ANNUAL REVIEWS

Annual Review of Marine Science The Formation and Distribution of Modern Ooids on Great Bahama Bank

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Annu. Rev. Mar. Sci. 2019. 11:491-516

First published as a Review in Advance on August 8, 2018

The Annual Review of Marine Science is online at marine.annualreviews.org

https://doi.org/10.1146/annurev-marine-010318-095251

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Keywords

Great Bahama Bank, GBB, ooid, sand body, EPS biofilm, organomineralization, digital terrain model, DTM

Abstract

Great Bahama Bank (GBB) is the principal location of the formation and accumulation of ooids (concentrically coated, sand-size carbonate grains) in the world today, and as such has been the focus of studies on all aspects of ooids for more than half a century. Our view from a close look at this vast body of literature coupled with our continuing interests stresses that biological mechanisms (microbially mediated organomineralization) are very important in the formation of ooids, whereas the controlling factor for the distribution and size of ooid sand bodies is the physical energy. Mapping and coring studies of the modern ooid sand bodies on GBB provide insight into the rock record from different perspectives. An important consequence of the dual influence of ooid formation and distribution is that the geochemical signature of ooids is not in equilibrium with the seawater in which ooids form; therefore, extracting the paleophysical energy record from oolitic deposits is potentially more accurate than doing so for the paleochemical record.

1. INTRODUCTION

Ooids are concentrically coated, sand-size carbonate grains that have long fascinated geologists, chemists, and geobiologists. Richter (1983) provided some historical perspective in his review of ooids. The geological interest stems from the fact that ooids are a key environmental indicator of high-energy depositional conditions (Figure 1a, b) and are also significant to the evolution of carbonate platforms and shelves of all ages and from diverse basins around the world, many of which have proven to be important reservoirs for hydrocarbons and mineral deposits [for example, the reservoirs described by Wilson (1975), Harris (1984a), Roehl & Choquette (1985), Keith & Zuppann (1993), and Harris & Weber (2006)]. The chemical interest comes from the fact that ooids are a precipitation phenomenon wherein a nucleus is coated by micron-thick layers of crystalline carbonate (generally aragonite in modern marine ooids) to form the cortex of the ooid (Figure 1c,d). Substantial debate persists concerning the roles of physical, chemical, and microbial processes in ooid growth, including whether carbonate precipitation on ooid surfaces is driven by seawater chemistry or microbial activity (Duguid et al. 2010; Diaz et al. 2014, 2015, 2017; Trower et al. 2017). The geobiological interest, which has been steadily increasing with findings based on new technologies and analytical approaches, stems from the question of whether microbes play a direct or indirect role in driving carbonate precipitation and how this insight might refine the understanding of where and when ooids form. Trends in ooid composition and size are thought to



Figure 1

(*a*) Photograph of the surface of a high-energy ooid sandbar (shoal) from the Joulter Cays sand body. The current-swept surface exhibits subtle topography and is adorned with current ripples. (*b*) Photograph of a loose ooid sediment sample from the sandbar shown in panel *a*. Note that the ooids are rounded and well sorted and that the grain surfaces are highly polished. (*c*,*d*) Photomicrographs of ooids, showing their internal structure. Ooids have a nucleus, which is variable in nature but is commonly a peloid surrounded by a well-formed layered cortex. Panel *b* adapted from Diaz et al. (2014) with permission; panels *c* and *d* adapted from Diaz et al. (2017) with permission.

record changes in seawater chemistry, paleoclimate, and paleoceanography over Earth's history, but new studies are challenging these assumptions.

Great Bahama Bank (GBB), the principal location of ooid formation and accumulation in the world today, has been the focus of studies on all aspects of ooids for more than half a century, with the goal of better understanding the characteristics of ancient oolitic systems (Illing 1954; Newell & Rigby 1957; Newell et al. 1960; Purdy 1961, 1963b,c; Imbrie & Buchanan 1965; Ball 1967; Enos 1974; Dravis 1977; Harris 1979, 1984b, 2010; Palmer 1979; Hine et al. 1981; Halley et al. 1983; Curtis 1985; Wanless & Tedesco 1993; Gonzalez & Eberli 1997; Rankey et al. 2006; Cruz 2008; Reeder & Rankey 2008, 2009; Harris et al. 2010, 2011, 2015; Rankey & Reeder 2011, 2012; Sparks & Rankey 2013; Purkis & Harris 2016; Rush & Rankey 2017). These studies, which have formed the basis for many facies models for carbonate sand bodies (summarized in Bathurst 1975, Halley et al. 1983, Tucker & Wright 1990, James & Jones 2015), include characterization of the individual grains (size, shape, and internal structure), investigations of their origin from chemical and biogeochemical perspectives, and detailing of the varied depositional environments that ooids form and accumulate within. The latter aspect has involved mapping, coring, and shallow seismic studies to assess the two- and three-dimensional nature of ooid sand body geometries and geologic history. In this review, we focus on studies addressing how and where ooids form-both topics that continue to be actively investigated—and draw almost exclusively from studies of ooid sand bodies on GBB.

GBB, a relatively flat-topped, isolated carbonate platform lying directly to the east of southern Florida, is a major modern location of carbonate deposition. Decades of geological studies of various aspects of GBB have provided much of the understanding of processes of carbonate sedimentation and numerous geological models to illustrate variations in depositional facies. GBB covers an area of more than 103,000 km² (590 km north–south and 160 km east–west), and the margin of this immense platform is 3,088 km long. Across its breadth, GBB displays a well-organized association of shallow, platform-top depositional environments (Newell et al. 1960; Purdy 1961, 1963b,c; Traverse & Ginsburg 1966; Ball 1967; Enos 1974; Reijmer et al. 2009; Kaczmarek et al. 2010; Harris et al. 2015; Purkis & Harris 2016) (**Figure 2**). Sixty percent, or 61,400 km², of the submerged portion of GBB lies in 5 m or less of water, and these portions of the platform contribute to its overall extremely grainy nature. This part of GBB includes areas along the margins of the platform (the high-energy grainstones shown in **Figure 2**) that are a focus of sediment production and accumulation and where accommodation has been locally filled, such as the ooid sand bodies in the Cat, Joulter, Schooner, and Exuma Cays and the southern Tongue of the Ocean (TOTO), displayed in a clockwise fashion in **Figure 3**.

2. HOW DO OOIDS FORM AND WHAT DO THEY RECORD?

Theories about the genesis of ooids have abounded over the last few centuries. Their origins have been linked to (*a*) eggs from insects, crinoids, or fish (Fournet 1853, Virlet-D'Aoust 1857); (*b*) aggregation of grain particles by physical rolling motion (Sorby 1879); (*c*) schizophycean blue-green and filamentous algae (Wethered 1895, Nesteroff 1956); and (*d*) aeolian aggregates (Mathews 1930). Some of these early hypotheses have been contested, and new hypotheses have continued to emerge; today, the primary hypotheses center around two contrasting views based on abiotic and biotic origins.

