canyon, hike through the world-famous Carlsbad Cavern, and view the basinal equivalents near a scenic overlook of Guadalupe Peak. Your observations should provide new insight into the potential complexities of shelf, slope, and paleokarst reservoirs.

<u>Field Trip Guide</u>

The Capitan Margin of the Guadalupe Mountains



Paul M. (Mitch) Harris
ChevronTexaco Energy Technology Company
San Ramon, CA

AAPG HEDBERG CONFERENCE
"Carbonate Reservoir Characterization and Simulation: From Facies to Flow Units"

March 2004 — El Paso, Texas

The Capitan Margin of the Guadalupe Mountains –
A Field Trip Guide

Paul M. (Mitch) Harris, *ChevronTexaco Energy Technology Company, San Ramon, CA*

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Field Trip Agenda

March 19

Proceed from El Paso, TX, to Carlsbad, N.M., stopping (time permitting) for overview of Guadalupian platform architecture and stratigraphy exposed along the Western Escarpment of the Guadalupe Mountains.

Evening discussion to introduce Permian Basin and Capitan margin

Overnight at Stevens Inn, Carlsbad

March 20

All-day hike in McKittrick Canyon of Guadalupe Mountains to examine stratigraphy, facies, organisms, and diagenesis of the outer shelf, platform margin and slope associated with the Capitan reef.

Evening discussion of Capitan subsurface data and other similar platform margins

Overnight at Stevens Inn, Carlsbad

March 21

Examine outer shelf facies in Walnut Canyon; the spectacular cave system of Carlsbad Cavern; and basinal equivalents to the Capitan in the Guadalupe Peak area of the Guadalupe Mountains.

Return to El Paso by 4:00 p.m.; end of trip at El Paso International Airport or nearby hotel

Field Trip Presentations

March 19

Introduction to Permian Basin

Capitan Margin on Outcrop

March 20

Capitan Margin in Subsurface

Carlsbad Caverns

Microbial-Dominated Platform Margins

Value of Capitan Margin as a Reservoir Analog: Yates Formation

Value of Capitan Margin as a Reservoir Analog: Tengiz Field

Introduction

The Late Permian (Guadalupian) mixed carbonate/siliciclastic sequences of the Delaware Basin, one of the long-lived subbasins of the Permian Basin, are well known both for their classic outcrop exposures revealed by basin and range structuring in the Guadalupe Mountains and for their prolific hydrocarbon production (Figure 1). A large number of stratigraphic and sedimentologic studies have established the Capitan reef and associated facies as a model for the understanding of carbonate facies in a shelf margin setting and of reciprocal sedimentation relations between a shelf and basin. Early studies focused on biostratigraphy, lithostratigraphy, and early concepts of reciprocal sedimentation. Focus shifted in the 1970's and 1980's to analysis of depositional facies and processes and on the relatively new understanding of early diagenesis of reef margins. More recently, the outcrops have been analyzed from a cyclostratigraphy and sequence stratigraphy perspective. A major emphasis on this trip will be the value of these classic outcrops as analogs for both shelf and slope carbonate reservoirs.

Early Studies

Providing the initial interest in the area were the superb field studies and subsequent detailed reporting of the geology of the southern Guadalupe Mountains by King (1942, 1948). The book by Newell *et al.* (1953) on the Capitan did much to further enhance the outcrops as research models for sedimentary geologists. The critical treatment of the Capitan sedimentology by Dunham in the late 1950's and 1960's, culminating in his detailed 1972 guidebook, stimulated interest and added new understanding. Dunham's work, plus the overall increase in sedimentary geology research in both academia and industry, provided impetus for additional research by many geologists.

Continuing Research

There was a major surge of research on the Capitan during the 1970's and 1980's. Published work focused on shelf-to-basin correlation (Kelley, 1972; Smith, 1973; Sneed, 1977), environments and cycles of shelf deposits (Motts, 1972; Smith, 1974), teepee structures (Assereto and Kendall, 1977), and comprehensive field guide overviews (Scholle and Halley, 1980; Toomey and Babcock, 1983). Graduate students under the supervision of L. C. Pray at the University of Wisconsin-Madison, studied Capitan sedimentology, stratigraphy and paleo- ecology. The first generation of Pray's students published their results along with the work of other authors in SEPM Permian Basin Section Publication 77-16 (Hileman and Mazzullo, 1977). That two-volume compilation and field trip guide discussed many aspects of the Capitan including: reef textures and paleo-ecology (J. A. Babcock, 1977; Toomey, 1977; Toomey and Cys, 1977; Yurewicz, 1977; Schmidt and Klement, 1977); backreef sedimentology and stratigraphy (Neese and Schwartz, 1977; Esteban and Pray, 1977; Sarg, 1977); reef and backreef diagenesis (Mazzullo, 1977; Mazzullo and Cys, 1977; Schmidt, 1977); and basinal carbonates and clastics (L. C. Babcock, 1977; Williamson, 1977).

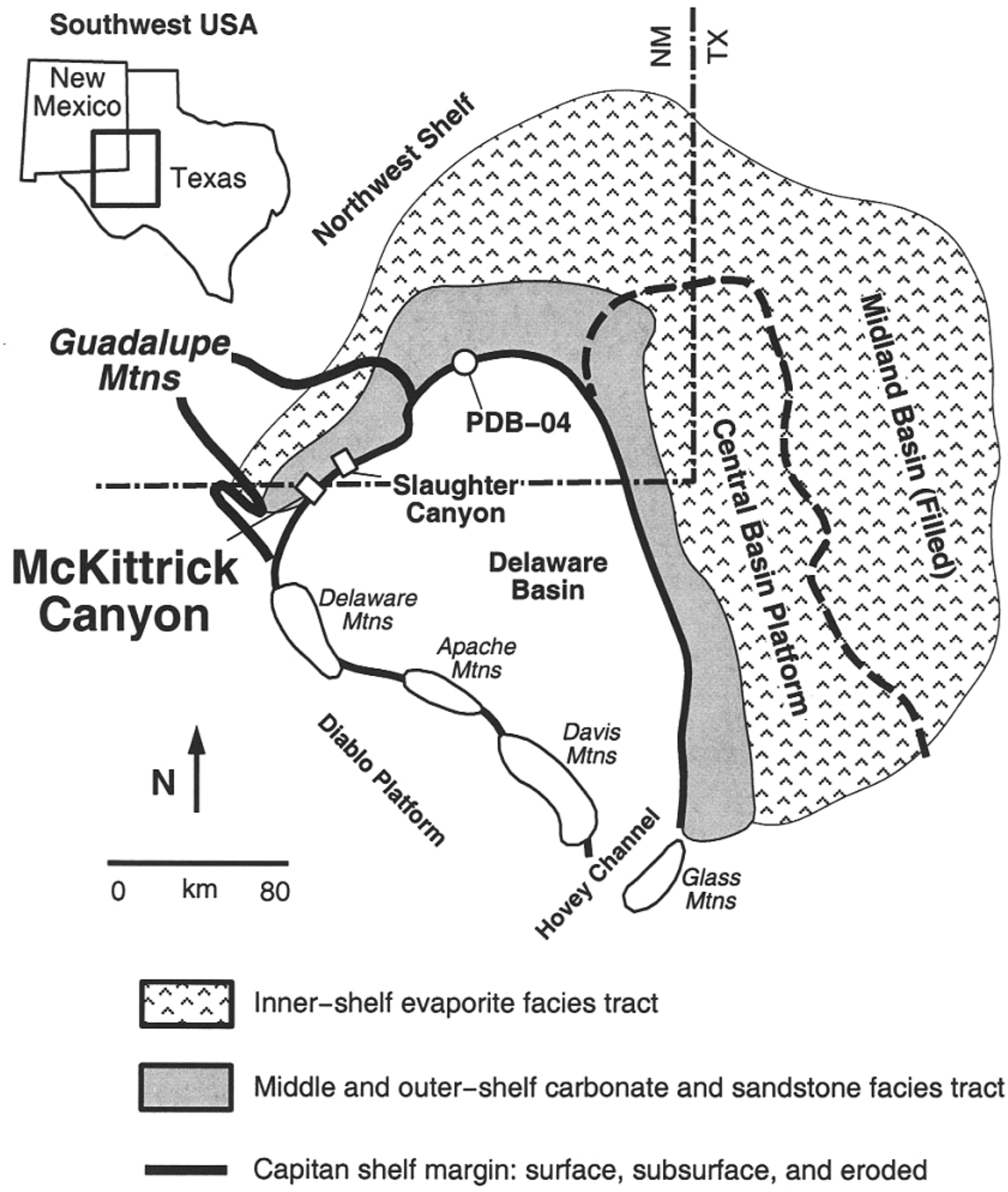


Figure 1. Map of West Texas and southeast New Mexico showing simplified facies distribution for Capitan time (modified after Ward *et al*., 1986). Note location of the Guadalupe Mountains, McKittrick Canyon, and the Gulf PDB-04 well.

Studies of the Capitan continued in the late 1980's and 1990's. SEPM Core Workshop Number 13 (Harris and Grover, 1989) was built upon descriptions of the Gulf PDB-04 well (see Figure 1 for location) which continuously cored the Bell Canyon, Capitan, Seven Rivers, Yates and Tansill formations. The descriptions (Garber *et al.*, 1989) are a unique documentation of lithologies, facies, and diagenesis of the Capitan in the subsurface. That workshop volume contained many other excellent articles on depositional features of the reef (Babcock and Yurewicz, 1989; Harwood, 1989), backreef and shelf equivalents (Parsley and Warren, 1989; Mazzullo *et al.*, 1989; Neese, 1989; Borer and Harris, 1989; Candelaria, 1989; Hurley, 1989; Sarg, 1989; Wheeler, 1989), and diagenesis (Mruk, 1989; Melim and Scholle, 1989). The Guide to the Permian Reef Geology Trail (Bebout and Kerans, 1993) is another important collection of descriptions and interpretations of the Capitan margin. The guide focuses on McKittrick Canyon which is unique in that it is possible to traverse in a single day's hike from the basin through the Capitan slope and reef into the outer shelf. An excellent and comprehensive review of most aspects of the Capitan is available in Hill's (1996) volume on the geology of the Delaware Basin. The most recent compilation on the Capitan (Saller *et al.*, 2000) brings together the latest work on the stratigraphic framework, biostratigraphy, facies analysis, diagenesis, and subsurface data.

Terminology

The focus of this part of our field trip is on the Capitan margin, which is synonymous with the Capitan reef complex of Pray or the Capitan depositional system of Saller *et al.* (2000). As used here, the Capitan margin applies not only to the Capitan reef itself but to its coeval strata of the backreef and of the basin. We will use the terms "reef", "forereef", and "backreef" in their positional sense; while remembering that Dunham (1970) suggested the term "stratigraphic reef" for the Capitan and other abrupt carbonate masses because he recognized little evidence of skeletal boundstone signifying an ecologic or "true" reef. On outcrop examination of reef exposures, we will discuss the function of organic communities, binding or creation of a framework by skeletal organisms or cements, or qualities such as wave resistance.

A number of formation names have been applied to the rock units along a depositional profile across the Capitan margin (Figure 2). From the work of King (1948), Newell *et al.* (1953), and Hayes (1964), (a) the Capitan Formation includes both reef and slope; (b) shelfward equivalents are mixtures of carbonates, siliciclastics, and evaporites of the Tansill (youngest), Yates, and Seven Rivers Formations; and (c) basinward equivalents are siliciclastics of the Bell Canyon Formation, with carbonate interbeds along the basin edge designated Lamar (youngest), McCombs, Rader, Pinery, and Hegler members. Newell *et al.* (1953) further recognized a three-fold subdivision of the Yates Formation using major siltstone interbeds, designating these, from oldest to youngest, Yates A, B, and C.

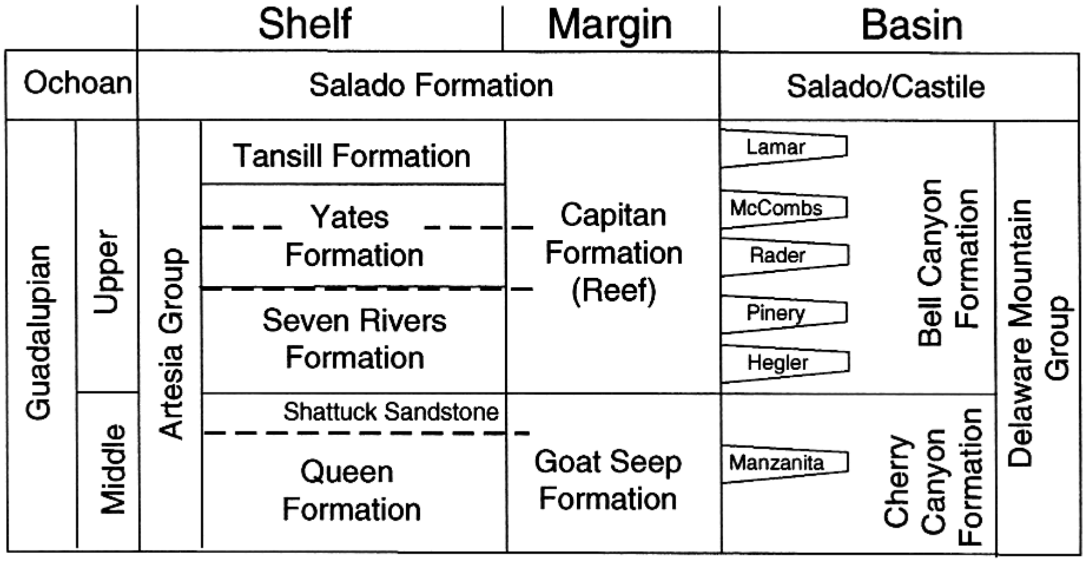


Figure 2. Stratigraphic nomenclature for the Capitan and Goat Seep margins (from Harris and Saller, 2000). Composite sequence boundaries of Kerans and Tinker (2000) are shown by dashed lines.

Stratigraphic Framework

Kerans and Tinker (2000) interpret three composite sequences (CSs) within the Capitan system (Figure 2). Their interpretations are based on the large-scale stratigraphic framework developed for the Guadalupe Mountains by Kerans *et al.* (1992, 1993) and Kerans and Fitchen (1995) and the detailed work within McKittrick Canyon by Tinker (1996, 1998). The correlation between the shelf and basin edge carbonates within their scheme includes:

1. a Seven Rivers CS to Manzanita, Hegler, and Pinery members of the Cherry Canyon and Bell Canyon formations,
2. a Yates CS to Rader and McCombs members of the Bell Canyon Formation, and
3. a Tansill CS to the Lamar member of the Bell Canyon Formation.

This sequence stratigraphic framework will be discussed in more detail during the field stop in McKittrick Canyon.

Detailed stratigraphic relationships for the Capitan margin generally suffer from the limited resolution of biostratigraphic control and the inability to trace beds or time lines from the shelf into the basin. A number of recent studies, however, are improving our understanding of the shelf-to-basin relations and inter-relationships between depositional facies. These include studies in McKittrick Canyon (Brown and Loucks, 1993a and b; Kerans and Harris, 1993; Borer and Harris, 1995; Brown, 1996; Tinker, 1998), Slaughter Canyon (Rankey and Lehrmann, 1996; Osleger, 1998), basin strata (Kerans *et al.*, 1992, 1993; Borer and Harris, 1995), and regional comparisons (Osleger and Tinker, 1999; Kerans and Fitchen, 1995; Kerans and Tinker, 2000; Harris and Saller, 2000).

