Evaluating the Controls on Reservoir Quality and Heterogeneity of Silurian Pinnacle Reefs, Michigan Basin*

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Search and Discovery Article #50405 (2011)
Posted April 25, 2011

*Adapted from oral presentation at AAPG Eastern Section Meeting, Kalamazoo, Michigan, September 25-29, 2010

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Abstract

A detailed sequence stratigraphic analysis of Silurian (Niagaran) "pinnacle" reefs in the Michigan Basin provides insight into the lateral and vertical variability of reservoir facies observed in the subsurface. Previous models have shown continuous reef growth during a single relative sea level rise with deposition of the Salina "A" Formations representing the end of Niagaran reef growth. In depth core analysis tied to wireline logs show that reefs consist of at least two orders of cyclicity. This sequence hierarchy is manifested by high-frequency sequences (few meters thick) driven by relative sea level variations and superimposed on large-order sequences (10's of meters thick) controlled by globally recognized sea level changes. Local changes in relative sea level are likely controlled by the combination of higher frequency eustatic variations along with subsidence and autocyclic mechanisms related to reef growth.

The higher frequency cyclicity plays a major role in controlling the vertical heterogeneity of these reservoirs. For example, reservoir quality in skeletal grainstones is related to their position within the higher frequency cycles. Grainstones deposited during transgressive phases retain higher porosity and permeability relative to those deposited in regressive phases which were prone to preferential cementation and porosity occlusion that occurs at or near cycle boundaries. In contrast, higher porosity and permeability values within the framework reef are associated with the regressive intervals and are due to exposure-related preferential dissolution and porosity enhancement, although in some reefs this porosity may be rapidly occluded by deposition of overlying evaporites. Understanding of the sequence hierarchy in these Silurian reefs provides additional insight into the episodic growth of the reefs relative to sea level fluctuations and provides a means to better explain, and thus predict, the vertical heterogeneity observed in reservoirs.

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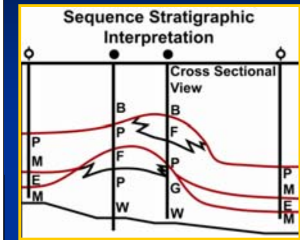
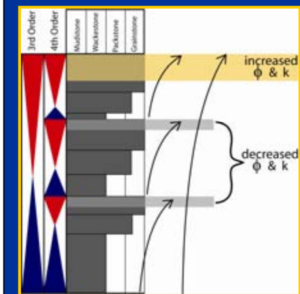
Conclusions



Modified from Weber, et al, 1994



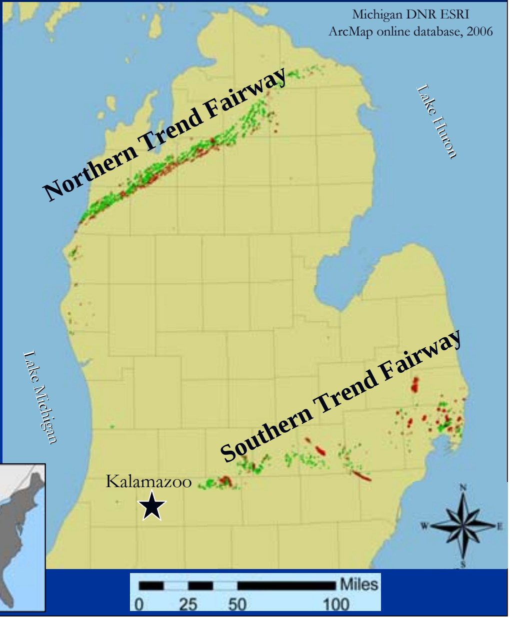
Ritter, 2008

- Sequence stratigraphic frameworks more accurately capture vertical and lateral continuity between facies
- Reservoir quality is controlled by primary depositional fabrics and position within a sequence stratigraphic framework
  - Facies close to 3rd order sequence boundaries have higher porosity and permeability
  - Facies positioned near 4th order HFS boundaries have lower porosity and permeability

Significance

- Niagaran reefs are economically important:
  - 400 MMBOE (green dots)
  - 2.7 tcf of gas (red dots)

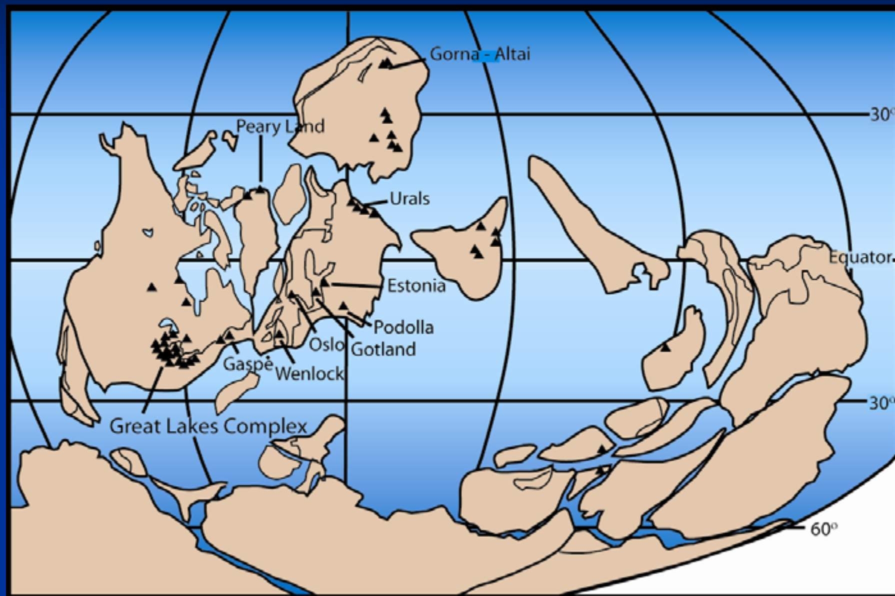
- Extensive storage units for natural gas



Outline

- Introduction
  - Geologic Background
  - Sequence Stratigraphy
- Methodology
- Sequence Stratigraphic Correlation
- Reservoir Quality Trends
- Conclusions

