

# **PS Significance of Microbialites in Reservoir Development and Evolution in Silurian Reef Slope Deposits at Pipe Creek Jr. Quarry, Indiana, and the Michigan Basin\***

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## **Abstract**

Microbial binding has been identified as a significant process, along with syndepositional marine cementation, that results in the early stabilization of steep carbonate slopes in the Holocene and in numerous ancient carbonate slope examples. This allows for the development and preservation of steep carbonate slopes and contributes to the overall framework and rigidity of the reef framework, and may lead to an early reduction in primary porosity and permeability which may adversely affect subsequent reservoir development and preservation during burial.

Silurian reefs in and around the Michigan Basin have been extensively studied because of their significant production of hydrocarbons (>500 MMBOE). The Silurian-age reef flanking beds exposed at the Pipe Creek Jr. Quarry in Indiana are distinguished by steeply dipping upper slopes approaching 45 degrees. These cyclically bedded units are characterized by coarse grainstone and boundstone facies with syndepositional marine cement. The abundance of marine cements likely aids in the early stabilization and rigidity of the slope flanks. However, in many of these beds there is clear evidence of microbial cements that may have aided in the stabilization. The steep flanking beds of the Silurian in both the quarry and subsurface of the Michigan Basin are characterized by *in situ* microbial and cement boundstones with characteristic microbial microfabrics.

Comparison of interpreted depositional processes and early diagenetic modification in the Silurian example, including an abundance of *in situ* microbially mediated cementation, to those described in numerous subsurface examples including the supergiant Tengiz Field in Kazakhstan and in the Holocene of the Bahamas, shows a remarkable similarity in depositional texture and fabric, potential reservoir geometry, and effects of early diagenesis on reservoir properties. The aim of this study is to evaluate the possible contribution of microbial binding and microbially mediated cementation to the stabilization and potential reservoir modification in the Silurian upper slope deposits exposed at Pipe Creek Jr.

Quarry and in the subsurface Silurian reefs of the Michigan Basin. Thin section petrography, SEM analysis, and confocal microscopy are being used, along with detailed mapping of the slope deposits in the quarry, to provide insight into possible reduction of initial porosity and permeability, influences on later diagenetic processes and final reservoir flow properties.

### **References Cited**

Grammer, G.M., R.N. Ginsburg, and P.M. Harris, 1993, Timing of deposition, diagenesis, and failure of steep carbonate slopes in response to a high-amplitude/high-frequency fluctuation in sea level, Tongue of the Ocean, Bahamas, *in* R. Loucks and R. Sarg, eds., AAPG Memoir 57, Recent advances and applications of carbonate sequence stratigraphy, p. 107-131.

Simo, J.A., and P.J. Lehmann, 2000, Diagenetic history of Pipe Creek Jr. Reef, Silurian, north-central Indiana, U.S.A.: *Journal of Sedimentary Research*, v. 70/4, p. 937-951.

## Abstract

Microbial binding has been identified as a significant agent, along with syndepositional marine cementation, in the early stabilization of steep carbonate slopes in the Holocene and in numerous examples of ancient carbonate slope deposits. This allows for the development and preservation of steep carbonate slopes and contributes to the overall rigidity of the reef framework, and may lead to an early reduction in primary porosity and permeability which may adversely affect subsequent reservoir development and preservation during burial. Silurian reefs in and around the Michigan Basin have been extensively studied because of their significant production of hydrocarbons (>500 MMBOE). The Silurian-age forereef slopes exposed at Pipe Creek Jr. Quarry (IN) are distinguished by steep depositional dips approaching 45°. These cyclically bedded units are characterized by abundant syndepositional abiotic marine cement which likely aids in the early stabilization and rigidity of these deposits. However, in many of these beds there is clear evidence of earlier microbial activity that may have aided in the stabilization.

The aim of this study is to evaluate the possible contribution of microbial binding and microbially mediated cementation to the stabilization and potential reservoir modification in the Silurian forereef slope deposits exposed at Pipe Creek Jr. Quarry and in the subsurface Silurian reefs of the Michigan Basin. This will be done in order to provide a more robust understanding of how syndepositional cementation (abiotic and microbial binding) may affect depositional and diagenetic heterogeneities, reduce initial reservoir quality in these potential reservoirs, and greatly influence final reservoir flow properties.

## Objectives

- Evaluate the significance and timing of syndepositional marine cementation (abiotic and microbially mediated) in the early stages of stabilization and lithification of these steep forereef slope deposits.
- Assess the effects of early marine cementation on the reduction of initial porosity and permeability as well as modifications in the initial pore system architecture.
- Provide insights applicable to characterizing steep forereef slope reservoirs in the Michigan Basin and elsewhere to develop a better understanding of depositional and diagenetic heterogeneities found in these reservoirs.

