Heterogeneity within Carbonate Reservoirs - Guidelines from Modern Analogs*

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Abstract and Contents

Abstract

Modern examples illustrate the distribution of carbonate facies within an overall depositional setting and can play 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. Several modern carbonate areas depict the geologic characteristics that can be expected in many ancient shallow-water settings, including those of the Late Paleozoic shelves and platforms of the Permian basin.

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

The geologic framework as illustrated by these modern areas can be important in the development scale analysis of Permian Basin reservoirs where lateral variation of porosity and permeability; i.e., reservoir quality, is commonly tied to facies changes and facies dimensions are required as input to reservoir models. The geologic framework as shown by the modern areas is also important at the exploration scale for reservoir facies...
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HETEROGENEITY WITHIN CARBONATE RESERVOIRS
GUIDELINES FROM MODERN ANALOGS

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ABSTRACT

Modern examples illustrate the distribution of carbonate facies within an overall depositional setting and can play 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. Several modern carbonate areas depict the geologic characteristics that can be expected in many ancient shallow-water settings including those of the Late Paleozoic shelves and platforms of the Permian Basin.

- **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
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The geologic framework as illustrated by these modern areas can be important in the development scale analysis of Permian Basin reservoirs where lateral variation of porosity and permeability, i.e. reservoir quality, is commonly tied to facies changes and facies dimensions are required as input to reservoir models. The geologic framework as shown by the modern areas is also important at the exploration scale for reservoir facies prediction and stratigraphic play concepts which are related directly to depositional facies patterns.

INTRODUCTION

Harris and Kowalik (1994) have published an extensive collection of satellite imagery of modern carbonate settings in which they explain how satellite images are acquired, processed, and interpreted, and also describe in detail color images covering a wide range of carbonate depositional settings. This work should be examined to better realize the full potential of modern analogs as aids for carbonate reservoir studies. The following brief sections emphasize the key attributes for several modern areas and include a representative satellite image to illustrate some of these attributes. With only one exception, the figures are subscenes of Landsat images at 1:250,000 scale which are useful for illustrating both regional- and reservoir-scale trends. Figure 6 is a SPOT image shown at 1:500,000 scale. The Remote Sensing Laboratory of Chevron Petroleum Technology Company digitally processed and plotted the images. To better visualize the scale of the patterns in depositional facies for the various key modern carbonate areas relative to the size of a well known Permian Basin reservoir, an outline of the Chevron-operated portion of McElroy Field is shown at the same scale for each Landsat image.

STUDY AREAS AND KEY ATTRIBUTES

### South Florida

- A siliciclastic-to-carbonate transition occurs within the Miami and northern Florida Keys area.
- The Florida Reef Tract contains a continuous, well-developed outer reef, and also a myriad of patch reefs and associated skeletal sands.
- The Florida Bay to Florida Reef Tract transition shows most of the important sedimentologic changes that occur seaward across a shelf as energy conditions also increase.
- The Quicksands area of tidal sand bars near the Marquesas Keys is an expansive accumulation of high-energy skeletal sands.
- Florida Bay contains a spectrum of mud-dominated depositional settings ranging from shallow subtidal to supratidal environments.
- The Everglades represent the marine to freshwater transition occurring along the coastline.

Figure 1 shows details of Florida Bay, the Florida Keys, and the Florida Reef Tract. The Florida Keys extend from A14 to O1 abruptly separating the Florida Reef Tract from Florida Bay. The seaward edge of the Reef Tract from
FIGURE 1. Subscene of Landsat Thematic Mapper image showing details of Florida Bay, the Florida Keys, and the Florida Reef Tract (image 51539-15205 acquired 5/18/88).
A18 to Q4 consists of a discontinuous outer reef and associated skeletal sands. Reefs are visible at O7 and P5. Skeletal sands are lighter colored, extending landward from the outer reefs to occupy the outer portion of the Reef Tract; sand waves are visible in several places. The inner part of the Reef Tract has muddier sediments with local buildups like Rodríguez Bank (L5), Tavernier Bank (J8), and tidal deltas between the Florida Keys (D13 and F11, for example). Florida Bay consists of depressions or lakes that are rimmed by mudbanks and scattered islands. Commonly visited localities include Crossbank (extending from D11 to D8 to F7 to I7), the lake it circumscribes, and the Crane Keys at F8.