Silurian Reef Complexes

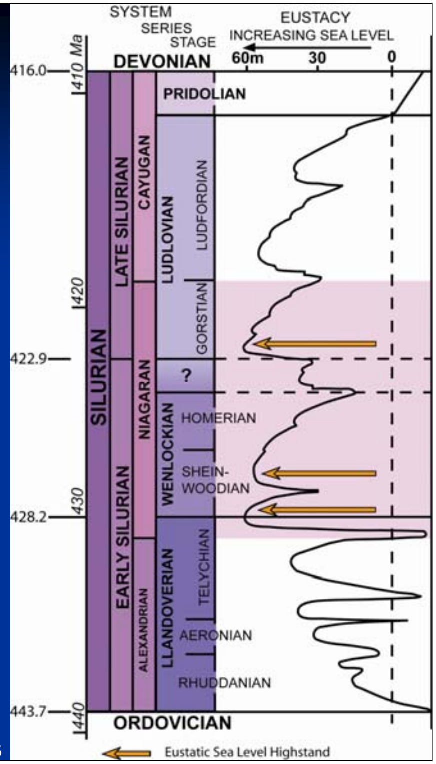


Modified from Copper & Brunton, 1991

Presenter's Notes: During the Silurian, similar reef geometries have been documented in other parts of the world. Here is a paleo-reconstruction of the continents and the black triangles represent locations of reefs and reef complexes. Notice that reefs are situated between 10-30 degrees North and South latitude.

Silurian Sea Level

- Transitional climate from icehouse to greenhouse conditions
- Three eustatic sea level highstands
- Expect to see evidence of sea level highstands in Michigan Basin



Modified from Ross & Ross, 1996

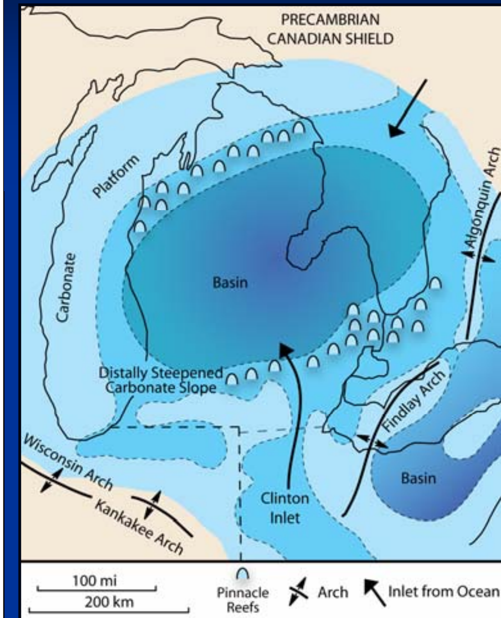
Presenter's Notes: The Silurian system is thought to be neither icehouse (+frequency, +magnitude) nor greenhouse (slower, less dramatic) but a transitional climate.

A number of previous studies documented that reef growth and associated geometries are related to sea-level fluctuation. Notice that during the Niagaran, there were three eustatic sea-level highstands.

Since these are global or eustatic signals, you would expect to see evidence of these signals in the Michigan Basin.

This eustatic sea level curve was established by using Benthic conodonts and graptolites as water depth indicators to infer bathymetry and upward changes in depositional facies from established local and regional transgressions and regressions.

Michigan Basin



- Shallow, nearly circular, intracratonic sea
- Northern Trend Reef Geometry
  - 300-600 ft in height
  - 200 acres
- Southern Trend Reef Geometry
  - < 350 ft in height
  - Up to 700 acres

Modified from Briggs & Briggs, 1974

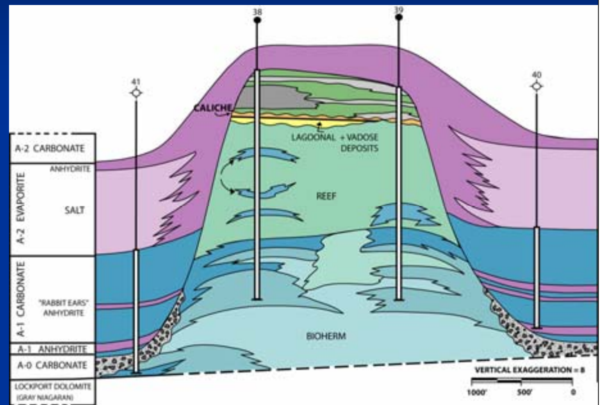
Presenter's Notes: The MI Basin during the Silurian was a shallow, nearly circular, intracratonic sea, 250 miles in diameter with deep water towards the center of the basin and Niagaran reefs along the margin. The black arrows represent possible inlets that connected the basin to open ocean waters.

The Niagaran reefs are divided into two trend fairways based on geographies and reef geometries. Reefs from the Northern trend are areally limited with high relief ranging from under 300 feet to over 600 feet in height and spanning up to 200 acres. In contrast, the reefs in the Southern trend are areally larger, covering up to 700 acres, but have less relief, with a maximum of 350 feet in height. The differences in reef geometries suggest that there may be differences in the relative timing of reef growth between the Northern and Southern trends. Another objective in this study is to see if there is a correlation between the relative geological timing of the reefs and, if so, at what level.

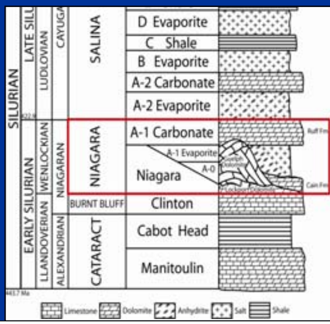
By utilizing a sequence stratigraphic approach in this study, we can evaluate the relative timing of reef growth between the two trends.