2.1. Abiotic Theories of Ooid Formation

Some theories of ooid formation follow the stance that ooids are inorganic precipitates that mainly originate from both chemical and physical factors. Based on this idea, several abiotic theories have been formulated.



Map of depositional facies (sediment types) on Great Bahama Bank based on seafloor sample data compiled into a geographic information system, integrated with a Landsat mosaic, and analyzed with eCognition. The facies map is superimposed on a simplified version of a bathymetric digital terrain model also developed for Great Bahama Bank. High-energy grainstones are sites characterized by the development of sandbar complexes containing variably thick, cross-bedded ooid sands. The remaining mapped grainstones are subtidal sand sheets containing more uniformly thin sands with variable grain types [superficial ooids, peloids, skeletal grains, and aggregate (grapestone) grains] and variable sedimentary structures (bioturbation, burrowing, and local laminations). Figure adapted from Harris et al. (2015) with permission.



Map showing locations on Great Bahama Bank where prominent ooid sand bodies are developing today: the Cat, Joulter, Schooner, and Exuma Cays and the Tongue of the Ocean (TOTO). Landsat views, all at the same scale, show the contrasting sizes and morphologies of the different sites. Figure adapted from Purkis & Harris (2017) with permission.

2.1.1. Physicochemical theory. The traditional view of ooid formation stresses that marine ooids are abiotically produced by direct precipitation from seawater triggered by physicochemical factors—e.g., shallow, warm, carbonate-saturated seawater of normal to elevated salinity and agitated water conditions (e.g., from tides and waves), which allows CO_2 degassing and an increase in alkalinity (Cayeux 1935, Davies et al. 1978, Tucker & Wright 1990, Sumner & Grotzinger 1993, Duguid et al. 2010). In this traditional model, the ooid formation is initiated by a suspended detritus nucleus (e.g., a peloid, shell fragment, or foraminifer) upon which precipitation commences, leading to the formation and accretion of concentric layers of aragonite batons and needles with a tangential or radial orientation—the ooid cortex. The abiotic model of ooid formation gained some momentum after the in vitro experiments of Linck (1903) produced synthetic ooids for the first time. Inorganic ooid-like structures were produced in other laboratory experiments using saturated solutions of CaCO₃ (Monaghan & Lytle 1956, Donahue 1965, Weyl 1967, Davies et al. 1978, Trower et al. 2017). However, many of the artificial ooids lacked the lamination and tangential structural pattern of Bahamian-like modern marine ooids.

2.1.2. Physical theory. A physical model stipulates that the back-and-forth rolling motion of the grains on the seabed promotes ooid accretion through the aggregation of small aragonite

needle deposits on an organic coating; this snowball mechanism was proposed by Sorby (1879). In contrast to the chemical model, the snowball model does not support direct $CaCO_3$ precipitation as a mechanism of ooid accretion but rather relies on the mechanical and physical addition (by trapping and binding) of aragonite particles and organic matter. Although this model represents one of the early reports on the presence of organics in ooids, it does not support the sorting, mineralogy, and thick lamination pattern of modern aragonitic ooids, nor does it explain the accretion on highly polished ooids (Morse & Mackenzie 1990).

2.1.3. Physicochemical theory under the presence of organic substances. Based on in vitro experiments with carbonate-supersaturated seawater amended with various sources of organic matter and different turbulent conditions, Davies et al. (1978) proposed that ooid grains are inorganic precipitates that follow a series of agitation, resting, and sleeping stages to influence cortex growth. They also concluded that organic matter facilitates ooid accretion. In their model, which obviates the role of microbes in the synthesis of organic membranes, ooid growth begins in the agitation phase, where precipitation is triggered by turbulence, a supersaturated solution of CaCO₃, and a nucleus. At the end of the agitation phase, Mg^{2+} and H^+ gradually inhibit ooid accretion. The ooid subsequently transitions into a resting phase, during which ooid surfaces are reactivated by the removal of Mg^{2+} and H^+ . The ooid is eventually brought back into suspension, and once a new organic coating has developed—when the ooid is buried in the subsurface (sleeping stage)—a new cycle begins.

2.1.4. Physicochemical theory via a metastable precursor. Most recently, Duguid et al. (2010) proposed a theory focusing on stable isotope (δ^{18} O and δ^{13} C) and trace element analyses (Mg/Ca and Sr/Ca) whereby an inorganic precipitate—purported to be amorphous calcium carbonate (ACC), a noncrystalline precursor phase of vaterite, calcite, or aragonite—develops on ooid outer cortices prior to the transformation of ACC into aragonite needles. They inferred the presence of ACC mainly on the Mg/Ca of ooid outer cortices, and it was not until recently that ¹³C{¹H} cross-polarization magic-angle spinning nuclear magnetic resonance (CPMAS-NMR) analysis provided direct evidence of ACC in ooids (Diaz et al. 2017).

2.1.5. Abiotic growth model theories based on size and age determination. Sumner & Grotzinger (1993) developed a numerical model for ooid growth dependent on the balance between mass lost per impact of the grain (increases with the cube of the radius) and the mass gained from precipitation (proportional to the surface area of the ooid). Their model, which assumes that ooid growth is enhanced by turbulence and seawater chemistry conditions, indicates that ooid size increases monotonically-while in suspension-until the grain reaches a critical maximum size, after which hydrodynamic forces can no longer sustain the grain in the saltation mode. Consequently, at this stage ooid growth halts, and the ooid is buried or washed ashore. By contrast, a new model based on experimental data contends that ooid growth does not follow a simple monotonic positive function of the ooid's lifetime, instead proposing that ooids spend most of their lifetimes near an equilibrium size once the dynamic balance-abrasion/precipitation-has been reached (Trower et al. 2017). This model incorporates abrasion rates as a function of grain size and sediment transport regimes given the significant disparity between abrasion/precipitation and radiocarbon net growth rates, the former being four orders of magnitude faster than the latter. Even though this dynamic equilibrium model predicts ooid size based on sediment transport regimes and explains the narrow distribution of ooid sizes in ooid-producing environments, the model is not fully validated with field data sets.

2.2. Biotic Theories of Ooid Formation

The pure physicochemical origins of ooids have been challenged given the association of ooids with diverse microbial communities that are able to mediate carbonate precipitation. As a result, numerous hypotheses have been put forward supporting the biological cause.

