A Field Trip Guide to The Guadalupe Mountains*

P.M. Harris[1]

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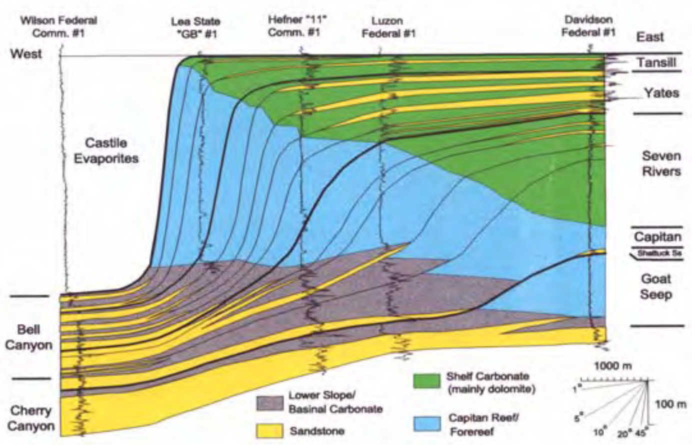
Introductory Statement

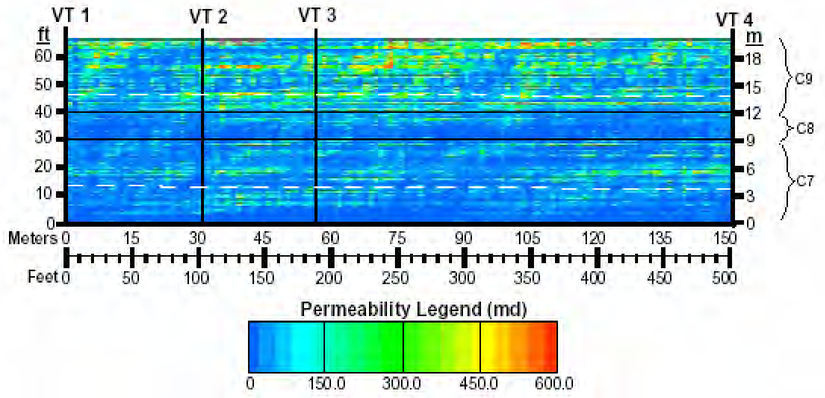
Well studied outcrops in the Guadalupe Mountains of New Mexico and Texas are a world-class laboratory for investigating most aspects of carbonate rocks. The outcrops serve as important analogs for other carbonate areas where the data is more limited and have had immediate application to subsurface hydrocarbon exploration and exploitation efforts in the immediately adjacent Permian Basin.

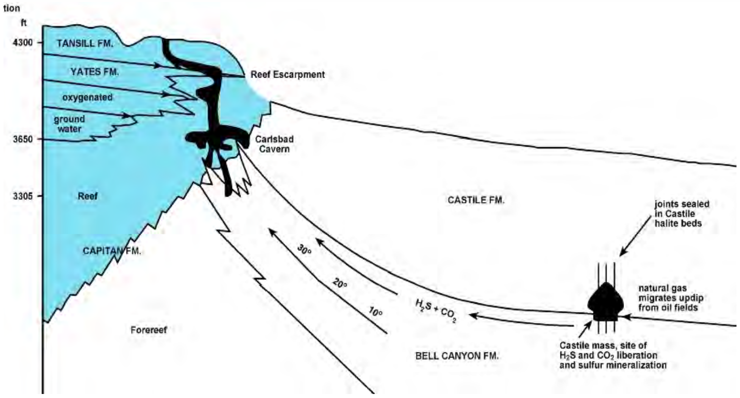
Large-scale outcrops like that of McKittrick Canyon and the Algerita Escarpment offer an unparalleled view into the inside of a carbonate platform. We will visit the Capitan reef margin in McKittrick Canyon, examine analogs for layered shelf reservoirs on Algerita Escarpment, and hike through the world-famous Carlsbad Cavern. Observations at these major stops and at additional other minor stops should provide new insight into carbonate stratigraphy, facies, and diagenesis, as well as into the potential complexities of shelf, slope, and paleokarst carbonate reservoirs.

Field Trip Guide

A FIELD TRIP GUIDE TO THE GUADALUPE MOUNTAINS







RICE UNIVERSITY AND UNIVERSITY OF MIAMI
FIELD TRIP

April 7 - 10, 2005

The Guadalupe Mountains –
A Field Trip for Rice University and the University of Miami

Well-studied outcrops in the Guadalupe Mountains of New Mexico and Texas are a world-class laboratory for investigating most aspects of carbonate rocks. The outcrops serve as important analogs for other carbonate 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.

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Field Trip Agenda

Day 1 – Thursday

Drive from El Paso to Guadalupe Mountains

Overview of Western Escarpment of the Guadalupe and Delaware Mountains to introduce the geology of the Permian Basin and the Guadalupe Mountains

Major field stop: McKittrick Canyon for overview of steep platform margin architecture and discussion of stratigraphy, facies, organisms, and diagenesis of the outer shelf, platform margin and slope associated with the Capitan reef

Examine roadcuts of Rader megabreccia and Lamar limestone (basin deposits), as well as the Castile evaporate (basin demise and top seal), to broaden the observations from McKittrick Canyon

Overnight at Stevens Inn, Carlsbad.

Day 2 - Friday

Major field stop: Shelf cycles and outer shelf – Capitan reef transition on outcrops in Walnut Canyon for examination of shelf facies and cyclicity and of reef facies, organisms, and diagenesis

Major field stop: Spectacular cave system of Carlsbad Cavern for a discussion of cave formation, cave facies, and paleokarst reservoirs

Lecture and discussions of Capitan-style of carbonate platform

Overnight at Stevens Inn, Carlsbad.

Day 3 - Saturday

Major field stop: Algerita Escarpment and other localities in the western portion of the Guadalupe Mountains for overview of ramp-style deposits of the San Andres and Grayburg Formations and discussion of stratigraphy, facies, reservoir quality, and reservoir modeling of layered shelf reservoirs.

Lecture and discussion of ramp-style of carbonate platform

Overnight at Stevens Inn, Carlsbad

Day 4 - Sunday

Examine roadcuts of Cherry Canyon and Brushy Canyon basinal clastics to discuss interplay between shelf and basin

Scenic overlook and wrap-up of field trip

Return to El Paso

Field trip leader and Guidebook preparation:	**Paul M. (Mitch) Harris** ChevronTexaco Energy Technology Company, San Ramon, CA
Co-leader:	**Andre Droxler** Rice University, Houston, TX

Why Are We Visiting These Outcrops?

Capitan Reef Margin

Our visit to McKittrick Canyon offers unparalleled insight into how a steep-sided carbonate platform margin develops through time. The manner in which the margin progrades and the shelf aggrades is quite obvious from the seismic-scale views. Our discussions will focus on the stratigraphy and interrelations between the shelf and basin; the depositional profile and facies of the outer shelf, platform margin, and slope associated with the Capitan reef; organisms and diagenesis of the reef margin; and the subsurface expression of these deposits on seismic and well data. In addition, we will discuss the implications of the stratigraphic and facies relationships on subsurface correlation and reservoir heterogeneity.

We will also briefly examine varied basin deposits near McKittrick Canyon, the outer shelf equivalents to the Capitan in Walnut Canyon, and basinal siliciclastics near a scenic overlook of Guadalupe Peak.

Algerita Escarpment

Our day visiting the Algerita Escarpment and other nearby localities in the western Guadalupe Moutnains is a unique chance to examine a ramp-style carbonate shelf-to-basin transition from a distance to see the large-scale stratigraphic relations and close-up to see the nature of the stratigaphic layering in these types of reservoirs. Our discussions will focus on the sequence- and cycle-scale stratigraphy, the facies of a cycle and their reservoir quality, the spatial distribution of porosity and permeability, and reservoir simulation modeling experiments of these outcrops. We will focus on the implications of the stratigraphic and facies relationships on reservoir heterogeneity.

The San Andres and Grayburg outcrops that we examine along the Algerita Escarpment are equivalent to the principle producing units in large carbonate reservoirs of the Permian Basin, so there is a direct relation between nearly all of our observations and the production character of these reservoirs.

Carlsbad Cavern

Our hike through the Carlsbad Cavern is a unique and spectacular opportunity to view and discuss the formation and facies of large cave systems, the myriad of cave ornamentation, and the relevance of these observations to recognizing paleokarst systems in the subsurface. We will discuss paleokarst reservoirs during our hike and focus on aspects of reservoir heterogeneity.

Background Geology Information

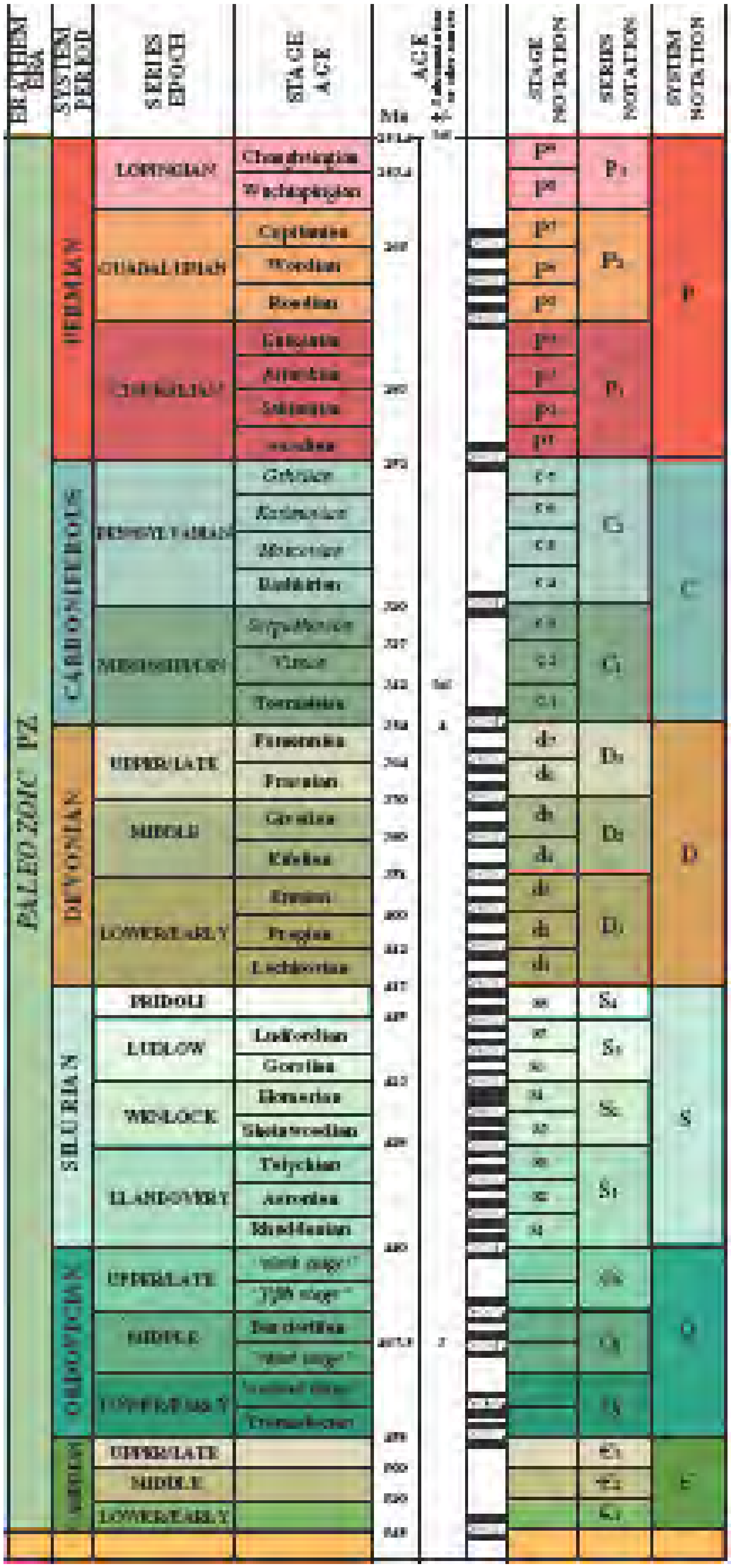


Figure 1. Geologic time scale.

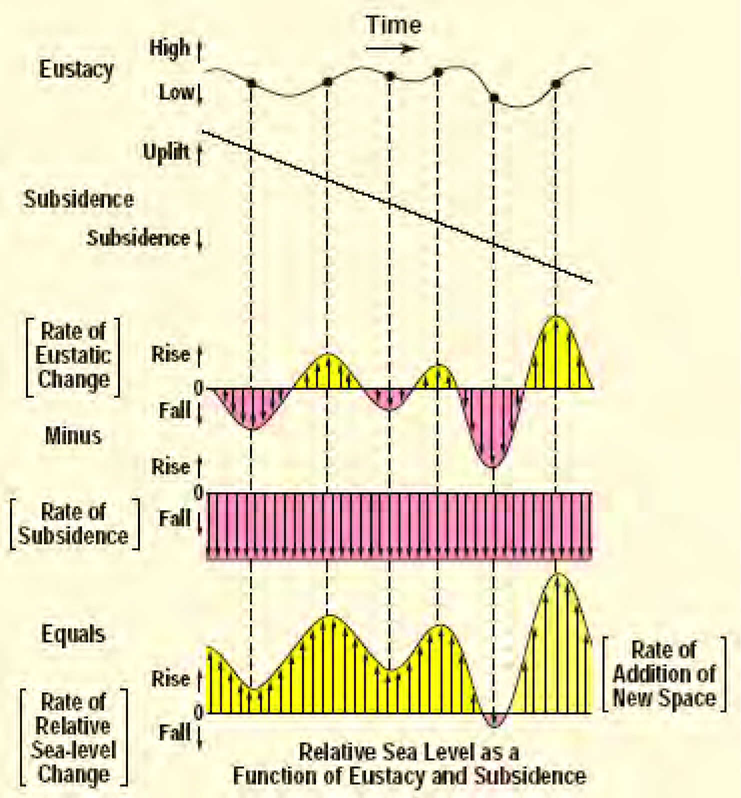


Figure 2. Relative sea-level changes through time control stratigraphy (layering).

