Lessons from a modern carbonate sandbody – A personal experience of comparative sedimentology

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Abstract

The notion that examination of modern environments can help one better decipher ancient deposits does not seem so unusual, but this view was incrementally developed through decades of studies that have shown just that. Presented here is a brief example of comparative sedimentology with emphasis placed on the lessons learned from the study of a modern ooid sandbody that heightens one’s ability to describe and interpret analogous subsurface settings. Core transects and surface sediment mapping in the Joulters sandbody of Great Bahama Bank illustrate the three-dimensional characteristics of an upward coarsening and shallowing cycle and highlight the internal complexity of a sandbody through time and space. This modern example graphically highlights difficulties in interpretation and correlation of grainstone cycles in analogous subsurface platform carbonate reservoirs.

KEYWORDS

depositional cycle, Great Bahama Bank, heterogeneity, ooid, stratigraphy

1 | INTRODUCTION

My involvement with carbonate sands (grainstones), from graduate research of a modern ooid sand system in the late 1970s through industry studies of potential exploration targets and producing reservoirs over 35 years, reinforced that there is a strong case for examining modern depositional systems with a comparative sedimentology outcome in mind. This personal case for comparative sedimentology is outlined here with the lessons learned from the study of a modern ooid sandbody applied to unravelling ancient grainstone counterparts.

The Bahamas are a Mecca for modern ooid sands, like those that repeatedly occur in the geological record and commonly serve as reservoirs for hydrocarbons. Forty-five percent of the platform-top of Great Bahama Bank (GBB) can be classified as grainstone (Harris, Purkis, Ellis, Swart, & Reijmer, 2015), which includes ‘high-energy’ grainstones characterized by the development of sandbar complexes wherein variably thick, cross-bedded ooid sands are found and accommodation space is locally filled (Figure 1). A comparison of the sites of high-energy grainstones (oolid sandbodies) located on the depositional facies map (Figure 1a) with corresponding locations on the water depth variation map (Figure 1b) clearly shows that sediment thickening has occurred in these sites of prolific ooid production and accumulation. The early understanding of the development of Bahamian ooid accumulations during the Holocene rise of sea-level came from areas that are characterized by bars and channels (Ball, 1967; Halley, Harris, & Hine, 1983). But not all ooid sands, modern and ancient, are preserved as bars and channels, suggesting that additional examples needed to be documented to be more useful from an analog perspective.

2 | THE MODERN EXAMPLE (JOULTERS OOID SHOAL)

The ooid sands lying immediately to the north of Andros Island on GBB, the Joulters ooid shoal of Harris (1977,
1979), are immediately obvious from aerial photographs or satellite imagery (Figure 2a). Filled nearly to sea-level over a large extent, the ooid sands restrict water exchange between the seaward and bankward sides of the shoal and aerially limit ooid production (Figure 2b). Readers are encouraged to examine Harris (1977, 1979) for more background on the Joulters area including details of the coring and sample examination methods and broader discussions of surface sediment distribution, surficial depositional environments, subsurface facies from coring, spatial distribution of facies, a geological model for shoal development, and marine and meteoric cementation. The extensive coring effort focused in the Joulters area resulted in 60 cores taken at an average spacing of 1.5 km. The salient points from these studies of this key area are summarized directly below.

2.1 | Environments and surface sediments

The Joulters sandbody is a 400 km² sand flat partially penetrated by tidal channels and fringed on the windward eastern and northern borders by mobile sands (Figure 2b). The active border of ooid sands covers 0.5–2 km in a dip direction, and extends approximately 25 km parallel to the shelf break and 5 km bankward of it. Holocene islands are aligned along the active eastern fringe and scattered throughout the sand flat. The variation in environments is produced by a decrease in grain agitation from the ocean-facing margin towards the shoal interior, reflecting in large part the inability of tide- and wind-driven currents to vigorously move platformward through the entirety of the sandbody. Superimposed on this broad pattern are local variations in environment related to tidal channels, islands, sand bars and grass-covered bottoms. Surface sediments of the shoal and surrounding area reflect these environments. Shoal sediments are primarily non-skeletal sands (ooids, peloids, skeletal grains and aggregate [grapestone] grains) and variable sedimentary structures (bioturbation, burrowing and local laminations).

