PS Significance of Microbial Binding in the Formation and Stabilization of Carbonate Forereef Slope Deposits*

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Abstract

Silurian (Cayugan) forereef slope deposits exposed at Pipe Creek Jr. Quarry, Indiana are characterized by steeply dipping beds (35-45°) consisting of grainstone facies with abundant syndepositional abiotic marine cement. In many instances, the early stabilization of steep carbonate slopes has been previously attributed to this syndepositional abiotic marine cementation. However, recent studies propose that extensive microbial binding can be another significant factor. Microbial binding likely facilitates abiotic cementation by partially stabilizing the sediments, and together allows for the development and preservation of steep carbonate slopes. The combination of microbial and abiotic early cements may lead to an early reduction in primary porosity and permeability which may adversely affect subsequent reservoir development and preservation during burial.

Comparison of interpreted depositional processes and slope geometry in the Silurian example to those described in subsurface examples including the supergiant Tengiz Field in Kazakhstan and the modern from Tongue of the Ocean in the Bahamas, shows similarity in terms of slope declivity, bed geometry, and the apparent presence of pervasive abiotic marine cements and microbial cements. The aim of this study is to quantify the contribution of microbial binding to the stabilization and potential reservoir modification in the Silurian forereef slope deposits exposed at Pipe Creek Jr. Quarry and compare with the subsurface Silurian reefs of the Michigan Basin.

Initial petrographic analysis reveals an abundance of syndepositional abiotic marine cements with varying morphologies as well as microfabrics indicative of early microbial binding such as asymmetric micritic crusts, trapping and binding structures and dense clotted micritic masses. Anticipated results with further analysis will provide insight into early reduction of porosity and permeability due to early abiotic marine cementation and microbial binding, identify if microbial binding precedes abiotic marine cements and provides a suitable substrate for later abiotic marine cementation, help to explain the early lithification and evolution of carbonate slopes, and further develop the fundamentals of sedimentology and diagenesis of Silurian (Niagaran) reefs in and around the Michigan Basin.

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Abstract

The geometry of carbonate slope deposits has been described as being the result of platform height and the volume of sediment transported from the platform, sediment texture and response to shear strengths, the balance between erosion and deposition, early lithification by abiotic marine cements, and *in situ* carbonate production and stabilization by microbial carbonates. Recent studies in modern examples of the Holocene of the Tongue of the Ocean (TOTO) in the Bahamas and the Miocene of the Cariatiz platform in SE Spain propose that the influence of these microbial carbonates, specifically microbial binding, is a significant early-stage slope-stabilizing factor in steep (35-45°) carbonate slopes. This microbial binding prevents slope failure by providing an early-stage lithification and preserves steep depositional slopes, which sometimes reach the angles of repose.

Although the effect of microbial binding in slope stabilization and lithification is well documented in Cenozoic examples of steep carbonate slopes, its significance and relationship with syndepositional abiotic marine cements in Paleozoic reef systems and steep carbonate slope deposits has not yet been fully determined or understood. Given the growing number of studies supporting the role of microbes in the precipitation of micrite, as well as binding and trapping, this study aims to describe microbial fabrics that may indicate *in situ* microbial production and syndepositional lithification. Results from this project will provide insights into the relationship between microbial binding and syndepositional abiotic marine cements in ancient reef systems in order to explain the early lithification and evolution of steep carbonate slopes such as forereef slopes, and further develop the fundamentals of sedimentology and diagenesis of Silurian (Niagaran) reefs in and around the Michigan Basin.

Objectives

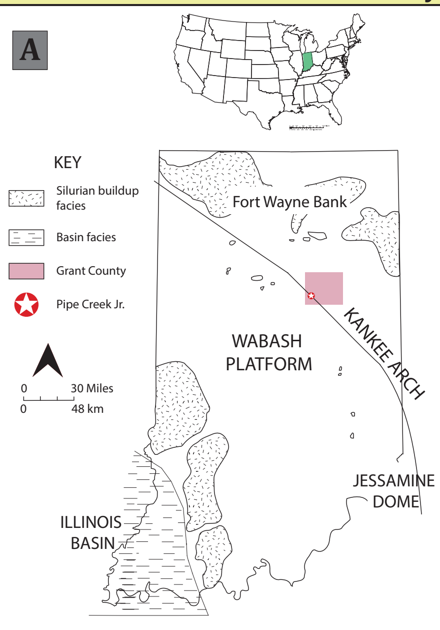
1) Determine if there is evidence of early microbial binding in the steep Silurian forereef slope deposits at the Pipe Creek Jr. quarry.

2) Evaluate the contribution of microbial binding to the stabilization and lithification of these deposits.