2.2.1. Early theories supporting a biological cause. Because neither the physical nor chemical theories completely explain the origin of ooids, other avenues inspired by biological observations have been explored, including coiling of calcified filaments in ooidal structures (Wethered 1895); the occurrence of algae, bacteria, and fungi in etched limestones (Rothpletz 1892, Nesteroff 1956); granular algal precipitates embedded in mucilaginous material (Rothpletz 1892); and aragonite precipitates of bacterial origin (Vaughan 1914, Monaghan & Lytle 1956, Lalou 1957). While most of these studies suggest ooid formation by cyanobacteria-interpreted as algae and/or blue-green algae—bioerosion of the grain by thallophytes led to some skepticism about their formative role (Walther 1888, Purdy 1963a). Nevertheless, these pioneer studies paved the way for the biological cause, leading to other lines of evidence, including the presence and characterization of organic matter (Mitterer 1971, 1972; Suess & Futterer 1972; Davies et al. 1978; Folk 1993; Folk & Lynch 2001), ooid-like structures produced by microbial communities (Fabricius 1977; Brehm et al. 2004, 2006), and aggregates of entombed cocci (also known as nannobacteria) and calcified rodshaped bacteria (Folk 1993, Folk & Lynch 2001, Kahle 2007). The latter observations heralded the hypothesis that modern and ancient marine ooids are mainly of bacterial origin, but uncertainty remains about the identity of the so-called nannobacteria because they are more than an order of magnitude smaller than normal bacteria (Maniloff 1997, Nealson 1997).

The notion that organic substances are associated with the development of ooid cortices arose as early as the 1950s (Monaghan & Lytle 1956; Lalou 1957; Newell et al. 1960; Shearman & Skipwith 1965; Mitterer 1968, 1972; Suess & Futterer 1972), and given recurrent observations on the elevated content of protein rich in aspartic and glutamic acids, some have suggested that proteinaceous material may play a fundamental role in ooid calcification by acting as a template for carbonate nucleation (Mitterer 1968, 1972; Mitterer & Cunningham 1985). For instance, studies of the effects of different sources of organic matter suggested that ooid formation is facilitated by organo-carbonate interactions triggered by specific organic macromolecules, which form stable membrane coatings through metal-bridging reactions with divalent cations (e.g., Ca²⁺ and Mg²⁺) (Davies et al. 1978, Ferguson et al. 1978). Based on these results, Davies et al. (1978) inferred that cortex accretion in Bahamian-type and quiet water ooids is regulated mainly by the nature and availability of organic matter (e.g., molecular weight, carboxyl group content, and hydrophobic or hydrophilic interactions) that acts as a growth surface for precipitation to occur. Davies et al. (1978) considered the above mechanism an abiotic process, but this mode of precipitation is not strictly inorganic since it relies on biological substances. While estimates of the content of the organic matter revealed that ooids harbor significant amounts of organics (1.9-3.1% of total organic carbon) (Summons et al. 2013, O'Reilly et al. 2017), biochemical analysis of the organic components showed that 33% are protein-rich glutamic and aspartic acids, known for the preferential binding of their carboxylic moieties to calcium ions (Mitterer 1971, Davies et al. 1978, Reitner 1993).

2.2.2. Recent findings supporting the biological mediation theory. A growing number of studies use an integrated approach that combines genomics, lipids, isotopic analyses, scanning electron microscopy (SEM), and confocal laser scanning microscopy to examine the relationship of microbes with ooid sands (Diaz et al. 2013, 2014, 2015, 2017; Edgcomb et al. 2013; O'Reilly et al.

2017; Tan et al. 2017). These new studies not only argue for a biological cause but have changed the notion that the microbial community structure of ooids is limited mainly to endolithic microborers with the sole functional capabilities to alter the chemistry and texture of the grain through micritization and cementation (e.g., Harris et al. 1979, Duguid et al. 2010). Moreover, the latest studies support the stance that ooid cortex formation is driven mainly by a microbially mediated organomineralization process that follows two mechanisms: (*a*) a biologically induced mechanism, whereby by-products of metabolic activities (e.g., photosynthesis, denitrification, sulfate reduction, ureolysis, and anaerobic sulfide oxidation) can change the physicochemical conditions of the microenvironments, inducing an increase in alkalinity and deposition of mineral particles (Jones & Goodbody 1984; Plée et al. 2008, 2010; Pacton et al. 2012; Diaz et al. 2013, 2014, 2015, 2017), and (*b*) a biologically influenced mechanism, whereby an organic material, such as microbial extracellular polymeric substance (EPS) exudates, serve as a template for carbonate mineralization through the adsorption of ions and mineral nucleation (Diaz et al. 2013, 2014, 2017; O'Reilly et al. 2017).

2.2.3. Molecular and geochemical studies supporting a biologically induced mechanism. Studies based largely on 16S rRNA (Diaz et al. 2013, 2014; Edgcomb et al. 2013; O'Reilly et al. 2017) and GeoChip 4 functional gene analyses have provided a detailed portrait of the community structure and functional capabilities of microorganisms, many of which relate to carbonate precipitation. The results are undoubtedly striking, as they have unveiled an unprecedented diversity of microorganisms, surpassing those of Bahamian stromatolites and thrombolite systems (Diaz et al. 2013, 2014). For instance, the functional gene diversity of the ooid shoals of GBB includes 39 different lineages, representing up to 1,000 different species within the bacteria, archaea, and eukaryotes. Among these lineages, assemblages of Proteobacteria are the most predominant and functionally diverse, accounting for 50% of the total bacterial diversity. Representatives of other taxonomic groups include Acidobacteria, Bacteroidetes, Actinobacteria, Planctomycetes, and Cyanobacteria (Diaz et al. 2014).

A GeoChip 4 analysis by Diaz et al. (2014), which used a gene microarray comprising more than 95,847 gene probes, revealed that ooid microbial communities are driven predominantly by geochemical processes that foster carbonate precipitation (in order of gene abundance: denitrification, autotrophic CO₂ fixation, sulfate reduction, and ammonification), whereas metabolic processes that are conducive to carbonate dissolution (e.g., aerobic sulfide oxidation, sulfate oxidation, and nitrification) are less prevalent. This study not only provides a snapshot of the metabolic potential of these communities but is in line with phylogenetic findings, which identified a similar microbial community structure based on 16S rRNA clone analysis and terminal fragment length polymorphisms (Thompson et al. 2008, Diaz et al. 2013, Edgcomb et al. 2013, O'Reilly et al. 2017). The putative functional capabilities of these communities are further supported by branched-chain fatty acids and saturated fatty acid lipids, some of which are commonly found in sulfate reducers and photoautotrophs (Edgcomb et al. 2013, Summons et al. 2013, O'Reilly et al. 2017). Likewise, isotope analysis of intracrystalline organic matter documents signatures consistent with photosynthesizers (Trienekens 2007, Diaz et al. 2015), sulfate reducers (Thompson et al. 2008), and diazotrophs (Diaz et al. 2015). Moreover, biomarkers for heterotrophy have been confirmed by the carbon isotopic composition of hydrocarbons (Summons et al. 2013) and bulk organic matter (Trienekens 2007, Summons et al. 2013, Diaz et al. 2015, O'Reilly et al. 2017).

