Modern Carbonate Sediment Facies Heterogeneity at the Development Scale - An Example from Joulters Cays, Bahamas*

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Abstract and Contents

Abstract

The ooid sand shoals of the Joulters Cays area of Great Bahama Bank were chosen for detailed sedimentologic study to investigate patterns of internal heterogeneity within a modern carbonate sand deposit and to develop criteria for predicting the lateral extent of porous and permeable carbonate sandstone facies in hydrocarbon reservoirs. Using aerial photographs, surface observations, and shallow coring, we documented three sedimentary facies in a 2.7-km^2 (1-m^2) study area dominated by mobile ooid sands. Cores were collected at the same spacing characteristic of wells in mature hydrocarbon reservoirs.

The shoal crest at the locality had aggrading and northward-prograding (parallel to depositional strike) washover bars composed of crossbedded, well sorted ooid sands. Burrowed, poorly sorted ooid sands were present seaward of the washover bars, and poorly sorted ooid sand and mud occupied a stabilized area bankward of the actively migrating shoal and in local areas between washover bars of the crest of the shoal. Intraclast-rich zones and mud layers were also present. The shoal was crosscut by tidal channels, and older washover bars were in the process of being dissected by tidal currents.

We anticipate that, upon burial and compaction, the poorly sorted ooid sand and mud facies will most likely retain negligible porosity and permeability, whereas both the well sorted ooid sand and poorly sorted ooid sand facies will maintain their high initial porosity and permeability. However, in many ancient subsurface reservoirs, rocks with depositional textures similar to the well sorted ooid sand facies have undergone considerable cementation and have low resultant porosity and permeability. Thus, in many settings, the poorly sorted ooid sand facies could retain the highest porosity and

permeability. Additional cementation of intraclast-rich zones will most likely result in thin, low-porosity barriers within a reservoir.

Hurricane Andrew, a category 4 hurricane with wind velocities of approximately 240 km/hr (150 mi/hr), passed over Joulters Cays in a westerly direction in August, 1992, subsequent to our coring program. The hurricane profoundly changed surface features in the study area by eroding washover bars on the crest of the shoal and transporting ooid sand seaward, leaving a nearly flat shoal crest overlain by a laterally continuous, decimeters-thick (foot-thick) lens of well sorted ooids that thins seaward and bankward. Post-hurricane tidal currents deposited a centimeters-thick (inches-thick) discontinuous layer of carbonate mud over this lens of well sorted ooids. This mud, although more likely to be preserved in tidal channels than on the shoal crest, has the potential to form low-permeability layers that will define reservoir compartment boundaries.

Modern sediment analog studies are an important addition to subsurface reservoir and outcrop analog characterization. Knowledge of the internal geometry of a sand shoal is critical for geologically targeted deployment of production technology and for predicting the efficiency of waterflood and enhanced oil recovery operations.

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ABSTRACT

The ooid sand shoals of the Joulters Cays area of Great Bahama Bank were chosen for detailed sedimentologic study to investigate patterns of internal heterogeneity within a modern carbonate sand deposit and to develop criteria for predicting the lateral extent of porous and permeable carbonate grainstone facies in hydrocarbon reservoirs. Using aerial photographs, surface observations, and shallow coring, we documented three sedimentary facies in a 2.7-km^2 (1-mi^2) study area dominated by mobile ooid sands. Cores were collected at the same spacing characteristic of wells in mature hydrocarbon reservoirs.

The shoal crest at this locality had aggrading and northward-prograding (parallel to depositional strike) washover bars composed of crossbedded well-sorted ooid sands. Burrowed, poorly sorted ooid sands were present seaward of the washover bars, and poorly sorted ooid sand and mud occupied a stabilized area bankward of the actively migrating shoal and in local areas between washover bars on the crest of the shoal. Intraclast-rich zones and mud layers were also present. The shoal was crosscut by tidal channels, and older washover bars were in the process of being dissected by tidal currents.

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INTRODUCTION

For many years regional depositional facies models have been used by exploration geologists to explore for new oil and gas productive fairways. Many of these regional- and subregional-scale models have been based on exploration-scale studies of modern depositional environments. In the case of carbonate depositional environments, exploration geologists have relied on modern facies studies in South Florida (Ginsburg, 1956; Enos and Perkins, 1977), the Bahamas (Purdy, 1963; Harris, 1979), and the Persian Gulf (Purser, 1973), among others.

In the past, many major hydrocarbon producing companies divided their staff between exploration and production departments. Once the exploration department had discovered an oil or gas reservoir, the development department was responsible for planning ways to efficiently recover the most resource. Infill well placement and completion intervals were chosen, in many cases, simply by correlating porous and permeable zones between wells. Geologically controlled lateral and vertical changes in porosity, permeability, and hydrocarbon saturation could be recognized from wellbore data, but they could not be reliably predicted between wells because production geologists lacked geologically realistic models at a between-well scale. Three legacies of this practice are (1) well locations in neat and orderly rows, without regard to the geometry of geologic features such as grainstone shoals and tidal channel deltas, (2) field recovery efficiencies that are generally in the range of 30 to 40 percent (Galloway et al., 1983), and (3) seemingly anomalous individual wells with either exceptionally low or exceptionally high producing rates within mature fields.

During the past 20 years, and especially during the past decade, geologists who formerly worked on regional, exploration-scale geologic interpretations have realized the tremendous need for smaller, development-scale geologic models to guide targeted infill drilling in mature hydrocarbon reservoirs. However, our understanding of modern carbonate sedimentary environments has generally not kept pace with this need for development-scale models.

We report here the results of a development-scale modern facies study of an ooid shoal on Joulters Cays, Bahamas. This study, based on analysis of shallow cores, surface sediment samples and observations, and aerial photographs, was designed to investigate depositional features at a scale that would be pertinent to predicting between-well heterogeneity in a maturely drilled hydrocarbon reservoir. Our choice of Joulters Cays provided an unanticipated additional opportunity when Hurricane Andrew passed over this area on August 23, 1992, providing us with an opportunity to contrast sedimentary features formed over the course of several decades with those formed during an infrequent (on a human time scale) high-energy depositional event.