**The Bahamas**

- The Bahamas Banks are steep-sided, isolated carbonate platforms that range widely in size.
- Classic platform-edge to interior facies changes and windward to leeward variation occur across the platforms, both in response to varied bottom agitation and energy settings.
- Ooid sand accumulations of several different styles are positioned along the margins of the platforms.
- The Andros Barrier Reef is one of the world's longest, and areas of dense patch reef development occur locally on the platforms.
- Well-studied muddy tidal flats on the leeside of Andros Island are the classic humid tidal flat example.
- A myriad of Holocene and Pleistocene islands expose stratigraphic relations and also the early diagenetic overprint.
- Deep-water troughs and reentrants, in which carbonate slumps, debris flows and turbidites occur, separate the platforms.

Figure 2 shows details of the tidal bar belt of ooid sand shoals that rims the cul-de-sac of Tongue of the Ocean on Great Bahama Bank. This area from the eastern edge of the cul-de-sac highlights the abruptness of the platform edge, the east-west trend of the tidal bars, and the irregularity of the bar crests. Although continuous across the width of the tidal bar belt, the sand bars are quite complex in detail. The sinuous bar crests are nearly exposed, bar flanks are also sites of active ooid formation, and the intervening channels have variable bottoms ranging from active sand waves, grass-stabilized muddy sands, hardgrounds, to bare Pleistocene bedrock.

**Caicos, British West Indies**

- The platform is relatively small, isolated, steep rimmed, and in an open oceanic setting. Windward - leeward variations of depositional settings are well expressed.
- Reefs are of three types: a nearly continuous barrier, high energy patches, and fringing.
- Ooid sands are widespread on the platform in areas where persistent waves agitate the bottom, and major accumulations occur on high-energy island beaches along the leeward side of the platform.
- The Caicos tidal flats differ from those of Andros in terms of dominant influences on sedimentation, preserved stratification, and associated evaporite minerals.
- Salinas are located in topographic depressions on the islands.

**Yucatan - Chinchorro Bank, Mexico**

- The area shows the high degree of variability that can exist along a regional coastline/shelf margin, from a carbonate sand-dominated ramp profile to a rimmed platform margin with fringing or barrier reefs and offshore platforms.
- The northern coastline of the Yucatan Peninsula displays a ramp-type shelf-to-basin profile with a variety of carbonate sand bodies occurring inboard on the ramp along the coastline.
- The areas of Cancun and Cozumel contain superb Holocene and Pleistocene grainstone accumulations that have been thoroughly studied from both a depositional and diagenetic aspect.
- Chinchorro Bank, an offshore isolated carbonate platform, shows substantial facies variation between its windward and leeward margins.

Figure 4 shows a complex carbonate sandbody and adjacent lagoon along the northern coastline of Yucatan. Yalahau Lagoon (J9) is only partially cut off from open
FIGURE 2. Subscene of Landsat Thematic Mapper image showing a portion of the tidal bar belt of ooid sands that rims the cul-de-sac of the Tongue of the Ocean on Great Bahama Bank (image 50942-14522 acquired 9/29/86).
FIGURE 3. Subscene of Landsat Thematic Mapper image showing the varied depositional environments along the northwestern portion of the Caicos Platform, British West Indies (image 52457-14333 acquired 11/22/90).
FIGURE 4. Subscene of Landsat Multispectral Scanner image showing a regional carbonate sandbody and adjacent lagoon along the northern coastline of Yucatan, Mexico (image 20350-15333 acquired 1/7/76).
circulation of the Gulf of Mexico by Isla Holbox (J6). This long barrier-spit complex has well-developed beaches, beach-dune ridges, and storm washover fans. The lagoon is filled with 1-3 m of carbonate mud and storm washover carbonate sands more proximal to Isla Holbox. Mangrove swamps occur along the southern coastline of the lagoon (D10) and partly fill the curving topographic swales (L15) that extend southward from the lagoon. The swales are the surface expression of the Holbox fracture zone. Figure 5 shows Chinchorro Bank, an isolated platform with a windward margin that is characterized by a nearly continuous barrier reef. The northern portion of the platform is composed of a series of elongate, subparallel ridges and lagoons. The most prominent ridge (I11 to L6) contains a trend of patch reefs, sand flats, and the large island, Cayo Central. This ridge fronts a large central lagoon (H12 to K5). The northwestern side of the central lagoon is marked by a second ridge (F11 to J4) which contains a distinctive patch reef trend with a well-developed continuous leeward sand flat. The southern part of the platform contains scattered patch reefs and sand flats; a trend of coalescing patch reefs forms a type of continuous barrier (F14 to H18) well behind the platform edge. The dark heavy line from F3 to N4 is an artifact of the image.