## Study Area

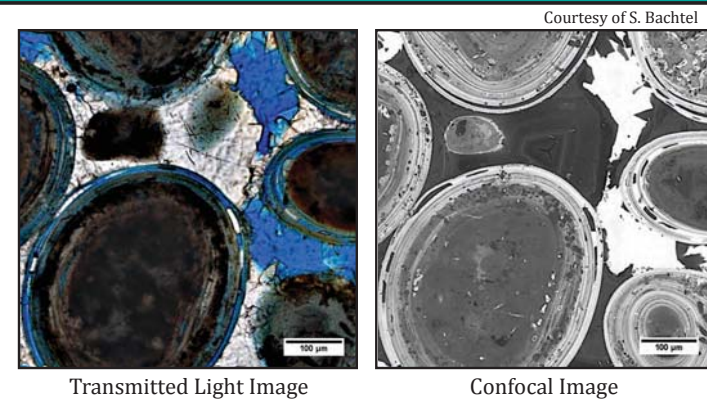
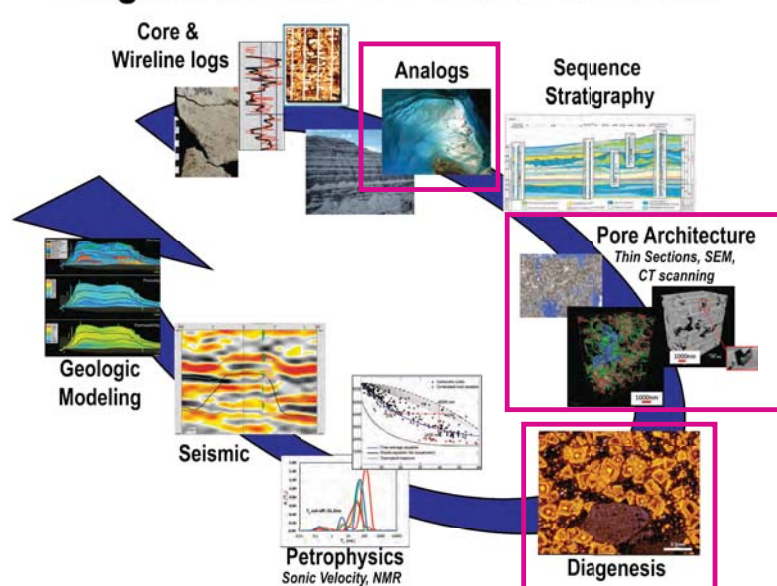
- **Figure A:** Silurian paleogeography
- **Figure B:** Location of Grant County (IN)



• **Figure C:** Google Earth image of Pipe Creek Jr. Quarry

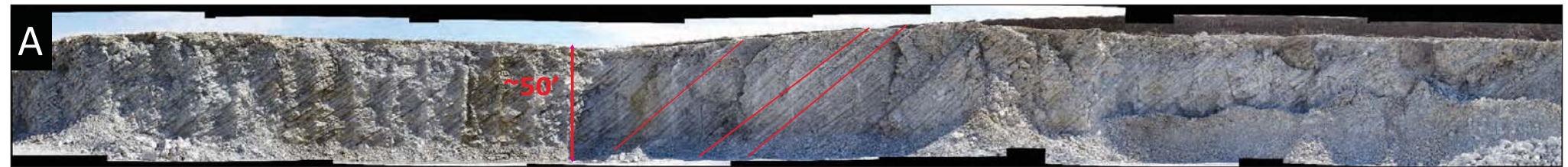
## Methods

### Integrated Reservoir Characterization



- Thin Section Petrography
- Scanning Electron Microscopy (SEM)
- Cathodoluminescence Microscopy
- Confocal Microscopy- Recent applications generate an increased image resolution

## Silurian Forereef Slope Deposits

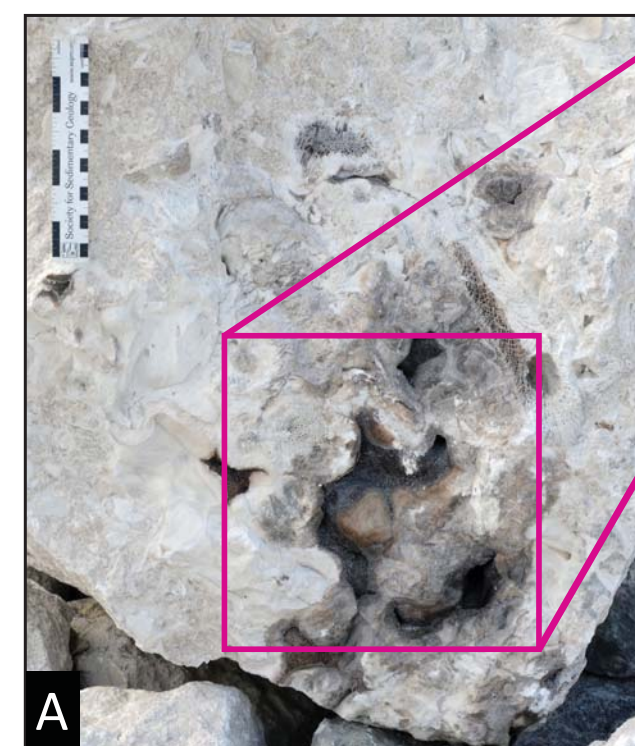


• **Figure A:** Tabular to wedge-shaped beds (15 to 100 cm thick) steeply dipping 35° to 45°

