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Statistical pattern analysis of surficial karst in the Pleistocene Miami oolite of South Florida

Paul (Mitch) Harris *, Sam Purkis, Bella Reyes

CSL – Center for Carbonate Research, Department of Marine Geosciences, RSMAS, University of Miami, 4600 Rickenbacker Causeway, Miami, Fl 33149, USA

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ABSTRACT

A robust airborne light detection and ranging digital terrain model (LiDAR DTM) and select outcrops are used to examine the extent and characteristics of the surficial karst overprint of the late Pleistocene Miami oolite in South Florida. Subaerial exposure of the Miami oolite barrier bar and shoals to a meteoric diagenetic environment, lasting ca. 120 kyr from the end of the last interglacial highstand MIS 5e until today, has resulted in diagenetic alteration including surface and shallow subsurface dissolution producing extensive dolines and a few small stratiform caves.

Analysis of the LiDAR DTM suggests that >50% of the dolines in the Miami oolite have been obscured/lost to urbanization, though a large number of depressions remain apparent and can be examined for trends and spatial patterns. The verified dolines are analyzed for their size and depth, their lateral distribution and relation to depositional topography, and the separation distance between them. Statistical pattern analysis shows that the average separation distance and average density of dolines on the strike-oriented barrier bar versus dip-oriented shoals is statistically inseparable. Doline distribution on the barrier bar is clustered because of the control exerted on dissolution by the depositional topography of the shoal system, whereas patterning of dolines in the more platform-ward lower-relief shoals is statistically indistinguishable from random. The areal extent and depth of dissolution of the dolines are well described by simple mathematical functions, and the depth of the dolines increases as a function of their size. The separation and density results from the Miami oolite are compared to results from other carbonate terrains. Near-surface, stratiform caves in the Miami oolite occur in sites where the largest and deepest dolines are present, and sit at, or near, the top of the present water table.
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1. Introduction

Exposures of the Miami oolite (equivalent to the oolitic facies of the Miami Limestone of Hoffmeister et al., 1967) in the vicinity of the Miami metropolitan area, South Florida, provide excellent examples of preserved primary sedimentary features and subsequent diagenetic changes of a "fossilized" carbonate sand body. This Pleistocene formation serves as a reference example for comparison to Holocene sand units in the Bahamas (Purkis and Harris, 2017), and also outcrop and subsurface examples in the geological record. The Miami oolite displays the preserved morphology of an ooid sand body, even though it has been subaerially exposed in a tropical climate since its deposition during the last interglacial highstand – Marine Isotope Stage 5e (MIS 5e). Purkis and Harris (2017) used a bare-earth airborne light detection and ranging digital terrain model (LiDAR DTM) (Fig. 1B) to quantitatively compare the Pleistocene sand body and its component features (dip-oriented tidal shoals and channels, strike-oriented barrier bar) to modern counterparts from the Bahamas and concluded that depositional morphologies were well preserved in the Miami oolite despite the ca.120 kyr of meteoric diagenesis. The "young" outcropping surface of the Miami oolite is indeed insightful from a depositional perspective, but at the same time, the high-resolution LiDAR DTM and select outcrops show a depositional surface that is locally modified by surficial karst features, primarily dolines, and a few shallow stratiform caves (Cressler, 1993; Florea et al., 2008; Cunningham and Florea, 2009), which are the focus of this study (Figs. 1 and 2).

It has long been recognized that the Pleistocene limestone surface in the Florida Keys (Dodd and Siemers, 1971) and in the Everglades (Craighead, 1964) has a karst topography ("riddled with dolines") that impacts Holocene sediment thickness and facies. Circular to oval dolines (or sinkholes), up to 75 m or more in diameter and >4 m deep, formed within the Miami oolite and the Key Largo Limestone on Bahia Honda and Big Pine Keys in the Florida Keys, ~200 km south of the present study area, and are usually completely filled with peat and/or carbonate sediment. Surficial dolines (karst pits) and small, shallow caves have also been recognized in outcrops of the Miami oolite (Halley and Evans, 1983; Cressler, 1993; Florea et al., 2015) and within the Biscayne aquifer (Cunningham and Florea, 2009). Cressler (1993) described 20 caves that are accessible from the surface with the longest estimated

* Corresponding author.
E-mail address: pmitchharris@gmail.com (P.M. Harris).

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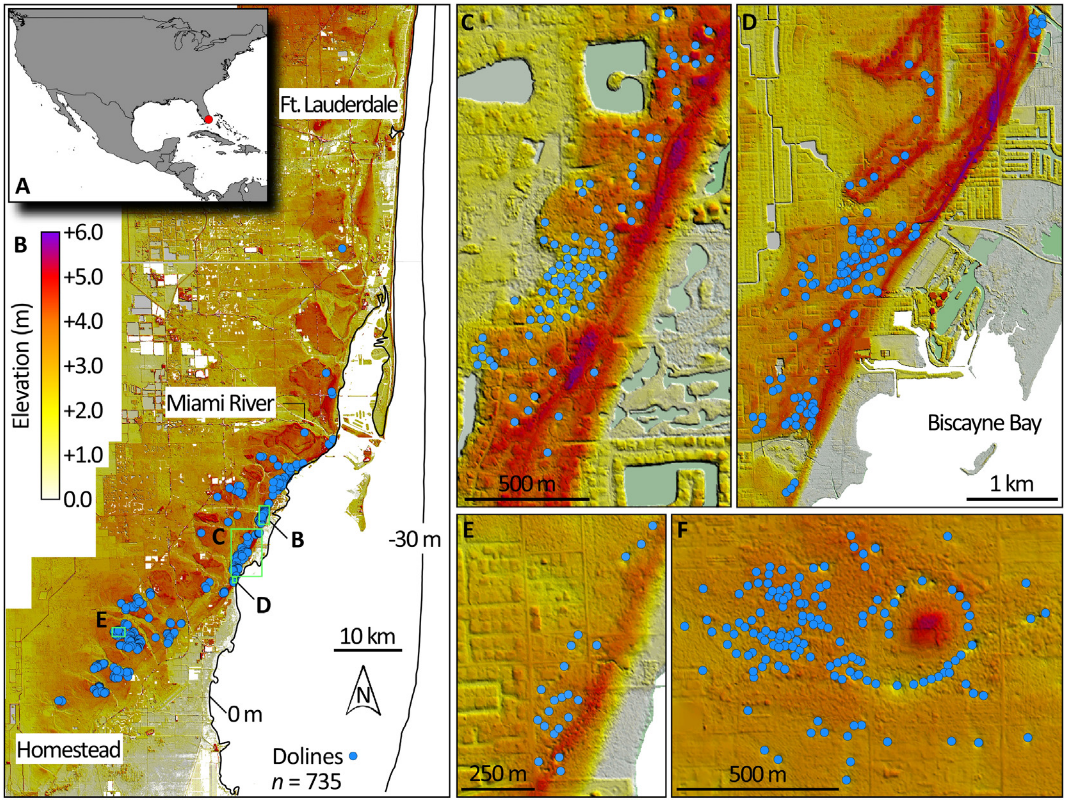

