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Heterogeneity in Hydraulic Conductivity of Oolitic Grainstone of the Miami Limestone: Results from the Constant-Head Method

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Introduction

- Miami Limestone is a Pleistocene ooid sand deposit with two main facies; a lower *burrow mottled facies* and an upper *relict bedded facies*[1].
- *Oolitic lithofacies* of the Miami Limestone receives roughly 150 cm of rainfall per year and is capable of draining several centimeters within an hour.[6, 7, 13]
- Fluid flow through carbonates is variable and likely scale dependent due to a wide range of possible depositional and diagenetic features.[2, 6, 14]
- Thus, characterizing hydraulic conductivity of a rock unit can be done on various scales.[14] To better characterize the local hydrogeology we use a whole-core analysis approach.[3, 14]
- Recent studies suggest fluid flow in the lower *burrow mottled facies* is controlled by *touching vug macropores*, but little is known of the controls in the upper *relict bedded facies*.[8]
- **Objective:** Establish lithologic and scale-based controls on hydraulic conductivity for the upper *relict bedded* oolitic grainstone facies of Miami Limestone.
- **Hypothesis:** Flow characteristics of upper *relic bedded facies* are controlled by a combination of depositional and diagenetic factors different from the lower facies.

Methods

- A 4.09 m composite core extracted in three overlapping segments from outcrop at Ransom Everglades Middle School, part of a topographic high of Miami Limestone.
- Composite core was cut into 15 segments.
- Each segment had dimensions measured for *Permeability Coefficient* calculation, was placed in a constant head permeameter to measure hydraulic conductivity (**Figure 1).**
- Subsamples analyzed for grain size and diagenetic features using a Philips XL-30 Field Emission Scanning Electron Microscope at UCAM[5].
- Thin sections cut from ends of each core segment
- Calculations for *hydraulic conductivity*, *permeability*, and *bulk density* derived for each core.
- For a pre-lithification baseline comparison two ooid sands from modern sand shoals (Bahamas, Turks & Caicos) tested for hydraulic conductivity.

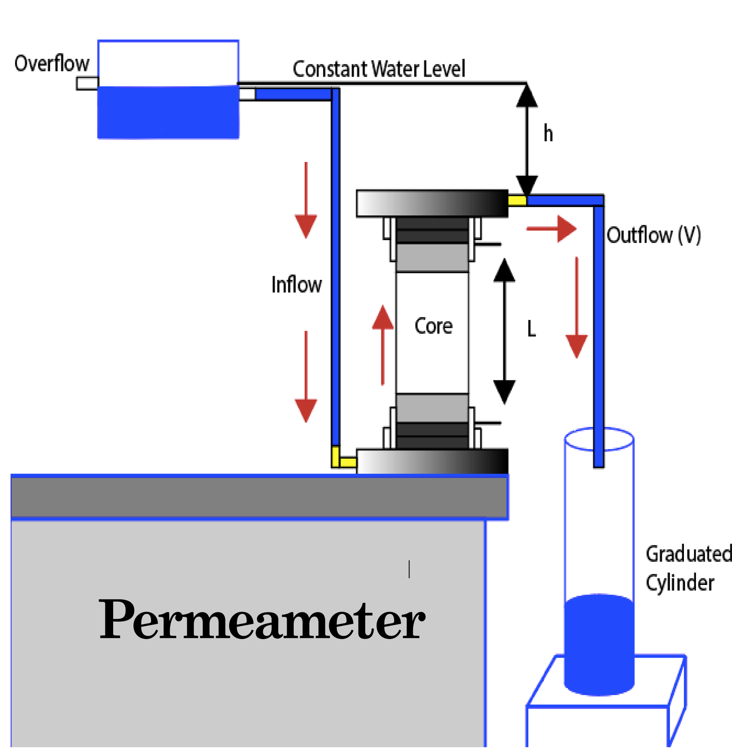

Figure 1. *Schematic of the constant head permeameter used to measure flow and calculate hydraulic conductivity in this study.*

A stabilized rate of outflow (V) was established, h and L were measured.

Results

SEM Petrography of Relict Bedded Facies – Miami Limestone

Table 1. Mean values and standard deviations in grain size throughout core (measured from SEM).