A primary control of the Capitan stratigraphy is inferred to be composite sea-level variation. Low-amplitude, high-frequency oscillations of relative sea level are suggested for much of the Permian shelf-top strata, including that of the Capitan margin (Neese and Schwartz, 1977; Hurley, 1989; Wheeler, 1989; Borer and Harris, 1991, 1995; Kerans and Nance, 1991; Lindsay, 1991; Sonnenfeld, 1991; Kerans and Harris, 1993; Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1999). Longley (2000), however, proposes that small-scale sequences and cycles were partly controlled by differential compaction on the outer shelf of the Capitan. Ye and Kerans (1996) proposed a eustatic curve for the Leonardian and Guadalupian by picking highstand and lowstand shorelines for individual sequences and using lithologic data to remove effects of compaction and isostacy. They suggest amplitudes of approximately 10 m for Capitan composite sequence-scale eustatic cycles, which is consistent with that proposed by Borer and Harris (1995). Cyclicity in the different facies tracts of the Capitan-equivalent shelf profile, and suggested relations with sea-level change, will be emphasized during our field stops.

One important difference between carbonate and siliciclastic depositional systems that impacts stratal patterns is that high rates of *in situ* carbonate production can cause aggradation or even progradation during transgression. Also, in a pure carbonate system, a lowstand system tract may be poorly developed in the basin since this represents a time of no or only limited carbonate production on the shelf. The greatest shedding of fine carbonate debris into the basin occurs during transgressive to highstand times when the shelfal carbonate factory is widespread (Schlager, 1992; Brown and Loucks, 1993). In a mixed system like the Capitan, attributes of both carbonate and siliciclastic sequence stratigraphic approaches need to be considered, as do the important interactions between the two depositional styles.

Kerans and Tinker (2000) argue that the complex biologic and diagenetic reef fabrics observed in scattered outcrop localities can be best understood within the context of the stratigraphic framework. There is no doubt about this! We hope our excursion into McKittrick Canyon serves to illustrate our current understanding of the stratigraphic framework, the approaches that are being used to develop the framework, and the possible implications of the refined framework for future studies.

Subsurface Relations

The subsurface stratigraphy of the Capitan margin is very similar to outcrop stratigraphy recognized in the Guadalupe Mountains (Borer and Harris, 1995; Osleger and Tinker, 1999; Harris and Saller, 2000). Seismic data of the Capitan margin (Harris and Saller, 2000; Figure 3) show characteristics that include (1) a massive prograding reef/slope, (2) backreef/shelf reflectors that dip and diverge basinward before disappearing into the massive reef, and (3) layered bottomset beds that thicken basinward by addition of younger reflectors. Wireline log cross sections (Garber *et al*., 1989; Harris and Saller, 2000; Figure 4) illustrate the stratigraphy in more detail than can be done using seismic data. Basinward dipping shelf strata are interbedded sandstones and carbonates that diverge and pass basinward into massive carbonate of the reef. Correlative markers within the massive reef are difficult to find. Slope carbonate beds thin and basinal siliciclastics thicken toward the basin. Bottomset beds in the basin consist of interbedded sandstones/siltstones and low-porosity carbonates.

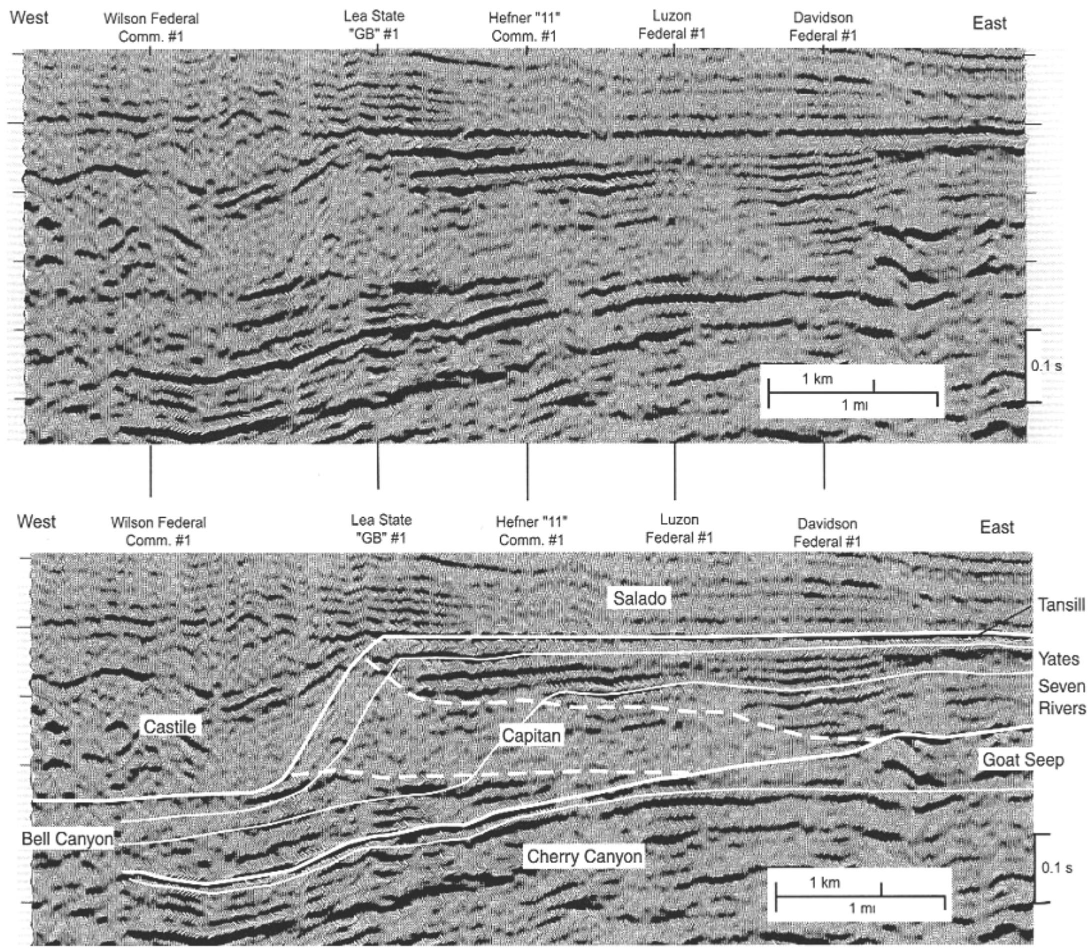


Figure 3. Uninterpreted (top) and interpreted (bottom) seismic line through the Capitan margin (from Harris and Saller, 2000). The line is flattened on the base of the Salado, and the vertical scale is two-way travel time. The vertical exaggeration is approximately 2:1. The location of the line is shown on Figure 8; Figure 4 shows details of the well data.

The lithologic differences between outcrops of the Capitan margin and their subsurface equivalents are due largely to variations in dolomitization and evaporite dissolution on outcrops. Distribution of porosity in the Capitan margin in the subsurface is closely related to depositional facies (Ward *et al.*, 1986; Harris and Saller, 2000). Shelf sandstones and some shelf carbonates adjacent to the reef have good porosity and moderate permeability, but porosity and permeability in those strata generally decrease landward. The subsurface Capitan reef has moderate porosity and high permeability and is a regional aquifer. Carbonate beds in the basin are generally not porous, but some basinal sandstone filling elongate channels have good porosity and moderate permeability.

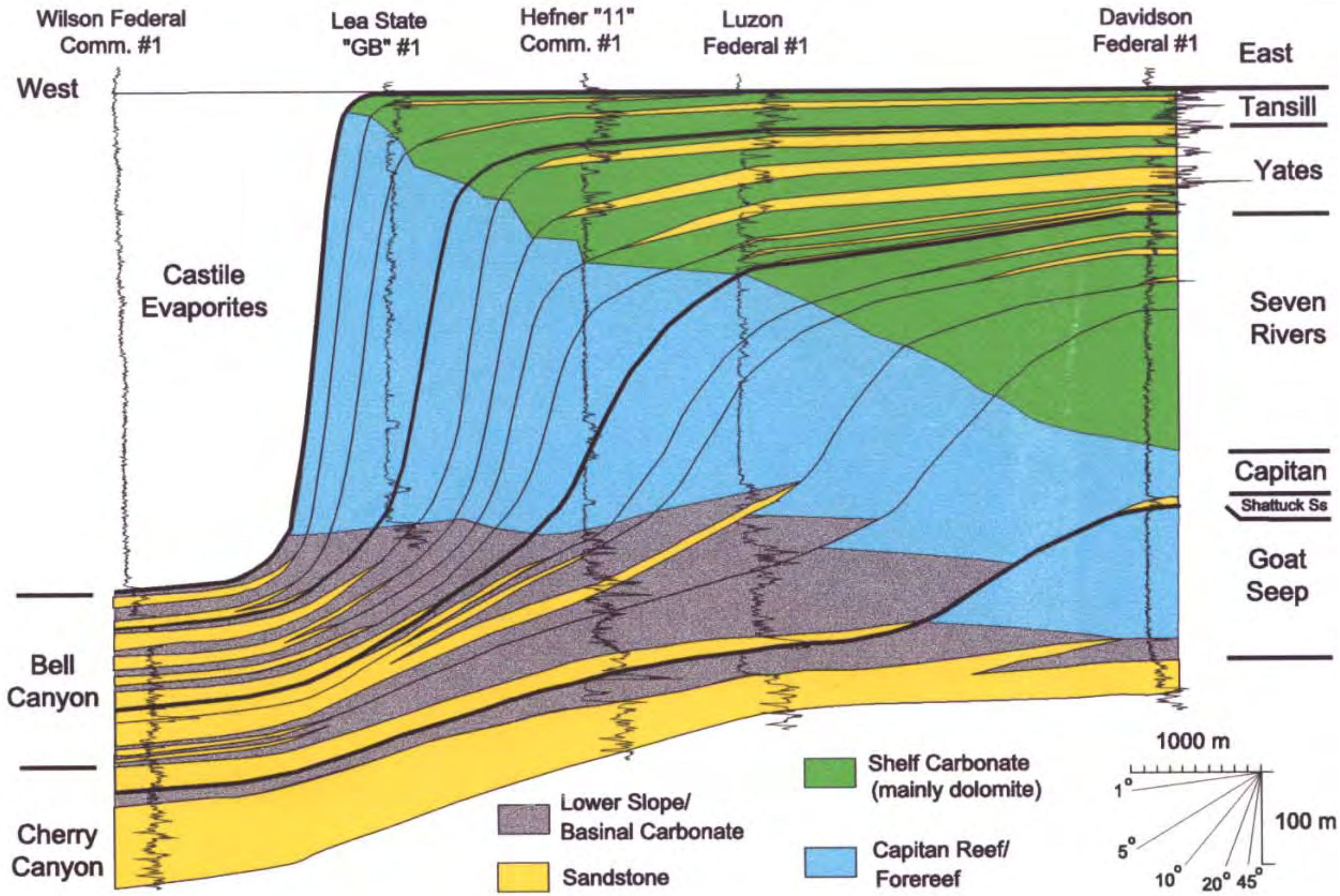


Figure 4. Subsurface stratigraphic cross section across the Capitan margin using wells located near the seismic line of Figure 3 (from Harris and Saller, 2000). Gamma-ray logs are shown for wells; locations of wells are shown on Figure 8. Correlations follow seismic geometries as well as log patterns; datum is top Tansill except for basin well where top Castile is used.

Hydrocarbon Production

Hydrocarbon reservoirs are present in both shelf and basin equivalents to the Capitan margin, but not in the reef itself. Hydrocarbon production on the shelf is primarily from sandstone beds of the Yates and Seven Rivers Formations, with only minor production from dolomites (Galloway *et al.*, 1983; Ward *et al.*, 1986; Borer and Harris, 1991; Harris and Saller, 2000). The most widespread hydrocarbon reservoirs occur in relatively well-sorted sandstones with porosities of 15-30% and permeabilities of 10-100 mD (Borer and Harris, 1991). Individual siliciclastic reservoir zones show complex interfingering with carbonates in a downdip direction and evaporites in an updip direction (Borer and Harris, 1991). Some porosity also occurs in carbonate beds, especially grainstones near the reef (Ordonez, 1984). Hydrocarbon production from these shelf deposits generally occurs in stratigraphic traps caused by facies changes and evaporite cementation, but combination stratigraphic-structural traps also occur in low-relief anticlines caused by compaction and draping over buried structures (Galloway *et al.*, 1983; Ward *et al.*, 1986; Broadhead, 1993).

A number of small oil fields occur in basin sandstones of the Bell Canyon Formation (Galloway *et al.*, 1983; Ward *et al.*, 1986; Williamson, 1977; Broadhead, 1993; Harris and Saller, 2000). Cumulative production from these fields is generally less than 30 million barrels of oil. The fields tend to be very elongate (1.5-19 km long by <1 to 6 km wide) apparently reflecting accumulation of reservoir sands in deep-water channels (Bozanich, 1979; Williamson, 1977; Bashman, 1996). Average porosity and permeability in three Bell Canyon fields were estimated at 24-25% and 10-80 mD, respectively by Payne (1976). Basin carbonates that are interbedded with sandstones in the Bell Canyon Formation are generally not porous.

The upper 122 m of Capitan reef in the Gulf PDB-04 well has porosity of 5-25% (average 10%) and permeability of up to 2 darcies (average 256 mD), whereas the lower Capitan has less than 5% porosity and less than 1 mD permeability (Garber *et al*., 1989). Wireline logs from other wells (Harris and Saller, 2000) also show that the Capitan reef, especially the upper portion, has >5% porosity and hydrologic data (Motts, 1968; Hill, 1996) indicate that the reef has excellent permeability regionally. Although porous and permeable, hydrocarbons do not occur in the Capitan reef because the reef does not have structural or stratigraphic closure. Hydrocarbons migrating out of the Delaware Basin apparently moved through the Capitan reef/slope and into permeable shelf deposits updip from the reef (Ward *et al.,* 1986). The Capitan Formation is a high permeability, fresh water aquifer around the margins of the basin.

Field Stop – Salt Flat Graben
Overview of Guadalupe and Delaware Mountains

Introduction

The outcrops of the Guadalupe Mountains, including those of the Capitan margin, are world famous. Factors leading to this geologic fame are the abundance of outcrops, the high relief and structural simplicity of the shelf-to-basin margin, and the setting of the Guadalupe Mountains adjacent to the extensive mineral resources in the Permian of this area. In the outcrops, the shelf margin separates shallow-water deposits to the northwest from deep-water deposits of the Delaware Basin to the southeast (Figure 1).

The western fault scarp of the Guadalupe – Delaware Mountains, which we view from Salt Flat Graben, is an excellent regional exposure of the Permian strata that formed along the northwest corner of the Delaware Basin (Figure 5). The fault scarp trends roughly north-south, whereas the trend of the margin separating the Northwest Shelf and Delaware Basin was northeast-southwest. Cenozoic Basin-and-Range faulting has uplifted the mountain fault block approximately 2.5 km along a normal fault system that is close to the base of the present high western escarpment. The topographic relief from the high western Guadalupes to the lower crest of the Delaware Mountains is not tectonic, but resulted from more rapid erosion of basinal evaporites and siltstones than of the shelf-margin carbonates to the north. It is this view (Figure 6) that provides an opportunity to examine the large-scale stratigraphic relations of the Capitan margin and older units.