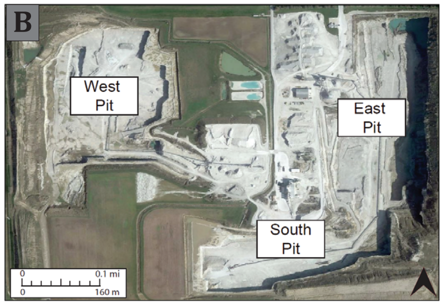
3) Determine a paragenetic relationship between microbial binding and abiotic marine cements.

4) Evaluate whether there is a windward vs. leeward orientation of the reef complex based on the relative amounts and distribution of microbial binding and syndepositional abiotic marine cements in the different locations (West, East, and South Pits) of the quarry.

Study Area



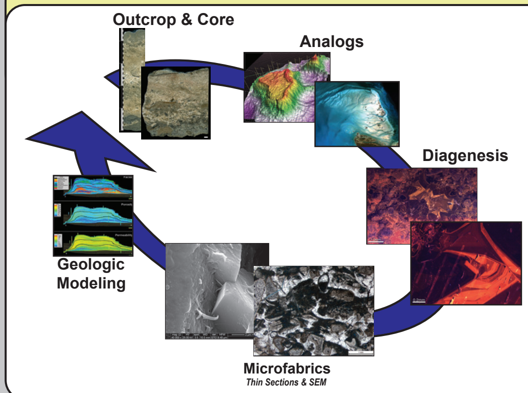
(Modified from Spengler and Read, 2010)



A) Silurian paleogeographic reconstruction of Indiana showing the Wabash Platform, the Fort Wayne Bank, Kankee Arch, Jessamine Dome, and the location of Grant County.

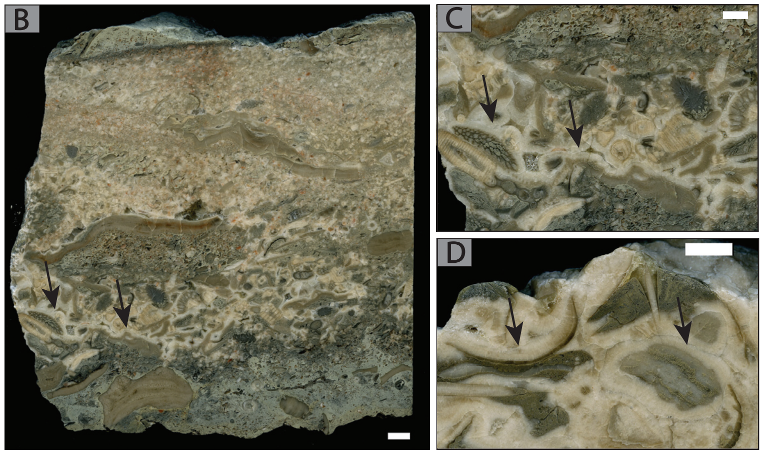
B) Aerial image of the active limestone quarry Pipe Creek Jr. Quarry. The quarry can be divided into three active pits which are labeled West, East, and South Pits (from Google Earth).

Methods



- Hand Sample Analysis (n=33)
- Thin Section Petrography (n=113)
- Cathodoluminescence Microscopy (CL) (n=5)
- Polished samples using a JEOL IB-19500CP cross section polisher (n=11)
- FEI Quanta 600F field emission environmental scanning electron microscope (ESEM) (n=11)

Silurian Forereef Slope Deposits



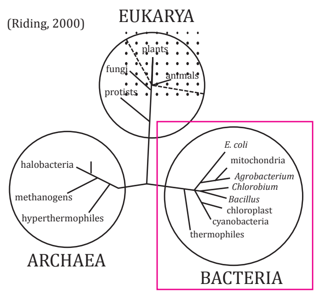
A) Tabular- to wedge-shaped beds (15 to 100 cm thick) steeply dipping 35° to 45°.

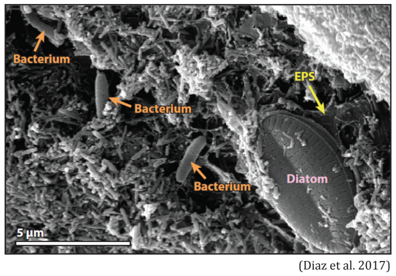
B) Transition from skeletal mudstone-wackestone (bottom) to coarse grainstone-packstone (top): characterized by abundant isopachous marine cements (black arrows; Scale bar: 1 cm).

C) Close-up of white- to light-gray isopachous marine cements in coarse grainstone-packstone (Scale bar: 1 cm).