2.2 | Facies anatomy and growth

Surficial environments and sediments guided the recognition of facies from cores taken throughout the Joulters sandbody and surrounding area. Sediment and rock coring documented six facies: skeletal sands (= grainstone), ooid sands (= grainstone), ooid muddy sands (= packstone), fine-peloid muddy sands (= packstone), pellet mud (= wackestone) and extremely localized lithoclast sand (= packstone) (Figure 3). In cross section, there are two basic parts to the sandbody: (a) a windward ooid grainstone...
fringe, up to 7 m thick where the Joulter Cays islands are present; and (b) a more widespread succession, 3–5 m in thickness, of pellet wackestone and/or lithoclast packstone at the base, fine-peloid packstone in the middle and ooid packstone at the top. This ‘cycle’ shows an upward increase in grain size, percentage of ooids and grain-supported fabric. The trend in the sandbody and its relief over the surrounding sea floor are the result of accumulation of ooid sands in one facies or another. The basic theme of facies geometry is therefore a fringe of ooid grainstone bordering a much wider sandbody comprised of two opposing sediment wedges: an upper bankward-thinning wedge of ooid packstone overlying a seaward-thinning wedge of fine-peloid packstone. The lower wedge is the thickest part of a sheet, approximately 2 m in thickness, and extending much further to the west into the platform interior.

The topography of the underlying Pleistocene limestone influenced sandbody development by initially localizing ooid formation and structuring bankward transportation, but sediments created a syndepositional topography that had a greater influence on ultimate sandbody growth. The growth history of the Joulters sandbody can be viewed in stages related to the interplay between rising sea-level, sedimentation rates, evolving depositional environments, and therefore filling of accommodation space over this portion of GBB. The relative timing developed for the stages is based on radiocarbon dating from cores (Harris, 1977, 1979), which facilitated a comparison to published curves showing Holocene sea-level rise (Fairbanks, 1989; Scholl, Craighead, & Stuiver, 1969). The first stage of bank flooding (Figure 4a) initiated deposition in the platform interior when this portion of the platform was first flooded by rising sea-level at approximately −5 m sea-level and 5 kyr before present. A shoal formation stage (Figure 4b) follows as sea-level rises to approximately −3 m over the next 2 kyr and ooid formation and accumulation were initiated. This represents a critical time as sufficient water depth covers most of the platform allowing cross-bank tidal flow and providing conditions conducive to localized ooid formation and also water quality leading to more widespread biological production of carbonate sands and muds. The timing portrayed on Figure 4a,b spanning initial flooding of the platform and initiation of substantial carbonate production and accumulation represents the lag time of Enos (1991) and lag depth as discussed by Harris, Kerans, and Bebout (1993) and Eberli (2013).

The stage of shoal development (Figure 4c) occurred between −3 and −1 m sea-level, and 3 to 1 kyr before present, during a phase of increased sea bottom agitation produced by a combination of topography building and the rising sea-level to result in development and expansion of a marine sand belt, sensu Ball (1967). This stage established the size and physiography of the shoal, changing platform sediments over a large area from muddy, fine-peloid packstones to ooid grainstones. The vast sand flat then formed in the last thousand years by reworking of mobile sands due to burrowing to produce an ooid packstone equivalent (Figure 4d). The stabilized sand flat environment developed as accommodation was broadly filled, tidal channels were progressively restricted resulting in less impactful tidal flow through the breadth of the sandbody, and high-energy conditions were increasingly limited to the seaward side of the shoal. Islands also formed relatively in the last few thousand years as indicated by radiocarbon dating of surface and core samples (Halley & Harris, 1979; Harris, 1977, 1979). The resulting facies patterns of the Joulters sandbody are products of changes in the depositional system (deposition altered locally by diagenesis, minus reworking and erosion, equals net accumulation) during the last 5,000 years.