Large-Scale Stratigraphic Framework

Deposits exposed along the western escarpment represent two major phases of basin-encroaching carbonate systems separated by a time when the shelf-to-basin transition regressed significantly northward (Figure 6). The Victorio Peak bank facies and Bone Spring basinal deposits, both Early Permian (Leonardian) in age, form the lower southward-tapering wedge of darker cliffs and underlying slope along the base of the major escarpment. This older shelf-to-basin transition is typified by low angles of dip at the shelf or basin margin. A major northward transgression of basinal shales, shaley carbonates, and siltstones over the Leonardian shelf was caused by shelf-edge subsidence and sea-level rise. The stage was then set for the subsequent basinward advance of the Guadalupian platform strata, including those of the Goat Seep and Capitan margins.

The composite sequence framework of Kerans and Tinker (2000) (Figure 7) illustrates the nature of Guadalupian platform margin development. The San Andres Formation is initially ramp-like and characterized by a ramp crest of grainstone-dominated cycles and isolated, small buildups localized over subtle breaks in slope (Kerans and Fitchen, 1995). Slopes steepen slightly in late San Andres and Grayburg time and minor sponge-crinoid-bryozoan buildups are localized at the shelf break. The first appearance

Figure 5. Landsat image of the Guadalupe and Delaware Mountains. Carlsbad, N.M., is in the upper right corner. Note the location of El Capitan on the southeast corner of the Western Escarpment. The Capitan margin trends from El Capitan towards Carslbad; the Reef Escarpment on outcrop is the exhumed paleoshelf margin.

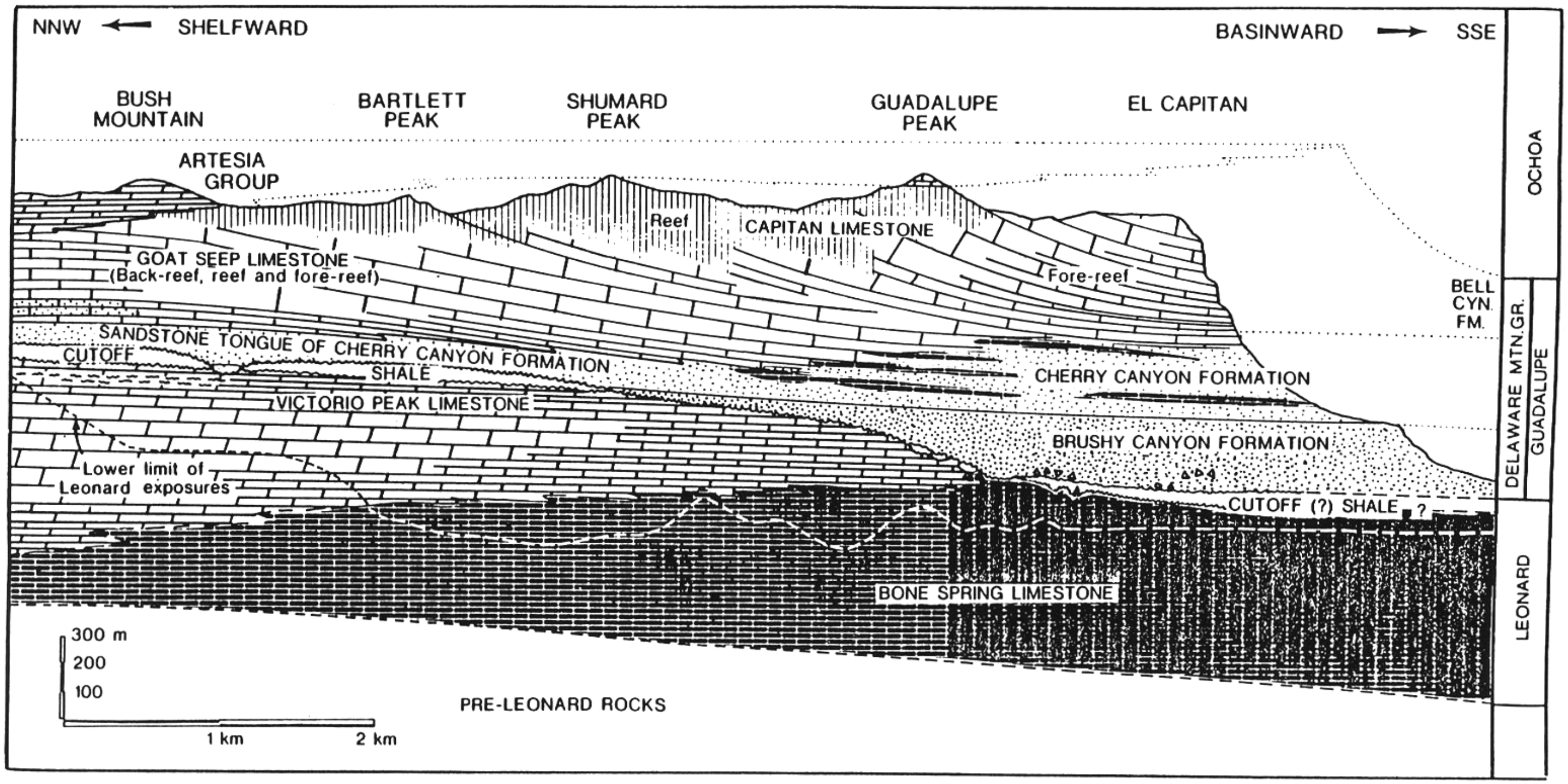
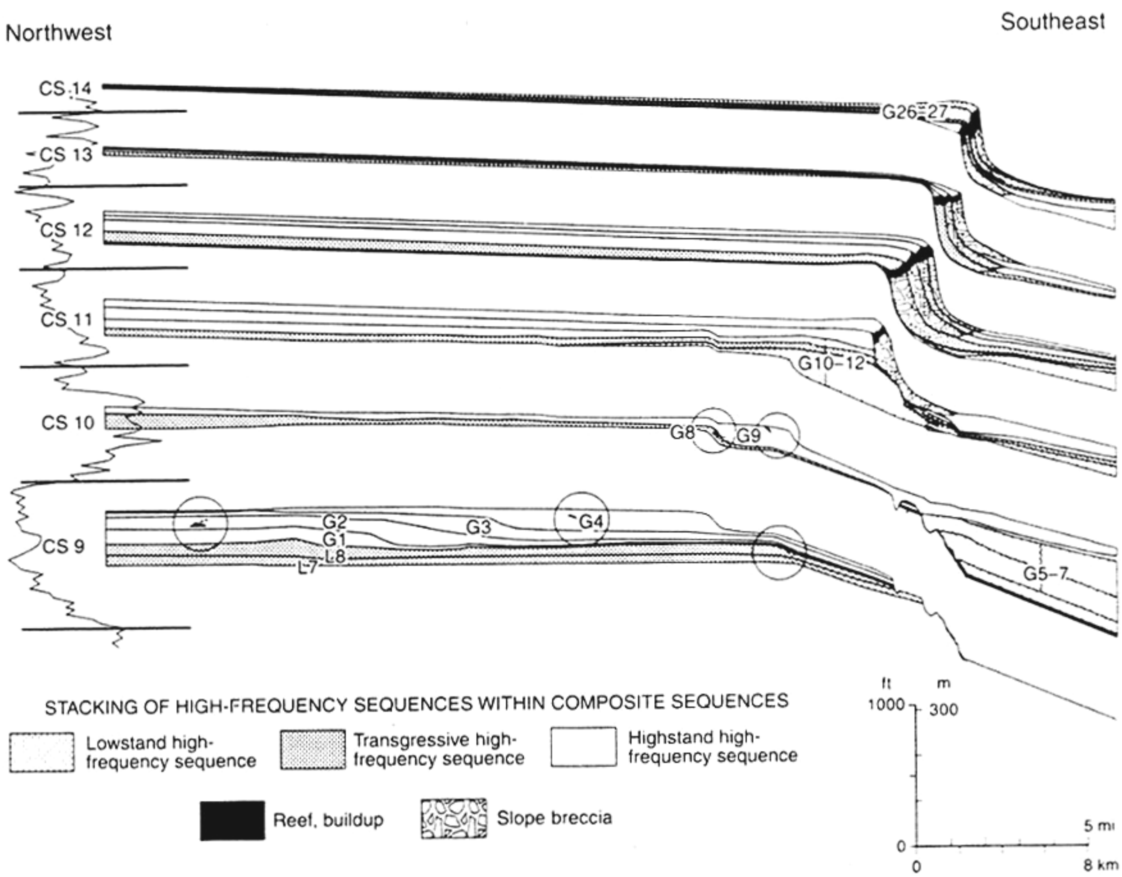


Figure 6. Diagrammatic cross section of the Western Escarpment, based on King (1948), showing the stratigraphy at the shelf-to-basin transition. Note the dotted lines across the top indicating the pre-erosional configuration of the Capitan margin.



COMPOSITE SEQUENCE	HFS	NORTHWEST SHELF	SHELF MARGIN	FORE-SLOPE	DELAWARE BASIN		
CS 14	G27–28	Tansill	*Upper* (Capitan "massive")	Capitan "bedded"	Lamar	Bell Canyon	DELAWARE MOUNTAIN GROUP
	G25–26	Yates	*Middle*		McCombs		
CS 13	G21–24				Rader		
CS 12	G17–20	Seven Rivers	*Lower*		Pinery Hegler		
	G15–16	Shattuck			Manzanita	Cherry Canyon	
CS 11	G13–14 G10–12	Queen Grayburg	Goat Seep		South Wells		
CS 10	G8–9	upper San Andres			CCT		
	G5–7				Brushy Canyon		
CS 9	G1–4 L7–8	lower–middle San Andres			Cutoff		

Figure 7. Composite sequence framework for the Guadalupian of the Guadalupe Mountains (from Kerans and Tinker, 2000). The cross sections show the relationship between inferred sea level, the composite sequences, and reef/buildup development shown in black. The table shows the tie between composite sequences, high-frequency sequences, and the lithostratigraphic terminology.

in the early Grayburg of slope and toe-of-slope megabreccias with boundstone clasts (Fekete, 1986; Crawford, 1989) indicates shelf-margin reef development by this time. Aggradation of the platform during Grayburg time built >150m of relief, which may have been subsequently enhanced by margin collapse (Kerans and Tinker, 2000). The Goat Seep reef margin initiates on the inherited steep topography. In turn, the Capitan margin occupies and accretes off the Goat Seep margin. The details of Capitan margin growth are discussed in the McKittrick Canyon field stop. In general terms, the high-angle foreset strata, that characterize the Goat Seep margin, abruptly initiated a new style of Permian deposition along the basin margin.

It was not until the late 1970's that the major boundary was recognized between the Grayburg and Goat Seep reef. This boundary was interpreted by Pray *et al.* (1980) as a submarine erosional escarpment. Subsequent outcrop studies (Fekete *et al.*, 1986; Franseen *et al.*, 1989; Kerans *et al.*, 1992; Kerans and Fitchen, 1995) interpreted this boundary to be a sequence boundary, although Kerans and Tinker (2000) raise the possibility that it is actually a sharp facies contact between reef and highly-aggradational bedded shelf.

Margin Progradation

The progradational history of the Capitan margin as viewed along the Western Escarpment is spectacular. The prominent light cliffs of the upper escarpment show the basinward progradation of massive carbonates of the Goat Seep and Capitan margins. Toward the north, an abrupt change can be seen from more flat-lying shelf deposits to the massive reef and steeply dipping foreslope strata. Erosion has removed some of the Guadalupian strata once present along this shelf-margin section (Figure 6). Massive foreslope strata of the Capitan extended further south of the present erosional south face of El Capitan, and only remnants remain of the once thicker back-reef equivalents of the Capitan along the high peaks, such as the ones forming the uppermost tip of Guadalupe Peak.

The amount of Capitan margin progradation varied around the northern edge of the Delaware Basin (Figure 8). Maximum progradation occurred in the north-central portion of the basin, with substantially less progradation in the northeastern and northwestern portions (Silver and Todd, 1969; cross sections by West Texas and Roswell Geological Societies; Garber *et al.*, 1989). Harris and Saller (2000) show 5 km of Capitan progradation in the northeastern Delaware basin, and Tinker (1998) shows a similar amount in McKittrick Canyon. Less progradation occurred during Yates and Tansill time as the margin steepened such that slopes into the basin approached 30° (King, 1948), and water depths increased in the basin to over 500 m in Tansill time. Borer and Harris (1995), Tinker (1998), Osleger (1998), and Kerans and Tinker (2000) examine the progradation of the Capitan margin in more detail by looking on a high frequency sequence basis.

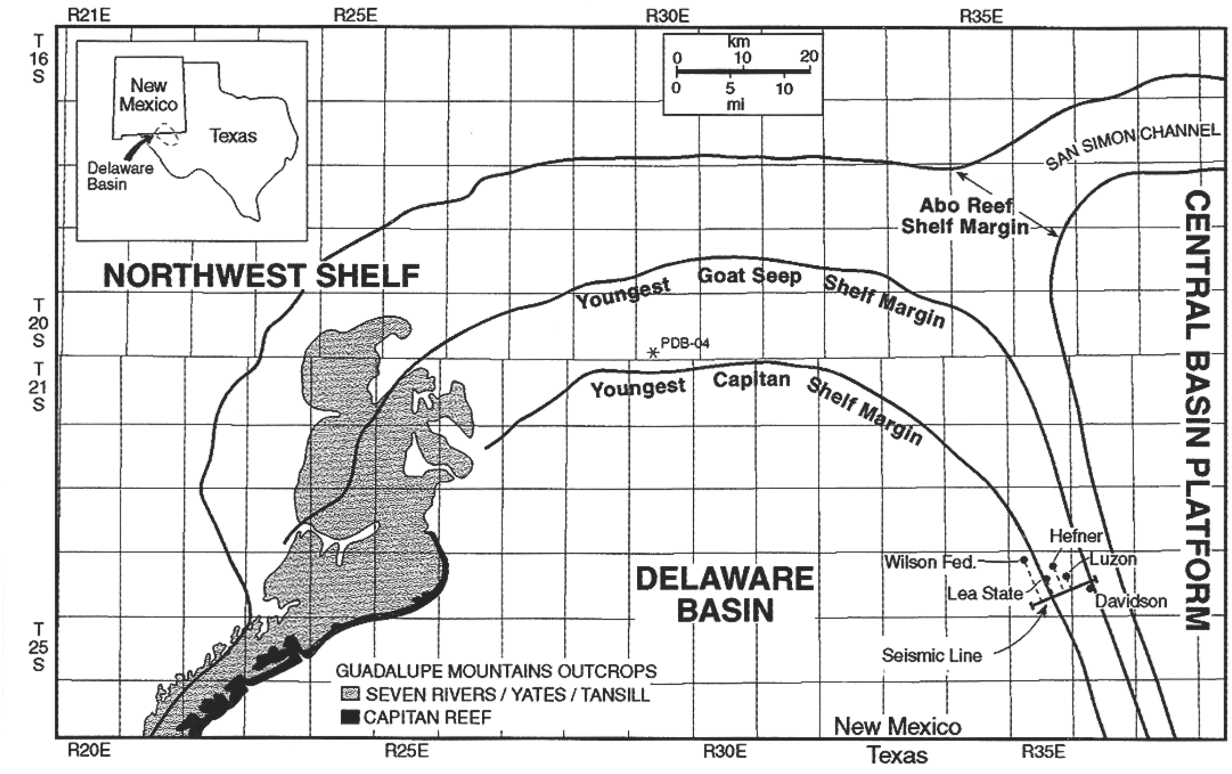


Figure 8. Map of northern Delaware Basin showing locations of the Guadalupe Mountains outcrops, the Gulf PDB-04 well, the seismic line of Figure 3, and the wells of Figure 4. The map indicates long-term progradational history by showing the positions of the youngest shelf margins of the Abo, Goat Seep, and Capitan. (Modified after Garber *et al*., 1989; Harris and Saller, 2000)

Value as Reservoir Analog

The view of the Western Escarpment also sets the stage for one of the main themes of the field trip: the value of these classic outcrops as analogs for both shelf and slope hydrocarbon reservoirs. We will examine the stratigraphy and facies of shelf and outer shelf environments and discuss the direct implications to reservoirs that produce from the Yates Formation in the Permain Basin. We will also examine the facies and diagenesis of reef and slope environments and discuss their importance as analogs for other steep, high-rising platform margins that are hydrocarbon reservoirs.

