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Ichnogenic Megaporosity and Permeability in Carbonate Aquifers and Reservoirs: Definitions and Examples*

H. Allen Curran¹ and Kevin J. Cunningham²

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Abstract

Biogenic megaporosity in sedimentary deposits (readily visible without magnification) typically has body-fossil moldic or ichnogenic origin. We consider ichnogenic megaporosity as pores greater than 4 mm associated with either burrow- or rhizolith-dominated ichnofabrics. Dominant bioturbators in shallow-marine environments typically include thalassinidean crustaceans and polychaetes. Callianassid shrimp commonly dominate the deep-tier fauna in carbonate and siliciclastic, sandy, shallow-marine settings; when fossilized their thickly lined, pelleted burrows (cm-scale outside diameters) are assigned to the ichnogenus *Ophiomorpha*. In the mostly Pleistocene carbonate rocks of the Biscayne aquifer of south Florida, *Ophiomorpha* is well lithified and burrows form a rigid framework, with interburrow macroporosity developed by matrix transport and dissolution. Tubular burrows commonly remain open or with fill washed clean in the vadose zone or removed by dissolution, resulting in intraburrow megaporosity. Both megaporosity types greatly enhance aquifer porosity and permeability, commonly in combination.

Lower Cretaceous carbonates of the Edwards-Trinity aquifer system in central Texas also manifest ichnogenic megaporosity in zones dominated by *Thalassinoides*, unlined, Y-branched burrows (cm-scale diameters). Again, both inter- and intraburrow megaporosity result from dissolution of carbonate matrix surrounding lithified burrow fills or fabric-selective leaching and removal of burrow fill material or both. Horizons with *Thalassinoides*-related intraburrow macroporosity in the Edwards-Trinity system have Lattice Boltzmann-calculated permeabilities within the range of *Ophiomorpha*-related permeabilities measured from the Biscayne aquifer. As a third example, outcropping upper Pleistocene regressive carbonate eolianites throughout the Bahamas often exhibit horizons with dense occurrences of rhizoliths, developed by diagenetic activity of plant roots interacting with host sediment. Branching rhizoliths can form sturdy frameworks with inter-rhizolith megaporosity, commonly resulting as matrix material is removed by sediment transport and dissolution. Intra-rhizolith megaporosity can occur when rhizolith tubules have fill material removed, although this process appears subordinate. Examples of rhizolith megaporosity also have been documented from the Biscayne aquifer system, and this form of megaporosity likely is widespread in carbonate eolianites elsewhere.

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Ichnogenic Megaporosity and Permeability in Carbonate Aquifers and Reservoirs: Definitions and Examples

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Brief Outline

- Intro – some background
- Callianassids – powerful bioturbators
- *Ophiomorpha* in Quaternary carbonates
- Ichnogenic megaporosity – definitions & examples
 - Conclusions

Ichnologic Characteristics of Carbonates versus Siliciclastics¹:

1. Carbonates comprise ~20-25% of the sedimentary rock record, with siliciclastics of much greater %. Carbs are less studied from the ichnologic perspective; however, ~50% of proven hydrocarbon reservoirs and many aquifers are in carbs.
2. Carbs lithify rapidly. Differential cementation processes enhance the definition of burrow matrix and fill material in trace fossils. Lithification much slower in siliciclastics or may never occur.
3. Typically little or no color contrast exists in carbs, limiting outlining of trace fossil forms. Sediment color contrasts common in siliciclastics, accentuating trace fossils.
4. Siliciclastics have a wider representation of sedimentary environment – glacial, fluvial, fluvio-deltaic, and deep-sea environments not represented in carb rocks.

¹Modified from Curran, 1994, and Knaust, Curran, & Dronov, 2012, Ch. 25, Knaust & Bromley volume.



Crescent Beach

Western North Atlantic Ocean

Gulf of Mexico

The Bahama Archipelago

Miami

South Florida

Eleuthera

San Salvador

Rum Cay

Exuma

Caicos

Caribbean Sea

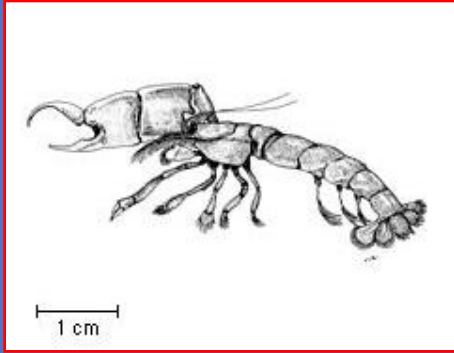
782 km

Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics

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Examples of Ichnogenic Megaporosity:

1. ***Ophiomorpha***-generated megaporosity: Miami Limestone of South Florida and Upper Pleistocene limestones of the Bahamas (Cunningham et al., 2009, GSA Bull., v. 121; Curran, 2007, Ch. 14, Miller, III volume).
2. ***Thalassinoides***-generated megaporosity: Edwards-Trinity aquifer system, Lower Cretaceous, Texas (Cunningham et al., 2012, Chap. 28, Knaust & Bromley volume); also Ghawar field carbonates, Upper Jurassic, Saudi Arabia (Pemberton & Gingras, 2005, AAPG Bull., v. 89).
3. ***Rhizomorph***-generated megaporosity: Upper Pleistocene limestones of the Bahamas (Curran field studies).
4. **Mangrove rhizomorph**-generated megaporosity: Key Biscayne carbonates, Holocene, Florida (Cunningham & Curran field studies).



What are callianassids?

Arthropoda: Crustacea: Malacostraca:
Decapoda: Axiidea:
Family **Callianassidae (ghost shrimp)**:
200+ living species¹

Where do callianassids live?

