Heterogeneity within Carbonates – Guidelines from Modern Examples*

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Course Summary And Outline

Modern examples illustrate the distribution of carbonate facies within an overall depositional setting. Facies maps, aerial photographs, and satellite imagery show the facies variation to be significant and detailed studies most often indicate an order to the facies patterns that is related to environmental controls. As reservoir analogs modern examples can be an integral part of a subsurface geologic model by indicating the dimensions, trend, and interrelationships of facies that might be related to reservoir and non-reservoir distribution.

There are four main parts to this course whose principle intent is to introduce the varied modern examples from a perspective that relates to subsurface issues and concerns:

1. Modern Examples as Subsurface Analogs – Some Personal Background

2. Reservoir Insight from Great Bahama Bank

- Introduction to GBB
- Andros Tidal Flats
- Joulters Ooid Shoals
- Andros Reefs and Slope

3. Inventory of Modern Examples – Satellite Images of Shallow Water Carbonate Depositional Settings

Several modern carbonate areas depict the geologic characteristics that can be expected in many ancient shallow-water settings.

Isolated carbonate platforms - the Bahamas, Caicos Platform in the British West Indies, Chinchorro Bank offshore of Yucatan, and portions of the Belize area.

Ramp-style shelf-to-basin transitions - Abu Dhabi and northern Yucatan

Rimmed shelf margins - South Florida, portions of Belize, and the Great Barrier Reef of Australia

Broad, deep shelf lagoons - the Great Barrier Reef and Belize

Reef variability - South Florida, the Bahamas, Caicos, Belize, the Great Barrier Reef, and Chinchorro Bank

Carbonate sand bodies – South Florida, the Bahamas, Caicos, northern Yucatan, and Abu Dhabi

Shallow lagoon/tidal flat settings - South Florida, the Bahamas, Caicos, Shark Bay in Western Australia, Abu Dhabi
Mixed carbonate and siliciclastic deposition - Belize, the Great Barrier Reef, Shark Bay and Abu Dhabi

4. An Oilfield Example - McElroy Field

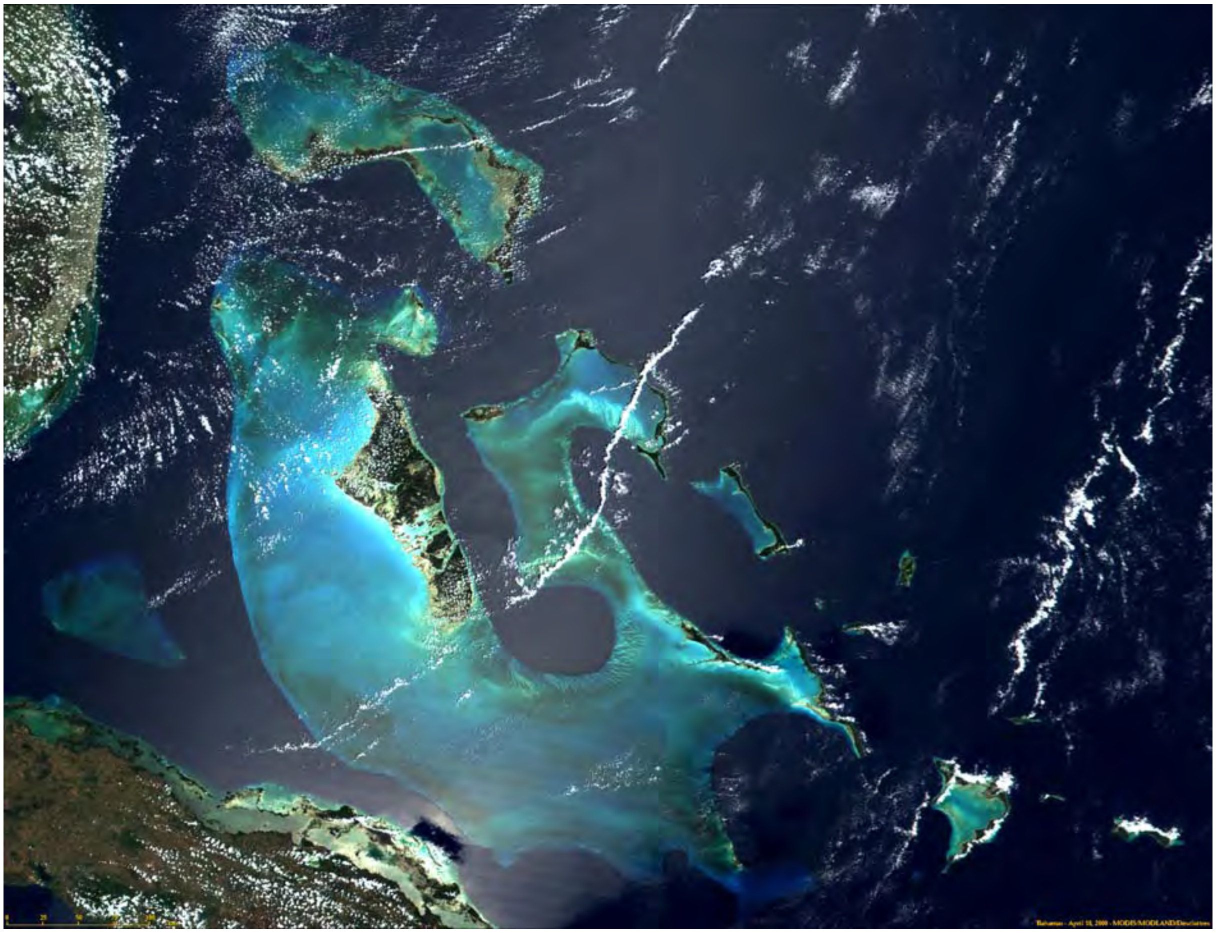
The geologic framework as illustrated by the modern areas can be important in the development scale analysis of carbonate reservoirs. This is particularly true in cases where the lateral variation of porosity and permeability; i.e., reservoir quality, is tied to facies changes, and facies dimensions are therefore required as input to reservoir models.

The geologic framework as shown by the modern areas is also important at the exploration scale, in situations where reservoir facies prediction and stratigraphic plays are related directly to depositional facies patterns.

Course Notes

HETEROGENEITY WITHIN CARBONATES –

GUIDELINES FROM MODERN EXAMPLES



Short Course Presented at
Rice University
March 16, 2005

HETEROGENEITY WITHIN CARBONATES –

GUIDELINES FROM MODERN EXAMPLES

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MODERN CARBONATES –
SOME PERSONAL BACKGROUND

Publication Themes

Carbonate Play Types

Depositional Cycles

Cementation

Heterogeneity

Facies Dimensions

Facies Dimensions within Carbonate Reservoirs - Guidelines from Satellite Images of Modern Analogs (pages 27 – 28)

Carbonate Facies Dimensions at the Reservoir- and Exploration-Scale: What Are Sources for This Information? (page 39)

Methods for Determining Interwell Facies Boundaries (and Constraining Geostatistical Correlation) (pages 41 – 43)

Value of Modern Analogs

Modern Analogs for Carbonate Reservoirs - Great Bahama Bank Revisited (page 47)

Carbonate Platforms: Exploration- and Production-Scale Insight from Modern Analogs in the Bahamas (page 49)

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Field Guide to Carbonate Sediments Along the Exuma Bank Margin, and A Virtual Fieldtrip to the Exuma Island Chain, Bahamas (page 59)

Publications are listed in chronological order on the following pages.

Marine Cementation

Paul M. (Mitch) Harris, 1978, AAPG Bulletin, v. 62 (9), p. 1758; also 1978, Trans. Gulf Coast Assoc. Geol. Socs., v. 28, p. 175-183.

During the last 5,000 years, the Joulters ooid shoal formed north of Andros Island on the margin of Great Bahama Bank. Sediment probing, coring, and observations of the seafloor have revealed the widespread occurrence of grainstone and packstone crusts (hardgrounds) and intraclasts within otherwise uncemented Holocene sands. The marine-cemented sands occur in fine-peloid, ooid, and skeletal facies and commonly are continuous across facies boundaries. Multiple cemented crusts are most common in a mobile shoal fringe, but the single most continuous crust occurs 15 km bankward extending across the shoal's western border.

Crusts are continuous for meters to several kilometers and range in thickness from millimeters to tens of centimeters. The lower surface of most crusts is gradational into underlying uncemented sands and the upper surface is sharply defined, more indurated, bored, and encrusted. Intraclasts range from poorly cemented platy chips of coarse-sand to medium-pebble size 1 to 2 mm thick, to well-cemented cobbles that are millimeters to centimeters thick. The crusts and intraclasts are cemented with acicular aragonite, rimming grains in a fringe 10 to 50µ thick, or with micrite (aragonite and magnesian calcite) enveloping grains and completely filling voids in a patchy distribution.

Syndepositional marine cementation in the Joulters ooid shoal punctuates Holocene sands with widespread less porous and permeable layers. Where exposed, the layers provide a stable bottom for colonization by hardground fauna. Recognition of crusts may prove a valuable clue in deciphering facies and diagenetic patterns in carbonate reservoirs and in understanding the timing of porosity-reducing diagenesis.

Meteoric Cementation

Paul M. (Mitch) Harris and Robert B. Halley, 1977, Holocene Island Growth and Diagenesis, Joulters Cays, Great Bahama Bank: Florida Scientist, v. 40 (supplement 1), p. 22.

Robert B. Halley and Paul M. (Mitch) Harris, 1977, Holocene Fresh-Water Cements, Joulters Cays, Bahamas: AAPG Bull., v. 61, p. 792-793; also 1979, Jour. Sed. Petrology, v. 49, p. 969-987.

Introduction

The recognition of early cements can be a valuable clue to deciphering facies and diagenetic patterns in carbonate reservoirs and in understanding the timing of diagenesis that affects porosity reduction. The islands in the Joulters Cays area reveal some of the diagnostic criteria for early meteoric (fresh-water) diagenesis. The area is important because it provides an example of contemporary cementation in fresh water that allows comparison between the distribution and the style of the cementation with the positions of ground water zones and sea level.

Occurrence

South Joulters Cay is formed from a number of northerly-trending beach dune ridges which rise as much as 6 meters above sea level. Most of the island surface consists of lightly cemented ooid sand. The more bankward ridges are better cemented than surface or core samples from seaward ridges. No soil has developed at the surface and there are no karst features on the friable limestone. Several open ponds, water wells, and borings all reveal fresh water beneath the island.

Seven cores were taken on the island along two eastwest transects. Holocene sands are moderately and poorly cemented in the upper 0 to 5 m, and poorly cemented and uncemented in the lower 3 to 6 m. Moderately and poorly cemented sands thin toward marine water. There is no difference in the degree of cementation above or below the ground water table. The percentage of calcite determined by x-ray diffraction is taken as a measure of the amount of cement. Samples taken across the water table have 91 to 94% ± 5% aragonite (ooids, aggregates, pellets, and scattered skeletal grains) and 6 to 9% ± 5% calcite (cement). The amount of cement is slightly greater at the water table; sands are equally well cemented above (vadose zone) and below (upper phreatic zone). The amount of cement decreases in the lower phreatic zone.

Cement Style

Although the sands are equally well cemented above and below the water table, the style of cementation changes across the water table. A blocky mosaic of calcite cements grains in the vadose zone. Cement distribution is uneven around the grains, and interparticle pore space is completely filled in a very patchy pattern.   The scale of the cement patchwork in thin sction varies from several millimeters to the scale of the individual adjacent pore throats which may be filled, partially filled, or empty. Cement is most common at grain contact positions, with single crystals commonly bridging the pore from one grain to another and forming a meniscus-shaped outline concave toward the interior of the pore. Size of cement crystals ranges from 10 to 50 um, generally larger where grains are further apart.

In contrast to these cements typifying the vadose zone, a rim of calcite rhombohedrons cements grains in the phreatic zone. Cement is more evenly distributed around the grains than in the vadose zone, but interparticle pore space is rarely completely filled. Many cement crystals grow from ooid surfaces into intergrain pores and do no actually bind grains together, thus the phreatic rock is more friable than that of the vadose zone. In the most common type of cement rim, the calcite crystals are well-formed, tens of microns long and closely spaced. Individual cement crystals are smaller and widely spaced in sands in the lower phreatic zone.

Because cemented sands immediately above and below the water table are of the same lithology and age, the change in style of cementation across the water table can be related only to its position. The abruptness of the cement change indicates that cementation is contemporary, that water table fluctuations have been limited during cementation, and that cementation is probably continuing at the present time. The change in cement texture is a permanent record of the position of the water table.

Porosity

Porosity of the cores that recovered Holocene rock, estimated by bulk density measurements for entire core sections, varies between 40 and 52% and averages 47%. There is little difference in porosity between samples from the vadose and phreatic zones. Because unconsolidated ooid sands have porosities between 44 and 47%, the porosity of cemented sands has not been decreased significantly, although an average of 7% by volume of calcite cement has been added. Pores occluded by cement may be balanced by pore space created by dissolution of grains. The source of calcium carbonate supplying the Joulters cements is dissolution by percolating fresh waters throughout the vadose and uppermost few meters of the phreatic zone. Ooid nuclei and lamellae are partially dissolved, and a portion of this carbonate is precipitated as calcite cement within a few meters of its origin.

Cementation of Holocene and Jurassic Grainstones

Paul M. (Mitch) Harris, 1980, AAPG Bulletin, v. 64 (5), p. 719-720, 1980.

Freshwater cementation of Holocene sands in the Bahamas provides a modern analog to enhance our understanding of some cements in Jurassic grainstones of southern Arkansas. The Joulters Cays, three late Holocene islands on Great Bahama Bank, formed when ooid sands were subaerially exposed and lithified by freshwater cements. Cement fabric above the standing water table (vadose zone) and below (phreatic zone) is strikingly different. Vadose cements, characterized by patchily distributed spar most common at grain-contacts, change abruptly across the water table to phreatic cements, displaying a uniform rim of rhombohedrons surrounding each grain. Vadose cements preserve primary porosity and increase variation in permeability more than phreatic cements.

The updip Smackover grainstone reservoirs in southern Arkansas are characterized by (1) early cements that predate hydrocarbon emplacement and that resemble the Joulter Cays freshwater cements, (2) preserved primary intergranular porosity, and (3) leached moldic porosity. Vadose imprint is characterized by poorly developed cement rims around grains, a grain-contact meniscus fabric producing rounded pores, and a patchy distribution of block spar with crystals that increase in size away from the grains. The meniscus fabric is only partly preserved where grain interpenetration has occurred during burial. Phreatic cements occur as moderately to well-developed non-isopachous rims around most or all of the grain margins. They line pores forming jagged boundaries, and are patchy to extensive y developed showing an increase in crystal size away from the grain. The cement rims are commonly broken and separated from the grains during compaction. Compaction features and late cements are not distributed uniformly in the grainstones, owing perhaps to heterogeneous porosity and permeability patterns established by early cements.

Depositional Facies and Stratigraphy

Arabian Gulf Coastal Flats

Godfrey P. Butler, Paul M. (Mitch) Harris, and Christopher G. St. C. Kendall, 1982, Recent Evaporites from the Abu Dhabi Coastal Flats, in Handford, C. R., Loucks, R. G. and Davies, G. R. (eds.), Depositional and Diagenetic Spectra of Evaporites - A Core Workshop: SEPM Core Workshop No. 3, p. 33-64.

Peter A. Scholle, Paul M. (Mitch) Harris, Eugene A. Shinn, and Robert B. Halley, 1986, Arid Carbonate Coastlines: AAPG Film, 31 minutes.

The Joulters Cays Saga

Paul M. (Mitch) Harris, 1976, Holocene Carbonate Sediments, Joulters Cays Area, Great Bahama Bank: Florida Scientist, v. 39 (supplement), p. 11.

Paul M. (Mitch) Harris and Karen Harris, 1977, Sediment Distribution by Factor Analysis, Joulters Cays Area, Great Bahama Bank: GSA Ann. Mtg., Abs. with Programs, v. 9, no. 7, p. 1006.

Paul M. (Mitch) Harris, 1978, Ooid Sand Shoal Facies, Joulters Cays, Great Bahama Bank: AAPG Bull., v. 62, p. 520.

Paul M. (Mitch) Harris, 1979, Facies Anatomy and Diagenesis of a Bahamian Ooid Shoal: Sedimenta 7, Comparative Sedimentology Laboratory, Univ. Miami, Miami Beach, FL, 163 p.

Paul M. (Mitch) Harris, 1979, Anatomy and Growth History of a Holocene Ooid Shoal: AAPG Bull., v. 63, p. 462-463.

Robert B. Halley, Paul M. (Mitch) Harris, and Albert C. Hine, 1983, Bank Margin Environments, in Scholle, P. A., Bebout, D. G. and Moore, C. H. (eds.), Carbonate Depositional Environments: AAPG Memoir 33, p. 463-506.

Paul M. (Mitch) Harris, 1983, The Joulters Ooid Shoal, Great Bahama Bank, in Peryt, T. M. (ed.), Coated Grains: Springer-Verlag, Berlin, p. 132-141.

Paul M. (Mitch) Harris, 1984, Cores from a Modern Sand Body; The Joulters Ooid Shoal, Great Bahama Bank, in Harris, P. M. (ed.), Carbonate Sands - A Core Workshop: SEPM Core Workshop No. 5, p. 429-464.

Albert C. Hine, Paul M. (Mitch) Harris, and A. Conrad Neumann, 1985, Carbonate Sand Bodies of the Bahama Banks: SEPM Slide Set No. 1, 70 slides with accompanying text, references and captions.

Harris, P. M., 2004, The Joulters Ooid Shoal – An Analog for Heterogeneity Within Carbonate Sand Reservoirs: University of Miami Comparative Sedimentology Laboratory Sedimenta CD Series No. 1.

The Joulters ooid shoal, north of Andros Island on Great Bahama Bank, was described in detail by Harris (1979). This shoal is important because it displays a variety of subenvironments in which ooid sands can accumulate, some of which are quite different from environments where ooids are generated.

Facies recognized in coring studies of the Joulters shoal include ooid grainstone, ooid packstone, fine-peloid packstone, pellet wackestone, and lithoclast packstone. Skeletal grainstone is also present on the shelf seaward of the shoal, but was not recovered in cores.

The area of the present-day shoal includes depositional environments that produce each distinctive facies. Ooid grainstone forms on current-swept, rippled sea bottoms such as the crests of active sand bars; ooid packstone forms on stabilized burrowed bottoms, including sand flats and relict sand bars; fine-peloid packstone collects on stabilized and burrowed bottoms farther from sources of ooid sands; pellet wackestone forms in restricted bottoms (such as in the lees of islands); and lithoclast packstone accumulates in active tidal channels. Each of these facies can occur in other settings as well, collectively forming what we refer to as an ooid shoal in the geological record.

The relief of the shoal above the surrounding seafloor is primarily a result of ooid sands in one of three facies: ooid grainstones in a narrow belt along the ocean-facing borders of the shoal, where ooid accumulation coincides with formation, and the more widespread ooid packstone and fine-peloid packstone facies which are the result of mixing of ooids with other grain types.

The Joulters sand shoal has a characteristic vertical succession of scattered lithoclast packstones and pellet wackestone at the base, fine-peloid packstone in the middle, and ooid packstone at the top, showing an upward increase in grain size, percentage of ooids, and grain-support fabric. This facies sequence thins to the south over a shallowing limestone surface, as well as to the north and west as overall sediment thickness decreases. Within the shoal, the thicknesses of the dominant facies are complementary; ooid packstone thins in a bankward direction as fine-peloid packstone thickens to form the thickest part of an interplatform sheet. Ooid grainstone directly overlies limestone along the seaward margin of the shoal and interfingers with the packstones bankward.

The interpreted growth through time of the Joulters ooid shoal suggests that the facies changes resulted from changing depositional patterns in response to rising sea level. The shoal grew in three stages: (1) an early bank-flooding stage during which muddy sands of fine-peloids and pellets accumulated in protected lows on the Pleistocene limestone floor, (2) a shoal-forming stage during which ooid production began on bedrock highs where bottom agitation was focused, and (3) shoal development in which the production and dispersal of ooid sands established the present size and physiography of the shoal. This changed the general nature of bank-margin sediments in the area from muddy peloidal sands to ooid sands.

Carbonate Facies and Reservoir Heterogeneity - The Value of Modern Analogs

Paul M. (Mitch) Harris, 1987, AAPG Bulletin, v. 71 (11), p. 1440-1441; also 1989, AAPG Film (51 minutes) and Slide Set (56 slides).

Secondary and enhanced processing of hydrocarbon fields requires a critical understanding of reservoir heterogeneity by both geologists and engineers. Carbonates have more varied facies and diagenetic patterns than their siliciclastic counterparts, thus offering a greater challenge to reservoir evaluation. This challenge is illustrated by American Petroleum Institute data showing average primary plus secondary recovery efficiencies of carbonate reservoirs of only 32% original oil in place. Studies of modern analogs are valuable because they constrain interpretations and lend predictability to unraveling facies patterns in reservoirs. These patterns help to understand the lateral continuity of stratification, variation within layers, heterogeneity, and performance of reservoir examples.

An appreciation of facies variability and depositional processes for carbonates can come from examination of modern environments of deposition. Common patterns in structural, textural, and diagenetic trends can be summarized from several modern settings for reefs and mounds, sand shoals, and lagoons and tidal flats. The lessons learned from detailed studies of modern examples center on several important points:

(1) the trend and continuity of facies belts vary, but the patterns are orderly when the setting is understood;
(2) typically, carbonate deposits form in localized ovoid or elongate thicks, not in widespread sheets;
(3) the depositional systems contain complex, highly variable facies patterns in map view;
(4) a predictable sequence of sediments, although not fully developed throughout the depositional environment, typifies the setting;
(5) the stratigraphy as revealed by sediment coring is highly variable, recording a short-lived, but exceedingly complex geologic history; and
(6) early diagenesis related to evolving depositional environments can significantly alter the porosity and permeability of the sediments.

Carbonate depositional systems, as shown by modern examples, are complex from the scale of a producing field right down to that of a pore throat. This fact, coupled with frequent control by facies over subsequent diagenesis, imparts the great heterogeneity to carbonate reservoirs. Log response and reservoir quality are directly related to facies and diagenesis, with varying grain size a major control over permeability amounts in porous intervals. Permeability affects recovery efficiency and thereby links the depositional facies through sediment texture to reservoir performance.

Heterogeneity in Grainstone Reservoirs - Investigation of a Modern Analog, Joulters Cays, Bahamas

Don G. Bebout, Paul M. (Mitch) Harris, Mark H. Holtz, Charles Kerans, Rick P. Major, Doug Ratcliff, Noel Tyler, and G. W. Vander Stoep, 1990, AAPG Bull., v. 74, p. 607.

Skeletal, peloidal, and ooid grainstones form major carbonate reservoirs for hydrocarbons throughout the world. Reservoirs in the San Andres and Grayburg formations of the Permian basin provide excellent examples of this reservoir type. Subsurface and outcrop studies have documented extreme permeability variability within thin grainstone units of shoaling cycles that occur within these formations.

The Joulters Cays ooid shoal, located north of Andros Island, Great Bahamas Bank, is the most thoroughly documented modern carbonate sand complex. But even at Joulters, the core spacing of previous studies was approximately one core per square mile, which does not approach the scale needed to address most problems of interwell heterogeneity. Using the existing regional core framework as a guide, a detailed coring program with well spacing approximating that in mature oil reservoirs (between 20 and 40 ac/well) was undertaken to examine the sediment variation and early diagenesis within some subenvironments of the active shoal.

Cores and box cores taken at Joulters are dominantly clean ooid sands (grainstones) with minor muddy sands (packstone). However, changes in depositional style across the shoal and the effects of these changes on the preserved texture are of particular significance. Variations in the penetration of resin through box cores suggest greater permeability differences that are related to minor changes in grain size. These differences are most evident within graded units of spillover-lobe cross stratification on the bankward side of the shoal. Parallel-laminated seaward-dipping units show less variation. Cemented zones (hardgrounds), ranging up to at least 1 mi^2 in extent, also may contribute to the permeability heterogeneity. These types of subtle depositional and early diagenetic fabrics influence subsequent diagenesis and resultant permeability variations in grainstone reservoirs.

The Holocene Sequence - Implications for Correlating Parasequences and Reservoir Layers

Paul M. (Mitch) Harris, Don G. Bebout, and Charles Kerans, 1991, AAPG Bull., v. 75, p. 589-590.

A successful geological approach to development of hydrocarbon reservoirs in carbonates begins with the detailed description of continuous cores from wells that are widely spaced throughout the reservoir. After calibrating downhole logs from uncored wells, the thinnest geologically meaningful sequences of facies are chosen, mapped field-wide, and then assigned petrophysical and production properties. Commonly, these reservoir zones are an upward-shoaling sequence of carbonate facies, i.e., shoaling cycle or parasequence.

Our understanding of the deposition of such sequences and component facies is enhanced by observations and models derived from modern analogs. For example, the coring of modern sediments in the Joulters Cays area of Great Bahama Bank has revealed the complexity of the modern sequence. Covering 400 sq km and averaging 4 m thick, the sequence graphically shows the rapidity with which complex facies relations can form and points out the difficulties of interpretation and correlation of cores from ancient examples. The Joulters shoal formed in only the last 5000 years. Nevertheless, the facies record of shoal growth, largely a response to a relative rise in sea level, indicates significant changes such as rapid expansion of ooid sands, island formation and associated meteoric diagenesis, ajor reworking by burrowing, and generation of hardground layers. In some facies the depositional texture, sedimentary structures, and grain types have all been modified since deposition. The shoal was more active in the recent past over a larger area than today, and ooid packstone, the most widespread facies, represents reworking of grainstones through burrowing during development of a vast sand flat.

In San Andres and Grayburg reservoirs of the Permian basin, the fundamental sequence, 3-12 m thick, often contains a thin mudstone base overlain by burrowed wackestone-packstone and capped by a thick planar- to cross-bedded packstone-grainstone. These facies, like the modern example, formed during a relative rise in sea level with the accompanying development of oolitic, peloidal, and skeletal shoals. Outcrop examples from the Algerita Escarpment of the Guadalupe Mountains and subsurface correlations from Farmer field show lateral facies relations within a sequence that are surprisingly similar to those of the modern example.

Evolution of Steep Carbonate Slope Deposits - Insight from Modern Analogs in the Bahamas

G. Michael Grammer and Robert N. Ginsburg, 1992, Highstand vs. lowstand deposition on carbonate platform margins: Insight from Quaternary foreslopes in the Bahamas: Marine Geology, v. 103, p. 125-136.

G. Michael Grammer, Robert N. Ginsburg, and Paul M. (Mitch) Harris, 1993, Timing of deposition, diagenesis, and failure of steep carbonate slopes in response to a high-amplitude/high-frequency fluctuation in sea level, Tongue of the Ocean, Bahamas, *in* Loucks, R. G., and Sarg, J. F., (eds.), Carbonate Sequence Stratigraphy, Recent Developments and Applications: AAPG Memoir 57, p. 107-131.

Introduction

The upper marginal slopes or foreslopes of carbonate platforms are an important transitional zone between shallow-water platform carbonates and deeper water basinal and distal slope deposits, and may contain significant reservoirs of hydrocarbons or metallic ores. Understanding of the depositional and early diagenetic processes operating along foreslopes is an integral part of evaluating the evolution of carbonate platforms and may be a key to the interpretation of inclined deposits (clinoforms/clinothems) often observed in outcrop and seismic profiles.

Slope Deposition

Sequence stratigraphic interpretations of carbonate platform margins are based to a large degree on concepts of variable timing and nature of deposition relative to fluctuations in sea level. Quaternary platform margins, such as those found in the Bahamas, provide a unique opportunity to calibrate the sedimentary record because of the well-constrained nature of sea-level history during this period. Detailed observations and sampling from a research submersible combined with high-resolution radiocarbon dating in the Tongue of the Ocean, Bahamas, have enabled us to document variations in deposition along the upper parts of the marginal slope during the most recent rise in sea level.

We have found that the steep marginal slopes around the Tongue of the Ocean record deposition during the early rise of sea level following the last lowstand some 18-21 Ka. Coarse-grained skeletal sands, gravel, and boulders derived from reefs growing along the overlying escarpment were deposited on slopes of 35-45^o and rapidly cemented in place (within a few hundred years). Deposition by rockfall and grainflow resulted in a series of elongate lenses oriented parallel to the slope. These lenses are generally less than 0.5m thick and pinch out downslope within tens of meters. Repeated deposition and cementation produced slope deposits that are both laterally discontinuous and internally heterogeneous. Radiocarbon dating of skeletal components and cements indicate that active deposition on the slopes ceased approximately 10,000 years ago as sea level rose above the escarpment and began to flood the top of Great Bahama Bank. Fine-grained, non-skeletal sands and muds derived from the platform top are presently bypassing these slopes and are deposited downslope as a wedge of sediment with slope declivities of 25-28°.