Our Field Stop

Our stop will be an overview and discussion of the Western Escarpment from the floor of the Salt Flat Graben. The purpose of the stop is to set the stage for our field examination of the shelf, shelf-margin, and basin deposits related to the Capitan. During the remaining drive to Carlsbad, the relations between the various components of the Capitan margin will become even more apparent. Our route will take us further around the northern rim of the Delaware Basin, moving up stratigraphic section and past our subsequent field localities.

Key Points

Regional setting
Large-scale stratigraphic framework
Stratigraphic nomenclature
Shelf-to-basin configuration
Reservoir analog potential

Field Stop – McKittrick Canyon
Permian Reef Geology Trail

Introduction

Outcrops along the Permian Reef Geology Trail (PRGT) in the mouth of McKittrick Canyon, Guadalupe Mountains National Park, are the focus of today's field stops. The trail traverses 610 vertical meters (1524 to 2134 m or 5,000 to 7,000 ft topographic elevation) through one of the world's finest examples of a rimmed carbonate margin. The present-day topography that was exhumed during the late Cenozoic uplift of the mountains displays approximately the shelf-to-basin depositional profile formed by the Capitan margin. A thorough introduction to the geology of the PRGT can be found in Bebout and Kerans (1994).

Sequence Framework and Depositional Model

Borer and Harris (1991) and Kerans *et al.* (1992) suggested that five siliciclastic-to-carbonate cycles are present in shelf deposits of the Yates Formation as seen in subsurface data and along the north wall of McKittrick Canyon. The upper three cycles are equivalent to the Yates A, B, and C of Newell *et al.* (1953). A modification of this cyclic framework (Kerans and Harris, 1993; Kerans and Fitchen, 1995; Borer and Harris, 1995; Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 2000) recognizes these cycles as Yates high frequency sequences (HFSs). Osleger and Tinker (1999) show that four Yates HFSs can be recognized thoughout the outcrop belt and correlated to the subsurface data of Borer and Harris (1991). A comparable HFS subdivision is also possible for the underlying Seven Rivers Formation and overlying Tansill Formations (Kerans and Fitchen, 1995; Tinker, 1998; Kerans and Tinker, 2000).

Tinker (1998) and Kerans and Tinker (2000) interpret the entire Capitan margin in the context of three composite sequences (CSs) and several HFSs (Figure 9). These HFSs coincide with more major shifts in depositional style that are represented in the north wall of McKittrick Canyon as apparent seaward steps of the reef-margin and associated facies tracts offsets (Borer and Harris, 1995; Tinker, 1998; Osleger and Tinker, 1999). The possible interrelationships between eustasy, tectonic subsidence, and the stratigraphy are discussed by Borer and Harris (1995), Ye and Kerans (1996), and Kerans and Tinker (2000).

Stratigraphic and depositional frameworks interpreted for the Capitan margin generally follow the concepts of Meissner (1972), Mazzullo *et al.* (1985), and Fischer and Sarnthein (1988) regarding the reciprocal relationship between shelf and basin strata (Figure 10). During highstands, the shelf was flooded and carbonates were deposited on the outer 10-20 km of the shelf, the shelf margin and slope. At highstand times, downslope carbonate debris beds accumulated repeatedly (Garber *et al.*, 1989; Brown and Loucks 1993), the shelf margin and slope prograded basinward, and the shelf aggraded. During sea-level fall, the shelf was subaerially exposed allowing siliciclastic

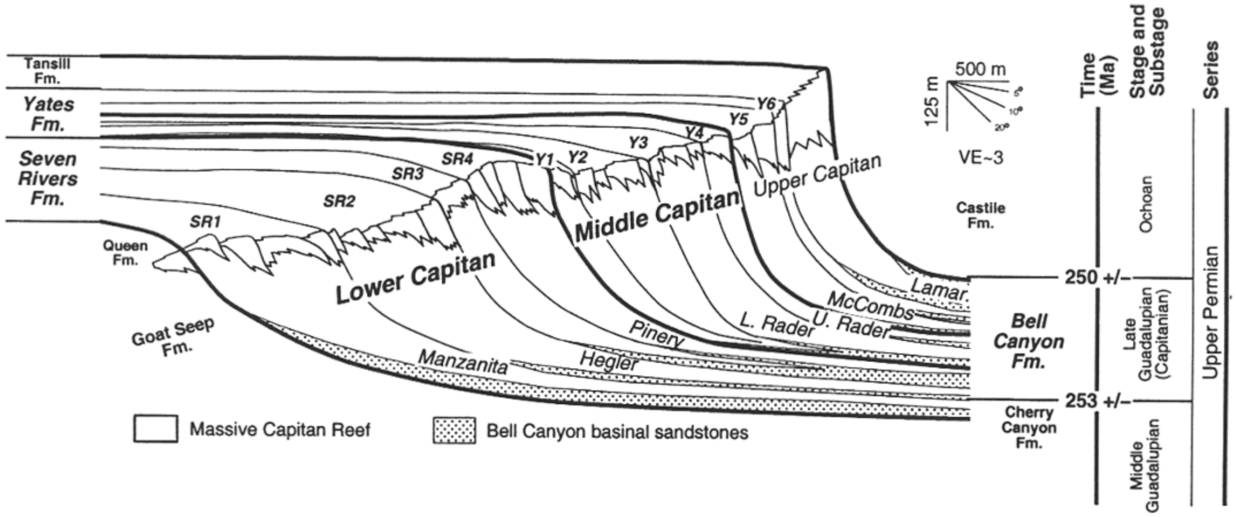


Figure 9. Simplified cross section of McKittrick Canyon (Tinker, 1998). Heavy lines are composite sequence boundaries; thin lines are high-frequency sequence boundaries. Time estimates are from Ross and Ross (1987).

sands and silts to be transported across the shelf and into the basin. Carbonate debris beds generated during lowstand conditions contain a siliciclastic matrix (Garber *et al.*, 1989). The relative lack of sand in the reef and upper slope indicates that they were generally bypass zones during times of low sea level. However, some sand did fill internal cavities, vugs and fracture porosity in the reef (Garber *et al.*, 1989; Kirkland *et al.*, 1993), and minor amounts of sandstone/siltstone occur on the upper slope (Mruk and Bebout, 1993). Although depositional models for the basinal sandstones are still being debated (Hill, 1996), several studies (*e.g.*, Borer and Harris, 1995), suggest that the time of maximum siliciclastic deposition in the basin was during lowstands. Sand was not trapped on the shelf until the subsequent transgression, when the shelf was reflooded (*e.g.*, Fischer and Sarnthein, 1988; Kerans and Harris, 1993; Borer and Harris, 1995; Tinker, 1998; Osleger, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 2000).

Tinker (1998) documented detailed facies relations between the shelf-crest, outer shelf and reef of the Capitan margin within the context of relative sea-level variations (Figure 10). A systematic variation of facies was observed in most of the Seven Rivers and Yates HFSs and CSs. Typical changes from the transgressive to highstand systems tract include: an increase in interpreted water depth over the shelf-margin reef; decreasing distance from the shelf-crest shoreline to the shelf margin; and increases in the width of the shelf-crest and outer-shelf facies diversity.

Although Capitan outcrops are spectacular, no single outcrop allows an unambiguous correlation between shelf and basin strata. Specific questions involve, which sands or surfaces on the shelf correlate with which sands in the basin, and which basin carbonates correlate with which shelf carbonates. Within the stratigraphic framework of

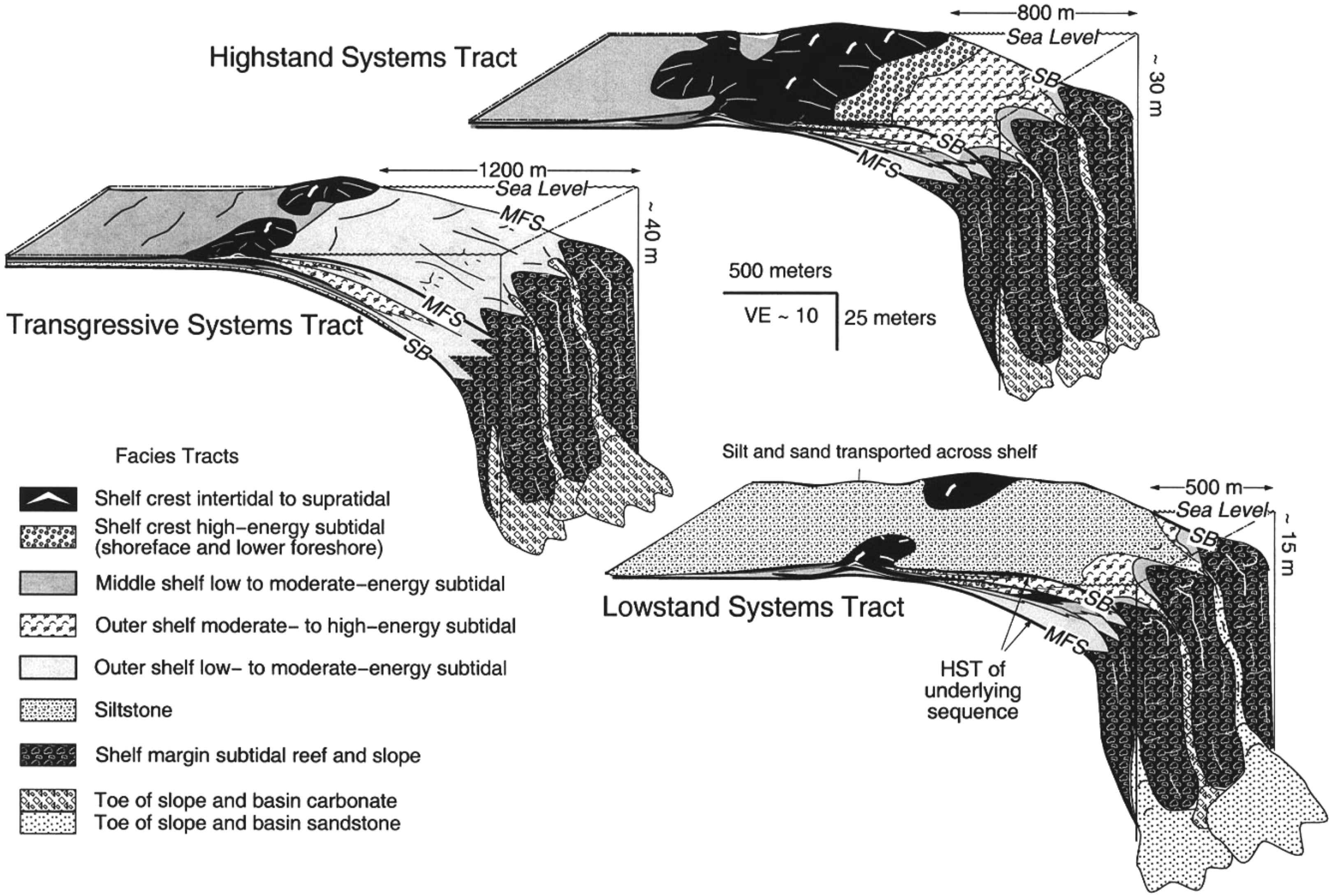


Figure 10. Three-dimensional models for Capitan facies distribution (from Tinker, 1998). The models are based on the Y3 HFS, but the systematic variation in facies with change in relative sea-level are observed in most of the Seven Rivers and Yates HFSs and CSs.

Kerans and Tinker (2000): (1) the Manzanita, Hegler, and Pinery carbonate members of the Cherry and Bell Canyon formations are correlated with Seven Rivers shelf strata; (2) Rader and McCombs carbonate members of the Bell Canyon Formation are correlated with Yates shelf strata; and (3) the Lamar carbonate member of the Bell Canyon Formation is correlated with Tansill shelf strata (Figure 9). These shelf-to-basin correlations are somewhat different from those of previous workers (Newell *et al.*, 1953; Wilde, 1975; Pray and Esteban, 1977; Garber *et al.*, 1989, and others)(Figure 2). The precise correlation between shelf and basin is still evolving, and will likely continue to receive much attention as sequence stratigraphic and biostratigraphic studies continue.

Shelf Profile and Stratal Geometries

Stratal geometries of the Capitan shelf-to-reef transition are characterized by a change from nearly flat-lying well-bedded shelf-crest strata, to more steeply basinward-dipping, crudely-stratified outer-shelf beds, that pass gradationally into massive shelf-margin reef facies (Figure 28). This basinward-sloping geometry, referred to locally as the "fall-in bed" profile (Esteban and Pray, 1977; Hurley, 1978, 1989), is best developed in Seven Rivers strata. As the Capitan reef generally shallowed through time (Babcock and Yurewicz, 1989) the dip of the fall-in beds became progressively less. Yates Formation shelf profiles are markedly more flat-topped than those of the Seven Rivers as is demonstrated (a) on outcrop by tracing distinctive recessive siliciclastic-rich intervals across the outer portions of the shelf (Neese and Schwartz, 1977; Hurley, 1989; Osleger, 1998; Tinker, 1998); and (b) in the subsurface from core and log correlations (Borer and Harris, 1991; Harris and Saller, 2000).

