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Discovery of Holocene ooid shoals in a siliciclastic delta, De Grey River, North West Shelf, Australia

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ABSTRACT

Onshore and offshore site investigations along the dryland tide-dominated De Grey River delta (northwestern Australia) led to the unexpected discovery of the largest yet-known marine ooid shoals in the Indo-Pacific region. Ooids exhibit up to 60 tangential aragonitic laminae that were formed around fluvial sediment grains during the late Holocene. Covering an area >1250 km², their spatial extent rivals in size individual ooid shoals from the Bahamas. Shoals appear to be spatially linked with the De Grey River, suggesting that fluvial outputs, combined with a macrotidal range, facilitated the precipitation of the ooids. Following their formation, ooids were reworked through tidal and wave processes along the delta. As a result, the delta sedimentary features, including beach ridges, mouth bars, and distributary channels, are composed of ooids.

This discovery broadens the range of depositional and climatic environments in which ooids can form and demonstrates that fluvial runoff may not inhibit aragonite precipitation. Such a configuration also provides a unique analogue for ancient ooids found in association with siliciclastic grains and further indicates that the interpretation of typical siliciclastic geomorphologies from geophysical data does not preclude the presence of carbonate grains.

INTRODUCTION

Marine ooids are spherical or ovoidal carbonate-coated grains with a diameter of <2 mm that develop around bioclasts, peloids, siliciclastic grains, or lithoclasts. They are typically formed in intertidal and shallow subtidal waters (Diaz and Eberli, 2019) and are especially abundant on high-energy tropical platforms, such as the Bahama Bank in the western North Pacific, where they form shoals tens of kilometers long and wide (Harris et al., 2019). Marine ooids have also been described in hypersaline and glacial environments (Davies, 1970; Rao et al., 1998).

Despite being studied for more than 100 years, processes involved in ooid formation are still subject to debate. Some researchers argue that ooids are abiotic precipitates (Davies et al., 1978; Duguid et al., 2010; Trower et al., 2017), while others consider ooids to be either biomediated or bio-induced (Edgcomb et al., 2013; O'Reilly et al., 2017). Recent reviews by Harris et al. (2019) and Diaz and Eberli (2019) indicate, at the very least, a microbial mediation. In any case, most models indicate that ooid formation requires rest and remobilization periods or, alternatively, permanent movement until the ooids are too heavy to be moved, at which point the accretion stops (Diaz and Eberli, 2019).

Modern marine ooids are not usually found in association with siliciclastic environments where terrestrial inputs can rapidly bury seabed sediments, hence limiting the potential for remobilization and carbonate coating. Yet, our study reports the discovery of extensive (1250 km²) Holocene marine ooid shoals that appear to be the main sediment contributor of the De Grey River delta system, the largest gauged fluvial system of the North West Shelf of Australia (Fig. 1). We explore the possible processes responsible for the formation of this peculiar depositional system and discuss how it affects current understanding of ooid formation mechanisms.

GEOLOGIC SETTING

The North West Shelf (NWS) is a continental margin stretching over 2400 km along Australia between the North West Cape (114°E) and Melville Island (130°E) (James et al., 2004). The continental shelf is dominated by carbonate sedimentation and is divided into three depth zones, with the inner ramp from 0 to 50 m below sea level (bsl); the midramp from 50 to 120 m bsl; and the outer ramp from 120 to 200 m bsl (James et al., 2004; Dix et al., 2005). Prominent shelf morphologies consist of drowned paleoshorelines and reefal deposits that formed atop these antecedent topographic highs (Lebrec et al., 2022b).

The Pilbara coast is situated along the NWS inner southern margin. It is an arid riverine coastal plain influenced by fluvial processes (Semeniuk, 1993), with terrestrial sediments restricted to the inner shelf (James et al., 2004; Lebrec et al., 2022b). The De Grey River delta is the largest and easternmost of the seven active deltas identified along the Pilbara coast (Fig. 1). It has a catchment area of 54,752 km² and an average annual water discharge of 1313 GL/yr (Water Data Online, http://www.bom.gov.au/waterdata/, last accessed 7 October 2022; Eliot et al., 2013). Fluvial discharge results mainly from periodic cyclones and tropical lows occurring during the austral summer. The delta front is affected by strong tidal currents with an estimated tidal range in excess of 7 m (Fig. 1).