• **Figure B:** Stained block with oil seeping from vuggy pores

• **Figure C:** Oil seeping from large vuggy pores can be seen in blocks throughout Pipe Creek Jr. Quarry

## Abiotic Marine Cementation: Hand Samples



• **Figure A:** Centimeter scale vuggy pores partially filled with abiotic marine botryoidal cement

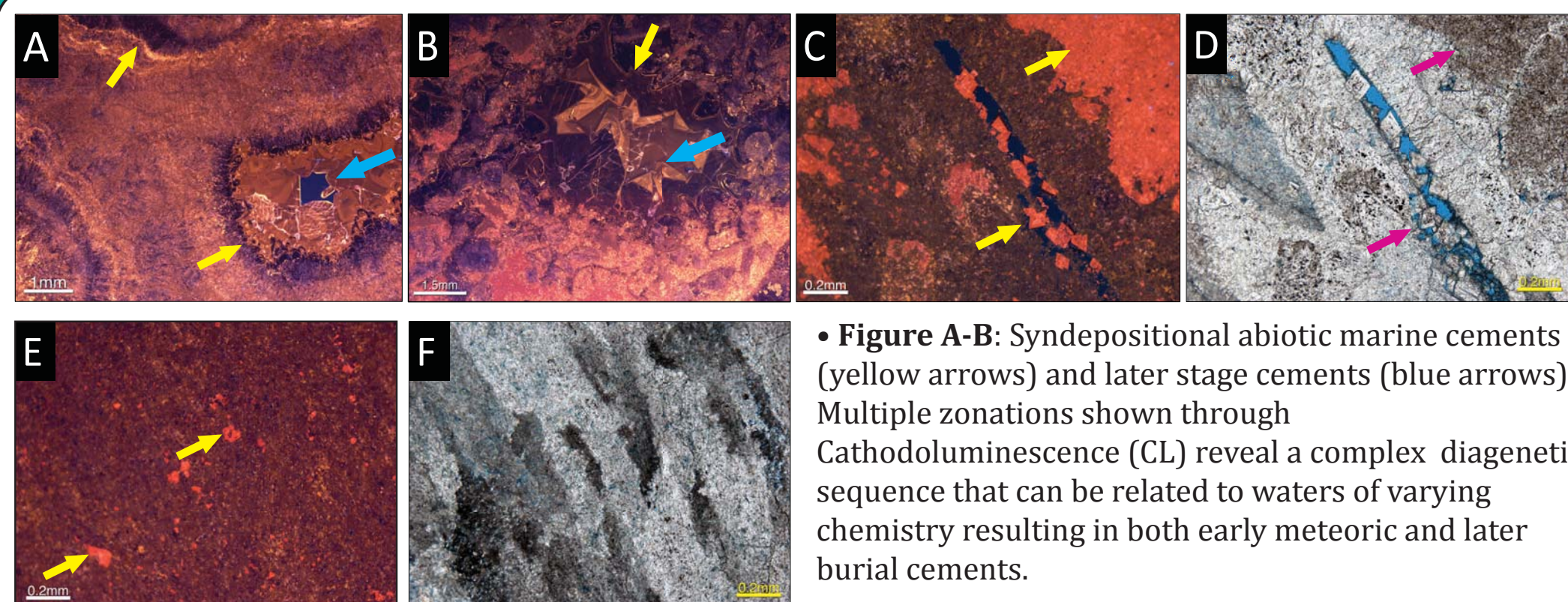
• **Figure A2:** Close up of botryoidal cement in large (cm scale) vugs



• **Figure B:** Pervasive abiotic marine botryoidal cement surrounding coral (c) and Stromatoporoid (s) fragments (arrows)

• **Figure C-D:** Abiotic marine cement filling most of the vuggy porosity (arrows). Morphologies of the abiotic marine cements vary from botryoidal to isopachous. Remaining pores can be oil stained in some examples.

## Initial Reservoir Development and Evolution



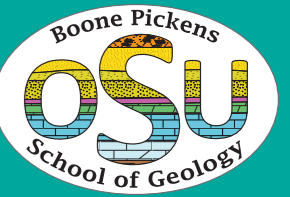
• **Figure A-B:** Syndepositional abiotic marine cements (yellow arrows) and later stage cements (blue arrows); Multiple zonations shown through Cathodoluminescence (CL) reveal a complex diagenetic sequence that can be related to waters of varying chemistry resulting in both early meteoric and later burial cements.

• **Figures C-D:** Dolomite can precipitated as a cement within be see as a cement in moldic porosity and locally replacing micrite-rich samples (arrows); **E- F:** The presence of dolomite crystals within some syndepositional isopachous radial fibrous cements indicate later stage of dissolution and dolomite precipitation.