2.3 | Diagenesis

Cementation by both marine and fresh waters is localized within the modern Joulters sandbody. Marine cementation
occurs on stable sea bottoms, where intraclasts and crusts, cemented both with acicular aragonite and micrite, punctuate the facies forming the relief of the shoal. The crusts can commonly be traced across facies boundaries and have been traced in the shallow subsurface by sediment probing for 100s of metres (Harris, 1979; Major, Bebout, & Harris, 1996). Sands exposed to freshwater in the youngest Holocene islands (Figure 5), which although they are a kilometre or less in size and only a few metres thick, do develop thin lenses of fresh water and are rapidly cemented by low-magnesium calcite. On south Joulter Cay, ooid sands in the vadose and upper phreatic zones are cemented, whereas sands in the lower phreatic zone are poorly cemented to uncemented (Halley & Harris, 1979). Vadose cements, a patchily distributed spar most common in grain-contact positions, change in a 1 m interval across the water table to upper phreatic cements, a uniform rim of rhombohedrons surrounding each grain. The source of cement calcium carbonate is small-scale dissolution of ooids occurring within nuclei, within lamellae and commonly in a micron-thick layer around the grains (Halley & Harris, 1979).

3 | APPLICATION TO THE ANCIENT

An interest in modern analogs for carbonate sand reservoirs, like the Joulters ooid shoal, is warranted based on the substantial number of carbonate reservoirs that produce from grainstones and packstones, such as those described by Wilson (1975), Peryt (1983), Harris (1984), Roehl and Choquette (1985), Keith and Zuppann (1993) and Harris and Weber (2006). The guiding premise is that modern analogs can have an important function as conceptual depositional environment (equivalent to facies) models providing an enhanced understanding of outcrop and reservoir
stratigraphy and facies analysis. The reservoir aspect includes improved characterization of reservoirs, better addressing interwell heterogeneities and providing quantitative facies attribute information for input in building reservoir models, for example, size, shape, complexity and distribution.

The development of the Joulters sandbody provides one possible scenario for the evolution of the bar and channel physiography seen elsewhere in Bahama sand shoal complexes (Ball, 1967; Halley et al., 1983; Harris, Purkis, & Ellis, 2011; Rankey & Reeder, 2011). The shoal-generating physiography has been erased as bar and channel topography was extinguished and filled in to form the vast sand flat, and ooid sands were mixed with other sediments by burrowing. The resulting accumulation—a narrow belt of ooid grainstone bordering a significantly wider belt of ooid packstone that becomes increasingly muddy with depth—is one that is observed in the geological record. Facies variability documented for the Joulters sandbody has served as a direct analog for guiding interpretations of outcrops and numerous subsurface examples where grainstones transition...
to packstones in a platformward direction (Bebout & Schatzinger, 1978; Harris et al., 1993; Major et al., 1996; Ottmann, Keyes, & Zeigler, 1973; Purkis & Harris, 2017; Smosna, 1984; Smosna & Koehler, 1993).

Studies of modern ooid shoals like the Joulters example have revealed facies attributes and relationships that from personal experience add value when studying ancient subsurface examples, that is, comparative sedimentology. Some examples of the types of insight that come from this comparison between the modern and subsurface are discussed below.

3.1 | Facies calibration

An obvious value from coring of modern environments, which was a major emphasis in the Joulters studies, is additional calibration of depositional textures and sedimentary structures with surficial depositional environments. This comparison provides facies recognition criteria that are essential when analysing subsurface counterparts. Figures 6 and 7 summarize some of the criteria (depositional texture, grain types, sorting, sedimentary structures) recognized in cores and thin sections from the active sand bar (ooid grainstone) and stabilized sand flat (ooid packstone), respectively. The Joulters sandbody graphically shows that ooid sands may accumulate in varied environments that are quite different and perhaps remote from their point of origin. The interpretation of environment in ancient examples thus should not be made on grain type alone, but must rely also on the sedimentary structures, depositional textures and vertical successions. The facies recognized during coring at Joulters form a complicated pattern when viewed in three dimensions (Figure 3), due in part to topographic irregularities and localized depocenters, but largely to the change in depositional patterns through time. These points centering on the notion that depositional cycles vary laterally in thickness and composition are of paramount importance in identifying and correlating depositional cycles (parasequences or high-frequency sequences) during outcrop and subsurface studies.