EXPLORATION-SCALE DEPOSITIONAL PATTERNS

The Joulters Cays area, immediately north of Andros Island on Great Bahama Bank (Figure 1), 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 of ooid sands, 0.5 to 2 km (0.3 to 1.2 mi) wide across 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 (Figure 1). To the west (platformward), 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. The area of detailed study described herein is approximately 2.7 km^2 (1 mi^2) of mobile ooid sands (mobile bar) lying just north of the northernmost of the Joulters Cays (Figure 1).

The relief of the Joulters Cays shoal above the surrounding sea floor results primarily from ooid sands accumulating in the mobile bar and stabilized flat (Figure 1). The mobile bar is a narrow belt along the active ocean-facing shoal margin where ooid accumulation coincides with ooid formation. Ooid and muddy fine-grained peloid sands, the more widespread sediment types exposed on the stabilized flat, result from ooids mixing with other grain types and with carbonate mud. The ooids exceed 7 m (23 ft) in thickness in the area of the Joulters Cays islands.

The basic facies pattern as revealed by regional coring within the shoal (Harris, 1979, 1983) is a fringe of ooid sand bordering opposing wedges of muddy ooid sand underlain by muddy, fine-grained peloid sand. Ooid sand directly overlies Pleistocene limestone bedrock along the seaward margin of the shoal and interfingers with muddier sediments bankward. Throughout most of the sand flat, the vertical succession consists of lithoclast sand and/or pellet mud at the base, muddy, fine-grained peloid sand in the middle, and muddy ooid sand at the top. This succession shows distinct upward trends of increasing grain size, sorting, ooid content, stratification, and grain-supported fabric. Regionally, the succession thins to the south as the underlying Pleistocene bedrock surface rises.

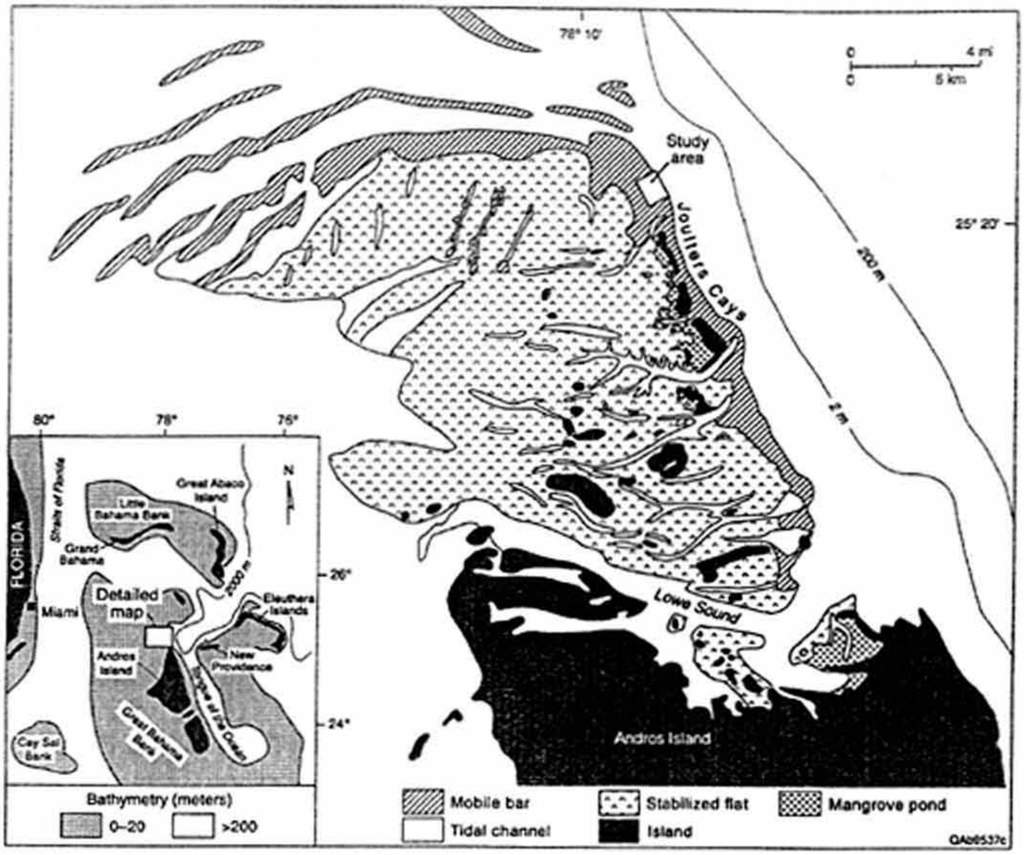

Figure 1. Location map (inset) for the Joulters Cays ooid shoal. The sedimentary facies map illustrates the regional interpretation of Harris (1979) and the area of the present reservoir-scale study.

Exploration-scale 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. High initial porosity was measured in similar clean sand by Halley and Harris (1979) and Enos and Sawatsky (1981), and it is confirmed here by thin-section estimation. 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 rocks having vastly different reservoir properties. An upper layer of muddy ooid sand thins bankward and overlies a more widespread lower layer of muddy, fine-grained peloid sand. 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 likely have better reservoir quality than the lower layer because of larger grain size and lower mud content.