Sample	Sample Depth (cm)	Sample Size (n)	Mean Size (microns)	Standard Deviation (microns)
4A Upper	25.4	20	427.1	73.3
4A Middle	80.0	20	616.7	77.6
4A Lower	138.4	20	726	93.8
4B Upper	161.3	10	441	110.1
4B Middle	222.3	6	415.5	131.3
4B Lower	284.5	10	515.9	77.2
4C Middle	353.1	7	497.2	146.6
4C Lower	373.4	10	514.8	66.1

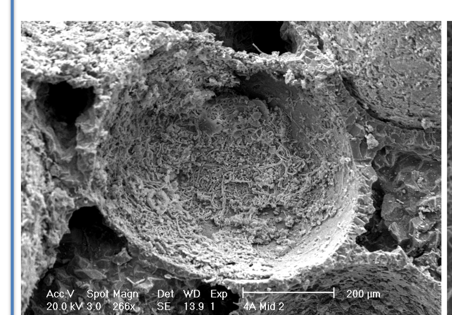
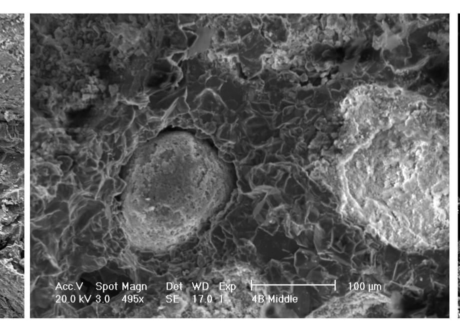
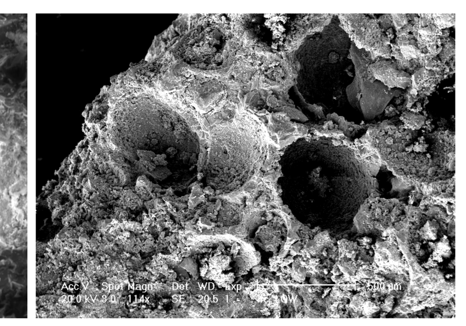

Figure 2. *Meniscus cement of calcite spar in segment 4A.* ***Figure 3.*** *Ooid grain pore spaces infilled by calcite spar in segment 4B.* ***Figure 4.*** *Thick, poorly consolidated calcite cement encasing dissolved ooids, segment 4C.*

Hydraulic Measurements in Miami Limestone Core Segments

Table 2. Conductivity values for fifteen core segments.

Core Segment Number	Mean Conductivity (cm/sec)
1	2.39×10^{-6}
2	1.60×10^{-5}
3	1.11×10^{-3}
4	3.30×10^{-4}
5	3.64×10^{-4}
6	1.26×10^{-4}
7	5.28×10^{-6}
8	5.61×10^{-5}
9	8.39×10^{-5}
10A	5.87×10^{-7}
10B	1.78×10^{-6}
11	5.42×10^{-5}
12	6.28×10^{-6}
13	1.94×10^{-6}
14	7.13×10^{-5}