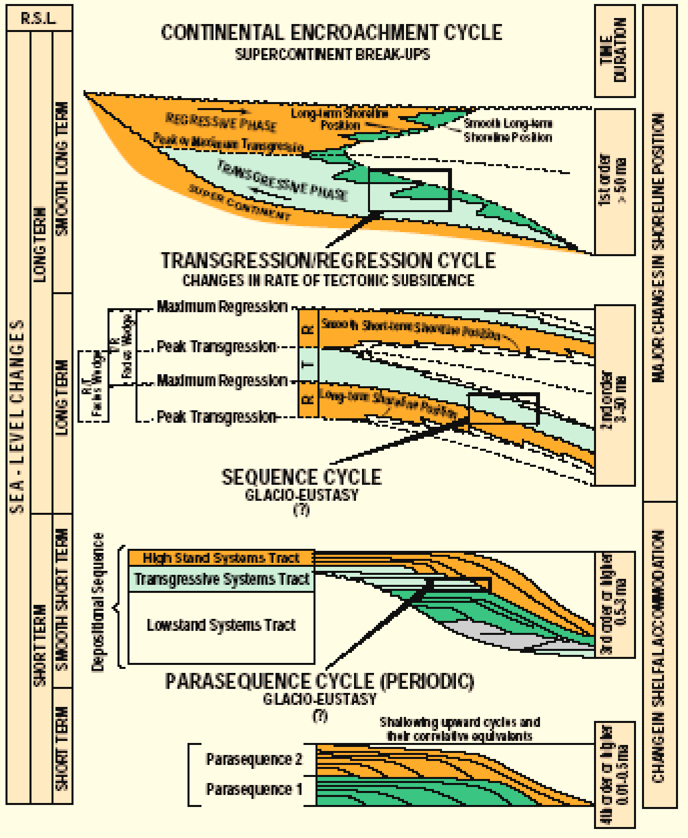
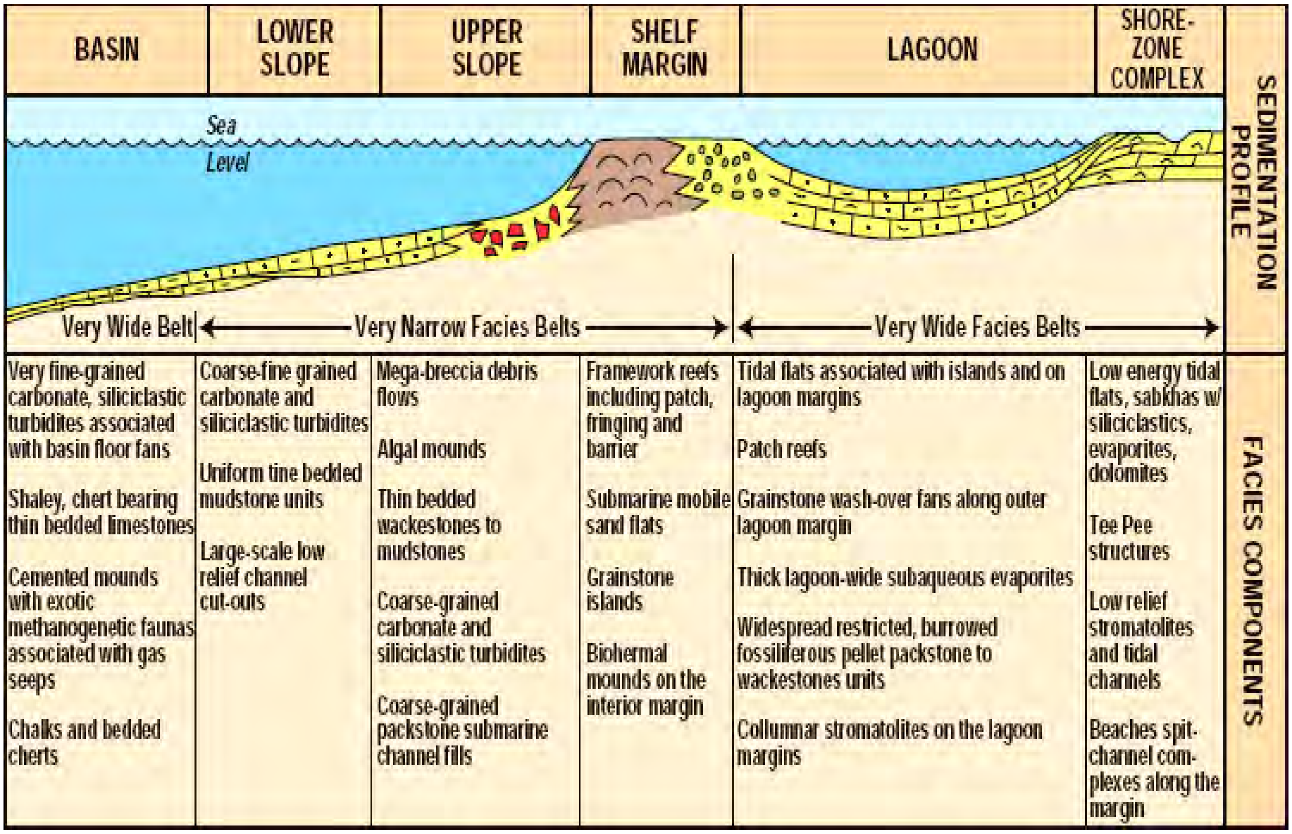
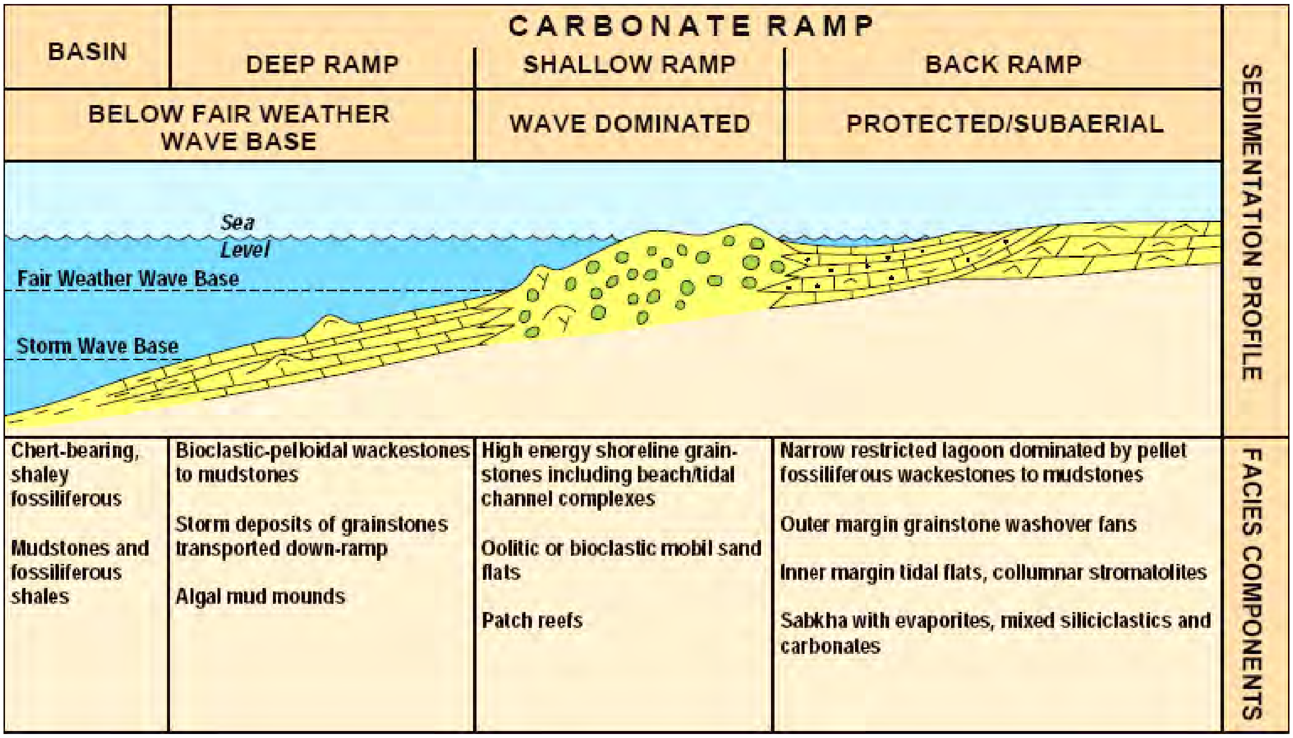


Figure 3. Geologic layering is systematically developed in response to the seal level change.



	BASIN	LOWER SLOPE	UPPER SLOPE	SHELF MARGIN	LAGOON	SHORE-ZONE COMPLEX
FACIES COMPONENTS	Very fine-grained carbonate, siliciclastic turbidites associated with basin floor fans Shaley, chert bearing thin bedded limestones Cemented mounds with exotic methanogenetic faunas associated with gas seeps Chalks and bedded cherts	Coarse-fine grained carbonate and siliciclastic turbidites Uniform tine bedded mudstone units Large-scale low relief channel cut-outs	Mega-breccia debris flows Algal mounds Thin bedded wackestones to mudstones Coarse-grained carbonate and siliciclastic turbidites Coarse-grained packstone submarine channel fills	Framework reefs including patch, fringing and barrier Submarine mobile sand flats Grainstone islands Biohermal mounds on the interior margin	Tidal flats associated with islands and on lagoon margins Patch reefs Grainstone wash-over fans along outer lagoon margin Thick lagoon-wide subaqueous evaporites Widespread restricted, burrowed fossiliferous pellet packstone to wackestones units Collumnar stromatolites on the lagoon margins	Low energy tidal flats, sabkhas w/ siliciclastics, evaporites, dolomites Tee Pee structures Low relief stromatolites and tidal channels Beaches spit-channel complexes along the margin

Figure 4. Carbonate platforms often develop steep slopes into the basin.



		CARBONATE RAMP		
	BASIN	DEEP RAMP	SHALLOW RAMP	BACK RAMP
	BELOW FAIR WEATHER WAVE BASE		WAVE DOMINATED	PROTECTED/SUBAERIAL
FACIES COMPONENTS	Chert-bearing, shaley fossiliferous Mudstones and fossiliferous shales	Bioclastic-pelloidal wackestones to mudstones Storm deposits of grainstones transported down-ramp Algal mud mounds	High energy shoreline grainstones including beach/tidal channel complexes Oolitic or bioclastic mobil sand flats Patch reefs	Narrow restricted lagoon dominated by pellet fossiliferous wackestones to mudstones Outer margin grainstone washover fans Inner margin tidal flats, collumnar stromatolites Sabkha with evaporites, mixed siliciclastics and carbonates

Figure 5. Carbonate platforms can also slope more gently toward the basin.

Salt Flat Graben - Introduction to Permian Basin and Overview of Guadalupe and Delaware Mountains

Location

The Late Permian (Guadalupian) mixed carbonate/siliciclastic sequences of the Permian Basin (Figure 6) are well known both for their classic outcrop exposures revealed by basin and range structuring in the Guadalupe Mountains (Figure 7) and for their prolific hydrocarbon production. 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.

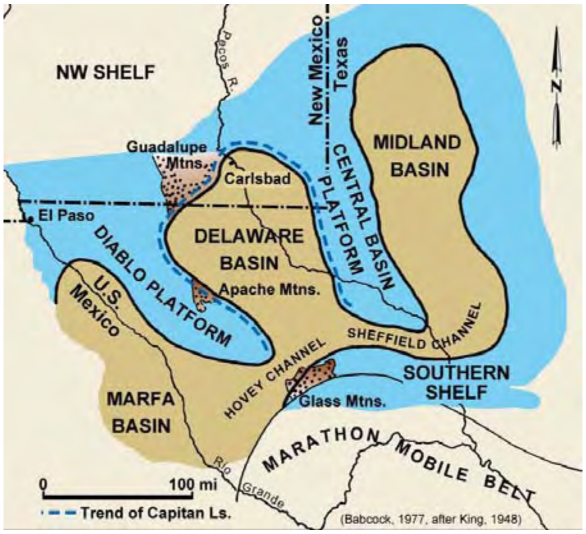


Figure 6. Map showing morphology and components of the Permian Basin. Note the location of the Guadalupe Mountains.

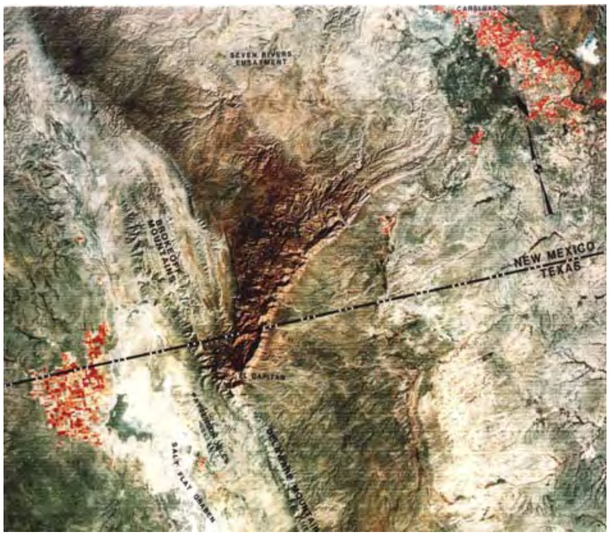


Figure 7. Landsat image of the Guadalupe and Delaware Mountains (from Harris and Kowalik, 1994). Carlsbad, N.M., is in the upper right corner.