3.2 | Facies geometry

A metre-thick veneer of Holocene sediments covers GBB in a complex fashion as shown by the facies maps of Purdy (1963a, 1963b), Traverse and Ginsburg (1966), Enos (1974), Reijmer et al. (2009), Kaczmarek, Hicks, Fullmer, Steffen, and Bachtel (2010), Harris et al. (2015) and Purkis and Harris (2016). These sediments of sand shoal, reef, tidal flat and platform interior origin generally do not form widespread sheets of equal thickness but occur in localized depocenters or buildups of varying size, shape and orientation (Purkis & Harris, 2016). The occurrence and geometry of facies patterns is due in large part to controls on deposition imparted by the pre-existing topography, as well as the hydrographic setting and initiation of varied sediment production and accumulation. It is not difficult to imagine the complexity that is probably to develop as subsequent sediments are deposited around local topographic irregularities, for example, the profound influence of islands on surrounding sediment thickness and composition as documented by Purkis and Harris (2016).

The Joulters sandbody is one such prominent sediment thick that thins regionally to the south towards Andros Island over a shallowing Pleistocene rock surface (Figure 3). Coring has shown that in a few metres thick interval of sediment representing a relatively brief period of time of accumulation, a complex succession of sediments can form largely as a result of localized topography, changes in relative sea-level, and varying rates of sediment production and accumulation. The Joulters succession (cycle) covers an area exceeding 25 km in a strike direction and 20 km in a dip direction. The modern sands responsible for the buildup of the sandbody above the sea floor vary from 3 to 5 m in thickness, and span the full depositional width of the sandbody in a 260-km² irregularly shaped area. Ooid-rich deposits exceed 7 m in thickness within the ooid grainstone fringe in the area of the Joulters Cays. A 1–2 m thick layer of time-equivalent sediment extends further to the north and west as part of a sheet-like accumulation covering much of GBB. There are significant facies and thickness variations across the width of the sandbody, and the surrounding platform equivalents are...
totally different facies. Outcrops scattered along the northern part of Andros suggest many of the modern environments also existed in the late Pleistocene (Hazard, Ritter, McBride, Tingey, & Keach, 2017). The geometry of such a composite sediment body, considering both Pleistocene and Holocene sands of the northern Andros area, could be quite complex in both dip and strike directions relative to the shelf break. But most striking perhaps is the variation that exists within the depositional facies that form the modern sandbody.

3.3 | Genesis of upward-shoaling cycle (parasequence)

Cores also capture the nature of the depositional cycle within a sand-dominated system, which is one of sediments reflecting increasing bottom agitation from bottom to top of the cycle that can be related to shoaling water conditions. Seeing first-hand how a cycle captured in cores of the modern can be compared and calibrated with the surficial environments can only enhance an interpretation of similar cycles in the ancient (Eberli, 2013; Harris et al., 1993). These cycles are often the basic building blocks of carbonate platforms and reservoirs and can equate with flow units in reservoirs (Grant, Goggin, & Harris, 1994; Kenter et al., 2006; Kerans, Lucia, & Senger, 1994). Having a firm set of criteria to recognize such cycles is essential, but the cross-sections through the Joulters sandbody (Figure 3) illustrate the variability that cycles will have within a relatively small area. Details of upward-shoaling cycles suggest limitations inherent to cyclostratigraphic correlation and explain aspects of reservoir heterogeneity.