Previous Models: Continuous Reef Growth

- Reef growth uninterrupted reaching 300-600 ft in height
- Deposition of Salina “A” Formations was entirely post-reef



Modified from Gill, 1973



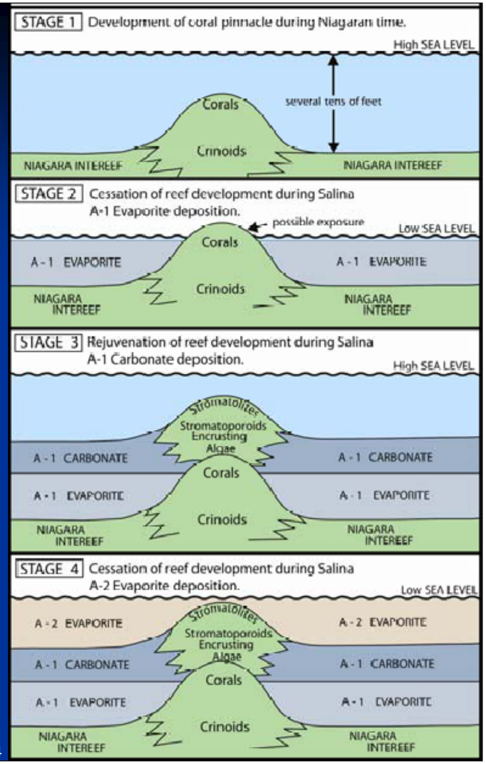
Modified from Cercone, 1984

Presenter’s Notes: Previous workers have suggested Niagaran reef growth is continuous, with reefs reaching 300-600 feet in height before the cessation of growth and deposition of the Salina “A” formations.

Although Gill suggests a continuous reef growth model, there appears to be some cyclic pattern in deposition.

Previous Models: Episodic Reef Growth

- Incorporates sea level fluctuations
- Deposition of the Salina “A” formations was quasi-contemporaneously



Modified from Mesolella et al., 1974

Presenter’s Notes: In contrast, Mesolella et al. presented an episodic reef growth model that suggested the Saline “A” formations were deposited quasi-contemporaneously.

To build further upon this episodic reef growth model, a sequence stratigraphic approach was used.

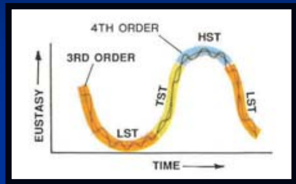
Sequence Stratigraphic Approach

- Sequence stratigraphic interpretations utilize:
  - Transitions in shelf-to-basin deposits
  - Depositional models that incorporate sea level fluctuations
  - Genetically similar depositional systems
- Divides sedimentary strata into time-equivalent (chronostratigraphic), genetically related rock units

Presenter's Notes: Sequence stratigraphic interpretations utilize transitions in shelf-to-basin deposits, depositional models that incorporate sea-level fluctuations and genetically similar depositional systems.

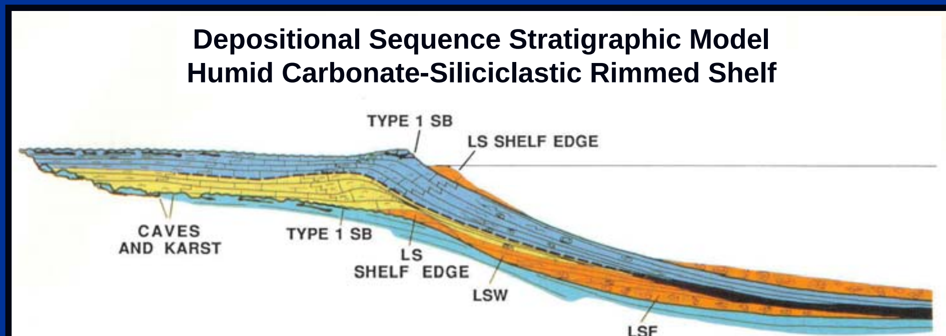
So, by creating a sequence stratigraphic framework, one can divide the sedimentary strata into time-equivalent, genetically related rock units.

Sequence Stratigraphy



Handford and Loucks, 1993

- Sea-level fluctuations influence facies distribution
- Deposition of facies occurs in a consistent, predictable pattern



Handford and Loucks, 1993

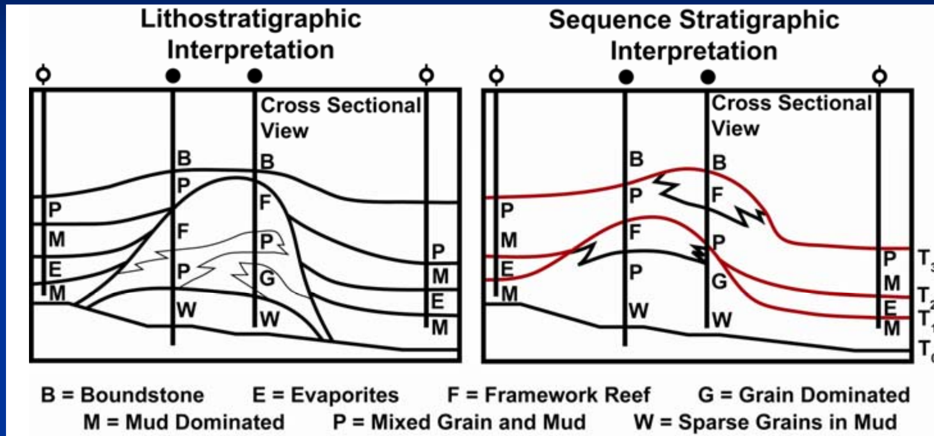
Presenter's Notes: To explain a sequence stratigraphic approach further, we provide some of the basic understandings of sequence stratigraphy. Note the changes in distribution and position of the facies belts over a single rise and fall of sea level.

Since sea level was controlling the deposition, there is a relatively consistent pattern of facies types, vertical successions, and geometries that enable us to distinguish between LST/TST/HST.

Sequence stratigraphic interpretations, therefore, often provide more accurate representations of the continuity of facies belts because they are divided into these time-correlative deposition units controlled by relative sea level fluctuations. Because the deposition of those facies occurs in a consistent and predictable pattern sequence stratigraphy is becoming increasingly utilized.