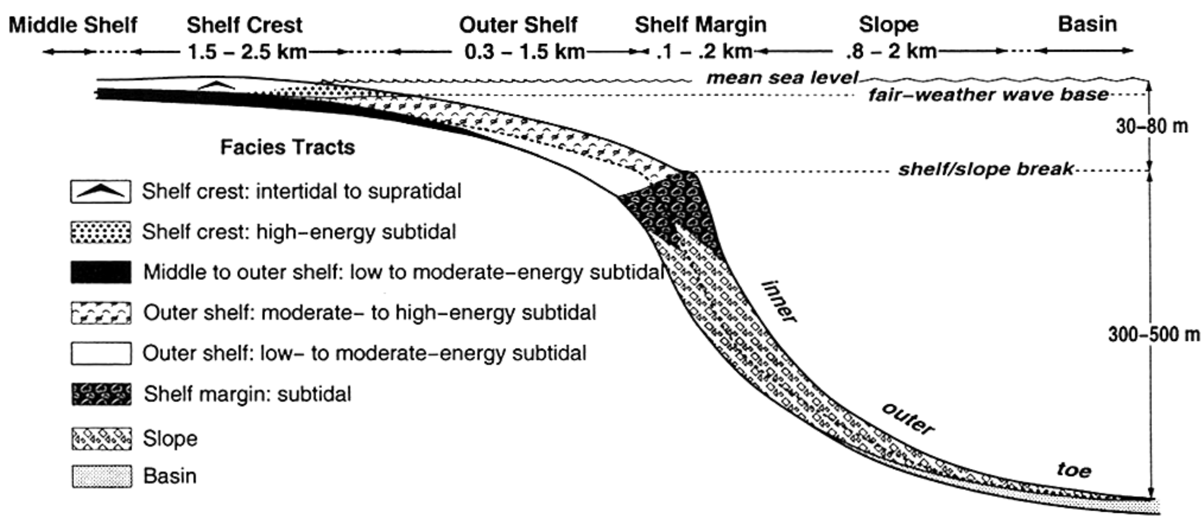


Figure 11. Generalized cross section showing the spatial distribution of major facies tracts of the Capitan margin related to a paleobathymetric profile (from Tinker, 1998).

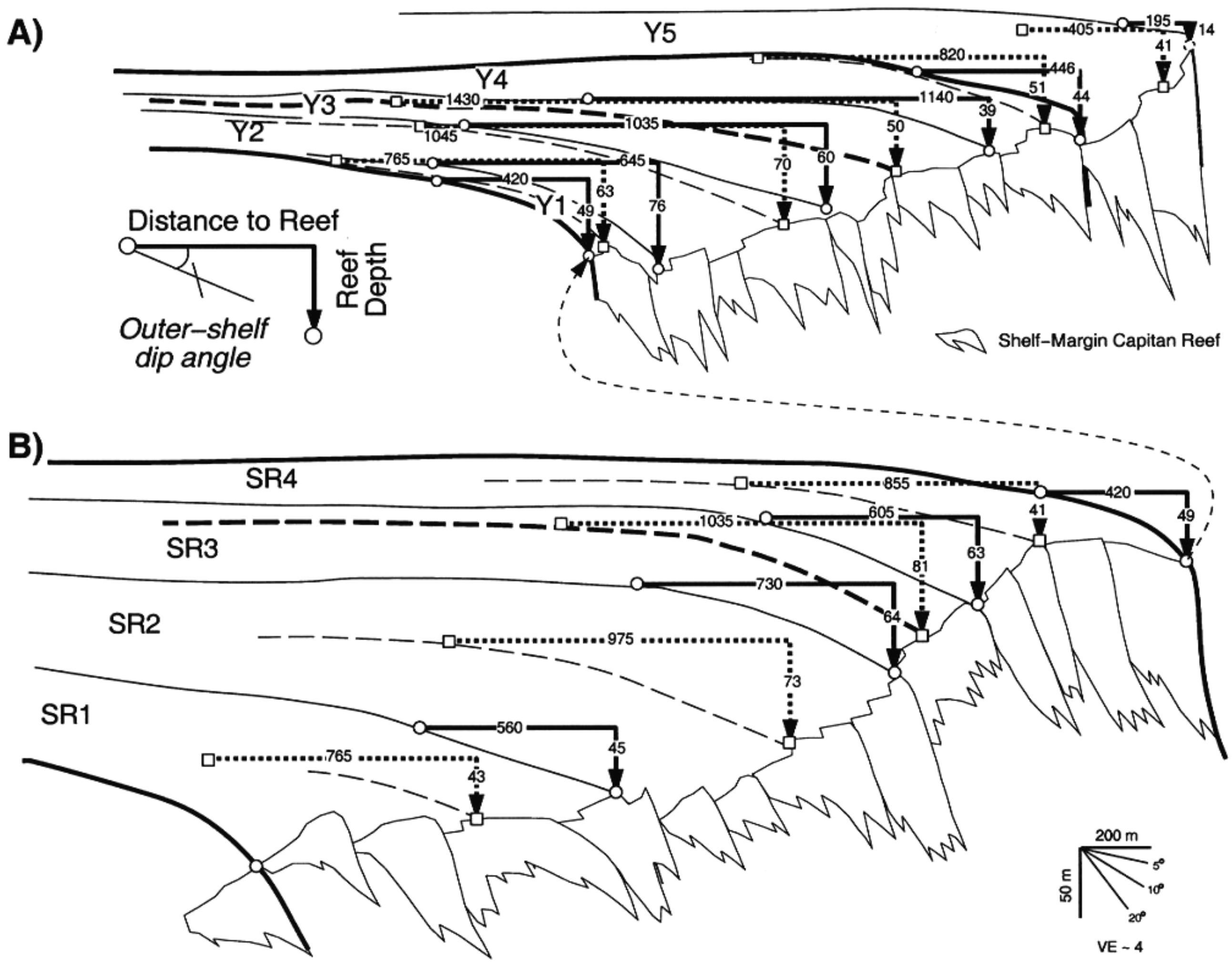
The origin of the "fall-in bed" profile remains controversial. Hurley (1989) used outcrop photographs, detailed field mapping, and geopetal fabrics to show an original depositional dip of 8 degrees for Seven Rivers fall-in beds and an additional post-depositional overprint of 2 to 3 degrees due to tectonic or compactional tilting. Many workers (*e.g.*, Kerans and Harris, 1993; Osleger, 1998; Tinker, 1998), have described textural, sedimentary structure, and biota changes along a dip profile that are consistent with increasing water depths toward the reef. In contrast, Saller (1996) measured geopetal dips from cavities in the Yates-age Capitan along the PRGT that suggest post-depositional tilting of the reef at approximately the same amount and direction as the dip of the overlying fall-in beds. Longley (2000) argues that the fall-in geometries are most likely produced by episodic syndepositional differential compaction at or near the shelf margin.

Recent outcrop studies (*e.g.*, Kerans and Harris, 1993; Tinker, 1998; Osleger, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 2000) focus on trends in downdip thickness changes, lateral extent and aspect ratios of facies tracts, and progradation:aggradation ratios to better document the details of outer shelf and reef progradation. The outcrops studies of Tinker (1998) and the computer modeling of Borer and Harris (1995) show how progradation is expressed by the episodic, but progressive seaward step-out of the shelf margin within individual HFSs (Figure 12). The large-scale outcrops of McKittrick Canyon clearly show that the apparent repeated shallowing of the reef and progressive flattening of “fall-in bed” dips are related to these short-term variations of the margin. Kerans and Tinker (2000) use facies-tract substitution and facies proportions within their sequence framework to better constrain interpretations of the water-depth setting of the Capitan and factors controlling its position along a dip profile.

Implications of HFS Framework

The stratal pattern and sequence interpretation discussed for McKittrick Canyon differs substantially from one made using the classic "Vail" model and may be considered a specific example for an attached mixed carbonate-siliciclastic shelf that experienced a complex hierarchy of high-frequency, relatively low-amplitude, sea-level fluctuations (Borer and Harris, 1995; Tinker, 1998). Key differences from a "Vail" model interpretation include: (1) transgressive aggradation and highstand progradation related to carbonate productivity; (2) high-frequency sand bypass to the basin; (3) significant time represented by high-frequency surfaces of erosion and/or nondeposition throughout entire the shelf section; and (4) a rapid seaward-shift in (siliciclastic) facies with a only minor relative sea-level fall.

In the shelf and outer-shelf equivalents to the Capitan, the HFS and smaller-scale cycles show many of the same attributes as longer-duration, seismic-scale sequences (Borer and Harris, 1995; Tinker, 1998; Osleger and Tinker, 1999). These include critical surfaces (erosion, bypass and flooding), spatial shifts in deposition through time (systems tracts), and internal facies stacking patterns. The basic components of the shelf cycles as recognized by most workers are (1) a surface of nondeposition or erosion formed during maximum sea-level fall, (2) transgressive siliciclastic-rich beds deposited during sea-level rise, and (3) regressive (highstand) carbonates deposited



The distance from shelf crest to reef is greater at the MFS than the sequence boundary of every HFS.

The depth to reef increases in the TST and decreases in the HST of the Seven Rivers and Yates composite sequences.

The outer–shelf dip angle ranges from 2 to 7 degrees, and tends to decrease at the MFS and increase at the sequence boundary of a composite sequence.

Figure 12. Summary of shelf-margin reef depth and progradation distance for Seven Rivers and Yates high-frequency sequences (from Tinker, 1998). Systematic changes are noted to the right of the figure.

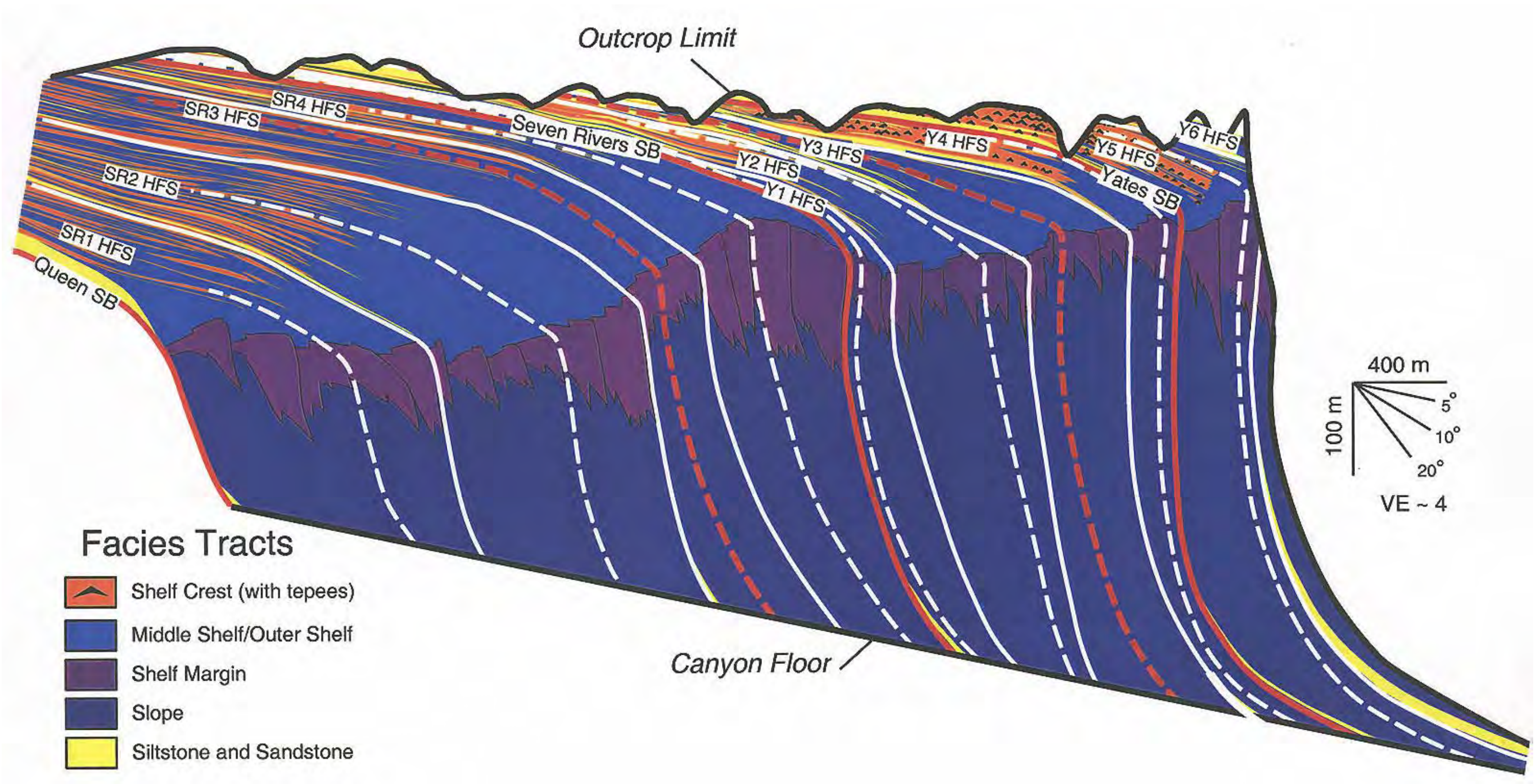


Figure 13. Simplified cross section of Capitan margin facies relations documented in McKittrick Canyon by Tinker (1998). Figure is shown with present-day, tectonically-enhanced basinward dip to the right. Solid red lines are CS boundaries, dashed red lines are CS MFSs, solid white lines are HFS boundaries, dashed white lines are HFS MFSs.

during late sea-level rise to early sea-level fall. These are the components for a small-scale siliciclastic-carbonate couplet as well as a HFS (Figure 13).

Nature of Reef

One of the longstanding, fundamental debates regarding the Capitan margin is whether the massive portion is an “ecologic”, “diagenetic”, or “stratigraphic” reef (Dunham, 1969). It is a bit ironic, but one of the historic problems in studying the Capitan reef has been a lack of exposure in which depositional fabrics can be clearly seen. Although large sections of canyons have outcrops of sparsely vegetated reef, surficial weathering has resulted in outcrop surfaces that reveal little of the underlying rock fabrics. For many years, reef fabrics could be clearly seen only on a few naturally etched outcrop “windows” and from slabbed samples. Workers who saw a dominance of wackestone concluded that the Capitan was a massive carbonate buildup (“stratigraphic reef”) but not an ecologic reef (Baars, 1964; Achauer, 1969; Dunham, 1970; Tyrrell, 1969). Others saw a dominance of syndepositional cement and concluded that inorganic cement was the critical binding agent in the reef (Schmidt, 1977; Mazzullo and Cys, 1977, 1978). Still others (Cronoble, 1974; J. A. Babcock, 1977; Yurewicz, 1977; Cys *et al.*, 1977; Scholle and Halley, 1980) observed substantial amounts of organic boundstone and concluded that much of the Capitan was an organic reef.

Construction of the PRGT in the early 1980's resulted in the exposure of many naturally etched surfaces. These areas, along with several artificially etched windows, have allowed for viewing of larger surfaces of reefal fabric than were previously possible. During the last decade, Capitan reef paleoecology has been the subject of many insightful articles including Noè and Mazzullo (1992), Weidlich (1996), Wood *et al.* (1994, 1996), Senowbari-Daryan and Rigby (1996), Noè (1996), Wood (2000), Weidlich and Fagerstrom (2000), and Kirkland *et al.* (2000). The etched outcrops clearly show that the Capitan is locally a framework with bryozoa, calcareous sponges, *Tubiphytes* and other organisms in growth position and with internal cavities (Kirkland *et al.*, 1993, 1998, 2000; Wood *et al.*, 1994, 1996; Wood, 2000). The framework was subsequently bound together by *Archaeolithoporella* and microbial micrite, and finally large volumes of botryoidal aragonite and sediment filled the internal cavities.