Prior to our study, ooids had been identified along the mid-to-outer ramps, where they form local accumulations that were deposited on tidal platforms during periods of lower sea levels (James et al., 2004; Gallagher et al., 2018; Hallenberger et al., 2019). The inner ramp, on the other hand, was thought to only include rare reworked ooids (James et al., 2004; Semeniuk,

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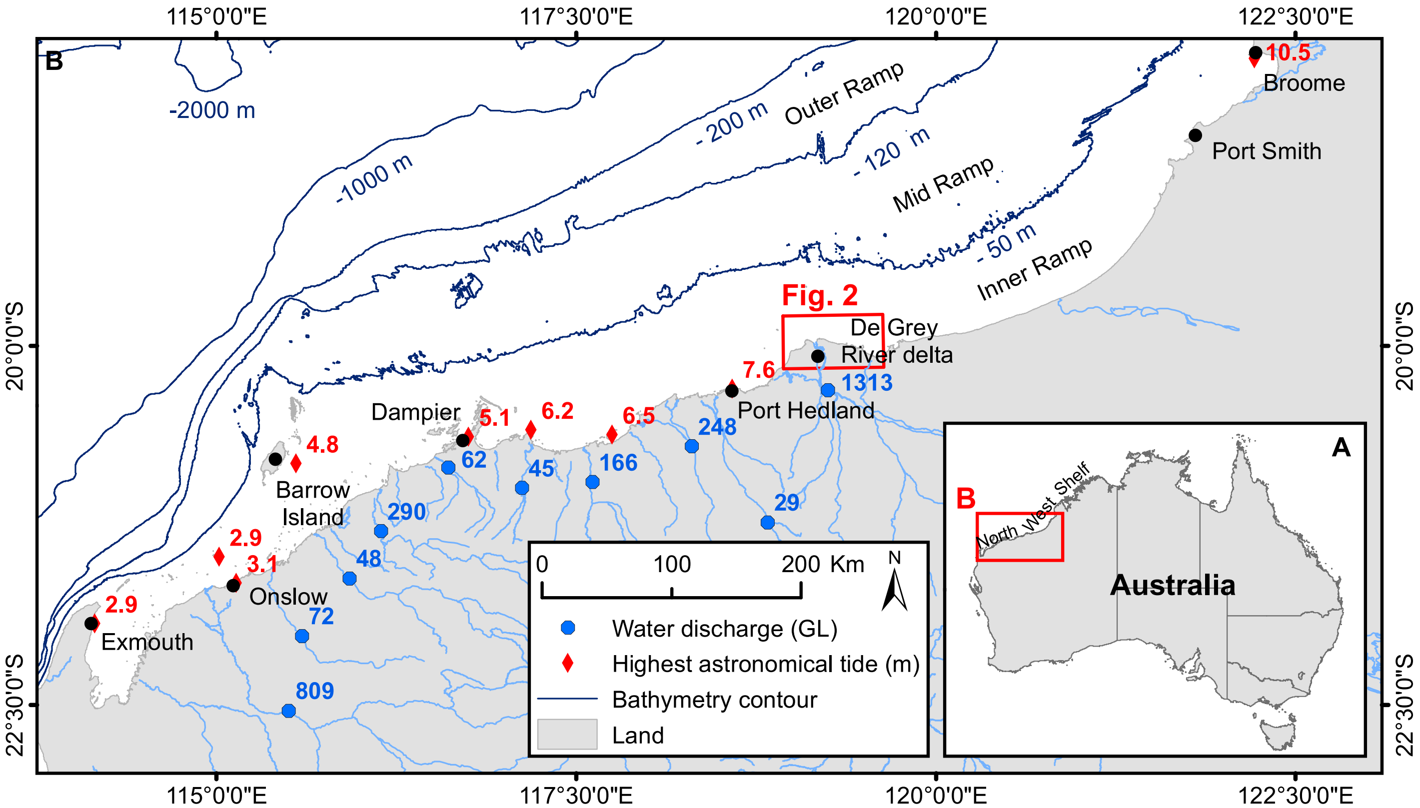

Figure 1. Location maps of the study area, with contours derived from Lebrec et al. (2021) bathymetry. Tide and water discharge values are from the Australian Hydrographic Office (2022) and Water Data Online (http://www.bom.gov.au/waterdata/, accessed 7 October 2022).