3.4 | Depositional model relative to sea-level change

Comparing the subsurface record of the Joulters sandbody revealed by cores that are calibrated by radiocarbon dating

FIGURE 6 Ooid sand (grainstone) characteristics. (a) Surface view of active ooid bar at low tide showing sand waves and ripples adorning clean, white sand sea bottom. (b) Loose sediment sample from active bar of clean, well-sorted, medium-sand size polished ooids. (c) Thin section of plastic-impregnated sample from active bar showing well-formed ooids in cross-polarized light. Note the ooids contain a nucleus, a peloid or pellet, surrounded by a well-formed cortex. Average ooid diameter is 400 μm. (d) Large-scale thin section from a plastic-impregnated core slab to show the grainstone texture and sedimentary structures that typify an active bar setting. Bedding is parallel with a dip from upper left to lower right; section is oriented with top being up in the core. Grapestone and skeletal grains form prominent coarser beds with looser sediment packing. Black shows primary interparticle porosity. Cross-polarized light; scale at bottom in millimetres
with a sea-level curve for the Holocene produced a robust depositional model tied to sea-level change (Figure 4). The overall rate of accumulation estimated from the Joulters coring paced the rise of sea-level at approximately 1 m/kyr. However, the accumulation rate was somewhat lower during the initial stage of bank flooding as a full range of sediment-producing organisms was not yet developed (Harris et al., 1993). An increase in accumulation rate coincides with the increased amounts of ooids produced during shoal formation and development. A decreasing rate of sea-level rise coupled with the high-sediment accumulation rate resulted in the sediment surface approaching sea-level through time as was indicated by the shoaling succession of facies in cores. These results corroborate the findings of others (Enos, 1991; James, 1979; Read, Grotzinger, Bone, & Koerschner, 1986), that carbonate sedimentation on the platform tends to lag behind the rate of relative sea-level rise, resulting in an initially deepening succession, but sediments accumulate at overall rates greater than the relative sea-level rise and consequently build to sea-level. The facies patterns depicted in the various stages of Figure 4 are a suggestion of what might be expected during the transgressive and highstand portions of a depositional cycle, which is information that can be helpful during reservoir characterization and modelling. Perhaps most insightful is the significant amount of change that is portrayed in the model, which is a direct indication of the level of heterogeneity to be expected. The rapidity of deposition in the Joulters sandbody reinforces the notion that platform carbonates locally have high-growth potential and shows that the facies relationships can become complex at the cycle (vertical) and interwell (lateral) scale. We can further speculate from the observations at Joulters coupled with the platform-wide assessment of accommodation filling across the top of GBB by Purkis and Harris (2016), that accommodation space may fill quickly and complexly, but locally, during the development of depositional cycles on ancient platform settings.
3.5 | Facies preservation

The preservation potential of facies as recognized in the sediment cores from Joulters is also variable, which only makes the recognition of depositional cycles during subsurface studies more challenging. The interpretation of cores from the Joulters example suggests that major changes of depositional environment have taken place in a brief span of time. Much of the area now occupied by the sand flat is believed to have evolved from a belt of active ooid bars and tidal channels. Through time one environment changed to another, and the sediments record most of the change with their grain types and depositional texture. Reworking can obliterate the sedimentary structures: laminations disrupted or destroyed by burrowing or, conversely, burrows destroyed during reactivation of a portion of the sea bottom. The depositional texture may also be modified after deposition as, for instance, when mud is mixed with the sediment by burrowing. Thus the widespread belt of ooid packstone recognized in cores of the Joulters sandbody (Figure 3) is believed to have formed as ooid grainstones were modified during formation of the sand flat. Mud sourced from green algae living on the sand flat and remobilized from the platform interior during exceptional storms (Major et al., 1996) was mixed with the sediments during burrowing, and peloids and pellets along with various skeletal grain types were added by the sand flat biota (Figure 7).