Marine benthos, mostly burrowers;
95% are intertidal to shallow-marine;
steep latitudinal gradient, with high
species numbers in the tropics and
low numbers at higher latitudes¹

¹data from Dworschak, 2000, *J. Crustacean Biology*, 20,
and pers. com., 2010.

Callianassids - true ecosystem “engineers” ...

Glypturus acanthochirus Stimpson, 1866



Callianassids ... “live predominantly in very shallow waters...and influence the whole sedimentology and geochemistry of the seabed.”
(Peter Dworschak, 2004)



Crescent Beach, Florida – Atlantic coast



Callianassid burrow opening & pellets



Emergent callianassid burrows



Callinectes major: length = 15 cm

TROPICAL HABITATS OF CALLIANASSIDS



Lagoons - Bahamas



Platform shelves - Bahamas



Adjacent to and within coral reefs - Bahamas

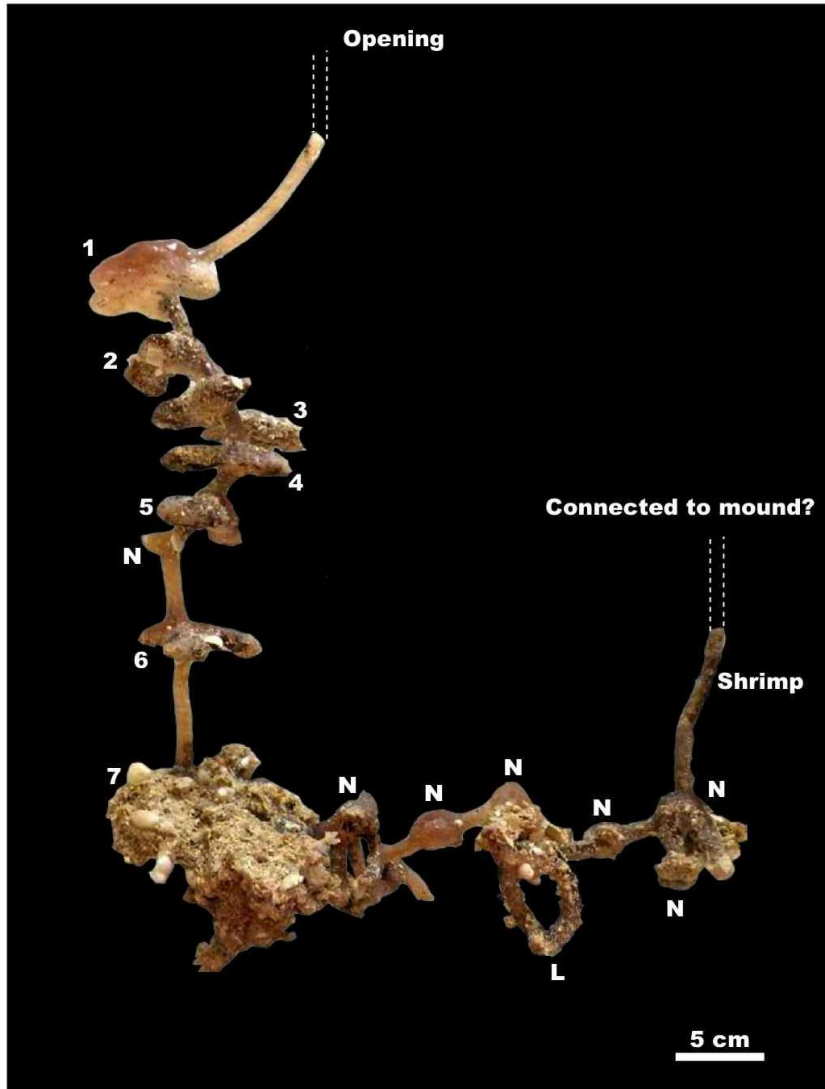


Leeward shelf of isolated platform - Caicos



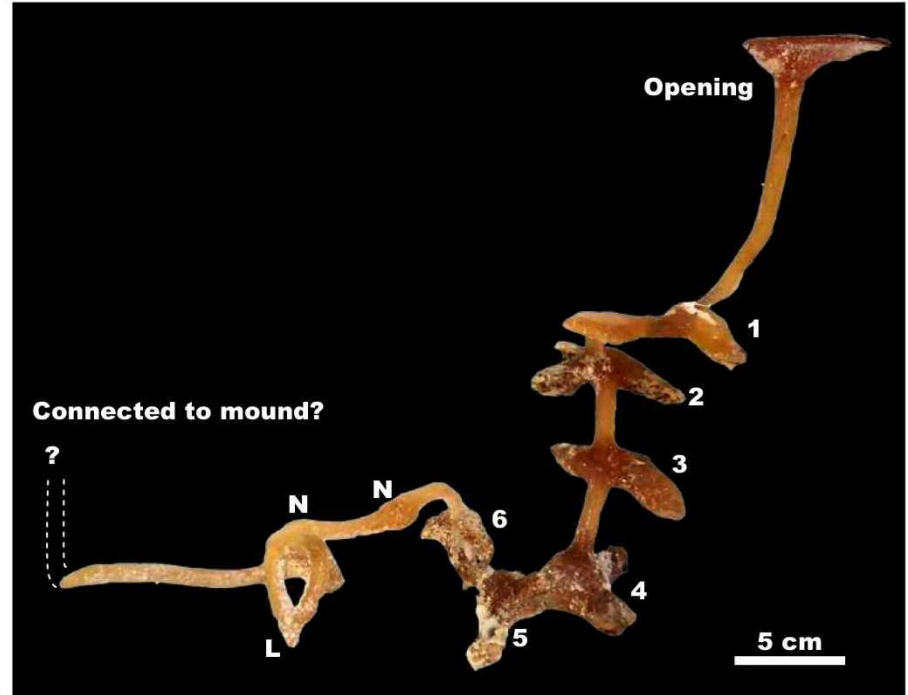
Offshore lagoon - shallow subtidal callianassid mounds and funnels,
Graham's Harbour, San Salvador.