DEVELOPMENT-SCALE DEPOSITIONAL FACIES PATTERNS

Three depositional subfacies predominate within the ooid-sand (mobile bar) facies of Harris (1979, 1983). Well-sorted ooid sand occurs on the active, high-energy shoal crest. The surface of the shoal crest is characterized by washover bars having curved axes convex in a bankward direction. The stoss sides of these bars slope seaward at 10 to 20 degrees; the lee sides slope platformward at approximately 20 to 30 degrees. These features are composed entirely of the well-sorted ooid sand facies. The geometry of washover bars and movement of ooids during the semidiurnal tidal cycle suggest that these features are largely built by incoming tides. Poorly sorted ooid sand is present on the seaward margin of the shoal and in the bankward, shallow subsurface part of the shoal. The poorly sorted ooid sand and mud facies accumulated in lower energy areas between washover bars on the crest of the shoal, where it is stabilized by filamentous algae, and in an area bankward of the active shoal, where it is stabilized by the sea grass *Thalassia*. The distribution of these facies within the detailed study area (Figure 2) is shown on cross sections in Figure 3. Differences in grain size, grain sorting, and sedimentary structures among these three facies will potentially lead to heterogeneity.

It should be emphasized that these sediments are unconsolidated. Were these sediments to be lithified, it is anticipated that well-sorted ooid sand and poorly sorted ooid sand would become grainstones and poorly sorted ooid sand and mud would become a packstone (terminology of Dun-

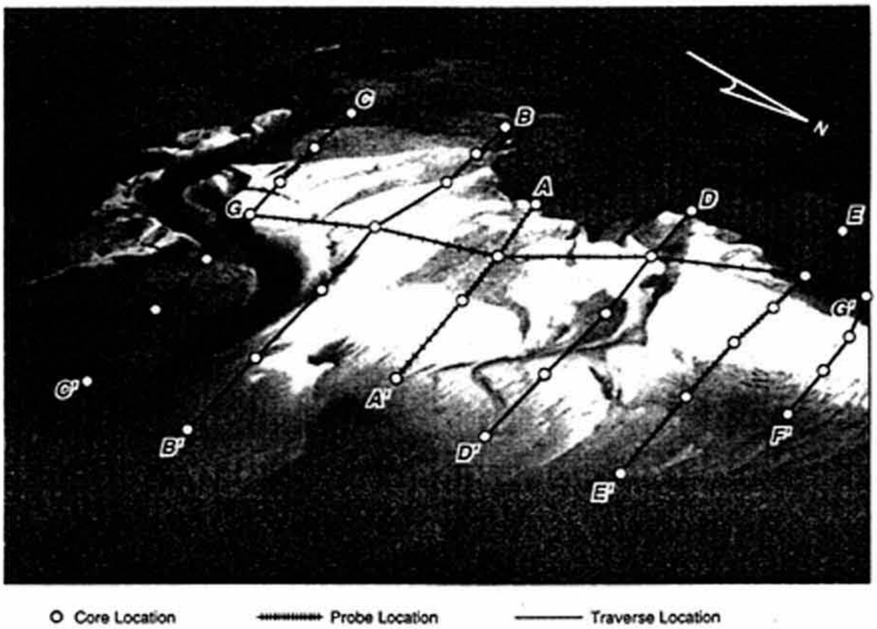

Figure 2. Low-altitude oblique aerial photograph of active part of shoal that is our detailed study area. Photograph was taken in 1989, before Hurricane Andrew. Light areas are large washover bars that extend 0.3 to 0.6 m (1 to 2 ft) above sea level at low tide and are flooded by several centimeters of water at high tide. The darker areas are muddier sediment stabilized by *Thalassia* and filamentous algae. Also shown are core locations (dots), probe locations (hachures), and lines of cross section. Cross sections A–A', D–D', and E–E' shown as Figure 3. There is no bar scale in this figure because this is an oblique photograph; compare cross section traces show here with Figure 3 for scale.

ham, 1962). As will be discussed in more detail in a following section, these subtle changes in depositional facies (as well as diagenetic overprint) would, upon burial, respond to compaction and cementation differently and probably result in significant permeability variability within a single grainstone depositional cycle or reservoir flow unit.

Well-Sorted Ooid Sand

The well-sorted ooid sand facies consists of 80 to 90 percent ooids (dominantly 0.4 to 0.5 mm in diameter), 5 to 20 percent coated pellets and unidentified grains (generally less than 0.2 mm in diameter), and 5 percent skeletal fragments. Scattered, poorly cemented intraclasts consist of broken burrow linings and hardground crusts. The sparse, somewhat rounded skeletal material includes fragments of pelecypods, gastropods, green alga *Halimeda,* peneroplid foraminifers, and red alga *Goniolithon*. Structures include crossbedding, horizontal burrows, tracks, and trails; vertically lined burrows; and horizontal and inclined laminations.

The well-sorted ooid sand facies coincides with the intertidal, most highly agitated central and seaward parts of the active shoal. This facies occurs at the surface in a broad band that is approximately 1.8 km (1 mi) wide in the south part of the study area and narrows to only 1 km (0.6 mi) toward the north. This facies, which is nearly 3 m (10 ft) thick in some locations, is most widespread in the lower, older part of the shoal, generally narrowing and shifting seaward stratigraphically upward. In washover bars (discussed below), however, this facies is consistently wider at the surface because these bars shift bankward over the less agitated surface environments (Figure 3).

Poorly Sorted Ooid Sand

The poorly sorted ooid sand facies contains 60 to 80 percent ooids (0.4 to 0.5 mm in diameter), 20 to 40 percent coated pellets and unidentified grains (0.1 to 0.2 mm in diameter), and 5 percent skeletal fragments. The skeletal fragments (primarily in the upper few centimeters) are from pelecypods, gastropods, *Halimeda,* peneroplid foraminifers, and *Goniolithon*. Burrows are common, and there are no laminations.

The poorly sorted ooid sand facies accumulated in a less agitated environment than the well-sorted ooid sand facies and occurs seaward of it at the surface and both seaward and bankward of it in the shallow subsurface (Figure 3). This facies is as much as 1.3 m (4 ft) thick and occurs in water depths of approximately 0.5 m (1.5 ft) at low tide; it is found in greater thicknesses where exposed at the surface on the seaward side of the shoal.