Leachate experiments from crushed ooids have also provided evidence in support of microbial activities within ooids (Diaz et al. 2015), including (*a*) positive δ^{15} N and δ^{18} O values of NO₃⁻, which are indicative of denitrification and/or anaerobic ammonium oxidation as well as metabolic processes that inject new sources of nitrogen through remineralization and nitrification; (*b*) δ^{34} S

values that are several per mil more negative than the $\delta^{34}S$ of the carbonate-associated sulfate; and (c) high levels of sulfate (up to 3 mM) in tandem with elevated S/Ca (21–53 mol mol⁻¹). The combination of $\delta^{34}S$ values along with the elevated levels of sulfate and S/Ca has been attributed to microbial chemolithotrophic oxidation of H₂S and preferential microbial use of NO₃⁻ over SO₄²⁻ (Diaz et al. 2015). SEM images of extracellular sulfur globules have also provided evidence of the incomplete oxidation of sulfide by both green sulfur and purple sulfur (Diaz et al. 2017). Together, these analyses suggest that ooids are regulated by a consortium of microbes that operate in syntrophic interactions to locally and directly foster the precipitation of carbonates.

2.2.4. Geochemical analyses supporting equilibrium offsets in the carbonic system by a microbially induced mechanism. Evidence of equilibrium offsets in the carbonic systems is supported by experimental data on leachate fluids that show heavier-than-expected levels of dissolved inorganic carbon in tandem with high levels of alkalinity that are at variance with the theoretical prediction levels (Diaz et al. 2015). The offset in alkalinity is partially explained by heterotrophic activities of a complex consortium of microbes (e.g., denitrification, sulfate reduction, and anaerobic sulfide oxidation) that induce chemical changes in the environment through the consumption of autotrophic biomass. For instance, the high levels of SO_4^{2-} and nitrogen species in the leachates, both of which surpass the levels expected for the stoichiometry of carbonate dissolution and nutrient concentration in Bahamian waters, provide convincing evidence that ooids precipitate in disequilibrium through both microbial mineralization and isotopic recalibration of the amorphous phase (ACC) before transforming into the crystalline aragonite phase (Diaz et al. 2015). Earlier studies conducted by Kahle (1965) also supported the idea that Bahamian ooids are precipitating in disequilibrium, given that the levels of Sr^{2+} in seawater are below the typical levels of Holocene ooids. Likewise, elevated values of δ^{11} B along with higher-than-expected boron-based pH estimates in shallow marine carbonates (e.g., Bahamian ooids) have been attributed to microbial uptake of CO_2 by photosynthesizers (Zhang et al. 2017). The offset $\delta^{11}B$ values provide further evidence that microbial mediation is an important process in shallow marine carbonate formation. Together, these findings support the notion that ooids precipitate out of equilibrium. This idea is also supported by offsets in the isotopic imprints of $\delta^{18}O$ and $\delta^{13}C$ on unaltered ooid cortices (Duguid et al. 2010), but despite evidence of disequilibrium fractionation for both δ^{18} O and δ^{13} C, Duguid et al. (2010) concluded that precipitation of ooid cortices is not related to microbial activity. However, the elemental and isotopic values should follow those of environmental waters in strictly inorganic precipitation.

2.2.5. Studies supporting a biologically influenced mechanism. Modern research on biomineralization has identified polymeric materials (e.g., EPS) of microbial origin on the outer and inner cortices of ooids using a myriad of techniques, including confocal image analysis (Diaz et al. 2013), phenol–sulfuric acid assays (Diaz et al. 2013, 2014), SEM imaging (Folk 1993, Folk & Lynch 2001, Tang et al. 2015, Diaz et al. 2017), and crystal violet staining (O'Reilly et al. 2017). Although the content of EPS in high-energy ooid-forming areas is affected by high shear forces—as opposed to that from quiescent inactive sites (Diaz et al. 2013, 2014)—a recent study by SEM analysis showed the pervasive presence of EPS on freshly preserved ooids from actively forming areas on GBB, which occur as desiccated or honeycomb-like structures; stranded filaments; thin, smooth sheets covering large surface areas; or a patchy distribution (Diaz et al. 2017). The detection of EPS in ooids has important implications because these substances play an important role in carbonate mineralization processes in microbial mat systems (Decho 2000, Dupraz & Visscher 2005, Braissant et al. 2007, Peng & Jones 2013). While fluctuations in local geochemical environments



Microbial communities from the active sandbars of Great Bahama Bank as viewed with scanning electron microscopy. (*a*) Aggregates of biofilm bacteria in association with an extracellular polymeric substance (EPS)–producing diatom. (*b*) Asexual reproduction by a rod-shaped bacterium in association with fungal filamentous hyphae and a cyanobacterium (spiral disk cells) within the Oscillatoriales group. (*c*) Biofilm rod-shaped bacterium ejecting EPS through a tubular appendage (*arrow*) and accumulation of EPS in its immediate surroundings. (*d*) Production of nanograins along the edges of an EPS matrix via a microbially induced mechanism. (*e*) Extracellular mineral precipitation by crescent-shaped bacteria embedded within an EPS matrix. Figure adapted from Diaz et al. (2017) with permission.

within EPS can promote microscale variations in precipitates (Jones & Peng 2014), others have suggested that differences in EPS biochemical composition influence the CaCO₃ crystal types (Kawaguchi & Decho 2002). The latter findings might explain some of the morphologically diverse arrays of aragonite crystals.

In addition to the mucus-like EPS occurrence in ooids, Diaz et al. (2017) identified wellpreserved viable microbial assemblages and provided evidence of biogenic signatures intrinsically related to organomineralization (**Figure 4**), including (*a*) in situ biological production of EPS by both bacteria and diatoms, (*b*) fingerprints of EPS degradation by heterotrophic bacteria, (*c*) extracellular mineralization by prokaryotes in the presence of EPS, and (*d*) the formation and ubiquitous occurrence of nanograin precipitates within microdomain areas of EPS. Based on ¹³C{¹H} CPMAS-NMR analysis, the identity of the nanograin precipitates was established as ACC and further supported by geochemical analyses of the mineral phase of the leachate ooids and nanograins with similar size distributions and morphologies as ACC (Diaz et al. 2015, 2017) (**Figure 5**). Diaz et al. (2017) provided compelling evidence for the association of EPS and microbes and their potential to locally foster precipitation, which supports the notion that an EPS biofilm and ACC provide the scaffold for precipitation to occur; based on various lines of evidence, the



Leached geochemical signature of ooids, scanning electron microscopy (SEM) photomicrographs of nanograin structures, and nuclear magnetic resonance (NMR) spectrum of Bahamian ooids. (*a*) Percentage composition of seawater, aragonite, and high-magnesium calcite (HMC) [amorphous calcium carbonate (ACC)] contributing to the leached geochemical signal of ooids. (*b*) SEM image of nanograins in ooids from the Great Bahama Bank. (*c*) Cross-polarization magic-angle spinning nuclear magnetic resonance (CPMAS-NMR) spectrum of a sample. The broad peak with a similar chemical shift as the reference ACC peak (synthetic) documents the presence of ACC in the modern ooids. Panel *a* adapted from Diaz et al. (2015) with permission; panels *b* and *c* adapted from Diaz et al. (2017) with permission.