Graham's Harbour Burrow #9



1,2,3...: Tiering chamber levels
 N: Node
 L: Loop

Graham's Harbour Burrow #8



1,2,3...: Tiering chamber levels
 N: Node
 L: Loop

These mostly complete casts reveal a very complex burrow form...

Tracemaker species and precise trace fossil counterpart unconfirmed...



Cast of callianassid burrow termini, Graham' s Harbour, San Salvador.



Mounded topography created by the callianassid, *Glypturus acanthochirus*,
Pigeon Creek, San Salvador.

Glypturus acanthochirus burrow system architecture...

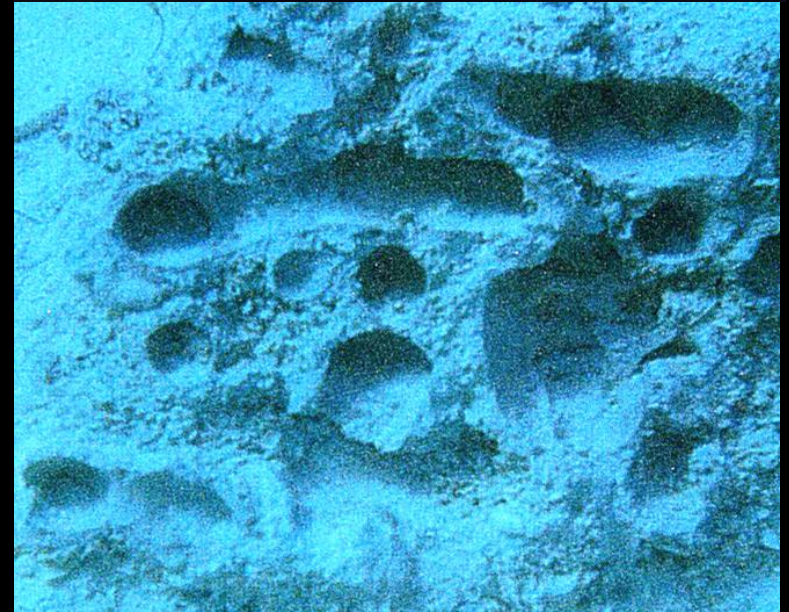


From Shinn, 1968, *J. Paleontology*, 42.



From Tedesco & Wanless, 1991, *PALAIOS*, 6.

Pen = 15 cm
length



Comparison of spiral trace fossil form (left, Miami Ls.) with segments of modern *Glypturus acanthochirus* burrow resin cast and burrow from Florida Bay (right; photos by Gene Shinn, from Enos, 1983, *in* Scholle et al., AAPG Memoir 33).

What is *Ophiomorpha*?

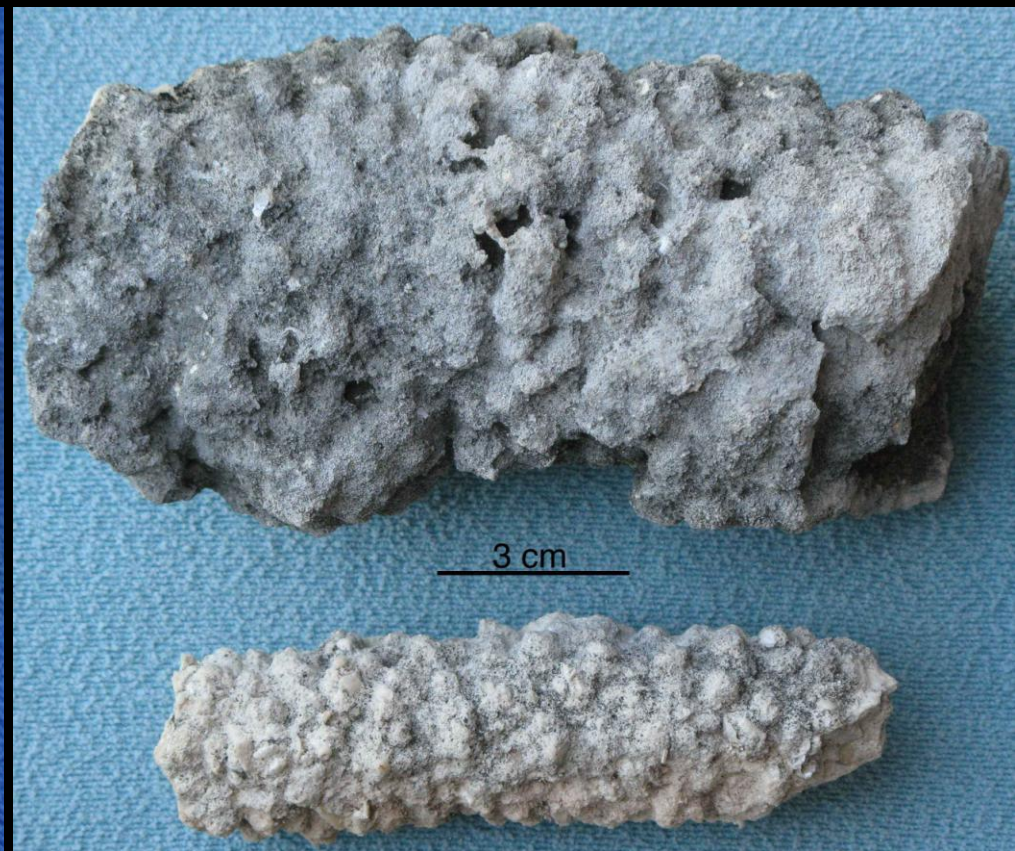
A fossilized burrow that is lined and commonly branches, with enlargement in area of branching; cylindrical shafts and tunnels normally 1 – 3 cm in diameter; outer surfaces are pelleted, inner surfaces smooth.