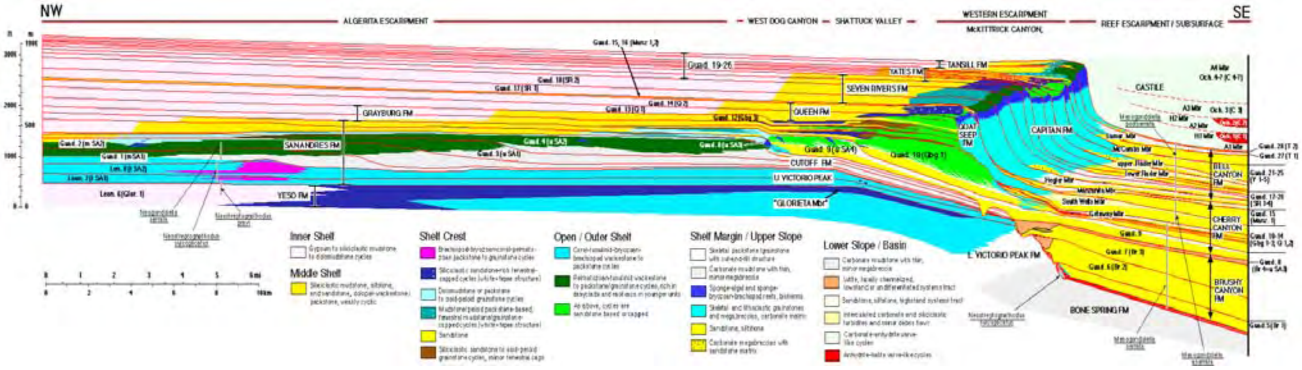


Figure 8. Cross section showing sequence stratigraphic framework developed for Permian outcrops in the Guadalupe and Delaware mountains (from Kerans and others, 1992)

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 6 and 7). 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 8) that provides an opportunity to examine the large-scale stratigraphic relations of the Capitan margin and older units.

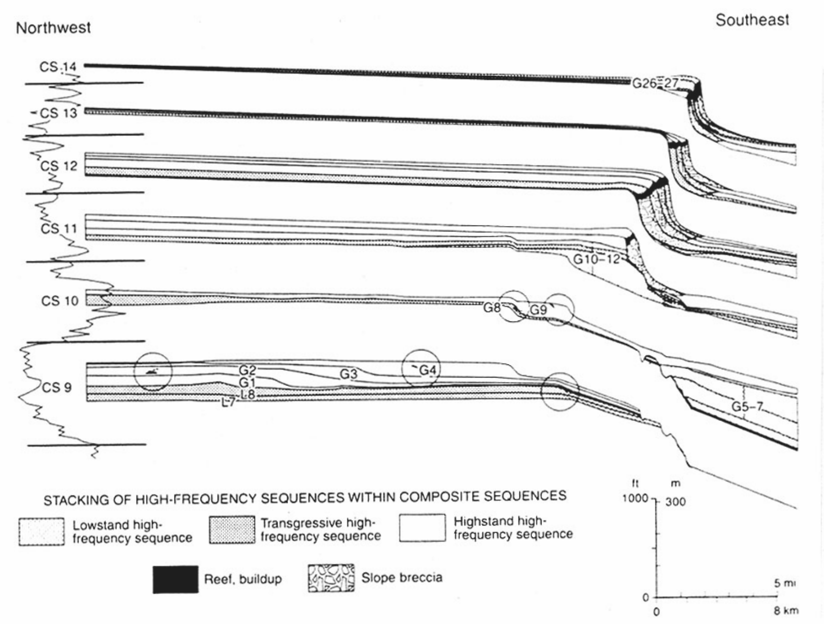
Large-Scale Stratigraphic Framework

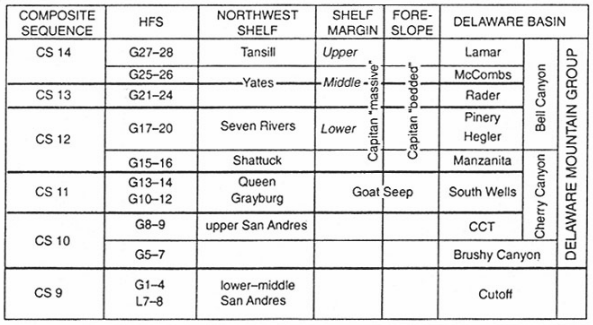
Deposits exposed along the western escarpment represent two major phases of basin-encroaching carbonate systems separated by a time when the shelf-to-basin transition regressed significantly northward (Figure 8). The Victorio Peak bank facies and Bone Spring basinal deposits, both Early Permian (Leonardian) 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 San Andres and Capitan margins.

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 (Figure 9). 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 in the early Grayburg of slope and toe-of-slope megabreccias with boundstone clasts 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. The Goat Seep reef margin initiates on the inherited steep topography. In turn, the Capitan margin occupies and accretes off the Goat Seep margin. 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.

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. Massive foreslope strata of the Capitan extended further south of the present erosional south face of El Capitan, and only





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 9. 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.

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. 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). Also, 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.

The purpose of the Salt Flat Graben 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.

Field Stop – McKittrick Canyon

Introduction

Outcrops in the mouth of McKittrick Canyon, Guadalupe Mountains National Park, are the focus of one of our major field stops (Figure 10). 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. The Permian Reef Geology Trail (PRGT) 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.

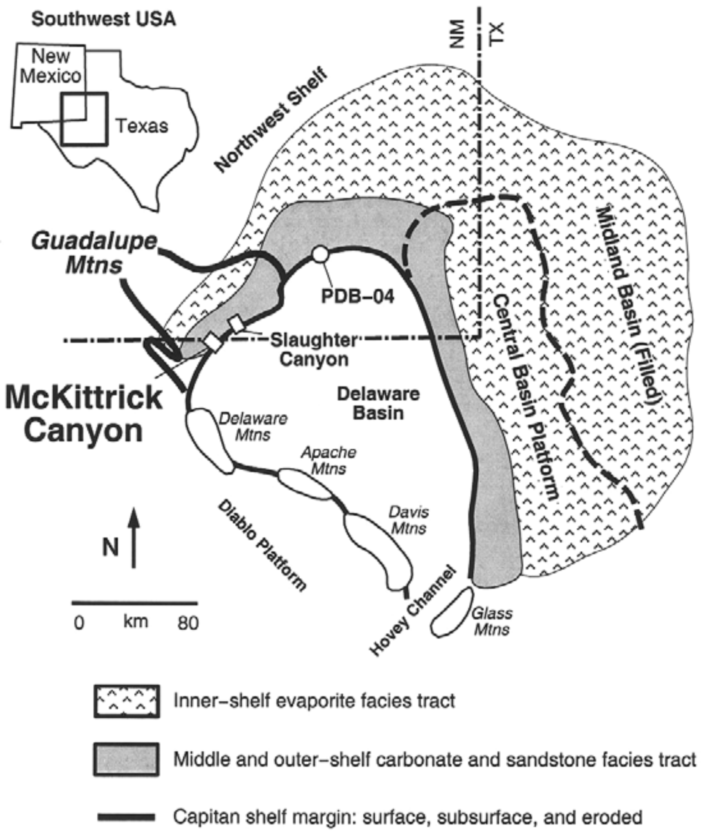


Figure 10. Map of West Texas and southeast New Mexico showing simplified facies distribution for Capitan time (modified after Ward *et al*., 1986). Note location of the Guadalupe Mountains and McKittrick Canyon.

A number of formation names have been applied to the rock units along a depositional profile across the Capitan margin: (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 (Figure 11).

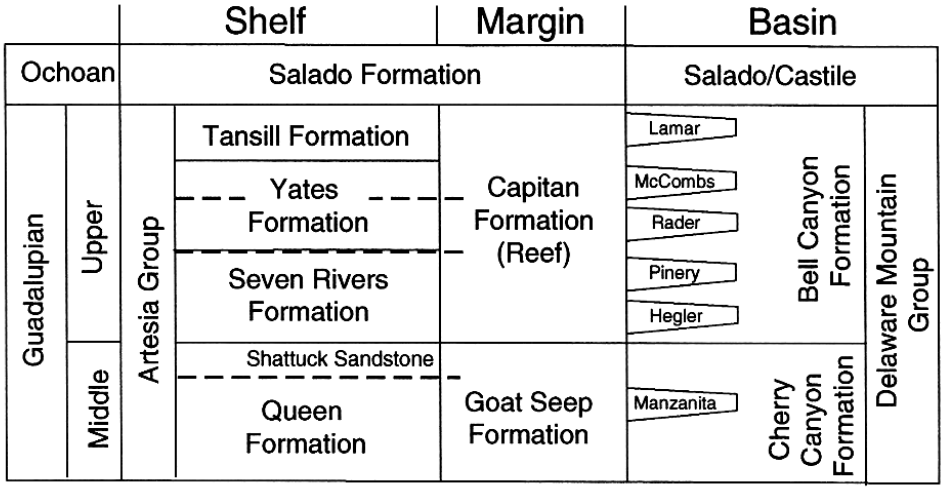


Figure 11. Stratigraphic nomenclature for the Capitan and Goat Seep margins (from Harris and Saller, 2000). Composite sequence boundaries of Kerans and Tinker (2000) are shown by dashed lines

Sequence Framework and Depositional Model

The Capitan margin is interpreted in the context of three composite sequences (CSs) and several HFSs (Figures 11 and 12). 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 (Figure 12).

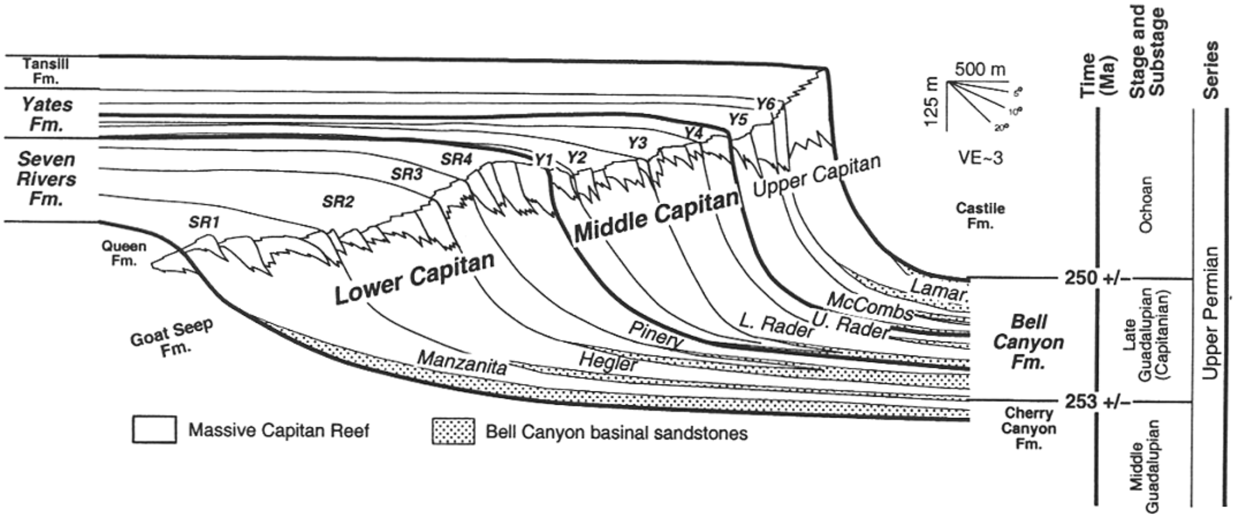


Figure 12. Simplified cross section of McKittrick Canyon (Tinker, 1998). Heavy lines are composite sequence boundaries; thin lines are high-frequency sequence boundaries. Time estimates are from Ross and Ross (1987).

During highstands, the shelf was flooded and carbonates were deposited on the outer 10-20 km of the shelf, the shelf margin and slope (Figure 13). At highstand times, downslope carbonate debris beds accumulated repeatedly, the shelf margin and slope prograded basinward, and the shelf aggraded. During sea-level fall, the shelf was subaerially exposed allowing siliciclastic sands and silts to be transported across the shelf and into the basin. Carbonate debris beds generated during lowstand conditions contain a siliciclastic matrix. 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, and minor amounts of sandstone/siltstone occur on the upper slope. Although depositional models for the basinal sandstones are still being debated, several studies 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.

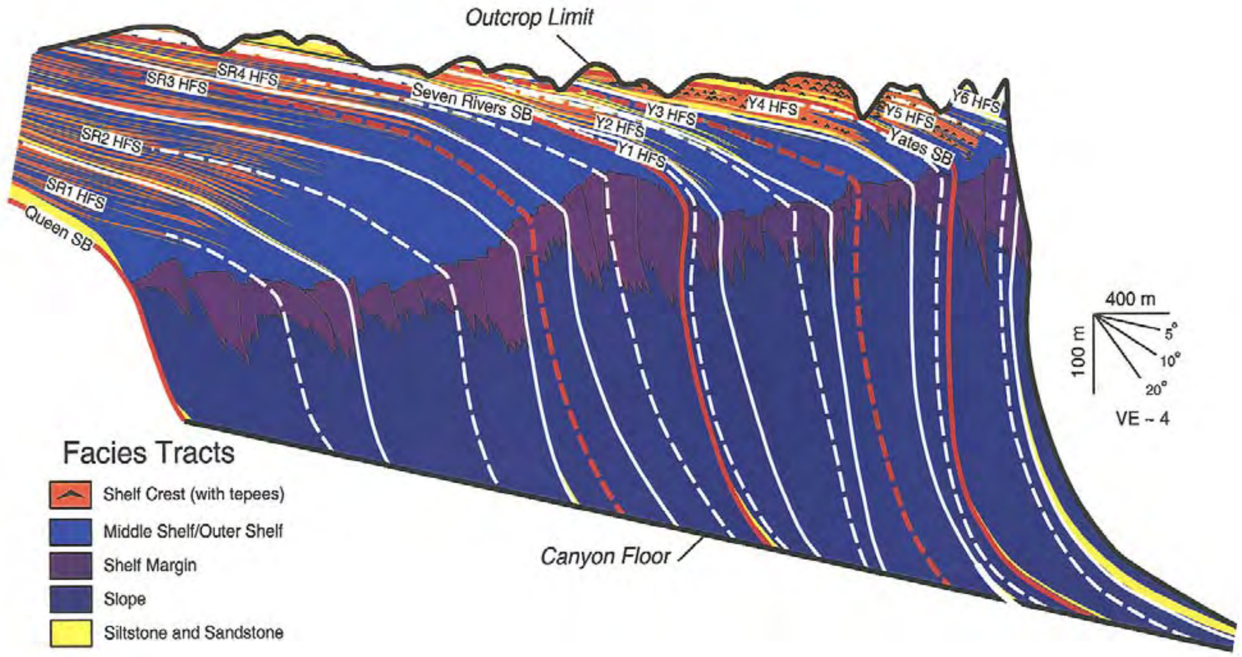


Figure 13. Simplified cross section of Capitan margin facies relations documented in McKittrick Canyon by Tinker (1998). Figure is shown with present-day, tectonically-enhanced basinward dip to the right. Solid red lines are CS boundaries, dashed red lines are CS MFSs, solid white lines are HFS boundaries,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

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 (Figures 13 and 14). This basinward-sloping geometry, referred to locally as the "fall-in bed" profile, is best developed in Seven Rivers strata. As the Capitan reef generally shallowed through time 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 on outcrop by tracing distinctive recessive siliciclastic-rich intervals and in the subsurface from core and log correlations.

