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Ichnogenic Porosity, High-Frequency Cyclostratigraphy, and Groundwater Flow in the Karst Biscayne Aquifer, SE Florida, USA

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The karst Biscayne aquifer is of major importance to the groundwater budget of southeastern Florida, especially in terms of freshwater supply for the restoration of the Everglades, needs of coastal metropolitan areas, and issues concerning saltwater intrusion near the coast. In Miami, our principal area of investigation, the aquifer primarily consists of two Quaternary carbonate units, the Miami Limestone (late Pleistocene) and older Fort Thompson Formation. Our recent studies of Miami Limestone outcrops and continuously cored boreholes penetrating both units indicate that ichnofabrics generated by callianassid burrowing are an important hydrologic element in the aquifer. Maximum intensity callianassid ichnofabric with robust segments of *Ophiomorpha* is a common characteristic of both lithostratigraphic units (Figures 1A and 2) and *Thalassinoides* are abundant in wackestone and packstone of the lower part of the Miami Limestone (MIS 7, Figure 3). Callianassids also have created dense *Thalassinoides*-dominant ichnofabrics in micrite-rich limestone of the Fort Thompson Formation. In the Miami Limestone, spiral segments of *Ophiomorpha* burrow systems have been documented at several sites (Figure 1B), as well as specimens of *Conichnus conicus* (Figure 1C). In addition, clusters of upwardly radiating *Ophiomorpha* shafts are present that have an overall bouquet-like shape and are, in some cases, superimposed on *C. conicus* specimens (Figure 1D). The identification of ichnotaxa present and evaluation of their ichnofabric-forming potential and characteristics will create a better understanding of (1) the role of ichnology within the context of a high-frequency cyclostratigraphy, and (2) the important linkage between biogenic porosity and groundwater flow.

In the Biscayne aquifer, biogenic porosity mostly manifests as two forms of touching-vug porosity: (1) macro-moldic porosity (readily visible without magnification) generated by the dissolution of organism hard parts, principally mollusc shells; and (2) ichnogenic porosity resulting from burrowing activity, primarily by callianassids. Our definition of ichnogenic porosity includes one or more of the following: intra- or inter-burrow porosity and less common intra- or inter-root porosity. The typical example results from dense occurrences of well-lined callianassid burrows (Figures 1A and 2). Burrow tubes commonly remained open or were later washed-clean or cleared of fill via dissolution, generating intra-burrow porosity. With dissolution *Ophiomorpha* segments may lose part or all of the burrow lining, usually from the inside outward. Also, the dense complex of *Ophiomorpha* formed rigid frameworks surrounded by a less well-lithified matrix that may have been transported or dissolved away, resulting in inter-burrow porosity (Figure 2). Such ichnogenic porosity commonly is associated with the lower-to-middle part of upward-shallowing subtidal and paralic high-frequency cycles (Figure 3). An uppermost aggradational high-frequency cycle (HFC5e) of the Miami Limestone (Figure 3), in some cases, shows a gradual upward decrease in the inner diameter of *Ophiomorpha* burrows. This decrease may be related to tiering of callianassids by age, with fully mature adults at depth and juveniles closer to the surface, or to possible tiering of different species of callianassids, driven by a slight shallowing of water depth during cycle accumulation.

It is suggested herein that much of the ground-water flow in the Biscayne aquifer is related to biogenic porosity that forms tabular-shaped stratiform flow zones (Figure 3). The hydrologic importance of biogenic porosity was determined for a 246 km² study area by