Poorly Sorted Ooid Sand and Mud

This facies contains a trace to 20 percent carbonate mud, 30 to 70 percent ooids, 20 to 40 percent coated pellets and unidentified grains, and 5 to 20 percent skeletal fragments. Burrows, the common structure in the cores, are expressed at the surface as mounds and depressions. Roots from the sea grass *Thalassia* are also common; living *Thalassia* and *Goniolithon* occur on the surface. Sparse, small bushes of *Halimeda* are present, particularly in the transition zone between this facies and the well-sorted ooid sand facies.

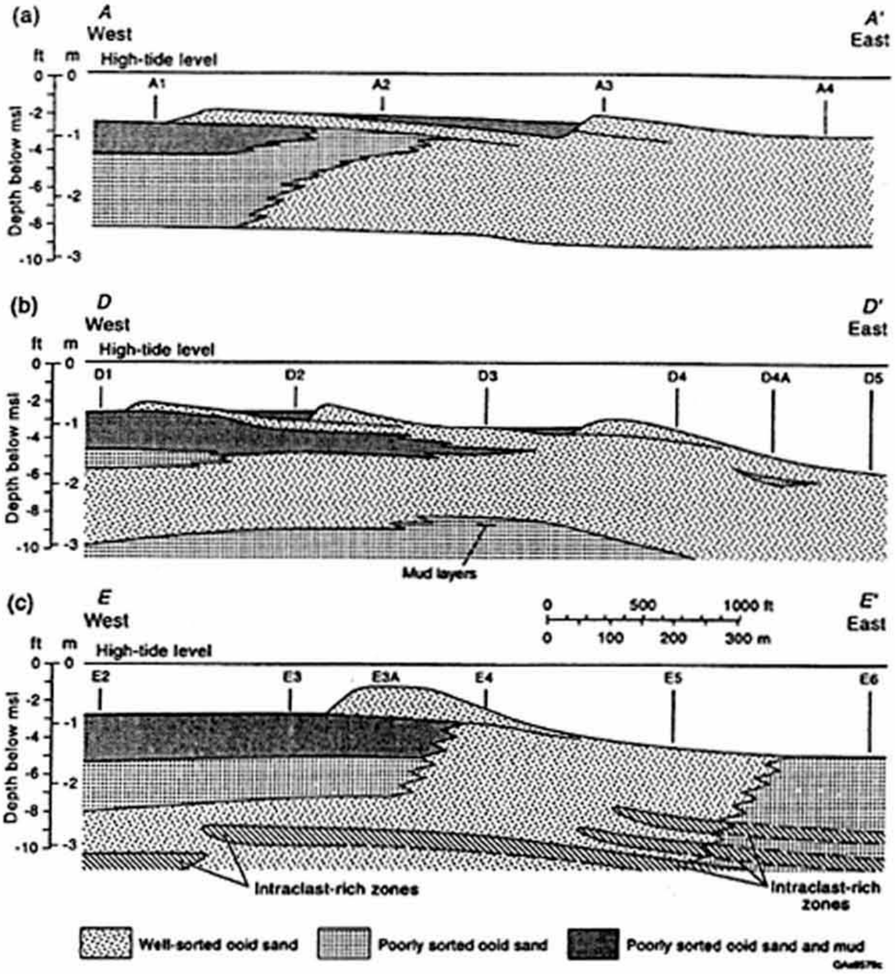

Figure 3. West-east (parallel to depositional dip) cross sections based on cores collected before passage of Hurricane Andrew. Core depths were calibrated to a sea-level datum. Location of sections shown in Figure 2. (a) Cross section A–A', which extends from the area dominated by poorly sorted ooid sand and mud—*Thalassia* to the shoal crest, but not as far seaward as the area dominated by poorly sorted ooid sand. (b) Cross section D–D', which crosses a similar set of facies to that in A–A', and includes buried mud layers interbedded with poorly sorted ooid sand in core D3. Because these mud layers were not encountered in adjacent cores, the lateral extent of these features is unknown. (c) Cross section E–E' reaches seaward to an area dominated by poorly sorted ooid sand. Interclast zones dipping seaward are encountered in cores of this cross section.

Peneroplid foraminifers and pelecypod fragments are prevalent.

The poorly sorted ooid sand and mud facies occurs within the upper 1 m (3 ft) of the stratigraphic section and is present at the surface on the very shallow water (several centimeters deep at low tide), bankward side of the shoal and in low areas between washover bars composed of well-sorted ooid sand. This facies grades downward and in some locations seaward into the poorly sorted ooid sand facies (Figure 3). It is stabilized by filamentous algae in low areas on the crest of the shoal and by *Thalassia* on the bankward side of the shoal. Coatings of algae and *Thalassia* give the surface a darker color on aerial photographs (Figure 2).

Sedimentary Features

Sparsely cemented intraclasts, including fragments of burrow linings and broken hardgrounds that have been cemented by various amounts of aragonite cement, are concentrated in thin zones less than 0.5 m (1.5 ft) thick in many of the cores. In these zones, as many as 30 percent of the sediment is intraclasts or large shell fragments, 40 to 80 percent are ooids, and as many as 70 percent are hardened pellets. Similar deposits are accumulating in troughs on the present-day surface.

These intraclast-rich zones are most common in the lower part of the well-sorted ooid sand facies in the north part of the study area. In cores, these zones are best represented on the seaward side of the cross section in Figure 3c, where they occur in an offlapping pattern that reflects the progradation of the shoal complex. These zones were correlated laterally as far as 600 m (1,970 ft) during sediment probing and were traced even farther by Harris (1979) in that regional study. Although the zones are partly lithified, porosity and permeability have not been greatly reduced in the intraclasts, as estimated by thin-section observations, but these zones could potentially form barriers to fluid flow should they subsequently serve as preferential nucleation sites for additional cementation.