2008). Such contrast is thought to reflect climatic variations and in particular the onset of the monsoon during wet interglacial periods (Hallenberger et al., 2019). One notable exception is the presence of isolated Pleistocene and Holocene oolites, respectively, near Port Smith and Port Hedland (Semeniuk, 1996; Hearty et al., 2006), which have a smaller geographic extent than both the mid-to-outer ramp deposits and the De Grey River shoals.

DATA AND METHODS

Our research builds on the integration of high-resolution digital elevation models (DEMs) with onshore and offshore sediment samples. DEMs included 10-m-resolution satellite-derived bathymetry from Lebrec et al. (2021) and 1-m-resolution light detection and ranging (lidar) data acquired in 2021 by Airborne Research Australia (Adelaide). Data gaps were filled using the 30-m-resolution Shuttle Radar Topography Mission (SRTM) grid from Gallant et al. (2011). Seabed bedforms were automatically measured using the workflow from Lebrec et al. (2022a), while shoal extents were calculated as aggregates of individual bedforms.

We collected offshore samples in July 2021 using a subsea drill rig operated by divers. The samples consist of three push cores with a penetration ranging from 0.4 m to 0.7 m, one drill core with a penetration of 3 m but a poor recovery, and 14 seabed samples. Thirty-two (32) onshore samples were collected during two field-work campaigns conducted in August 2019 and 2021 (see the Supplemental Material[1]).

In total, 29 samples were impregnated with blue epoxy to prepare covered thin sections. Each thin section was half stained with alizarin red S and potassium ferricyanide. The mineral composition of these samples was determined by random powder X-ray diffraction analysis using a Panalytical Aeris diffractometer. Results were interpreted using High Score Plus software (https://www.malvernpanalytical.com/) and a Rietveld fit. A selection of ooids was age dated using single-stage accelerator mass spectrometry (AMS) radiocarbon measurements following Yokoyama et al. (2019), including acid cleaning as well as calibration values from Heaton et al. (2020) and Squire et al. (2013).

RESULTS

The De Grey River delta is a dryland deltaic system with a width of 80 km and an inboard length of 30 km (Fig. 2). The delta exhibits low-lying relief apart from 10-m-high and 200–500-m-wide beach ridges, which can be followed laterally over more than 40 km. Fluvial sediments are carried to the delta-front through a main active channel belt. Additional inactive distributary channels, associated with levees and crevasse splays, can be seen from both lidar and SRTM topography, especially eastward. The river channel belt, initially 200 m wide inland, becomes increasingly wider seaward to reach a maximum width of 7 km at the river mouth. The inner estuarine part of the river mouth is occupied by a 3-km-wide composite mouth bar that extends seaward over at least 5 km. Such morphologies are characteristic of tide-dominated, wave/fluvial-influenced deltas (TWF), sensu Ainsworth et al. (2011).

Farther offshore, the mouth bar complex transitions into an attached subtidal delta-front shoal complex (DFSC), which is deflected eastward (Fig. 2A). The DFSC has an east-west length of 40 km and a maximum width of 10 km. The De Grey River shoals are covered in sandwaves that have a wavelength of between 50 and 100 m and a height of less than 1.5 m, and they exhibit a subtle asymmetry, typical of tidal environments along the NWS (Lebrec et al., 2022a). The outer boundary of the complex exhibits an increase in water depth of ~5 m. Additional smaller shoals (s in Fig. 2), with less defined boundaries, can be observed on either side of the DFSC. Shoals disappear farther away from the mouth bar, indicating that they are tied to the delta. Altogether, they cover an area of 1250 km^2.

Ooids were identified throughout the deltaic system. They are primarily developed around

[1]Supplemental Material. Sample coordinates and ooid percentages. Please visit https://doi.org/10.1130/GEOL.S.21935982 to access the supplemental material and contact editing@geosociety.org with any questions.