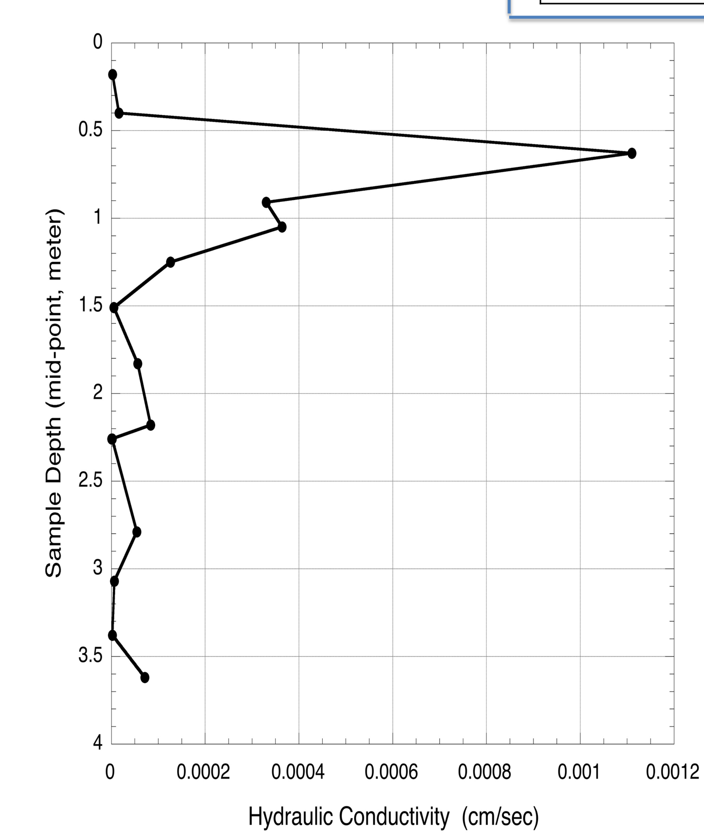

Figure 5. *Hydraulic conductivity versus depth of core segment.*

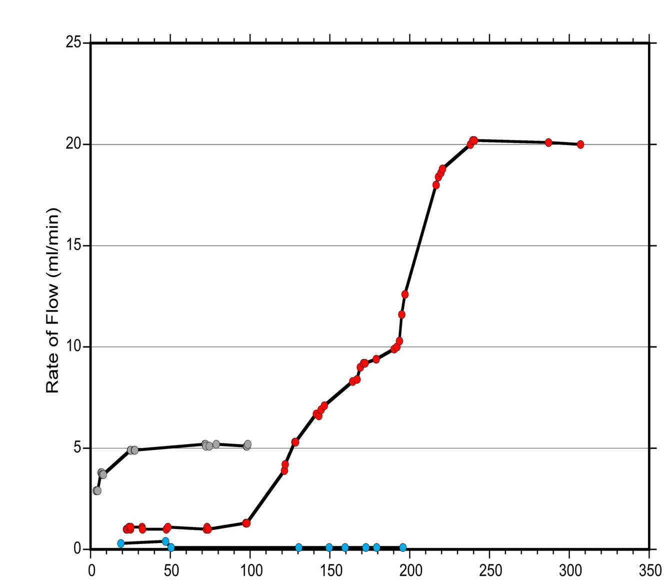

Figure 6. *Conductivity behaviors: consistent low flow (10B, blue), rapid increase and early plateau (8, grey), slow increase followed by rapid increase (5, red).*

Miami Limestone Core Bulk Density

Table 3. Bulk density (g/cm³) of each core segment.

Core	Bulk Density (g/cm³)
1	1.71
2	1.58
3	1.64
4	1.59
5	1.53
6	1.58
7	1.52
8	1.65
9	1.47
10A	1.45
10B	1.35
11	1.45
12	1.50
13	1.49
14	1.49

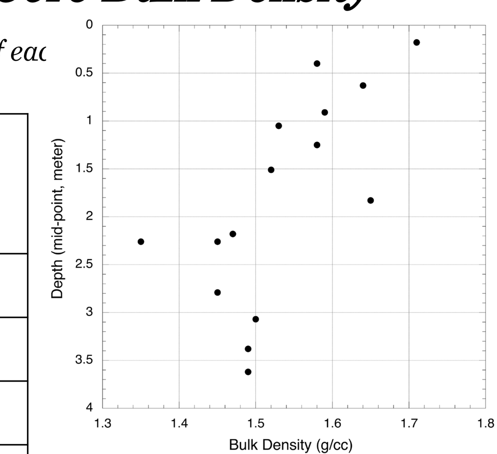

Figure 7. *Bulk density versus depth for the 15 core segments.*

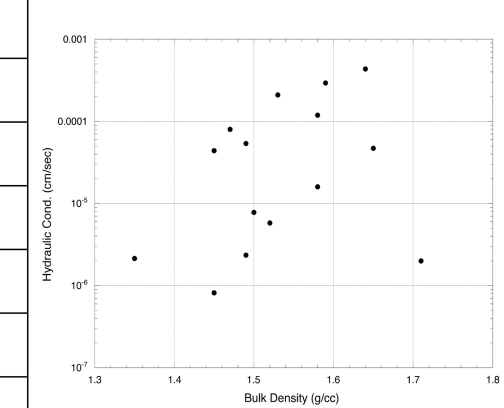

Figure 8. *Bulk density versus hydraulic conductivity for the 15 core segments.*

Whole Core (Total) Porosity Miami Limestone

Table 4. Core segment porosity based on bulk density measurement.