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 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 13). 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.

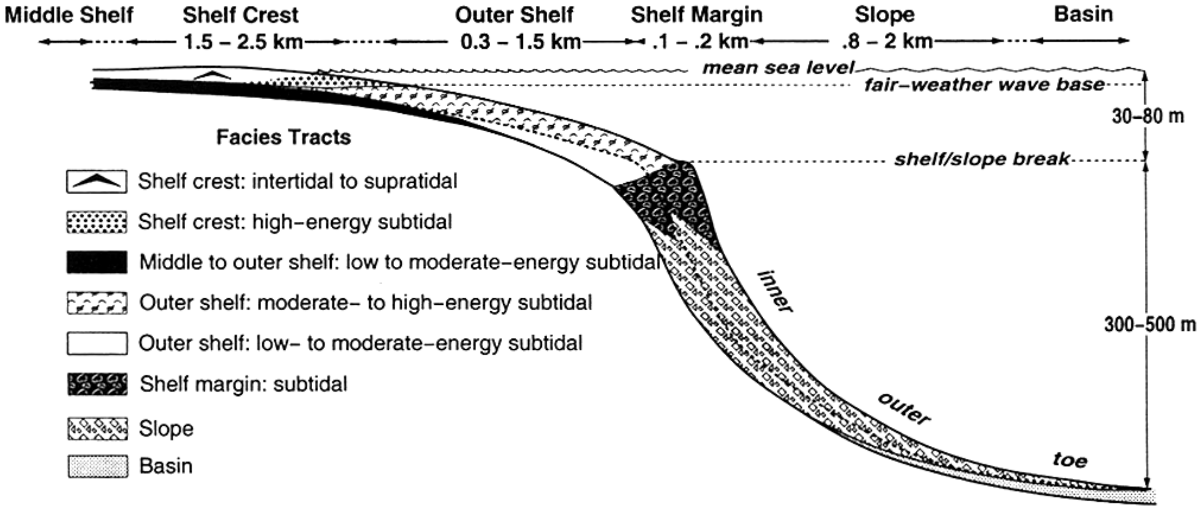


Figure 14. Generalized cross section showing the spatial distribution of major facies tracts of the Capitan margin related to a paleobathymetric profile (from Tinker, 1998).

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. Others saw a dominance of syndepositional cement and concluded that inorganic cement was the critical binding agent in the reef. Still others 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 showing that the Capitan is locally a framework with bryozoa, calcareous sponges, *Tubiphytes* and other organisms in growth position and with internal cavities. 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 shows gradual deepening of water from the shelf into the basin. Other models suggest shallowing at the shelf margin to form a barrier reef, or shallowing at a position landward of the reef where pisolite shoals define the shelf crest, or both. 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 14).

Subsurface Relations

The subsurface stratigraphy of the Capitan margin is very similar to outcrop stratigraphy recognized in the Guadalupe Mountains. Seismic data of the Capitan margin (Figure 15) 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 (Figure 16) 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.

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.

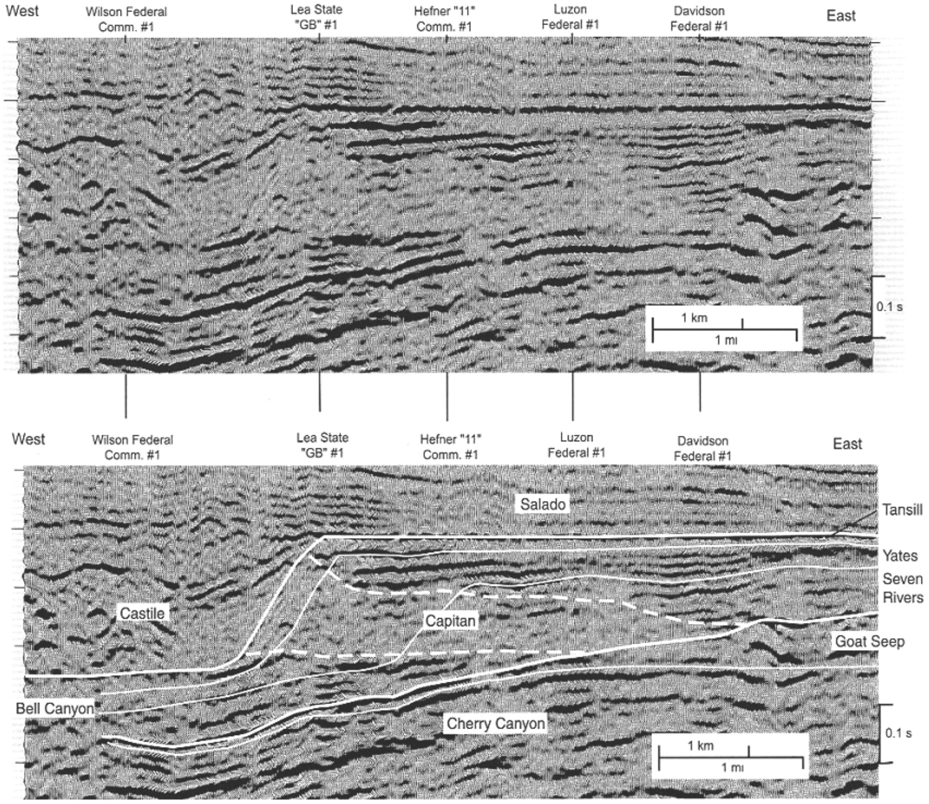


Figure 15. Uninterpreted (top) and interpreted (bottom) seismic line through the Capitan margin (from Harris and Saller, 2000). The line is flattened on the base of the Salado, and the vertical scale is two-way travel time. The vertical exaggeration is approximately 2:1.

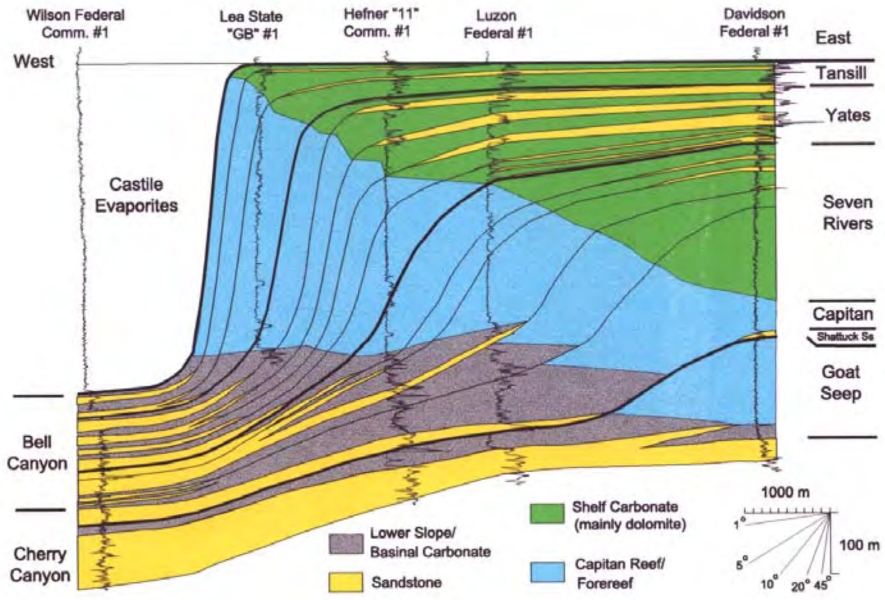


Figure 16. Subsurface stratigraphic cross section across the Capitan margin using wells located near the seismic line of Figure 15 (from Harris and Saller, 2000). Gamma-ray logs are shown for wells. Correlations follow seismic geometries as well as log patterns; datum is top Tansill except for basin well where top Castile is used.

Roadcut Stops Near McKittrick Canyon

Rader Slide – toe-of-slope and basin edge deposit of reef and slope debris representing times of exceptional failure of the carbonate margin and slope

Lamar Limestone – basin floor deposit of black, organic rich mudstone representing times of near anoxia in the Delaware Basin and forming a possible source rock for hydrocarbons

Castile Evaporite – basin-fill deposit of interlaminated gypsum (anhydrite) and calcite representing the demise of the Delaware Basin and forming a top seal over underlying hydrocarbon reservoirs

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. Individual siliciclastic reservoir zones show complex interfingering with carbonates in a downdip direction and evaporites in an updip direction. 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.

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. The Capitan Formation is a high permeability, fresh water aquifer around the margins of the basin.

A number of small oil fields occur in basin sandstones of the Bell Canyon Formation. 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.

Significance of Capitan Outcrops to Subsurface Reservoir Characterization

Many aspects of the Capitan margin that we have examined in McKittrick Canyon and related stops are similar to those of the supergiant Tengiz Field in the Caspian Basin of western Kazakhstan. Tengiz produces oil from an isolated carbonate platform (areal extent of 160 km^2) of Devonian and Carboniferous age (Figure 17).

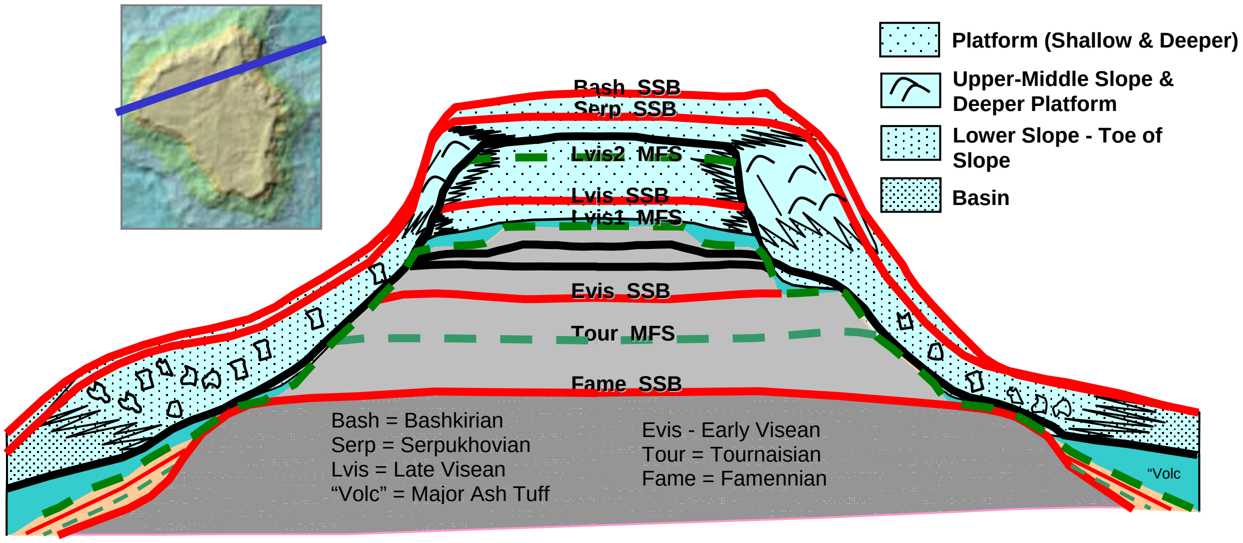


Figure 17. Geologic model for Tengiz field based on seismic, core, log, and biostratigraphy data. Bold lines mark seismic-scale supersequence boundaries (SSB). MFS = Maximum Flooding Surface; TST = Transgressive Systems Tract ; HST = Highstand Systems Tract. Modified after Weber and others (2003).

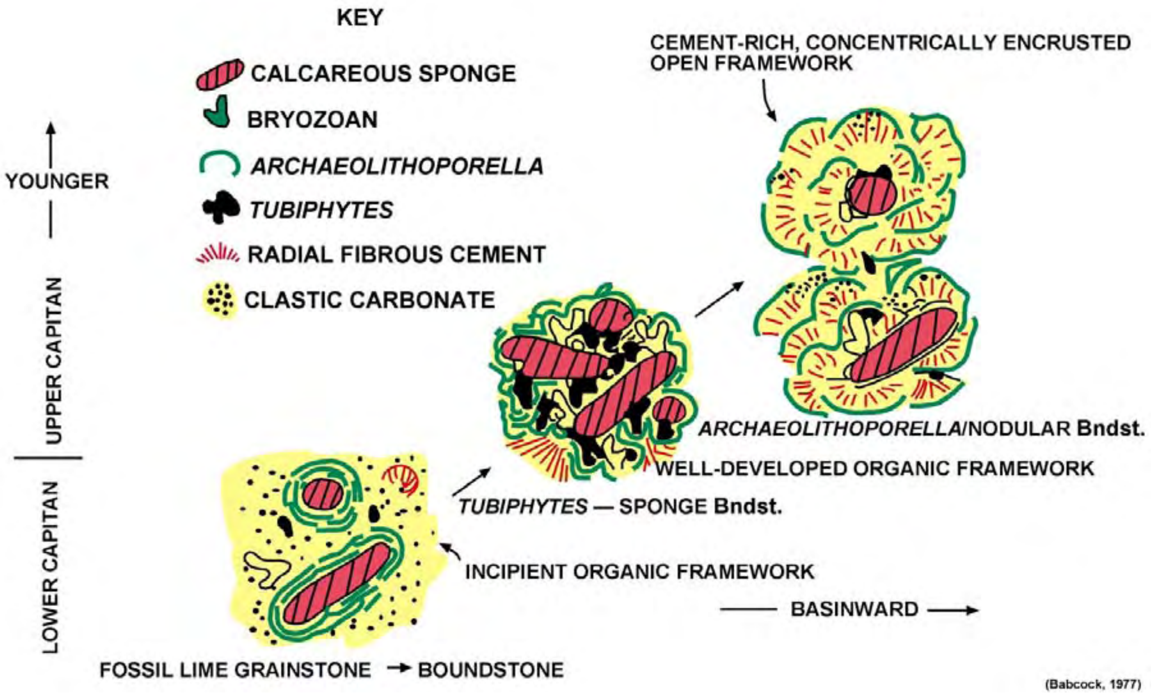
The stratigraphic framework was developed through an integrated interpretation of seismic, core, log, and biostratigraphic data. An initial broad Late Devonian platform exhibits was followed by punctuated backsteps during the Tournaisian and Viséan. The Serpukhovian is characterized by several kilometers of platform progradation. Drowning in the Early Bashkirian halted carbonate platform growth. Paleotopographic relief from the top of the Bashkirian platform to the basin floor approaches 1,500 meters.