Two discrete mud layers, the upper layer 2 cm (0.8 in) thick and the lower layer 4 cm (1.6 in) thick, separated by 4 cm of poorly sorted ooid sand occur at the top of the burrowed, poorly sorted ooid sand facies in core D3 (Figure 3b). Because these mud layers were not recovered in any other core, the

(a)
(b)
(c)

Figure 4. Vertical aerial photographs of the Joulters Cays ooid shoal taken in (a) 1947 and (b) 1967. (c) Oblique aerial photograph taken in 1989.

layers are presumably local in distribution (which is corroborated by posthurricane field observations of discontinuous mud layers on the surface of the shoal, reported below) and of only minor importance from a reservoir heterogeneity perspective. Other occurrences of mud layers associated with ooid sands in the Bahamas were reported in tidal channels by Boardman and Carney (1991) and Shinn et al. (1993). Because of some variability in the localized settings where mud can be deposited and preserved in direct association with ooid sands, some mud layers probably will have greater lateral extent and greater importance as potential low-permeability layers and fluid-flow barriers.

IMPLICATIONS FOR RESERVOIR CHARACTERIZATION

Development-scale patterns of heterogeneity within the active part of the Joulters Cays shoal are inferred from the facies distribution (Figures 2 and 3). The well-sorted ooid-sand facies occurs

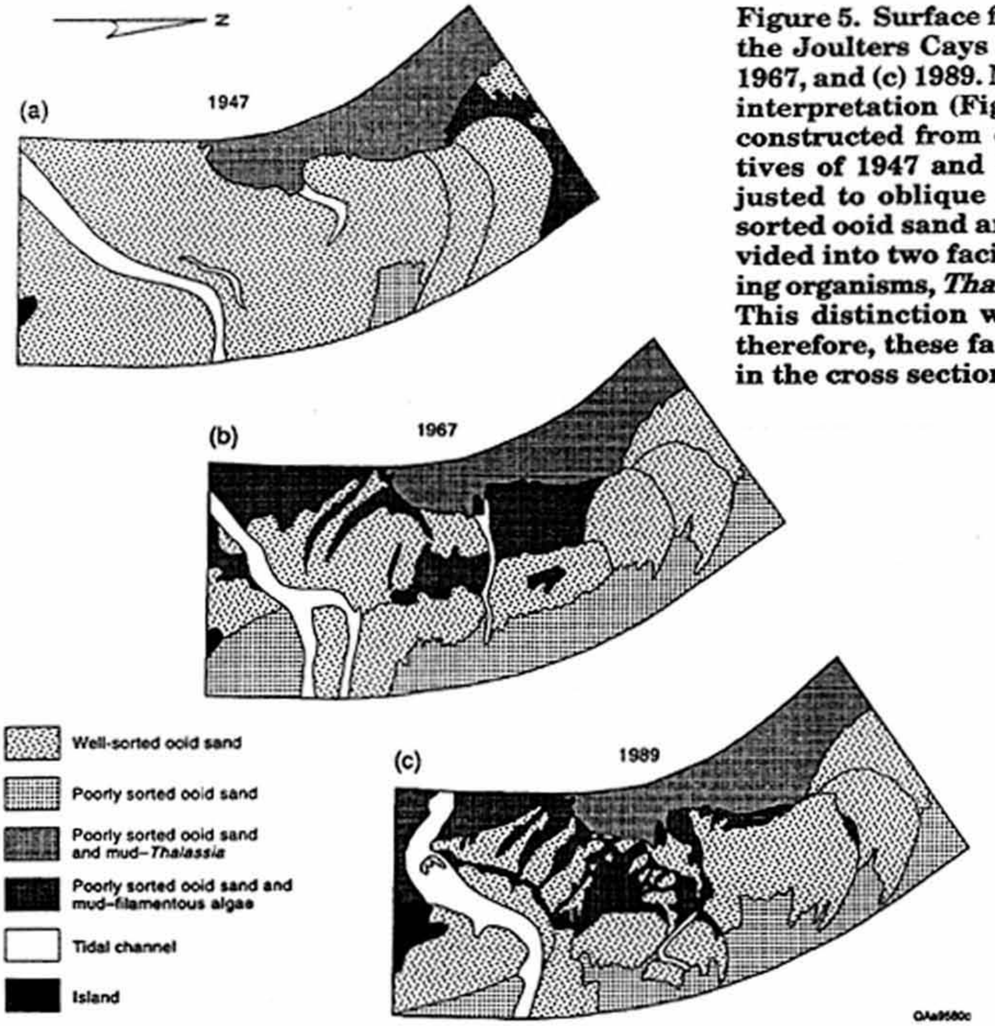

Figure 5. Surface facies-distribution maps of the Joulters Cays ooid shoal in (a) 1947, (b) 1967, and (c) 1989. Maps based on photograph interpretation (Figure 4) and cross sections constructed from cores (Figure 3). Perspectives of 1947 and 1967 maps have been adjusted to oblique view of 1989. The poorly sorted ooid sand and mud facies has been divided into two facies on the basis of stabilizing organisms, *Thalassia* or filamentous algae. This distinction was not possible in cores; therefore, these facies are not distinguished in the cross sections in Figure 3.

in the center of the shoal complex where the entire area (305 to 607 m [1,000 to 2,000 ft] wide and 1.8 to 2.4 m [6 to 8 ft] thick) 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 platformward 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 platformward.