Cracks and slide scars, similar to the Neptunian dikes observed in ancient slope deposits such as the Permian Capitan Formation of west Texas and New Mexico, are common features of the steep-cemented slopes. The cracks are a few centimeters wide and may extend for tens of meters across the slope with an arcuate, convex-up expression. The slide scars are generally a few meters wide by several meters long and cut back into the slope a few meters to less than 1 meter, although one large example is 30m wide, extends downslope for 75m, and has exposed 10m of the interior of the slope. Transects downslope from slide scars show that large blocks of the slope, some in excess of 10m across, have been transported for tens or hundreds of meters downslope. The release and transport of such blocks may be one mechanism by which turbidity currents are initiated in deeper slope environments.

Discussion of Slope Development and Sea-level Fluctuation

The questions of how and when the steep slopes along the Bahamas platform formed are of primary interest because of the similarity to steeply dipping slope deposits documented from the fossil record. Carbonate slopes from the Permian of west Texas and New Mexico, the Devonian of Western Australia, the Triassic Dolomites of northern Italy, the Cretaceous of east-central Mexico, and the Miocene of the Gulf of Suez all exhibit primary depositional slopes of 30-40°. In addition to slope declivity, the geometry and thickness of beds as well as the dominant texture of the slope deposits in the Tongue of the Ocean are also similar to these ancient examples. Steep-slope profiles similar to those observed in outcrop are also frequently observed in seismic profiles in the subsurface.

Researchers working on both modern and ancient carbonate slopes have suggested a myriad of downslope, gravity-induced mechanisms for the deposition of sand-sized and coarser grained sediments. On modern slopes, previous workers have indicated that relatively large-scale turbidity currents and debris flows appear to be the dominant mechanism for the downslope transport of coarse detritus. On ancient carbonate slopes, all types of sediment gravity flows have been proposed, but again the predominant depositional mechanisms are interpreted to be debris flows or turbidity currents. Observations from the Tongue of the Ocean, however, suggest that the steep slopes formed by an alternative mechanism. The apparent lack of matrix and poor sorting of the deposits, combined with upslope imbrication of clasts, suggests that deposition took place through a combination of episodic rockfall and grainflow processes. The resulting deposits are characterized by elongate (parallel to slope) lenses of coarse-grained and poorly sorted sediment, that are discontinuous in both strike and dip directions.

Conclusions

The upper slopes around the Tongue of the Ocean provide a modern example of how steeply dipping foreslopes may develop along carbonate platform margins and are remarkably similar to the clinoforms often described from fossil platforms. The awareness that primary depositional slopes of 35-45^o were deposited during the early rise of sea level following the last lowstand and that the steep slopes were apparently stabilized by syndepositional cementation, provides valuable insight into how and when some fossil slopes may have formed. In addition, the recognition that the Tongue of the Ocean slopes formed by the amalgamation of localized lenses and not large-scale mass-flow deposits may have important implications to the understanding of steep carbonate slopes in the subsurface. Realization of the internal heterogeneity of slope deposits and discontinuous nature of the lenticular beds may be a critical component to the accurate evaluation of possible reservoir facies. Evidence for "highstand" failure of the slopes provides an alternative to the accepted dogma of lowstand failure and may represent one means by which highstand turbidites are initiated.

Ancient Outcrop and Modern Examples of Platform Carbonate Cycles - Implications for Subsurface Correlation and Understanding Reservoir Heterogeneity

Paul M. (Mitch) Harris, Charles Kerans, and Don G. Bebout, 1993, in Loucks, R. and Sarg, J. F. (eds.), Carbonate Sequence Stratigraphy - Recent Developments and Applications: AAPG Memoir 57, p. 475-492.

Detailed geologic studies of hydrocarbon reservoirs in platform carbonates commonly show reservoir zones occur within 1 - 15 m thick upward-coarsening successions of lithofacies, i.e. upward-shallowing cycles. Our understanding of the depositional history and reservoir characteristics of such cycles and their component facies is enhanced by observations of ancient outcrop examples and models derived from modern analogs.

Outcrops of the Permian San Andres Formation along the Algerita Escarpment of the Guadalupe Mountains contain cycles 3 to 12 m thick, with thin mudstone/wackestone bases, overlain by burrowed wackestones and packstones, and capped by thick massive to planar or cross-bedded packstones and grainstones. These facies formed during relative rise and/or stabilization of sea level during which carbonate sand shoals developed. The outcrops also display lateral facies relationships within the cycles on the scale of hundreds of meters that are representative of those commonly observed in analogous hydrocarbon reservoirs of the Permian Basin of Texas and New Mexico.

Core and surface sediment mapping in the Holocene Joulters Cays ooid-shoal complex of Great Bahama Bank reveals the three-dimensional complexity of an upward-coarsening and shallowing cycle. This facies mosaic is like that observed in two dimensions at Algerita Escarpment or in one dimension in a core from a reservoir. This modern example points out difficulties in interpretation and correlation of grainstone cycles in subsurface studies of platform carbonate reservoirs. The modern shoal complex which extends over 400 km^2 varies greatly in thickness but averages 4 m thick. Shoal growth, largely in a response to a relative rise of sea level, records rapid expansion of ooid sands, island formation and associated meteoric diagenesis, local shoal stabilization and reworking by burrowing, and generation of hardground layers.

Sand generation and topography varied greatly in the Joulters Cays area during flooding of the platform and development of the shoal. Such variation should be expected in ancient examples as was observed at Algerita Escarpment. Within the upper grain-dominated part of the cycle at Joulters, depositional facies geometries and early diagenetic alteration contribute to fine-scale heterogeneities. This is at a scale equivalent to documented hydrocarbon reservoir heterogeneities.

Satellite Images of Shallow Water Carbonate Depositional Settings - Examples of Exploration- and Development-Scale Geologic Facies Variation

Paul M. (Mitch) Harris, 1994, Satellite Images and Description of Study Areas, in Harris, P. M. and Kowalik, W. S. (eds.), Satellite Images of Carbonate Depositional Settings: Examples of Reservoir- and Exploration-Scale Geologic Facies Variation: AAPG Methods in Exploration Series No. 11, p. 29-140.

Paul M. (Mitch) Harris, William S. Kowalik, Brad P. Dean, and Anthony J. Lomando, 1995, Satellite Images of Shallow Water Carbonate Depositional Settings - Examples of Exploration- and Development-Scale Geologic Facies Variation: AAPG Bulletin, v. 79 (13), p. 39-40.

Paul M. (Mitch) Harris and William S. Kowalik, 1995, Facies Dimensions Within Carbonate Reservoirs - Guidelines from Satellite Images of Modern Analogs: AAPG Bulletin, v. 79 (8), p. 1221.

Information from modern shallow water carbonate settings is commonly incorporated into analysis of reservoir-scale heterogeneity problems and exploration-scale plays. The modern analogs provide a means to illustrate the distribution of porous carbonate facies within the overall setting. Often these analogs become an important part of the geologic model as they show the scale, trend, and interrelationships of facies that might be related to reservoir and non-reservoir rock distribution.

We acquired and processed 30 Landsat and SPOT satellite images from 9 "classic" carbonate areas that should help fulfill the needs of most exploration and development geologists for analogs. The images include a variety of depositional settings and are important because they show contrasting ways in which the different settings may be related.

- The Bahamas, Caicos Platform, Chinchorro Bank, and portions of Belize, for example, are isolated carbonate platforms, whereas the other areas are attached shelves.
- The Abu Dhabi and northern Yucatan areas are often cited as modern examples of ramp-style shelf-to-basin transitions.
- South Florida, portions of the Belize area, and the Great Barrier Reef of Australia are superb examples of a rimmed shelf margin.
- A broad, deep lagoon is especially well expressed in the Great Barrier Reef and Belize shelf examples.
- South Florida, Belize, the Great Barrier Reef, Shark Bay and Abu Dhabi contain areas of mixed carbonate and siliciclastic deposition.
- Variability of reef continuity and distribution is shown in South Florida, the Bahamas, Caicos, Belize, the Great Barrier Reef, and Chinchorro Bank.
- Carbonate sand bodies assume variable morphologies in the Bahamas, Caicos Platform, Yucatan, and Abu Dhabi areas.

The images illustrate the geologic framework in modern carbonate environments and thereby graphically depict the geologic characteristics that can be expected in ancient carbonate settings. The geologic framework is important at the development scale where lateral variation of porosity and permeability, i.e. reservoir quality, are commonly tied to facies changes, and facies dimensions are required as input to reservoir models. The geologic framework is essential at the exploration scale for reservoir facies prediction and stratigraphic play concepts which are related directly to depositional facies patterns.

Overview of Carbonate Play Types - Important Characteristics Relevant to Exploration

Paul M. (Mitch) Harris, 1995, AAPG Bulletin, v. 79 (13), p. 40; also 1995, Introduction to Carbonates and Overview of Carbonate Play Types - Notes for a Short Course, Permian Basin Graduate Center, June 26, 1995, Midland, Texas, unpaginated.

Carbonate play types, i.e. a family of geologically similar prospects or producing pools that share a common reservoir genesis, are highly varied and therefore offer many exploration possibilities. Common depositional plays and their important characteristics are:

- Reefs, banks, and buildups (localized biogenic accumulations) occur in elongate trends along windward shelf margins or the edges of intrashelf basins, in isolated equidimensional forms as a fairway on an outer shelf or ramp, and on basement or salt-cored highs within the basin. Requirements of the biota (nutrients, minor turbidity, normal salinity) may further limit distribution. Variations in biota have occurred through geologic time, and a vertical sequence usually reflects growth stages.
- Carbonate sands (nonskeletal and/or skeletal sand deposits) occur as tidal bars, shoal complexes, or sheets, forming a high energy trend on ramps and shelves, either as a sand-dominated shelf margin or at the edge of intrashelf basins. Such sands may also fringe shallow biogenic buildups and cap deeper-water buildups. Upward-shoaling sequences are common.
- Downslope debris (shelf, shelf-margin, and slope debris redeposited downslope) forms elongate wedges, lobe-shaped fans, slump blocks, and channel fills along the toe-of-slope and basin margin adjacent to a regional shelf margin or locally surrounding pinnacle buildups. The play is absent in ramp settings unless the ramp is distally steepened. Debris flow and turbidite sequences occur, and porosity is inherited from the shelf and also formed in the subsurface.

Some diagenetic plays and their characteristics are:

- Dolomite in cyclic sequence (dolomitized tidal-flat and inner-shelf facies within cyclic strata) occurs on the inner portions of ramps and shelves and also behind emergent shelf margins. Evaporite-capped cycles are common, generally producing multiple thin porosity zones.
- Subunconformity play (secondary porosity formed by dissolution below exposure and unconformity surfaces) is both localized and regional in extent. The former consists of moldic porosity capping upward-shoaling, high-frequency cycles, or vugular and cavernous porosity associated with an intrabasinal unconformity and due to exposure by local tectonism or small-scale eustatic fall. The later is cavernous porosity and brecciation formed during major exposure of tectonic or long-term eustatic origin and associated with an interregional unconformity.

- Burial diagenesis (porosity formed by dolomitization or dissolution in the deep subsurface) commonly follows joint or fracture patterns, and involves fluids of meteoric, connate, or hydrothermal character. Porosity is highly variable.

Reef Styles of Modern Carbonate Platforms

Paul M. (Mitch) Harris, 1996, Bulletin of Canadian Petroleum Geology, v. 44 (1), p. 72-81.

Modern areas of carbonate deposition illustrate the distribution of carbonate facies within an overall depositional setting, and therefore can play an integral part in a subsurface geologic model by indicating the dimensions, trend, and interrelationships of facies that might be related to reservoir and non-reservoir distribution. Several modern carbonate areas depict the geologic characteristics that can be expected in ancient reef settings like those of the Devonian in the Western Canada Sedimentary Basin.

The generalized styles of reefs shown by the various modern areas are:

- Rimmed shelf/platform margin reefs - South Florida, Bahamas, Caicos Platform in the British West Indies, Belize, and the Great Barrier Reef of Australia
- Smaller isolated reefs within shallow shelves and lagoons (South Florida, the Bahamas, and Caicos) or broad, deep shelves and lagoons (Belize and the Great Barrier Reef)
- Isolated carbonate platforms or banks separated by deep water - Chinchorro Bank offshore of Yucatan, and the offshore Belize platforms

The geologic framework and distribution of reef facies as illustrated by these modern areas can be important in the development scale analysis of ancient reservoirs where reservoir quality is tied to facies changes and facies dimensions are required as input to reservoir models. The geologic framework is also important at the exploration scale for reservoir facies prediction and stratigraphic play concepts that are related directly to depositional facies patterns.

Facies Heterogeneity in a Modern Ooid Sand Shoal - An Analog for Hydrocarbon Reservoirs

Rick P. Major, Don G. Bebout, and Paul M. (Mitch) Harris, 1996, University of Texas Bureau of Economic Geology, Geological Circular 96-1, 30 p.

The Joulters Cays area, immediately north of Andros Island on Great Bahama Bank, displays a variety of environments in which ooid sands can accumulate. The Joulters Cays shoal is a 400-km^2 (155-mi^2) sand flat, partly cut by numerous tidal channels and fringed on the ocean-facing borders by mobile sands (Harris, 1979, 1983). This active border or ooid sands, 0.5 to 2 km (0.3 to 1.2 mi) wide depositional dip, extends the length of the shoal for 25 km (15.5 mi) along its windward side and terminates abruptly to the east (seaward) onto the shelf margin. To the west (platform-ward), mobile sands grade into the sea-grass- and algae-stabilized sand-flat part of the shoal and eventually into the deeper water platform interior. Joulters Cays are three islands that lie within the active area of the shoal.

Exploration-Scale Heterogeneity

Heterogeneity of the Joulters Cays shoal is inferred on the basis of the distribution of depositional facies. Clean ooid sand along the active margin of the shoal occurs as subtidal-bar, channel-fill, beach, and island facies. In cross-section, the sand body occurs as an irregularly shaped area 2 km (1.2 mi) wide and 2 to 3 m (6.6 to 9.8 ft) thick. High initial porosity was measured in similar clean sands by Halley and Harris (1979) and Enos and Sawatsky (1981) and was also confirmed in these sands by thin section analysis. Immediately bankward of the clean ooid sand are widespread, somewhat irregularly-shaped layers containing mixtures of carbonate mud and sand that will most likely result in vastly different reservoir properties. An upper layer of muddy ooid sand, some 20 km (12.4 mi) wide and from 4 to less that 1 m (13 to less than 3.2 ft) thick, thins bankward and overlies a more widespread lower layer of muddy, fine-grained peloidal sand more than 30 km (>18.6 mi) wide and ranging from 5 to 2 m (16 to 6.6 ft) in thickness. These layers will most likely have initial porosities lower than those of the more seaward, clean ooid sand, judging from measured values of similar sands by Enos and Sawatsky (1981) and from thin-section estimations. In addition, the upper layer will most likely have better reservoir quality that the lower layer because of larger grain size and lower mud content.

Development-Scale Heterogeneity

Local-scale patterns of heterogeneity within the active part of the Joulters Cays shoal are also inferred from the facies distribution. The well-sorted ooid sand facies occurs in the center of the shoal complex where the entire area which is 305 to 607 m (1,000 to 2,000 ft) wide and 1.8 to 2.4 m (6 to 8 ft) is exposed at low tide. The poorly sorted ooid sand facies occurs both bankward and seaward of the well-sorted ooid sand facies. Although the limits of the poorly sorted ooid sand facies were not encountered in this study, the regional study of Harris (1979) indicates that it forms a very narrow band seaward of the shoal and occurs over a very broad area several kilometers wide on the platform-side; the poorly sorted ooid sand facies and associated poorly sorted ooid sand and mud facies are 0.6 to 1.5 m (2 to 5 ft) thick at the shoal and thin platform-ward.

Heterogeneity is inferred because of mud content, burrowing, and grain type variations. These subtle variations occur on a scale of hundreds of meters (approximately 1,000 ft), which is consistent with well spacing in mature hydrocarbon reservoirs like those in the southwestern United States. The scale of variation observed in the Joulters Cays region should therefore be considered when correlating at the common development interwell scale. In addition, the heterogeneity observed in this area occurs within a single facies (i.e. ooid sands) as identified within the more regional, exploration-scale core study of Harris (1979). By analogy, similar subtle textural variations can be expected to produce local heterogeneity within ooid grainstone reservoirs.

Recent Evolution of a Bahamian Ooid Shoal: Effects of Hurricane Andrew

Rick P. Major, Don G. Bebout, and Paul M. (Mitch) Harris, 1996, Preservation Potential of Major Storms in Marginal Marine Carbonate Sediments: South-Central Section GSA Annual Meeting, GSA Abstracts with Programs, v. 28, no. 1, p. A52; also 1996, GSA Bulletin, v. 108, no. 2, p. 168-180.

Hurricane Andrew, a category 4 hurricane having wind velocities of ~240 km/hr, passed north of Joulters Cays, Bahamas, in a westerly direction on August 23, 1992. We documented three sedimentary facies in a 2.7 km^2 study area dominated by mobile ooid sands before the hurricane, using aerial photographs, surface observations, and shallow coring. The shoal crest at this location had aggrading and northward-prograding (parallel to depositional strike) washover bars composed of cross-bedded, well-sorted ooid sands. Burrowed, poorly-sorted ooid sands were present seaward of the washover bars, whereas poorly sorted ooids and mud occupied a stabilized area bankward of the actively migrating shoal and local areas between washover bars on the crest of the shoal. The shoal was cross-cut by tidal channels, and older washover bars were being dissected by tidal currents.

Although Hurricane Andrew profoundly changed surface features within the study area, its effects will probably be only partly preserved. The hurricane eroded washover bars and transported sediment seaward, leaving a nearly flat shoal crest overlain by a laterally continuous, decimeter-thick lens of swell-sorted ooid sand that thins seaward and bankward. Post-hurricane tidal currents deposited a centimeter-thick discontinuous layer of carbonate mud over this lens of well-sorted ooid sand and transported ooids seaward off the shoal.

The well-sorted ooid sand layer will most likely be reworked when an actively migrating shoal crest is reestablished, although some of this storm deposit may be preserved on the shoal crest where the ooid sand layer was deposited in areas of normally less agitated conditions. Ooids my also be preserved in finer grained sediments seaward of the shoal, as suggested by previous studies. Mud deposits on the shoal crest may be preserved where buried beneath reestablished washover bars, although some of this mud will be removed by reworking during diurnal tides.

Analog for Exploration- and Development-Scale Heterogeneity in Grainstone Reservoirs; Exuma Islands, Bahamas

McNeill, D. F., Eberli, G. P., and Harris, P. M., 2004, Analog for Exploration- and Development-Scale Heterogeneity in Grainstone Reservoirs; Exuma Islands, Bahamas: AAPG International Conference & Exhibition, Program and Abstracts, p. A48.

The complexity of ooid sands as reservoirs has caused us to revisit the modern bank-margin grainstone setting to improve our understanding of exploration- and development-scale heterogeneity. In the Exuma Islands, Bahamas, one can observe spatial variability of both depositional and diagenetic facies that create potential reservoir heterogeneity and stratigraphic traps. The Exuma island chain (250 km long) contains hundreds of islands, often two or three paralleling each other, which are both Holocene and Pleistocene in age. On an exploration scale the islands and surrounding sands form a large sand-body parallel to the platform edge. This elongated sand belt is extremely heterogeneous on the smaller scale. A variety of facies are juxtaposed because both antecedent and syndepositional topography set the stage for a complex pattern of modern ooid sand accumulation. The sands form lobate deltas, marine bars, and along beaches and are locally transported to accumulate in sand-rich tidal flats, dune ridges, and deeper water settings in both a platform and seaward direction. The spatial patterns of facies as viewed on satellite images show the potential complexity of a similar fossilized example.

Specific lessons learned from this modern analog are: 1- antecedent eolian topography forms a template for the distribution of modern ooid sands (tidal delta, stacked eolianites, tidal flat); 2- the geometry (lobate to elongate to bank interior) of the modern ooid sand bodies is dictated by the focused energy between the antecedent template; 3- the discontinuous island morphology allows focused tidal circulation that sweeps lime mud from the margin and platform interior; 4- widespread marine and meteoric cementation form Holocene islands creating new topography; 5- reservoir-scale heterogeneity in tidal delta and grainy tidal flat settings is apparent at the 100-m scale, with variation between clean ooid grainstone and muddy ooid packstone textures.

Carbonate Facies Dimensions at the Reservoir- and Exploration-Scale: What Are Sources for This Information?

Paul M. (Mitch) Harris, 1997, Sedimentary Events and Hydrocarbon Systems, CSPG-SEPM Joint Convention, Program with Abstracts, p. 123.

Knowledge of the spatial distribution of carbonate facies is necessary to determine patterns of heterogeneity within a reservoir or to predict a reservoir's regional extent. Facies dimension information is critical for improved reservoir characterization in determining areal variograms, designing templates for attribute distribution, and indicating directional bias for interpolation. The same type of information is valuable at the exploration scale in conceptualizing a geologic model, investigating stratigraphic trap configuration, and understanding porosity distribution. What sources can provide information for enhancing the interwell correlation of facies?

Holocene examples are valuable as analogs. As examples, satellite images, aerial photographs, or surface sediment maps illustrate facies dimensions and can be used to show any patterns relative to simulated well spacing. Of more value, however, are the results of coring studies from modern environments where the spatial distribution of facies within a depositional cycle is provided. But Holocene studies are often insufficient analogs for portraying reservoir quality variations because they lack the diagenetic complexities of their subsurface counterparts.

Outcrop analogs can provide two- or even three-dimensional views of facies with greater diagenetic overprint than found in the modern examples and over a more substantial stratigraphic thickness, i.e. for a stack of depositional cycles. Porosity and permeability can be measured on outcrop within a cycle and facies framework, and as such provide a more complete view of both facies and reservoir quality dimensions. Questions always remain, however, on how well a modern or outcrop analog actually compares with a particular reservoir or subsurface stratigraphic layer.

Methods for Determining Interwell Facies Boundaries (and Constraining Geostatistical Correlation)

Paul M. (Mitch) Harris, 1998, AAPG Annual Convention Program and Abstracts, A275, 3 p.; also 1998, West Texas Geological Society Bulletin, v. 37(6), p. 5-7.

Using carbonate examples, some methods for determining facies boundaries at the interwell scale, and therefore potentially constraining geostatistical correlation, are presented. Modern environments and outcrops are valuable as reservoir analogs. Crosswell seismic profiles and horizontal well data are direct detection methods within a reservoir. Although all of the methods have shortcomings, they should be utilized to the fullest extent possible, in conjunction with geostatistical approaches, during a reservoir characterization effort.

Robust statistical programs for characterizing and mapping facies from core, log, seismic, and engineering data are developing at a rapid pace. These programs present to the subsurface geologist opportunities for portraying spatial facies relations to use in building reservoir models. Varying certain geostatistical parameters creates multiple correlation scenarios (realizations) that honor existing data and collectively can be used to determine probabilities for various aspects of the correlation between wells. The ease with which geostatistical correlation is developed and displayed makes the approach a necessary one, but there is also a down side from the geological perspective. Time and budget limitations often create situations in which available geological data that should be viewed as possible constraints for the geostatistical correlation are overlooked.

Knowledge of the spatial distribution of carbonate facies is necessary to determine patterns of heterogeneity within a reservoir layer or to predict a reservoir's regional extent. This facies dimension information is critical for improved reservoir characterization in determining facies boundaries between well locations. From the standpoint of building reservoir models and assigning properties within a reservoir layer, facies dimensions are necessary for constructing variograms, designing templates for attribute distribution, and indicating directional bias for interpolation. What are some sources of information for enhancing the interwell correlation of facies and potentially guiding geostatistical correlation?

Four types of information that can improve correlation are briefly introduced. Information from modern and outcrop examples is valuable as analogs for a particular reservoir, whereas crosswell seismic profiles and horizontal well data are direct sources of information from the reservoir.

Holocene environments are valuable as analogs for conceptualizing facies patterns within a single reservoir layer. As examples, satellite images, aerial photographs, or surface sediment maps illustrate facies trends and dimensions and can be used to show patterns for a particular depositional setting relative to simulated well spacing. However, of more value in visualizing the anatomy of a reservoir layer are the results of coring studies from modern environments, where the spatial distribution of facies within a depositional cycle is documented. How well the facies patterns from a Holocene example actually compare with a particular reservoir or reservoir layer is always a cause for concern and therefore a shortcoming. In addition, Holocene studies are often insufficient analogs for portraying reservoir quality variations because of their limited stratigraphic thickness and lack of diagenetic complexity.

Outcrop analogs provide two- or even three-dimensional views of facies with greater diagenetic overprint than is found in the modern examples and over a more substantial stratigraphic thickness, i.e., for a stack of depositional cycles. Porosity and permeability, when measured on outcrop within a cycle/sequence and facies framework, are used to illustrate fluid flow scenarios. As such, outcrop analogs provide a more complete view than subsurface data of both facies and reservoir quality dimensions. The stratigraphic and facies relations recognized on outcrop are reasonably used as a template for correlating subsurface data. Questions always remain, however, on how well the details of facies and diagenesis from an outcrop actually compare with a particular reservoir or reservoir layer.

Crosswell seismic profiling is a suitable method of directly measuring interwell changes of petrophysical facies. High vertical resolution crosswell data collected in carbonate reservoirs with close well spacing detects interwell variations of impedance that can be related to porosity. When combined with downhole log and core data and compared with porosity models, the seismic data map porosity, but not necessarily permeability, between wells. These petrophysical facies relate directly to depositional facies in simple cases, or relate to some combination of depositional facies and post-depositional modification in more diagenetically complex examples. In a similar sense, 3-D seismic data, when combined with existing wells and larger-scale porosity models, provide a crude approximation of interwell facies distribution. Shortcomings of using crosswell seismic data to define facies boundaries are understanding the exact relationship between impedance and porosity for the particular reservoir and, although dropping dramatically, cost for acquisition and processing.

Log and core information from horizontal wells directly detect facies and petrophysical changes between vertical wells. By combining horizontal and vertical well information, a 3-D view of depositional and petrophysical facies boundaries is determined. As valuable as this information is for the particular drilled layer, drawbacks of horizontal well data are likely to be the number and orientation of wells, hole problems that affect logging, and the relatively small area of investigation of each wellbore.

Modern and outcrop analogs remain valuable sources of facies dimension information, although they are not direct comparisons for a reservoir, especially for petrophysical properties. Crosswell seismic and horizontal well data directly detect interwell facies and petrophysical boundaries, but not enough of either type of data is often available due to cost and area of investigation. Given the shortcomings of the various methods, some choose to ignore these potentially valuable sources of information. Instead, they should be utilized to the fullest extent possible during a reservoir characterization effort. Information from the different methods must be examined quantitatively where possible to apply facies boundary insight throughout a reservoir model and better constrain geostatistical correlation.

Characterizing Carbonate Reservoirs: Approaches for Determining the Boundaries and Internal Facies Patterns of Small-Scale Cycles

Paul M. (Mitch) Harris, 2000, AAPG Bulletin, v. 84 (9), p. 1433.

In many carbonate reservoirs, a key component that must be well understood for reservoir characterization purposes is the small-scale cycle, as it appears to exert a fundamental control over fluid flow behavior. Understanding the nature of these cycles can be challenging in cases where core control is less than optimum. Modern and outcrop analogs, as well as crosswell seismic data, may provide clues to better understand the boundaries and internal facies distribution of cycles.

Modern environments are valuable for conceptualizing the spatial distribution of facies for a time-slice. Combining remote sensing data such as satellite images and aerial photographs with surface sediment maps provide facies trends and dimensionality data that can be used to show patterns and assist the modeling of a reservoir relative to simulated well spacing. These map data are of even more value when combined with coring studies that provide the vertical dimension of facies within the modern cycle.

Outcrop exposures offer two- or even three-dimensional views of cycles with greater diagenetic overprint than found in the modern examples. Cycle boundaries and spatial facies variation can be examined in detail. Porosity and permeability measured on outcrop within a cycle and facies framework serve as a template for modeling flow-unit dimensions.