Geologic range: Permian? to Recent, confirmed presence in Jurassic – R strata.

Tracemaker: Callianassid shrimp.

Environmental occurrence: Marine intertidal to deep-sea, with preference for shallow subtidal environments.





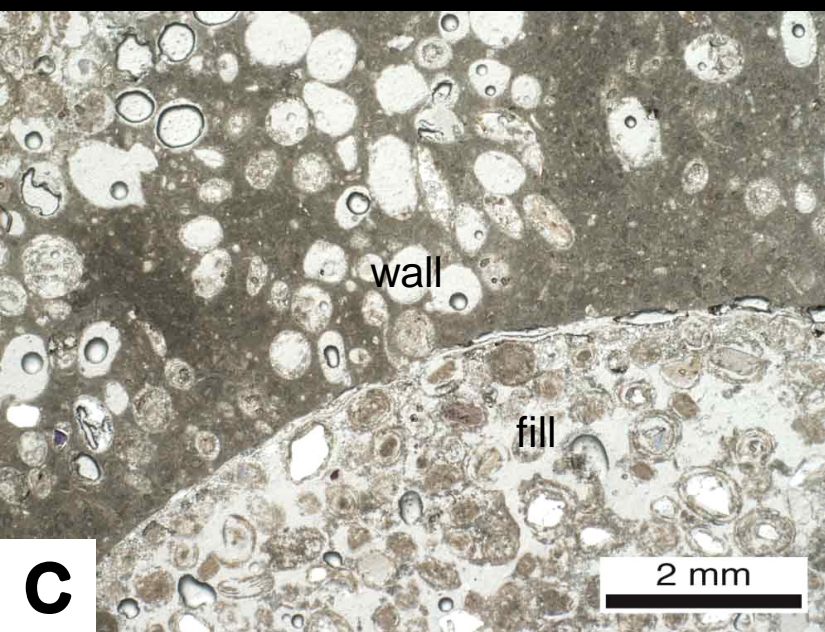
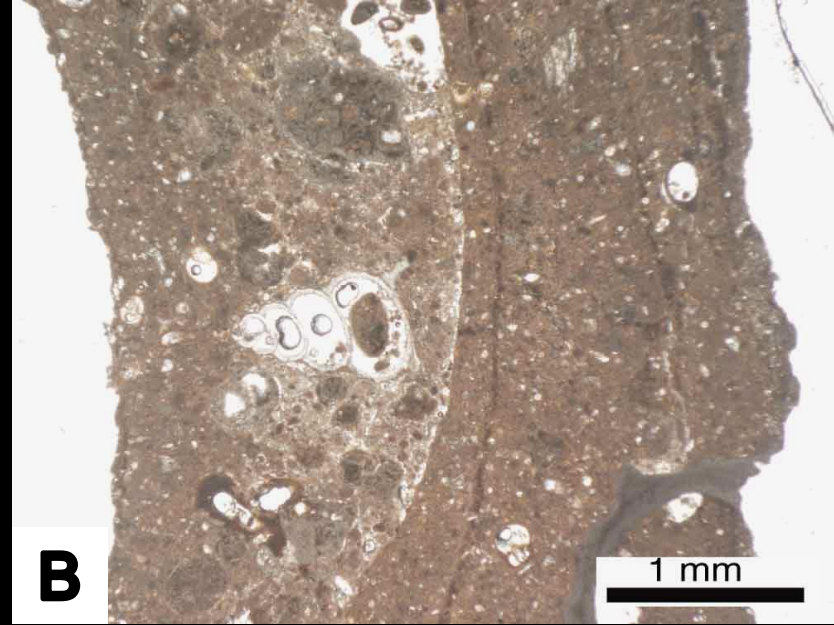
Size variation of *Ophiomorpha* shafts & tunnel segments,
all Upper Pleistocene, Bahamas.



Basal parts (maze) of *Ophiomorpha* burrow systems exhibiting distinctive tunnel-terminus structures, Harry Cay, Little Exuma.



A: Large terminus structure (Rum Cay); B: Cluster of openings leading to terminus; C: Loop structure; D: Large pellets on *Ophiomorpha* tunnel (Harry Cay, Little Exuma).



Photomicrographs: A – *Ophiomorpha* wall, note reactivation surfaces; B – wall close-up; C – dense *Ophiomorpha* wall and less dense fill; D – *Favreina* in burrow fill material.

Ophiomorpha ichnofabric

Ichnofabric index
(from Droser and
Bottjer, 1989)



Clifton Pier cliffs,
New Providence



Cockburn Town fossil coral reef,
San Salvador

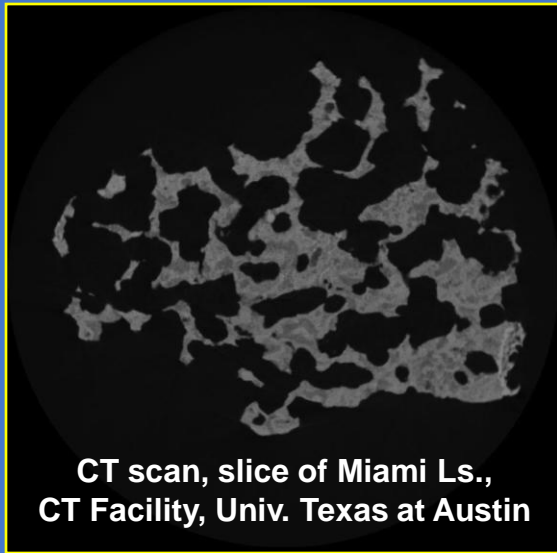


Ichnogenic megaporosity:

1. **Intraburrow** megaporosity – occurs within the confines of burrows, e.g., as with *Ophiomorpha*.
2. **Interburrow** megaporosity - occurs between the walls of burrows, with the burrow walls serving as a framework, e.g., *Ophiomorpha* shaft and tunnel complexes.