Core	Porosity Value
1	0.37
2	0.42
3	0.39
4	0.41
5	0.44
6	0.42
7	0.44
8	0.39
9	0.46
10A	0.46
10B	0.50
11	0.46
12	0.45
13	0.45
14	0.45

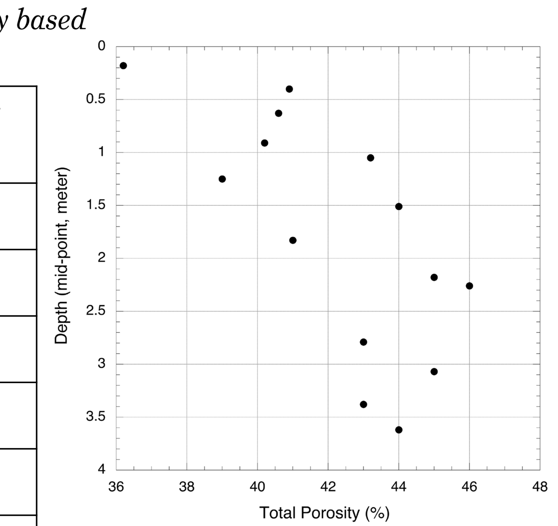

Figure 9. *Core segment porosity versus depth.*

Hydraulic Conductivity Ooid Sand

Table 5. Hydraulic conductivity values of unconsolidated ooid sands.

Ooid Sands Trial Number	Turks and Caicos K (cm/sec)	Shroud, Exumas K (cm/sec)
1	0.00821	0.00642
2	0.00823	0.00648
3	0.00834	0.00645
4	0.00834	0.00642
5	0.00821	0.00628
6	0.00827	0.00635
7	0.00817	

Table 6. Statistical values of unconsolidated ooid sands from Turks and Caicos and the Bahamas.

Statistical Parameter	Turks and Caicos	Bahamas
Graphic Mean Size (mm)	0.43	0.41
Inclusive Graphic Standard Deviation (Sorting, Φ)	0.31 (Very Well Sorted)	0.35 (Very Well Sorted)
% Mud (<63 microns)	0	0
% Sand (63 microns – 2 mm)	100	99.77
% Gravel (>2 mm)	0.0	0.23

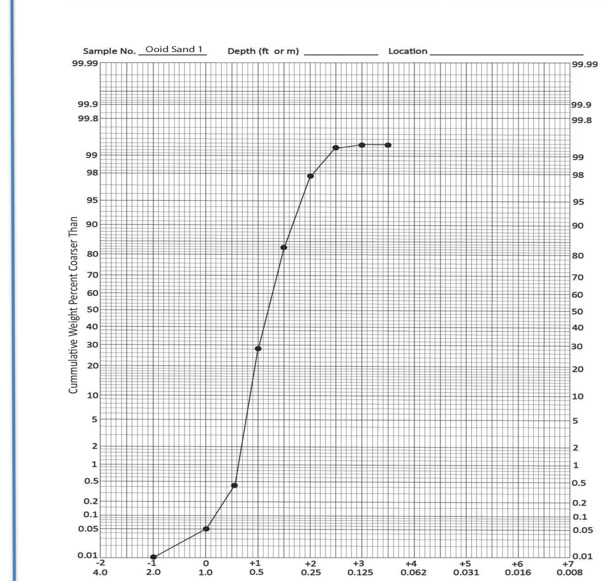
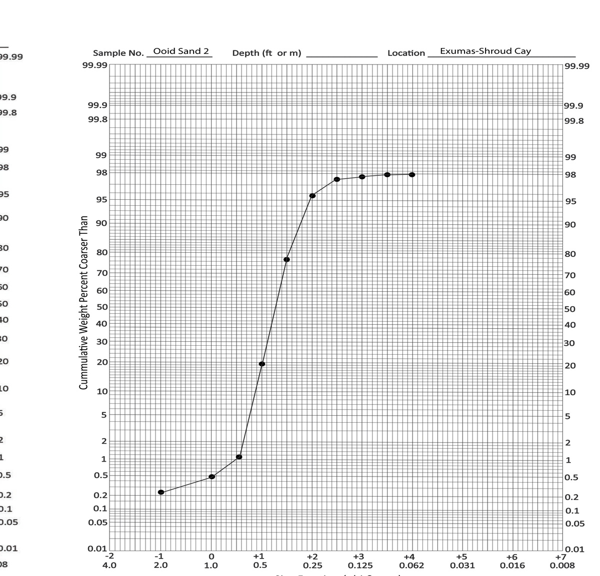

Figure 10. (left) *Cumulative frequency grain-size curve for ooid sand sample, Turks and Caicos.*
Figure 11. (right) *Cumulative frequency grain-size curve for ooid sand sample Exumas, Bahamas.*