Crosswell seismic profiling may also prove to be a suitable method of directly measuring cycle-scale reservoir units and interwell changes of facies. High vertical resolution crosswell data has been collected in carbonate reservoirs with close well spacing. The data are capable of resolving cycles and show indications of detecting interwell variations of impedance. When combined with log and core data and compared with porosity models, the seismic data can reasonably be used to map "petrophysical" facies between wells.

Modern Analogs for Carbonate Reservoirs - Great Bahama Bank Revisited

G. Michael Grammer, Paul M. (Mitch) Harris, and Gregor P. Eberli, 2000, AAPG Bulletin, V. 84 (13), p. A57.

Study of modern depositional environments in the Bahamas formed a cornerstone of carbonate facies analysis in previous decades. Numerous workers provided details on facies types, depositional processes, and early diagenesis that were incorporated into the development of classical carbonate facies models. The Bahamas continue to be an invaluable modern laboratory for a new generation of studies that focus more on the details of reservoir distribution and evolution through time.

Modern environments are valuable as analogs for conceptualizing the spatial distribution of reservoir facies within a single time-slice and for obtaining a first-order quantitative approximation of geometrical attribute for potential reservoir facies. Combining remote sensing data such as satellite images and aerial photographs with surface sediment maps provide facies trends and dimensionality data that can be used to show patterns and assist the modeling of a reservoir relative to simulated well spacing. These two-dimensional data are of even more value when combined with wither results of coring studies from modern environments, or from detailed outcrop work that provide the third (i.e. vertical) dimension to the reservoir system. Combining this geometrical data with recent advances in our understanding of early diagenesis enhances the predictability of probable reservoir and flow unit distribution in the subsurface. New insights, such as the potential for syndepositional marine cementation at depths up to 100m, the presence of "meteoric" diagenetic fabrics in marine burial environments, and effects of pore architecture on petrophysical characteristics of carbonate rocks have all led to a better understanding of the distribution of potential reservoirs in the subsurface.

Carbonate Platforms: Exploration- and Production-Scale Insight from Modern Analogs in the Bahamas

Grammer, G. M., Harris, P. M., and Eberli, G. P., 2001, Leading Edge (Society of Economic Geophysicists), March, v. 20, no. 3, p. 252-261.

The search for hydrocarbons in carbonate rocks depends on a thorough understanding of the primary depositional controls on carbonate sediments as well as their postdepositional changes. When a reservoir is discovered, interpretation of depositional facies and a search for applicable analogs become essential for both primary and enhanced field development. Understanding the various lithofacies types, their distribution, and geometry along different styles of carbonate platforms is the first step in evaluating the reservoir potential of carbonate systems. This analysis must be done at regional (or seismic) scale and at production or enhanced production scales to maximize the hydrocarbons that can be extracted from any carbonate reservoir. Postdepositional change, or diagenesis, is another key factor as diagenetic change may create additional porosity and permeability or, sometimes, reduce or completely destroy porosity in carbonates. Key processes in the diagenetic change of carbonate sediments include cementation in freshwater and seawater environments, compaction, dissolution, and dolomitization whereby the original limestone sediments are transformed in whole or in part to dolomite.

In this paper, we review some key findings from studies in the Bahamas over the past two decades that have direct impact on how we explore for, and ultimately exploit carbonate hydrocarbon reservoirs. We first discuss some major advances in our understanding carbonate platform evolution at the exploration scale and then some key findings that have led to advances in understanding carbonate reservoirs. We use the natural laboratory of Great Bahama Bank (GBB) to focus on two fundamental problems in dealing with subsurface carbonates: a stratigraphic framework and reservoir distribution. Establishing a stratigraphic framework is essential in understanding regional geology during exploration, but it is just as critical during reservoir development for establishing a layering scheme for reservoir studies. Likewise, knowledge of the distribution of depositional and diagenetic facies is critical to both exploration and development. At the regional scale, understanding facies distribution is essential for formulating stratigraphic plays; and development-scale variations in reservoir quality are intimately tied to the relations between facies. Stratigraphy and reservoir distribution are linked at both exploration and development scales; knowing how they are related in an area is a major step toward success in the subsurface.

Comparative Sedimentology of Carbonate Platforms – Lessons learned from the Bahamas

Paul M. (Mitch) Harris, G. Michael Grammer, and Gregor P. Eberli, 2001, GSA Annual Meeting and Exposition Abstracts, v. 33(6), p. A-443.

Recent studies of modern carbonate environments in the Bahamas continue to refine depositional and diagenetic models. New insights into the stratigraphic framework of carbonate platforms include an understanding of how isolated platforms may coalesce through progradation along leeward margins by highstand shedding of bank-top derived sediment. The resulting “highstand wedge” mimics in many ways the “lowstand wedge” of classical sequence stratigraphy, suggesting that further refinement of these models is needed. Additionally, seismic reflectors in pure carbonate systems have been shown to be the result of lithologic and diagenetic change, many regionally correlatable seismic sequence boundaries are indeed chronostratigraphic horizons, and failure of platform margins and slopes and subsequent deposition of megabreccias may occur during both lowstands and highstands of sea level.

For depositional models, key lessons include that lithofacies types and distribution are relatively consistent across platforms but are dependent upon paleogeography and paleoceanography. The role of antecedent topography in initiating development of both reefal and sand bodies is strongly coupled to the windward margin positioning of these facies, while the sedimentary make-up (grain vs. mud dominated) of proximal slope facies is also dependent on the windward/leeward orientation of the margin. In addition, details of the genesis of shallowing upward cycles in different environments, coupled with the realization that unfilled accommodation space is common, adds to our understanding of ancient platform equivalents and suggest limitations inherent to cyclostratigraphic correlation.

Important advances from a diagenetic perspective include a realization that syndepositional marine cementation takes place not only in shallow subtidal and intertidal environments, but also at depths of at least 60-75 m. These findings suggest that paradigms associated with slope stabilization and the formation of submarine hardgrounds and seismic reflector horizons need to be revisited. Other recent work has focused on the role of micro-organisms in the cementation process while also documenting the presence of “meteoric-like” moldic porosity fabrics occurring in a marine phreatic environment.

Isolated Carbonate Platforms – Lessons Learned from Great Bahama Bank

Gregor P. Eberli, Paul M. (Mitch) Harris, and G. Michael Grammer, 2002, AAPG Annual Convention Program and Abstracts, p. A48.

Studies of carbonate platforms in the Bahamas continue to refine stratigraphic, depositional, and diagenetic models. Stratigraphic insights include understanding how isolated platforms may coalesce through progradation along leeward margins by highstand shedding of bank-top derived sediment. Also, that seismic reflectors in pure carbonate systems have been shown to be the result of lithologic and diagenetic change, and many regionally correlatable seismic sequence boundaries are indeed chronostratigraphic horizons. The failure of platform margins and slopes and subsequent deposition of megabreccias may occur during both lowstands and highstands of sea level.

Lithofacies, which are relatively consistent across platforms, are dependent upon paleogeography and paleoceanography. The role of antecedent topography in initiating development of both reefal and sand bodies is strongly coupled to a windward margin location, and the sedimentary make-up (grain vs. mud dominated) of proximal slope facies is also dependent on the windward/leeward orientation of the margin. In addition, details of the genesis of shallowing upward cycles in different environments, coupled with the realization that unfilled accommodation space is common, adds to our understanding of ancient platform equivalents and suggest limitations inherent to cyclostratigraphic correlation.

Syndepositional marine cementation takes place in shallow subtidal and intertidal environments, but also too much greater depths, suggesting that paradigms associated with slope stabilization and the formation of submarine hardgrounds and seismic reflector horizons need to be revisited. Other recent work has focused on the role of microbial communities in cementation and documenting the presence of “meteoric-like” moldic porosity fabrics in the deep marine phreatic environment.

Reservoirs in Isolated Carbonate Platforms – Insight from Great Bahama Bank

Paul M. (Mitch) Harris, Gregor P. Eberli, and G. Michael Grammer, 2003, AAPG International Conference & Exhibition, p. A38.

Studies of Great Bahama Bank (GBB), the largest isolated carbonate platform in the Bahamas, continue to refine stratigraphic, depositional, and diagenetic models. These models are of particular importance in understanding the architecture and reservoir quality of reservoirs in isolated platforms.

Stratigraphic and depositional studies provide an understanding of the lateral growth potential and pulsed progradational nature of GBB. Ancestral isolated platforms coalesced to form GBB through progradation along their leeward margins by highstand shedding of bank-top derived sediment. The growth and diagenesis of platform strata are intimately linked to sea level. The role of antecedent topography on the platform top in initiating development of both marginal reefs and sand bodies is strongly coupled to a windward margin setting. Likewise, the sedimentary make-up (grain vs. mud dominated) of proximal slope facies is dependent upon the windward/leeward orientation of the margin. Details of the genesis of platform top shallowing upward cycles, coupled with the realization that unfilled accommodation space is common, add to our understanding of ancient platform equivalent strata. This nature of cycle variability suggests limitations inherent to cyclostratigraphic correlation and explains aspects of reservoir heterogeneity.

Syndepositional marine cementation clearly takes place to great depths down the flanks of GBB, suggesting that paradigms associated with slope stabilization and architecture need to be revisited. The presence of “meteoric-like” moldic porosity and cementation fabrics in the marine phreatic environment deep within the platform poses the dilemma of correctly interpreting the stratigraphic context of similar diagenetic features in reservoirs. Dolomite within this same deep marine phreatic environment corroborates a model for dolomite formation that is likely typical for isolated platforms.

Integration of Outcrop and Modern Analogs in Reservoir Modeling – Overview with Examples from the Bahamas

G. Michael Grammer, Paul M. (Mitch) Harris, and Gregor P. Eberli., 2004, Integration of Modern and Outcrop Analogs in Reservoir Modeling – Overview and Examples: in Grammer, G. M., Harris, P. M., and Eberli., G. P., (eds.), Integration of Outcrop and Modern Analogs in Reservoir Modeling, AAPG Memoir 80, p. 1-22.

Development of a geologically-constrained reservoir model, and subsequent up-scaling of the model for reservoir simulation, depends upon critical input parameters defining both the geometrical attributes and distribution of the targeted reservoir facies. To accurately characterize the potential reservoir, one must address the geologically-defined variability within the system. Gross differences in sedimentary facies, as well as more local variations in aspects such as grain size/type, grain sorting, sedimentary structures and diagenetic overprint, may all influence the internal make-up and geometry of sedimentary deposits, and thus, the heterogeneity of potential reservoirs. Integration of geologically-based elements is, therefore, a fundamental step in the characterization of the probable lateral and vertical distribution and variability of reservoir facies in the subsurface. Such a geologically-based model not only increases our understanding of reservoir heterogeneity, but also provides the foundation for which the rest of the reservoir- and ultimately simulation-models can be built.

In the last several years, we have seen the development of high-resolution sequence and cycle stratigraphy, and with it, the advent of a refined mode of interpretation for depositional systems. Using a sequence stratigraphic approach, sedimentary systems are analyzed dynamically through time, rather than as a single time slice as was previously done with static depositional or facies models. These dynamic conceptual models offer better predictability of the distribution of potential reservoir facies and their reservoir quality, especially when combined with recent advances in our understanding of the detailed internal architecture and diagenesis of depositional systems.

In many reservoirs, key components that must be well understood for reservoir characterization include the facies types and probable diagenetic alteration, as well as the vertical stacking patterns associated with high frequency cycles. It is at this scale (i.e. meter scale) that fundamental controls over fluid flow behavior in the reservoir are often exerted. Thorough understanding of the nature of these cycles in the subsurface, however, can be challenging, especially in cases where core control is less than optimal. It is here that outcrop analogs have been shown to provide valuable insight into the understanding of the boundaries and internal facies distribution of these high frequency cycles.

Rarely, however, do we get a full three-dimensional picture of potential reservoir distribution from outcrop alone, especially from the standpoint of aerial dimensions. Outcrop studies typically provide solid data on the vertical dimensions of a system, but the lateral aspects are generally limited because the exposures are either strike oriented, dip oriented, or at some orientation oblique to these directions. As a means to enhance our understanding of the 2-D aerial distribution of possible reservoir facies, it can be invaluable to incorporate spatial data from the study of modern analogs (e.g. Grammer et al., 2001). Through the evaluation of modern depositional systems, we can realize a first-order approximation of the two-dimensional aerial distribution of principal facies belts in a particular depositional setting during at least one time slice (i.e. the present Holocene). There are undoubtedly limitations to using the “Modern” as an analog because certain boundary conditions, such as climate and tectonic variability, relative position of sea level and rates of sea level rise or fall, might be different in ancient systems being studied. Nevertheless, in the absence of high quality 3-D seismic data, modern depositional systems are one of the only data sets from which reservoir modelers can extract the 2-D aerial distribution of potential reservoir facies that is needed to accurately drive geologically-constrained 3-D reservoir models.

Recent Field Guides

Harris, P. M., 2004, The Joulters Ooid Shoal – An Analog for Heterogeneity within Carbonate Sand Reservoirs: University of Miami Comparative Sedimentology Laboratory Sedimenta CD Series No. 1.

Outline of CD Contents:

- Joulters area satellite image-
- Other satellite views of the Joulters Ooid Shoal
- Sedimenta VII - Facies Anatomy and Diagenesis of a Bahamian Ooid Shoal
- Appendices from original Ph.D. dissertation - Sedimentology of the Joulters Cays Ooid Sand Shoal, Great Bahama Bank
- Important lessons to be learned from Great Bahama Bank and the Joulters area
- Related abstracts and publication summaries

McNeill, D. F., Eberli, G. P., Harris, P. M., and Cruz, F. E. G., 2004, Field Guide to Carbonate Sediments Along the Exuma Bank Margin, and A Virtual Fieldtrip to the Exuma Island Chain, Bahamas: University of Miami Comparative Sedimentology Laboratory Sedimenta CD Series No. 2.

Outline of CD Contents:

- Introduction and Background
- Introductory PowerPoint Presentations
- Digital Field Guide with 11 major stops
- Petrography of Pleistocene, Holocene, and Modern Sediments, Exuma Margin

RESERVOIR INSIGHT FROM GREAT BAHAMA BANK

Introduction to GBB
Andros Tidal Flats
Joulters Ooid Shoals
Andros Reefs and Slope

Overview of Great Bahama Bank

(abstracted and modified from Paul M. (Mitch) Harris, Clyde H. Moore, and James Lee Wilson, 1985, Carbonate Platforms, in Warme, J. E. and Shanley, K. W., eds., Carbonate Depositional Environments, Modern and Ancient, Part 2: Colorado School of Mines Quarterly, v. 80, no. 4, 60 p.)

Introduction

Environments

Great Bahama Bank, along with the other shallow-water platforms that comprise the Bahamas, display a well-documented facies zonation (Purdy, 1963). Coral reefs, ooid shoals, or coralgal sands rim margins with more open circulation. The interior of the platform, which is subject to poorer water circulation and shielded from predominantly easterly winds by Andros Island, is covered by lime muds and pelleted muds. The more open shelves intermediate between the platform margin and interior are sites of grapestone deposition.

As the energy is focused along the margins of the platforms, the facies are more variable there than in the interiors. The margins can be classified as windward, leeward, or tide-dominated (Hine et al., 1981). The windward margins are the most complex: reefs and associated skeletal sands form along open margins; tidal deltas are associated with inter-island gaps; wide belts of tidal bars form in re-entrants; and skeletal sands may be transported seaward (Palmer, 1979; Grammer, 1991). Leeward, open margins are dominated by offbank sand and mud transport (Palmer, 1979, Wilber et al., 1990; Grammer et al., 1993). These margins are characterized along their edges by wide belts or sheets of nonskeletal sands. Finally, large tidal-bar belts commonly form at the ends of embayments, where tidal currents are more rapid.

Sea Level and Stratigraphy

Deposition of Holocene, shallow-platform carbonates in the Bahamas did not begin until the margins and flat-topped interiors of the platforms were submerged during the latest rise in sea level approximately 7,000 years ago. The submergence curve of Scholl et al. (1969) for South Florida suggests that the rise in sea level has slowed from 30 cm in 250 years between 5500 and 3500 y.b.p. to less than 30 cm in the last 1000 years. Based upon the high-resolution sea level curve for the Caribbean region by Fairbanks (1989), the Florida curve represents the tail end of a flooding event that began as early as 18,000 y.b.p., following a lowstand where sea level was at least 120 meters (about 400 ft.) lower than today.

The facies succession, as revealed by coring of modern environments, is a function of changes in the rates of sea-level rise and sedimentation. Such relative sea-level changes may be the products of eustatic fluctuations, but may also be a response to subsidence or uplift. Relative sea-level rise has an obvious effect on the sediment type and nature of deposition, and the rate and extent of relative sea-level fall may markedly affect the diagenesis and erosion of carbonate sequences.

Shoaling-upward cycles in carbonates are common in stable platforms and shelves like Great Bahama Bank (James, 1979). The shelf interior has few complete shoaling-upward cycles because hiatuses are common and not all sea-level rises extend all the way across the shelf interior (Eberli et al., 1997). In contrast, shelf-margin and basin centers may lack shallow-water sediments because subsidence was so rapid that evidence of progradation-dominated cycles is obscured. Thus, where subsidence was extremely fast, cycles can be hidden by rapid subsidence. Instead of the asymmetric shoaling-upward cycles common to stable shelves, symmetrical shoaling-upward and deepening-upward cycles might be produced.

Lagoons and Tidal Flats

Lagoons

Lagoons (platform interiors) in the Bahamas, protected by wide shallow seas, reefs, pre-existing islands, or by mobile carbonate sand barriers, are characterized by continuous, wide sheets of poorly sorted sediments that are commonly extensively burrowed. The sediments either formed *in situ* or were transported from a seaward barrier by the winnowing action of waves and currents.

In normal marine settings, faunal remains are abundant but not diverse. However, the setting may be several tens of kilometers from the open sea. As in epeiric seas, elevated salinity causes faunas to steadily decrease in species diversity. At the landward margins of such lagoons, where salinities are frequently at their highest, the only biota may be subtidal blue-green algal stromatolite heads and mats.

The principal facies in shallow-water lagoons are clean carbonate sands, muddy skeletal sands, and lime muds. In deeper water, marls and shales are common. The sands in shallow water form on stable flats where current energy is sufficient to winnow lime mud but not grains. Grains may be oolitic, but are more commonly pellets, grapestones, or oncolites.

Lime muds form in areas with restricted circulation. Along the landward margins of lagoons or epeiric seas, the muddy sediments are usually dolomitic and stromatolitic, well bedded, and widely distributed laterally. In subtidal areas, faunal abundance is low, but diversity is high. In intertidal areas, the opposite can be true.

Tidal Flats

Tidal-flat sediments include those in the intertidal zone (flooded by daily tides) and the supratidal zone (flooded by wind and spring tides). Sediments range from carbonate sands to muds and commonly contain algal stromatolites. Tidal-flat sediments occur as widespread sheets that are often dissected by channels.

Bedding is thin and even, and contacts are sharp. Evaporites, however, show irregular bedding and may be nodular. Collapse breccias of angular fragments tend to parallel depositional strike and are local.

Traced landward, the principal facies belts are sandy tidal flats, muddy tidal flats, mangrove/ algal flats, and supratidal flats. The sandy flats, commonly cross-bedded and winnowed, reflect storm wave and current movement. The muddy tidal flats are burrowed and homogenized; bedding planes may be irregular, in part a result of the burrowing. Mangroves, algae, and other plants bind and trap transported lime mud and may also aid its precipitation. Algae produce a variety of structures in response to desiccation and erosion; the most significant are lamellar fenestral fabrics and dome heads.

Tidal creeks rework the tidal-flat sediments, developing sandy or muddy point bars. The channel margins may be marked by levees. If these are made of lime mud, they generally exhibit a variety of laminations, mud cracks, and intraclasts. The levees may pond water in the overbank areas, where sediments are highly burrowed.

Supratidal-flat sediments vary according to their climatic settings. For instance, with high salinities and high magnesium concentrations, dolomite cement replaces calcium carbonate. In arid regions gypsum and anhydrite can precipitate directly within the sediment. Simultaneously halite may precipitate locally on the sediment surface, but is usually removed by wind or marine flooding.

Reservoir and Source Potential

Tidal-flat muds and pelleted sands have low porosities due to dewatering and compaction. However, dolomitization of these deposits forms reservoirs by creating good porosity and permeability. Tidal-flat carbonates are commonly associated with evaporites that act as seals to the reservoirs. Examples of production from tidal-flat sequences include the Ordovician Ellenburger Formation, the Ordovician Red River of the Williston Basin, the Permian Basin carbonates of Texas, and the Cretaceous offshore of West Africa.

Tidal-flat carbonates have abundant algal organic matter mixed into them. There may be ample opportunity for the organic matter to be oxidized and come in contact with fresh waters. However, some tidal-flat sequences were evidently deposited quickly enough to retain a relatively high percentage of organic matter. In addition, there is a growing belief that evaporites can have sufficient organic content to serve as hydrocarbon sources.

Sand Shoals

Carbonate sand accumulations of reservoir-size commonly occur near the seaward edges of banks, platforms, and shelves. Less commonly they form in regional deepwater settings. Bank-margin sand accumulations may grade over short distances landward or seaward into other environments.

The development of these bodies requires sand-sized sediments and a means of removing smaller or larger material. These requirements are met where a change in shelf slope coincides with wave action or strong tidal currents in a zone of high carbonate production.

In modern carbonate settings like Great Bahama Bank, sand bodies occur in many different forms, nearly all of which have ancient counterparts. Back-reef sheets, belts, and lobes of skeletal sand form along open platform margins where sediment transport is toward the bank. Gaps between small islands may be the sites of tidal deltas. Commonly the flood tide delta is enlarged as a result of storm-created currents. If re-entrants or embayments occur along a margin, tidal and storm-generated currents can generate wide belts of tidal bars.

Along windward margins, which are dominated by large islands, skeletal sands generated within the fore-reef environment can be carried seaward to the marginal escarpment. There they can accumulate behind rocky barriers or be carried farther seaward into deep water. In contrast to the variety of sand bodies that form along windward margins, leeward open margins are dominated by offbank sand and mud transport. Here wide belts or sheets of nonskeletal sands form at the bank edge with coeval muds and sandy muds deposited seaward of the platform margin in deeper waters.

The vertical sequence of deposits in modern sand shoals usually records progressive shallowing because these shallow-water sites provide optimum conditions for carbonate production. Therefore, platform carbonate sediments usually accumulate at greater rates than that of relative subsidence and repeatedly build up to sea level or above. In this manner, cyclical packages form, each a few meters thick. Similar shoaling-upward sequences are recognized in thick, ancient carbonate sand deposits of all ages.

Potential Reservoir and Source Rocks

Sand shoals do not have good source potential, being oxygenated and highly agitated. Lateral facies equivalents must therefore be called upon to act as the sources of hydrocarbons trapped in sand-shoal reservoirs. In terms of reservoir quality, the sands have high initial porosities that may be preserved in the subsurface. Marine cementation, leading to the formation of hardgrounds and intraclasts, rarely cements a thick continuous section of sands. Instead, only localized zones are cemented in otherwise unlithified sediments. Because sand shoals are commonly localized on paleohighs and generally build up to and above sea level, secondary porosity usually develops shortly after deposition.

The best-documented example of production from sand-shoal reservoirs occurs in the Jurassic Smackover Formation of the U.S. Gulf Coast. Other well-known examples are the San Andres Formation in the Permian Basin and the Arab D in the Persian Gulf.

Bahama Ooid Shoals

Both ooid shoals and coral reefs occur along most of the platform margin in the Bahamas. The two environments may co-exist or laterally replace one another along windward margins. Along leeward margins, sands transported from the bank may bury older or contemporaneous reefs (Hine and Neumann, 1977; Palmer, 1979).

Ooid sands can form in lobe-shaped or elongate submarine bars, in beaches, in tidal deltas between islands, or in subenvironments associated with these sites. Ooids mixed with other sand grains or with lime mud can be found as islands and dunes, as well as channel bars and levees within vast sand flats. An ooid shoal is a succession of these environments produced during the Holocene sea-level rise.

Coring and seismic profiling of ooid shoals in the Bahamas has been done by Ball (1967), Buchanan (1970), Hine (1977), Dravis (1977), Harris (1979), Palmer (1979), Halley and Harris (1979), and Hine et al. (1981). Their studies document facies, sedimentary structures, vertical sequences, and the geometry of bank-margin ooid accumulations. These are the critical sedimentary features in our interpretation of ancient oolite deposits seen in outcrop or in borehole cores.

The primary difference between the tidal-bar and marine-sand types of linear sand belts of Ball (1967) and Halley et al. (1983) is their orientation to the trend of the bank-margin. Tidal-bar belts develop perpendicular to the margin, whereas marine sand belts forms parallel to the bank edge. Both types respond primarily to daily tidal flows and to wave- and storm-generated currents; but significant differences exist between them, as well as between individual sand accumulations within each sand belt. Such differences result from antecedent topographic control, response to sea-level change or storms, bed-form distribution, the role of diagenesis, development of benthic communities, sediment type, sediment thickness, and lateral facies changes.

Reefs and Organic Buildups

Reefs and organic buildups commonly form where there is a break in slope on the seafloor, or landward of this slope break, within the slightly deeper water of platform interiors and epeiric settings. Most reefs and buildups are both continuous and parallel to the depositional strike of the shelf edge, or are present as a series of isolated buildups on either side of the shelf break.

Barrier Reefs and Mud-Skeletal Banks

Reefs like the Andros Barrier Reef and mud-skeletal buildups are best developed where open marine waters shoal against a basin margin. Antecedent topography, faulting, or the juxtaposition of active shallow-water accumulation and deeper-basin starvation controls the slope of the seafloor on which the buildup grows. Barrier reefs tend to be massive, but have associated, discontinuous, thin beds of sediment.

Reef geometry is expressed as thick sheets or ribbons that parallel depositional strike. The major subenvironments are the reefs frame (the reef crest and seaward wall), seaward reef apron, back reef, and barrier island (sand cays). Reefs act as sediment sources for areas both landward and seaward. Major reef contributors through geologic time have included corals, stromatoporoids, calcareous sponges, algae, and rudists. Associated faunas are very diverse. (See James and Macintyre, 1985).

The reef frame is characterized by *in situ* growth of calcareous organisms interbedded with calcareous sands, silts, and muds that form as the result of bioerosion and episodic storms. The frame is usually massive and cavernous, with voids filled by bladed and fibrous marine cements and by internal sediment that is commonly perched on or within these cements. Within the reef crest, the skeletal framework may vary from 20 to 80 percent of the rock volume, with a reciprocal distribution of sediment-cement fill.

The reef apron is composed of silt- to boulder-sized debris derived from the reef frame and mixed with *in situ* fore-reef biota. It typically has a chaotic texture, but may locally exhibit cross-bedding. Many cited examples of Holocene fore-reef and upper-basin slope deposits contain huge blocks of reef rock that slumped from the cliff-like fore-reef face (e.g. Grammer et al., 1993). Precipitous fore-reef slopes are characteristic of Quaternary and Holocene reefs, which owe much of their relief to antecedent topography. Similar fore-reef cliffs occur in the Upper Devonian of the Canning Basin in Australia, the Permian of West Texas, the Cretaceous of Mexico, and in parts of the Mesozoic margin of the East Coast of the United States. Most pre-Holocene coral-reef buildups, however, lack this steep fore-reef cliff, and have correspondingly less reef-core rock rubble.

Reef-apron sediments may be stabilized or encrusted by foraminifera, sponges, or algae. A typical fore-reef facies of late Mesozoic and Cenozoic reef buildups is composed of a “gravel” or irregular red algal nodules.

Back-reef sediment is formed by both localized patch-reef framework, which grew as carpets or patch reefs, and by skeletal debris transported from the reef crest. The patch reefs tend to be massive and lens-like, while the adjacent back-reef sediments are generally burrowed, widespread, sheet-like, and varied in grain size from sand to mud. Barrier islands or beaches may occur just behind the reef crest and show many of the characteristics of siliciclastic barrier islands. They form as a series of linear carbonate sand bodies parallel to depositional strike. The seaward margin tends to be smooth, but storm washover fans and flood-tidal deltas serrate the lee side. Sedimentary structures associated with the islands include cross-laminated carbonate sands from the beach face, lamellar fenestral ("bird’s-eye") limestone, algal stromatolites, and storm washover layers. Early diagenetic changes and cementation may produce beach rock and tepee structures.