Commonly, intra- and interburrow megaporosities occur together, creating highly porous and permeable rock!

Definitions modified from Cunningham et al., 2009, GSA Bull., 121.



CT scan, slice of Miami Ls.,
CT Facility, Univ. Texas at Austin

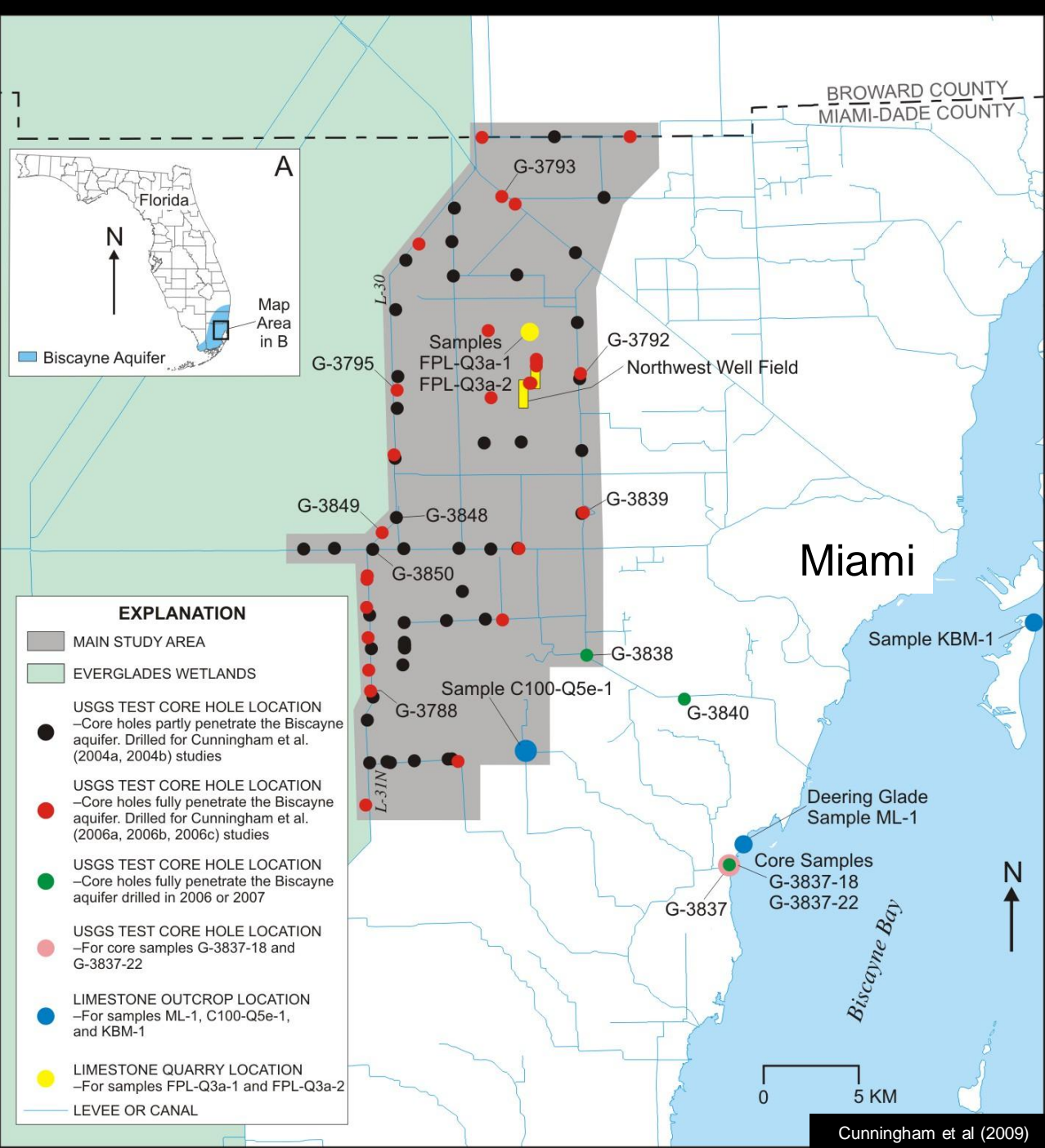


Intraburrow megaporosity:
generated by callianassid
burrows (*Ophiomorpha*),
Upper Pleistocene grainstone,
San Salvador.





Interburrow megaporosity: within an *Ophiomorpha* framework, Upper Pleistocene grainstone, San Salvador.



Location of cores in Miami area reported in Cunningham et al., 2009, GSA Bull., 121.



Miami Limestone: A – *Ophiomorpha* maze; B – multiple mazes; C – robust shaft.



Lens cap =
4.7 cm diameter

Miami Limestone: **maximum intensity ichnofabric** generated by callianassid burrowing. Note numerous *Ophiomorpha* shafts and tunnels...