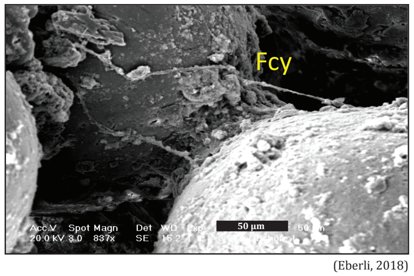
D) Hand samples show isopachous marine cements that can reach up to a few millimeters in thickness (Scale bar: 1 cm).

Microbial Carbonates





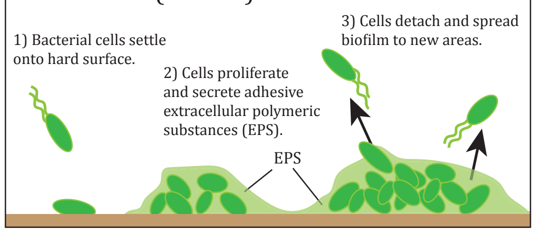
(Diaz et al. 2017)



(Eberli, 2018)

- Produced by benthic microbial communities, which include bacteria, filamentous cyanobacteria (FCY), and algae.
- Formed by three main processes:
  1) trapping or agglutination of particles
  2) mineralization
  3) biomineralization of organic tissues like extracellular polymeric substances (EPS)
- EPS are produced by microbes and accumulate outside of cells to form a protective and adhesive matrix that attaches microbes to substrates, provides physical and chemical protection, and can also aid in nutrient absorption.

How an EPS (biofilm) is formed



(Modified from Larimer at al. 2017)

Significance of Microbial Binding in the Formation and Stabilization of Carbonate Forereef Slope Deposits

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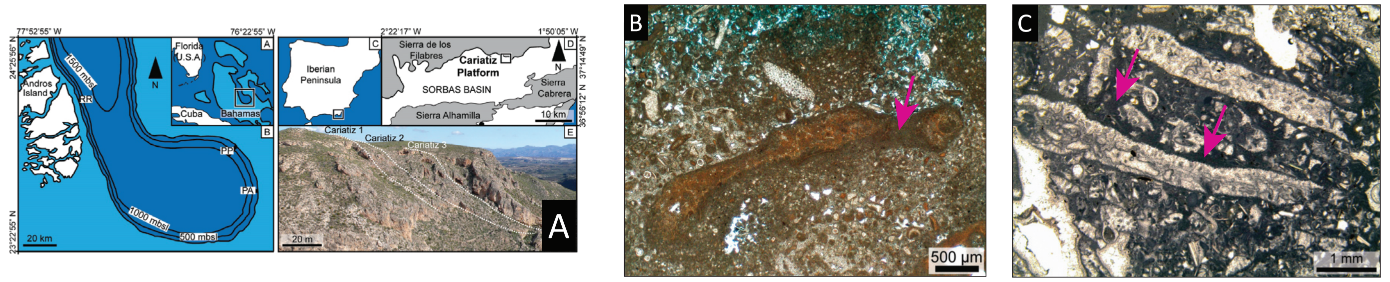
Modern and Ancient Analogs

1) Holocene Tongue of the Ocean (Bahamas) and Miocene Cariatiz Slopes (Spain):

(Figures from Reolid et al. 2017)

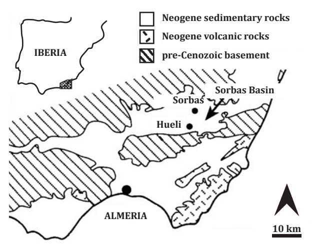


• **Fig. A:** Location of steep (>35°) Holocene and Miocene carbonate slopes of the Tongue of the Ocean (Bahamas) and the Miocene Cariatiz Platform (Iberian Peninsula).

• **Fig. B-C:** Microfabrics indicative of microbial binding (pink arrows); **B)** *Halimeda* plate encrusted by dense micrite **C)** Dense micrite connecting *Halimeda* plates.

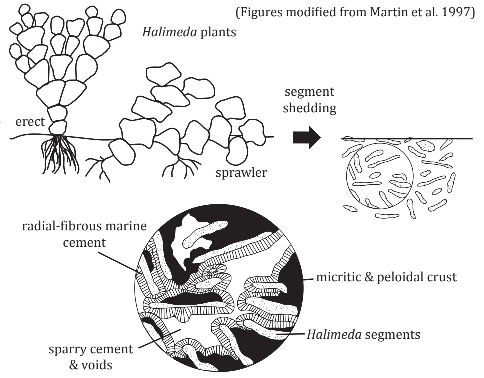
2) Late Miocene *Halimeda* algal-microbial segment reefs, Sorbas Basin (Spain):

(Figures modified from Martin et al. 1997)