Certain depositional environments may stand a better chance of preservation due to the effects of early cementation. The sand cays of the Joulters ooid shoal, for instance, have become rapidly cemented during freshwater cementation (Halley & Harris, 1979; Figure 5). Island ‘dune’ ridges up to 5 m above present sea-level on south Joulter Cay were rapidly cemented by meteoric cements and are therefore less probable to be reworked during storms or by changes in sea-level. Beaches are partially cemented by both marine and freshwater cements and similarly may not be eroded as readily during storms or by longshore currents. The cemented islands may play a role in the development of subsequent deposits in the area. If the next major sedimentation event follows an increase in relative sea-level, the islands might well be depositional highs around which bottom agitation is centred resulting in the formation of additional ooid shoals or other high-energy facies. Purkis and Harris (2016) stressed the importance of islands in localizing sedimentation and filling of accommodation space by examining sediment thickness and occurrences of islands across GBB.

3.6 | Subsurface record in 3-D

Coring of the Joulters sandbody has shown that a relatively thin (few metres thick), but complex succession of sediments can form over a brief period of accumulation time as a result of changes in relative sealevel and localized topography. As mentioned, there are significant facies and thickness changes across the width of the shoal and the surrounding bank equivalents are totally different facies. Clean ooid grainstones border the shoal on two sides as dictated by the hydrologic setting, therefore a trend toward ‘more seaward’ deposits may actually exist in more than one direction. Grainstones of ooids, grapestones and peloids are also formed in localized areas within the sand flat, as beaches around small islands and as levees or lobe-shaped fans along tidal channels. Thus the distribution of grainstones, in which a hydrocarbon reservoir may be best developed if the producing porosity type is primary interparticle porosity, can be challenging to predict and correlate. Finally, the fine-scale time lines that outline the development of a sandbody such as Joulters are complex as suggested on Figures 3 and 4 emphasizing again the generalizations made when a thick section of ancient limestone is analysed.

The extensive coring of the Joulters sandbody, initially by Harris (1977, 1979) and later by Major et al. (1996), provides a fairly complete subsurface picture in ‘3D’ for this sand-dominated system—a relatively narrow belt of ooid grainstone bordering a wider belt of ooid packstone that becomes increasingly muddy with depth. As such, the Joulters ‘model’ serves as an important template for the type of vertical and lateral facies relationships and for the degree of thickness variation expected within a cycle on a reservoir-scale. Having an appreciation of the nature of these variations can only help when analysing outcrops, correlating logs and cores, characterizing a reservoir or building reservoir models.

The original suite of 60 cores with average 1.5 km spacing from Harris (1977, 1979) gives a regional, exploration-scale view providing information on facies variability across distances of tens of kilometres. Heterogeneity can be inferred based on the distribution of depositional facies shown in Figure 3. Clean, ooid sand (grainstone) along the active margin of the shoal occurs as subtidal bar, channel-fill and island facies. In cross-section, the ooid grainstone occurs in an irregularly shaped area 2 km wide and averaging approximately 3 m in thickness. High-initial porosities were measured in similar clean modern sands by Halley and Harris (1979) and Enos and Sawatsky (1981). Immediately, platformward of the ooid sand are widespread, somewhat irregularly shaped layers with mixtures of carbonate sand and mud that will most probably result in very different reservoir properties. The upper layer of muddy ooid sand (packstone), nearly 20 km wide and from 4 to less than 1 m thick, thins toward the platform and overlies the more widespread layer of muddy, fine-peloid sand (packstone), which is more than 30 km wide and ranging from 5 to 2 m in thickness. These layers will most probably have initial porosities lower than the more
seaward clean ooid sand, based on measured values of similar sands by Enos and Sawatsky (1981). And the upper layer will likely have better reservoir quality than the lower because of coarser grain size and lower mud content.