A VISUAL ICHNOPOROSITY / PERMEABILITY SCALE: all samples heavily burrowed



1. LOW porosity/permeability >>>



2. INCREASING porosity/permeability >>>



3. INCREASING porosity/permeability >>>



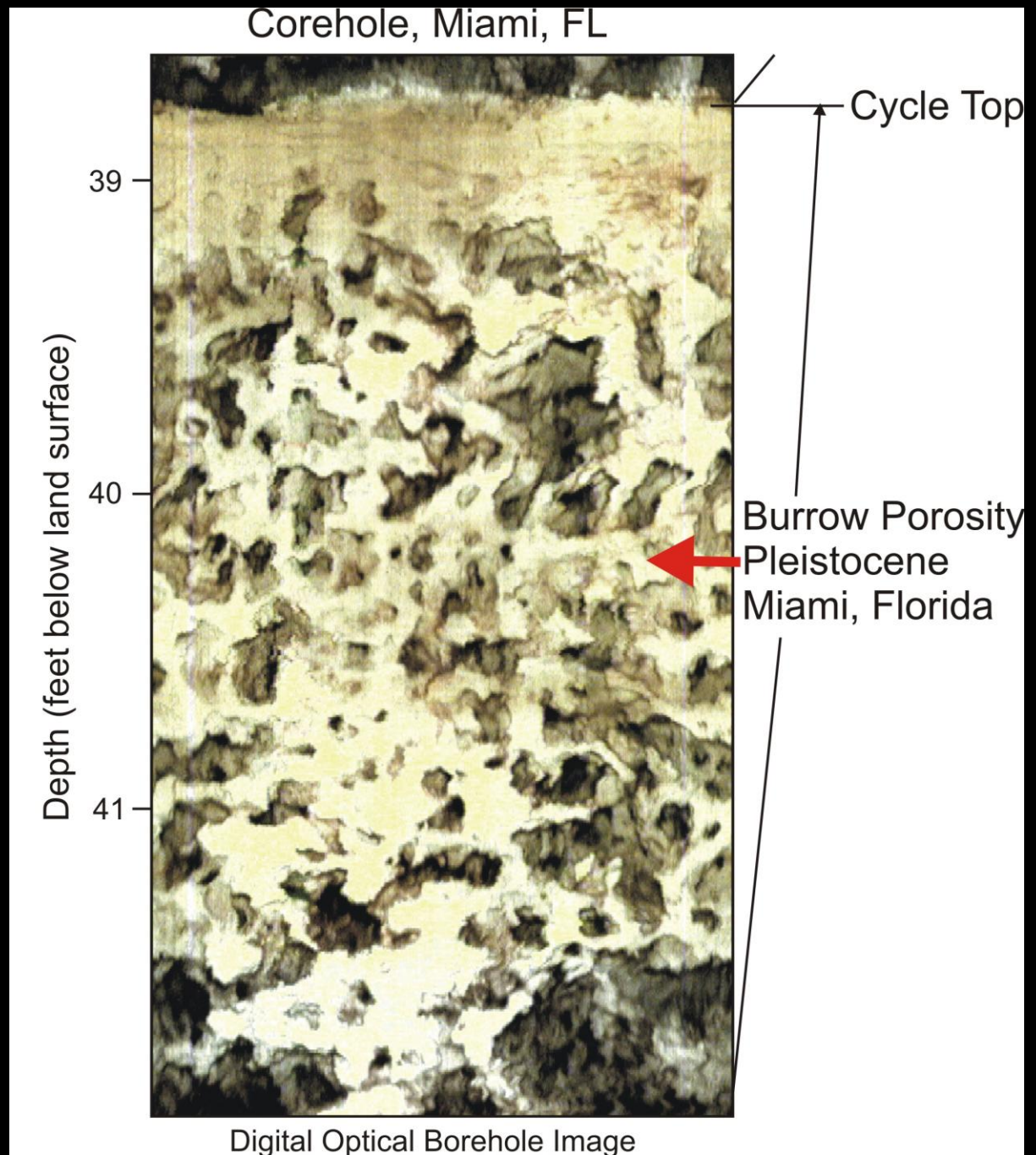
4. MAXIMUM porosity/permeability (pen = 15 cm)