Heterogeneity is inferred because of mud content, burrowing, and grain type variations. These subtle variations occur on a scale of a few hundreds of meters (approximately 1,000 ft), which is consistent with well spacing in mature hydrocarbon reservoirs like those of the Permian Basin. The scale of variation illustrated here should thus be considered when correlating at the common development interwell scale. In addition, the heterogeneity portrayed here occurs within a single facies (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 DEPOSITIONAL HISTORY

To better understand and calibrate the stratigraphy and facies patterns observed in cores (Figure 3), we analyzed the recent (approximately 40 yr) geological development of the study area with the aid of sequential aerial photographs. Using surface observations and the 1989 aerial photograph taken at the time of our first field excursion, we divided the poorly sorted ooid sand and mud facies into two facies on the basis of whether they are stabilized by *Thalassia* or filamentous algae. Thus, the low-energy, bankward part of the shoal, which remained remarkably unchanged from 1947 until 1989, is occupied by the poorly sorted ooid sand and mud–*Thalassia* facies, and the low-energy areas on the crest of the shoal are occupied by the poorly sorted ooid sand and mud–filamentous algae facies. Although some *Thalassia* was observed in cores, the filamentous algae were not recognized in cores; therefore, our cross sections do not distinguish these two facies.

In 1947 (Figures 4a and 5a), the well-sorted ooid sand facies was spread across nearly the entire north Joulters Cays study area. The poorly sorted ooid sand and mud–*Thalassia* facies on the bankward (west) side of the bar virtually matches the present-day position of this facies. The poorly sorted ooid sand and mud–filamentous algae facies occurred on the north end of the bar, where northward-prograding washover bars of well-sorted ooid sand had not yet migrated. A relatively small area of poorly sorted ooid sand occurred on the seaward margin in approximately the center of the study area. Note that the major washover bars in the south part of the study area were not dissected by tidal channels, presumably because the bars had sufficiently low topography that receding tides were able to drain uniformly across the bars without causing significant erosion.

By 1967 (Figures 4b and 5b), the washover bars of well-sorted ooid sand had migrated to the north end of the study area. In the south part of the study area, washover bars had aggraded to a sufficient height that receding tidal currents were beginning to erode bar crests. The areas between washover bar highs contained poorly sorted ooid sand and mud–filamentous algae. Note that the washover bar in approximately the middle of the study area was partly dissected and that the crest of the bar was then approximately midway between the seaward and bankward margins of the study area.

In 1989 (Figures 4c and 5c), when cores used to construct the cross sections in Figure 3 were collected, the washover bars in the south part of the study area were severely dissected by tidal currents, and large areas contained poorly sorted ooid sand and mud–filamentous algae. The washover bar in approximately the center of the study area had migrated bankward and nearly reached the margin of the poorly sorted ooid sand and mud–*Thalassia* facies, which has remained remarkably stable for at least 40 yr.

The pattern illustrated by these changes that were recorded by aerial photographs suggests aggradation of washover bars and progradation northward by longshore drift. As the washover bars both aggrade and prograde, they form a barrier to seaward drainage of tide waters. In the south part of the study area, washover bars have thus been dissected by tidal currents. We anticipate that if this pattern continues without interruption, with further progradation northward and aggradation in the center of the study area, the central tidal channel will deepen and widen and the central washover bars will be dissected.

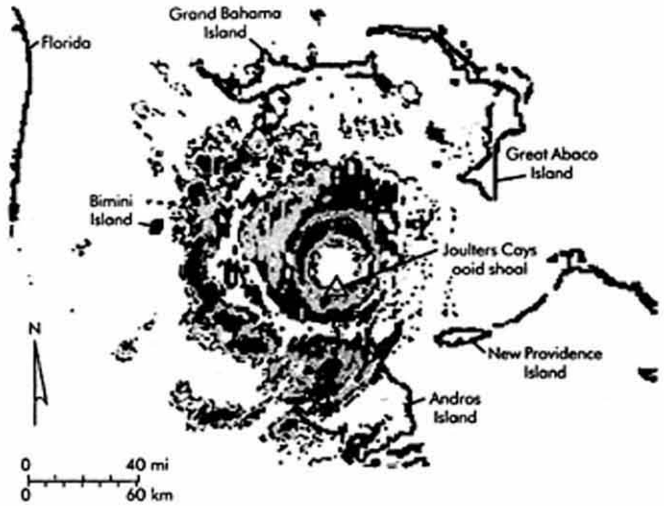

Figure 6. Radar image of track of Hurricane Andrew recorded by the National Weather Service.

EFFECTS OF HURRICANE ANDREW

Hurricane Andrew, a category 4 hurricane with wind velocities of approximately 240 km/h (150 mi/h), passed over Joulters Cays in a westerly direction on August 23, 1992. Before the passing of Hurricane Andrew, the study area (Figures 4c and 5c) displayed distinctive surface features dominated by tidal current washover bars (light areas) that extended 30 to 60 cm (1 to 2 ft) above sea level at low tide and were flooded by only a few centimeters (1 to 3 in) of water at high tide. The bar crests typically were embellished by variously oriented symmetrical ripples. These topographically high features provided nominal protection for sparsely grass-stabilized areas (dark areas on the bankward side of the shoal), in which grains were less well sorted and some carbonate mud accumulated, and also provided some protection for filamentous-algae-stabilized areas between washover bars on the crest of the shoal, where slightly muddy sediment also accumulated.

Hurricane Andrew passed from east to west over the study area, and the center of the storm was just north of the Joulters Cays ooid shoal (Figure 6). Winds blew over the shoal generally from west to east because of the counterclockwise rotation of the storm cell. Consequently, sediment was transported seaward off the shoal. The boundary between the active, high-energy part of the shoal and the grass-stabilized area to the west remained relatively unchanged after the passing of the storm (Figure 7). In contrast, the surface of the active part of the shoal changed considerably. Low areas, which were previously the sites of deposition of poorly sorted ooid sand and mud–filamentous algae (Figure 5c), are now covered by a decimeters-

(a)

(b)