Interwell-scale heterogeneities in hydrocarbon reservoirs are often on the scale of hundreds of metres or less (Bebout & Harris, 1990). Depositional facies variability and early diagenetic alteration both contribute to fine-scale heterogeneities in the grain-rich upper portion of the succession at Joulters that appear to be at an equivalent scale. To capture more information from the modern analog at the reservoir development-scale, Major et al. (1996) built upon the regional framework in the Joulters area with additional coring in a subarea of a portion of the active shoal. Thirty-nine cores were taken in a 2.7 km² area, with an average core spacing of 330 m. Three depositional facies, identified from cores by Major et al. (1996), occur within the ooid sand (grainstone) facies of Harris (1977, 1979). Well-sorted, cross-bedded ooid sand occurs on the active, high-energy bar crest in the area of the shoal investigated in detail. Burrowed ooid sand (also grainstone) accumulated along the edges of the shoal. A poorly sorted ooid sand (also grainstone), which is stabilized by seagrass and algae, occurs just bankward of the bar crest and represents a transition into the adjacent sand flat. Differences between the three facies that can be inferred to lead to heterogeneity are grain size, grain sorting, sedimentary structures (both physical and biogenic) and mud content. These subtle variations occur on a scale of hundreds of metres, a scale to be considered when correlating at the common development interwell scale. Given that the heterogeneity portrayed here occurs within a single facies—the ooid grainstone of Harris (1977, 1979)—then by analogy similar subtle textural variations can be expected to produce local heterogeneity in ooid grainstone reservoirs.

3.7 Diagenetic overprint and porosity modification

Although not the main focus of the Joulters studies, valuable insight into recognizing marine, meteoric vadose and meteoric phreatic cements comes from the descriptions of beachrock, hardground and island dune samples. Of greater importance perhaps to subsurface studies is the data provided by probing and coring on the spatial distribution of marine hardgrounds and meteoric-water lenses associated with the islands. Major et al. (1996) mapped the distribution of marine hardgrounds by close-spaced sediment probing in a subarea of the active sand shoal, and the hardgrounds were correlated as far as 600 m. Porosity and permeability have not been greatly reduced in these modern lithified zones, but such zones could form baffles or barriers to fluid flow should they subsequently serve as preferential nucleation sites for additional cementation. The marine, as well as the island-associated meteoric diagenesis previously discussed, are important aspects of near-surface diagenesis that can cause early modification of porosity and permeability, probably influence subsequent fluid flow and diagenetic overprint, and play a role in creating the heterogeneity that typifies many carbonate reservoirs.

4 SUMMARY

The Joulters sandbody is a vast expanse of muddy sands (packstones) rimmed by clean sands (grainstones), which would produce a thin (average thickness 4 m) reservoir layer of significant scale (400 km²). Diagenesis always plays a role in determining the ultimate reservoir quality in a carbonate reservoir, but in cases where the diagenesis is controlled by rock type, for example, cement-reduced interparticle porosity in limestones, the Joulters analog serves as an insightful example of how these rock types can be interrelated. The strength of the Joulters example as an analog for carbonate sand reservoirs comes from the combined view of satellite imagery, surface facies mapping, sediment coring and rock coring of the islands. These results collectively illustrate the strike elongated nature of carbonate sand reservoirs relative to the platform margin, lateral heterogeneity that is inherent in such depositional systems and reservoirs due to tidal channels, and complexity that is added due to beach/island complexes and their associated diageneis.

The geological framework as illustrated by modern analogs such as Joulters can be important in development-scale reservoir analysis. The modern studies are valuable during outcrop and reservoir characterization as they constrain interpretations and lend predictability to unravelling facies patterns, which in turn help to understand the lateral continuity of stratification, variation within layers, heterogeneity and performance of reservoirs. The facies relations recognized during coring of the Joulters analog has had direct application to interpretations of subsurface examples by Ottmann et al. (1973), Bebout and Schatzinger (1978), Smosna (1984), Smosna and Koehler (1993), Harris et al. (1993), and Major et al. (1996). Application to reservoirs is particularly true in cases where reservoir quality is tied to facies changes, and facies dimensions are therefore required for reservoir characterization and are critical as input to reservoir models. Differences between facies and within facies impact the heterogeneity of reservoirs at various scales. A geologically based model provides the foundation for reservoir characterization and simulation models, and modern systems are an important source of data to assess the aerial distribution of potential reservoir facies. As a notable example, Rush and Rankey (2017) captured process-based stratigraphic trends, and therefore vertical,
lateral and azimuthal facies heterogeneities, in geocellular models for a portion of the Schooner Cays sandbody from analyses of satellite imagery, two-dimensional high-frequency seismic (chirp) data and sediment cores. Their models aim to assess prospective modelling trends for subsurface oolitic reservoirs, such as the size, orientation and shape of potential reservoir bodies, and thereby explore the potential patterns of three-dimensional distributions of rock fabrics and reservoir heterogeneity. The geological framework is also important at the exploration scale in situations where reservoir prediction and stratigraphic plays are related directly to depositional facies patterns.