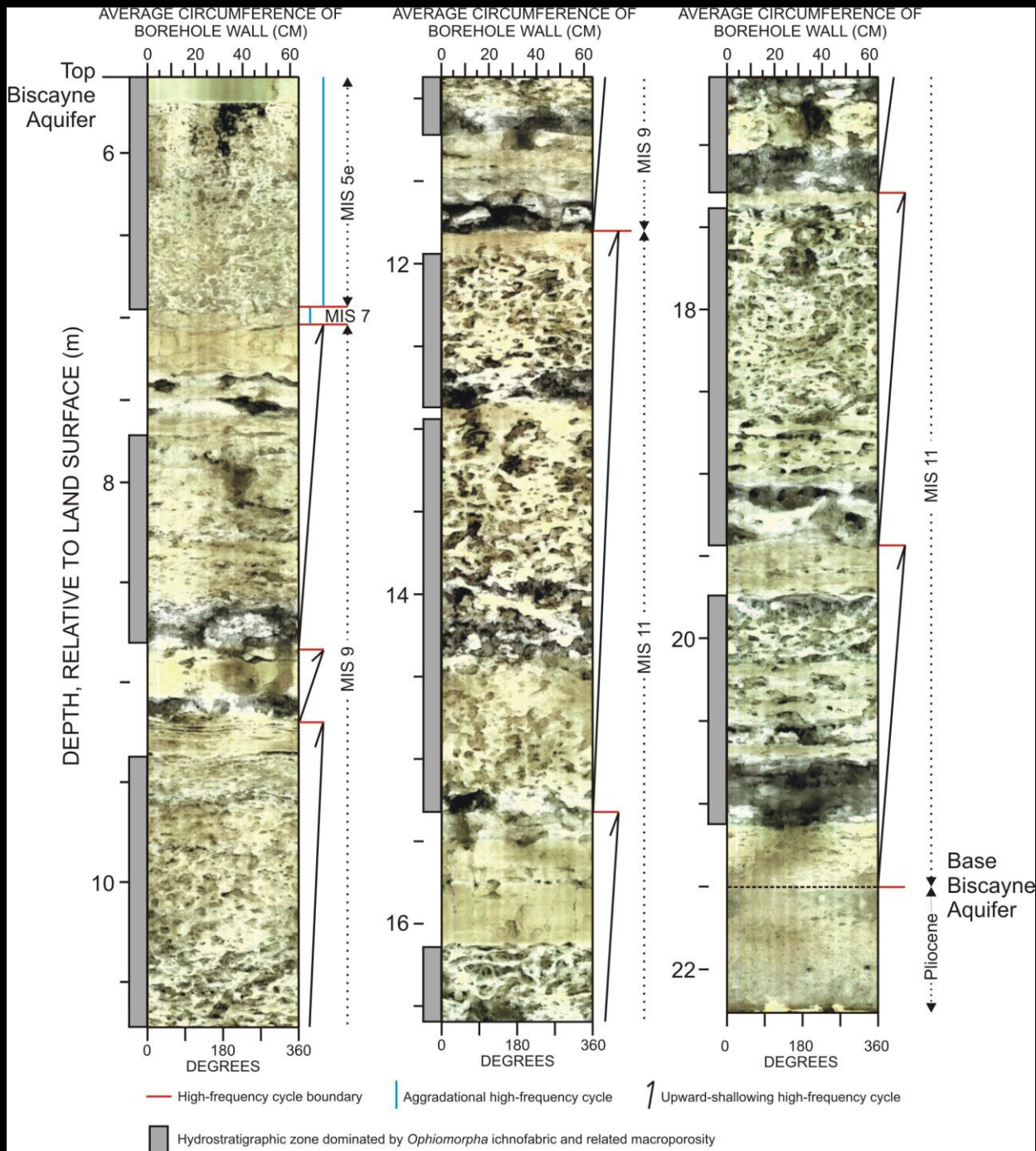
Ichnogenic porosity in the Biscayne aquifer, Miami, Florida...

(from Cunningham et al., Geol. Soc. America Bull., 2009, 121)



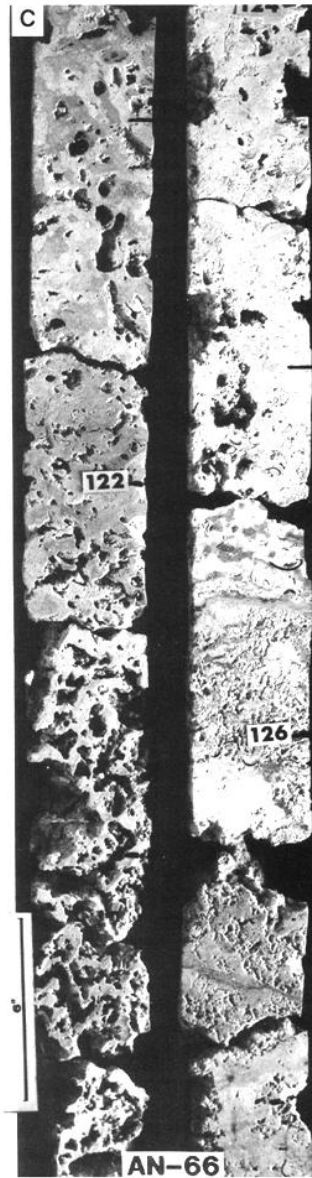
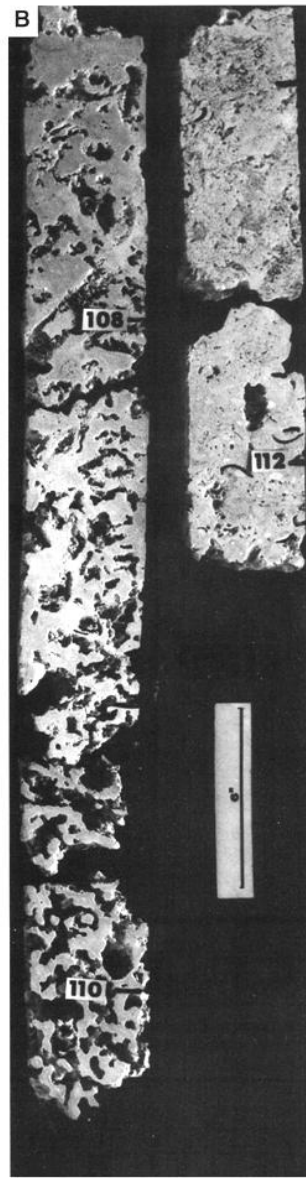
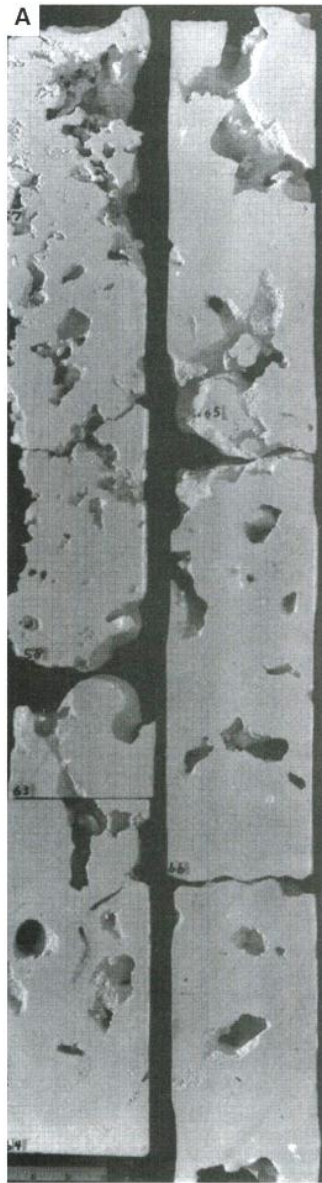
Ophiomorpha segments from core boreholes.