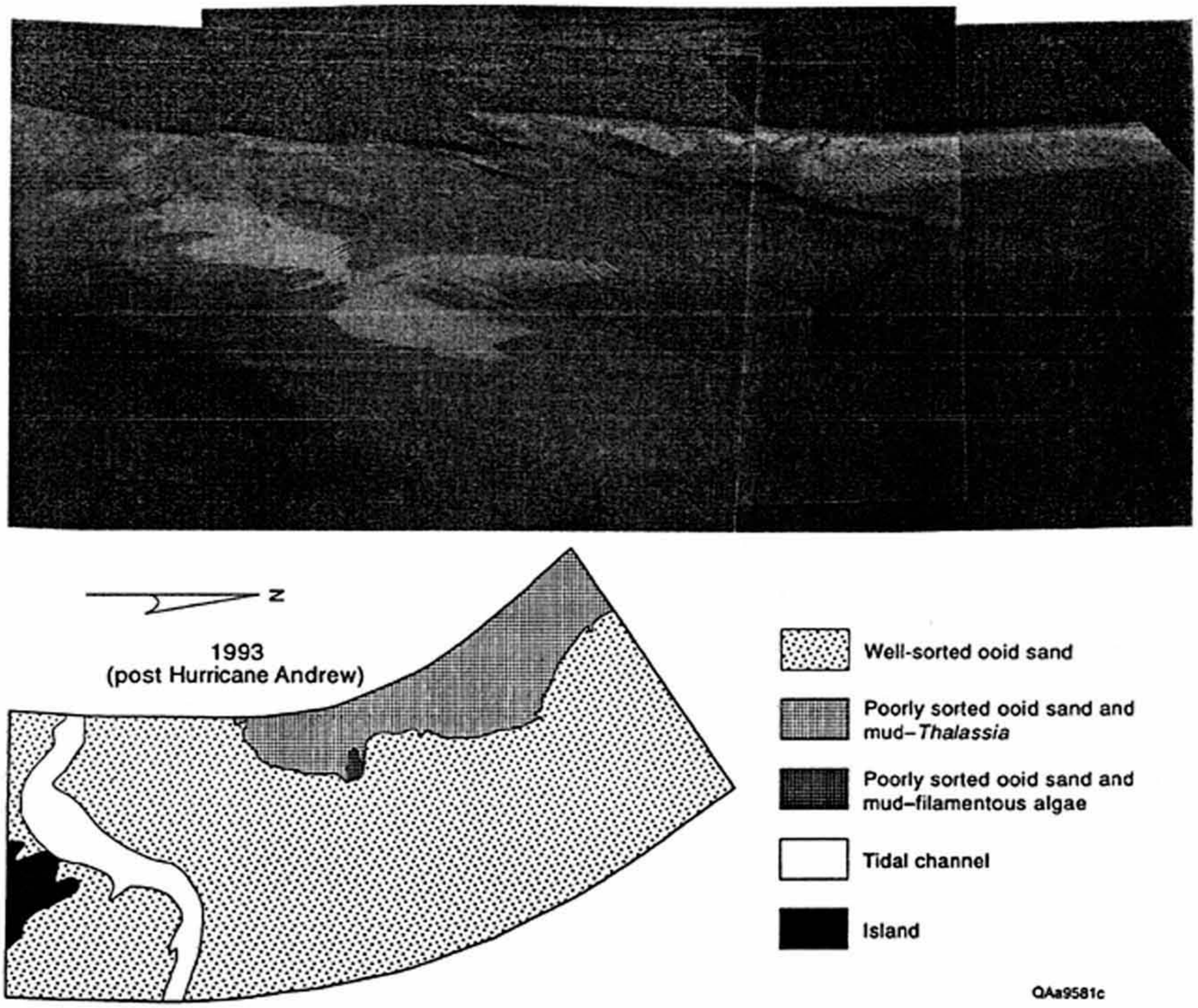

Figure 7. (a) Low-altitude oblique aerial photograph taken in 1993 of active part of ooid shoal at north end of Joulters Cays area. (b) Surface-sediment distribution map of same area seven months after passing of Hurricane Andrew. The perspective of map has been adjusted to the same oblique view used in Figure 5.

thick (foot-thick) layer of well-sorted ooids. The posthurricane relief across the active part of the shoal is reduced, and the surface is now relatively featureless. Ooids not trapped in low areas on the shoal were transported seaward.

Very thin (a few millimeters to 1 cm thick), laterally discontinuous layers of carbonate mud, generally no more than a few square meters in area, were observed on the surface of the shoal crest at low tide. Tide floodwaters observed a few weeks after Hurricane Andrew contained large amounts of suspended carbonate mud, suggesting that mud on the shoal crest was delivered to this depositional site by tide waters.

The changes in surface features of the Joulters Cays ooid shoals caused by Hurricane Andrew were profound, but they will probably be only partly preserved. Prevailing winds and currents that caused formation of the aggrading and northward-prograding washover bars illustrated in Figures 4 and 5 will, in all likelihood, reestablish the pattern of well-sorted ooid sand washover bars flanked seaward by poorly sorted ooid sand and flanked bankward and in low areas on the crest by poorly sorted ooid sand and mud. Although the storm layer of well-sorted ooid sand may be preserved in some low areas on the crest of the shoal, we have not found recognizable ooid storm beds from previous storms in the prehurricane cores we collected on the shoal crest.

Those ooids swept seaward by easterly (counterclockwise) storm currents will most likely be preserved in areas normally having less agitated conditions, where fine-grained sediments are normally deposited. Indeed, Harris (1979) reported ooid grains, many of them micritized, in cores collected a few kilometers seaward of our study area. Because prevailing tidal currents transport ooids bankward rather than seaward, those ooids in seaward locations may be the result of earlier storms. The thin, discontinuous mud layers deposited on the crest of the shoal probably have relatively low preservation potential. Several months after Hurricane Andrew passed over the study area, we observed diurnal tides resuspending these muds. (Shinn et al. [1993] reported a similar observation on ooid shoals at Cat Cay, Bahamas.) Moreover, the very discontinuous nature of these deposits suggests that they had at one time been much larger. However, if prevailing tidal currents reestablish washover bars before the mud deposits are completely removed, some of the deposits may be preserved beneath washover bars. There they will provide local permeability barriers when these sediments are buried and lithified. Indeed, shallow subsurface mud layers on the shoal crest, such as the pre-Andrew layer observed in core D3 (Figure 3b), probably formed by this process during an earlier storm.