Shelf Profile Key:
LST – orange   TST – yellow   HST - blue

Application of Sequence Stratigraphy



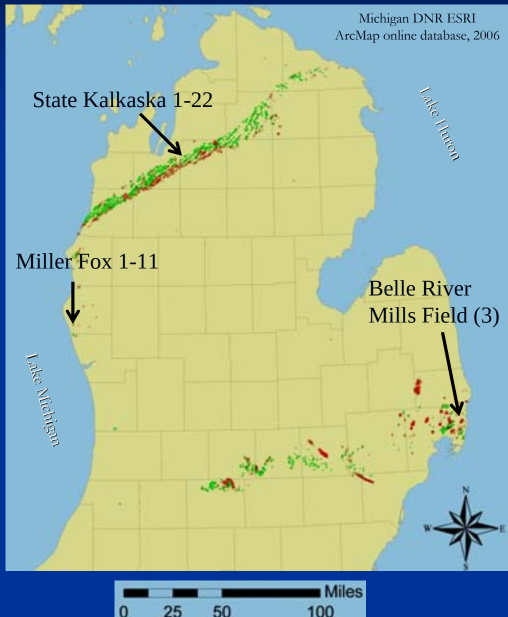
Modified from Weber, et al, 1994

- Sequence stratigraphic correlations more accurately capture vertical and lateral continuity between facies

Presenter's Notes: Sequence stratigraphic approach is becoming increasingly utilized because lithostratigraphic interpretations can lead to erroneous correlations of certain rock types when the assumed lateral and vertical continuity of similar rock units are actually discontinuous chronostratigraphically.

Based upon the differences between these two schematic representations, a sequence stratigraphic interpretation provides a more accurate representation of the continuity of facies belts because they are divided into time-correlative deposition units controlled by relative sea level.

Methodology



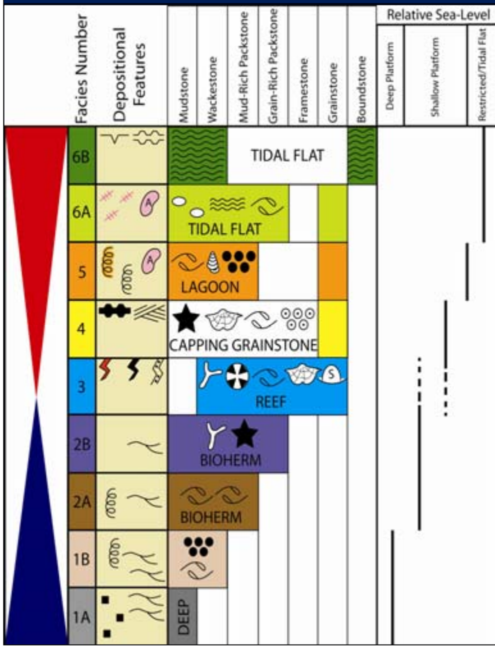
- Utilized 5 cores to:
  - Identify and correlate key facies & surfaces
  - Interpret depositional environments
  - Evaluate stacking patterns, associated facies and/or sequence boundaries to intervals of improved reservoir quality

Presenter's Notes: Now after explanation of what a sequence stratigraphic approach is and what the applications are, we discuss how this approach was utilized.

Five cores were chosen to provide a representation of reefs in the Northern and Douthern trends; they were selected because of the completeness of the cored interval and the availability of wireline log suites.

Each core was used to analyze facies and interpret depositional environments, evaluate the patterns seen in the facies stacking or vertical succession, and compare those patterns to any intervals of improved porosity and permeability.

Ideal Facies Succession



Restricted Facies

- Cyanobacterial Boundstones
- "Flat-Pebble Conglomerates"
- Bioturbated Wackestones to Peloidal Grainstones