Hydraulic Conductivity Ranges for Cores and Ooid Sands

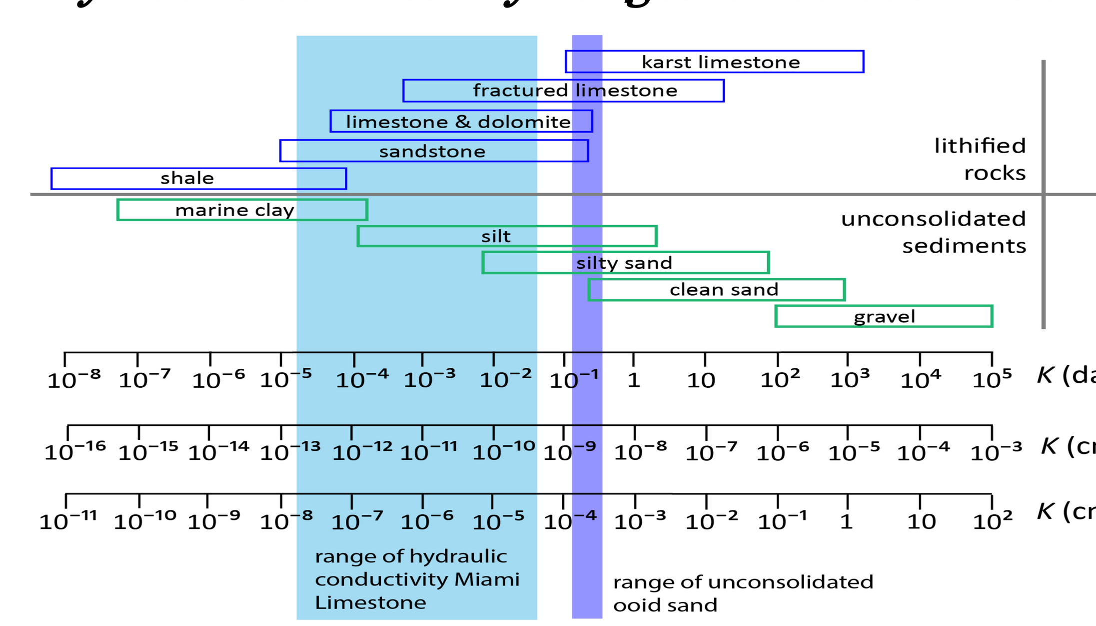

Figure 12. *Typical hydraulic conductivities of rock and sediment types.*[4] *Hydraulic conductivity values of ooid sands are shown in purple and values of core segments are shown in blue (excluding core segment 3). Base figure is from Freeze & Cherry (1979)*

Discussion

- Results show early lithification (meteoric) reduces hydraulic conductivity by up to 4 orders-of-magnitude.
- Cores with higher conductivity tend to exhibit larger ooid grain size and better preservation of original pore space, as shown by less calcite cement infill.
- Cores with higher conductivity are found at shallower depth and exhibit greater bulk density, suggesting less dissolution of original material.
- Well-cemented coquina beds are found at various core intervals. Core segments with coquina beds exhibited lower hydraulic conductivity values than those without coquina, suggesting coquina retards fluid flow.

Conclusions

- Initial cementation and lithification of ooid sands can decrease hydraulic conductivity several orders of magnitude relative to unconsolidated sands.
- Sub-meter scale analysis shows grain size, degree of diagenesis, burrows and lithofacies to be main factors controlling fluid flow through bedded oolitic deposits.
- Larger ooid grains (vadose zone) that retain original aragonitic material are key to greater hydraulic conductivity.
- Unlike outcrops with *touching vug macropores (*in lower *burrow mottled facies)*, flow in *relict bedded facies* is controlled by matrix and intraparticle porosity.

Acknowledgments

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References

1. Caglar 2014 2. Cunningham et. al. 2009 3. Diaz et al. 2018 4. Freeze & Cherry 1979 5. UM University Center for Advanced Microscopy 6. Ginsburg 2010 7. Halley & Evans 1983 8. Harris & Purkis 2020 9. Hoffmeister et. al. 1967 10. MacIntyre & Reid 1992 11. Neal et. al. 2008
12. Puri & Vernon 1964 13. Truss et. al. 2007 14. Whitaker & Smart 2000