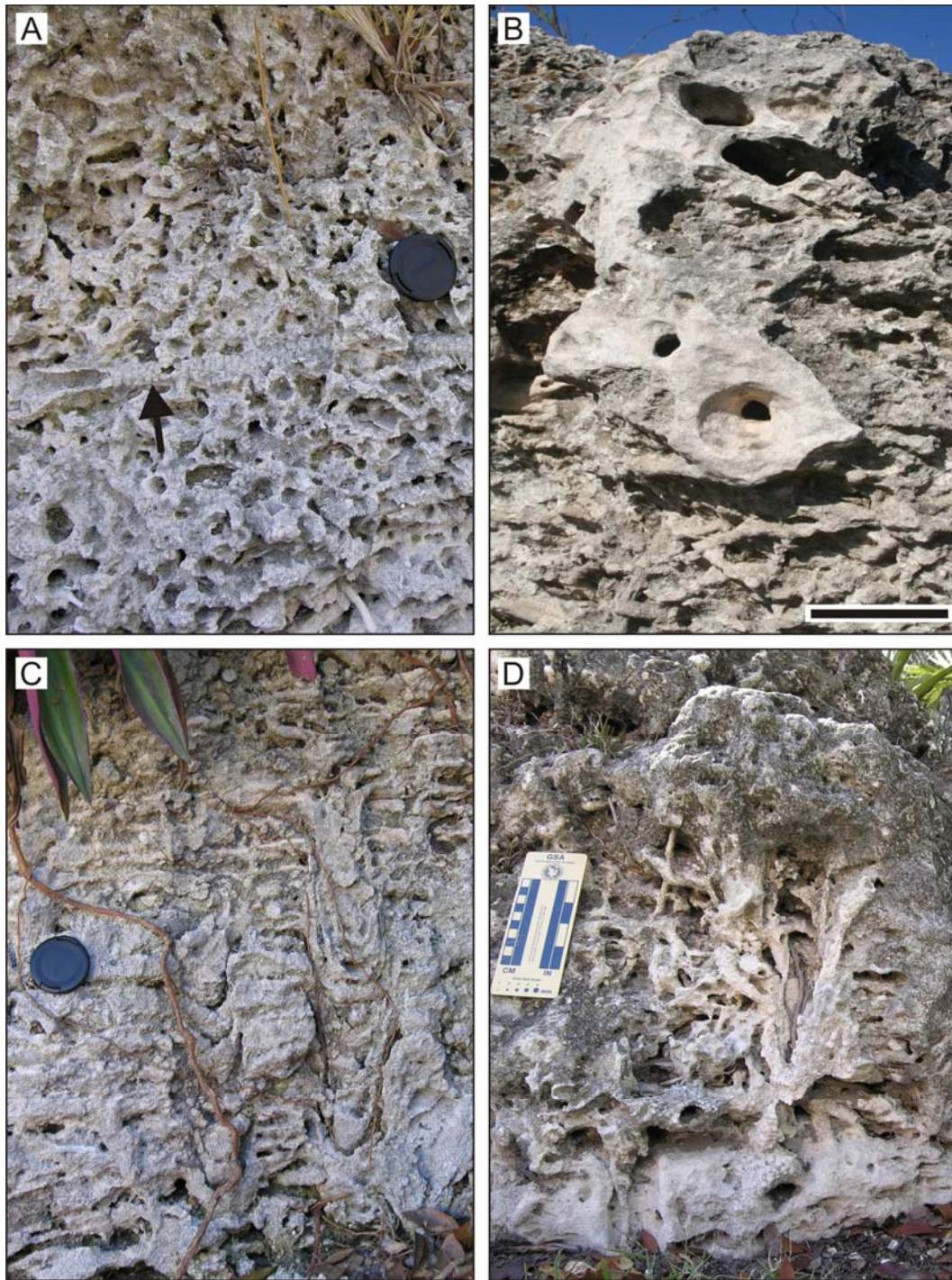


Figure 1. Trace fossils from the Miami Limestone (late Pleistocene, MIS 5e), Miami, Florida. A. Maximum intensity ichnofabric generated by callianassid burrowing. Note the presence of numerous segments of *Ophiomorpha* shafts and tunnels, including a well-pelleted tunnel (arrow) in the foreground. Lens cap for scale = 4.7 cm in diameter. B. Spiral *Ophiomorpha* segment, likely formed by the callianassid *Glypterus acanthochirus*. Matrix sediment also intensely burrowed by callianassids. Bar scale = 10 cm. C. Two well-developed *Conichnus conicus* specimens in parallel vertical orientation. Lens cap for scale = 4.7 cm in diameter. D. A cluster of *Ophiomorpha* shafts creating a bouquet-like shape and possibly superimposed on a *C. conicus* specimen. Note the presence of very robust and well-pelleted *Ophiomorpha* tunnels at the base of this exposure.