**Belize**

- A spectrum of reef types, including barrier, fringing, patch, and pinnacle, are well displayed within the reef tract.
- The reef trend is lengthy, second only to the Great Barrier Reef, and shows the "classic" reef profile of depositional facies relationships as well as some significant facies variation along its trend.
- Extensive isolated platforms occur immediately east of the barrier trend.
- Siliciclastics mix with carbonates along the Belize coastline and part way into the lagoon and may be important elements of the antecedent topography that localized reef growth.
- The lagoon floor deepens substantially from north to south presenting the opportunity to evaluate reef growth in different stages of development relative to variable water depth.
- Belize reefs, including their deeper water portions, have been extensively studied to characterize organism, facies, and diagenetic characteristics.

Figure 6 shows the southern portion of the Belize reef tract and lagoon as well as two offshore isolated platforms. Dangriga (F11) and some of the small rivers along the coastline are visible. The shelf lagoon is wide and deep, and the barrier rim of the shelf is very continuous and well developed. Islands along the reef rim include Middle Long Cay (H1), Rendezvous Cay (H4), South Long Cay (J7), Columbus Cay (K10), and Tobacco Cay (J13). Columbus Reef (K7 to K10) displays a broad reef flat and sand apron immediately leeward. Portions of two offshore isolated platforms are visible: the southern end of the Turneffe Islands (M2) and Grovers Reef (Q14). Grovers Reef contains an almost continuous barrier reef enclosing a shallow lagoon with hundreds of patch reefs.

**Great Barrier Reef, Australia**

- The reef province is unparalleled in length as it extends "continuously" along the northeastern Australian continental shelf for approximately 2250 km.
- A semi-continuous line of elongate reefs exists along the edge of the shelf and a diversity of smaller reef types including algal bioherms and fringing reefs occurs landward across the shelf.
- Reef distribution and development reflect both wind and current influence.
- Reefs in the area have been the focus of detailed studies of organism and facies zonation, diagenesis, growth history, and accumulation rates.
- Mixing of terrigenous and carbonate sediments occurs in the reef trend adjacent to the mainland coastline and rocky islands.

Figure 7 shows details of the shelf-edge ribbon reefs in the northern Great Barrier Reef. The reefs have a current swept, cemented reef crest, and are separated by deep, narrow channels. Reefs from D1 to P20 have a well-developed reef crest of algal-encrusted pavement and a sand apron with scattered patch reefs extending shelfward. Locally, reef growth extends along the narrow channels as cuspat projections facing shelfward (reefs from B1 to M10). Reefs also fringe Lizard Island (D12), a high rocky island formed of Permian granite, on its eastern and western sides.

**Shark Bay, Western Australia**

- Shark Bay has the dimensions of a minor epicontinental sea and contains a wide range of depositional settings, biotic communities, and sediment types.
- Seagrasses are responsible for the development of localized banks and a vast carbonate shoal complex, further restricting tidal influx into major subbasins and facilitating development of hypersaline conditions.
- Cyanobacterial mats, organic-laminated sediments, and minor evaporites form in the southern subbasins in protected, intertidal, high-salinity settings.
Figure 5. Subscene of Landsat Thematic Mapper image showing Chinchorro Bank, an isolated platform offshore of Mexico (image 42130-15375 acquired 5/9/88).
- Siliciclastics mix with biogenic carbonates within a major seagrass-stabilized bank that has developed along the coastline immediately to the north, and Pleistocene siliciclastics form much of the topography that segments Shark Bay into its major geomorphic features.

Figure 8 shows the main geomorphic and bathymetric features of Hamelin Basin in Shark Bay. Hutchison Embayment (P6) and Nilemah Embayment (J19) are principle areas of intertidal-supratidal cyanobacterial-dominated flats. A sublittoral platform rims the basin. It is narrow around the southern margin, widens to the north along the eastern edge, and projects further into the basin from the western margin as a series of promontories. The embayment plain in Hamelin Basin slopes gently from 6 m depth in the south to 9 m in the north. The large dark area in the southwestern part of Hamelin Basin (114) is not due to deep water, but instead is due to benthic organic ooze composed mainly of diatoms.