Although the preservation potential of this mud layer is low on the shoal crest, preservation in adjacent tidal channels is almost a certainty. After Hurricane Andrew passed over Joulters Cays, Shinn et al. (1993) reported thin beds (as much as 5 cm [2 in] thick) of laminated carbonate mud in troughs of ooid dunes and ripples in high-energy subtidal channels of Joulters Cays. They proposed that a slurrylike mixture of carbonate mud, which resulted from the passing of Hurricane Andrew, moved through the channels. As the storm winds and currents waned, mud settled to the channel floor and was preserved in ripple troughs. Shinn et al. (1993) proposed that an older, more compacted mud layer stratigraphically below the Hurricane Andrew mud layer is also a storm deposit. Boardman and Carney (1991), whose investigation predated Hurricane Andrew, attributed the older mud layer in these tidal channels to direct precipitation from seawater at a time when the tidal channel was separated from the open sea by migrating ooid sand bars. The mud layers deposited in tidal channels will be important, albeit local, permeability barriers when these sands have been buried and lithified. Note in Figure 1 that although the tidal channels are local phenomena, their linear extent is as much as three-quarters of the width of the shoal.

ANCIENT ANALOGS

Carbonate grainstones analogous to the sediments investigated at Joulters Cays are hydrocarbon reservoirs of various geologic ages (Peryt, 1983; Harris, 1984; Roehl and Choquette, 1985; Keith and Zuppann, 1993). Hydrocarbons are produced from Mississippian ooid grainstone reservoirs in the Illinois, Anadarko, Appalachian, and Williston Basins and the Hugoton Embayment (Keith and Zuppann, 1993). The most prolific area of production from Mississippian ooid grainstones is the Illinois Basin, where the Ste. Genevieve Limestone accounts for 743 million barrels (MMbbl) of oil, or 18 percent of the cumulative production from the basin (Keith and Zuppann, 1993). In the Hugoton Embayment of southwestern Kansas, Damme field has produced 13 MMbbl of oil from Mississippian ooid grainstone shoal facies (Handford, 1988; Parham and Sutterlin, 1993). Grainstones, although not exclusively ooid grainstones, are a principal reservoir facies in the San Andres and Grayburg Formations of the Permian Basin in West Texas and New Mexico, which have a combined cumulative production of 7.7 billion barrels, or 46 percent of the oil produced from the entire basin (Bebout and Harris, 1990). Grainstones of Jurassic Arab-C and Arab-D reservoirs of the Middle East, many of which are ooid grainstones, are prolific reservoirs; indeed, the giant Qatif field of Saudi Arabia alone has an estimated ultimate recovery of 9 MMbbl of oil (Halbouty et al., 1970; Wilson, 1985). Jurassic ooid grainstone reservoirs also occur in northern Louisiana and eastern Texas (Ventress et al., 1984) and the Paris Basin, France (Cussey and Friedman, 1977; Purser, 1978). Cretaceous ooid grainstones are oil and gas reservoirs in the Gulf Coast of Texas (Bebout and Loucks, 1977; Fitchen et al., 1997), and in the Middle East (Longacre and Ginger, 1988).

Depositional facies variability and early diagenetic alteration both contribute to reservoir-scale heterogeneities in the carbonate sand deposits of Joulters Cays area and potentially in ancient analogs. For example, interwell-scale heterogeneities in hydrocarbon reservoirs of the San Andres and Grayburg Formations of the Permian Basin have been documented on a scale of hundreds of meters or less (Bebout et al., 1987; Ruppel and Cander, 1988; Bebout and Harris, 1990; Harris and Walker, 1990a,b; Longacre, 1990; Major et al., 1990). The details of this level of variability have been shown in outcrop analogs for these same reservoirs in the Guadalupe Mountains (Kerans and Nance, 1991; Grant et al., 1994; Harris et al., 1994; Barnaby and Ward, 1995; Kerans and Fitchen, 1995; Kerans et al., 1995).

Thin-section examination demonstrates that both the well-sorted ooid sand facies and poorly sorted ooid sand facies of the Joulters Cays area were mud free and had high initial porosity at the time of deposition (Halley and Harris, 1979). In some ancient subsurface settings, however, similar well-sorted ooid grainstones are cemented by calcite or anhydrite cement and have low resultant porosity (Bebout et al., 1987; Harris and Walker, 1990a,b; Longacre, 1990). In these ancient settings, the more poorly sorted ooid or peloid grainstones and packstones commonly retain primary porosity and thus become the better reservoir facies.

At Joulters Cays, the poorly sorted ooid sand facies occurs on the seaward and landward sides of the well-sorted ooid sand facies and also underlies the poorly sorted ooid sand and mud facies. If the early-cemented intraclasts that we encountered as layers in the Joulters Cays shoal were to act as nucleating sites of later cements, layers of tightly cemented ooids could form impermeable barriers as much as 0.6 m (2 ft) thick within the otherwise permeable facies, causing a reservoir to become vertically partitioned.

CONCLUSIONS

Core samples of modern carbonate sediments collected from Joulters Cays at a spacing comparable to well spacing in a mature Permian Basin oil field indicate the three-dimensional complexity of an upward-coarsening and upward-shallowing stratigraphic section. This modern example illustrates the difficulties in interpreting and correlating grainstone zones in subsurface studies of platform carbonate reservoirs. Formation of this sand body, local shoal stabilization and reworking by burrowing, and generation of hardground layers all result in features that are significant at a development scale. Additionally, facies patterns produced by migrating sand bars within the active parts of the shoal are impacted by short-term storm events.

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