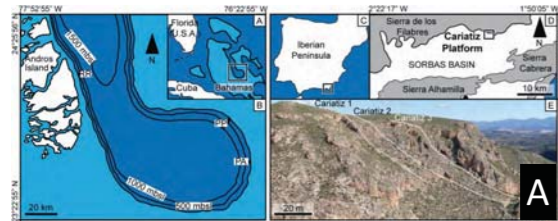


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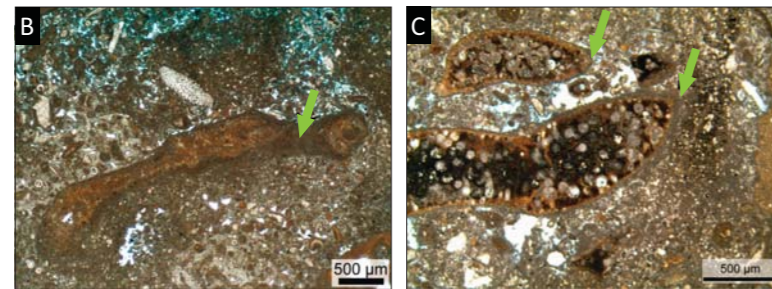


## Microbial Binding (Reolid et al., 2017)

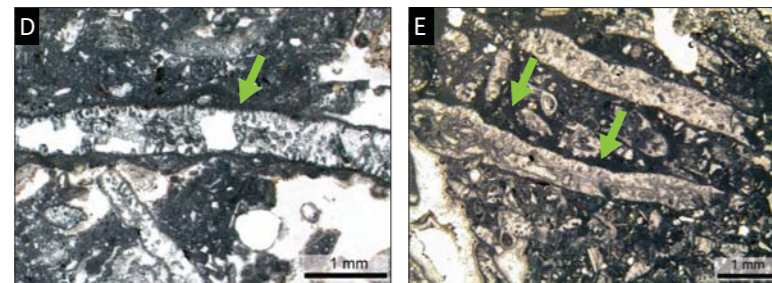


• **Figure A:** Location of steep (35°-45°) Holocene and Miocene carbonate slopes of the Tongue of the Ocean (Bahamas) and the Miocene Cariatiz Platform (Iberian Peninsula).

• **Figure B-E:** Microfabrics indicative of microbial binding (green arrows)  
B) *Halimeda* plate encrusted by dense micrite  
C) & D) Micritic crusts over *Halimeda* plates  
E) Dense micrite connecting *Halimeda* plates

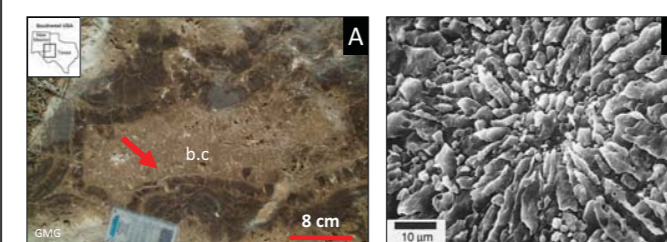
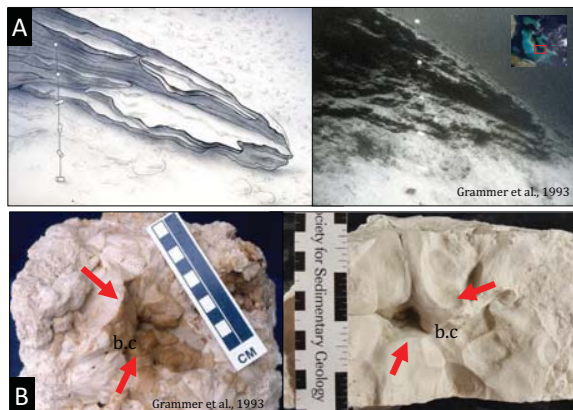


• B and C: Holocene Tongue of the Ocean, Bahamas



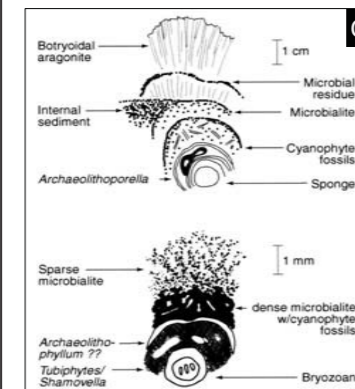
• D and E: Miocene Cariatiz Platform, Iberian Peninsula

## Analogs: Tongue of the Ocean (TOTO) and Permian El Capitán Reef

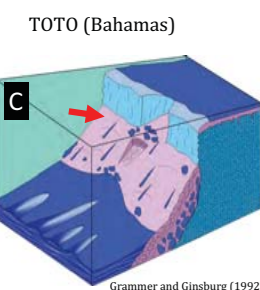


• **Figure A:** Void filling abiotic marine botryoidal cements, similar to those found at Pipe Creek Jr. Quarry

• **Figure B:** SEM photomicrograph of peloid in microbial micrite (radial feature) from the middle Capitán Formation (Kirkland et al., 1998)



• **Figure C:** Idealized microstratigraphic cycles for the middle (above) and upper (below) Capitán. Microbialites, as well as microbial residue between stages of abiotic marine botryoidal cements, can be seen (Kirkland et al., 1998)