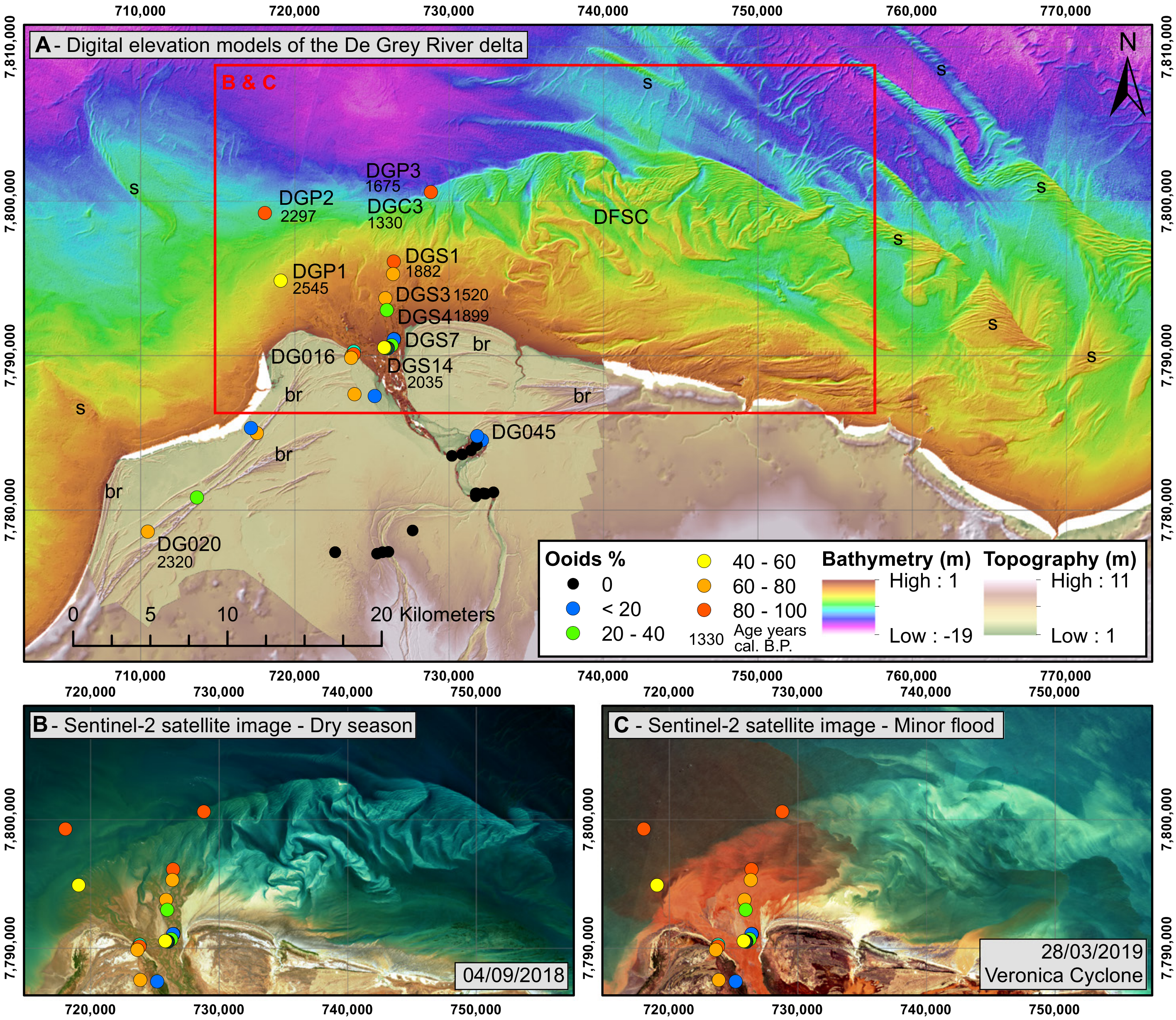

Figure 2. (A) Geomorphology of the De Grey River delta (northwest Australia) and sample locations. Symbology shows the visual percentage of ooids per sample. WGS84 UTM 50S. (B,C) Satellite images, courtesy of the European Space Agency, illustrating delta seasonality between the dry season (B) and wet season (C), when red plumes can be observed. DFSC—delta-front shoal complex; s—smaller shoals (less defined boundaries); br—beach ridges.