ACC nanograin is of biological origin (Diaz et al. 2015, 2017). Moreover, the common occurrence of pennate diatoms along with the in situ production of EPS further suggests the putative role of diatoms in ooid growth since diatoms secrete copious quantities of EPS (Paterson 1989, Smith & Underwood 1998, Diaz et al. 2017) that serve as a template for carbonate mineral nucleation and energy substrate for heterotrophs (e.g., sulfate reducers, denitrifiers, and anaerobic sulfide oxidizers).

2.3. New Conceptual Models of Ooid Formation

The growing body of evidence implicating organomineralization in ooid formation has led to the recent emergence of new hypotheses that argue for the inorganic origin of ooids (Tang et al. 2015, Diaz et al. 2017, O'Reilly et al. 2017, Tan et al. 2017).

2.3.1. Organomineralization through prenucleation of amorphous calcium carbonate aggregates of biogenic origin. Diaz et al. (2017) developed a microbially mediated organomineralization model in which concentric lamina growth is triggered by organomineralization processes (e.g., microbially induced and influenced mechanisms) that occur on localized areas within biofilm EPS matrices. In their model, ooid cortex accretion does not follow the traditional mechanism of classical crystal growth but occurs through sequential precipitations from an ACC metastable phase to an aragonite crystal phase. Given the inherent association of ACC with EPS biofilms and associated microbes, the authors postulated that biofilm EPS in ooid outer cortices promotes the first stages of CaCO₃ precipitation by providing nucleation sites for the formation of a thin layer of ACC nanograins that eventually transitions into aragonite crystal layers (**Figure 6**). In contrast to the model of Duguid et al. (2010), who advocated for ACC abiotic origins, this model provides tangible evidence on the identity and occurrence of ACC and attributes its formation



Scanning electron microscopy (SEM) micrographs depicting a conceptual model of ooid accretion process. (a,b) Extracellular polymeric substance (EPS) on ooid outer cortices serves as a template for CaCO₃ precipitation via amorphous calcium carbonate (ACC) development. (*c*) Aggregates of ACC lead to the development of a thin layer in the outer cortex. (*d*) ACC crystallizes into aragonite crystals, forming a new cortical layer that grows over a preexisting one. (*e*) The new accreted lamina in the outer cortices is polished by mechanical abrasion, resulting in concentric lamina growth. Figure adapted from Diaz et al. (2017) with permission.

to biotic processes based on the high Mg/Ca ratios of the leachates, which are within the range of ACC values associated with organic molecules (Diaz et al. 2015), the intrinsic association and pervasiveness of EPS with ACC nanograins, and the detection of a ¹³C{¹H} CPMAS-NMR peak characteristic of RCOOH groups.

The Diaz et al. (2017) model, which also departs from Davies et al. (1978) in its inclusion of an ACC metastable phase, stipulates that ooid accretion starts in the active phase (suspension/ temporary resting stage) at the sediment–water interface, where an EPS matrix on ooid outer cortices facilitates the formation of ACC and its transformation into aragonite crystals. While ACC formation and transformation into aragonite crystals are envisaged to occur in the resting stages of the active phase, EPS colonization of the outer cortices occurs in the sleeping stage (the longest period of ooid growth) when ooids are resting in the shallow subsurface or in lower-energy portions of the active sandbars (shoals). Reexposure of ooids to turbulent flows leads to a polished layer before the start of a new growth cycle. Ooid growth is terminated or undergoes a deterioration phase when the ooids are washed away from the active bar, when the energy in the water is not sufficient to bring the ooid into saltation, or when the grains are deeply buried. It is in the low-energy zones that heavy microbial colonization leads to the cementation and decay of grains via micritization and/or the aggregation of grains (e.g., the formation of grapestones).

2.3.2. Organomineralization through a conveyor belt model. A recent study based on the molecular characterization and distribution of carbonate-bound lipids in oolitic sands from a leeward beach on Cat Island on GBB has implicated heterotrophic degradation as a mechanism of calcification and has stressed the potential importance of sediment transport in ooid accretion (O'Reilly et al. 2017). These findings, based on the lipid profiles in surf and offshore areas, prompted the authors to suggest that periodic benthic grain transport from biofilm-covered zones to surf zone areas (where ooids are actively forming) is the mechanism that triggers organic matter colonization and subsequent ooid growth. This conveyor belt model, previously introduced by Mariotti et al. (2014, 2018), stipulates that ooid accretion occurs in offshore sites away from surf zones (active sites) while undergoing cyclic transport from turbulent to nonturbulent microbially stabilized areas. The sediment transport is halted once the ooids reach a threshold size, at which point the ooids drop out from the conveyor belt zone and become grapestones. While this model may apply to some beach and near-beach sites, and while occasional onshore transport might be possible on windward beaches, this model is not applicable to the vast majority of ooid sand bodies from GBB and elsewhere, especially those that form in large tidal sandbars and deltas and display a very sharp facies boundary from the active ooid shoal to the surrounding facies (Harris 1979, Cruz 2008, Rankey & Reeder 2012), limiting the potential back-and-forth transport of ooids from highly turbulent to stabilized areas (Rankey & Reeder 2011). The net circular hydrodynamic pattern of the tidal channels is another factor preventing ooids from leaving the shoal complex (Reeder & Rankey 2008).