Several paleobathymetric profiles have been proposed for the Capitan margin. The uninterrupted slope model of King (1948) shows gradual deepening of water from the shelf into the basin. Other models suggest shallowing at the shelf margin to form a barrier reef (Newell *et al*., 1953), or shallowing at a position landward of the reef where pisolite shoals define the shelf crest (Dunham, 1972), or both (Kirkland-George, 1992). Bedding configuration and facies relations suggest a general profile with a topographic crest coincident with a teepee-pisolite shelf-crest facies tract and a seaward-sloping outer-shelf, *i.e.* falling-in, toward a deeper water reef (Figure 11). The discussions immediately above, however, concerning the controversy surrounding the nature of the “fall-in beds” are applicable here as well regarding the paleobathymetric profile for the reef. Different areas studied by different workers represent reef margins of varying ages and locations. It is probable that the nature of the Capitan varied laterally (Pray, 1989) and with time (Borer and Harris, 1991, 1995; Osleger, 1998; Tinker, 1998;

Osleger and Tinker, 1999; Kerans and Tinker, 2000; Weidlich and Fagerstrom, 2000; Figure 13), and that the Capitan was sometimes a deeper reef and other times a shallow reef. One needs only to examine exposures along the north wall of McKittrick or Slaughter canyons to demonstrate that the shelf profile and depth of water over the reef clearly varied significantly during development of the Capitan margin.

Our Field Stop

Our field stop at McKittrick Canyon will be a day-long hike of the PRGT. We will use the following guide during our hike:

Bebout, D. G. and Kerans, C., 1993 (eds.), Guide to the Permian Reef Geology Trail, McKittrick Canyon, Guadalupe Mountains National Park, West Texas: Guidebook 26, Bureau of Economic Geology, University of Texas, Austin, 48 p.

Tinker (1998) provides the best documentation of the detailed geologic framework shown by the McKittrick canyon outcrops.

Tinker, S. W., 1998, Shelf-to-Basin Facies Distributions and Sequence Stratigraphy of a Steep-Rimmed Carbonate Margin: Capitan Depositional System, McKittrick Canyon, New Mexico and Texas: Journal of Sedimentary Research, v. 68, No. 6, p. 1146-1174.

Key Points

Detailed stratigraphic framework (cycles, HFSs, and CSs)
Outer-shelf, shelf margin, slope and toe-of-slope facies
Vertical and lateral facies relations
Response of facies to sea-level change
Nature of reef margin
Reef biota and textures
Diagenetic Overprint
Implication of shelf stratigraphy and facies to reservoir layering and heterogeneity
Implication of reef and slope facies and diagnesis to reservoir quality
Importance of fracturing in reef

Field Stop – Walnut Canyon

Yates Cycles

Yates high-frequency sequences (HFSs) and cycles, like those present in Walnut Canyon, are discussed by Borer and Harris (1995), Osleger (1998), Tinker (1998), Osleger and Tinker (1999), and Kerans and Tinker (2000). These HFSs coincide with more major shifts in depositional style that are represented in the north wall of McKittrick Canyon as apparent seaward steps of the reef-margin and associated facies tracts offsets (Borer and Harris, 1995; Tinker, 1998; Osleger and Tinker, 1999). Our focus in Walnut Canyon will be a 1-D analysis, as the stratal geometries are lacking in the flat-lying beds of the shelf setting, with an emphasis on facies and diagenetic attributes of a mixed siliciclastic-carbonate cycle.

An important element of the uppermost Yates cycles is the interplay between siliciclastics and carbonates. According to reciprocal sedimentation concepts, siliciclastic sands are carried across the shelf during lowstands of sea level when the shelf was subaerially exposed (Figure 10). However, most of the outcropping shelf sands were interpreted to be deposited in a subtidal environment (Pray, 1977; Candelaria, 1989). As a result, questions emerged as to whether some sands were deposited during highstands of sea level when the shelf was flooded (Pray, 1977). The perspective of the shelf sands and carbonates was broadened greatly when subsurface data from inner and middle shelf environments (Borer and Harris, 1991; Andreason, 1992) were added to descriptions of outcropping outer shelf deposits (Figure 14). Most shelf sands occur above subaerial exposure surfaces (unconformities) which probably represent the time when most basinal sands were carried across the shelf (Mazzullo *et al.*, 1985; Fischer and Sarnthein, 1988; Borer and Harris, 1995; Osleger, 1998; Osleger and Tinker, 1999). These shelf sands are interpreted as being the transgressive portions of shelf cycles, with final deposition by a reworking of eolian dune sands and sand blown into adjacent subtidal environments (Kerans and Harris, 1993; Borer and Harris, 1995; Tinker, 1998; Osleger, 1998; Osleger and Tinker, 1999). With continued flooding of the shelf, carbonates form the upper portion of the shelf cycles.

Kerans and Harris (1993), Tinker (1998), Rankey and Lehrmann (1996), Osleger (1998), Osleger and Tinker (1999), and Longley (2000) examined the lateral variation and stacking patterns of cycles on outcrop in McKittrick and Slaughter canyons. Their work shows there is substantial variation in the nature of a cycle, albeit a carbonate cycle or a mixed carbonate-siliciclastic cycle, depending on its position along the depositional profile and within a sequence. A comparison of Figures 13 and 14 shows the nature of this variability as documented from both outcrop and subsurface data.

Teepee Structures

Teepee structures form through multiple cycles of exposure, desiccation, flooding, sediment fill, and/or marine cementation (Assereto and Kendall, 1977; Warren, 1983; Figure 15). Kerans and Fowler (1995) showed that well-developed teepees are not

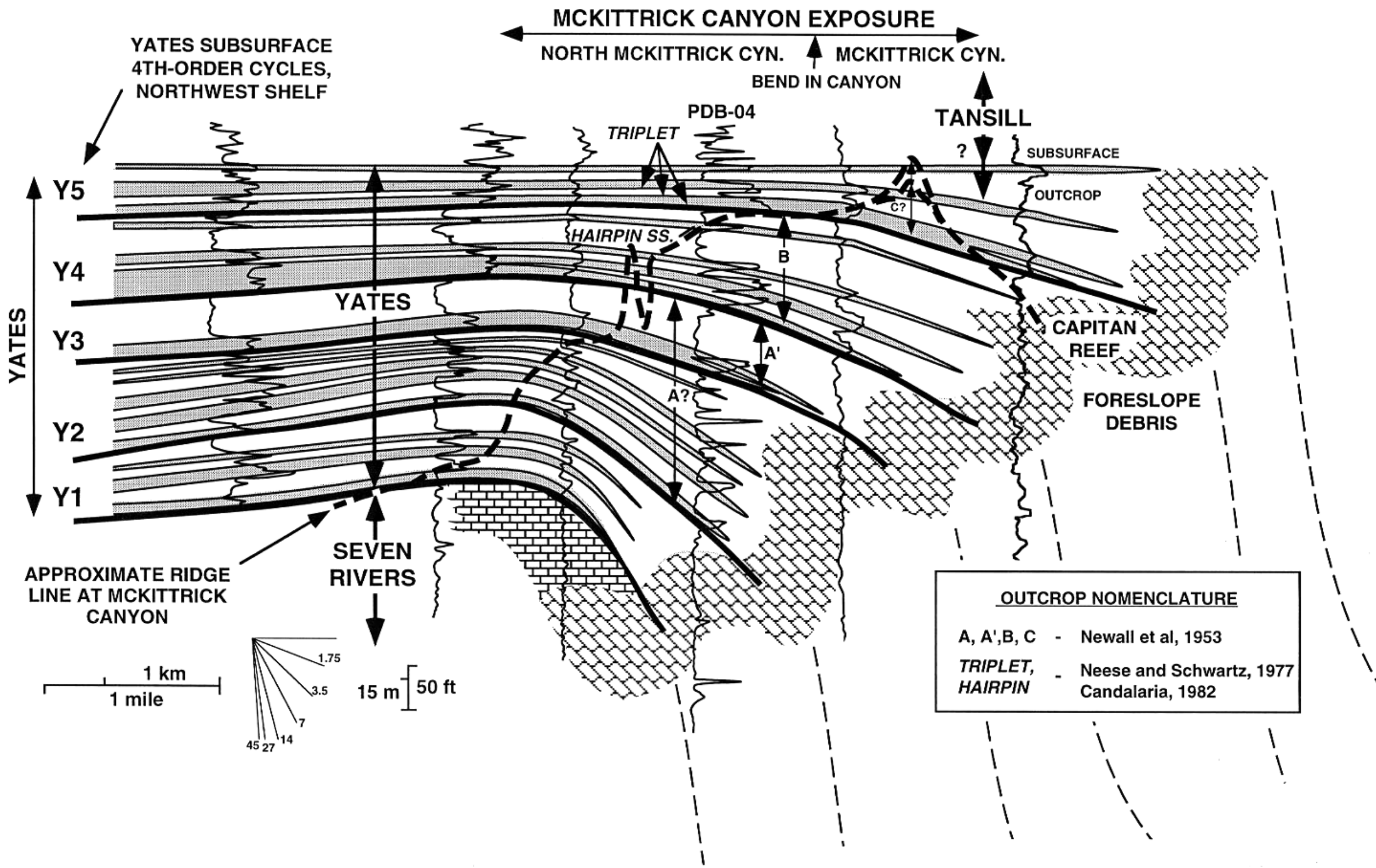


Figure 14. Yates subsurface cross section of Borer and Harris (1991) tied to outcrop exposures by Borer and Harris (1995). Gamma-ray logs are shown for the wells (note PDB-04 well location); siliciclastic beds are shaded. The Triplet unit within the upper Yates is identified.

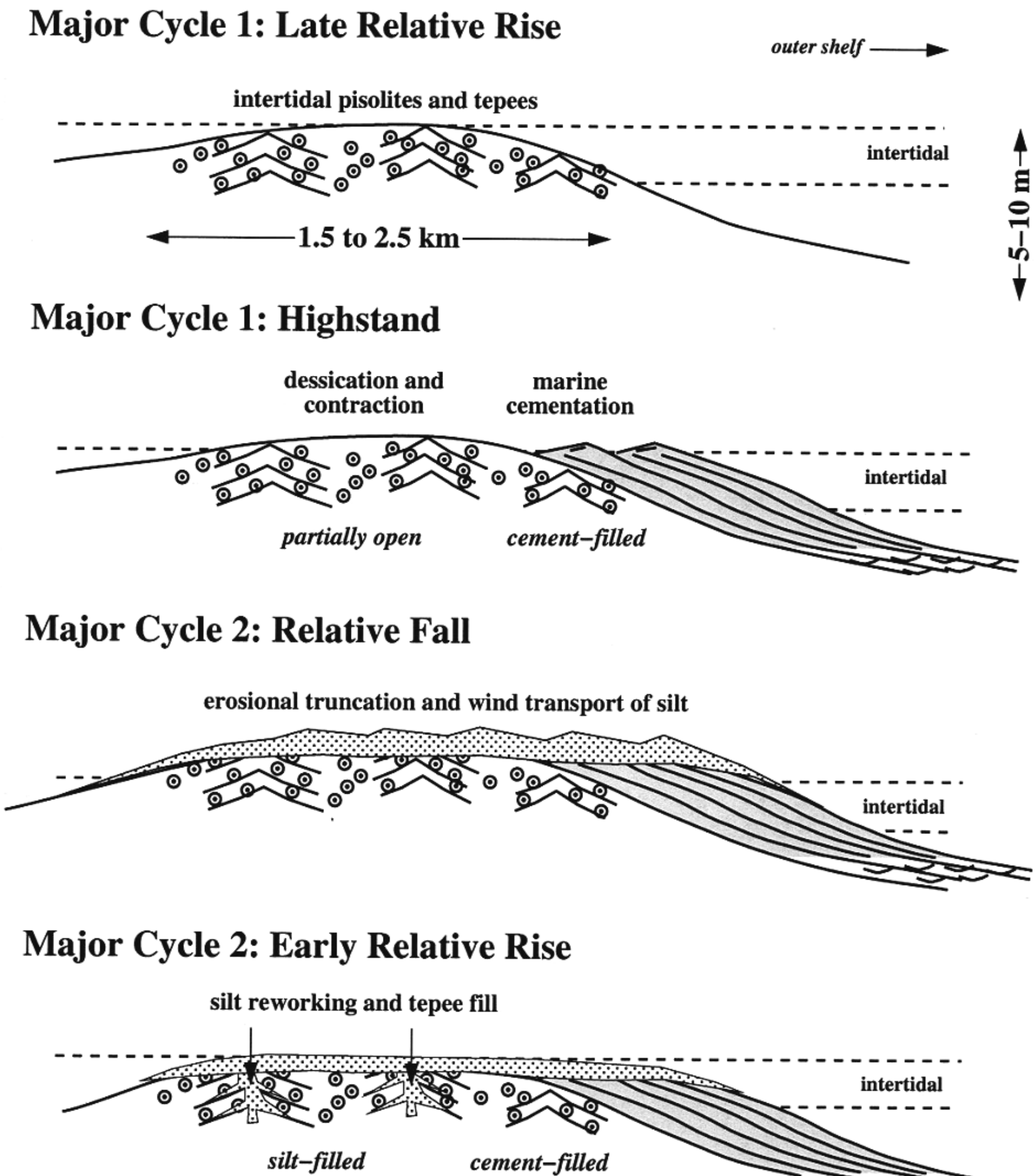


Figure 15. Model showing formation of cement-cored and sand-cored teepee structures in the Capitan shelf-crest, intertidal to supratidal facies tract. Gray-shaded areas are high-energy facies. (Figure from Tinker, unpublished)

found on rapidly prograding shelf or ramp margins because the steady migration of the shoreline position from one cycle to the next does not permit repeated desiccation and flooding. Kerans and Tinker (2000) expanded the discussion by pointing out that during times of high aggradation several factors occur that would promote teepee formation. The shoreline position of each successive cycle or sequence is offset only slightly, thus forcing the repeated desiccation/cementation cycle required for teepee formation. The high accommodation also favors steep-rimmed margins and narrow facies-tract widths bringing the shelf-crest complex closer to open ocean circulation and enhancing marine cementation.

Our Field Stop

Three distinctive cycles, occurring throughout this part of Walnut Canyon, are termed the Triplet unit of the uppermost Yates Formation (Newell *et al.,* 1953; Esteban and Pray, 1977; Neese and Schwartz, 1977; Neese, 1989; Candelaria, 1982, 1989; Borer and Harris, 1989.) The cycles occur within the uppermost HFS recognized within the Yates (Kerans and Harris, 1993; Borer and Harris, 1995; Osleger, 1988; Tinker, 1988; Osleger and Tinker, 1999). We will examine one of the prominent siliciclastic beds and a peritidal carbonate horizon containing well-developed teepee structures.

Key Points

- Characteristics of shelf sheet sands
- Sedimentologic and diagenetic attributes of teepee structures
- Carbonate-siliciclastic cycles and sea-level change
- Reciprocal sedimentation model
- Shelf stratigraphy and facies as an analog for reservoir heterogeneity

Field Stop - Carlsbad Cavern

Cave Location

Numerous caves are present in the Guadalupe Mountains, with Carlsbad Cavern and Lechuguilla Cave being the most spectacular (Figure 16).