quartz (>80%) and, to a lesser extent, feldspar, lithic, peloid, and bioclastic nuclei (Fig. 3). The coating consists of up to 60 concentric aragonitic tangential laminae that locally exhibit micro-boring (Fig. 3B). While the number of laminae varies, the resulting ooids are almost uniformly within the medium sand-size fraction (250–500 µm). In some cases, ooids have multiple nuclei or a first ooid was reused as the nucleus of another one (Figs. 3C and 3D). The color, relative abundance, and level of preservation of the ooids vary between sedimentary features.

Onshore, ooids are mainly found within beach ridges, where they constitute up to 90% of the grains (Fig. 3E). At such sites, ooids are yellow to brown and appear to be coated with eolian dust. They often exhibit traces of impact, and, more rarely, part of the coating is broken. Some of the beach ridges are entirely cemented and show widespread meniscus cements.

Along the active distributary channel belt, the relative abundance of ooids varies with the distance from the river mouth (Fig. 2). Upstream, sediments do not contain any ooids (Fig. 3F), but they become increasingly common toward the estuarine river mouth (Fig. 3G), and, at the main mouth bar complex, samples can contain up to 50% ooids (Fig. 3H). These ooids are generally intact and have colors ranging from gray to yellow.

Nearshore, sediments collected along the axis of the river mouth contain between 25% and 60% ooids. East of sample location DGS3, DFSC samples contain between 70% and 95% ooids (Figs. 3A and 3I). These ooids are intact and exhibit colors ranging from gray to brown. The drill core DGC3 shows that ooids can be observed at a depth of 3 m, with similar abundance, suggesting that the entire complex is dominated by ooids.

Radiocarbon dating returned ages between 2545 cal. (calibrated) yr B.P. and 1330 cal. yr B.P. (Table 1). Given that the measurements were conducted on whole ooids that exhibit tens of laminae, they represent an amalgam of laminae formation history. Hence, considering that ooids take hundreds of years to form (Diaz and Eberli, 2019) and that the ooids were