High-Energy Facies

- Capping Skeletal Grainstones

Framework Reef Facies

- Coral & Stromatoporoid Framestones

Bioherm Facies

- Bryozoan Wackestones
- Mudstone to Packstone with Stromatactis Fabric

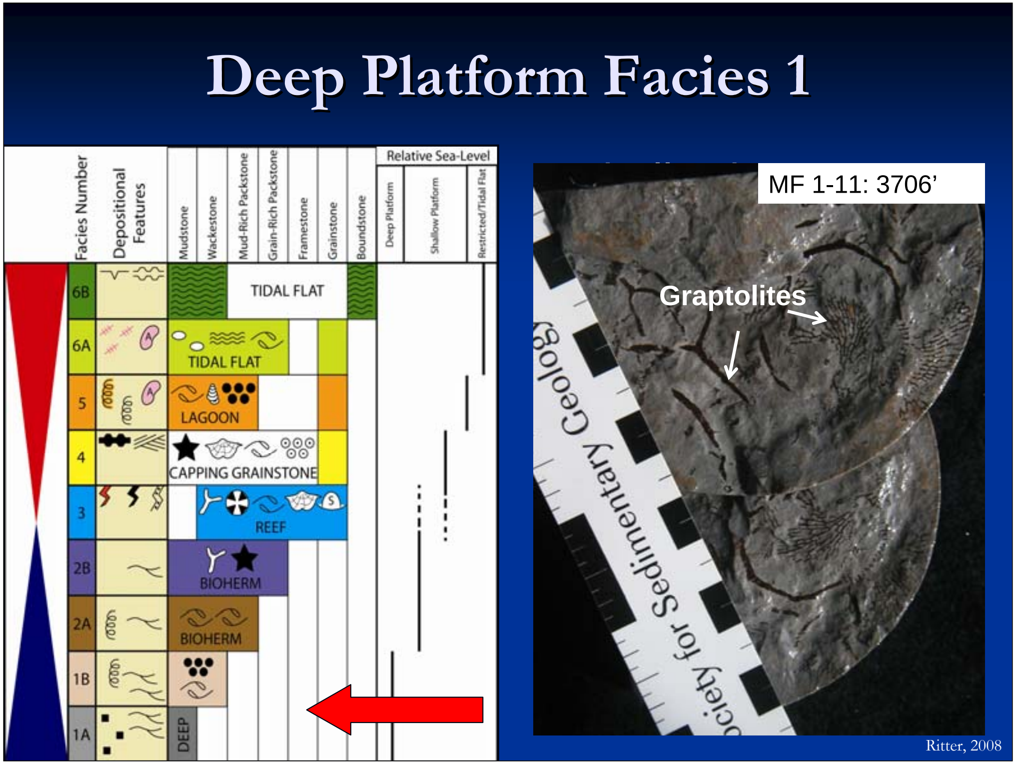
Deeper Platform Facies

- Bioturbated Mudstones to Peloidal Mud-rich Packstones
- Graptolite Mudstones

Ritter, 2008

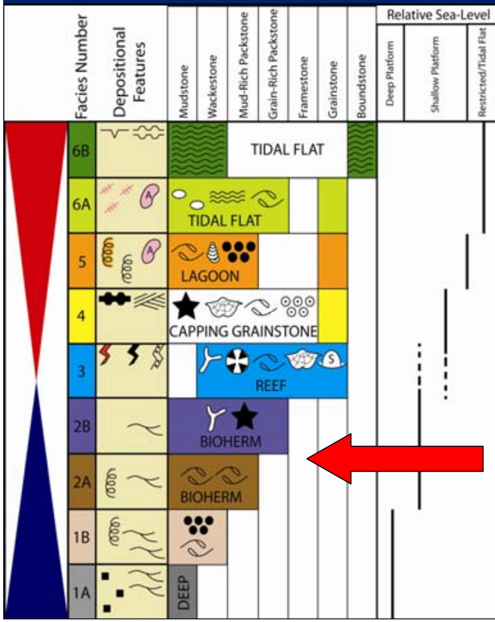
Presenter's Notes: From the core analysis, six facies were identified and an ideal facies succession was established.

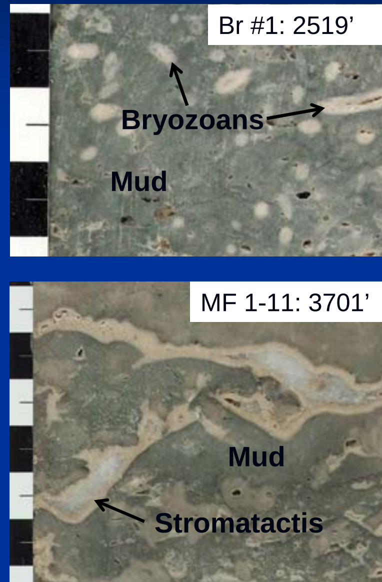
In general, a rise in relative sea level was characterized by a deepening phase or transgression which is represented by a vertical facies change towards deeper-marine conditions. This is illustrated schematically by the upright (blue) triangle. In contrast, a fall in relative sea level was characterized by a shallowing-upwards, regressive phase represented by a vertical facies change towards increasingly shallower-marine conditions and possibly subaerial exposure (the downward-pointing (red) triangle in the illustration).



Presenter's Notes: Facies 1 is characterized by mudstones with wispy stylolites and graptolite fragments. Because of the abundance of mud and low presence or diversity of fauna, Facies 1 is interpreted as having been deposited in the subtidal environment.

Bioherm Facies 2

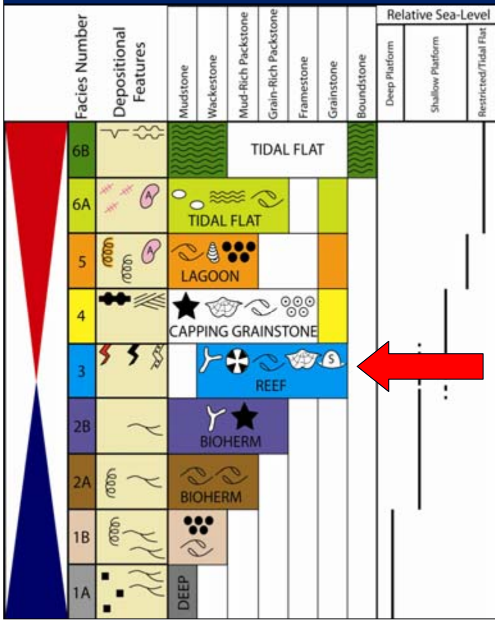


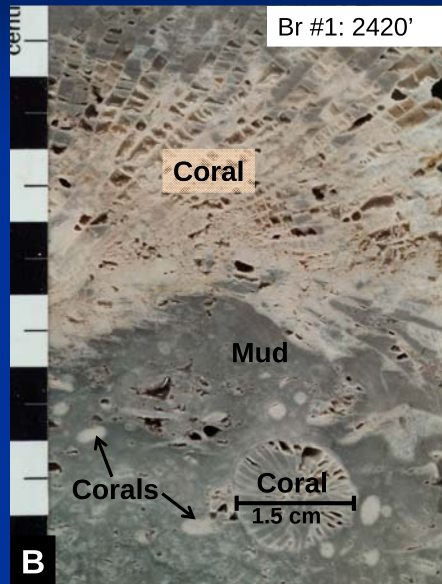


Ritter, 2008

Presenter’s Notes: Next is the bioherm facies which is made up of mudstones and wackestones with stromatactis fabric and a slightly increased fauna diversity compared to facies 1, containing crinoid fragments, bryozoans and stromatoporoids. Therefore, this facies is interpreted as having been deposited in a slightly shallower, subtidal environment.