Seismic and well data clearly show two principle regions within the buildup – platform and flank – that directly relate to reservoir quality and production characteristics. On the platform, hydrocarbons are produced from Upper Viséan through Bashkirian grainstones and mud-lean packstones. Multiple porosity types are recognized, but matrix permeability is controlled primarily by intergranular porosity. Within the flanks, in-place upper-slope microbial boundstone and transported lower-slope boundstone debris form thick and areally extensive mappable reservoirs (Late Viséan and Serpukhovian) that have distinctive seismic facies and production/performance characteristics. Fractures contribute to non-matrix permeability in these boundstones.

Field Stop – Walnut Canyon

Outer Shelf-to-Reef Transition

Outcrops at the mouth of Walnut Canyon allow close-up examination of reef facies and the transition from massive reef to bedded outer shelf. Spectacular on these outcrops are the variety of sponges, algae including phylloid algae, and pervasive marine cements. There is abundant evidence within the reef to suggest syndepositional cementation to the point that the reef was cracking open (Neptunian fissures) and rehealing.



(Babcock, 1977)

Figure 18. Capitan reef boundstone consists of primarily sponges and bryozoans, only locally framebuilding, abundant encrusting organisms and marine cements, and sediment filling growth cavities and fractures.

Yates Cycles

Yates high-frequency sequences (HFSs) and cycles, like those present in Walnut Canyon, 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. 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 19). 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. The perspective of the shelf sands and carbonates was broadened

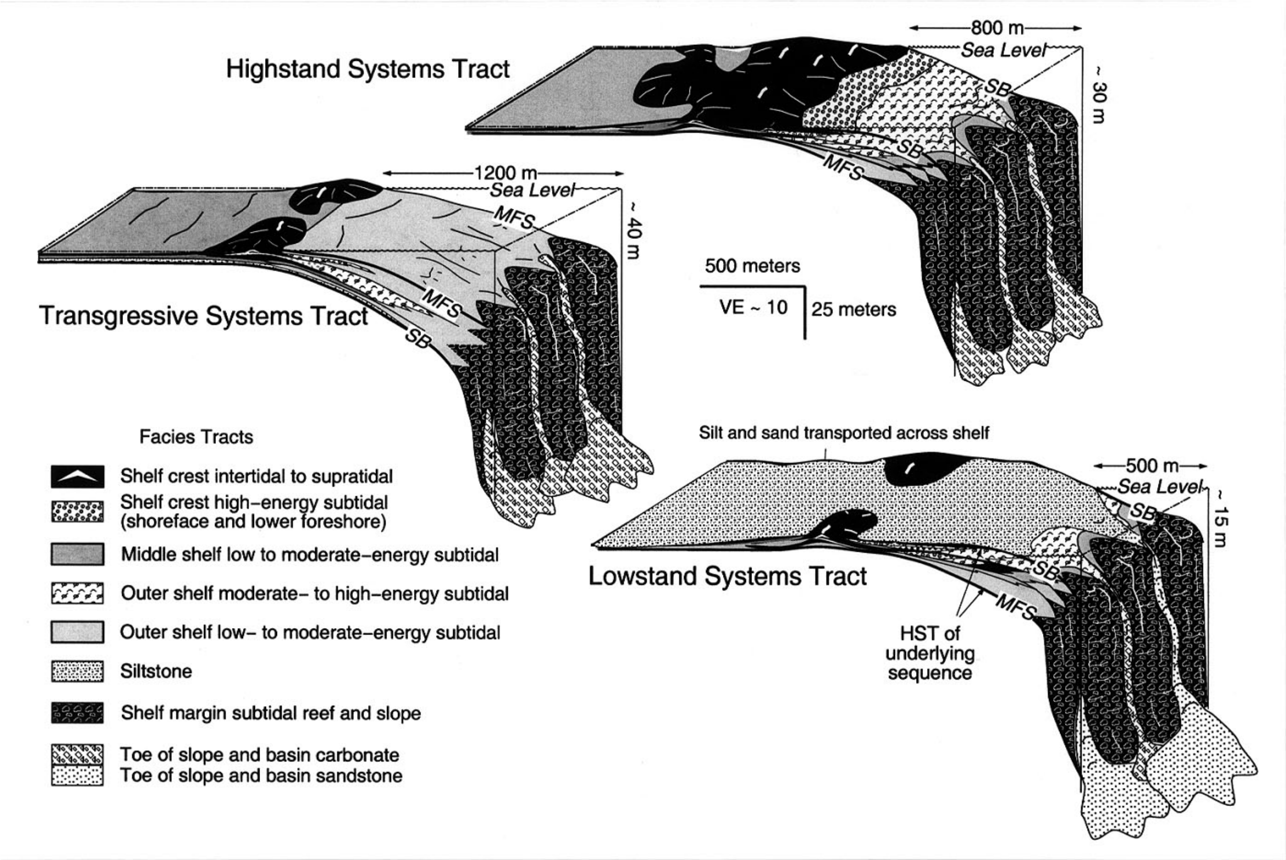


Figure 19. Three-dimensional models for Capitan facies distribution (from Tinker, 1998). The models are based on the Y3 HFS, but the systematic variation in facies with change in relative sea-level are observed in most of the Seven Rivers and Yates HFSs and CSs.

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 20). Most shelf sands occur above subaerial exposure surfaces (unconformities) which probably represent the time when most basinal sands were carried across the shelf. 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. With continued flooding of the shelf, carbonates form the upper portion of the shelf cycles.

Several workers have 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 20 and 21 shows the nature of this variability as documented from both subsurface and outcrop data.

Three distinctive cycles, occurring throughout this part of Walnut Canyon, are termed the Triplet unit of the uppermost Yates Formation. The cycles occur within the uppermost HFS recognized within the Yates. We will examine one of the prominent siliciclastic beds and a peritidal carbonate horizon containing well-developed teepee structures.

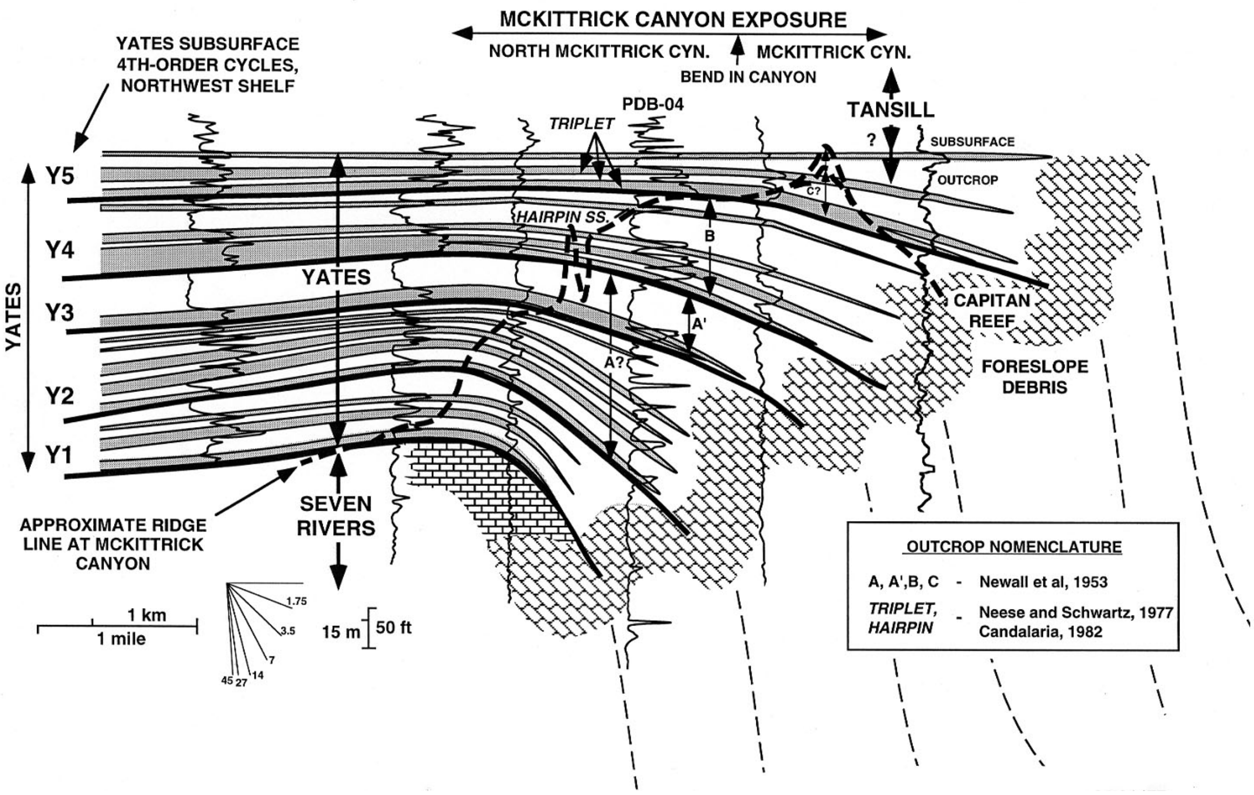


Figure 20. Yates subsurface cross section of Borer and Harris (1991) tied to outcrop exposures by Borer and Harris (1995). Gamma-ray logs are shown for the wells; siliciclastic beds are shaded. The Triplet unit within the upper Yates is identified.

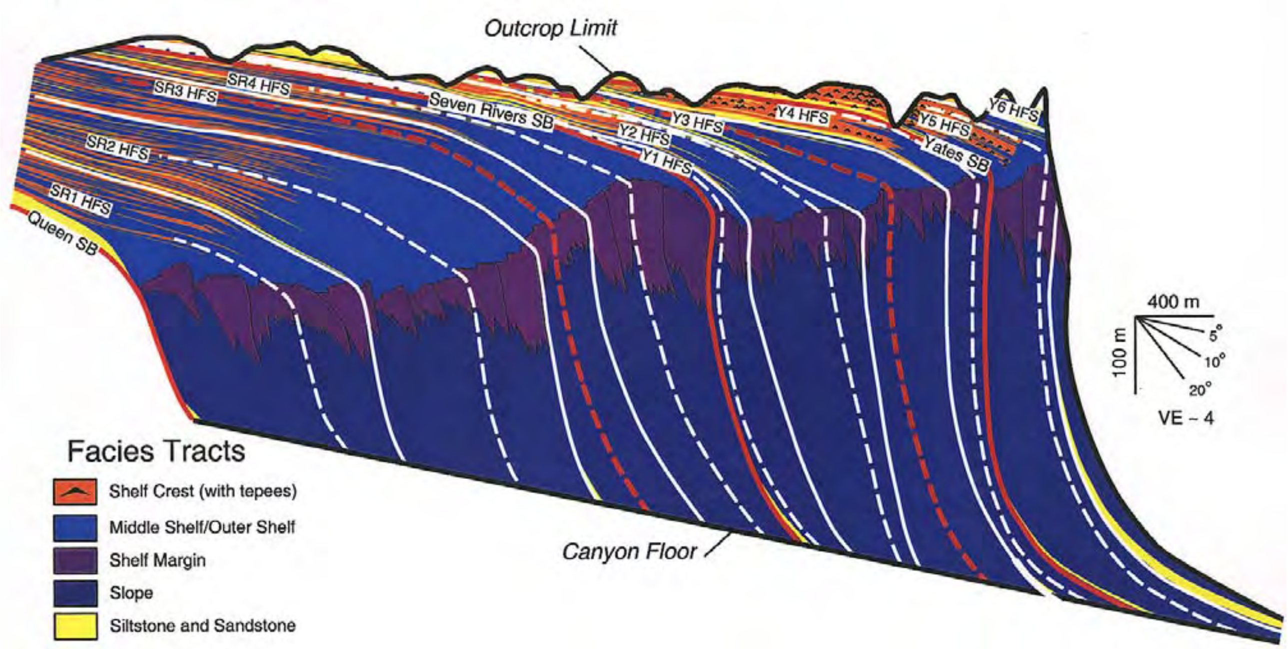


Figure 21. Simplified cross section of Capitan margin facies relations documented in McKittrick Canyon by Tinker (1998). Solid red lines are CS boundaries, dashed red lines are CS MFSs, solid white lines are HFS boundaries, dashed white lines are HFS MFSs.

Teepee Structures

Teepee structures form through multiple cycles of exposure, desiccation, flooding, sediment fill, and/or marine cementation (Figure 22). Kerans and Fowler (1995) showed that well-developed teepees are not 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.