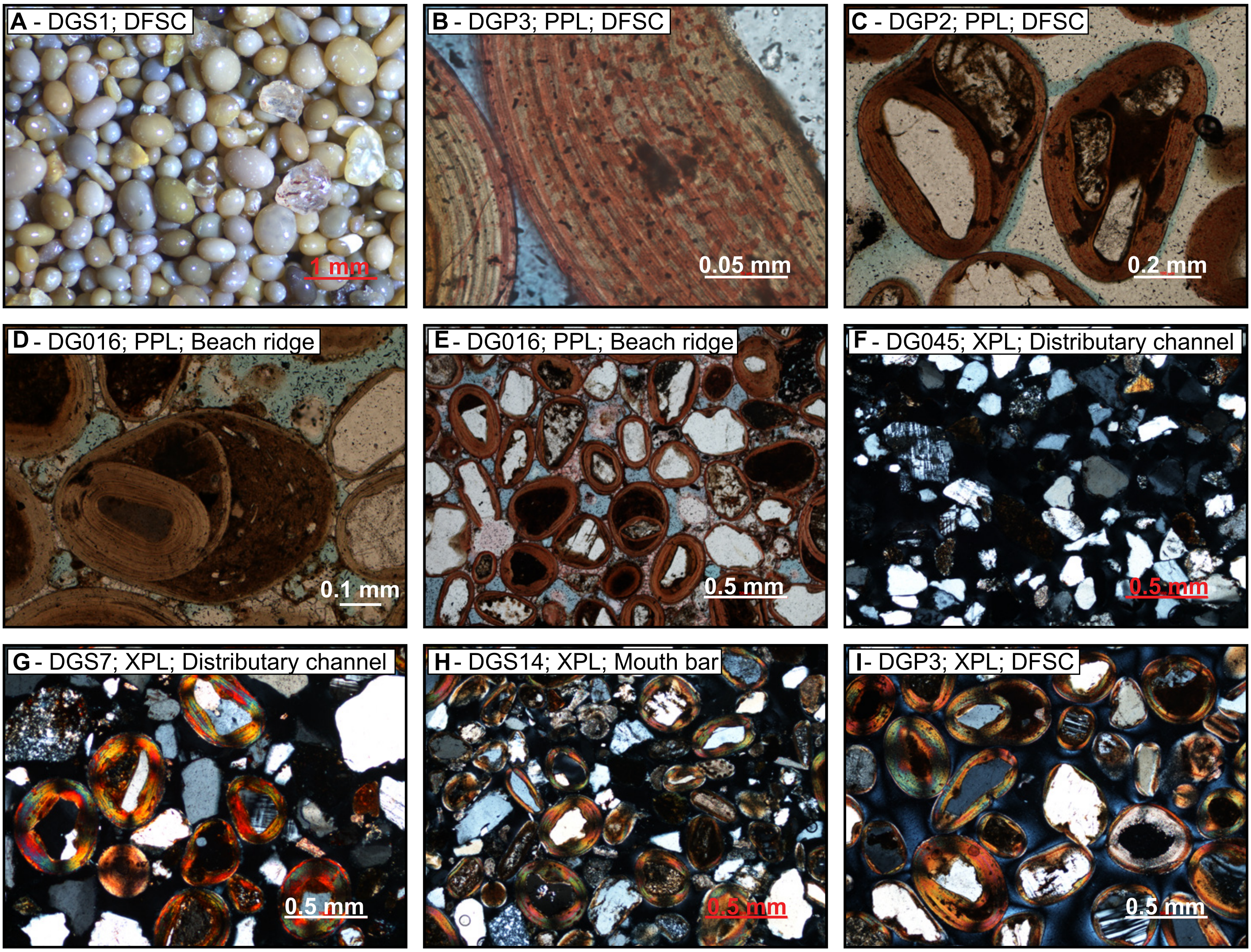

Figure 3. Examples of De Grey River delta (northwestern Australia) sedimentary facies. (A) Macroscale view. (B) Ooid cortex. (C,D) Composite ooids. (E) Cemented beach ridge. (F) Inland distributary channel. (G) Nearshore distributary channel. (H) Mouth bar. (I) Delta-front shoal complex (DFSC). Sample locations are shown in Figure 2. PPL—plane-polarized light; XPL—cross-polarized light.

acid leached, the relatively young ages suggest that ooid formation has been active in the last millennium.

DISCUSSION

Origin of the De Grey River Delta Ooids

The De Grey River delta hosts the largest known Holocene ooid shoals in the Indo-Pacific region. However, their proximity to a fluvio-deltaic system makes this an atypical depositional system. What is even more confounding is that this style of deposit is not known to occur with any other dryland delta system along the Pilbara coast. It begs the questions: where do ooids form, and what is unique about this environment to enable such accumulation?

First, we hypothesize that De Grey ooids are formed on the DFSC before being reworked along the coast, and that the "factory" is still active. The ooids disappear farther upstream of the river mouth and are mainly coating fluvial sediments, while most of the shelf is characterized by bioclastic sediments (James et al., 2004). The age of the ooids also becomes younger eastward, toward the DFSC. This indicates that they are formed locally, in the offshore realm. Additionally, the climate, fluvial runoff, and sea level have remained stable since, and throughout, the formation of the ooids (Lewis et al., 2013; Kuhnt et al., 2015; Ishiwa et al., 2019), hence implying that the oceanographic conditions enabling ooid development are still present.