**Abu Dhabi Coastline**

- The Abu Dhabi area is a modern analog for a carbonate ramp, as the seafloor is gently inclined from the shoreline to bathymetric axis of the basin at 80-100 m.
- The hot, arid climate of the Middle East stimulates the formation of evaporite minerals including dolomite, gypsum, anhydrite, and halite.
- Sediment composition, patterns in sediment distribution, and stratigraphy vary greatly along the coastline due to its orientation with respect to onshore winds and proximity of upwind barriers.
- The area illustrates the close lateral juxtaposition of potential reservoir, i.e. reef, ooid shoal, and lagoon, and sealing facies, and also shows significant progradation of

**Figure 6.** SPOT High Resolution Visible image showing the southern portion of the Belize reef tract and lagoon as well as portions of two offshore isolated platforms (image 16123169002101645302x acquired 2/10/90). (SPOT Image Data Copyright CNES, 1994, provided by SPOT Image Corp.)
FIGURE 7. Subscene of Landsat Thematic Mapper image showing a portion of the trend of shelf-edge ribbon reefs in the northern Great Barrier Reef, Australia (image 52026-234651 acquired 9/17/89).
FIGURE 8. Subscene of Landsat Thematic Mapper image showing the principal features of Hamelin Basin in Shark Bay, Western Australia (image 51424-015054 acquired 1/24/88).
Figure 9. Subscene of Landsat Thematic Mapper image showing the complex morphology where the offshore barrier and coastline merge in the eastern Abu Dhabi area (image 51314-06200 acquired 10/6/87).
the updip tidal flat and sabkha over lagoonal muds.

Figure 9 shows the complex morphology where an offshore barrier and the coastline have merged in the eastern Abu Dhabi area. Ooid and skeletal sand shoals are interspersed among islands and promontories and cut by tidal channels of varying sizes. Landward of the larger tidal channels (F14, for example), carbonate sands abut the shoreline. In more protected settings (as at K11 and O8), pellets and carbonate mud occur adjacent to the shoreline. The mainland shoreline, as well as the leeward portions of some of the islands, are lined by a continuous belt of intertidal flats. The flats appear dark on the image due to the covering of cyanobacterial mats. The sabkha is wide and well-developed, extending inland to Pleistocene quartzose dunes in the southeast corner of the image.

SUMMARY AND APPLICATION

The modern examples briefly described in the preceding sections illustrate the distribution of carbonate facies within an overall depositional setting and can play 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. Table 1 highlights the major depositional environments for each of the areas mentioned in the preceding sections and is meant to facilitate comparisons of the environments. These areas depict the geologic characteristics that can be expected in many ancient shallow-water settings including those of the Late Paleozoic shelves and platforms of the Permian Basin.
- 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
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- Mixed carbonate and siliciclastic deposition - South Florida, Belize, the Great Barrier Reef, Shark Bay and Abu Dhabi

The geologic framework as illustrated by these modern areas can be important in the development-scale analysis of Permian Basin reservoirs where: (a) the lateral variation of porosity and permeability, i.e. reservoir quality, is commonly tied to facies changes; (b) reservoir quality is controlled by aspects of diagenesis that are directly linked to facies variation; and (c) facies dimensions are required as input to reservoir models. The geologic framework as shown by the modern areas is also important at the exploration scale for reservoir facies prediction and stratigraphic play concepts which are related directly to depositional facies patterns. Although other areas should also be considered as analogs in selected cases, the areas discussed in this paper cover a wide range of depositional settings and show the many ways that the settings can be linked within a region. These examples should be examined further to provide ranges of facies dimensions and give indications of likely lateral facies relationships. Interested readers are urged to examine the following articles for more information on each of the areas.

Table 1.

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ANOTATED REFERENCE LIST

Overview of All Areas


South Florida


The Bahamas


Comprehensive overview of sand shoal facies, diagenesis, and geologic history - Harris, P. M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal: University of Miami Comparative Sedimentology Laboratory, Sedimenta 7, 163 p.


Geologic development of Pleistocene island - Garrett, P.


### Caicos, British West Indies


### Yucatan - Chinchorro Bank, Mexico


### Belize


**Great Barrier Reef, Australia**


**Shark Bay, Western Australia**


**Abu Dhabi Coastline**