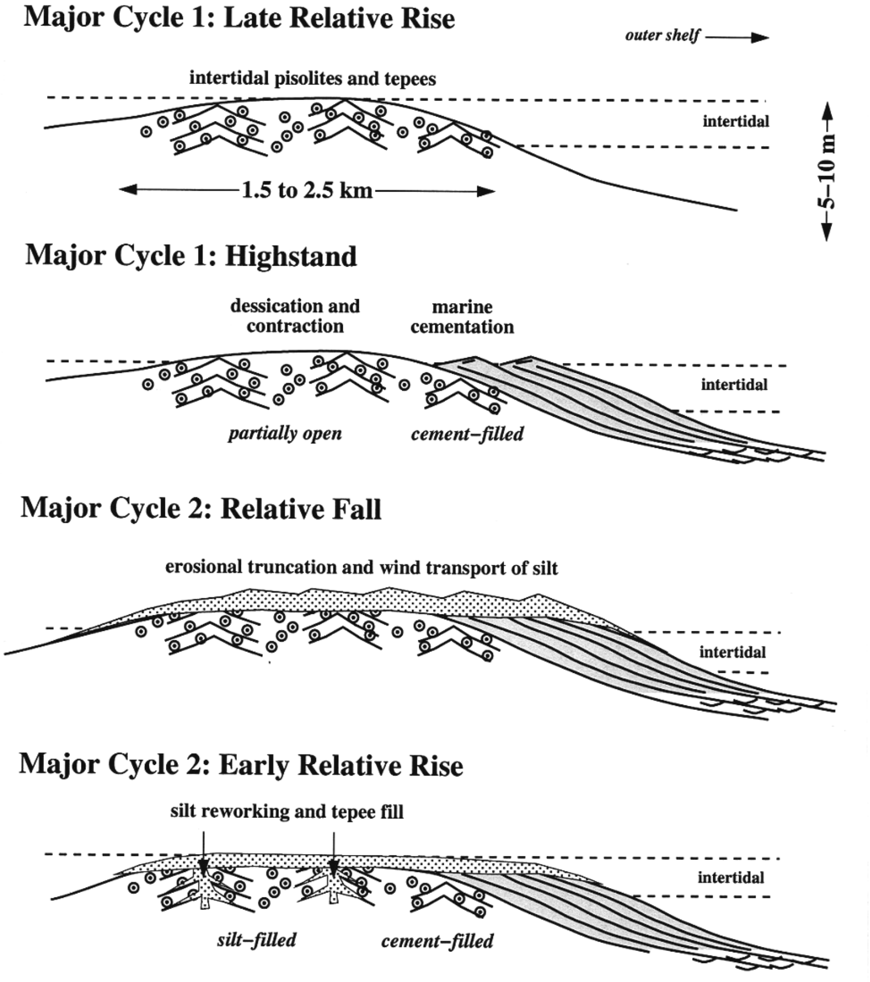


Figure 22. Model showing formation of cement-cored and sand-cored teepee structures in the Capitan shelf-crest, intertidal to supratidal facies tract. Gray-shaded areas are high-energy facies. (Figure from Tinker, unpublished)

Field Stop - Carlsbad Cavern

Cave Location and Origin

Numerous caves are present in the Guadalupe Mountains, with Carlsbad Cavern and Lechuguilla Cave being the most spectacular (Figure 23). A geological hike through Carlsbad Caverns is one of our major field stops.

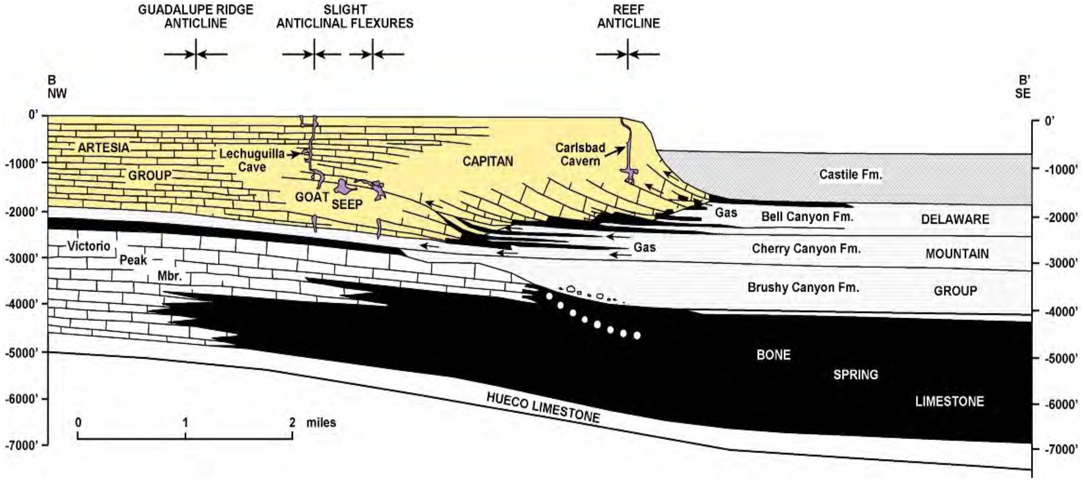


Figure 23. Cross section showing the position of the major cave systems relative to the Permian stratigraphy and facies.

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. During the last twenty years, a more complex model has evolved for development of caverns in the Capitan system. Based on cave geometries and the geochemistry of the cave fill, four stages of cave development are postulated. 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 24). This model has been substantiated and is now being considered for other cave systems around the world.

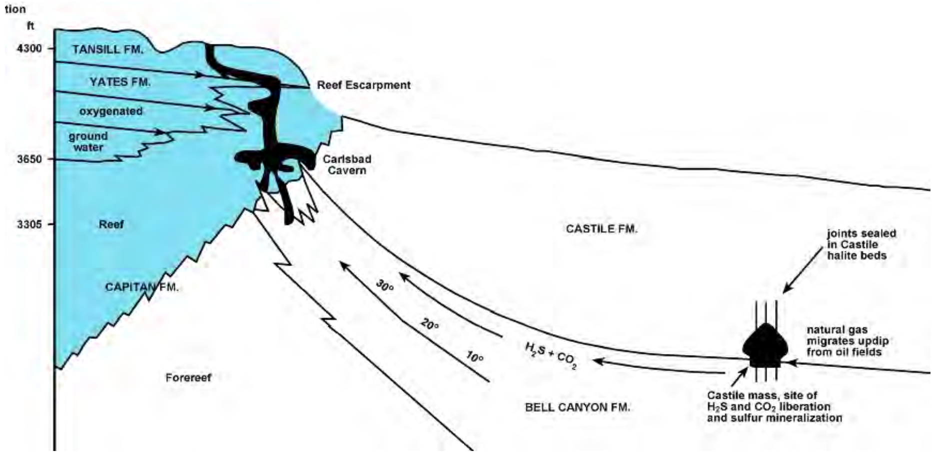


Figure 24. Schematic cross section showing the sulfuric acid burial karst model for forming the Carlsbad Cavern (from Hill, 1987).

The sulfuric acid karst model for cave formation (Figure 24) involves gas ascension from the basin into the reef along the Bell Canyon sandstones. Natural gas migrated updip 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 Guadalupe Mountains.

Our Cave Hike

The Carlsbad Cavern Visitor Center is situated directly above the Capitan reef and along what is termed the Reef anticline (Figure 25). 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. With the lowering of regional base level, horizontal levels of cave passage were developed at new water table positions.

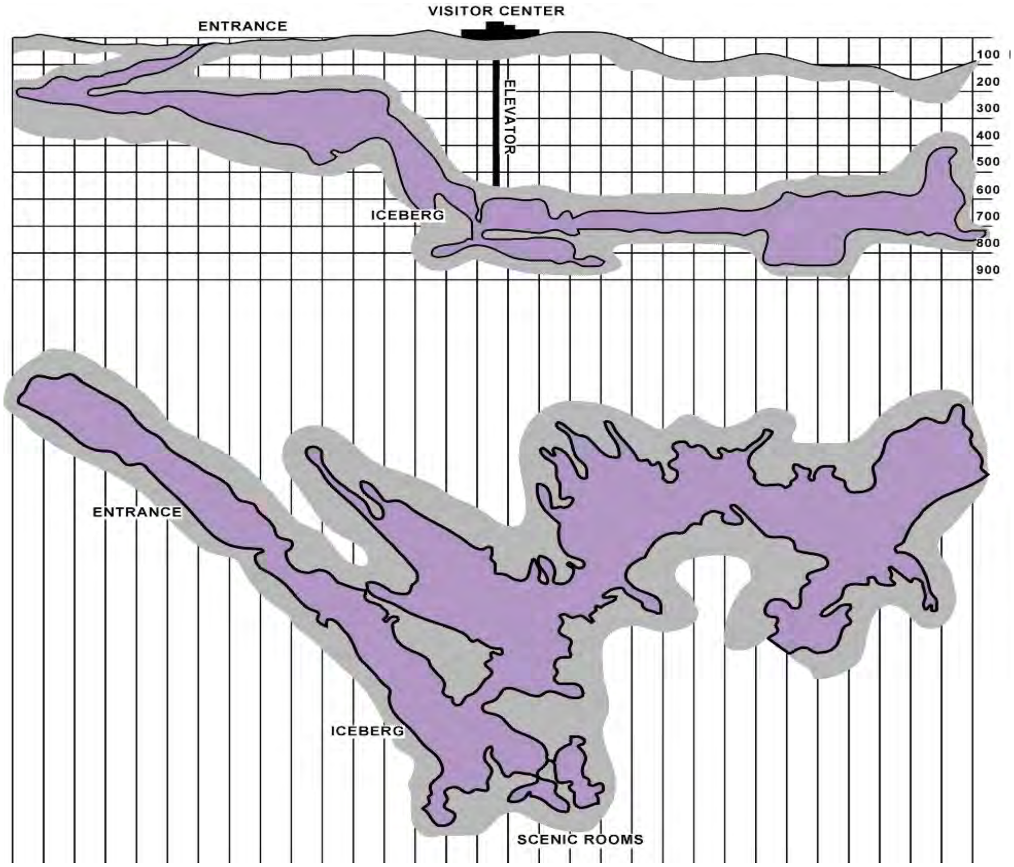


Figure 25. Schematic cross section and map showing cave development.

Significance of Carlsbad Cavern to Subsurface Reservoir Characterization

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 (Figure 26).

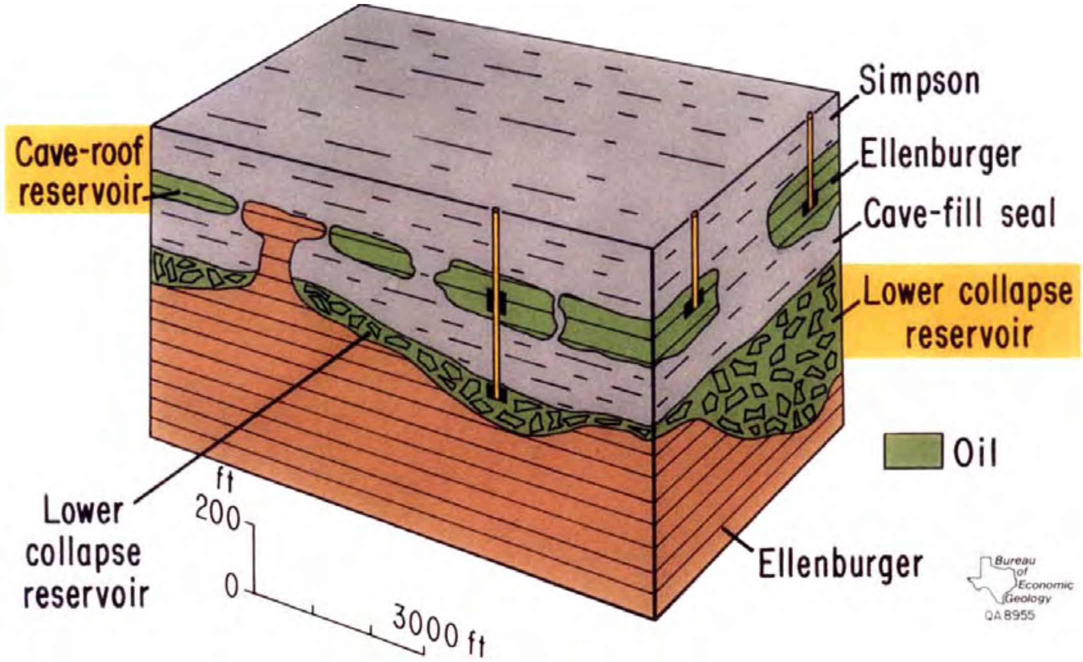


Figure 26. Facies to be expected in a paleokarst reservoir (from Kerans, 1989).

Our hike is an opportunity to compare observations from Carlsbad Cavern with what we might expect in paleokarst reservoirs in the subsurface. How would we recognize such reservoirs, and what aspects of them lead to reservoir heterogeneity?

Field Stop – Algerita Escarpment

Introduction

Reservoirs of the San Andres and overlying Grayburg formations in the Permian Basin have a combined cumulative production of 7.7 Bbbl of oil. Their low recovery efficiency (30%) makes them prime candidates for improved field development through strategic infill drilling, selective completion, and enhanced recovery. Superb outcrops of these reservoir-bearing carbonates are present along the Algerita and Shattuck Escarpments in the western Guadalupe Mountains (Figure 27). The outcrops are readily accessible and have stratigraphic relations and small-scale permeability patterns that are comparable to their subsurface equivalents. The Lawyer Canyon locality of the Algerita Escarpment is one of our major field stops.

Figure 27. Landsat image from Harris and Kowalik (1994) showing outcrops of the Algerita Escarpment and location of the detailed study area of Lawyer Canyon.

Sequence Framework

The Algerita Escarpment is an important outcrop analog for the subsurface reservoirs because of its scale and, as mentioned previously, its similarity with regard to stratigraphy and permeability patterns. A 366m thick San Andres section, including a diverse array of dolomitized carbonate ramp facies, spans approximately 27 km of an oblique-dip carbonate ramp profile along the Algerita Escarpment (Figure 28). Geologic measured sections and oblique aerial photomosaic mapping clearly show that the upper San Andres carbonate ramp complex, like many thick carbonate-platform units, consists of multiple depositional sequences that exhibit basinward shifts in facies tracts across sequence boundaries. Locally developed karst surfaces aid in defining the sequence boundaries. Within these sequences at Algerita Escarpment, cyclic ramp crest facies are present in both transgressive and highstand systems tracts.