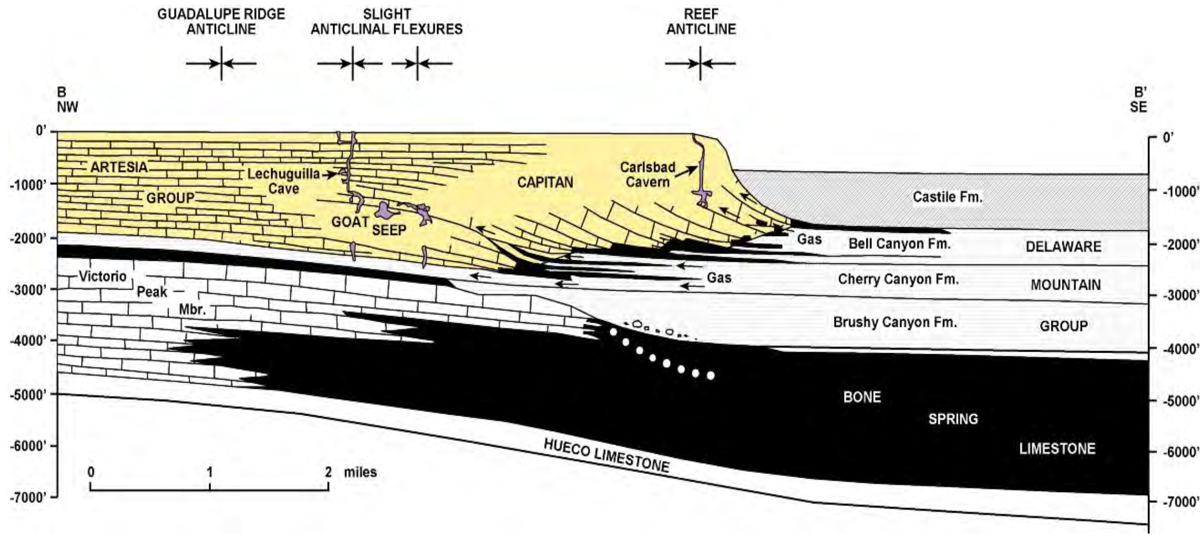


Figure 16. Cross section showing the position of the major cave systems relative to the Permian stratigraphy and facies.

Cave Origin

The theories of local cave formation have changed over the last 50 years. Dissolution was initially attributed to "normal cave processes" of carbonic acid occurring in rainwater (Bretz, 1949). During the last twenty years, a more complex model has evolved for development of caverns in the Capitan system (Jagnow, 1979, 1989; Hill, 1989, 2000; DuChene and McLean, 1989). Based on cave geometries and the geochemistry of the cave fill, Hill (1987, 1995, 1996, and 2000) postulated four stages of cave development. The last and volumetrically most important dissolution event was “sulfuric acid karst” associated with basinal hydrogen sulfide mixing with oxidizing freshwater during the last 15 million years (Figure 17). This model has been substantiated and is now being considered for other cave systems around the world.

The sulfuric acid karst model for cave formation (Figure 17) involves gas ascension from the basin into the reef along the Bell Canyon sandstones. Natural gas migrated updid from the oil fields to the east and encountered anhydrite at the base of the Castile Formation. Reactions between the gas and the anhydrite solutions produced hydrogen sulfide, carbon dioxide, and coarse replacement calcite. Hydrogen sulfide moved updip along interfingerings of the Bell Canyon Formation and where this gas mixed with oxygenated ground water moving downdip along backreef beds, sulfuric acid formed, which dissolved out the large cave passages in the Gualdalupe Moutains.

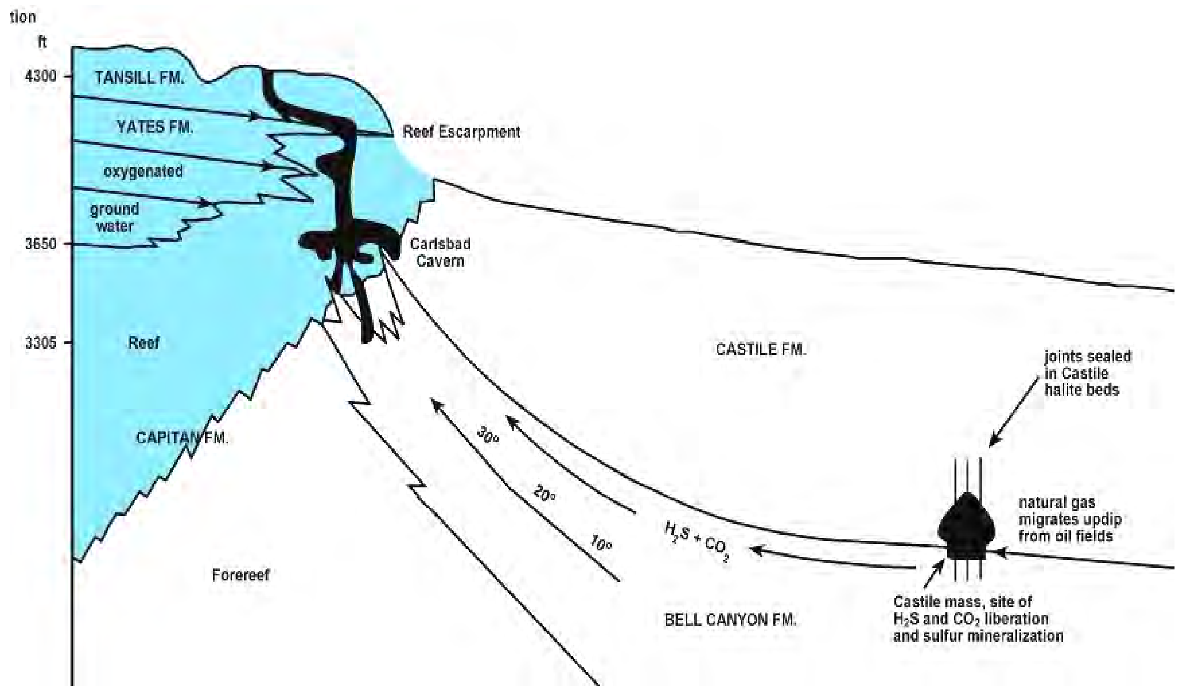


Figure 17. Schematic cross section showing the sulfuric acid burial karst model for forming the Carlsbad Cavern (from Hill, 1987).

Our Field Stop

The Carlsbad Cavern Visitor Center is situated directly above the Capitan reef and along what is termed the Reef anticline (Figure 18). The cavern is developed primarily along a series of joints that are parallel or perpendicular to the reef front. Passages are confined to the limestone reef, being sandwiched between backreef and forereef deposits. The natural entrance to the cavern is a paleospring developed in the Tansill formation. According to the work of Hill (1987), the entrance paleospring was operative ~1 Ma ago, but had ceased functioning by the time the Big Room level was being excavated (~0.75-0.85 Ma). With the lowering of regional base level, horizontal levels of cave passage were developed at new water table positions.

Our field stop will be a self-guided geologic walking tour proceeding from the natural entrance along the marked trail. Hill (1993) provides an invaluable guide for our hike.

Hill, C. A., 1993, Geologic Walking Tour of Carlsbad Cavern: New Mexico Geological Society Guidebook, 44th Field Conference, Carlsbad Region, New Mexico and West Texas, p. 117-128.

Large cave systems like Carsbad Cavern provide a glimpse of the type of cave facies that one might expect in the subsurface: fractured cave roof, cave fill sediment, and cave floor collapse breccia. Our hike is an opportunity to compare observations from Carlsbad Cavern with what we might expect in paleokarst reservoirs in the subsurface.

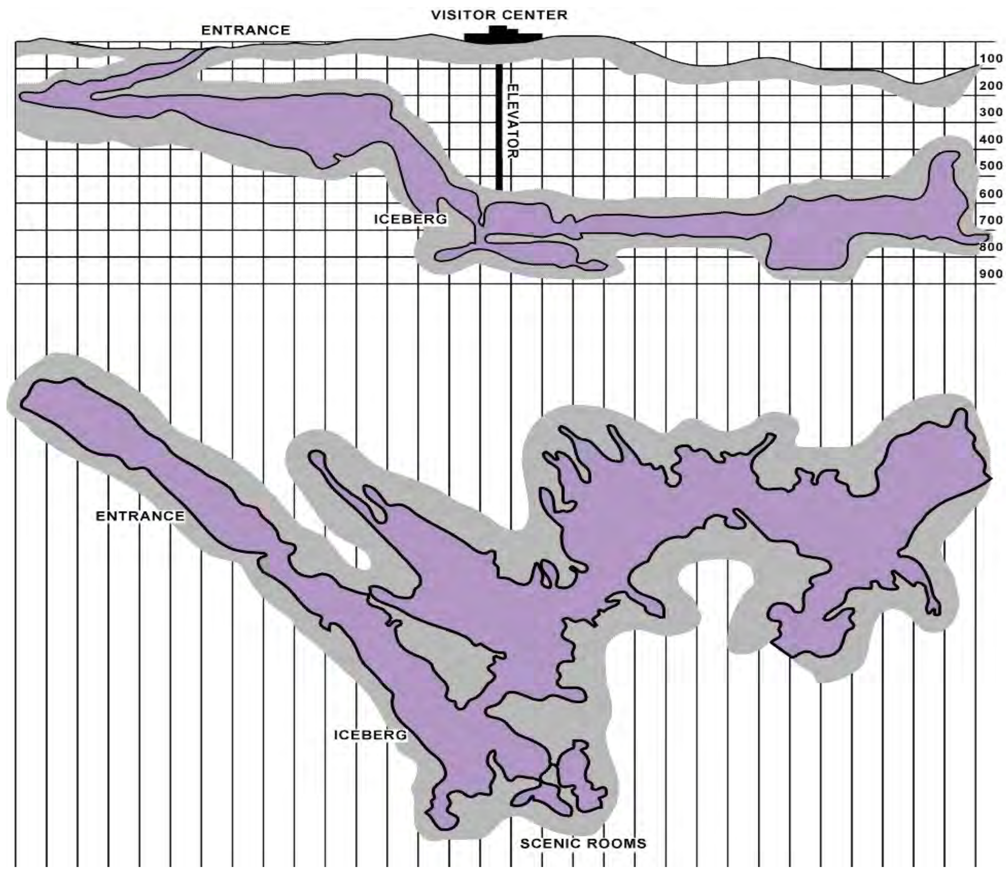


Figure 18. Schematic cross section and map showing cave development and the basic route of our cave tour.

Key Points

Origin of cave system
Attributes of cave diagenesis
Resultant "cave facies"
Paleokarst reservoirs

Field Stop - El Capitan Overlook

Basinal Siliciclastics

A thick succession of siltstones, sandstones and minor carbonates fills the Delaware Basin. Only the Bell Canyon, which is the uppermost portion of the Delaware Mountain Group, is age-equivalent to the Capitan margin. Ideas on the deposition of these basinal deposits have evolved over time. King (1948) and Newell *et al.* (1953) initially proposed deposition of the Brushy Canyon (older than the Capitan) as a shallow-marine environment based on the abundance of sand and abundant ripples. The recognition of graded beds in the basinal deposits (Hull, 1957; Jacka *et al.*, 1968) suggested deposition as deep water turbidites. The stratigraphic position of the basin-fill has led most subsequent workers to invoke deeper water depositional environments (Payne, 1976; Bozanich, 1979; Williamson, 1977, 1979). Harms (1974) and Harms and Williamson (1988) proposed deposition by density currents created when high-salinity shelf waters flowed down into the less saline basin. Mazzullo *et al.* (1985) and Fischer and Sarnthein (1988) proposed deposition of sands and silts in the basin largely by eolian processes during base-level falls when the adjacent shelves were exposed above sea level. In this model, sands were carried across the shelf in dunes before deposition in subtidal environments at the basin margin (Figure 19). Those sands were episodically carried down slope and into the basin by gravity flows. In contrast, silts were transported largely as air-borne dust. Although concentrating on the Brushy Canyon, stratigraphic and depositional analyses by Gardner and Sonnenfeld (1996) have clarified depositional processes which are also probably applicable to the Bell Canyon.

The source for the siliciclastics of the Delaware Basin is still being debated. Kocurek and Kirkland (1998) proposed that the basinal siliciclastics were derived from eolian systems in the Whitehorse Group of the Anadarko Basin. Previous workers hypothesized on a more northerly or northwesterly source.

Timing of Siliciclastic Bypass to Basin

The timing and nature of siliciclastic bypass into the Delaware Basin is arguable. Is sand and silt being transported to the basin across a few major surfaces**,** *i.e.,* 3rd-order sequence boundaries? Or, are the numerous high-frequency exposure surfaces apparent in outcrops and cores important times of sand bypass? In light of the high-frequency stratigraphic hierarchy apparent in shelf strata of the Capitan, at what level does the reciprocal sedimentation proposed by Meissner (1972) actually operate? The outcrops of outer-shelf facies in McKittrick and Walnut canyons, the subsurface studies of Borer and Harris (1991), and computer modeling of Borer and Harris (1995) suggest that siliciclastics readily bypassed across numerous surfaces within the Capitan margin with only minor fluctuations of relative sea level.

Borer and Harris (1995) argued for repeated input of siliciclastic sands into the basin during high-frequency subaerial exposure and bypassing of the shelf. Mruk and Bebout

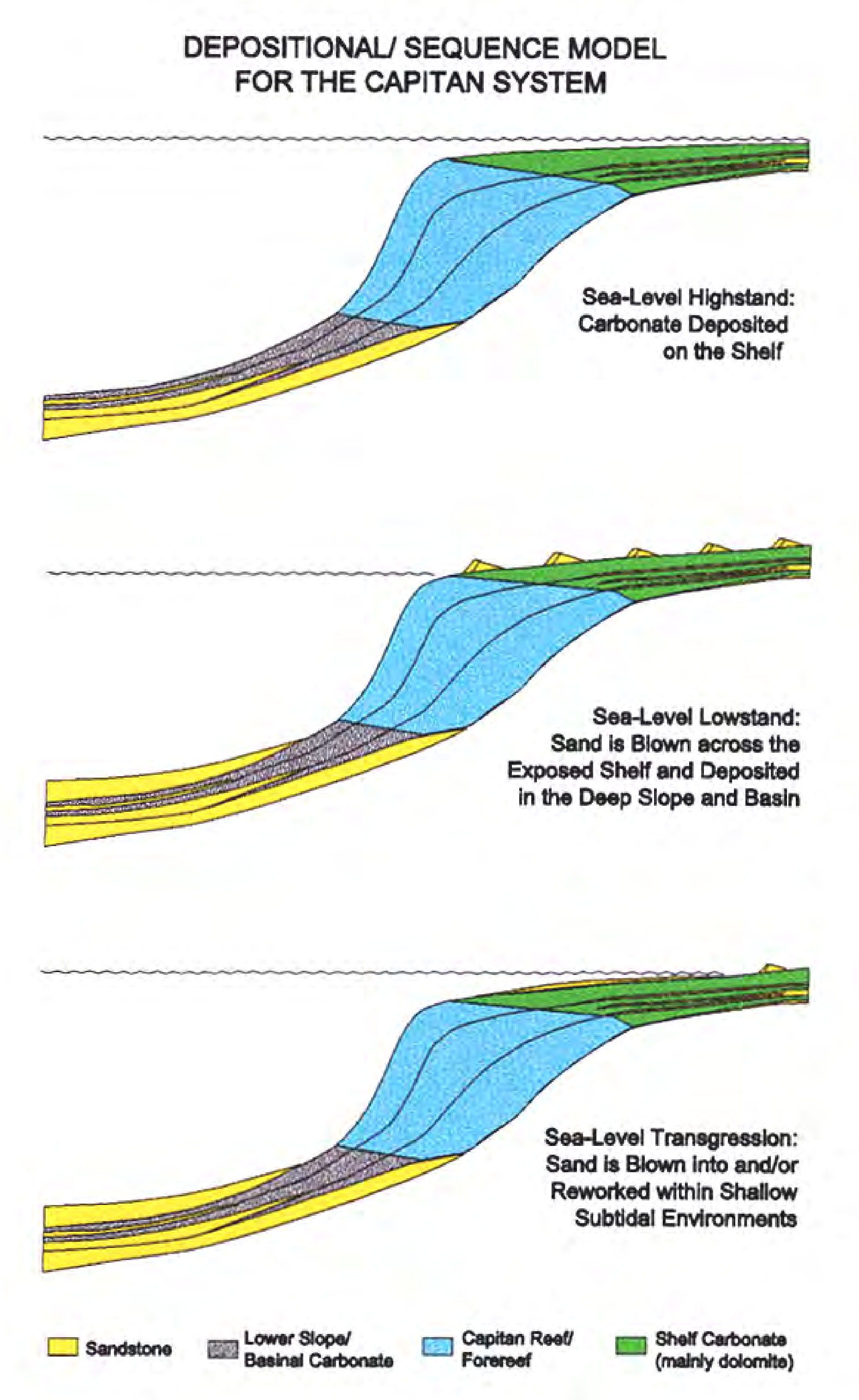


Figure 19. Simplified model based on reciprocal sedimentation concept and stressing changes in sea-level position and related shelf, shelf-margin, and basin stratigraphy of the Capitan margin. (from Harris and Saller, 2000).