Mud-skeletal banks are massive elongate bodies that form both parallel and perpendicular to the seaward edge of the platform margin. They range from knoll-like mounds of a few square meters to massive linear belts trending for hundreds of kilometers along depositional strike. The thickness of the banks varies from one to over 100 meters. Beds may be thick to massive and range from horizontal to clinoform. Modern carbonate mud banks form in conjunction with sea grasses and green calcareous algae that bind and trap fine-grained sediments derived from breakage in more turbulent water. Sediment in ancient banks of this kind varies from lime mud to fossiliferous sand, is commonly neomorphosed, and may contain cavities filled by sediment and cement.

Pinnacles, Patch Reefs, and Mounds

Pinnacles form during relatively rapid sea-level rises, when carbonate production only locally keeps pace. Bottom agitation is not as great over pinnacles, patch reefs, and sediment mounds as on shelf-edge reefs; therefore, organisms tend to be different, and winnowing and frame-building are less important. These structures are also more symmetrical than shelf-edge reefs, and relatively less oriented with respect to waves and winds. Frame builders form pinnacles and patch reefs. “Mounds” are designated as accumulations of lime silt and mud trapped by sponges, octocorals, algae, and crinoids.

Pinnacle reefs, patch reefs, and sediment buildups are localized landward or seaward of the crest of the basin margin. They may be localized on highs formed by previous karst topography or some other local irregularity that causes waves to shoal and break or focuses swift tidal currents. Core facies of these bodies are generally massive to thick-bedded, while the flank beds have thin, irregular beds. Changes in texture tend to radiate outward from the buildup core. Seaward buildups commonly contain more porous, coarse-grained carbonates than the more shelfward mounds, but pore-filling marine cements occur more readily in a seaward direction.

As with barrier-reef buildups, the pinnacle reefs are characterized by in situ boundstones of calcareous organisms and sediments. The reef frame is massive and cavernous, and the voids are filled with sediment and marine cement. These sedimentary features are exquisitely displayed in Silurian pinnacles from the Michigan Basin. Major facies variation occurs as buildups that initiated in deep water grew upward into shallow water. Their basal sediments are usually finer grained than their crests. The faunas at the base are usually a pioneer community of low diversity, while the fauna of the crest may be a more diverse climax community. Lower contacts are gradational with the platform sediments below the bodies. Most pinnacles are sharply overlain by basinal marls and shales similar to those deposited on the deeper parts of the platform. In rare instances the bodies coalesce upward and are sharply overlain by tidal-flat sediments.

Potential Reservoir and Source Rocks

The belt of reef and mud buildups at the depositional surface tends to be a narrow, ribbon-like feature less than about 100 m wide. The apron of skeletal sand shed back of the reef may be even narrower, while lagoonal sediments may stretch for tens of miles back of these buildups. All these facies may be quite extensive in the subsurface, due to landward backstepping and basinward progradation.

The reservoir potential of reefs and buildups are widely assumed to be high. However, studies indicate that both primary and secondary cements and internal sediments more often than not plug the porosity of reef boundstones and framestones. Proximal back-reef sand deposits can retain significant amounts of primary porosity, especially in reef tracts where accumulation of skeletal rubble was rapid. Quiet-water carbonates of deeper lagoons tend to be muddy sediments (that is, wackestones and packstones) with relatively low porosities and permeabilities. Fore-reef deposits and the aprons of mud buildups may have somewhat greater reservoir potential, especially if the reef itself is plugged by carbonate cements and acts as the updip seal in a stratigraphic trap.

Some barrier-reef deposits have proved to be major hydrocarbon reservoirs, although most lack an immediate updip trap. An excellent example of a giant field in a barrier reef is the Oligocene reef complex at Kirkuk, Iraq. Part of the Devonian Leduc reservoir trend of Western Canada has the characteristics of both a linear mud-skeletal margin and barrier-reef complex.

Reef-tract and linear mud-skeletal sediments typically have relatively low source potential. This is in part due to the shallow, turbulent environment, but also to the efficient recycling of organic detritus within the reef community’s trophic structure. Thus, little organic debris “leaks” from the crest community into the apron or the back margin lagoon.

In contrast to barrier facies, major hydrocarbon discoveries are common in ancient pinnacle-reef and mud buildups. Reservoir volumes of pinnacles tend to be more sharply limited than for shelf-edge reservoirs. This is because the porous core facies is typically bounded by either relatively impermeable flank and margin deposits, basinal shales, or basinal evaporites. These deposits form the seal, but make recharge of reservoir hydrocarbons unlikely. Examples of oil fields in pinnacle reefs are the Silurian of the Michigan Basin and the Devonian of Western Canada. Pinnacles may be associated with fairly rich source rocks, both at their flanks and in basinal sediments enclosing them. Organic productivity and preservation in the sedimentary column tend to be high for pinnacles situated on the lower basinal slope, but decline updip.

Summary

The preceding brief discussion of depositional environments of carbonate platforms, and Great Bahama Bank in particular, outlines the general patterns of sedimentation and simplified vertical sequences in modern lagoons, tidal flats, sand shoals, reefs, and buildups. Over the years, the studies have proven to be valuable analogs for calibrating core studies and formulating depositional models for ancient subsurface examples. Certainly, the areas emphasized here, and the Florida-Bahamas region in general, lack some features that may limit their usefulness as universal analogs, such as evaporite-dominated coastlines and “pinnacle” reef morphologies. These shortcomings, however, are offset by fact that the area has been long serving as an accessible field laboratory where the organisms, sediments, structures, sequences, morphologies, and processes of the fundamental building blocks of platform carbonates have been scrutinized.

Coordinated by R. Randy Ray and Lee Lawyer

Carbonate platforms: Exploration- and production-scale insight from modern analogs in the Bahamas

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The search for hydrocarbons in carbonate rocks depends on a thorough understanding of the primary depositional controls on carbonate sediments as well as their postdepositional changes. When a reservoir is discovered, interpretation of depositional facies and a search for applicable analogs become essential for both primary and enhanced field development. Understanding the various lithofacies types, their distribution, and geometry along different styles of carbonate platforms is the first step in evaluating the reservoir potential of carbonate systems. This analysis must be done at regional (or seismic) scale and at production or enhanced production scales to maximize the hydrocarbons that can be extracted from any carbonate reservoir. Postdepositional change, or diagenesis, is another key factor because diagenetic change may create additional porosity and permeability or sometimes reduce or completely destroy porosity in carbonates. Key processes in the diagenetic change of carbonate sediments include cementation in freshwater and seawater environments, and compaction, dissolution, and dolomitization, whereby the original limestone sediments are transformed in whole or in part to dolomite.

In this paper, we review some key findings from studies in the Bahamas over the past two decades that have direct impact on how we explore for and ultimately exploit carbonate hydrocarbon reservoirs. We first discuss some major advances in understanding carbonate platform evolution at the exploration scale and then some key findings that have led to advances in understanding carbonate reservoirs. We use the natural laboratory of Great Bahama Bank to focus on two fundamental problems in dealing with subsurface carbonates: a stratigraphic framework and reservoir distribution. Establishing a stratigraphic framework is essential in understanding regional geology during exploration, but it is just as critical during reservoir development for establishing a layering scheme for reservoir studies. Likewise, knowledge of the distribution of depositional and diagenetic facies is critical to both exploration and development. At the regional scale, understanding facies distribution is essential for formulating stratigraphic plays; development-scale variations in reservoir quality are intimately tied to the relations between facies. Stratigraphy and reservoir distribution are linked at both exploration and development scales; knowing how they are related in an area is a major step toward success in the subsurface.

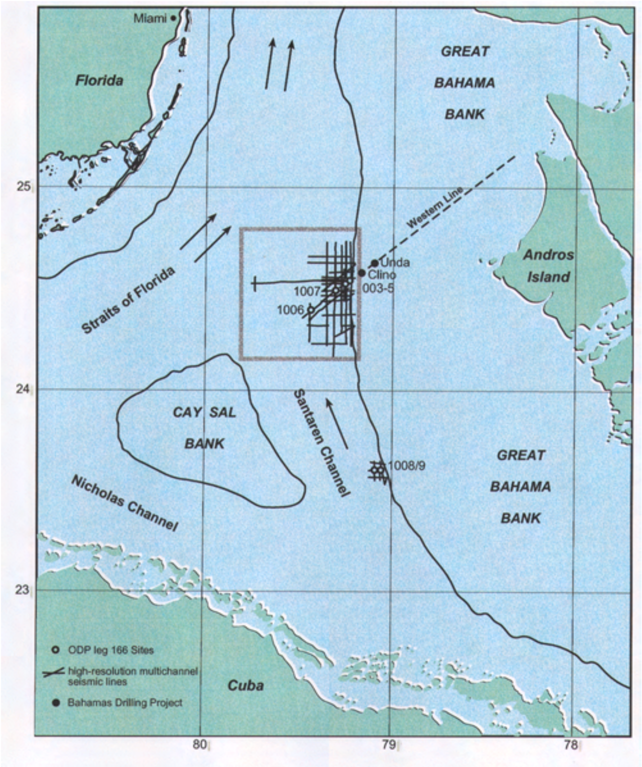

Figure 1. Great Bahama Bank is about 50 miles east of Florida and separated from it by the deepwater Straits of Florida within which the Gulf Stream flows. Unda and Clino are two drill holes of the Bahamas Drilling Project (University of Miami) on the margin of GBB along the Western Line. Gray box indicates high-resolution multichannel seismic transects and ODP Leg 166 drill sites. (Modified from Anselmetti et al., 2000.)

Understanding the various carbonate facies types, the controls on their formation, and their distribution on carbonate platforms is in large part the result of extensive study of modern analogs. Shortly after World War II, the study of modern sedimentary environments in carbonate and siliciclastic environments grew rapidly as petroleum companies realized the value of applying lessons from modern environments to similar ancient reservoirs found in the subsurface. Much study focused on the Bahamas, a broad expanse of modern carbonate banks southeast of the continental United States (Figure 1). Studies in the Bahamas over the last several decades have led to development of depositional facies models for platform interior, carbonate sand, reef, tidal flat, and slope deposits. In addition, tremendous insight has been gained about the various diagenetic processes and mechanisms and how they affect carbonate sediments from the standpoint of reservoir potential. Each model enhances both exploration and production strategies.

In recent years, we have seen the development of sequence and seismic stratigraphy and with it the advent of a refined mode of interpretation for depositional systems. In sequence stratigraphy, sedimentary systems are divided

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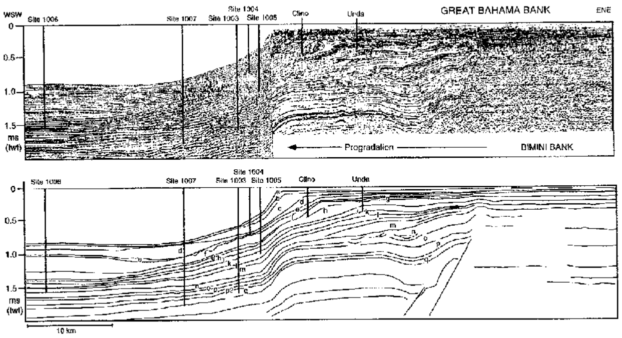

Figure 2. High-resolution seismic line of the margin of GBB (top) coupled with, and along the same transect, as the Western Line, showing the drilling locations during ODP Leg 166. The geometries of the Upper Miocene to Holocene seismic sequences (a-q) are generally sigmoidal with a steepening of foresets in the younger sequences (bottom). Note the approximate 25 km of platform progradation which has taken place on this leeward margin since the mid-Miocene. (Modified from Eberli et al., 2000.)

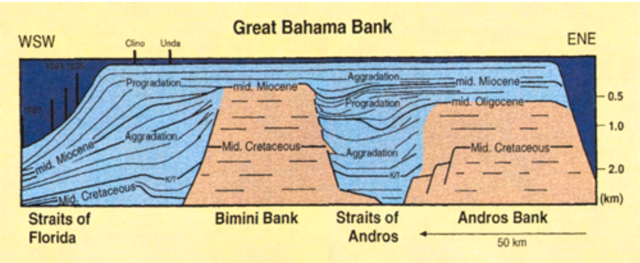

Figure 3. Cross-section illustrating the complicated internal architecture of the GBB. Two nuclear banks, Andros and Bimini, coalesced through the infilling of an intraplatform seaway, the Straits of Andros. Progradation of the western (leeward) margin of GBB during the Neogene expanded the bank more than 25 km into the Straits of Florida. (Modified from Eberli et al., 1997.)

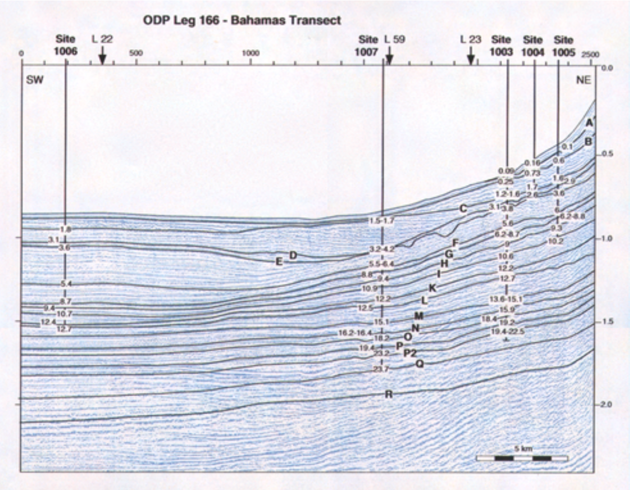

Figure 4. Chronostratigraphic ages assigned to seismic sequence boundaries. The minor age differences observed along individual sequence boundaries are variable only within seismic and biostratigraphic resolution, indicating that seismic reflections and sequence boundaries are indeed time lines (from Eberli et al., 2000).

into genetically related deposits that form during the same general time span (i.e., during highstands of sea level, lowstands, or during periods of sea-level transgression). Using a sequence stratigraphic approach, sedimentary systems are analyzed dynamically through time, rather than as a single time slice as was previously done with depositional facies models. When combined with advances in understanding of the detailed internal architecture and diagenesis of carbonate depositional facies, these dynamic conceptual models, based on a sequence stratigraphic approach, offer better predictability of the distribution of potential reservoir facies and their potential reservoir quality.

For many years the Bahamas and ancient carbonate platforms by comparison were thought to have been built mostly through vertical growth of their margins combined with the subsequent sedimentary infill of the inner platform or "lagoonal" environments. In this model, carbonate platforms grow vertically, with little or no change in the lateral position of their margins. In recent years, however, it has been documented that carbonate platforms are in fact quite dynamic, growing both laterally and vertically, and that the architectural evolution of carbonate platforms depends on a number of environmental factors but principally variations in sea level and accommodation space. Study of high-resolution multichannel seismic data collected across Great Bahama Bank (Figure 1) documented for the first time that the evolution and geometry of carbonate platforms occur in response to changes in sea level and are quite different during sea-level lowstands, transgressions, and highstands. From these studies we realized that carbonate platforms are quite susceptible to rapid lateral growth, especially along leeward margins where tremendous volumes of sediment are swept off of the shallow carbonate bank top by winds and waves to be deposited on the flanks of the platform (Figure 2).

Studies of seismic and core borings from the interior and marginal areas of Great Bahama Bank document that GBB was a series of smaller banks, rather than one "megabank" that simply grew vertically (Figure 3). These smaller banks coalesced laterally through rapid progradation along leeward margins combined with periods of more aggradational or vertical growth to give us the modern Great Bahama Bank. In the late Cretaceous, the present northwestern GBB consisted of two small banks, separated by a seaway called the Straits of Andros. Since that time, these platforms have grown vertically about 1500 m, and their margins have prograded laterally as much as 25 km. In the mid-Miocene, another seaway, the Bimini Embayment, formed within the westernmost of these banks, the Bimini Bank. Subsequent lateral progradation of the western (leeward) margins filled the embayments and, farther south, shifted the bank margin westward to its present position. These studies have provided the

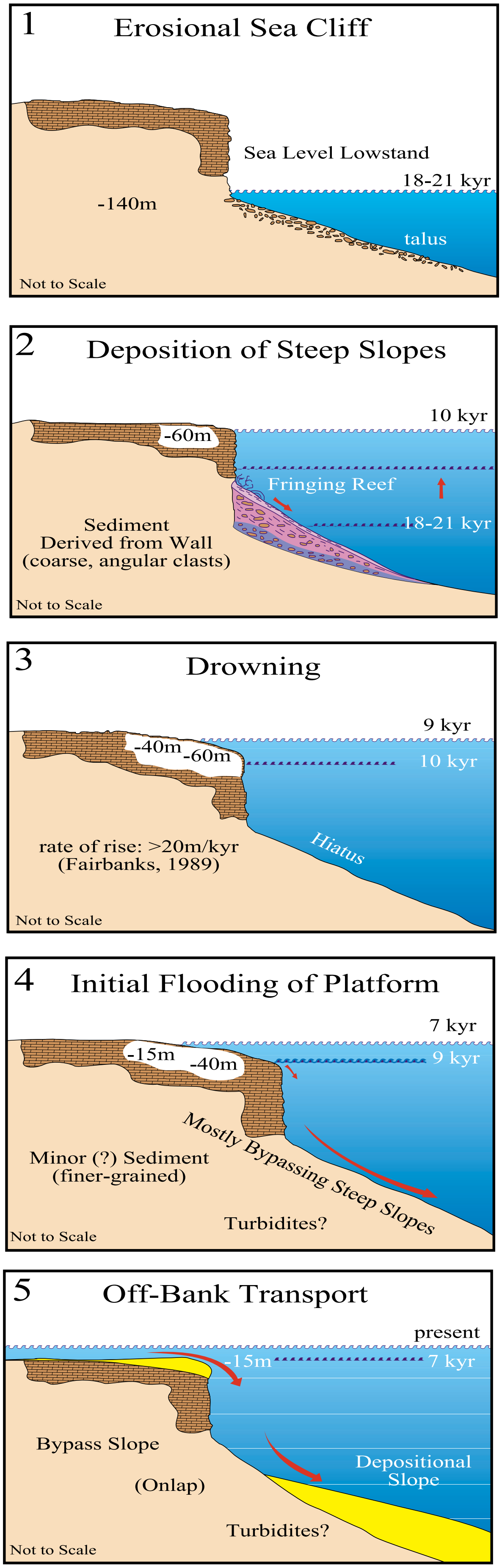

Figure 5. Sequential development of the marginal slopes around GBB during the last 20 000 years or so with the latest rise in sea level. Note the reef-dominated, coarse talus debris deposited during the transgressive phase before sea level reaches the top of the platform. These deposits may be either good reservoirs or conduits for hydrocarbons moving updip into platform margin reefal deposits. Highstand wedges consisting of large volumes of banktop-derived sediment form after the platform is flooded and sediment is exported down the slope. Fine-grained sediments of poor reservoir quality bypass the steep marginal slopes and reside in a downdip position commonly associated with "lowstand fans." (From Grammer and Ginsburg, 1992.)

understanding of the mechanics of carbonate platforms and how they respond to variations in sea level but, in addition, they have increased our prospective exploration targets within carbonate systems. For example, knowledge that carbonate platforms may prograde laterally with time indicates that there may be a number of locations for the bank margins, each with some potential for platform margin reservoirs such as back-reef sands, reefs, or proximal slope deposits.

Leeward margin slope. Leg 166 of the Ocean Drilling Program (ODP) collected high-resolution seismic data from GBB and drilled five cores along a slope-to-basin transect along its western side. The multichannel seismic data collected across the GBB margin and the adjacent Straits of Florida (Figure 4) indicate that the Neogene strata along this transect are controlled by two sedimentation mechanisms. First, westward-dipping layers are a product of sea-level-controlled sediment input derived from the platform top and deposited along the slope to basin. And second, eastward- or northerly dipping drift deposits in the basin axis are deposited at and beyond the toe of slope by ocean currents, including contour currents. Seismic facies along the slope are characterized by partly chaotic, persistent cut-and-fill geometries caused by processes acting on and within submarine canyons oriented downslope. Interfingering lobes of redeposited carbonates at the toe of slope produce a mounded seismic facies, and the distal drift sediments display a highly coherent seismic facies with a continuous succession of reflections, indicating very regular sedimentation in the Straits of Florida.

The ODP cores were 2-30 km from the modern platform margin along a line defined by seismic data. Neogene sediments collected from the slope environment consist of peri-platform oozes intercalated with calcareous turbidites. The lithologic alternations and hiatuses in sedimentation observed in the cores are interpreted to be the result of sea-level fluctuations that control the relative amounts and type of carbonate productivity. During sea-level highstands, the top of GBB bank is flooded and a highly prolific carbonate factory is established which produces large volumes of sediment that are shed off-bank, especially along leeward margins of the platform (Figure 5). During sea-level lowstands, the platform top is exposed and little or no sediment is being produced because GBB bank is an isolated, pure carbonate system, without associated siliciclastic sediments. Slope deposition during these times is mostly limited to pelagic background sedimentation. The deeper water, basinal deposits consist of more homogeneous fine-grained carbonate silts and mud deposited more or less continuously (i.e., without major hiatuses). These sediments were deposited as drift deposits by the Florida Current that flows nearly parallel to the strike of the platform (i.e., contour currents).

Chronostratigraphic significance of seismic reflectors. Both the slope and basinal sedimentary systems are contained in 17 seismic sequences within the Neogene section, and all sequence boundaries can be traced from Great Bahama Bank into the Straits of Florida. The seismic reflection pattern shows prograding downlap surfaces that terminate either toward the west (slope deposits) or toward the east or north (drift deposits). Biostratigraphic age determination indicates that the ages of the seismic reflections correlate from site to site across the entire transect within the resolution of seismic data and biostratigraphy. This implies that the seismic reflections of sequence boundaries have chronostratigraphic significance across both depositional environments.

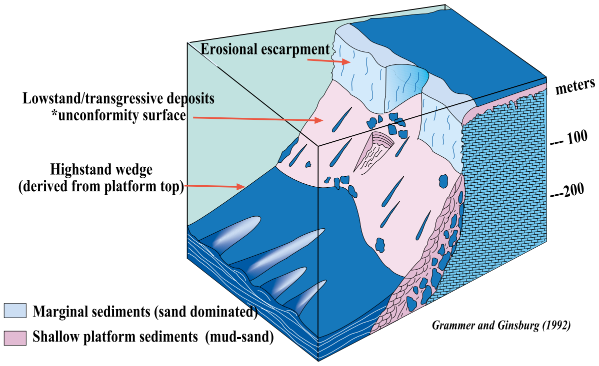

Figure 6. Block diagram illustrating key features, geometry, and environments of the marginal slope environments around GBB. (From Grammer et al., 1993.)

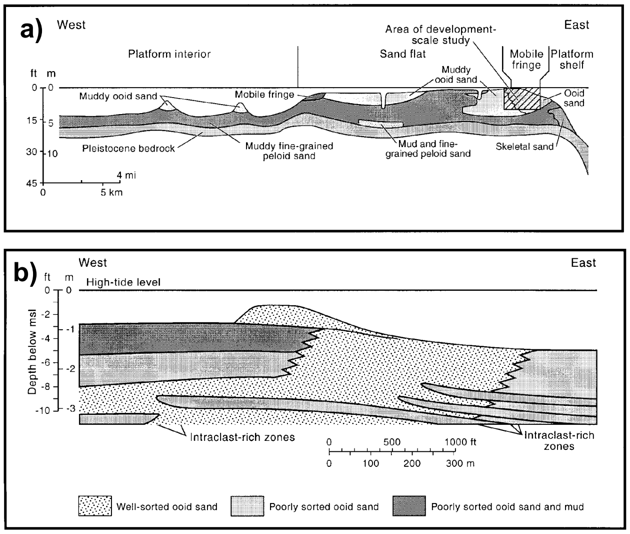

Figure 7. Cross-section of the north part of the Joulters shoal (from Harris, 1979) showing the exploration-scale facies framework (a). The area of a development-scale coring study within ooid sand is shown on the more detailed cross-section (b). This section reaches seaward into an area of poorer-sorted sand and bankward into muddy sands. (Figures modified from Major et al. and reproduced with permission from the Bureau of Economic Geology, University of Texas at Austin.)

Increasing refinement of sequence stratigraphic models. In the slope environment, reservoir potential strongly depends on both highstand and lowstand sedimentation, and the windward or leeward orientation of the margin. Extensive off-bank shedding of fine-grained sediment, especially along leeward margins, results in rapid lateral progradation through downslope deposition of a "highstand wedge" of platform-derived sediment (Figure 6). High-resolution single-channel seismic combined with high-resolution radiocarbon dating of sediments indicates that these highstand wedges are 70-90 m thick on leeward margins and have been deposited over just the last 7000 years, when the most recent sea-level rise flooded the top of GBB. Even taking into consideration the high initial porosities and water content of these sediments (e.g., assume 50% compaction as possible), it is easy to see the

Table 1. Key lessons learned from the Bahamas

Platform Evolution and Stratigraphy

- isolated carbonate platforms may coalesce through lateral progradation by highstand shedding of bank-top derived sediment, especially along leeward margins
- highstand shedding of platform-derived sediment results in a “highstand wedge” of sediment on the slope that mimics a “lowstand wedge” in both geometric attributes and positioning
- marginal slope sedimentary processes and lithofacies are variable between windward and leeward margins
- failure of platform margins and slopes and the formation of megabreccias occurs during both lowstands and highstands
- biostratigraphy and magnetostratigraphy confirm that several of the regionally correlatable sequence boundaries are chronostratigraphic horizons
- seismic reflector horizons in pure carbonate systems are typically the combined result of lithologic and diagenetic change
- unfilled accommodation space has significant implications to the application of cyclostratigraphy and the limitations inherent in regional correlations

Diagenesis

- characterization of diagenetic processes and environments (freshwater vadose, meteoric phreatic, marine phreatic, burial)
- marine cementation occurs in shallow to very deep settings (platform top to basin floor)
- syndepositional marine cementation occurs rapidly in the intertidal, shallow subtidal, and deeper subtidal (~100 m) realms and may influence the sedimentary deposits in a “geologically instantaneous” time frame
- depositional cycles influence the diagenetic overprint and subsequent reservoir quality in carbonates
- dissolution of aragonite grains in the marine phreatic zone, as well as the freshwater phreatic zone, can create moldic porosity

Lithofacies and Depositional Bodies

- lithofacies types and their distribution are relatively consistent across carbonate platforms and are a function of paleogeography and paleoceanography (e.g., windward versus leeward orientation, tidal range and influence, wave regimes, paleoaltitude, etc.)
- ooid shoal and reefal belts tend to be best developed along windward margins where they typically develop on preexisting topographic highs
- whereas ooid shoal belts tend to initiate on antecedent highs, the resulting facies distribution and geometry are a result of varying syndepositional processes
- sedimentary wedges along leeward slopes range from grain dominated to mud dominated, depending on the configuration of the platform top
- the genesis and evolution of shallowing-upward cycles have been defined in several environments (sand shoals, tidal flats, interior platform, and reefs)

Inferences for Reservoir Distribution

- the distribution and nature of stratigraphic traps have been established in several environments (sand shoals, tidal flats, interior platform, reefs, and slopes)
- tidal flat, ooid shoal, reefal, and proximal slope reservoirs are laterally extensive along strike, but may be foreshortened in a dip direction
- coarse-grained talus wedges with good initial reservoir potential form along proximal slopes during lowstand and transgressive phases
- tidal flat, ooid shoal, and reefal reservoirs may be segregated horizontally and vertically at the production and enhanced-production scales

potential for tremendous volumes of sediment to be deposited in these highstand wedges, at least along leeward margins of carbonate platforms. These large sediment wedges, however, have limited reservoir potential unless they are interbedded with coarser-grained turbidite and debris flow deposits. Therefore, it is critically important to the development of exploration and development models to realize that these “highstand wedges” have the same seismic-scale geometrical attributes and sit in the same position sequence-stratigraphically as what is typically described as a “lowstand wedge,” which could have significantly different reservoir potential.

Further refinement of the architecture and facies within the slope sequences also has been provided by recent seismic data and cores from Bahamas Drilling Project and ODP Leg 166. The most important aspects are the: (1) occurrence of marginal reefs on the leeward margin; (2) recognition of deep channel incisions of up to 150 m that are associated with sequences and run perpendicular to the margin from the upper slope to the toe of slope; (3) abundance of small-scale channeling of the middle and lower slope; and (4) accumulation of thick carbonate turbidite deposits at the toe of slope. In addition, these cores also provided new insight into the diagenetic overprint of slope and platform margin strata. Most important in this regard is the documentation of dissolution/precipitation features in the marine phreatic zone that produce petrographic fabrics common in the meteoric realm. This finding has important implications for assessing porosity types within a sequence stratigraphic framework.