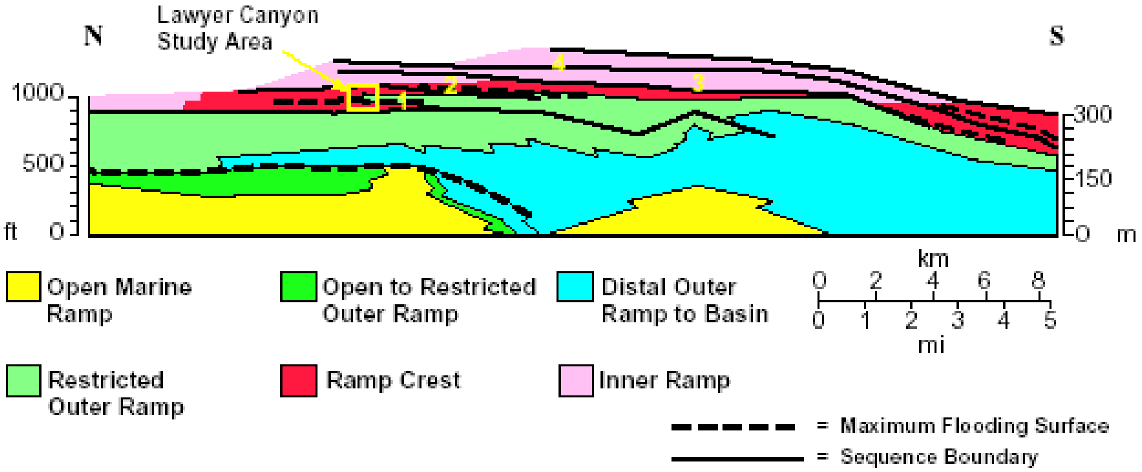


Figure 28. Cross section showing sequence framework for the Algerita Escarpment and the location of detailed study area (from Grant and others, 1994).

Cycle Framework

The fundamental geologic unit recognized with the outcrop geologic measured sections and cores is a 3 to 12 m thick, upward-coarsening carbonate cycle (Figure 29). The cycles generally consist of a basal dolomudstone and an upper grain-rich portion, and based on the grain types, sedimentary structures, succession of depositional textures, and similiarity to modern carbonate sand deposits, are interpreted as products of shoaling sedimentation that filled accommodation space produced by an increase in water depth on the ramp crest.

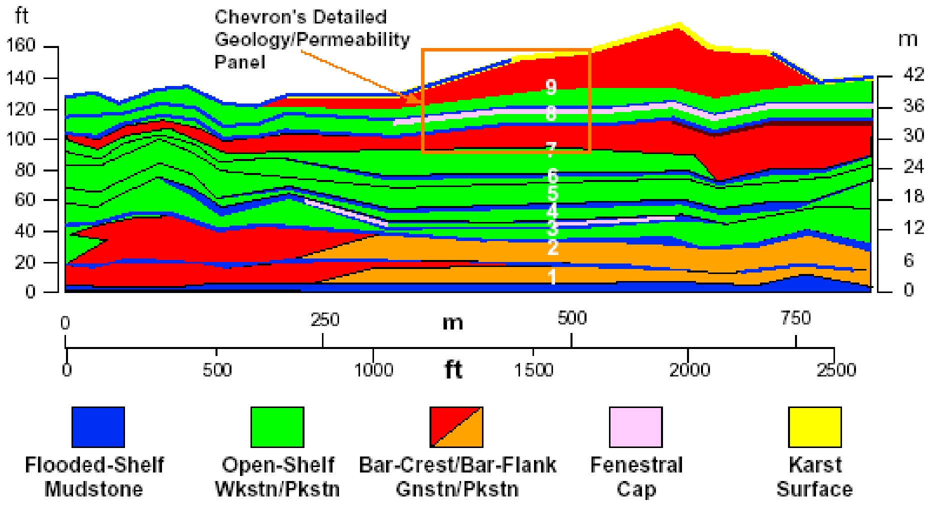


Figure 29. Cross section showing cycles recognized in the detailed Lawyer Canyon study area (from Grant and others, 1994).

Although all of the cycles are laterally continuous across the study area, they are not equally well expressed and thicknesses vary (Figure 29). The thicker cycles typically exhibit more lateral and vertical facies variations. In addition to the variations in cycle thickness and lithofacies of a cycle, diagenetic changes (differential cementation/dolomitization and the development of moldic porosity) can potentially impact permeability distribution.

Permeability and Lithofacies

Mean permeability is different for each of the four dominant lithofacies that comprise a cycle. The basal dolomudstone, burrowed, barflank, and barcrest lithofacies have permeabilities that are statistically different by geometric mean (kg) at a 95% confidence level. An upward-increasing trend in geometric mean permeability would be produced by the characteristic arrangement of the lithofacies within a depositional cycle, i.e. dolomudstones at the base and barcrest dolograinstones at the top (Figure 30).

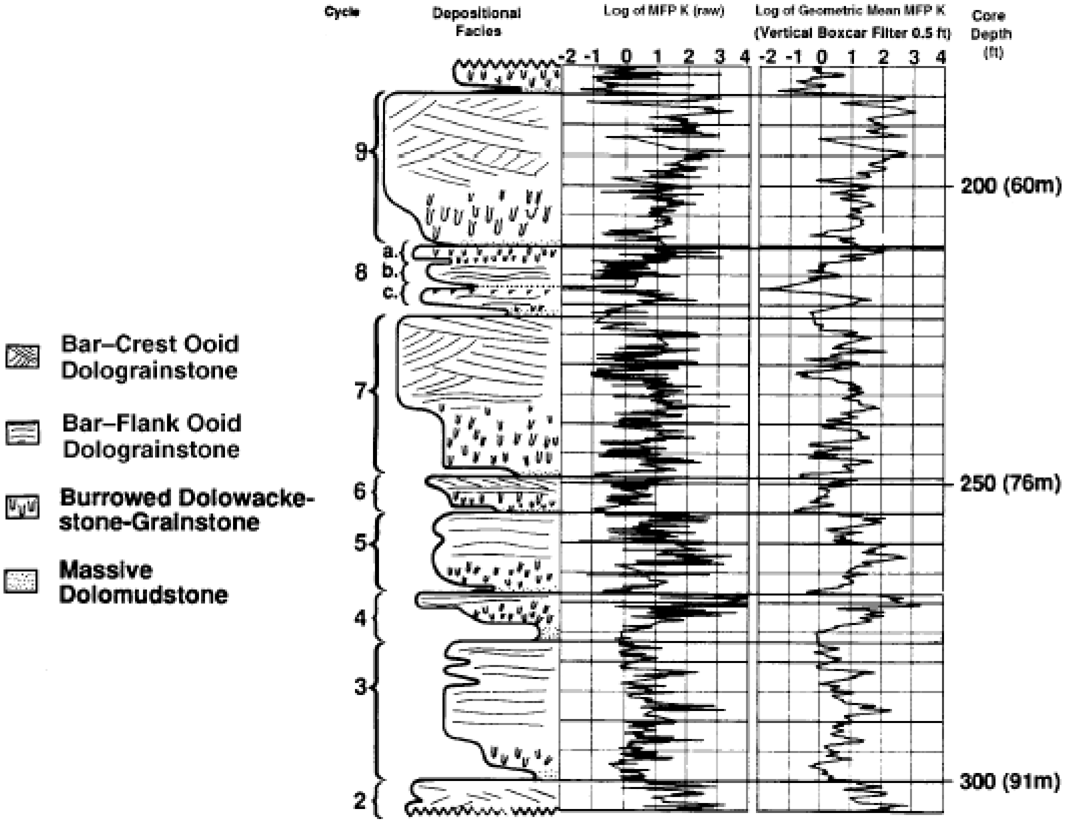


Figure 30. Permeability data measured on core from the Algerita Escarpment by Grant and others (1994).

Spatial Correlation of Permeability

The outcrops illustrate the extreme variablity of permeability vertically and laterally that exists in carbonates, and can be related to lithofacies and porosity type. To calculate the spatial correlation of permeability measurements made on outcrop and core for geostatistical model generation, the semi-variogram was used (hereafter called "variogram"). The variogram is a statistical tool that measures the semi-variance, i.e. half of the variance, of a property, in our case permeability, as a function of distance. Three statistical parameters, the range, sill, and nugget, are obtained from a variogram analysis and applied to a subsequent model generation technique. The range is the distance at which correlation in a property ceases, the sill is the level of variance reached at the range, and the nugget describes the small-scale, i.e. less than the smallest interval spacing, variability of the data.

To assess spatial correlation patterns vertically, i.e. perpendicular to bedding through a succession of cycles, the extensive permeability data set collected on the Algerita 1 core (Figures 30 and 31) was analyzed. The vertical permeability correlation range is approximately 5.5 m, which corresponds to the spacing between muddier and grainier lithofacies within and between cycles. The range of correlation coincides with the average cycle thickness and supports the conclusion that the depositional cycles may constitute a fundamental flow unit in analogous cyclic shelf- or ramp-carbonate reservoirs. The small-scale textural and diagenetic variations are reflected in a high nugget value (60% of the total dataset semi-variance) at separation distances less than 30 cm. The nugget parameter will influence the local scale heterogeneity pattern produced in the conditionally simulated permeability field discussed below.

To assess horizontal permeability variation, nearly 600 permeability measurements were collected along an 85 m horizontal transect in the barcrest dolograinstone lithofacies of a cycle (Figure 31). The 3.6 m correlation range for the horizontal data is used to control the horizontal geostatistical properties of conditionally simulated permeability fields.

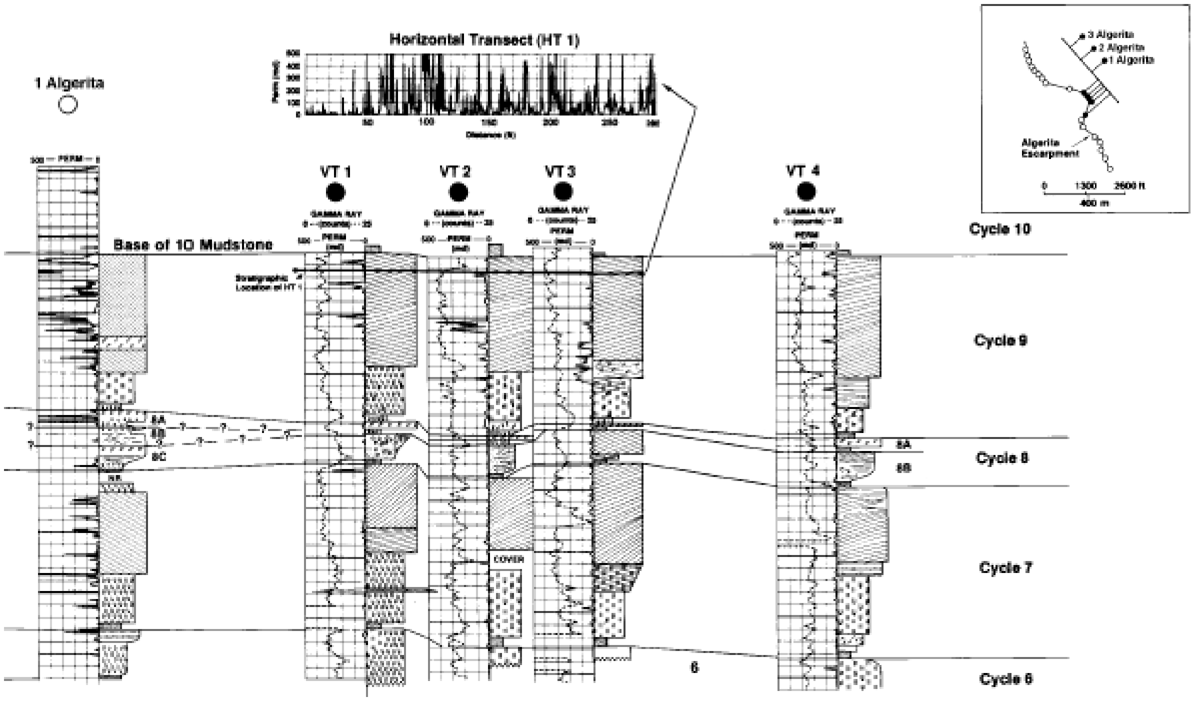


Figure 31. Core and outcrop facies and permeability data for the Lawyer Canyon study area (from Grant and others, 1994).

Two distinct styles of dolomite, observed within the dolograinstones on outcrop, potentially explain the short horizontal correlation range. Brown (as seen on outcrop) permeable dolomite areas are porous dolograinstones with well-connected interparticle porosity whereas the blueish (as seen on outcrop) nonpermeable dolomite areas are tightly cemented dolograinstones with medium crystalline cement.

Permeability and Fluid Flow Modeling

The flow modeling experiments are aimed at identifying those factors that, in a reservoir with a geologic framework like that of the outcrop (Figure 31), would control displacement efficiency (effects of heterogeneity pattern on uncontacted mobile oil) and vertical sweep efficiency (effects of heterogeneity pattern on viscous, capillary, or gravitational crossflow). The flow modeling experiments are of a cross section composed of three cycles (Figure 32).

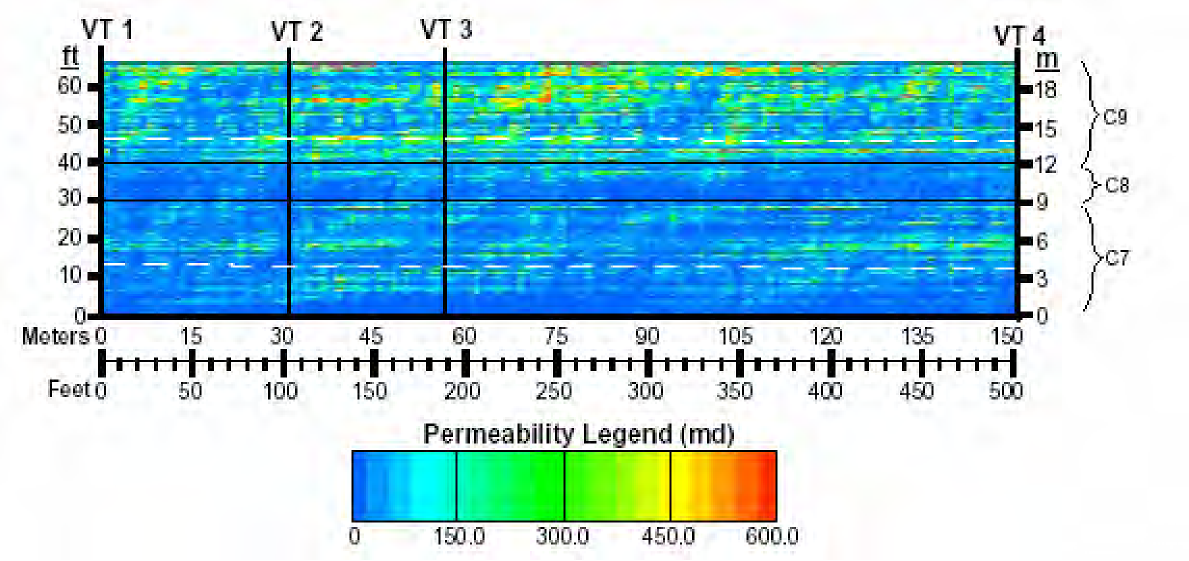


Figure 32. Cross section showing permeability model for three outcrop cycles (from Grant and others, 1994).