Considering the degree of reworking of facies presented in the growth stages of the Joulters sandbody and the variability in preservation potential imparted by the early diagenetic overprint, it is not unreasonable to question whether the Joulters lessons represent a common theme in ancient deposits. Certainly, the upward coarsening and shallowing succession documented for the modern section in the Joulters area is common in ancient settings and is one of the several types of shallowing-upward sequences discussed by James (1979). The lateral facies variability bears also the striking similarities to that recognized in Pleistocene limestones of South Florida (Evans, 1984; Halley, Shinn, Hudson, & Lidz, 1977; Purkis & Harris, 2017; Usdan, 2014) and the Bahamas (Beach & Ginsburg, 1980; Garrett & Gould, 1984) as well as numerous ancient subsurface examples (Bebout & Schatzinger, 1978; Major et al., 1996; Ottmann et al., 1973; Smosna, 1984). Halley et al. (1977) equated the shoal and channel portion of the Miami oolite in South Florida to modern Bahamian tidal-bar belts including the Joulters example, and further suggested Joulters as an early-stage analog for the barrier bar portion of the Miami oolite. Evans (1984) and Usdan (2014) used Joulters to illustrate how cross-bedded and burrowed facies can be coeval and to show the diversity of sand movement directions (cross-bedding) formed in areas dominated by ebb, flood and longshore currents. Evans (1984) further used the results of coring in the Joulters area from Harris (1979) as an analog to interpret the facies anatomy and developmental history of the Miami oolite, in that in its early stages, the Miami oolite sand complex matured from a tidal-bar belt into a sand flat similar to Joulters, and later the complex developed a marine bar belt (barrier bar) seaward of the original tidal-bar belt.

The complexity revealed by coring of the Joulters sandbody cannot be fully addressed in normal subsurface situations with downhole log and limited core information, especially when some of the relationships occur at distances less than well spacing even in extensively developed fields. But an appreciation of the general nature of such facies variability is needed in reservoir studies to guide correlations of cycles and flow units and to constrain inputs for reservoir models. Because of the preservation potential of entire shoal complexes, the modern ooid sandbodies of GBB including Joulters serve as analogs for the stratigraphic aspect of the rock record. Beyond revealing architectural trends that may be of use in reservoir characterization, Harris et al. (2011) explored how morphometric analysis of modern sandbodies may also provide insight into the processes controlling their distribution and sculpting their geometry. Consequently, the sedimentary products of the hydrodynamic processes that form and shape modern ooid sandbars and sandbodies can provide insight into facies interpretation, the vertical succession of facies (i.e. a stratigraphic cycle or sequence), and the changes in depositional conditions that produced the observed spatial facies patterns.

An understanding of surficial depositional environments and their associated sediments that comes from visiting a modern environment can only sharpen one's eye when faced with trying to interpret rocks on outcrop, in cuttings, or cores. It is not an exaggeration that a cross-bedded ooid grainstone will be looked at from an entirely different point of view after examining a modern ooid sand shoal and experiencing first-hand this dynamic landscape and its hydrodynamic setting. In a similar manner, coring of the modern settings can reveal facies relationships that improve one's ability to unravel challenges in subsurface correlation and modelling.

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