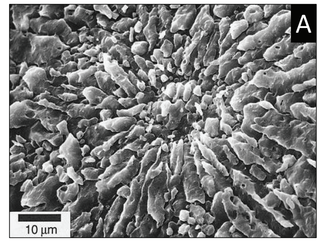


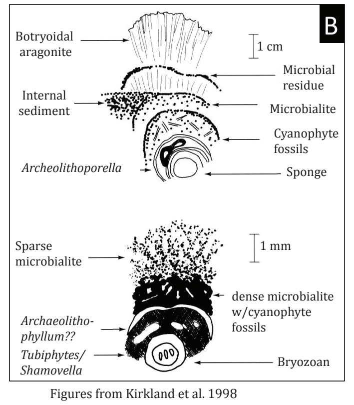
• Early lithification by microbial carbonates and abiotic cements stabilized algal plates (that otherwise could have been readily transported) by binding them close to their sites of growth.

• Early lithification occurred by two processes:
  a) precipitation of micritic crusts around and between segments
  b) precipitation of isopachous cements over remaining surfaces



2) Permian Capitan Reef (West Texas and New Mexico):



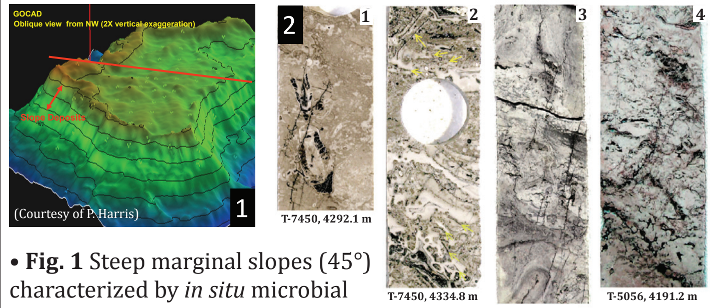


Figures from Kirkland et al. 1998

• **Fig. A:** SEM photomicrograph of peloid in microbial micrite (radiaxial feature) from the middle Capitan Formation. Gravity defying peloidal micrites are interpreted to be precipitated within mucilaginous microbial aggregations.

• **Fig. B:** Idealized microstratigraphic phases of lithification for the middle (above) and upper (below) Capitan. Microbialites, as well as microbial residue between stages of abiotic marine botryoidal cements, can be seen.

3) Carboniferous Tengiz Field (Kazakhstan):

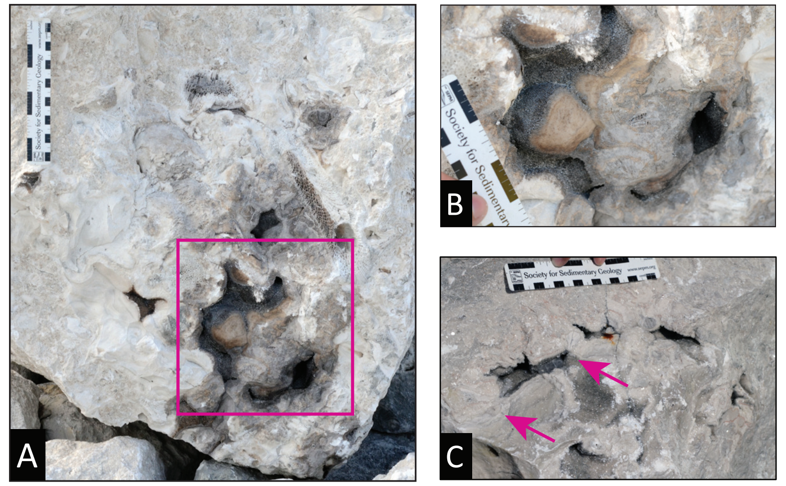


(Figures modified from Collins et al. 2006)

• **Fig. 1** Steep marginal slopes (45°) characterized by *in situ* microbial boundstone facies in upper slope.

• **Fig. 2** *In situ* microbial boundstone facies include Type A, B, C:
1) **Type C boundstone**- skeletal rich with micritic to peloidal microbial texture
2) **Type C boundstone**- thick banded cements of probable marine origin
3) **Type B boundstone**- irregular to rounded, concentrically laminated microbial masses and cements
4) **Type A boundstone**- dominant peloidal to micritic matrix