Windward margin slope. Studies of marginal slope deposits along modern carbonate platforms such as the Bahamas provide valuable insight into the sedimentary processes, depositional architecture, and sequence evolution of equivalent subsurface slope deposits. In these environments, reservoir potential results from the interplay among paleogeographic orientation and geometry of the platform, mass flow depositional processes, and early diagenetic modification. In the 1990s a series of studies used manned submersibles and state-of-the-art sampling and analytical techniques to evaluate the depositional and diagenetic processes and resulting products along marginal slopes in the Bahamas. One key advantage of working with young deposits such as those found in the Bahamas is the ability to date sediments and diagenetic products with resolution that is orders of magnitude higher than we can obtain in the Mesozoic and Paleozoic. These high-resolution dating techniques enable us to accurately determine the timing of both sedimentary and diagenetic events and relate them to high-frequency fluctuations in sea level (see for example, Figure 5).

In the marginal slope environment, coarse-grained talus deposits accumulate through rockfall processes in a strike-elongated but dip-foreshortened zone at the base of rimmed margins. High-resolution dating of sediments and coexisting marine carbonate cements indicate that these deposits form primarily during the transgressive phase of sea-level rise and, on windward margins, also during highstands. Although areally limited, these deposits may have good reservoir or conduit potential, especially along windward margins, where they are less likely to be subsequently covered by fine-grained sediments derived from the bank top.

Farther downslope, steeply dipping (30-45°) proximal slope deposits consist of coarse-grained sediment deposited by a combination of rock-fall and grain flow processes. These deposits are formed during transgression and early highstand and are often characterized by a series of highly porous and permeable lenticular beds with preferential flow characteristics developed in a dip dimension (Figure 6). Proximal slope deposits, which may form along either windward or leeward margins, have high initial reservoir potential but may be adversely affected by extensive syndepositional cementation.

Carbonate sands. The Joulters ooid shoal, north of Andros Island on Great Bahama Bank, shows spatial variability of both depositional and diagenetic facies that create reservoir heterogeneity and stratigraphic traps. These carbonate sand bodies have been extensively studied through surface sampling and shallow coring and have provided much of our understanding of how ooid shoals develop and how they evolve with changing sea level.

The Joulters example points out difficulties in interpretation and correlation of grainstones in subsurface studies of platform carbonate reservoirs. The modern shoal complex which extends over 400 km^2 varies greatly in thickness. Sand generation and topography varied greatly in the Joulters Cays area during flooding of the platform and development of the shoal. Shoal growth, largely in response to a relative rise of sea level, records rapid expansion of ooid sands, island formation and associated meteoric diagenesis, local shoal stabilization and reworking by burrowing, and generation of marine hard-ground layers.

A characteristic vertical succession revealed by coring the Joulters shoal consists of scattered lithoclast sands and pellet muds at the base, peloid sands in the middle, and ooid sands at the top, showing an upward increase in grain size, percentage of ooids, and grain-support fabric (Figure 7a). This facies sequence thins to the south over a shallowing limestone surface and to the north and west as overall sediment thickness decreases. Within the shoal, the thicknesses of the dominant facies are complementary; ooid sands thin in a bankward direction as peloid sands thicken to form the thickest part of an interplatform sheet.

The facies changes resulted from changing depositional patterns in response to rising sea level. The shoal grew in three stages: (1) an early bank-flooding stage in which muddy sands of peloids and pellets accumulated in protected lows on the Pleistocene limestone floor; (2) a shoal-forming stage during which ooid production began on bedrock highs where bottom agitation was focused; and (3) shoal development in which the production and dispersal of ooid sands established the present size and physiography of the shoal.

Heterogeneity of potential reservoir quality within the Joulters Cays shoal is inferred on the basis of the distribution of depositional facies (Figure 7b). Clean ooid sand along the active margin of the shoal occurs as subtidal-bar, channel-fill, beach, and island facies. In cross-section, the sand occurs as an irregularly shaped area 2 km wide and 2-3 m thick. Immediately bankward of the clean ooid sand are widespread, somewhat irregularly shaped layers, extending another 18 km or more onto the platform, containing mixtures of carbonate mud and sand. The upper ooid-rich layer will most likely have better reservoir quality than the lower layer because of larger grain size and lower mud content.

Patterns of heterogeneity on a scale of hundreds of meters, i.e., interwell-scale, within the active part of the Joulters Cays shoal are also inferred from the facies distribution. A well-sorted ooid sand facies occurs in the center of the active shoal, with a more poorly sorted ooid sand facies both bankward and seaward. Heterogeneity is inferred because of mud content, burrowing, and grain type variations. By analogy, similar subtle textural variations can be expected to produce local heterogeneity within ooid grainstone reservoirs.

Exploring the complicated relationship between diagenesis, porosity, and sonic velocity in carbonates. Carbonate sediments are prone to rapid and pervasive diagenetic alterations that change the mineralogy and pore structure within the rock. In particular, cementation and dissolution processes continuously modify the pore structure to create or destroy porosity. These modifications also alter the elastic properties of the rock and, therefore, the sonic velocity. The result is a complicated and dynamic relationship among diagenesis, porosity, and sonic velocity.

Core material and sediments from Great Bahama Bank recently have been used for experimental studies that document the evolution of porosity and velocity through various stages of diagenetic alteration. These experiments show that compaction due to burial depth is not the principal controlling parameter that determines porosity and velocity of carbonates. In fact, early diagenesis (e.g., pervasive syndepositional cementation) can produce a nearly noncompactable rock that maintains its porosity to great burial depth. Constructive early diagenesis in the form of cementation significantly increases the velocity in carbonates without necessarily reducing much of the porosity. Likewise, destructive dissolution processes might increase porosity without reducing the sonic velocities of carbonates. What has been seen is that with carbonates in general, sonic velocity is not only a function of total porosity but also of the porosity type. Understanding the generation of porosity types in carbonates, therefore, offers the potential for prediction of diagenetic patterns and rock properties, such as permeability, from sonic and porosity logs.

Summary. Studies of modern carbonate analogs, such as those found in the Bahamas, have provided a wealth of information on the controls and processes of carbonate platform evolution and the potential development of reservoir facies in the subsurface. In addition to the major insight gained from the studies discussed above, additional fundamental knowledge has been obtained from other studies that help us to understand the details of carbonate facies deposition, diagenesis, and evolution with respect to sea-level change. Many key findings from studies of the Bahamas are summarized in Table 1. The interested reader is directed to the partial list of key references included at the end of this paper to learn more about carbonate platform evolution and reservoir potential.

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Andros Tidal Flats

Key Points

1. Sediment source and depositional model
2. Distribution of both reservoir and seal-prone facies
3. Genesis of shallowing-upward cycle (parasequence)
4. Diagenetic overprint
5. Potential mud-dominated reservoirs - strike elongated, lateral heterogeneity due to channels, variable extent in dip direction

Overview

The tidal flats of Andros Island provide an ideal opportunity to examine sedimentary structures and facies relationships in peritidal sequences. Similar deposits are significant exploration targets where porosity has developed through dolomitization or freshwater leaching. The resulting deposit is characterized by the interfingering of potential reservoir, seal, and source facies.

Laterally extensive accumulations of carbonate mud occur along the western edge of Andros Island. Protected from tidal currents and prevailing winds by the island of Andros, muds have built up nearly to sea level as a tidal flat and related subenvironments. The tidal flat is a bankward prograding wedge that has formed as muds, originating across the interior of Great Bahama Bank, were transported to the east during storms to deposit along the backside of Andros. To the north, the tidal flats are relatively narrow and only partly penetrated by tidal channels; whereas to the south the tidal flat belt is extremely wide and wet, being cut by more substantial tidal channels and containing numerous ponds and lakes.

Facies

Two parallel facies belts characterize the Andros tidal flats. One is a channeled belt with tidal channels cutting approximately perpendicular to the strike of the tidal flat, channel levees, ponds localized between adjacent levees, and beach ridges fronting the belt and separating it from the offshore marine environment. The other is an inland algal marsh lying essentially updip of the channels and covered with a stromatolitic algal (cyanobacterial) cover.

The bottoms of channels vary within the channeled belt, but commonly have exposed Pleistocene rock in their axes and are mud-covered along their flanks. The muds are stabilized by sea grasses or occur as mound-like, algal-coated buildups. Laminated muds and fine sands characterize the levees and algal marsh, whereas the ponds contain bioturbated, fossiliferous muds. These are only subtly different from burrowed, pelleted muds that occur in the marine environment offshore of the tidal flats. Blocks of algal-coated, cohesive mud are reworked from the levees as the channel undercuts them. The crests of the levees are mud cracked, as is the mat of blue-green algae on the supratidal algal marsh.

The Holocene sediment record of the tidal flats is of bioturbated, unlayered, pelleted mud and silt (Shinn et al., 1965; Hardie and Ginsburg, 1977). Layered sediment exists only as a thin cap over bioturbated sediment in the channeled belt and as thin-bedded inland algal marsh sediment. Homogenization of layered sediment by marine organisms is a major sedimentary process on subtidal and intertidal parts of the tidal flats. Layering is preserved where burrowing organisms are excluded by prolonged exposure above sea level (Ginsburg et al., 1977). The crest and backslope of the levees are exposed over 90 percent of the time, the ponded areas only 10 to 60 percent of the time. The duration of subaerial exposure largely controls: (1) variations in the algal mats; (2) physical layering of sediments; (3) formation of intraclasts and mud clasts by desiccation; and (4) burrowing by crustaceans, worms, and insects.

Stratigraphy

The Holocene record of the tidal flats begins with a freshwater marsh accumulation unconformably overlying Pleistocene limestone bedrock. Flooding seas significantly eroded the marsh sediments underlying most of the present-day tidal flat, except beneath the inland algal marsh, which has remained a freshwater marsh without interruption. Accumulation was mainly by vertical accretion in a complex of environments (channels, channel bars, levees, ponds, and marshes) behind a protecting barrier beach ridge. The distribution of tidal environments behind the barrier is complex. The basic stratigraphic record consists of a basal unit of bioturbated subtidal and intertidal sediment overlain by a thinner, well-layered unit deposited by the most severe onshore storms.

Sediment from a lower intertidal channel-margin is a bioturbated, pelleted mud with a minor admixture of high-spired gastropod shells and foraminifera tests. The rock equivalent would be wackestone or mudstone. Numerous roots and worm burrows penetrate the sediment, thereby producing vague, discontinuous laminations.

The sediment from a supratidal levee would also be a wackestone or mudstone, but would contain distinctive structures. Such sediments are of laminated, pelleted mud with numerous cracks and fenestral voids. Scattered roots penetrate the sediment but do not significantly disrupt the laminations. Subtle color changes between laminae reflect variation in the amount of oxidation.

Sediment from the algal marsh is most distinctive. In cores, thin beds of pelleted lime mud and fine skeletal sand alternate with darker, algae-rich layers. The rock equivalent would be wackestone, or sometimes packstone. The sediment layers represent deposition during storms. Sediment is washed and blown onto the algal marsh from the offshore and channeled-belt environments.

Joulters Ooid Shoals

Key Points

1. Facies types, distribution and geometry
2. Depositional model relative to sea level change
3. Distribution and geometry of reservoir facies
4. Subsurface record in 3-D
5. Diagenetic overprint by marine and fresh waters
6. Genesis of shallowing-upward cycle (parasequence)
7. Potential grainstone/packstone reservoirs - strike elongated, lateral heterogeneity due to channels and beach/island complexes

Overview

The Joulters ooid shoal, north of Andros Island on Great Bahama Bank, was described in detail by Harris (1979, 1983, 1984). This shoal is important because it displays a variety of subenvironments in which ooid sands can accumulate some of which are quite different from environments where ooids are generated. Ooid sands are important reservoirs in several basins, so a close analysis of their complexity is warranted. We will observe spatial variability of both depositional and diagenetic facies that create reservoir heterogeneity and stratigraphic traps and discuss the implications of these changes to interpretation and correlation of depositional cycles.

Depositional Facies

Facies recognized in coring studies of the Joulters shoal include ooid grainstone, ooid packstone, fine-peloid packstone, pellet wackestone, and lithoclast packstone. Skeletal grainstone is also present on the shelf seaward of the shoal, but was not recovered in cores.

The area of the present-day shoal includes depositional environments that produce each distinctive facies. Ooid grainstone forms on current-swept, rippled sea bottoms such as the crests of active sandbars. Ooid packstone forms on stabilized burrowed bottoms, including sand flats and relict sandbars. Fine-peloid packstone collects on stabilized and burrowed bottoms farther from sources of ooid sands, whereas pellet wackestone forms in restricted bottoms (such as in the lees of islands). Lithoclast packstone accumulates in active tidal channels. Each of these facies can occur in other settings as well, collectively forming what we refer to as an ooid shoal in the geological record.

The fence diagram on the following page shows the important facies relationships revealed by coring the Joulters shoal. The relief of the shoal above the surrounding seafloor is primarily a result of ooid sands in one of three facies. Ooid grainstones are found in a narrow belt along the ocean-facing borders of the shoal, where ooid accumulation coincides with formation. Ooid packstone and fine-peloid packstone facies are more widespread where they are the result of mixing of ooids with other grain types.

The Joulters sand shoal has a characteristic vertical succession of scattered lithoclast packstones and pellet wackestone at the base, fine-peloid packstone in the middle, and ooid packstone at the top, showing an upward increase in grain size, percentage of ooids, and grain-support fabric. This facies sequence thins to the south over a shallowing limestone surface, as well as to the north and west as overall sediment thickness decreases. Within the shoal, the thicknesses of the dominant facies are complementary; ooid packstone thins in a bankward direction as fine-peloid packstone thickens to form the thickest part of an interplatform sheet. Ooid grainstone directly overlies limestone along the seaward margin of the shoal and interfingers with the packstones bankward.

Growth History

The interpreted growth through time of the Joulters ooid shoal suggests that the facies changes resulted from changing depositional patterns in response to rising sea level. The shoal grew in three stages: (1) an early bank-flooding stage in which muddy sands of fine-peloids and pellets accumulated in protected lows on the Pleistocene limestone floor, (2) a shoal-forming stage during which ooid production began on bedrock highs where bottom agitation was focused, and (3) shoal development in which the production and dispersal of ooid sands established the present size and physiography of the shoal. This changed the general nature of bank-margin sediments in the area from muddy peloidal sands to ooid sands.

During stage 3, ooid sands were transported farther bankward as a belt of active bars broadened. Eventually the exchange of water between the seaward and bankward sides of the shoal was increasingly restricted by three mechanisms: widespread sediment buildup approaching sea level, restriction of tidal channel flow, and island formation along the shoal's ocean-facing margin. The series of bars and channels became an intertidal sand flat where the sediments are a mixture of burrowed ooid and peloid sands. These overlie and grade bankward into the muddier sands of the bank interior.

Andros Reefs and Slope

Key points (reefs)

1. Facies types, distribution and geometry of barrier and patch reefs
2. Distribution of both reservoir and seal-prone facies
3. Depositional model relative to sea level change
4. Effects of diagenesis on reservoir potential
5. Genesis of shallowing-upward cycle (parasequence)
6. Potential boundstone and grainstone reservoirs-

*barrier - strike elongated, very limited in dip direction, lateral heterogeneity due to channels

*patch - general strike elongated trends of grainstone sheets with isolated reefs, variable positioning in dip directions

Reef Overview

Reefs are important exploration targets in many areas. The open margins of Great Bahama Bank introduce the various reef and reef-related lithologies that are likely to be encountered in an ancient example. The size, shape, and orientation of individual buildups, as well as the relationships between buildups and associated sediments, are the large-scale patterns that should prove useful in analyzing subsurface shelf-edge deposits.

The Andros Barrier Reef lies east of the Joulters Cays shoals and Andros Island on the windward margin of the Tongue of the Ocean, which is one of the many deep-water reentrants in the Bahama platforms. The reef abruptly separates the deep water from a very narrow back-reef area consisting of skeletal sands with localized patch reefs. The backreef widens to the south of Andros as the reef trend diverges from Andros itself. Immediately north of Andros, the reef becomes discontinuous and ends altogether along the margin seaward of the Joulters area.

Patch Reefs

Organisms on the patch reefs seaward of the Joulters Cays area are essentially the same as those observed on the shelf-edge reefs. The significant differences between the two types of reefs are their positions on the open shelf and the geometries of the buildups. The shelf-edge reefs form as discontinuous, relatively narrow belts along the strike of the actual shelf edge and develop back-reef and fore-reef deposits. In contrast, patch reefs are scattered across the shelf immediately behind the shelf-edge. They occur as isolated or coalescing buildups within a more widespread sheet of skeletal sands.

Shelf-Edge Reefs

The Andros barrier reef extends for over 160 km, making it the third longest modern barrier reef. Like the outer Florida reefs, the Andros barrier is made up of coral reefs and clean skeletal sands. The reef flat is composed of skeletal sands and coral fragments and is covered with only a few feet of water at low tide. Typical reef profiles are compared in figures on the following pages.

A terrace of oriented, branching corals, slopes from the reef flat down to about a 3-m water depth, and a second terrace covered with massive head corals extends to about 7 m deep. Both terraces are incised by grooves that run normal to the trend of the reef. These sand-bottomed grooves are 3 to 6 m wide and 3 m deep. Coralline limestone spurs between the grooves may be 60 m wide. The spurs form by differential coral growth; the shifting substrate within the grooves is unfavorable for coral colonization.

Seaward of the reef, beginning in about 40-50 m of water depth, is a vertical wall extending to about 200-300 meters depth beyond which there are steep talus slopes.

Reef Growth Rates

Most Holocene reefs of the Bahamas and South Florida have developed over pre-existing highs. These highs may be earlier Holocene dune or reef topography or may lie along a major break in slope formed by reef growth during Pleistocene time (Enos and Perkins, 1977). The reefs have grown at rates of 1 to 5 m per 1000 years (Shinn et al., 1977). In some areas the rise in sea level eventually outpaced the reef's ability to grow. In other areas faster buildup formed thicker accumulations. Where reefs reached the surface, the accumulation rate eventually ceased because the rate of relative sea-level rise slowed during the latest Holocene.

Reef Stratigraphy

Coring shows that the reefs have a coral-algal framework, plus accumulations of sand-size sediment veneered with coral rubble and scattered in-place colonies. The rate of upbuilding of coral reefs is mostly controlled by the type of coral, *Acropora palmata*, which dominates most Caribbean shallow-reef communities, is capable of vertical rates that match the rate of sea-level rise at any time during the Holocene (Adey, 1975). Coral reefs comprising *Diploria* and *Montastrea* grow much slower, and thus generally lagged behind a rapidly rising sea level. A declining sea-level rise or stillstand might allow these slower-growing reefs to reach close enough to the surface to develop *Acropora palmata* communities.

The sedimentary package of the outer platform and platform margin of the Bahamas Banks, as well as that of the more extensively studied South Florida area, shows upward changes to progressively less restricted environments of deposition (Enos and Perkins, 1977). The vertical sequence closely parallels lateral changes in depositional textures, sedimentary structures, and organic populations, all of which can be observed in surface sediments from the inner shelf to the shelf break. Upward in the sequence, grain size increases erratically, the percentage of fine sediment decreases, sorting improves, sedimentary structures are less disrupted by bioturbation, and the organisms present indicate open circulation. *Halimeda*, corals, and red algae are more abundant in the top of the sequence, whereas mollusks are more common toward the base.

Stratigraphic cross sections across the shelf show that the sequence is basically transgressive, reflecting progressively more open circulation and greater agitation up to the present. The relative restriction in the lower part of the sequence probably resulted from the depositional topography, such as reefs at the shelf break, early in the Holocene cycle (Enos and Perkins, 1977). Deposition occurred during a continuous but decelerating eustatic sea-level rise; however, the overall transgressive sedimentary sequence may have been broken by laterally discontinuous regressive sequences due to restriction behind local depositional topography.

Key points (marginal slopes)

1. Dynamics of slope deposition
2. Evolution relative to sea level change
3. Effects of early diagenesis
4. Windward vs. leeward variability and effects on potential reservoir distribution
5. Potential reservoirs - strike elongated with minimal discontinuity, very limited in dip direction

Slope Introduction

The upper marginal slopes or foreslopes of carbonate platforms are an important transitional zone between shallow-water platform carbonates and deeper water basinal and distal slope deposits, and may contain significant reservoirs of hydrocarbons or metallic ores. Understanding of the depositional and early diagenetic processes operating along foreslopes is an integral part of evaluating the evolution of carbonate platforms and may be a key to the interpretation of inclined deposits (clinoforms/clinothems) often observed in outcrop and seismic profiles.

Slope Deposition

Sequence stratigraphic interpretations of carbonate platform margins are based to a large degree on concepts of variable timing and nature of deposition relative to fluctuations in sea level. Quaternary platform margins, such as those found in the Bahamas, provide a unique opportunity to calibrate the sedimentary record because of the well-constrained nature of sea-level history during this period. Detailed observations and sampling from a research submersible combined with high-resolution radiocarbon dating in the Tongue of the Ocean, Bahamas, have enabled us to document variations in deposition along the upper parts of the marginal slope during the most recent rise in sea level.

The steep marginal slopes around the Tongue of the Ocean record deposition during the early rise of sea level following the last lowstand some 18-21 Ka. Coarse-grained skeletal sands, gravel, and boulders derived from reefs growing along the overlying escarpment were deposited on slopes of 35-45^o and rapidly cemented in place (within a few hundred years). Deposition by rockfall and grainflow resulted in a series of elongate lenses oriented parallel to the slope. These lenses are generally less than 0.5m thick and pinch out downslope within tens of meters. Repeated deposition and cementation produced slope deposits that are both laterally discontinuous and internally heterogeneous. Radiocarbon dating of skeletal components and cements indicate that active deposition on the slopes ceased approximately 10,000 years ago as sea level rose above the escarpment and began to flood the top of Great Bahama Bank. Fine-grained, non-skeletal sands and muds derived from the platform top are presently bypassing these slopes and are deposited downslope as a wedge of sediment with slope declivities of 25-28^o.

Cracks and slide scars, similar to the Neptunian dikes observed in ancient slope deposits such as the Permian Capitan Formation of west Texas and New Mexico, are common features of the steep-cemented slopes. The cracks are a few centimeters wide and may extend for tens of meters across the slope with an arcuate, convex-up expression. The slide scars are generally a few meters wide by several meters long and cut back into the slope a few meters to less than 1 meter, although one large example is 30m wide, extends downslope for 75m, and has exposed 10m of the interior of the slope. Transects downslope from slide scars show that large blocks of the slope, some in excess of 10m across, have been transported for tens or hundreds of meters downslope. The release and transport of such blocks may be one mechanism by which turbidity currents are initiated in deeper slope environments.

Discussion of Slope Development and Sea-level Fluctuation

The questions of how and when the steep slopes along the Bahamas platform formed are of primary interest because of the similarity to steeply dipping slope deposits documented from the fossil record. Carbonate slopes from the Permian of west Texas and New Mexico, the Devonian of Western Australia, the Triassic Dolomites of northern Italy, the Cretaceous of east-central Mexico, and the Miocene of the Gulf of Suez all exhibit primary depositional slopes of 30-40^o. In addition to slope declivity, the geometry and thickness of beds as well as the dominant texture of the slope deposits in the Tongue of the Ocean are also similar to these ancient examples. Steep-slope profiles similar to those observed in outcrop are also frequently observed in seismic profiles in the subsurface.

Researchers working on both modern and ancient carbonate slopes have suggested a myriad of downslope, gravity-induced mechanisms for the deposition of sand-sized and coarser grained sediments. On modern slopes, previous workers have indicated that relatively large-scale turbidity currents and debris flows appear to be the dominant mechanism for the downslope transport of coarse detritus. On ancient carbonate slopes, all types of sediment gravity flows have been proposed, but again the predominant depositional mechanisms are interpreted to be debris flows or turbidity currents. Observations from the Tongue of the Ocean, however, suggest that the steep slopes formed by an alternative mechanism. The apparent lack of matrix and poor sorting of the deposits, combined with upslope imbrication of clasts, suggests that deposition took place through a combination of episodic rockfall and grainflow processes. The resulting deposits are characterized by elongate (parallel to slope) lenses of coarse-grained and poorly sorted sediment, that are discontinuous in both strike and dip directions.

Slope Conclusions

The upper slopes around the Tongue of the Ocean provide a modern example of how steeply dipping foreslopes may develop along carbonate platform margins and are remarkably similar to the clinoforms often described from fossil platforms. The awareness that primary depositional slopes of 35-45^o were deposited during the early rise of sea level following the last lowstand and that the steep slopes were apparently stabilized by syndepositional cementation, provides valuable insight into how and when some fossil slopes may have formed. In addition, the recognition that the Tongue of the Ocean slopes formed by the amalgamation of localized lenses and not large-scale mass-flow deposits may have important implications to the understanding of steep carbonate slopes in the subsurface. Realization of the internal heterogeneity of slope deposits and discontinuous nature of the lenticular beds may be a critical component to the accurate evaluation of possible reservoir facies. Evidence for "highstand" failure of the slopes provides an alternative to the accepted dogma of lowstand failure and may represent one means by which highstand turbidites are initiated.

INVENTORY OF MODERN EXAMPLES –

SATELLITE IMAGES OF SHALLOW WATER CARBONATE DEPOSITIONAL SETTINGS

Satellite Images of Shallow Water Carbonate Depositional Settings

This compilation of Landsat and SPOT satellite images from key modern carbonate areas should help fulfill the needs of most geologists for reservoir analogs. Images are from several "classic" areas, including South Florida, the Bahamas, the Caicos Platform in the British West Indies, Yucatan and Chinchorro Bank in Mexico, Belize, Great Barrier Reef and Shark Bay in Australia, and the coastline of Abu Dhabi. In addition to their use as analogs, the satellite images can be important teaching materials. Many of the same modern areas are often used as case studies to introduce grain types, depositional settings, and sedimentary processes.