3. WHERE DO OOIDS FORM AND ACCUMULATE?

A small portion of GBB ooids form in agitated waters of beaches, but the vast majority form within high-energy sand bodies consisting of shallow-water sandbars that alternate with tidal channels (Figure 3). The mechanism of ooid formation is presumably the same, or at least very similar, in all areas where ooids form on GBB. The difference in the surface distribution of environments and morphology of each ooid accumulation reflects the controls on deposition particular to each site, i.e., the antecedent topography, hydrodynamic regime, sediment-organism interrelationships, and chemical binding of grains. The best-developed tidal sandbars develop in platform-margin sites with water depths ranging between 0 and 8 m and where peak spring tidal velocity exceeds 30 cm/s (Rankey & Reeder 2011). In these areas, the sandbars may be long and narrow with varying sinuosity (tidal-bar belt of Ball 1967) or lobe-shaped (marine sand belt of Ball 1967). Alternatively, gaps between islands laterally restrict and concentrate tidal currents and may promote the development of lobe-shaped tidal deltas (Ball 1967; Rankey et al. 2006; Reeder & Rankey 2008, 2009; Harris 2010). Tidal flow and wave-generated currents cause sands to be in motion over much of the length of the individual sandbars or tidal delta lobes, because there is a tidal exchange of water between the seaward and bankward sides of the sand body through the channels (Ball 1967, Halley et al. 1983, Rankey et al. 2006, Rankey & Reeder 2011). Embayments in a carbonate platform, such as TOTO and the northern Exuma Sound on GBB, give rise to particularly strong currents by amplification of tidal flow (Ball 1967) and produce vast ooid sand bodies. Velocities across all of these ooid-producing sites decrease toward the platform interior owing to friction and lateral dissipation of the flow, thus limiting the formation of ooids and bars in the distal reaches of the sand bodies.

3.1. Morphological Descriptions of Great Bahama Bank Sandbar Systems

Three of the principal ooid sand bodies on GBB—TOTO, the Schooner Cays, and the Exumas show a range of the depositional conditions and sand body attributes typifying these settings (**Figures 3** and 7). Satellite imagery and a suite of morphometric tools facilitate a comparison of the geometric character of sandbars within and among the three sand bodies (Harris & Ellis 2009; Harris 2010; Harris et al. 2010, 2011) and lead to a more robust characterization of the sand body morphology.

Rimming the southern end of TOTO is the broadest expanse of high-energy sands found in the Bahamas, comprising a tidal bar and channel belt (sensu Ball 1967) that extend parallel to the platform edge for 155 km and cover 3,120 km² (Purdy 1961, Ball 1967, Palmer 1979, Halley et al. 1983, Harris & Kowalik 1994, Harris et al. 2011). This sand body is generally characterized by a lack of islands and long, narrow sandbars separated by wide, deep channels. Individual sandbars extend onto the shallow platform by on average 20 km but up to 27 km (**Figures 7** and **8***d*). The sandbars and channels gently curve and trend at a high angle to the long axis of the sand body, which itself varies considerably in direction as it wraps around the southern end of the cul-de-sac of TOTO. The character of the sandbars and channels is not uniform throughout the length of the sand body. Long, linear sandbars that parallel each other and whose seaward terminations are coincident with the platform edge, but individual sandbars are commonly not as long and are typified by irregular, even parabolic shapes that trend in multiple directions. The sandbars to the west are set back from the platform edge, narrow, subparallel, and sinuous in part.

A variation of the tidal-bar motif occurs at the northern end of Exuma Sound in the Schooner Cays area (Ball 1967; Dravis 1977, 1979; Budd 1984; Curtis 1985; Harris & Kowalik 1994; Rankey et al. 2006; Harris et al. 2011; Rankey & Reeder 2011; Rush & Rankey 2017). The Schooner Cays, described by Ball (1967) as a tidal-bar-belt style of sand body that also includes TOTO, does in fact display contrasting geomorphic forms. In this case, the sand body, covering 716 km² and extending along the platform edge for 62 km, is progressively set back from the platform edge toward the west. In comparison with TOTO, the Schooner Cays contain broader and more irregular sandbars up to 17 km long, averaging 12 km, with relatively narrow channels and a few small islands (Figures 7 and 8e). As with TOTO, the sandbars and channels in the Schooner Cays are not uniform throughout the length of the sand body. The southeastern portion, which is perhaps most similar to the central portion of TOTO, contains individual sandbars that are narrow and sinuous. The curving bars are generally subparallel. The central portion contains depositional patterns that are different from those in the southeast and in TOTO. Sandbars are amalgamated into wider features that in detail are formed of sandbars and channels at angles oblique to the trend of the broader feature. Bars are shorter and channels are less throughgoing. A large proportion of the northwest portion of the Schooner Cays is filled with a broad expanse of shallow sand.

Sands associated with tidal channels and the numerous islands of the Exumas chain along the western edge of Exuma Sound occur primarily as flood tidal deltas in a linear belt, set back from the platform edge (Harris & Kowalik 1994, McNeill et al. 2004, Harris 2010, Harris et al. 2011). In the northern portion of the Exumas, delta lobes extend up to 8 km, averaging 6 km, onto the platform and form a deposit extending 100 km along the platform edge and covering nearly 450 km² (Figures 7 and 8*c*). The islands, often with two or three paralleling each other, and



Tongue of the Ocean (TOTO), Schooner Cays, and Exumas ooid sand bodies of Great Bahama Bank, highlighted on Landsat Enhanced Thematic Mapper Plus (ETM+) imagery by showing their respective digital terrain models in color. Water depths within the sand bodies range from 0 m (warmer colors) to 8 m (cooler colors). The clear water and relatively consistent light seafloor color support using the digital numbers of each offshore pixel in Landsat ETM+ band 1 (reflected blue light) as an approximation of water depth (sensu Harris & Kowalik 1994, Harris & Ellis 2009, Harris et al. 2010); therefore, band 1 was used to develop the bathymetric digital terrain models. The brightness and water-depth relationships are only an approximation for TOTO and the Schooner Cays because of the relative lack of depth measurements as control points; the relationship is better constrained for the Exumas, where more depth soundings are available from published navigation charts (Harris & Ellis 2009, Harris et al. 2010). Figure adapted from Harris et al. (2011) with permission.



Morphology of ooid sandbars within the sand bodies of (*a*,*b*) the Miami oolite, (*c*) the Exuma Cays, (*d*) the Tongue of the Ocean (TOTO), and (*e*) the Schooner Cays. Sandbar outlines in each case are extracted from digital terrain models. The terrain for the Miami oolite is gridded from bare-earth airborne lidar topography (panel *a*); the terrain for the modern examples is shown in **Figure 7**. The sandbars or shoals (*gray polygons*) for all sites are plotted to the same scale. Solid blue lines represent the position of the platform (or shelf) margin, taken as the 30-m bathymetry contour. The plots are oriented such that open water is to the right of the platform margins. North is indicated in each panel; the scales are identical for all panels. Note the similarity in dip extents and strike extents between the Pleistocene Miami oolite and Holocene sands of the Exuma Cays. Figure adapted from Purkis & Harris (2017) with permission.

the interisland gaps (channels) between them control the distribution of the modern sands. The central portion of the Exumas sand body has a more westerly trend than the surrounding portions and contains wide channels with associated long, linear sandbars. Flood tidal delta lobes are more uniformly developed but still variable to the north and south. The channels are relatively closely spaced in the southern portion and are regularly spaced but with a different interval in the northern portion.