Results: Diagenesis

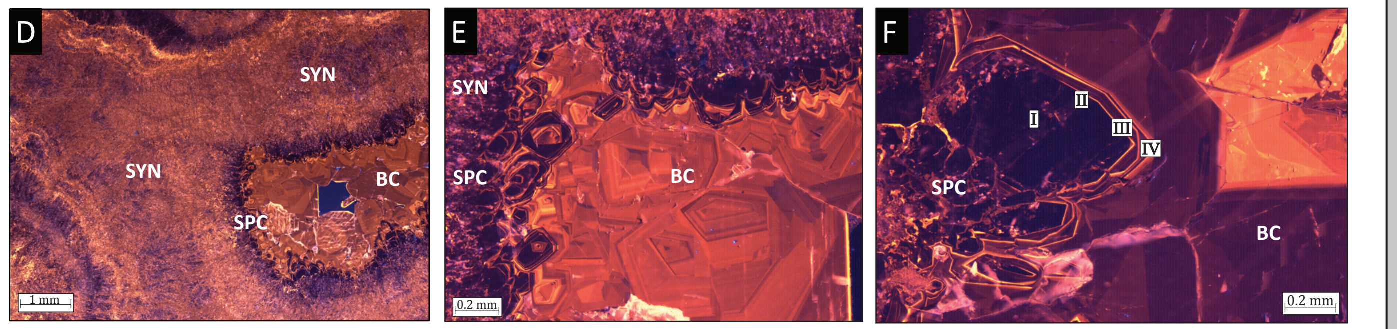


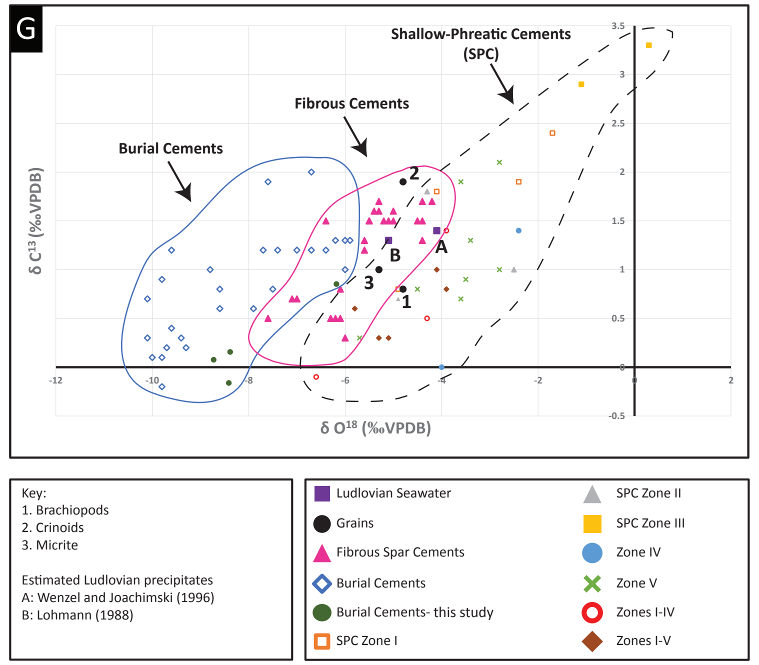
• **Fig. A:** Centimeter scale vuggy pores partially filled with abiotic marine botryoidal cement (pink box).

• **Fig. B:** Close up of botryoidal cement in large (cm scale) vugs.

• **Fig. C:** Abiotic marine cement filling most of the vuggy porosity (pink arrows). Morphologies of these cements vary from botryoidal to isopachous to radiaxial fibrous cements. Remaining pores can be oil stained in some examples.

• **Fig. D:** Under cathodoluminescence, syndepositional radiaxial fibrous cements (SYN) show blotchy to weak luminescence.





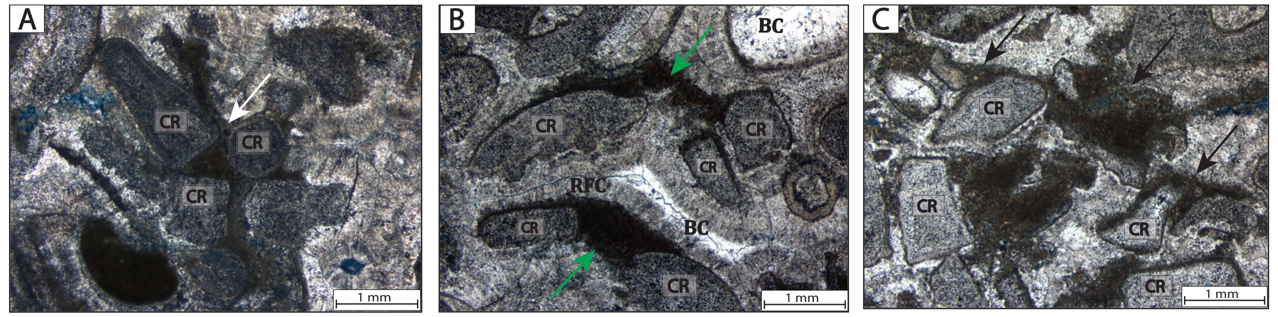
(Modified from Simo and Lehmann, 2000)

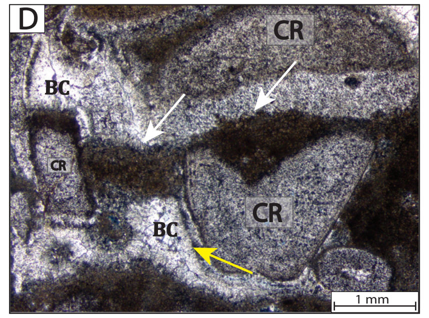
• **Fig. E:** Shallow-meteoric phreatic (SPC) and burial cements (BC) show variations of bright and dull luminescence. BC zones show concentric and sectoral zoning, as well as multiple zonations.