Framework Reef Facies 3

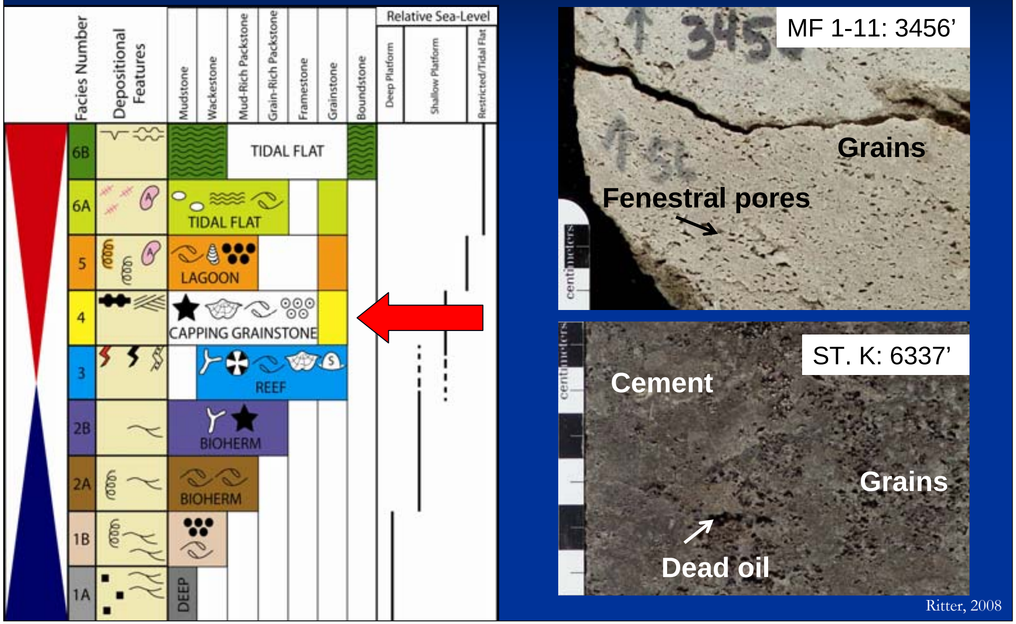




Ritter, 2008

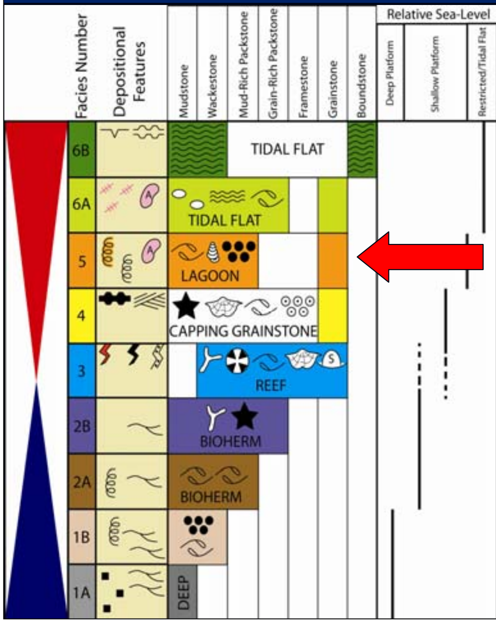
Presenter’s Notes: Facies 3 is the framework reef facies characterized by stromatoporoids and tabulate corals with wackestones to diverse skeletal grainstones infilling voids in and around the skeletal framework. This facies is thought to have been deposited at or near sea-level in the shallow subtidal.

Capping Facies 4



Presenter's Notes: Next is the capping facies or Facies 4 – which is characterized by skeletal grainstones that stratigraphically "cap" the reef facies and were deposited in a relatively moderate to high-energy shallow-platform environment at or near sea level.

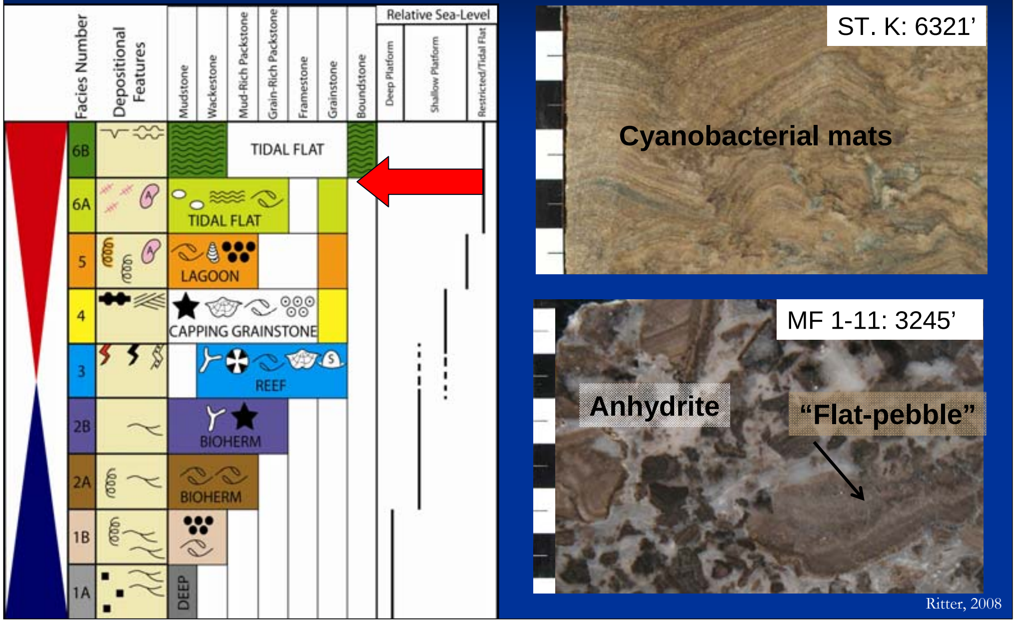
Lagoon Facies 5



Ritter, 2008

Presenter's Notes: Next is the lagoon facies characterized by burrowed or bioturbated wackestones and peloidal grain-rich packstones which is followed by the tidal flat facies.

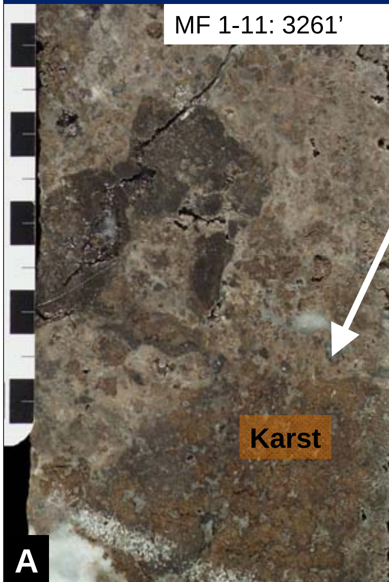
Tidal Flat Facies 6A & 6B



Ritter, 2008

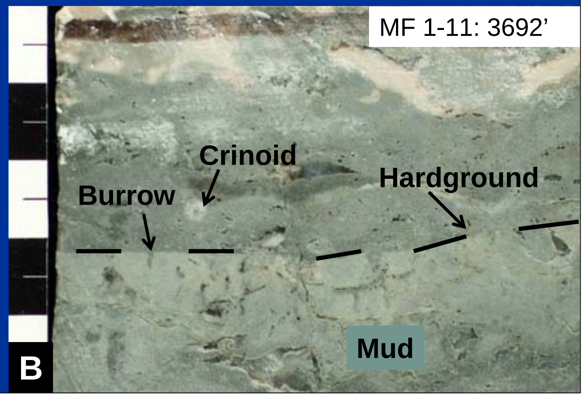
Presenter’s Notes: The tidal flat facies, Facies 6 A & B, representing the shallowest depositional environment, is characterized by cyanobacterial mats and breccias consisting of those mats with abundant anhydrite cement.