The flow simulations (Figure 33) investigate the level of detail required to represent the “effective” reservoir heterogeneity description for the three cycles. One model is a facies-averaged model ("layercake") wherein the facies delineated on outcrop were assigned their respective geometric mean permeabilities. There is no aspect of spatial correlation in the "layercake" model. The other three models were generated using geostatistics to show the effects of grid size (for scaling issues), permeability anisotropy on oil sweep efficiency, and water cycling rates for a waterflood.

The “detailed” geostatistical model of Figure 33 represents the highest resolution permeability field (21,877 cells) generated from the geostatistical techniques. The “coarse” model of Figure 33 is a coarser-grid (3,068 cells) version of the “detailed” model and is designed to test the averaging effects of fractal conditional simulations in the presence of detailed data. The “layercake,” “detailed,” and “coarse” models have isotropic, i.e., kv/kh = 1, permeabilities in each cell. In contrast, the “realistic” model of Figure 33 incorporates anisotropic permeability by facies and cycle as derived from whole-core permeability data collected on the Algerita 1 core (Figure 30). In addition, the “realistic” model tests the effectiveness of the dolomudstones as vertical barriers to crossflow by retaining high spatial correlation but low permeabilities for cells at the base of each cycle, consistent with outcrop observations. Fractures were not modeled in any of the simulations, since our goal was to illustrate the relationship between fluid flow, cycles, and lithofacies variation.

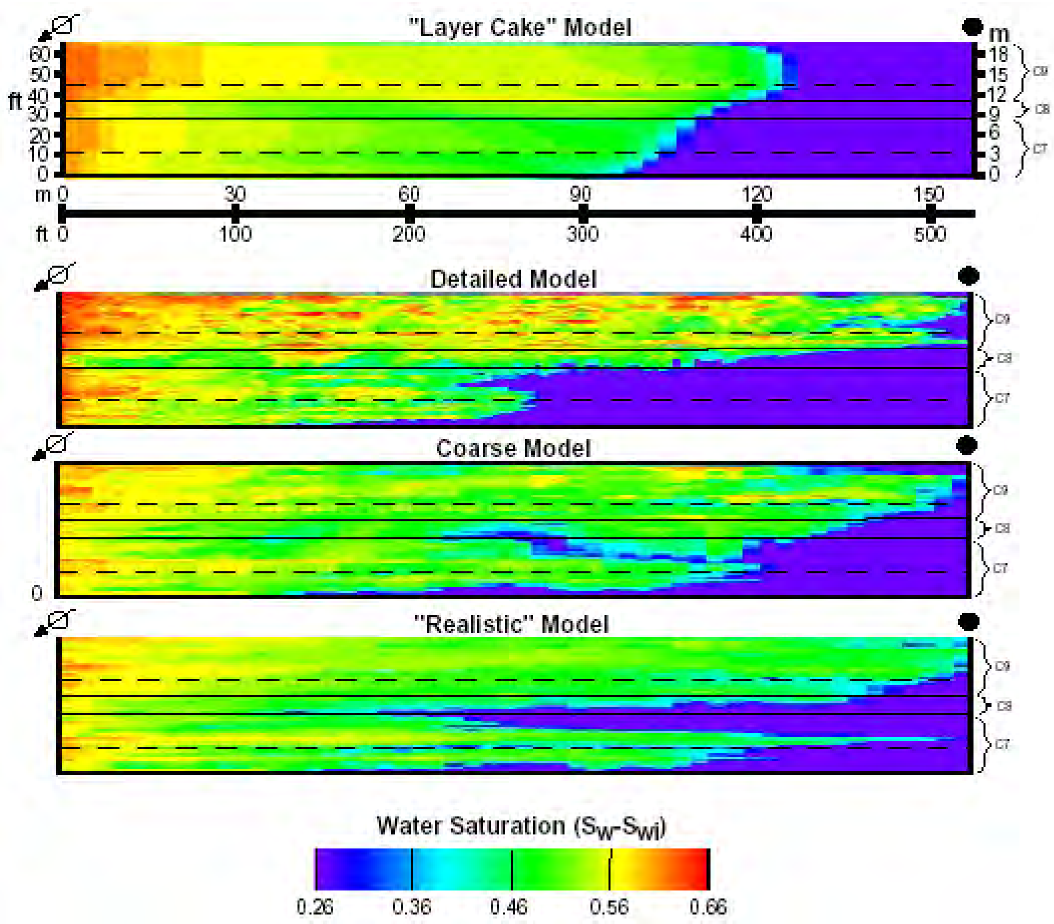


Figure 33. Cross sectional fluid flow models generated for outcrop cycles (from Grant and others, 1994).

The short correlation range from the horizontal variogram results in nearly uncorrelated permeability patterns in the “detailed”, “coarse”, and “realistic” geostatistical models, and, as a result, dominates the vertical sweep efficiency with little difference seen in recovery curves. Given the short variogram ranges modeled on outcrop, we conclude that a coarser-grid, fractal representation will perform equally as well as a fine-grid model, geologically "realistic" model, and a geometrically averaged facies model for estimating sweep efficiency. Although the sweep efficiency does not appear to change by the grid refinement, the processing rates yield different recovery responses in terms of actual water breakthrough times and resulting oil rate schedules.

Visual examination of the water saturation profiles from the models show the impact of various carbonate lithofacies on fluid flow. The upward increasing permeability trends of the thicker depositional cycles are evident from the high water saturations present in the barcrest dolograinstone facies (dashed lines delineate the base of the barcrest facies).

The thinner cycle lacks development of grain-rich barcrest and barflank facies, and as a result, has a water saturation profile that lags behind.

Significance of Outcrop Studies to Subsurface Reservoir Characterization

At the largest scale, stratigraphic relationships can be used to predict the geometry and occurrence of thick cycles containing dolograinstones, those which contribute most to production in the earliest phases of a waterflood. Conversely, the grouping of poorly developed cycles, those which will retain most of the bypassed oil and compartmentalize fluid-flow, can also be predicted by a better understanding of the stratigraphic framework.

The individual depositional cycle is, in many cases, probably equivalent to a fluid-flow unit. In other cases, a succession of thick cycles or of thin cycles may comprise a flow unit. It is important to delineate cycles in analogous subsurface reservoirs, like McElroy Field from the Permian Basin since they likely have distinct vertical permeability patterns, spatial statistics, and flow boundaries. In addition, careful attention should be focused on the cycle stacking pattern within the overall framework, i.e. how and where the cycle thickness changes occur stratigraphically, as this can predictively guide log and core intrepretations in the subsurface. In that groupings of well-developed and poorly-developed cycles potentially can compartmentalize fluid flow, their thickness of several tens of meters increases the likelihood that downhole logs and seismic data can be successfully used to realistically map flow units in carbonate reservoirs.

The McElroy Field, Central Basin Platform of the US Permian Basin, produces approximately 17,000 BOPD under a mature waterflood from the Grayburg Formation. Core studies document the stacking of numerous small-scale cycles within a larger-scale progradational motif, i.e., upward shallowing, for the main producing zone in the field (Figure 34).

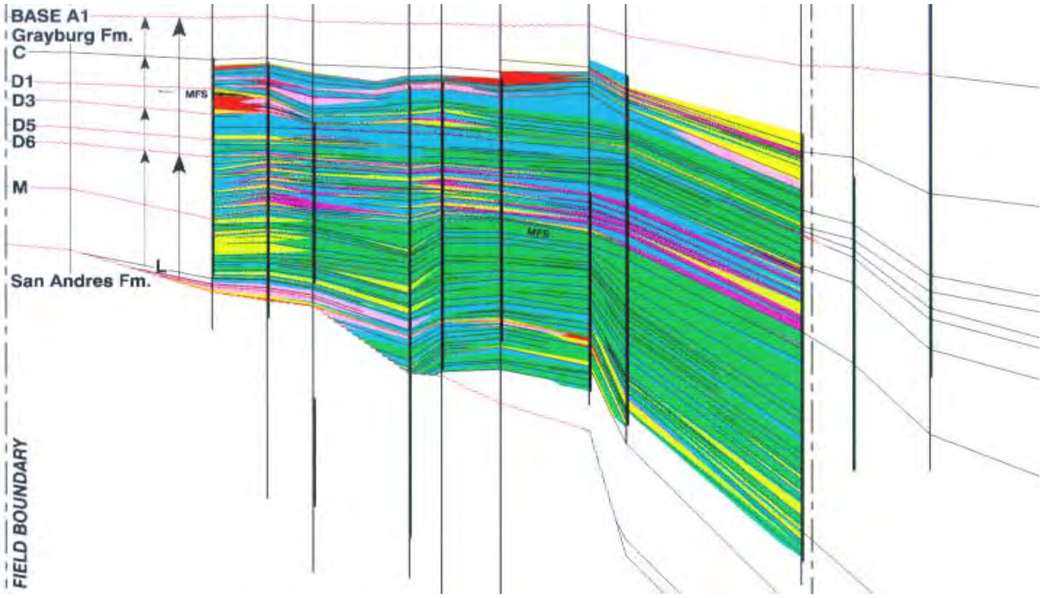


Figure 34. Cross section through McElroy Field in Texas. Cycles like those examined on the Algerita Escarpment are identified from the core and log data (from Lindsay, 1995).

Dolograinstones in McElroy Field are dominated by intercrystalline/intergranular porosity with a narrow size range of pore throats that results in most of the nearly 20% porosity being effective to oil flow. In contrast, dolopackstones are less porous and contain both moldic and intercrystalline/intergranular porosity. Their bimodal pore system results in a wider range of pore throat size and more ineffective porosity.

Layering in this type of dolomite reservoir is stratigraphically controlled; therefore a thorough understanding of the stratigraphy is needed for determining reservoir architecture. Lateral and vertical shifts of facies must be understood to assess reservoir variation within layers, as facies boundaries generally equate with subtle variations in dolomite characteristics and associated reservoir quality. The typically fine crystalline dolomite results in low permeability reservoirs, but a long production history for the field attests to good connectivity. Meteoric overprint produced moldic and enhanced intercrystalline porosity leading to patchily distributed zones of higher porosity and permeability, whereas evaporite cementation and replacement further complicates the reservoir quality distribution.

Field Stop – Basinal Siliciclastics

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. The Cherry Canyon is in part equivalent to the San Andres Formation. 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 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 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 35). 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 and ther San Andres, at what level does the reciprocal sedimentation proposed by Meissner (1972) actually operate?

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

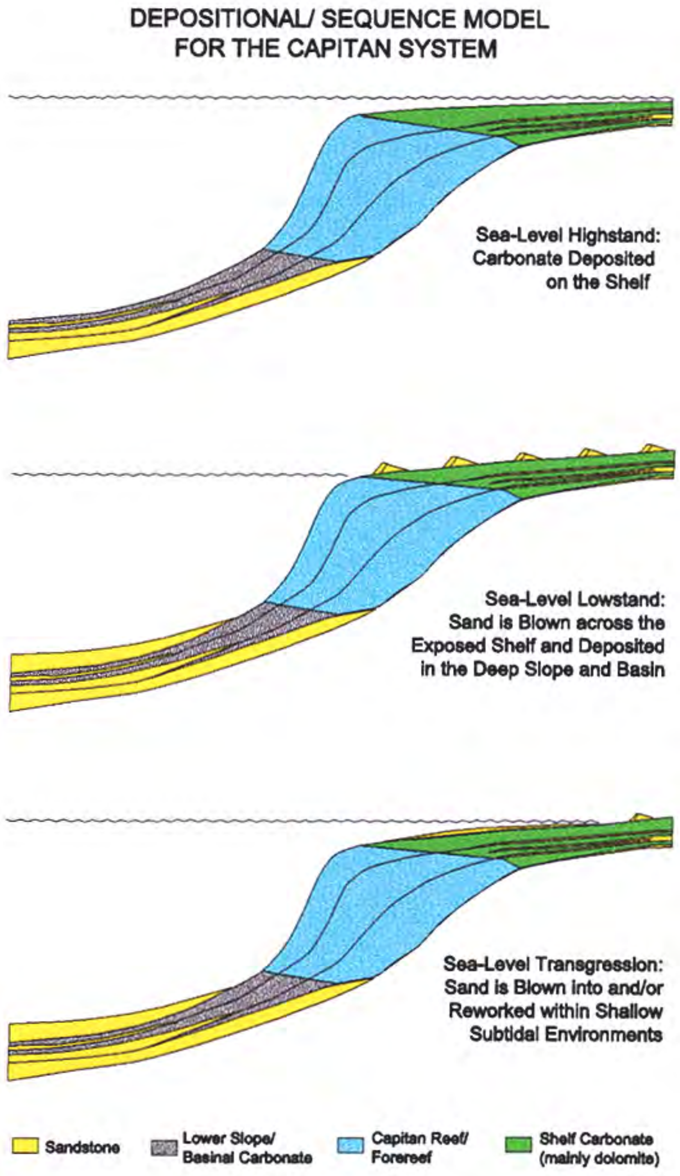


Figure 35. Simplified model based on reciprocal sedimentation concept and stressing changes in sea-level position and related shelf, shelf-margin, and basin stratigraphy of the Capitan margin. (from Harris and Saller, 2000).

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 (e.g. the Rader Slide). 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. 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.

Field Stop – Overlook and Wrap-Up

Some Key Points

Stratigraphy (layering) is a response to changes in relative sea-level

Carbonate facies (rock types) are varied but organized along shelf profiles and within cycles and sequences

The Capitan and San Andres are insightful examples of a rimmed-style and ramp-style of platform margin, respectively

Stratigraphy, facies, and subsequent diagenesis (alteration) control porosity and permeability (reservoir quality)

Outcrops like those in the Guadalupe Mountains have value as a training ground for geologists and as analogs for hydrocarbon reservoirs