We will review the images from the standpoint of:

- **Isolated carbonate platforms** - the Bahamas, Caicos Platform in the British West Indies, Chinchorro Bank offshore of Yucatan, and portions of the Belize area

- **Ramp-style shelf-to-basin transitions** - Abu Dhabi and northern Yucatan

- **Rimmed shelf margins** - South Florida, portions of Belize, and the Great Barrier Reef of Australia

- **Broad, deep shelf lagoons** - the Great Barrier Reef and Belize

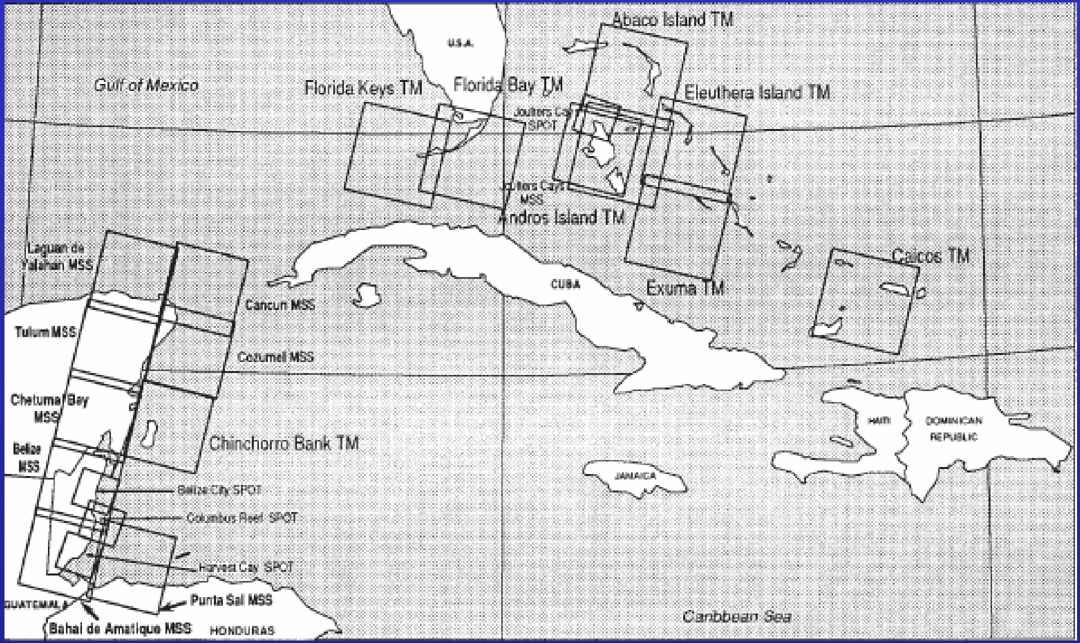
- **Reef variability** - South Florida, the Bahamas, Caicos, Belize, the Great Barrier Reef, and Chinchorro Bank

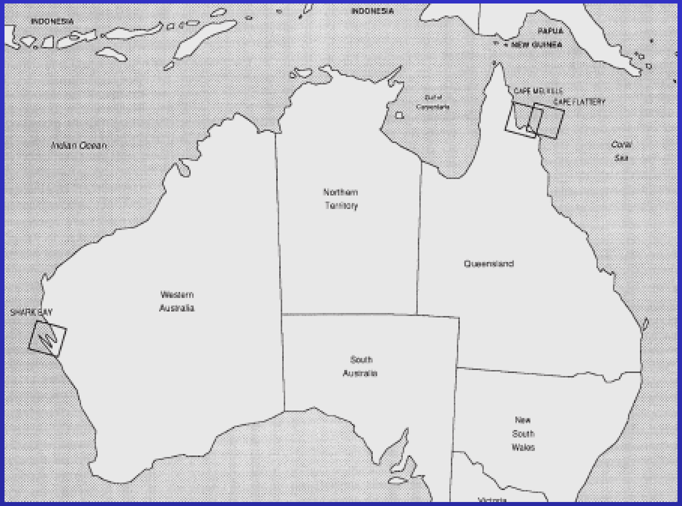
- **Carbonate sand bodies** – South Florida, the Bahamas, Caicos, northern Yucatan, and Abu Dhabi

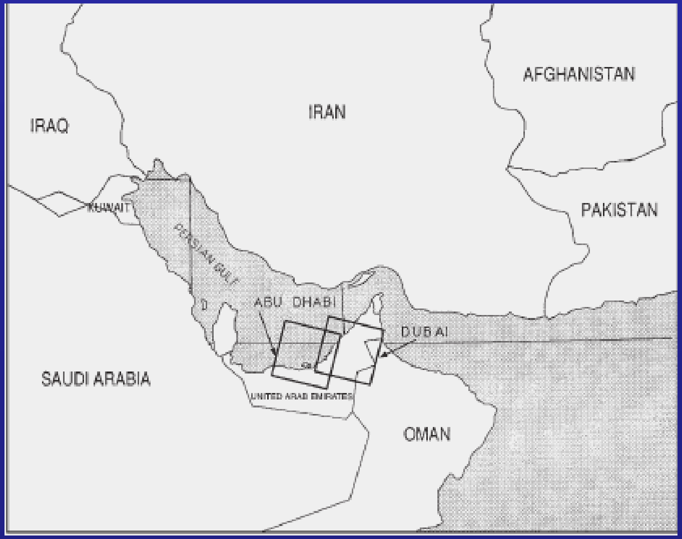
- **Shallow lagoon/tidal flat settings** - South Florida, the Bahamas, Caicos, Shark Bay in Western Australia, Abu Dhabi

- **Mixed carbonate and siliciclastic deposition** - Belize, the Great Barrier Reef, Shark Bay and Abu Dhabi

Inventory of Modern Examples - Satellite Images of Shallow Water Carbonate Depositional Settings