Surfaces



- Karst with associated terra rossa deposits

- Submarine Hardground



Ritter, 2008

Presenter’s Notes: Particular attention was also paid to key surfaces (such as karst), which represent subaerial exposure events. Hardgrounds are thought to have formed during periods when carbonate sedimentation was slow or had ceased, allowing the upper few centimeters to lithify by calcite cementation. Other researchers have suggested that submarine hardgrounds may be the subaqueous, diagenetic representation of a subaerial exposure event. Submarine hardground surfaces were carefully documented for possible correlation to subaerial exposure events.

Sequences and Cycles

	Thickness	Identified by:	Controls
5th Order Cycles	3-33 feet (1-10 m)	Vertical succession of facies	Relative sea level changes, ecological
4th Order HFS	10-140 feet (3-40 m)	Well defined shoaling upwards facies succession	Relative sea level changes
3rd Order Sequences	130-260 feet (40-80 m)	Bounded by well developed karst and abrupt deepening	Eustatic sea level changes

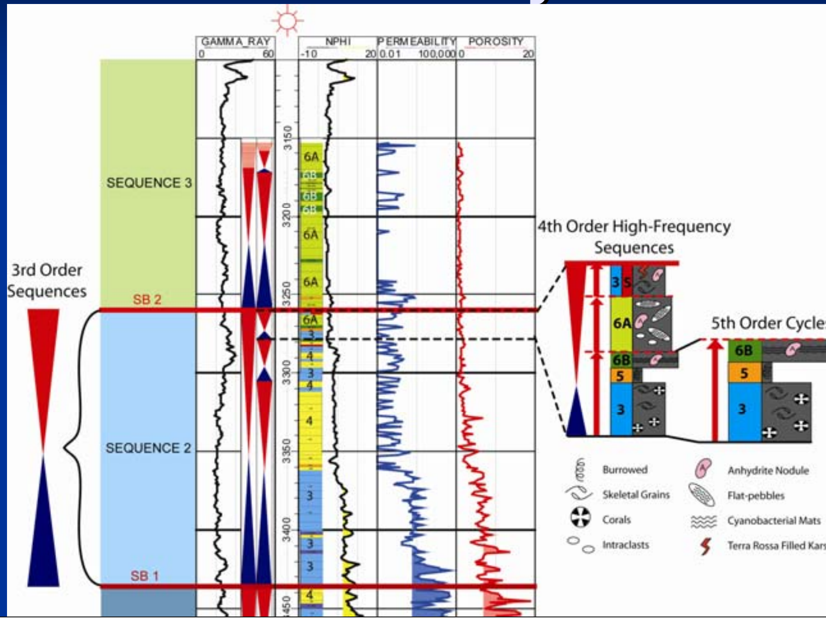
Presenter's Notes: From the facies stacking pattern, three orders of cyclicity were identified.

Fifth-order cycles were identified by this vertical stacking pattern of facies, but it should be noted that few cycles contain a complete succession of facies. Fifth-order cycles are the most problematic for regional correlation in the Michigan Basin because it is unclear if they represent relative sea-level changes, shifts in ecological niches or both.

4th order display a well-defined, shoaling upwards succession of depositional facies characterized by major changes in relative sea level.

3rd order are generally bounded by major exposure events characterized by pronounced karst and correlate to the 3rd order eustatic sea level fluctuations identified worldwide during the Silurian, Therefore, 3rd order sequence have more regional importance and can be correlated at a larger scale than the higher frequency cycles.

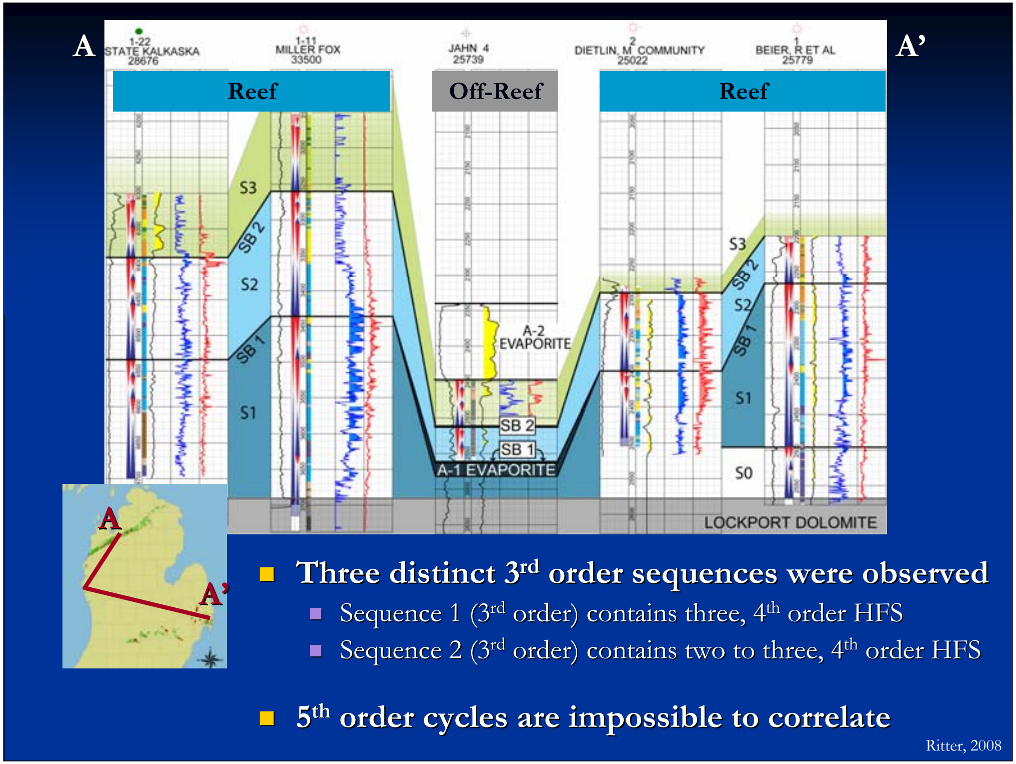
Sequence and Cycle Hierarchy



Ritter, 2008

Presenter's Notes: The relationship between these third-, fourth- and fifth-order sequences and cycles can be seen in this illustration.