3.2. Hydrodynamic Controls and Sedimentological Response

Consideration of prevailing tides, ocean currents, and winds, along with surficial sediment (facies) and bathymetric maps, provides insight into the observed patterning of sediment textures broadly atop GBB and within the ooid sand bodies. The tidal range on GBB is microtidal, approximately 1 m near the margins of the platform and decreasing onto the platform—for example, the range is only 0.3 m at the Three Creeks portion of the Andros tidal flats (Hardie & Garrett 1977, Reeder & Rankey 2008). The tides vary between approximately 0.75 m during neap tides and 1 m during

spring tides on northern Little Bahama Bank (Reeder & Rankey 2009, Rankey & Reeder 2011, Rankey & Doolittle 2012). Because of the relatively shallow water depths on the platform top, the volumetric exchanges during the tidal cycles are magnified as water is forced through narrow channels and shallow water. In some cases, these channels are between mobile geomorphic features such as sandbars or sand cays, and in other cases, they are located between bedrock islands. Flow velocities associated with the tides range from 30 to approximately 100 cm/s within different ooid shoal complexes of Little Bahama Bank (Rankey et al. 2006, Reeder & Rankey 2009, Rankey & Reeder 2011), and similar velocities were measured on GBB in a tidal inlet of the Exumas (Gonzalez & Eberli 1997) and a tidal channel of the Schooner Cays area (Rankey & Reeder 2011). Currents passing through bedrock-bounded channels are the strongest in the Bahamas and can far exceed 100 cm/s twice daily (Reeder & Rankey 2008). Current measurements across three transects in the Schooner Cays revealed a decrease in maximum speeds from 80 cm/s to 50 cm/s in a platform-ward direction through the sand body; in the platform interior, tidal currents are minimal, and wave-induced currents rarely exceed 12 cm/s (Rankey & Reeder 2011).

Sedimentological trends across the Schooner Cays sand body and other sites that parallel the decrease in current speed in a platform-ward direction include a decrease in grain size, shallowing tidal channels, and transitions from longitudinal to more transverse-oriented bars (Rankey & Reeder 2011). The change in sandbar geometry across many sand bodies suggests a relation to current changes. For example, both the TOTO and Schooner Cays sand bodies display linear, flow-parallel tidal sandbars near the platform margin that transition to arcuate bends or parabolic bars locally near their bankward terminations. The formation of ooids, transport of sediment, and generation of bar forms are limited in the platform interior because elevated tidal current velocities near the platform margin decrease when flood tides impinge farther onto the platform top. This motif of positive feedbacks among flow velocity, ooid grain size, tidal sandbar height, channel depth, sandbar shape, and even the width of the oolitic facies belt (sand body) is a general pattern in the Bahamas (**Figure 9**) and directly supports the notion that ooid sands and sand bodies



Figure 9

Schematic illustration of the positive correlations among ooid size, sandbar height, and width of the facies belt (sand body) based on observations and measurements of the Holocene sand bodies in the Bahamas by Rankey & Reeder (2011). These relationships support the notion that ooid size and accumulation are controlled by hydrodynamic processes.

are formed and shaped by hydrodynamic processes. The depositional features of different scales within and among the various sand bodies of GBB, as depicted in **Figure 7**, illustrate that smaller-scale elements (surface bedforms and sandbar type) shape or create the larger-scale features (sand bodies), while the larger-scale features provide boundary conditions constraining the smaller-scale characteristics.

3.3. Subsurface Geology of Great Bahama Bank Sandbar Systems

Although the subsurface record of modern Bahamian ooid sand bodies has been only locally investigated with coring and shallow seismic measurements, the results show how the sites of ooid production have dynamically changed and been modified during the last few thousand years of deposition. For instance, a plunging nose of Pleistocene limestone extending northward from Andros Island mainly influenced the sediment patterns of the Holocene Joulter Cays ooid sand body (Harris 1979, 1984b) (**Figure 3**). Here, antecedent topography initially localized ooid formation during the early stages of platform flooding and later structured bankward sediment transportation as the topography influenced tidal and longshore current movements around the ridge and onto the platform. During the last 5,000 years, the relationship between relative sea level and sedimentation rate was such that a coarsening-upward sequence formed during the development of the ooid sand body. Coring has shown that in a few-meters-thick interval of sediment, a complex succession of sediments can form largely as a result of depositional topography and changes in relative sea level. The Joulter Cays succession covers an area in excess of 25 km in a strike direction and 20 km in a dip direction, and within that footprint, there are significant facies and thickness changes across the breadth of the shoal.

In contrast to the Joulter Cays, where Pleistocene topography directly influenced Holocene sediment production and dispersal during early stages of shoal development, other examples reveal that oolitic successions need not always be directly associated with antecedent highs. Cruz (2008) used high-resolution seismic imaging of the Cat Cays sand bodies along the western margin of GBB (Figure 3) to show contrasting thicknesses of Holocene grainy deposits and distinct morphologies between the north and south parts of the area. The internal geometry of the sand body suggests that irregular Pleistocene topography was a probable factor during initial stages of platform-margin flooding, with a margin-parallel rock ridge affecting current flow and controlling subsequent sediment accumulation on the platform side of the ridge. High-frequency seismic data and coring from Lily Bank, a modern tidally dominated ooid sand body on the northern edge of Little Bahama Bank, suggest that ooid deposition began when water movement intensified from the funneling of tidal flow through narrow reentrants between reefs near the platform margin (Hine 1977, Sparks & Rankey 2013). Similarly, coring and seismic profiling by Palmer (1979) throughout the massive TOTO ooid tidal-bar belt and by Rush & Rankey (2017) in the southeastern portion of the Schooner Cays sand body showed highly variable sediment thickness (1-8 m thickness differential) between bars and channels overlying relatively flat Pleistocene surfaces.

4. IMPLICATIONS FOR THE GEOLOGIC RECORD

4.1. Preservation Potential of Depositional Topography and Sedimentary Patterns

The modern ooid sand bodies on GBB provide insight into sedimentary patterns in the rock record from different perspectives. The sand bodies analyzed by mapping of the depositional environment or facies document a range of depositional facies relations that can serve as templates

for determining the depositional patterns in their ancient counterparts. Such analogs are invaluable when mapping subsurface data sets, where limited-resolution seismic data and insufficient well data are the common challenges.