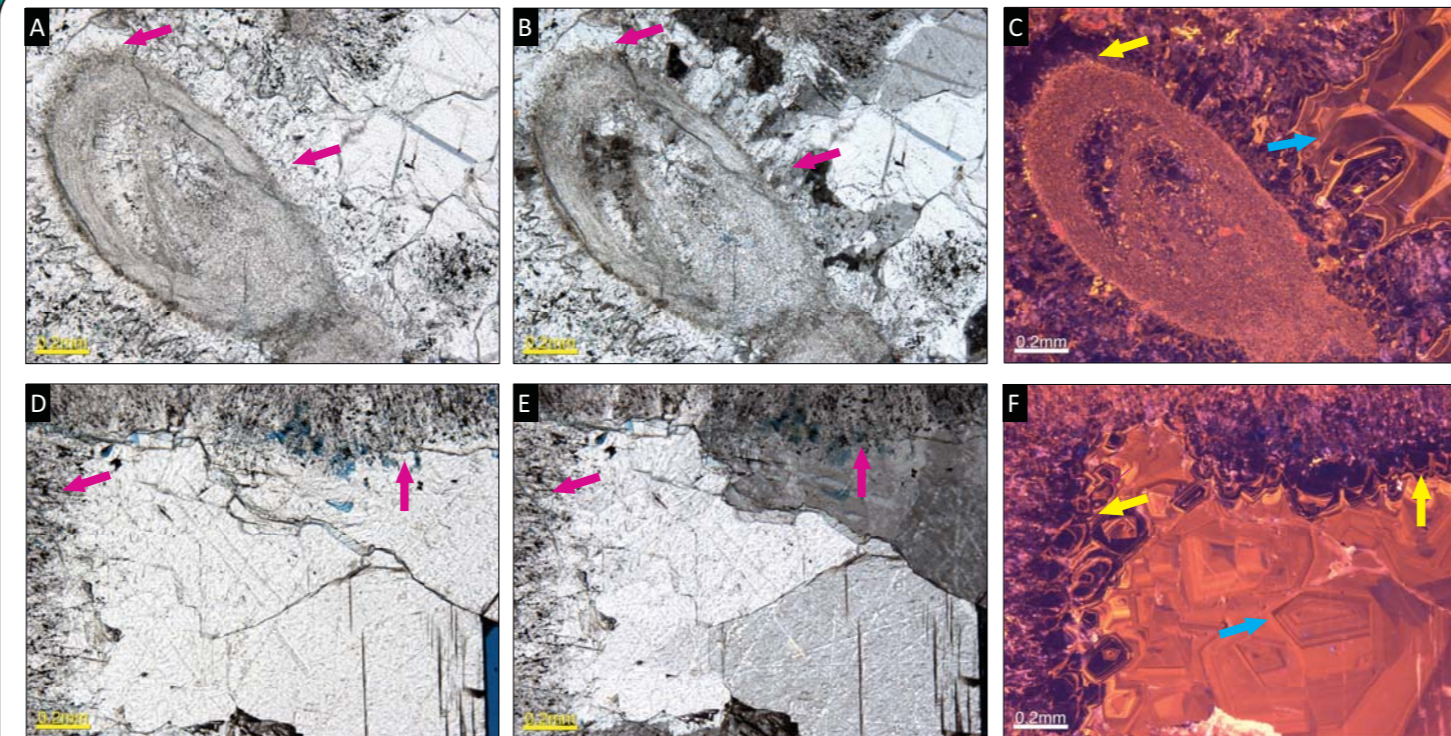


• **Figure A:** Holocene proximal carbonate slope deposits in the Tongue of the Ocean (TOTO)

• **Figure B:** Void filling abiotic marine botryoidal cements (b. c.) at TOTO Bahamas and Pipe Creek Jr.

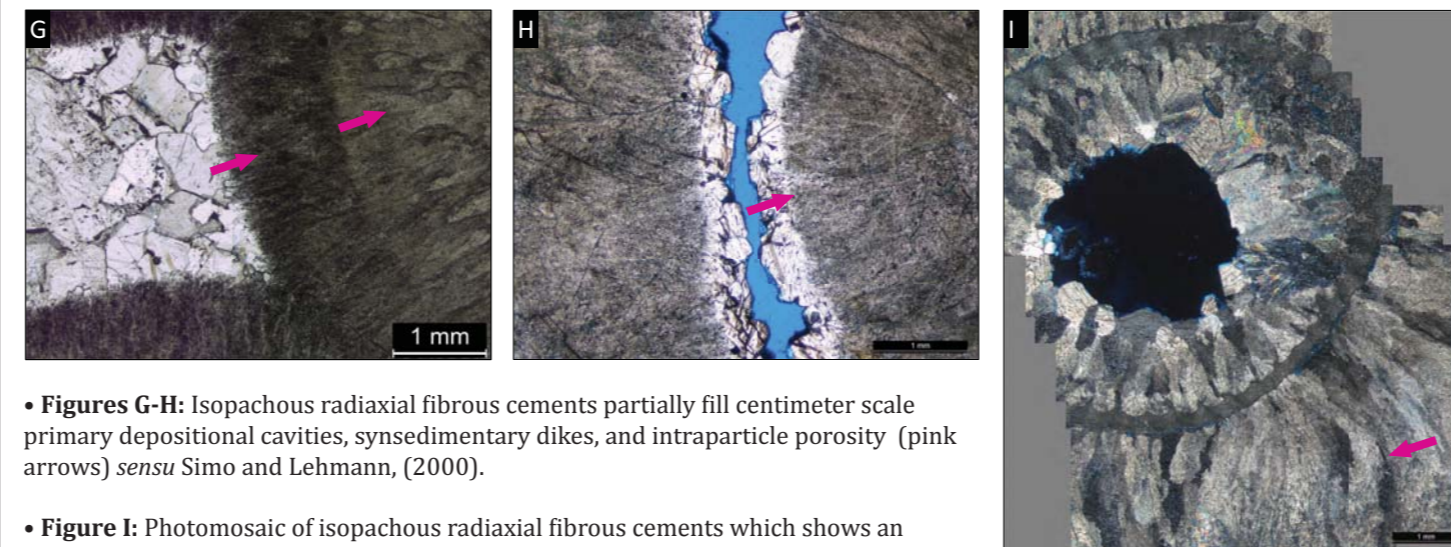
• **Figure C:** Bahamas marginal slope model; steep cemented slope with evidence of microbial binding (red arrow)