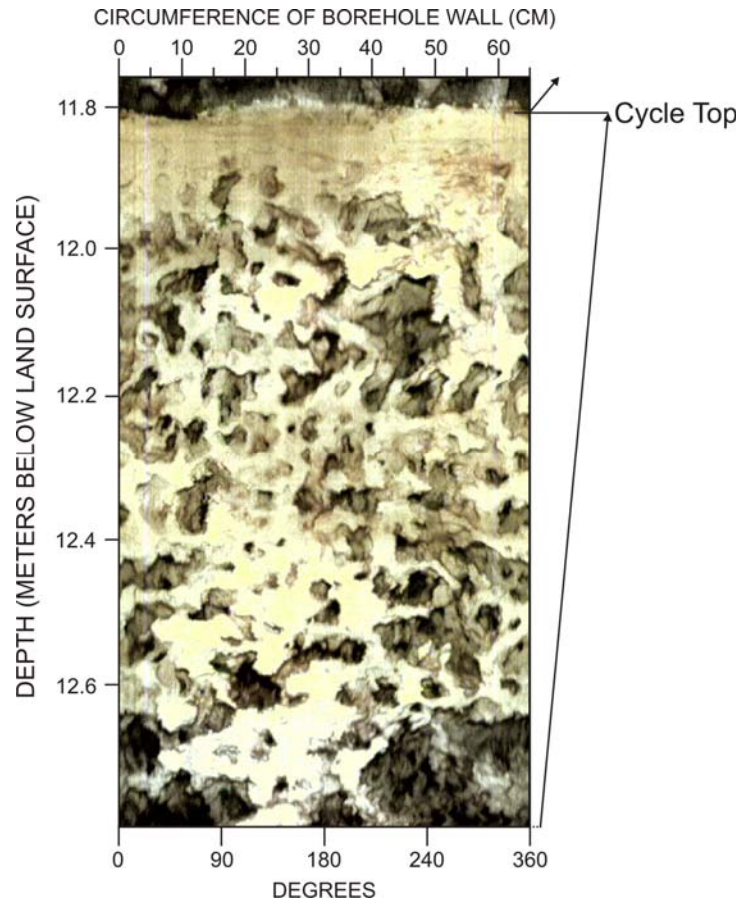


Figure 2. Example of ichnogenic porosity (intra- and inter-burrow) formed by the dense occurrence of *Ophiomorpha* shafts and tunnels. Photograph was acquired by a digital-optical borehole-image tool scanning a borehole wall in the Fort Thompson Formation (Pleistocene, MIS 11), Biscayne aquifer, Miami, Florida. The borehole wall image has been unwrapped to display an entire 360° view. Throughout the vertical interval, the borehole has a diameter of about 20.3 cm and an approximate circumference of 65 cm.

examining outcrops, cores, and borehole geophysical data that include digital-optical borehole-image logs, and flowmeter, fluid-conductivity and fluid-temperature measurements. Digital-optical borehole-image logs and 72 of 85 geophysical measurements (85%) in 21 boreholes indicate that ichnogenic porosity is the principal pore type in groundwater flow zones, with macrofossil moldic porosity also important in some zones (Figure 3). Most of the remaining borehole geophysical measurements (15%) across groundwater flow zones detected inflow or outflow from bedding-plane vugs. To emphasize the potential for ichnogenic porosity to control groundwater flow, about 74% of the vertical thickness (about 12 net meters) of the Biscayne aquifer is characterized by this pore type in one borehole on the western perimeter of the study area. Recent, combined geologic studies along the line of section (Figure 3) and associated hydraulic responses during a convergent tracer test (Renken et al., 2005) suggest the Biscayne aquifer behaves as a dual-porosity medium (A.M. Shapiro, USGS, written comm.). Stratiform zones with substantial ichnogenic porosity form the principal pathways for groundwater flow. Computer-aided tomographic (CT) 3-D modeling indicates complex flow paths exist within the tightly-spaced burrow complexes. CT research currently is being combined with lattice Boltzmann flow modeling (Sukop et al., 2006, 2007) that includes quantifying the range of hydraulic conductivity of various types of Biscayne aquifer ichnogenic porosity.

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