Fig. 1. (A) Location of the Miami oolite in the vicinity of the Miami metropolitan area, South Florida, USA (*red dot*). (B) Bare-earth airborne LiDAR topography of the Pleistocene Miami oolite sand body of the metropolitan Miami area (modified with permission from Purkis and Harris, 2017). The formation, which extends 95 km north to south from Ft. Lauderdale to Homestead and is approximately 15 km wide, consists of dip-oriented highs (shoals or bars, 1–4 km in length and 1–3 km in width) and lows (channels). A strike-oriented barrier bar fronts the dip-oriented shoals and channels except in the southerly portions of the sand body. The shoals and barrier bar add up to 6 m of terrain to the otherwise flat landscape of Broward and Miami-Dade Counties. The present-day coastline and −30 m shelf contours plotted as black lines. The sand body is increasingly offset from the shelf margin to the south. Dolines ($n = 735$) digitized from the LiDAR surface and validated in the field (blue dots) variably develop throughout the deposit. (C), (D), and (E) emphasize karst dissolution on the barrier bar, whereas (F) shows dolines developed around a topographic high on a lower-relief platform-ward shoals. Locations of (C), (D), (E), and (F) indicated with green boxes in (B). LiDAR data courtesy of the Florida Division of Emergency Management Statewide Coastal LiDAR Project. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

at ~120 m with a vertical extent of 4.5 m (see Fig. 2H) and Florea et al. (2015) surveyed a subset of these and discovered seven additional caves.

A closer examination of the surface topography over a broader exposure of the Miami oolite in this study using the robust LiDAR DTM provides an opportunity to investigate the extent and spatial characteristics of this surficial karst with a more quantitative, and potentially predictive, approach that will have applicability to other exposed and subsurface karst terrains. Karst-modified hydrocarbon and aqueous carbonate reservoirs are often characterized by extreme heterogeneity, with reservoir compartmentalization commonly attributed to the products of meteoric diagenesis, including dolines, caves, fracture-controlled solution features, vuggy porosity, and collapse breccias. However, the amount of karst overprinting in these systems can vary laterally and its role in influencing reservoir character can range from insignificant to extensive. Our quantitative analysis of the Miami oolite can perhaps aid prediction where karst is, or is not, a dominant factor, and thereby be a potential control on reservoir character in analogous karsted settings. The results are also relevant to urban planners tasked with assessing levels of risk in karst-vulnerable areas.

2. Background to the Miami oolite

2.1. Depositional facies regions

A number of studies address the depositional history as well as early diagenetic alteration of the Miami oolite. These include Hoffmeister et al. (1967) who mapped the surface geology and subdivided the Miami Limestone into two distinct facies – the bryozoan facies and the oolitic facies. As shown by Parker et al. (1955), Hoffmeister et al. (1967), as well as Perkins (1977), the oolitic facies (here termed the "Miami oolite") forms the elevated Atlantic Coastal Ridge along the eastern side of the south Florida peninsula, and the low-lying area to the west of the ridge is composed of the bryozoan facies. The Miami oolite was deposited as mainly shallow marine shoals (tidal bars) and tidal channels during MIS 5e when sea level was ca. 6 to 7 m higher than present (Osmond et al., 1965; Hoffmeister et al., 1967; Halley et al., 1977; Usdun, 2014). The Miami oolite is a wedge-shaped unit reaching its maximum thickness of approximately 11 m along its seaward edge. By contrast, the bryozoan facies to the west is the thinner and more widespread platform interior equivalent (Halley and Evans, 1983; Evans, 1984). Halley et al. (1977), Halley and Evans (1983), and Evans (1984) further studied the morphology of the Miami oolite and divided the sand body into two distinct areas which are relevant to the current study: (i) the shoal and channel system where the main orientation of the individual elements is perpendicular to the overall trend of the sand body; and (ii) a barrier bar which is oriented parallel to the strike trend of the body and positioned along a portion of its seaward boundary. Of particular importance to the analysis of dolines and shallow, stratiform caves in the Miami oolite are the differences in elevation, topography, and orientation between these two areas. The barrier bar is strike-oriented and has a higher, but more variable elevation (due to ridges and troughs) (Fig. 1C, D, and E) than the more platform-ward, dip-oriented, and lower relief shoals and channels (Fig. 1B, F). The lowest areas of the depositional topography of the Miami oolite, and currently the lowest surface elevations, are the tidal channels that

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