## Initial Observations: Abiotic Marine Cement



• **Figures A-C:** Syndepositional abiotic marine cements include isopachous linings (yellow arrows) on skeletal grains (brachiopod). CL reveals one initial stage of syndepositional abiotic marine cement (pink arrow) and a later stage multiple phases (zonations) of meteoric and/or burial cement (blue arrows). These later stages of cements further occlude porosity.

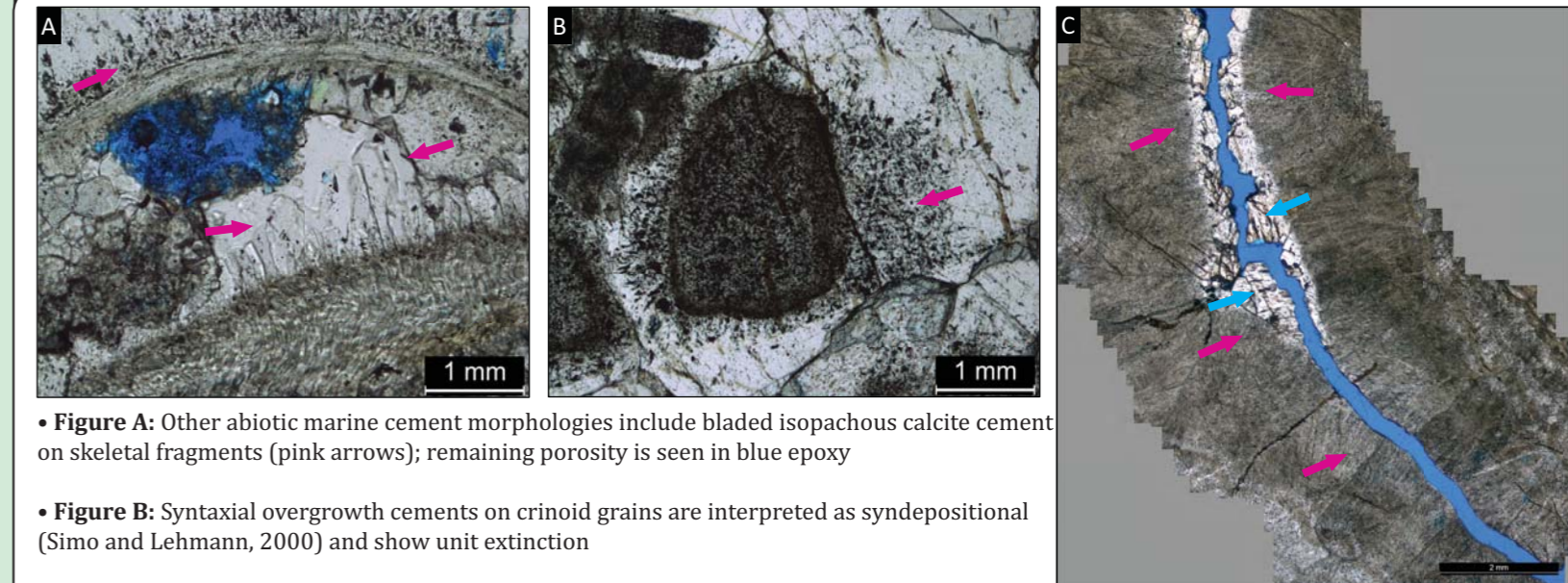
• **Figures D-F:** Other morphologies of syndepositional abiotic marine cements include isopachous radial fibrous (pink arrows). Under CL the cements appear blotchy to weakly luminescent as described by Simo and Lehmann, (2000). Non-luminescent dogtooth cement with thinner banding can be seen as a rim preceding the later stages of blocky cements (yellow arrows).



• **Figures G-H:** Isopachous radial fibrous cements partially fill centimeter scale primary depositional cavities, syndepositional dikes, and intraparticle porosity (pink arrows) sensu Simo and Lehmann, (2000).