• **Fig. F:** SPC Zones I-IV are consistent with what was identified by Simo and Lehmann (2000). Zone I is nonluminescent; Zone II is characterized by bright-orange luminescence; Zone III exhibits orange-brown to dull luminescence, and Zone IV is nonluminescent, with thin, irregular, and discontinuous bright-orange luminescent subzones.

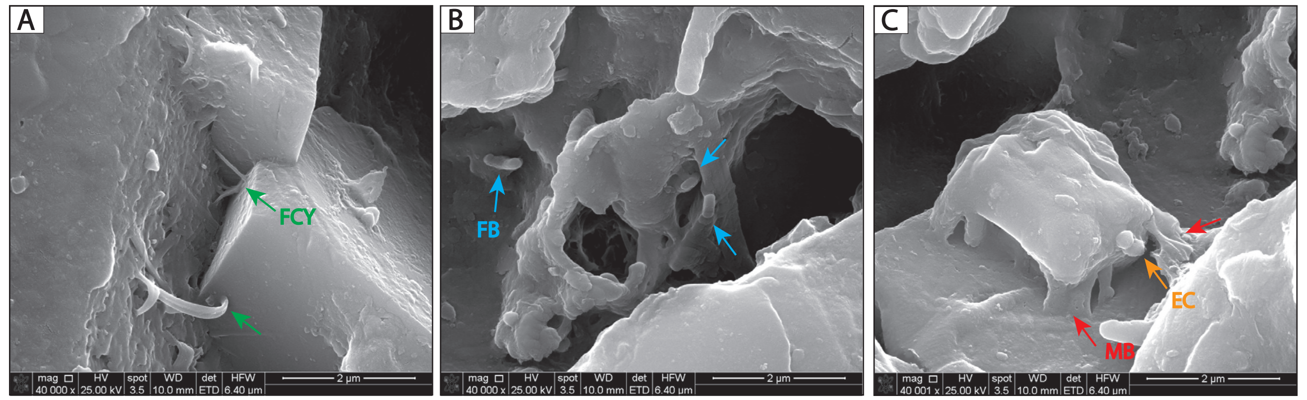
• **Fig. G:** $\delta^{13}C$ vs. $\delta^{18}O$ values for skeletal grains, micrite, and various cements from Simo and Lehmann (2000) and this study. C/O values for burial cements, syndepositional radiaxial fibrous cements, and shallow-meteoric phreatic cements are also shown. Syndepositional radiaxial fibrous cements exhibit isotopic values consistent with known Silurian seawater values (A and B in plot).

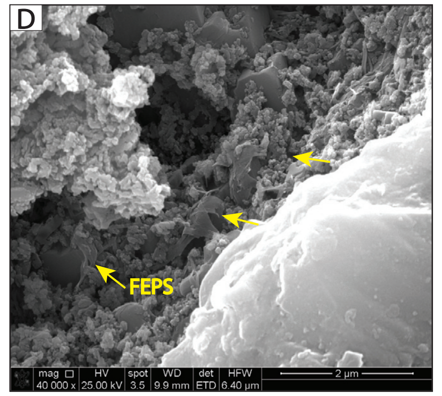
Results: West Pit





• Photomicrographs of the dense micrite in samples collected from the West Pit:
A) Dense micrite (white arrows) acts as a trapping mechanism for crinoid grains (CR).
B) Micritic bridge-like structures bind crinoid grains (CR) and may show some degree of preferential precipitation (green arrows) based on nearby geopetal structures. Radiaxial fibrous marine cements (RFC) appear to succeed microbial binding.
C) Micritic crusts and micritic bridges on crinoid grains (CR) show better development on the upper parts of the crinoid grains (black arrows) based on geopetal structures.
D) Micritic bridge-like structures are lithified early and allow for the preservation of an internal cavity which is later occluded with blocky calcite cements (BC; Yellow arrows)





• SEM images of ion-milled samples of the forereef slope deposits; Scale bar in all photomicrographs is 2 microns.:

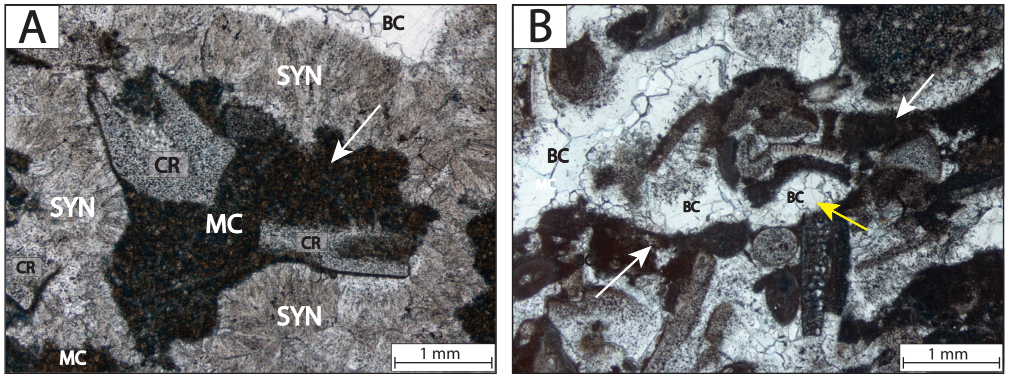
A) Green arrows indicate filamentous cyanobacteria fossils (FCY), which are often slightly curved.

B) Blue arrows show fossilized bacterium (FB).

C) Micritic bridges (MB) creating binding structures extending from the surface of the pore (red arrows). Entombed *coccus* (EC) shaped bacteria can also be seen (orange arrows).

D) Fossilized extracellular polymeric substances (FEPS) within residual porosity (yellow arrows).

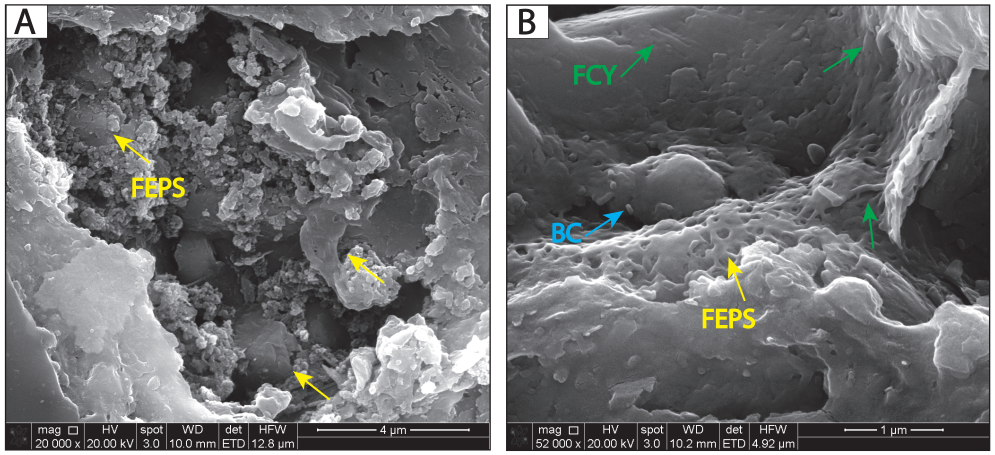
Results: East Pit



• Photomicrographs of dense micrite in samples collected from the East Pit of the Pipe Creek Jr. Quarry:

A) Dense micrite matrix (MC; white arrow) connecting crinoid grains (CR). Syndepositional radiaxial fibrous cements (SYN) surrounding the dense micrite matrix.

B) Micrite bridges (white arrows) were lithified early and can preserve some of the original porosity which was subsequently occluded by later abiotic cements such as clear blocky calcite (BC; yellow arrow).

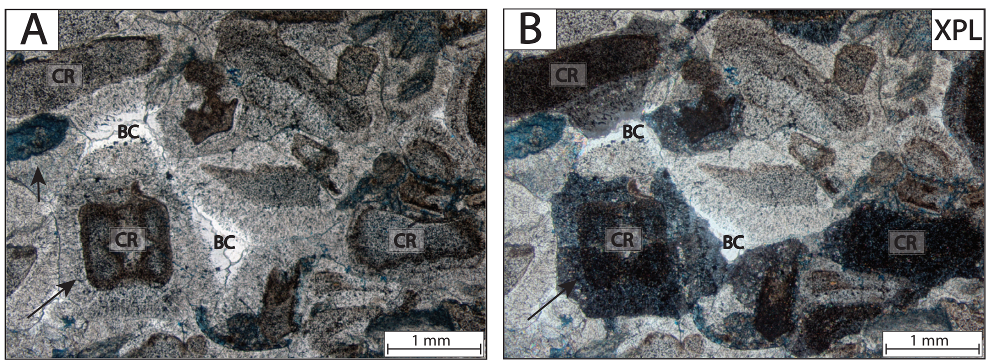


• SEM images of ion-milled samples of the forereef slope deposits from the East Pit:

A) Fossilized extracellular polymeric substances (FEPS; yellow arrow) within remaining porosity. Scale bar is 4 microns.