(1993), Brown and Loucks (1993), and Brown (1996) documented high-frequency siliciclastic input toward the basin within the slope and toe-of-slope at McKittrick Canyon outcrops. A distinct small-scale cyclicity is readily apparent in the basinal strata (Meissner, 1972; Kerans *et al.,* 1992, 1993; Borer and Harris, 1995; Gardner and Sonnenfeld, 1996) including the Bell Canyon Formation. A remaining question is the mechanism responsible for gravity flows to transport sand into the deep basin. The sediments are clay-poor, making a true "turbidity current" difficult to envisage. Similarly, the stratigraphic consensus appears to be that deposition occurred during lowstands of sea level when the shelf was exposed, making dense hypersaline brines difficult to concentrate on the shelf.

Shelf-to-basin relations are not known in detail in the Delaware Basin due to limited biostratigraphic control and the inability to trace beds or time lines from the cyclic shelf deposits, through the massive reef and foreslope, and into basinal siliciclastics. The presence of a strong hierarchy of depositional cycles on the shelf and also in the basin suggests that the cycles may be useful as a correlation tool. In order to use cycles for correlation, the link between shelf and basinal sedimentation needs to be well established, as was investigated by Tyrrell (1969) and Brown and Loucks (1993) for the Tansill and toe-of-slope equivalent Lamar deposits, and periods of potential missed cycle beats need to be recognized.

The current shelf-to-basin correlation scheme for the Capitan shelf margin is loosely based largely on a series of five carbonate tongues that prograded part way into the basin at discrete times (King, 1948; Newell *et al.,* 1953; Kerans and Tinker, 2000). But the genetic implications of these carbonate wedges are not well understood. Are they highstand deposits, lowstand deposits, or both? Certainly, they do not all have the same character and the detailed geology within an individual wedge suggests they consist of several genetic packages (Reekman, 1986; Lawson, 1989; Brown and Loucks, 1993). Also, the carbonate tongues are only easily recognizable proximal to the toe of slope so they cannot be used as correlation tools further into the basin. The tongues are difficult to recognize (particularly in cores and logs) within the slope proximal to the reef as was discussed by Garber *et al.* (1989).

Our Field Stop

Our stop will be a scenic overlook of El Capitan, an overview and discussion of the basin deposits in the Delaware Basin, and a chance for final discussions of all of the previous stops.

Key Points

- Relation between shelf and basin siliciclastics
- Reciprocal sedimentation model
- Characteristics of basin sands and silts
- Local hydrocarbon production
- Field trip wrap-up

Major References

Of the extensive literature on the geology of the Capitan margin, only a few of the most pertinent are given below. Papers in SEPM Special Publication 65 (Saller *et al.*, 2000) contain citations for most of the literature on the Capitan.

Compilations

Saller, A. H., Harris, P. M., Kirkland, B., and Mazzullo, S. J. (eds.), 2000, Geologic Framework of the Capitan Reef, SEPM Special Publication No. 65, 224 p.

Harris, P. M. and Grover, G. A. (eds.), 1989, Subsurface and Outcrop Examination of the Capitan Shelf Margin, Northern Delaware Basin – A Core Workshop: SEPM Core Workshop, No. 13, 481 p.

Hileman, M. E. and Mazzullo, S. J., 1977 (eds.), Upper Guadalupian Facies, Permian Reef Complex, Guadalupe Mountains, New Mexico and West Texas: 1977 Field Conference, v. 1, SEPM, Permian Basin Section, Publication 77-16, 508 p.

Field Guides

Harris, P. M. and Simo, J. A., 2000, Permian Platforms and Reefs in the Guadalupe and Hueco Mountains: SEPM Field Guide No. 9, 82 p.

Bebout, D. G. and Kerans, C., 1993, (eds.), Guide to the Permian Reef Geology Trail, McKittrick Canyon, Guadalupe Mountains National Park, West Texas, Guidebook 26: Austin, Bureau of Economic Geology, University of Texas, 48 p.

Reid, S. T., Bass, R. O. and Welch, P., (eds.), 1988, Guadalupe Mountains Revisited: West Texas Geological Society Publication 88-84, 202 p.

Toomey, D. F. and Babcock, J. A., 1983, Precambrian and Paleozoic Algal Carbonates, West Texas-Southern New Mexico: Colorado School of Mines, Professional Contributions, v. 11, 345 p.

Scholle, P. A. and Halley, R. B., 1980, Upper Paleozoic Depositional and Diagenetic Facies in a Mature Petroleum Province (A Field Guide to the Guadalupe and Sacramento Mountains of West Texas and New Mexico): U. S. Geological Survey, Open File Report 80-383, 191 p.

Pray, L. C. and Esteban, M. (eds.), 1977, Upper Guadalupian Facies, Permian Reef Complex, Guadalupe Mountains, New Mexico and West Texas: 1977 Field Conference Guidebook, v. 2, SEPM, Permian Basin Section, Publication 77-16, 194 p.

Dunham, R. J., 1972, Capitan Reef, New Mexico and Texas – Facts and Questions to Aid Interpretation and Group Discussion: SEPM, Permian Basin Section, Publication 72-14, 297 p.

Key Older References

Hill, C. A., 1987, Geology of Carlsbad Cavern and Other Caves in the Guadalupe Mountains, New Mexico and Texas: New Mexico Bureau of Mines and Mineral Resources Bulletin, v. 117, 150 p.

Ward, R. F., Kendall, C. G., and Harris, P. M., 1986, Upper Permian (Guadalupian) Facies and Their Association with Hydrocarbons - Permian Basin, West Texas and New Mexico: AAPG Bulletin, v. 70, p. 239-262.

Tyrrell, W. W., Jr., 1969, Criteria Useful in Interpreting Environments of Unlike but Time-Equivalent Carbonate Units (Tansill-Capitan-Lamar), Capitan Reef Complex, West Texas and New Mexico, *in* Friedman, G. M. (ed.), Depositional Environments in Carbonate Rocks: SEPM Special Publication No. 14, p. 80-97.

Silver, B. A. and Todd, R. G., 1969, Permian Cyclic Strata, Northern Midland and Delaware Basins, West Texas and Southeastern New Mexico: AAPG Bulletin, v. 53, p. 2223-2251.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U. S. Geological Survey, Professional Paper No. 446, 69 p.

Newell, N. D., Rigby, J. K., Fischer, A. G., Whiteman, A. J., Hickox, J. E., and Bradley, J. S., 1953, The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico, A Study in Paleoecology: San Francisco, W. H. Freeman and Co., 236 p.

King, P. B.,1948, Geology of the Southern Guadalupe Mountains, Texas: U. S. Geological Survey Professional Paper 215, 183 p.

Key Recent References

Kerans, C. and Tinker, S. W., 2000, Extrinsic Stratigraphic Controls on Development of the Capitan Reef Complex, *in* Saller, A. H., Harris, P. M., Kirkland-George, B., and Mazzullo, S. J. (eds.), Geologic Framework of the Capitan Reef: SEPM Special Publication No. 65, p. 15-36.

Osleger, D. A. and Tinker, S. W., 1999, Three-Dimensional Architecture of Upper Permian High-Frequency Sequences, Yates-Capitan Shelf Margin, Permian Basin, USA, *in* Harris, P. M., Saller, A. H., and Simo, J. A. (eds.), Advances in Carbonate Sequence Stratigraphy - Application to Reservoirs, Outcrops, and Models: SEPM Special Publication No. 63, p. 169-185.

Tinker, S. W., 1998, Shelf-to-Basin Facies Distributions and Sequence Stratigraphy of a Steep-Rimmed Carbonate Margin: Capitan Depositional System, McKittrick Canyon, New Mexico and Texas: Journal of Sedimentary Research, v. 68, No. 6, p. 1146-1174.

Osleger, D. A., 1998, Sequence Architecture and Sea-Level Dynamics of Upper Permian Shelfal Facies, Guadalupe Mountains, Southern New Mexico: Journal of Sedimentary Research, v. 68, p. 327-346.

Kirkland, B. L., Dickson, J. A. D., Wood, R. A., and Land, L. S., 1998, Microbialite and Microstratigraphy: The Origin of Encrustations in the Middle and Upper Capitan Formation, Guadalupe Mountains, Texas and New Mexico, U.S.A.: Journal of Sedimentary Research, v. 68, p. 956-969.

Hill, C. A., 1996, Geology of the Delaware Basin, Guadalupe, Apache, and Glass Mountains, New Mexico and West Texas: SEPM, Permian Basin Section, Publication 96-39, 480 p.

Saller, A. H., 1996, Differential Compaction and Basinward Tilting of the Prograding Capitan Reef Complex, Permian, West Texas and Southeast New Mexico, USA: Sedimentary Geology, v. 101, p. 21-30.

Rankey, E. C. and Lehrmann, D. J., 1996, Anatomy and Origin of Toplap in a Mixed Carbonate-Clastic System, Seven Rivers Formation (Permian, Guadalupian), Guadalupe Mountains, New Mexico, USA: Sedimentology, v. 43, p. 807-826.

Senowbari-Daryan, B. and Rigby, K., 1996, Brachiopod Mounds not Sponge Reefs, Permian Capitan-Tansill Formations, Guadalupe Mountains, New Mexico: Journal of Paleontology, v. 70, p. 697-701.

Wood, R., Dickson, J. A. D., and Kirkland, B. L., 1996, New Observations on the Ecology of the Permian Capitan Reef, Texas and New Mexico: Paleontology, v. 39, p. 733-762.

Borer J. M. and Harris, P. M., 1995, Computer Simulation of the Yates Formation (Permian, Delaware Basin) - Sequence Stratigraphy and Shelf-to-Basin Correlation Implications, *in* Martin, R. L. (ed.), In Search of New Permian Basin Oil and Gas Fields: Using Today's Technologies and Tomorrow's Ideas for Exploration, Development, and 3D Seismic in a Mature Basin: West Texas Geological Society Symposium, Publication 95-98, p. 111-132.

Mutti, M. and Simo, J. A., 1994, Distribution, Petrography and Geochemistry of Early Dolomite in Cyclic Shelf Facies, Yates Formation (Guadalupian), Capitan Reef Complex, USA, *in* Loucks, R. L. and Sarg, J. F. (eds.), Carbonate Sequence Stratigraphy - Recent Developments and Applications: AAPG Memoir 57, p. 515-534.

Wood, R., Dickson, J. A. D., and Kirkland-George, B., 1994, Turning the Capitan Reef Upside Down: A New Appraisal of the Permian Capitan Reef, Guadalupe Mountains, Texas and New Mexico: Palaios, v. 9, p. 422-427.

Brown, A. A. and Loucks, R. G., 1993, Influence of Sediment Type and Depositional Processes on Stratal Patterns in the Permian Basin-Margin Lamar Limestone, McKittrick Canyon, Texas, *in* Loucks, R. G. and Sarg, J. F. (eds.), Carbonate Sequence Stratigraphy - Recent Developments and Applications: AAPG Memoir 57, p. 133-156.

Scholle, P. A., Ulmer, D. S., and Melim, L. A., 1992, Late-Stage Calcites in the Permian Capitan Formation and Its Equivalents, Delaware Basin Margin, West Texas and New Mexico - Evidence for Replacement of Precursor Evaporites: Sedimentology, v. 39, p. 207-234.

Borer, J. M. and Harris, P. M., 1991, Lithofacies and Cyclicity of the Yates Formation, Permian Basin - Implications for Reservoir Heterogeneity: AAPG Bulletin, v. 75, p. 726-779.

Appendices - Field Trip Presentations

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Capitan Margin on Outcrop – pages 1-22

Capitan Margin in Subsurface – pages 1-20

Carlsbad Caverns – pages 1-7

Microbial-Dominated Platform Margins – pages 1-15

Harris, P. M. and Kenter, J.A.M., 2003, Steep, Microbial-Dominated Platform Margins – Examples and Implications: AAPG Annual Convention Program and Abstracts, p. A71.

Value of Capitan Margin as a Reservoir Analog: Yates Formation – pages 1-8

Borer, J. M. and Harris, P. M., 1991, Lithofacies and Cyclicity of the Yates Formation, Permian Basin - Implications for Reservoir Heterogeneity: AAPG Bulletin, v. 75, p. 726-779.

Borer, J. M. and Harris, P. M., 1995, Computer Simulation of the Yates Formation (Permian, Delaware Basin) - Sequence Stratigraphy and Shelf-to-Basin Correlation Implications, in Martin, R. L. (ed), In Search of New Permian Basin Oil and Gas Fields: Using Today's Technologies and Tomorrow's Ideas for Exploration, Development, and 3D Seismic in a Mature Basin: West Texas Geological Society Symposium, Publication No. 95-98, p. 111-132.

Value of Capitan Margin as a Reservoir Analog: Tengiz Field – pages 1-16

Harris, P. M., Bassant, P., and Kuanysheva, G., 2003, Geologic Framework and Reservoir Distribution, Tengiz Field, Kazakhstan: XVth International Congress on Carboniferous and Permian Stratigraphy, Abstracts, p. 197-198.

Weber, L. J., Francis, B. P., Harris, P. M., and Clark, M., 2004, Stratigraphy, Facies, and Reservoir Characterization - Tengiz Field, Kazakhstan: in Ahr, W. M., Harris, P. M., Morgan, W. A., and Somerville., I., (eds.), Permo-Carboniferous Carbonate Platforms and Reefs, Joint SEPM Special Publication No. 78 – AAPG Memoir 83 (in press).