• **Figure I:** Photomosaic of isopachous radial fibrous cements which shows an undulose extinction in XPL and is pervasive throughout the forereef slope deposits. In hand sample, this cement can be up to 3cm thick sensu Simo and Lehmann, (2000).

## Initial Observations: Abiotic Marine Cement

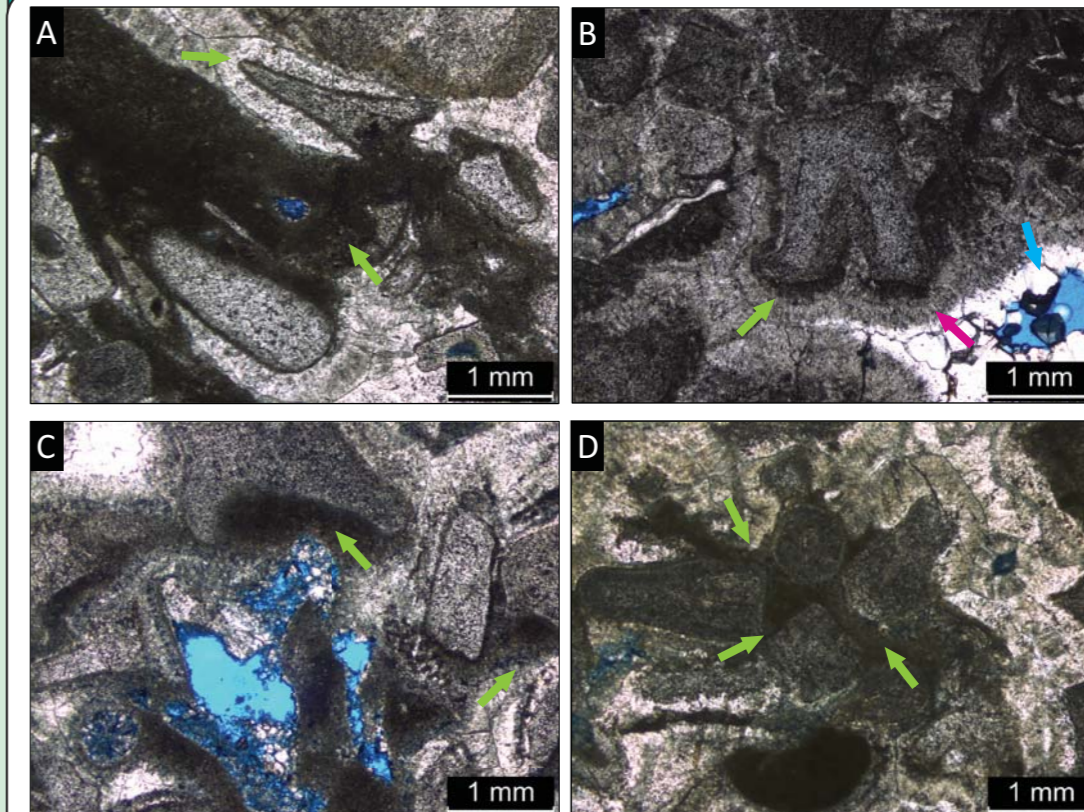


• **Figure A:** Other abiotic marine cement morphologies include bladed isopachous calcite cement on skeletal fragments (pink arrows); remaining porosity is seen in blue epoxy

• **Figure B:** Syntaxial overgrowth cements on crinoid grains are interpreted as syndepositional (Simo and Lehmann, 2000) and show unit extinction

• **Figure C:** Photomosaic of centimeter scale void filling cements; 1) isopachous radial fibrous cements filling initial porosity (pink arrows) and 2) "postdepositional" clear calcite cements (blue arrows). Initial paragenesis is based on superposition and crosscutting relationships

## Initial Observations: Microbial Binding



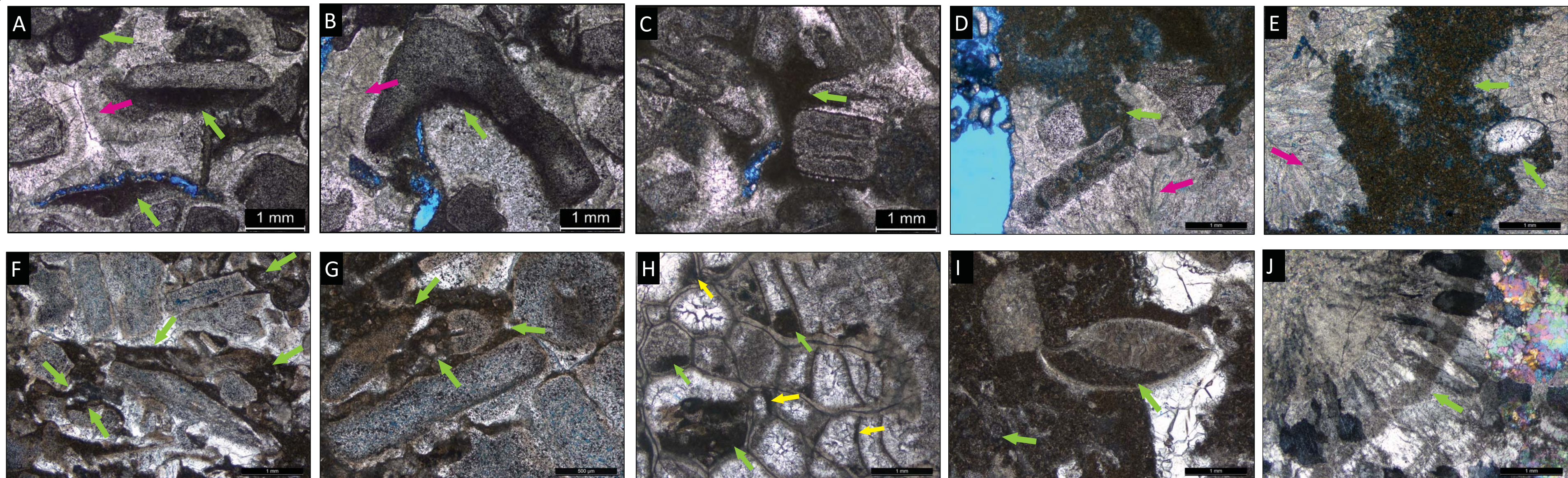
**Figures A-D:** Description of microfabrics indicative with early microbial influence as described by Reolid et al., 2017 (green arrows).