Second, we suggest that a unique combination of tidal energy and fluvial sediments enabled the formation of the De Grey River ooids. Indeed, tidal energy, which is a key driver to ooid formation (Diaz and Eberli, 2019), increases gradually eastward, but no other ooid deposits were identified apart from those at Port Smith and Port Hedland (Fig. 1). De Grey River fluvial sediments may therefore have the correct grain size, given the sediment density and the local tidal energy, to enable distinctive rest and remobilization periods and, in turn, ooid development. The seasonality of the sediment discharge may then maintain nuclei supply without burying the factory. Additionally, the De Grey River waters may facilitate

TABLE 1. RADIOCARBON AGE DATING RESULTS FOR OOIDS FROM DE GREY RIVER DELTA, NORTH WEST SHELF, AUSTRALIA

Sample	DGP1	DGP2	DGP3	DGC3	DGS1	DGS3	DGS4	DGS14	DG020
Radiocarbon age (yr B.P.)	3018 ± 35	2793 ± 31	2300 ± 27	1986 ± 21	2467 ± 55	2175 ± 23	2482 ± 32	2578 ± 28	2806 ± 25
Age (cal. yr B.P., p95)	2545	2297	1675	1330	1882	1520	1899	2035	2320

Note: p95 is 95% probability.

the development of the ooids. Carbonate alkalinity measurements conducted in water pools along the river returned values between 200 and 265 mg/L (Pinder et al., 2010), while the seawater was measured at 102 and 108 mg/L off Mardie Creek, east of Dampier (Wellington, 2020). Moreover, the river may supply nutrients and organic matter to the system that could trigger carbonate precipitation.

Significance of this Discovery

The De Grey River delta ooid shoals cover an area (1250 km^2) similar to the individual Bahamas ooid shoals reported by Harris et al. (2019) such as Tongue of the Oceans (3120 km^2), Schooner (716 km^2), Exumas (450 km^2), and Joulter (400 km^2) cays, and should therefore not be regarded as a local oddity. Gallagher et al. (2018) questioned whether the lack of ooids in the Indo-Pacific oceans was the result of the oceanographic conditions or a sampling bias. The discovery of the De Grey River ooids, combined with previous work from Davies (1970), Jones (1973), Semeniuk, (1996), James et al. (2004), Hearty et al. (2006), and Gallagher et al. (2018), clearly shows that the lack of ooids is indeed a result of sampling bias. The northwest marine region of Australia alone is a major ooid province, and additional ooid factories should be expected in Indo-Pacific oceans. Importantly, the region includes ooids formed in varying depositional environments and affected by different sedimentary processes, and their study could help to improve existing ooid development models that rely largely on the Bahamas ooid shoals.

Modern marine ooids have been described in association with tidal-, wave-, and wind-dominated environments (Diaz and Eberli, 2019), but never in the vicinity of river mouths supplying siliciclastic sediments. This implies that the identification of ooids may not necessarily indicate an environment with limited fluvial-sediment supply and that fluvial runoff may not completely inhibit aragonite precipitation. Thus, ooids may form in more diverse environments than previously thought, which has key implications for their use as a proxy for paleoclimate and paleoenvironment reconstructions; in particular, for ancient ooid deposits described along mixed siliciclastic-carbonate platforms (e.g., Braga et al., 1995; Rodríguez-Martínez et al., 2022).

CONCLUSIONS

The De Grey River delta, located on the arid Pilbara coastal plain of the NWS, is a tide-dominated, wave- and fluvial-influenced dryland delta that has been mostly understudied until now. Our collection of both onshore and offshore sediment samples revealed that the delta hosts a 1250 km^2 ooid factory rivalling in size the individual ooid shoals from the modern Bahamas.

De Grey River delta ooids are formed around siliciclastic grains along a delta-front shoal complex, suggesting that their formation is tied to the river outflow, before they are reworked along the coast. As a result, the delta coastal sedimentary features, including beach ridges, mouth bars, and distributary channels, are mainly composed of ooids. This indicates that ooids can form in tide-dominated fluvio-deltaic environments, and in turn that fluvial runoff may not completely hinder aragonite precipitation. This discovery further challenges the separation between carbonate and siliciclastic domains with an example of typical siliciclastic morphologies consisting of carbonate-coated grains. This also implies that the identification of fluvio-deltaic morphologies from geophysical surveys may not systematically exclude carbonate sediments.

The discovery of the De Grey River delta ooids, combined with previously reported ooid accumulations in the region, means that the northwest marine region of Australia should be recognized as a major ooid province. The region could therefore be an alternative location in which to investigate ooid formation mechanisms, and may provide closure on the long-lived question of whether ooids are biotic or abiotic.

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