South Florida

The Bahamas

Bahamas - April 18, 2000 - MODIS/MODLAND/Descloitres

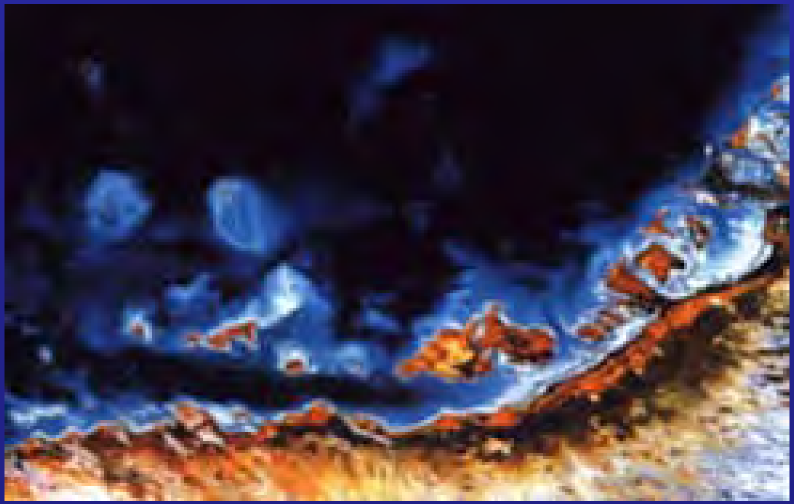
Caicos Platform, BWI

Yucatan, Mexico

Great Barrier Reef, Australia

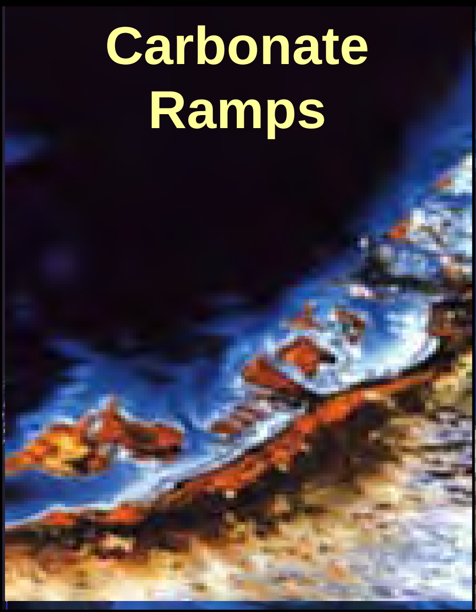
Shark Bay, Australia

Abu Dhabi

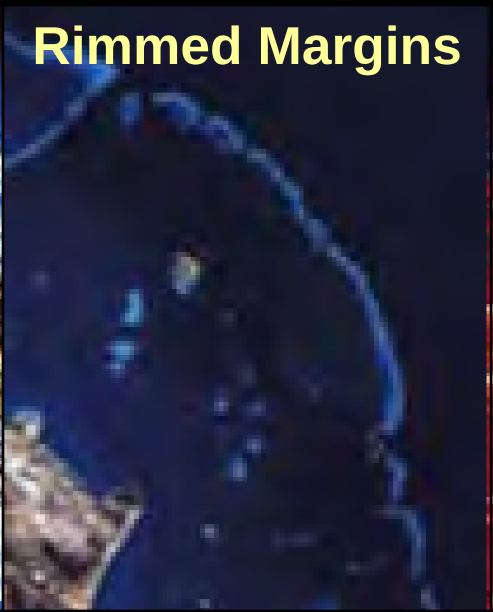


Consider Analogs by Themes

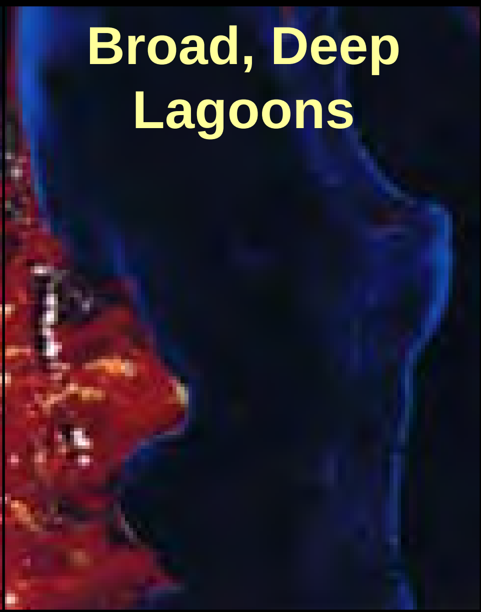
Isolated Carbonate Platforms



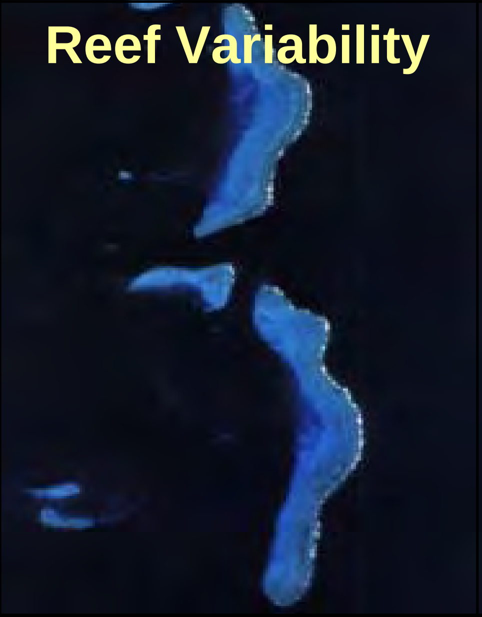
Carbonate Ramps



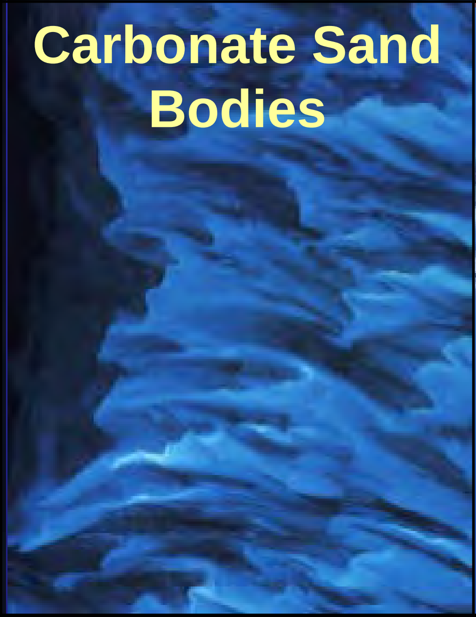
Rimmed Margins



Broad, Deep Lagoons



Reef Variability



Carbonate Sand Bodies

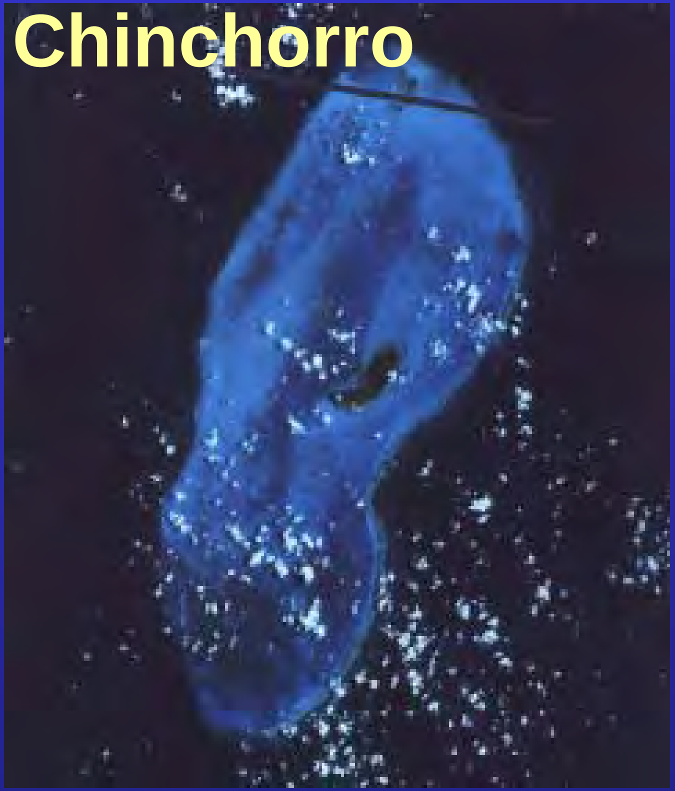
Shallow Lagoon/Tidal Flat

Mixed Clastics/ Carbonates

Isolated Carbonate Platforms - Bahamas

Isolated Carbonate Platforms

Caicos



Chinchorro

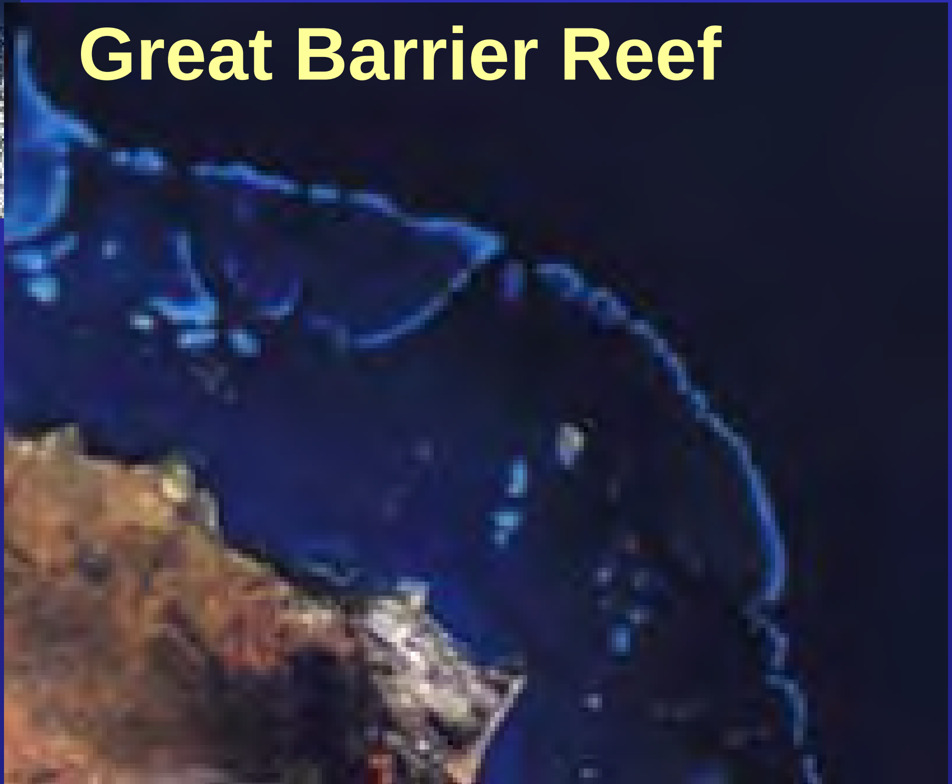
Belize

Carbonate Ramps – Abu Dhabi

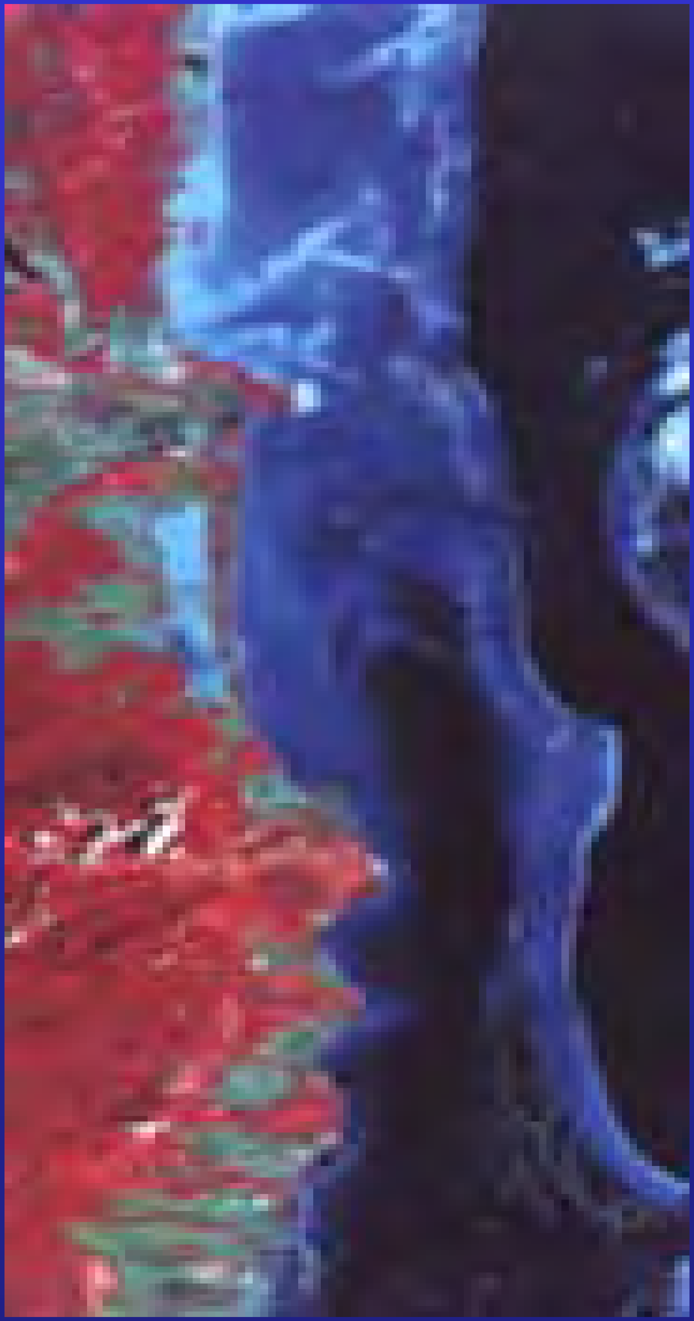
Abu Dhabi

Northern Yucatan

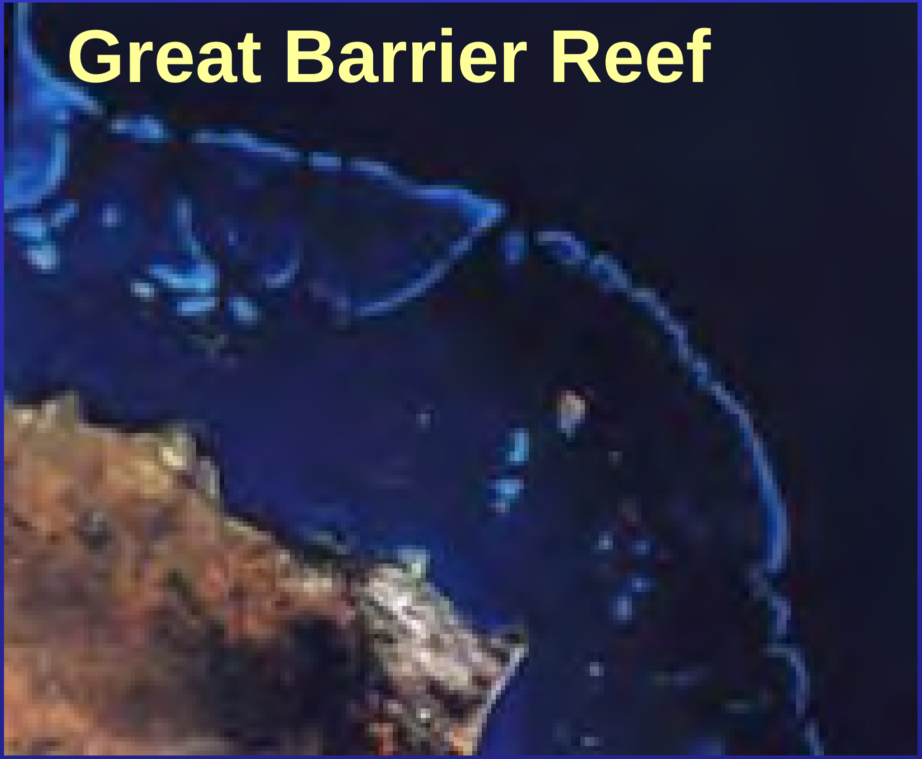
Rimmed Margins



Rimmed Margin – Belize



Broad, Deep Lagoons


Great Barrier Reef


Belize

Reef Variability

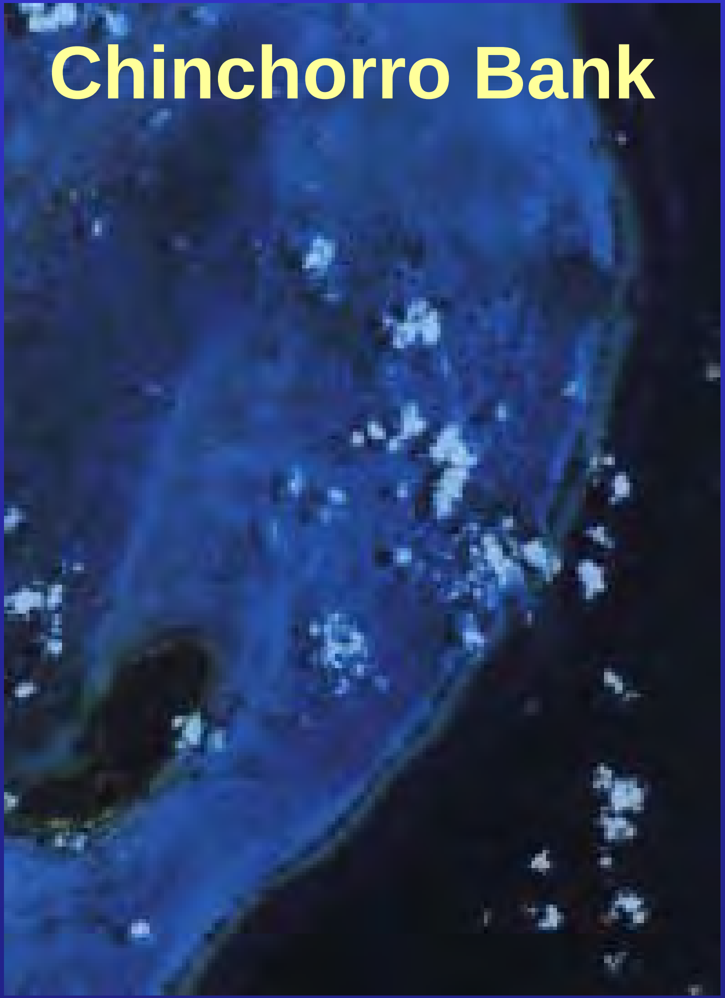

Florida Keys


Bahamas

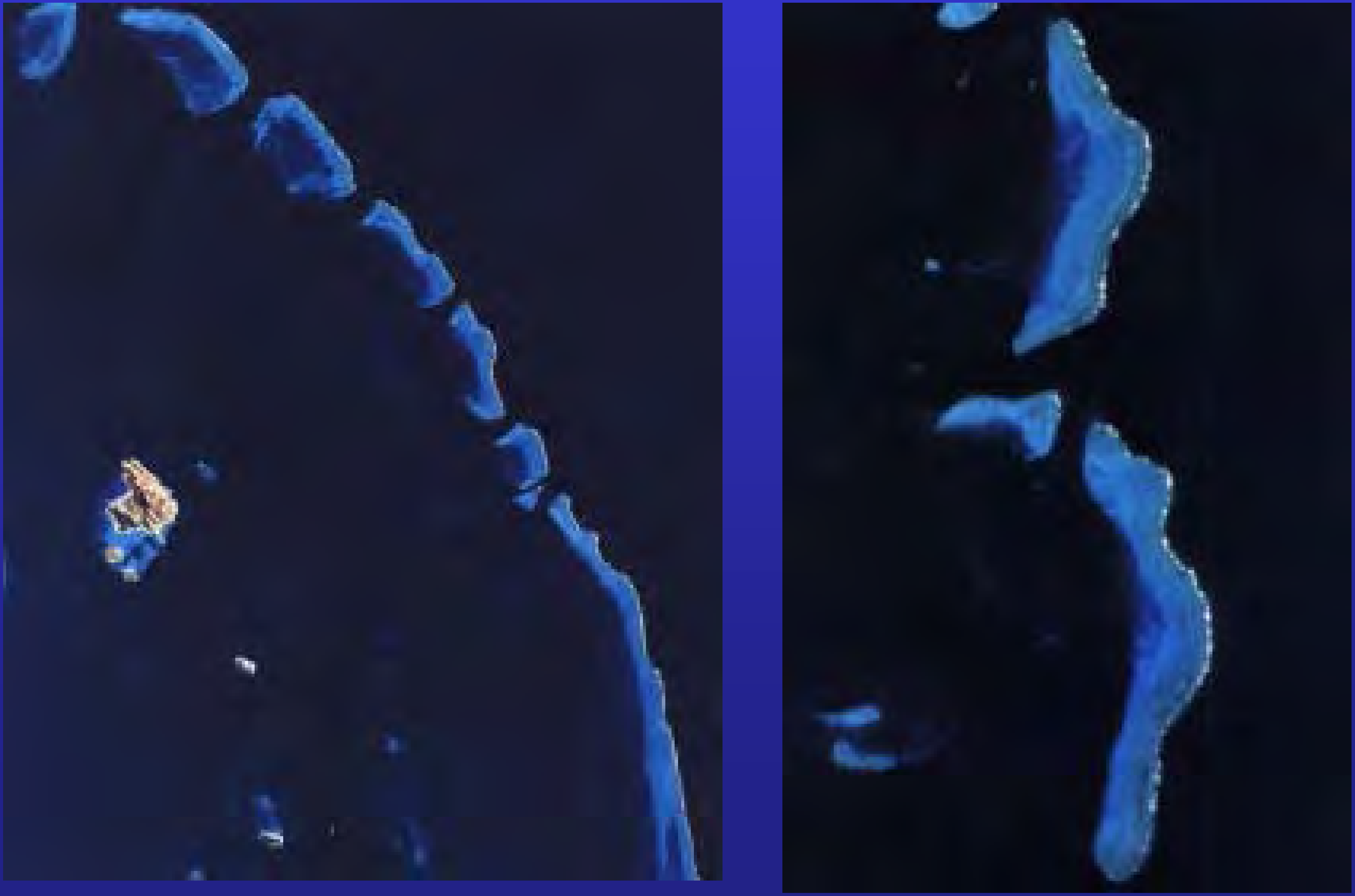
Reef Variability – Bahamas

Reef Variability – Caicos

Reef Variability

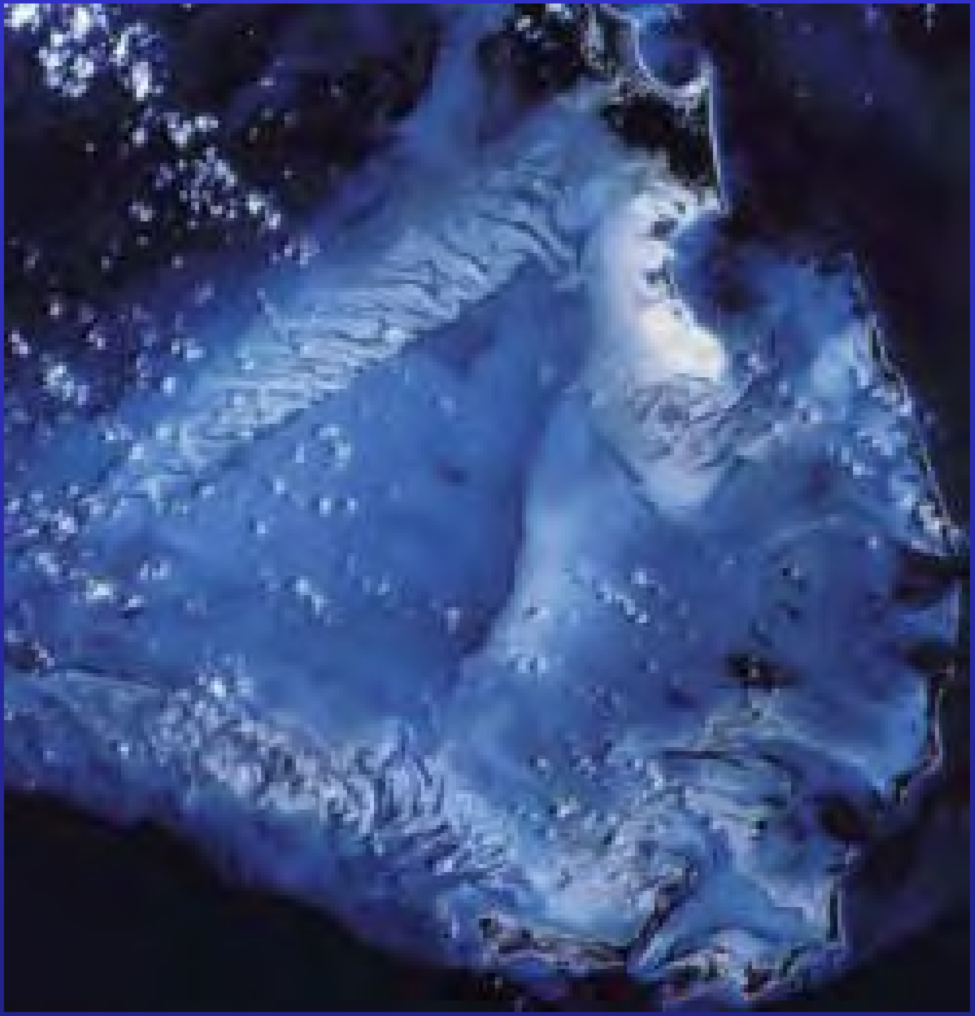


Reef Variability – Great Barrier Reef



Carbonate Sand Bodies - Florida

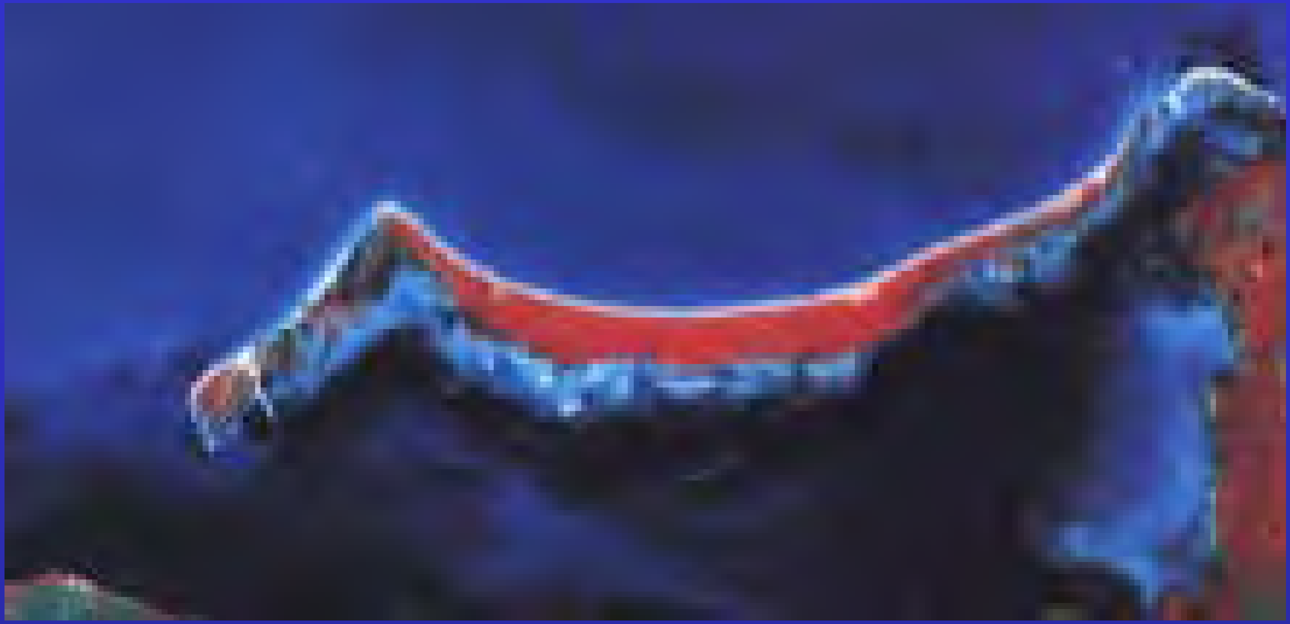
Carbonate Sand Bodies - Bahamas



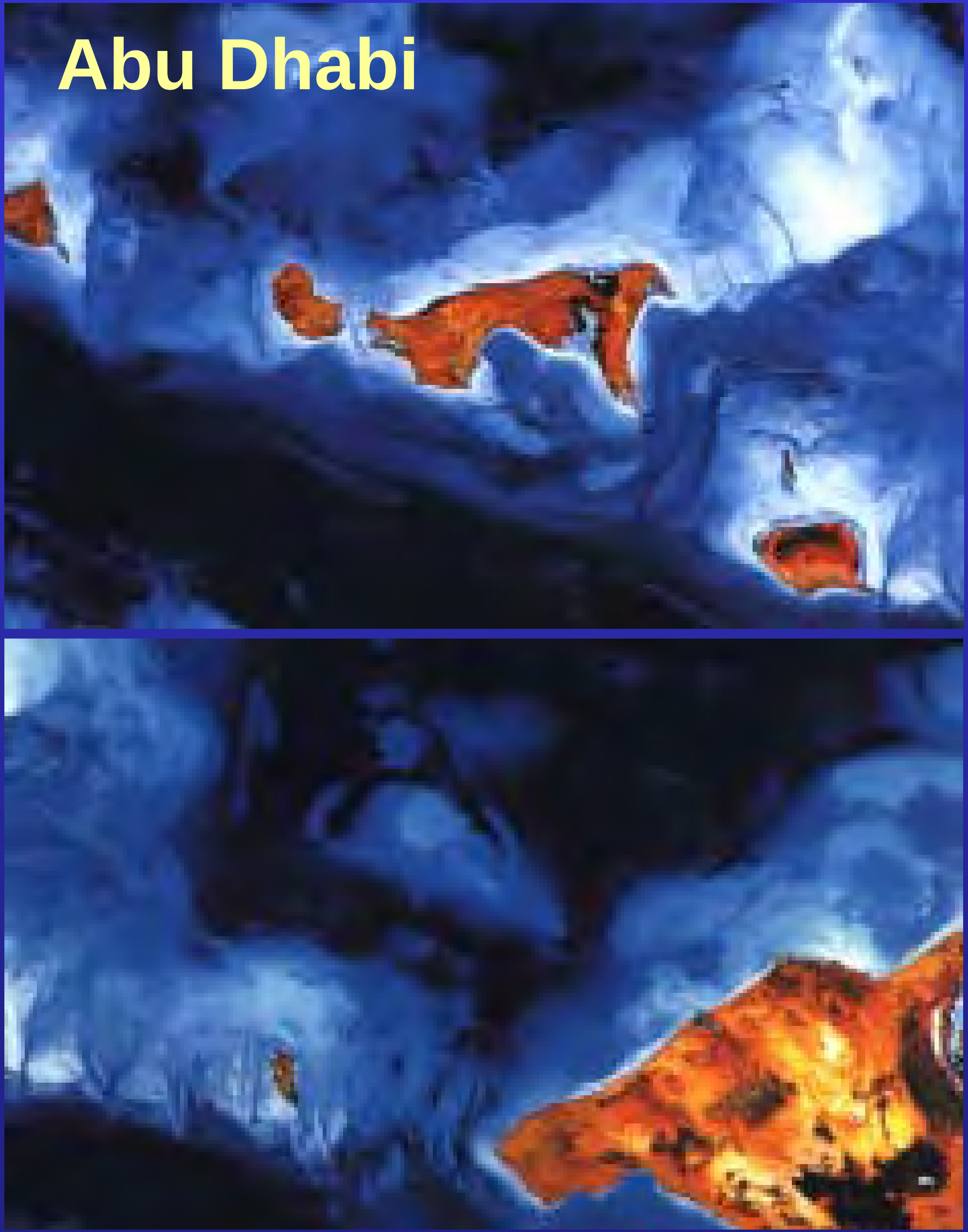
Carbonate Sand Bodies - Bahamas

Carbonate Sand Bodies - Caicos

Carbonate Sand Bodies – Northern Yucatan



Carbonate Sand Bodies

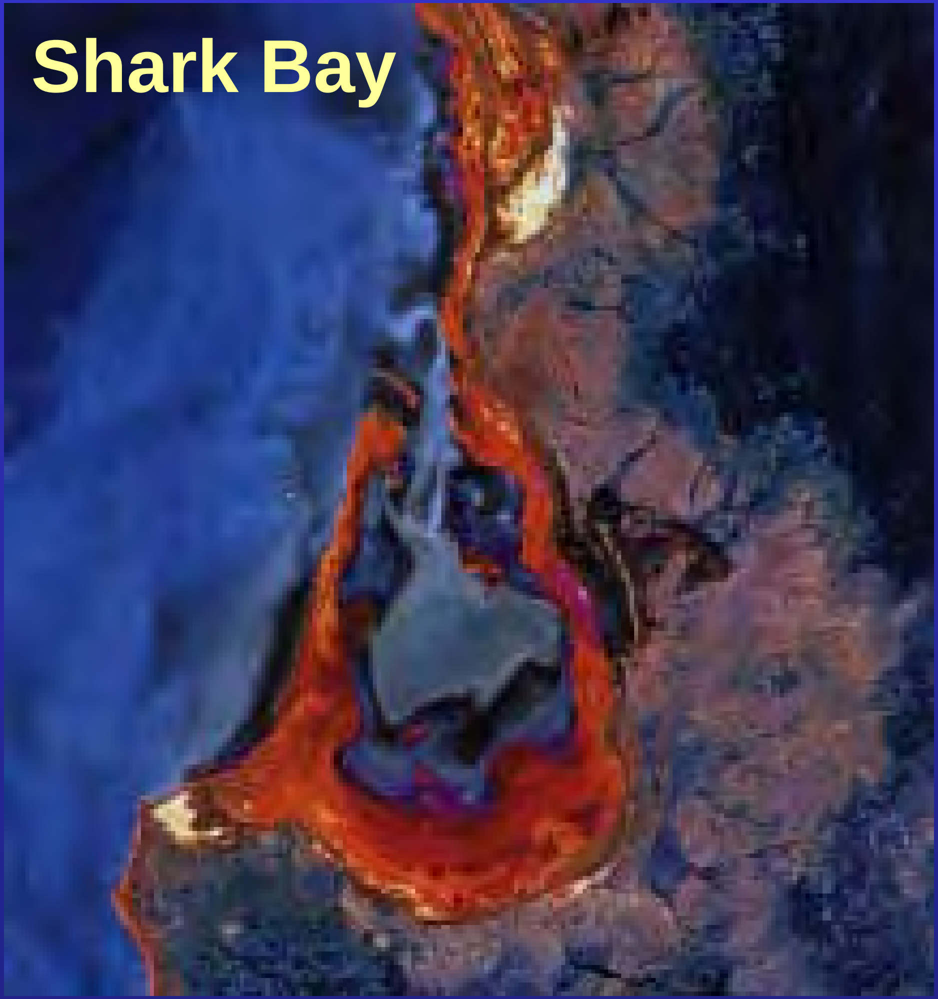


Shallow Lagoon/Tidal Flat – Florida Keys

Shallow Lagoon/Tidal Flat – Bahamas

Copyright Space Imaging

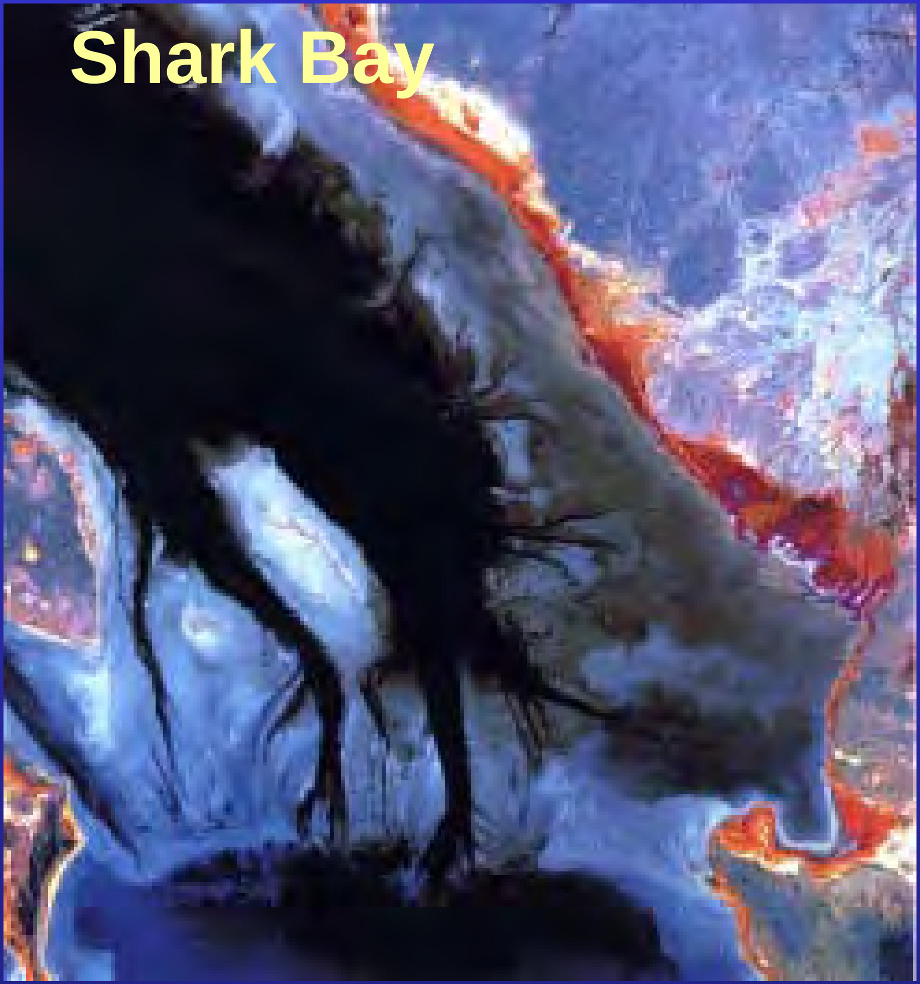
Shallow Lagoon/Tidal Flat

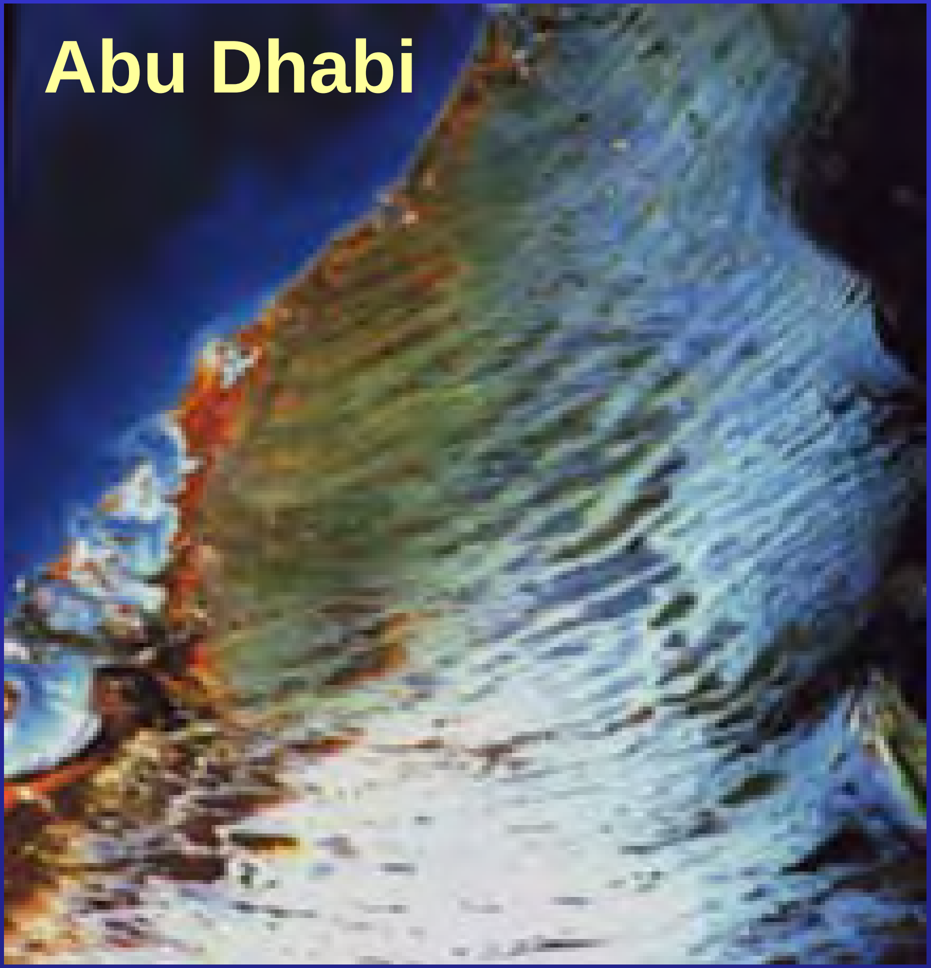


Shallow Lagoon/Tidal Flat – Abu Dhabi

Mixed Carbonates/Clastics

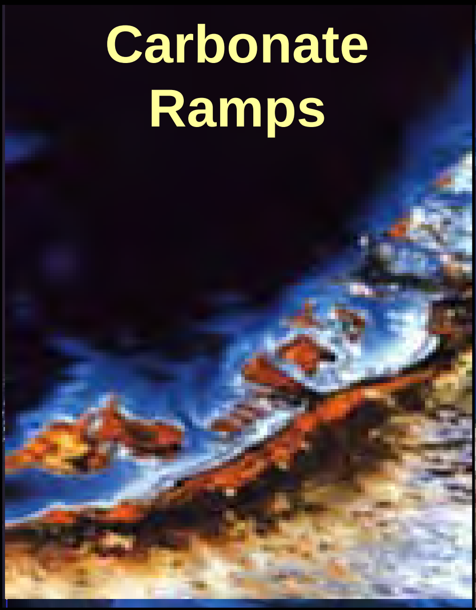
Mixed Carbonates/Clastics

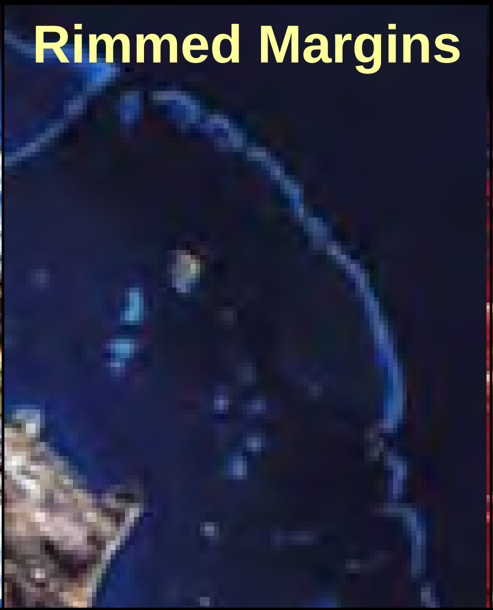


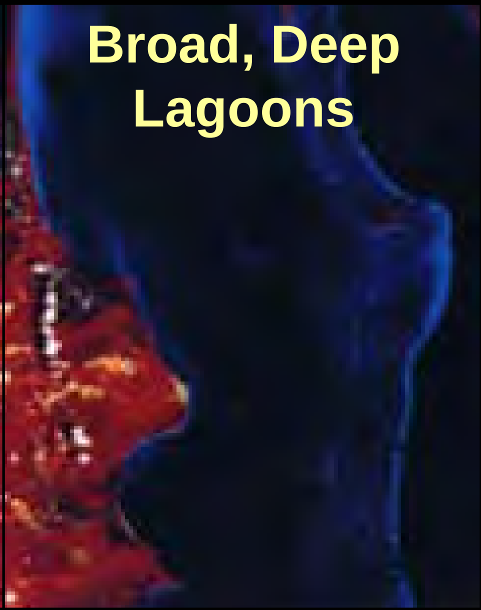


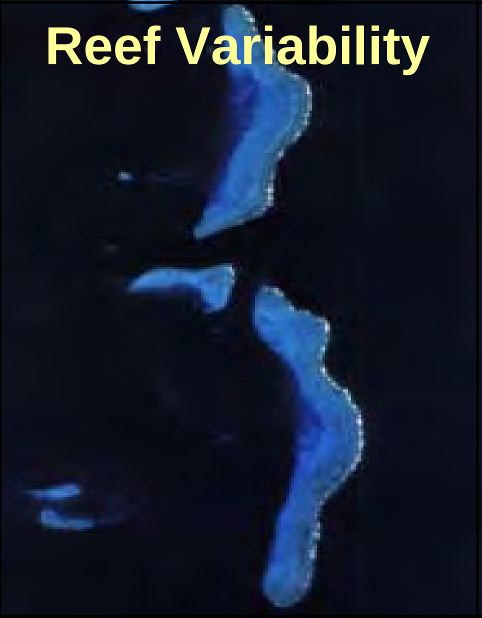
Consider Analogs by Themes

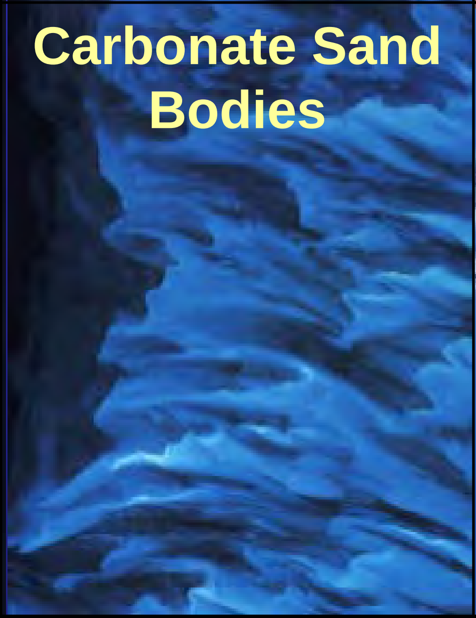

Isolated Carbonate Platforms


Carbonate Ramps


Rimmed Margins


Broad, Deep Lagoons


Reef Variability


Carbonate Sand Bodies


Shallow Lagoon/Tidal Flat

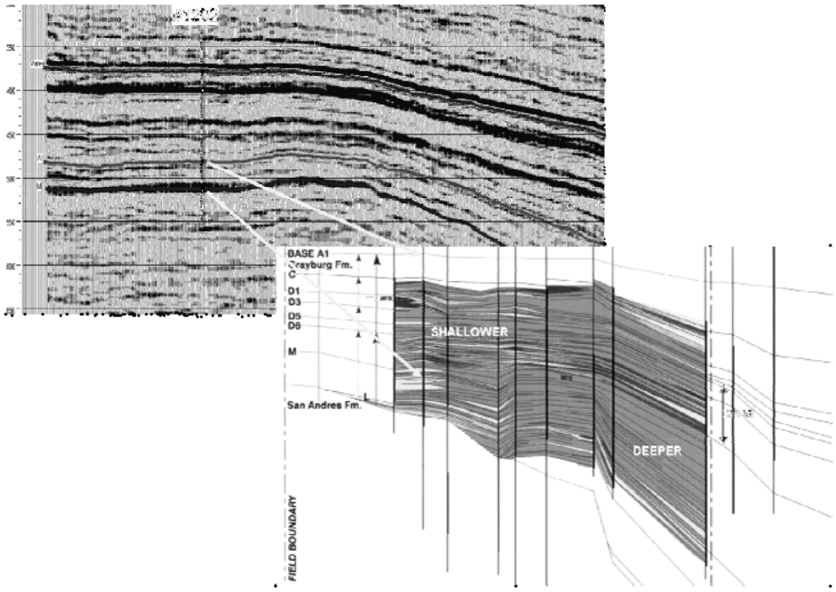

Mixed Clastics/ Carbonates

AN OILFIELD EXAMPLE
MCELROY FIELD

McElroy Field

Paul M. (Mitch) Harris, 2004, Unique Approaches to Analysis of a Cyclic Shelf Dolomite Reservoir: AAPG Hedberg Conference “Carbonate Reservoir Characterization and Simulation: From Facies to Flow Units”, March 14-18, 2004 — El Paso, Texas.

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. Dolograinstones 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. This 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. Because of its complexity and long production history McElroy field has been investigated in a great amount of detail, including the utilization of some unique approaches to reservoir analysis.

Crosswell Seismic

Geologic "ground-truthing" suggests that cross-well seismic data, when integrated with facies-based porosity models, adds value to reservoir characterization. The coincidence of reflectors with decreases in porosity or gypsum cement from whole-core analysis suggests that total porosity and mineralogy dominantly influence velocity. Reflectors correlate fairly well with major log variations; S-wave reflectors correspond almost exactly with increases in sonic velocity, resistivity, and bulk density, and decreases on the neutron log from high to low porosity (or gypsum). Although major stratigraphic boundaries (sequence boundaries and flooding surfaces) generally coincide with reflectors, lithofacies and small-scale depositional cycles do not relate directly to the seismic data. Comparing geostatistical porosity models directly to the seismic suggests that S-wave reflection images appear to be resolving lateral changes in porosity of less than 56 m but more than 15 m.

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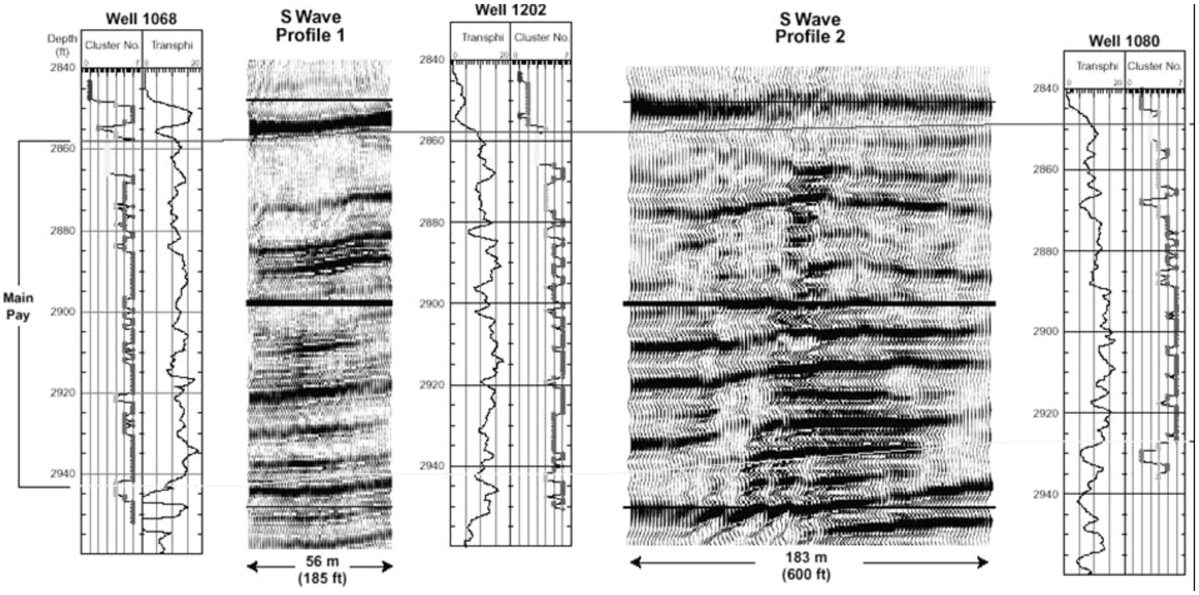

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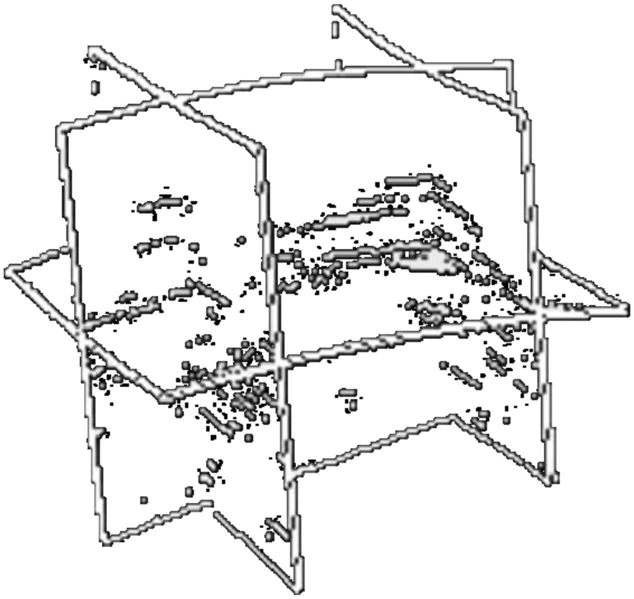
The method involved the following: (1) developing a log trace to identify zones of high vuggy porosity, (2) creating a detailed geostatistical model of total porosity using well log data, (3) creating a geostatistical permeability model based on total porosity, (4) creating a separate detailed geostatistical model of secondary porosity, and (5) superimposing exceptionally high permeability in areas of the permeability model defined by high secondary porosity.