• **Figure A:** Well developed micritic crusts and micrite patches binding bioclasts. Remaining porosity is seen in blue.

• **Figure B & C:** Asymmetric micrite envelopes locally on skeletal grains. Abiotic syndepositional marine cements include isopachous radial fibrous cements (pink arrows). Later stage cements include clear blocky calcite which could be meteoric or burial (blue arrows).

• **Figure D:** Trapping and binding structures locally connecting bioclasts (crinoid grains)

## Initial Observations: Microbial Binding



**Figures A-J:** Description of microfabrics indicative with early microbial influence (green arrows); Abiotic syndepositional marine cements include isopachous radial fibrous cements (pink arrows). Remaining porosity (blue epoxy) in some cases, is rimmed with dolomite crystals.

- **Figures A-B:** Asymmetric micrite envelopes possibly related to variable light conditions and/or water circulation during the precipitation of microbial cements
- **Figure C:** Dense micrite locally connecting skeletal fragments (crinoid grains)
- **Figures D-G:** Dense micrite trapping and connecting skeletal fragments; percentage and distribution of microbial binding and microbially mediated cements could provide insights into windward and leeward orientation. In these samples, the micrite has been replaced by dolomite which is reported to have formed after the precipitation of syndepositional calcite cements (Simo and Lehmann, 2000).
- **Figures H-I:** Geopetal structures on tabulate coral and brachiopod shell; Microbial micrite preceeds syndepositional abiotic marine cements and appears to be “gravity defying” in some sections of the tabulate coral (yellow arrows). Early microbial binding could serve as a sediment stabilizing agent that provides a suitable setting for the subsequent precipitation of abiotic marine cements.
- **Figure J:** Black partings in isopachous radial fibrous cements could be related to organic or microbial coatings formed during interruptions of cement growth (Grammer et al., 1993).

### Key Points

1. Silurian-age forereef slope deposits exposed at Pipe Creek Jr. Quarry are characterized by steep depositional dips of 35°-45° with abundant syndepositional abiotic marine cements as well as evidence of microbial binding. Abiotic marine cements seen in hand sample include large void- filling botryoidal cements which are also reported in other steep carbonate slopes like the Holocene Tongue of the Ocean and the Permian Capitán Reef.
2. Initial analysis through Optical Cathodoluminescence (CL) reveals a complex diagenetic history in which different cementation stages can be identified. These include 1) syndepositional abiotic marine cements, 2) multiple phases of post depositional meteoric and burial cements, and 3) dolomitization (matrix replacive and void filling cements).
3. Petrographic analysis reveals varying morphologies associated with syndepositional abiotic marine cements. These include isopachous radial fibrous, bladed isopachous calcite cement, and syntaxial overgrowths. These syndepositional abiotic marine cements significantly reduced initial porosity and permeability in these deposits. Later stage abiotic cements (meteoric or burial?) further occluded remaining porosity.
4. Potential microfabrics indicative of microbial binding as described by Reolid et al., 2017 can be seen in these Silurian forereef slope deposits. These fabrics include: trapping and binding structures, asymmetrical thick micritic crusts, and dense clotted micrite. This microbial binding may form a stable substrate for the precipitation of the subsequent abiotic marine cements.
5. Relative amounts of microbial binding may be related to windward vs. leeward slopes and associated variations in circulation. Microbial binding may also be related to water depth.

### Future Work

1. SEM analysis for a better image resolution of probable microbial binding and microbially mediated cements
  2. Image analysis to quantify the amount of porosity occluded by 1) syndepositional marine cements (abiotic and microbially mediated) and 2) post depositional clear blocky calcite cements
  3. Confocal Microscopy
- Additionally:*
5. Stable isotope analysis to obtain a better understanding of the cement paragenesis associated to changes in water chemistry in the system
  6. Further analyze the origin, percentage, and distribution of dolomite in the system.

### Acknowledgments