B) Fossilized mucus-like EPS (FEPS; yellow arrow) lining remaining porosity . This FEPS contains fossilized bacterial communities which include filamentous cyanobacteria (FCY; green arrows) and bacterium (BC; blue arrow). Scale bar is 1 micron.

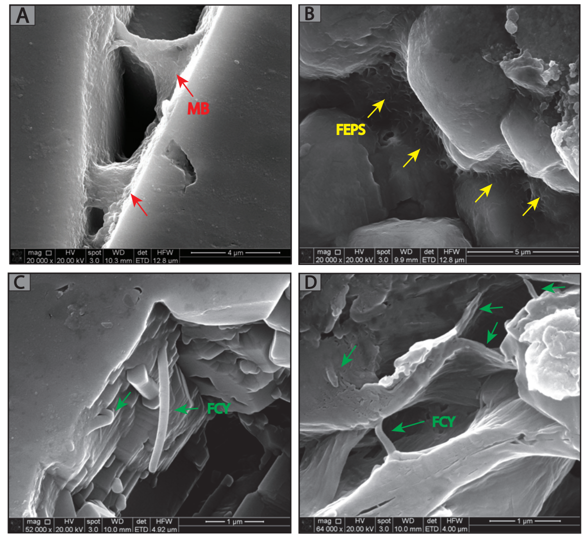
Results: South Pit



• Photomicrographs showing early syntaxial overgrowth cements typically found in samples from the South Pit of the Pipe Creek Jr. quarry:

A-B) Coarse grainstone-packstones showing syntaxial overgrowth cements (black arrow) on crinoid grains (CR). This cement morphology can be easily identified by its unit extinction in cross polarized light (black arrow). Later stage cements include blocky clear calcite cements (BC).

Results: South Pit



• SEM images of ion-milled samples of the forereef slope deposits from the South Pit:

A) Micritic bridges (MB) create a binding structure that extends from the surface of pores (red arrows; Scale bar is 4 microns).

B) Fossilized EPS (FEPS) has a honeycomb-like appearance (yellow arrows; Scale bar is 5 microns).

C) Fossilized cyanobacteria (FCY) have a curved shape and protrude from the pore surfaces (green arrows; Scale bar is 1 micron).

D) The entanglement of FCY forms colony-like structures (green arrows; Scale bar is 1 micron).

Key Points and Implications

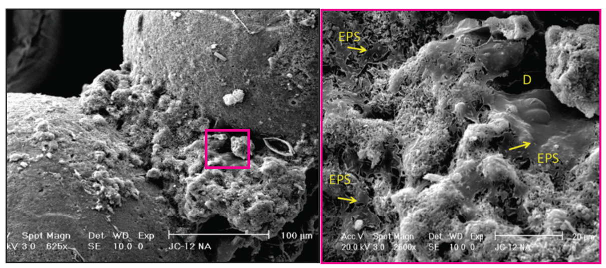
1) Distinct microfabrics indicative of microbial binding have been identified in thin sections, and fossilized bacterial communities and bacterial biofilms, (such as EPS), were identified in SEM.

2) Microbial binding of sediments in the forereef slopes is interpreted as an early stage stabilizing and lithifying agent that inhibits slope failure and conserves the steep angles of the forereef slopes.

• Stabilization by microbial binding precedes the stabilization by abiotic marine cement which have been reported to grow as fast as 8-10mm/yr (Grammer et al. 1993).

3) Windward and leeward orientations of the Pipe Creek Jr. reef complex were determined by the relative abundance of syndepositional abiotic marine cements and microbial binding.

• Based on this work, the West Pit appears to be the most pervasively cemented section of the reef and is interpreted as likely being in a windward facing location.
• Abiotic cement morphologies and microfabrics indicative of microbial binding in the East Pit are similar but neither are as prevalent and widespread as observed in the West Pit.
• The most likely leeward margin of the reef (South Pit) is characterized by abundant syntaxial overgrowth cements and lacks large (cm-scale) void filling botryoidal and radiaxial fibrous cements that are typically found along windward margins of reefs.



(Eberli, 2018)

As described by Eberli (2018), the fusion of grains by micritic cements produces a stiff rock with the ability to resist compaction thereby preserving primary interparticle porosity. The combined result is a fast, high impedance rock with high permeability.

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