UNIQUE APPROACHES TO ANALYSIS OF A CYCLIC SHELF DOLOMITE RESERVOIR

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

Allan and Wiggins, 1993 (after Hild, 1986)

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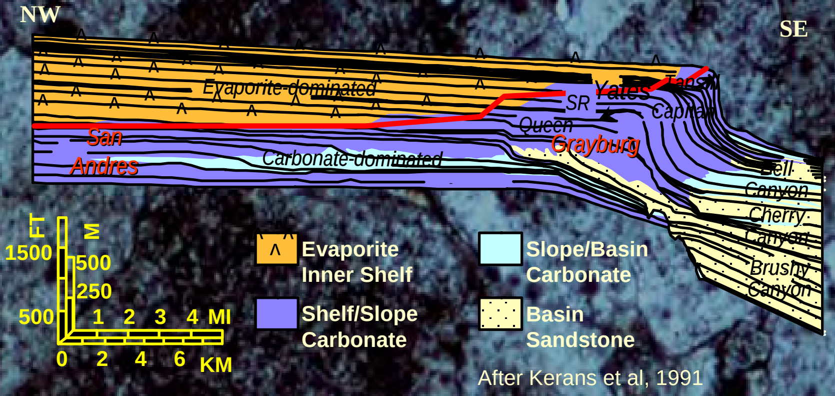
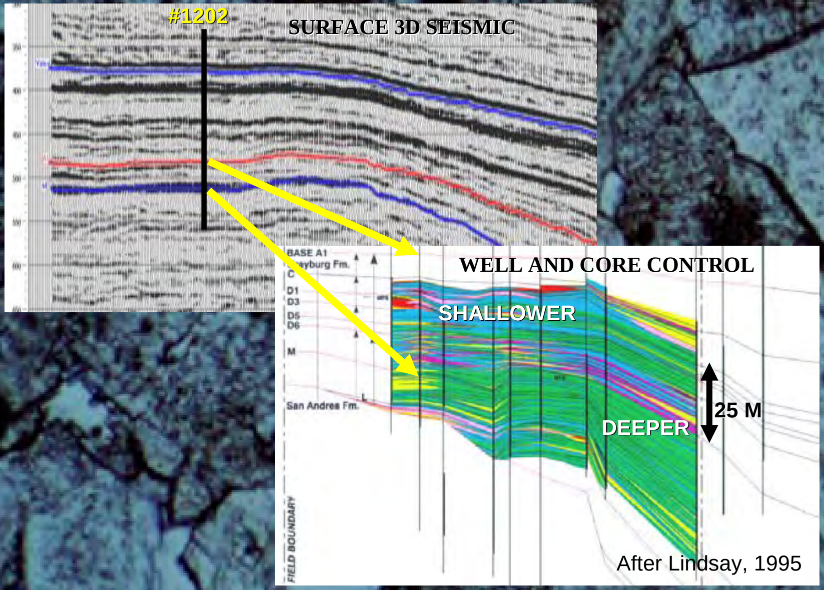
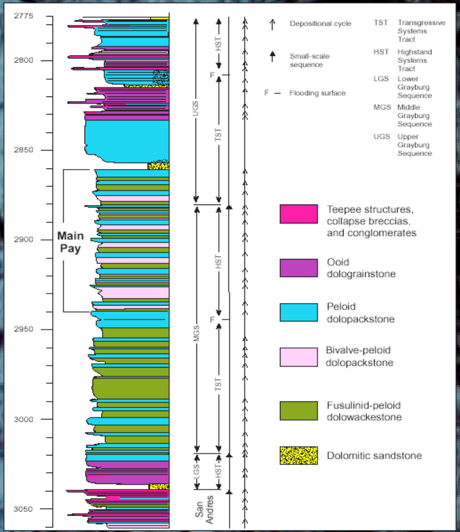


After Kerans et al, 1991



After Lindsay, 1995



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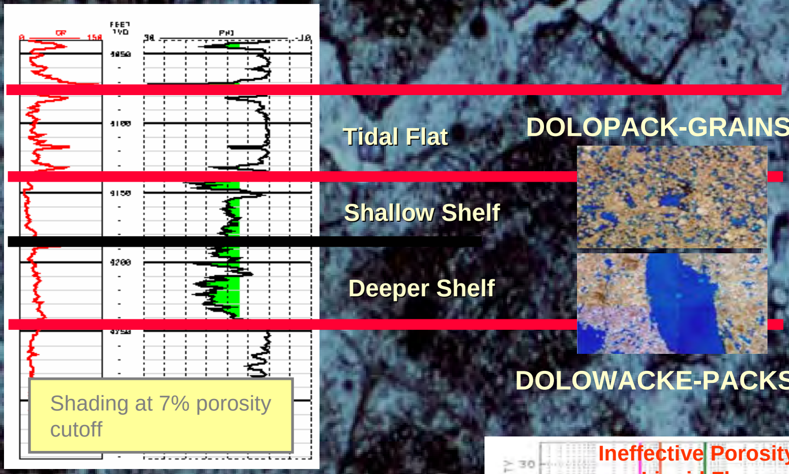
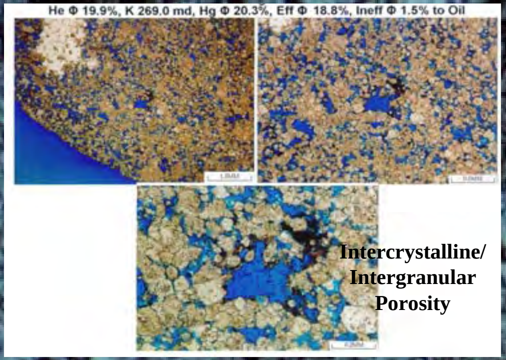


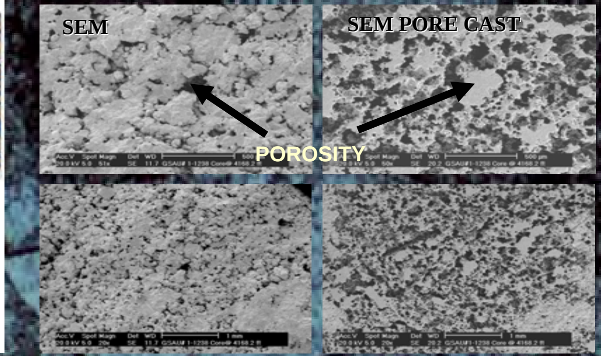
Shading at 7% porosity cutoff

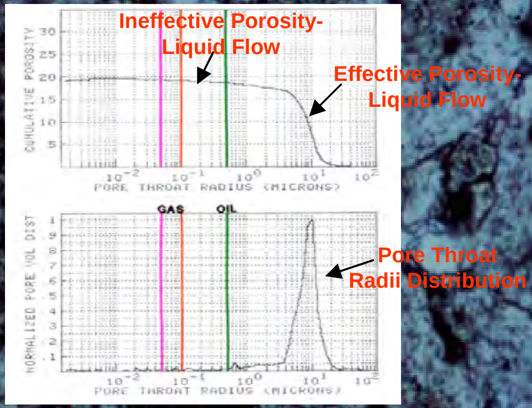
DOLOPACK-GRAINSTONE

DOLOWACKE-PACKSTONE

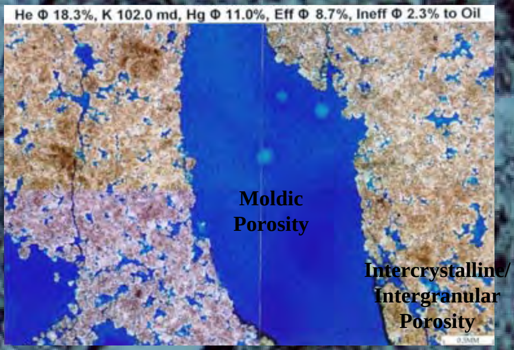
DOLOPACK-GRAINSTONE

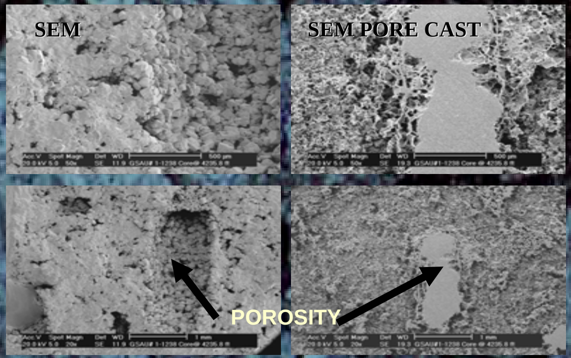

He Φ 19.9%, K 269.0 md, Hg Φ 20.3%, Eff Φ 18.8%, Ineff Φ 1.5% to Oil

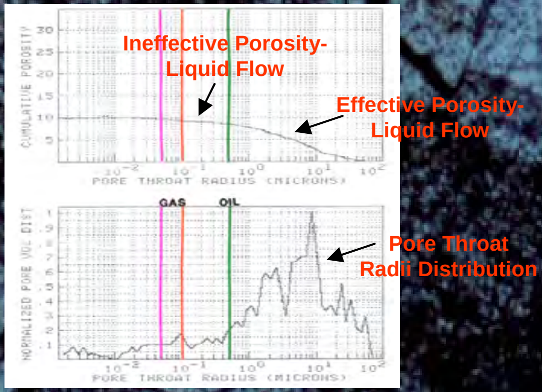




DOLOWACKE-PACKSTONE


He Φ 18.3%, K 102.0 md, Hg Φ 11.0%, Eff Φ 8.7%, Ineff Φ 2.3% to Oil





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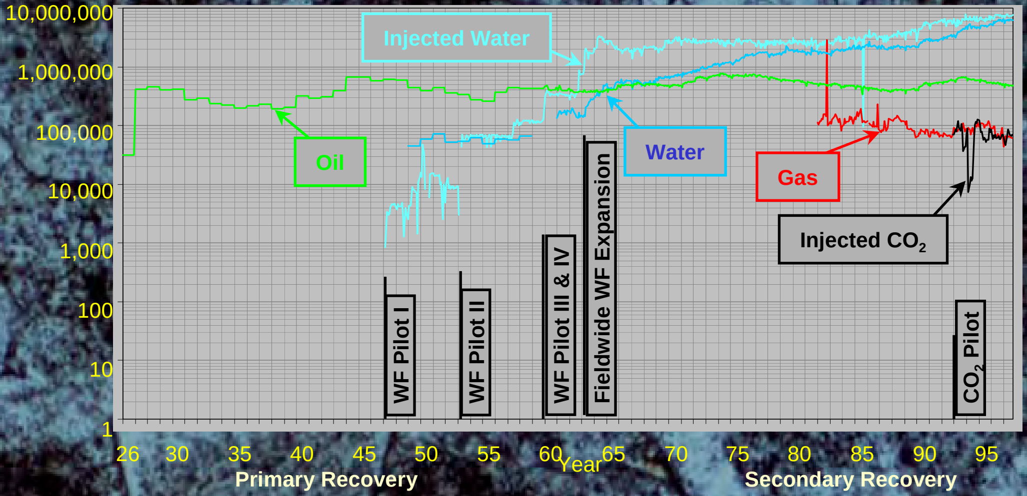

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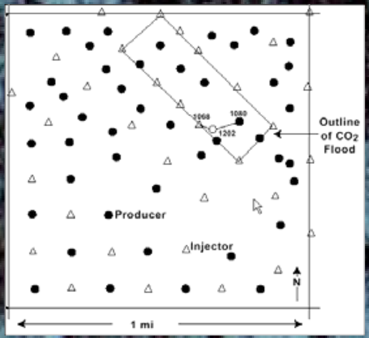
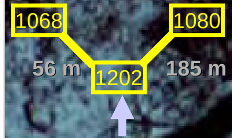
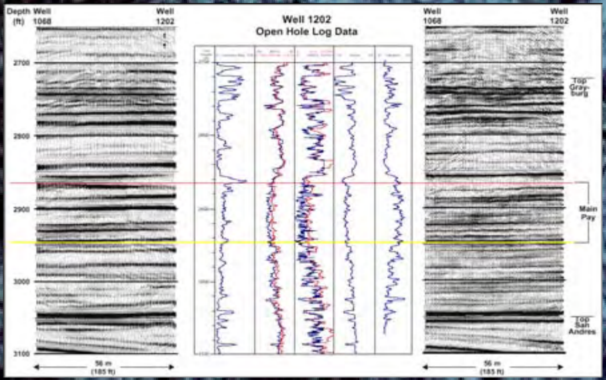


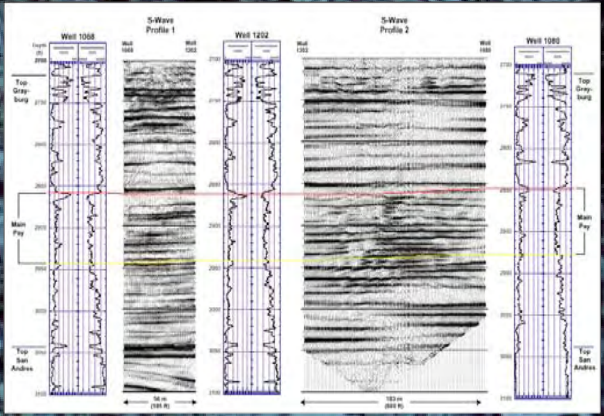
After Tucker et al, 1998



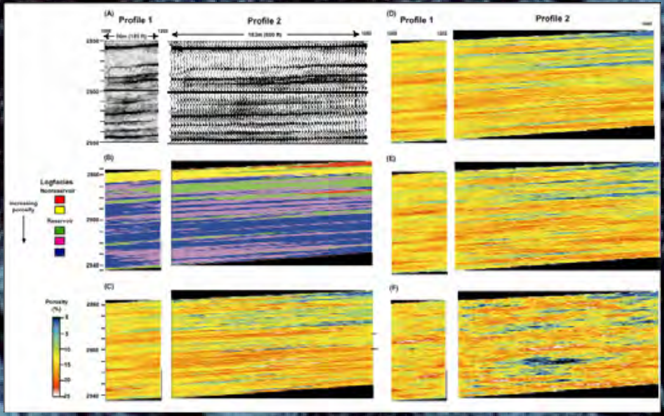
KEY WELL
WITH CORE
AND LOGS



Reflectors = increases in sonic, resistivity, and bulk density also decreases on neutron from high to low porosity (or gypsum)



Reflectors, along with GR and sonic log, suggests interwell variation



Images resolve lateral changes in porosity <56 m but >15 m

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Log Facies

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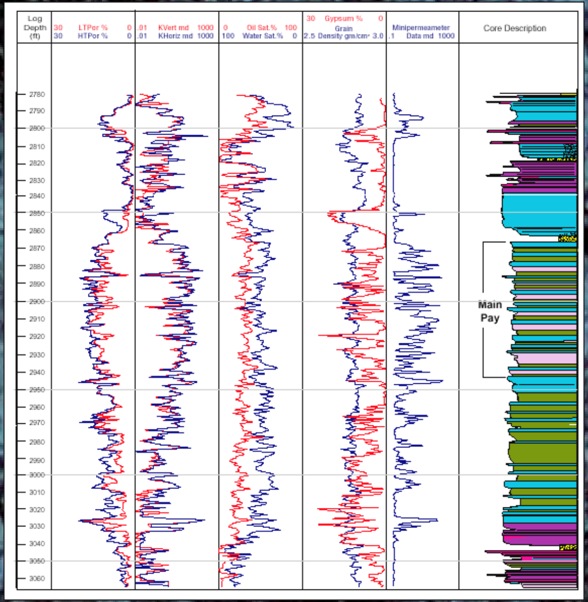
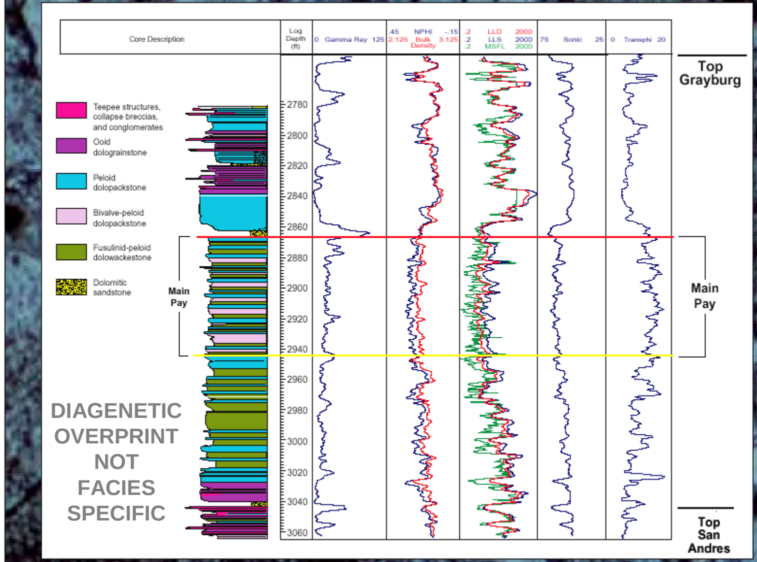
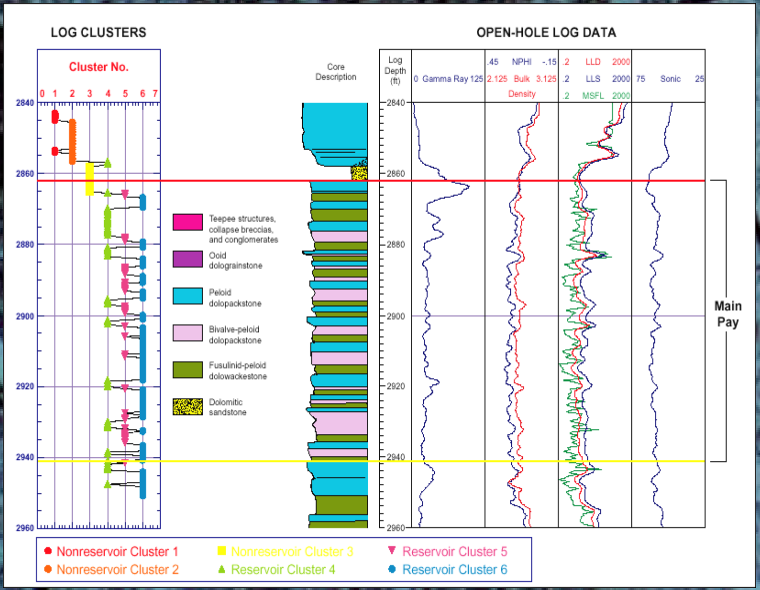


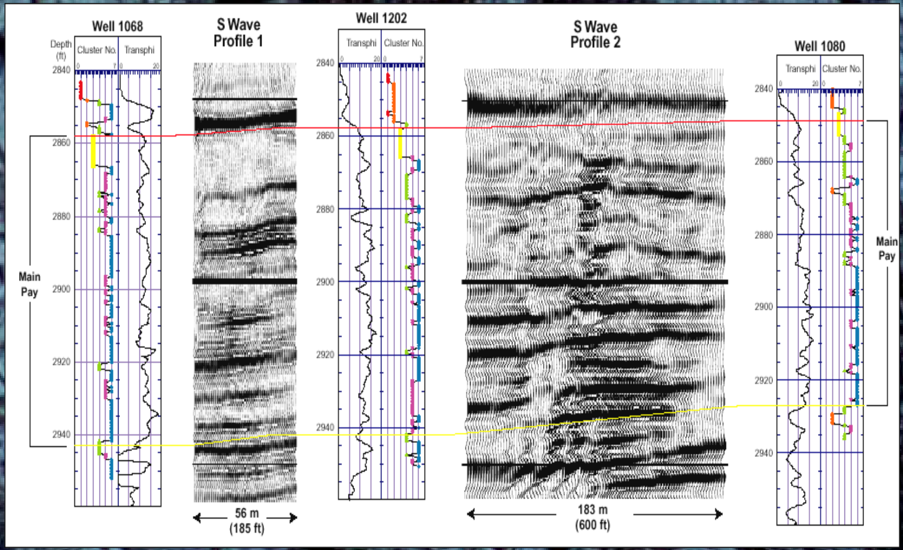
Poor Correlation Between Measured Variables and Core-Based Lithofacies



Poor Correlation Between Logs and Core-Based Lithofacies



Log-based Clusters Do Not Consistently Match Core Facies



Log Facies Better Relate to Porosity and Seismic Reflections

After Tucker et al, 1998

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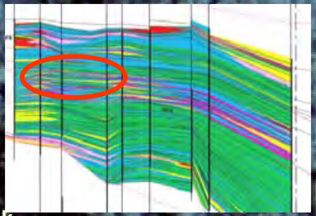
VUGGY ZONES

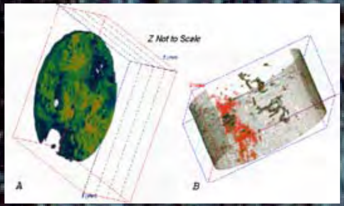
Logs, Cores, CT Scans, and Production History

Thin Zones of High por and k

Early Water Breakthrough in Waterflood

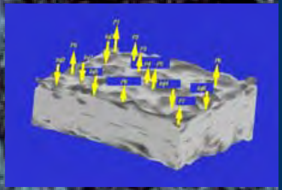
High Production and Injection Rates

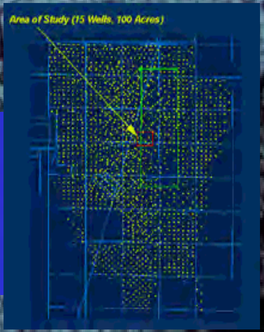




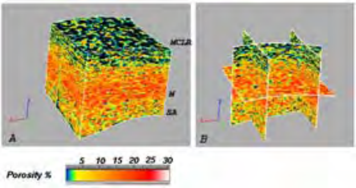
100 Acre Area in the Vuggy Part of the Field

9 Producer and 6 Injector Wells

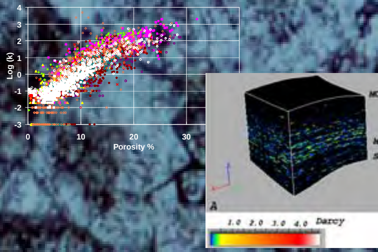




Generate Geostatistical Distribution of Total Porosity



Use Por-k Scatter Diagram from Closest Cored Wells and Cloud Transform to Generate Permeability Cube



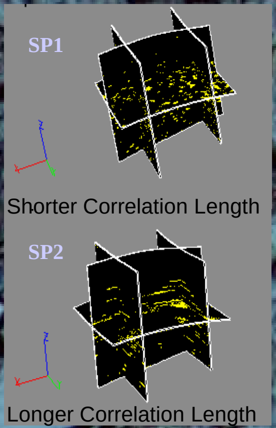
DISTRIBUTE VUGGY ZONES

Sonic Log Derived Porosities Represent Matrix Porosities

Total Porosities from Other Logs

Total - Matrix Porosity > 0.08 Indicates "Vuggy" Zones

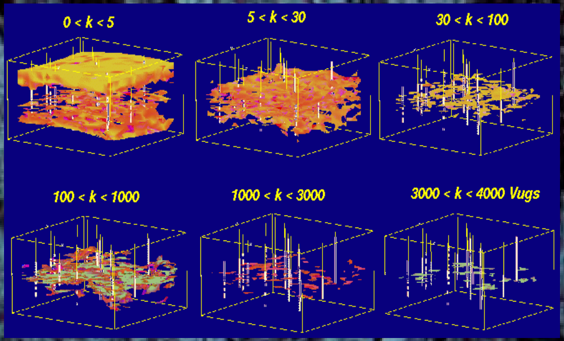
Delta Porosity Trace from 291 Wells Used to Generate Two Cubes of Secondary Porosity



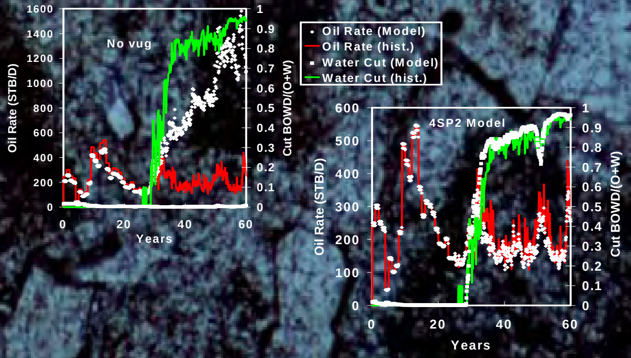
Shorter Correlation Length

Longer Correlation Length

Superimpose Secondary Porosity Cube on Permeability Cube and Assign High Permeability to Vugs

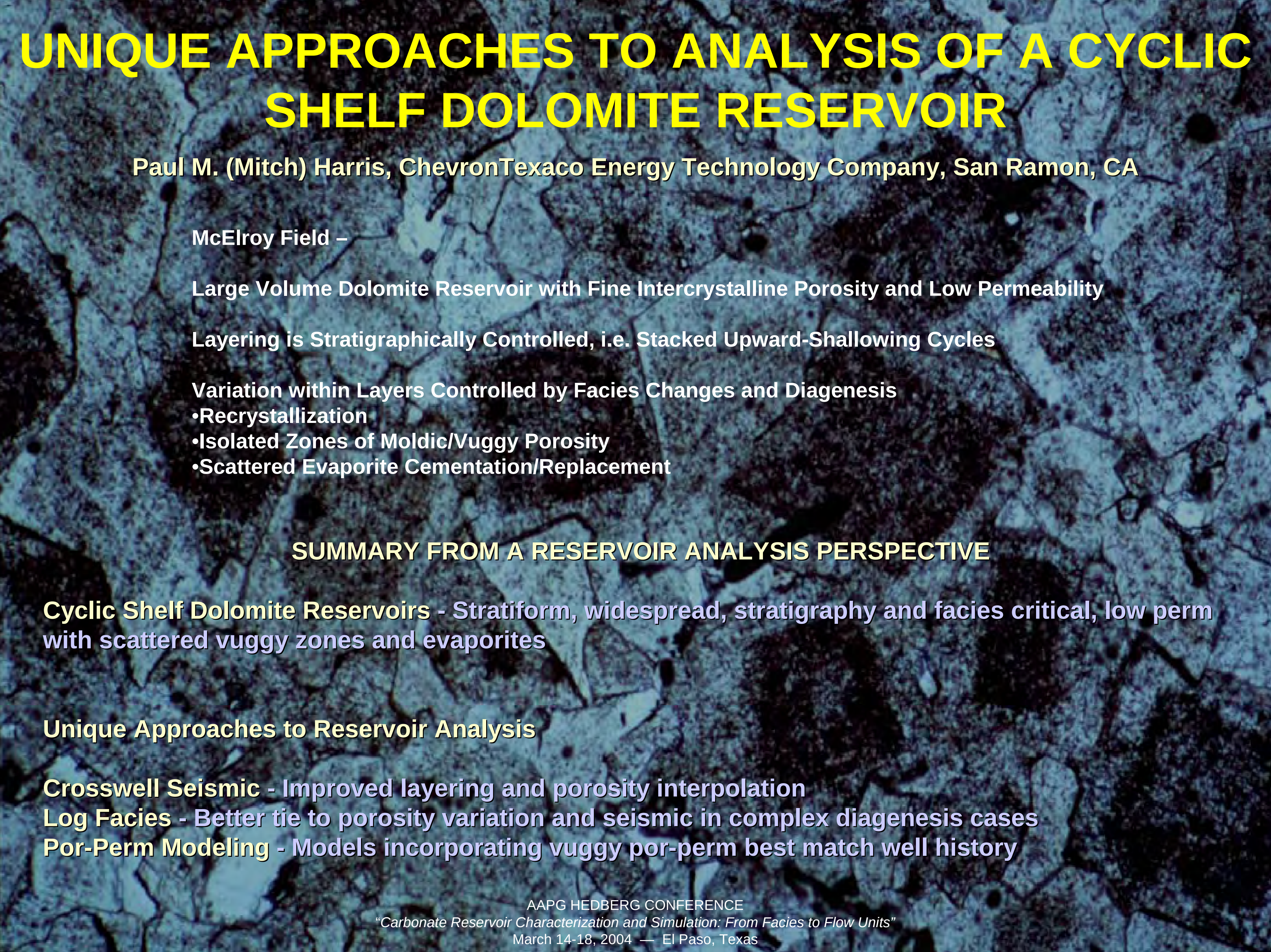


Vuggy Zones were Assigned Permeability of 3, 4 or 5.5 Darcy



Primary Recovery and Waterflood Periods Were History Matched
Higher Permeability and Better Correlated Vuggy Zones Matched Best

After Dehghani et al, 1999



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McElroy Field –

Large Volume Dolomite Reservoir with Fine Intercrystalline Porosity and Low Permeability

Layering is Stratigraphically Controlled, i.e. Stacked Upward-Shallowing Cycles

Variation within Layers Controlled by Facies Changes and Diagenesis
- **Recrystallization**
- **Isolated Zones of Moldic/Vuggy Porosity**
- **Scattered Evaporite Cementation/Replacement**

SUMMARY FROM A RESERVOIR ANALYSIS PERSPECTIVE

Cyclic Shelf Dolomite Reservoirs - Stratiform, widespread, stratigraphy and facies critical, low perm with scattered vuggy zones and evaporites

Unique Approaches to Reservoir Analysis

Crosswell Seismic - Improved layering and porosity interpolation
Log Facies - Better tie to porosity variation and seismic in complex diagenesis cases
Por-Perm Modeling - Models incorporating vuggy por-perm best match well history

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