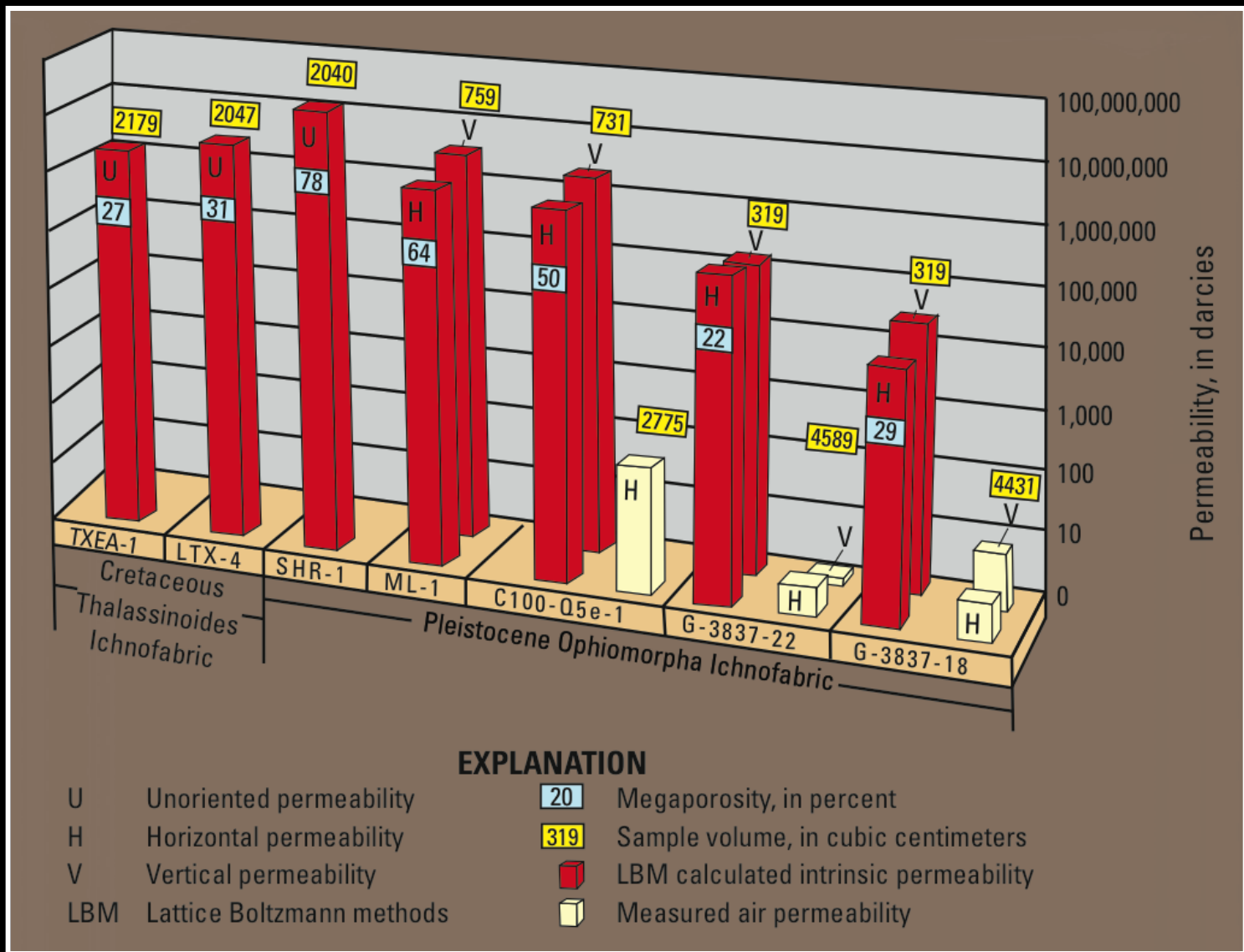


Ichnogenic porosity through full vertical extent of the Biscayne aquifer = 77% of this core!

(from Cunningham et al., Geol. Soc. America Bull., 2009, 121)



Crustacean burrow-generated megaporosity: Left – Plio-Pleistocene limestone cores, Bahamas (from Beach, 1995, AAPG Mem. 63): Right – Biscayne aquifer, Florida.



Megaporosity and permeability values for limestone samples with high Ichnofabric measures (modified from Cunningham et al., 2012, Ch. 28, Knaust & Bromley volume).



Rhizomorph-generated megaporosity; A,B - North Eleuthera, C,D – San Salvador; all Upper Pleistocene carbonate **eolianites**.



Mangrove rhizomorph-generated megaporosity – Holocene exposure at Crandon Park, Key Biscayne, Florida.

Conclusions:

1. Burrowing activities of callianassids can profoundly modify the characteristics of tropical, shallow-marine carbonate sediments, creating distinctive ichnofabrics.
2. Dense occurrences of *Ophiomorpha* can result in high levels of ichnogenic megaporosity and permeability in counterpart carbonate rocks.
3. Zones of high ichnoporosity and permeability can be important as aquifers and likely also as petroleum reservoirs. *Ichnologists and sedimentologists should continue investigation and evaluation of ichnoporosity and permeability in other geologic settings.*

End!