Purkis & Harris (2017) addressed the question of the preservation potential of the depositional topography of modern sand bodies, and therefore the potential significance of facies maps of modern sites, by examining the surface morphology of the Pleistocene Miami oolite in south Florida using a robust airborne lidar digital terrain model (Figure 8a) and select outcrops and comparing the results quantitatively with modern examples from GBB. Previous studies have shown that the geomorphic forms of ancient oolitic sand deposits can have similarities to those of modern deposits (Harris 1984a, 2010; Garrett & Gould 1986; Harris et al. 1993; Keith & Zuppann 1993; Rankey & Reeder 2011), but the Miami oolite provides exceptional examples of preserved primary sedimentary features and subsequent diagenetic changes of a fossilized, but still relatively young, ooid sand body. The Miami oolite has been subaerially exposed in a tropical climate since its deposition during the last interglacial high stand 129,000-116,000 years ago (Hoffmeister et al. 1967, Halley et al. 1977, Evans 1984, Usdun 2014). The comparison with the modern examples builds a convincing case that the surface morphology has not been drastically altered by meteoric diagenesis during approximately 120,000 years of subaerial exposure. The Miami oolite sand body, extending 95 km north to south and approximately 15 km in width, consists of sandbars (or shoals) separated by tidal channels similar to the modern counterparts (Purkis & Harris 2017) (Figure 8b). The Miami oolite is partly bounded on the ocean-facing side by a prograding barrier bar not unlike that forming in the modern Joulter Cays area, which along with the sandbars and channels covers approximately 1,000 km². Comparing the results of quantitative interrogation of the sandbars and channels of the Miami oolite with Harris et al.'s (2011) digital terrain models of the Exumas, Schooner Cays, and TOTO ooid sand bodies from GBB reveals numerous similarities in their size, shape, and spatial patterns (Figure 8). For example, the Exumas (Figure 8c) are a particularly compelling analog for the Miami oolite with respect to length and overall visual comparison between the morphologies of the sand bodies, bar shape, number of tidal channels, channel length and width, and high areas parallel to the strike trend of the sand body (islands in the Exumas and possible islands as part of the Miami oolite barrier bar). The Miami oolite serves as a key reference example for comparison with Holocene ooid sand bodies in GBB, further validating the concept of comparative sedimentology and emphasizing how results from modern areas can potentially improve the interpretation of a fossilized example.

4.2. Stratigraphic Insight

Because of the high preservation potential of entire shoal complexes, the modern ooid sand bodies of GBB serve as analogs for the stratigraphic aspect of the rock record. Consequently, the sedimentary products of the hydrodynamic processes that form and shape modern ooid sandbars and sand bodies 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. The Joulter Cays example shows the rapidity with which complex facies relations can form (Harris 1979, 1984b; Major et al. 1996a,b). The shoal, covering more than 400 km² in area and averaging 4 m in thickness, formed during the last \sim 5,000 years. Nevertheless, the record of shoal growth, largely a response to changes in relative sea level and varying sedimentation rates, indicates significant changes, such as rapid expansion of ooid sands, major reworking of sands by burrowing, and island formation. In some cases, the depositional texture, sedimentary structures, and grain types have all been modified since deposition. These changes point out the difficulty of interpreting cores from ancient examples. From a quantitative comparative sedimentology perspective, modern examples can serve as templates for geological and reservoir models. Rush & Rankey (2017) captured process-based stratigraphic trends, and therefore vertical, lateral, and azimuthal facies heterogeneities, in geo-cellular models for a portion of the Schooner Cays sand body (**Figure 3**) from analyses of satellite imagery, two-dimensional high-frequency seismic (chirp) data, and sediment cores. The models aim to assess prospective modeling trends for subsurface oolitic reservoirs, such as the size, orientation, and shape of potential reservoir bodies, and thereby explore potential patterns of three-dimensional distributions of rock fabrics and reservoir heterogeneity. Diagenetic alterations will through time change petrophysical properties like the porosity and permeability of oolitic sand bodies, but Cruz et al. (2006) showed how these changes follow a predictable trend and how early diagenesis lays the grain for future alterations.

4.3. Ooids as Archives of Past Conditions

Besides the microbial involvement in precipitation that leads to ooid formation, accretion, and cementation processes, microbes can induce textural and geochemical transformations of the grains through a cascade of microscale biological processes in tandem with geochemical conditions. This provides cautionary implications for the use of ooids as archives for paleo-environmental reconstructions in both modern and ancient environments, as ooids are constantly reshaped by biotic and abiotic factors that occur during and after growth. For instance, Duguid et al. (2010, p. 249) concluded that "analysis of unaltered cortex indicates that ooids precipitate rapidly and out of equilibrium with seawater." Furthermore, early diagenetic processes within ooids have been suggested to induce significant alterations to the values of carbonate-associated sulfate and nitrate, both of which are used as proxies to interpret oceanic values in carbonates (Diaz et al. 2015). Together, these processes could alter paleo-environmental imprints of the past record and therefore lead to questionable interpretations of the proxy record (e.g., temperature, salinity, ocean chemistry, and sea level changes).

The physical control of ooid grain size and sand body size and morphology (Figure 9) seemingly has a direct relationship to the current strength (e.g., Rankey & Reeder 2011, Trower et al. 2017, Harris et al. 2018). Purkis et al. (2017) investigated water circulation atop GBB using the hydrodynamic model MIKE 3 (http://www.mikepoweredbydhi.com). The model simulation was forced by prevailing ocean hydrodynamics surrounding the platform (including the Florida Current) as well as tides, winds, and atmospheric pressure. Current intensity and direction are examined through high-resolution time steps, and the platform can be partitioned into zones of mean annual hydrodynamic energy. Areas of vigorous tidal exchange in the model correspond to localities on GBB where high-energy ooid sand bodies have developed along the platform margin, and there is a predictive relationship between increasing peak current velocity and increasing area of the sand body for the Cat Cays, Joulter Cays, Schooner Cays, and TOTO areas in that doubling the peak current velocity increases the area of the sand body by a factor of three (Harris et al. 2018). Rankey & Reeder (2011) field documented that sand bodies with stronger currents have coarser ooids. For example, the ooids of the Schooner Cays (mean size of 600 µm) are associated with average peak speeds of approximately 90 cm/s, whereas those of the Cat Cays (mean size of $360 \mu m$) have lower speeds. The authors further showed that coarser ooids are associated with larger sandbar forms and speculated that if the width of the sand body is controlled by tidal energy, then stronger currents, larger ooids, and larger sandbars could characterize broader ooid facies belts. Although more modeling and field observations are needed, these results suggest that ooid sand bodies can be exploited to discern tidal strengths that existed in the past, all the way back to the Neoproterozoic. Thus, an important consequence of the dual influence of ooid formation and accumulation is that the geochemical signature of ooids is not in equilibrium with the seawater in which ooids form; therefore, extracting the paleophysical energy record from oolitic deposits is potentially more viable than extracting the paleochemical record.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank our colleagues at the University of Miami CSL – Center for Carbonate Research for their interaction, discussions, and support. This research was partially funded by the Industrial Associates Program of the CSL – Center for Carbonate Research. We give very special thanks to Sam Purkis for interaction and discussion on the morphology of ooid shoals, and Peter Swart for discussion on the chemistry associated with ooid growth and alteration.

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