Fifth-order, shallowing-upward cycles are bundled into fourth-order, high-frequency sequences that are grouped into larger third-order depositional sequences. Cut-offs: 7% porosity, 10 md permeability.



Presenter's Notes: This is a regional correlation of the five cores based on the sequence stratigraphic framework.

Three distinct 3rd order sequences were observed in both the Northern and Southern reefs which likely correlate to three eustatic sea-level fluctuations. Sequence 1 (3rd order) contains three 4th order HFS. Sequence 2 (3rd order) contains two to three 4th order HFS.

The 5th order cycles are impossible to correlate because of too much local variability controlled primarily by the evolutionary change in individual reefs and an incomplete data set. Cut-offs: 7% porosity, 10 md permeability.

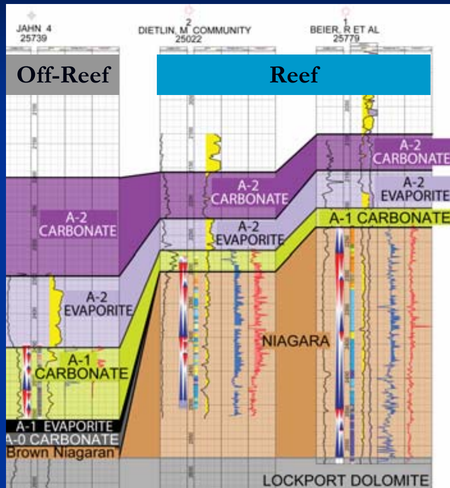
Additional Information:

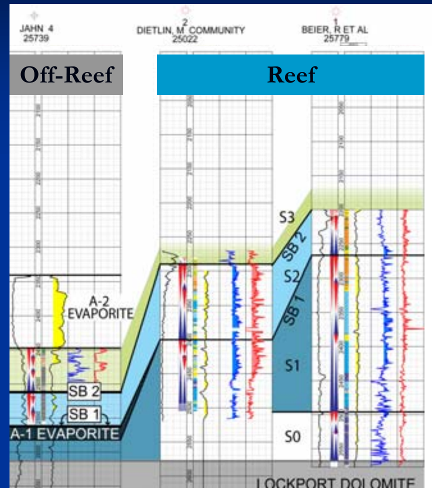
Three 3rd order depositional sequences were identified (S0, S1, S2 and S3) and are generally bounded by major exposure events characterized by pronounced karst. In one instance, a 3rd order sequence boundary (SB 0) is only apparent by a major deepening phase characterized by an abrupt change in facies from relatively shallow-platform deposits to deep, basinal mud with rip-up clasts derived from the underlying strata. SB 0 most likely represents the base of Sequence One not preserved in the other cores. Therefore, the Lockport Dolomite, although labeled as the base of the cross-section, does not represent a sequence boundary.

Sequence 1 and 2 are completely recorded in all of the cores and are characterized by well developed karst and associated terra rossa deposits. SB 1 represents a drop in sea level of at least 150 feet based on reconstruction of reef height and off-reef cores in the BRM. It also marks the beginning of evaporite deposition within the basin deposits (in off-reef cores).

Three distinct 3rd order sequences were observed in both Northern and Southern reefs which correlate to the three eustatic sea-level fluctuation documented by other studies of Silurian reefs worldwide. It is impossible to evaluate all 3rd order sequences because of limitations of core data (i.e., missing sections of core) for regional correlations. However, Sequence 1 (3rd order) contains three 4th order HFS across the basin and Sequence 2 shows 2-3 HFS in cores of this part of the section. The 5th order cycles are impossible to correlate because of too much local variability, controlled primarily by the evolutionary change in individual reefs and an incomplete data set.

Lithostratigraphy VS Sequence Stratigraphy





- The Salina "A" formations are considered entirely post-reef deposits
- The Salina "A" formations deposited "quasi-contemporaneous"

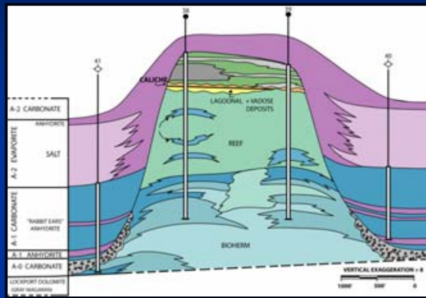
Ritter, 2008

Presenter's Notes: Salina "A" formations are considered post-reef deposits.

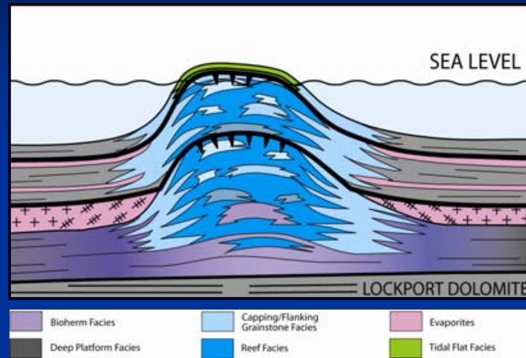
Based on the sequence stratigraphic framework, it is not reasonable to consider the deposits as post-reef but as "quasi-contemporaneous."

A-0 Carbonate and A-1 Carbonate are the off-reef, basinal muds and inter-reef facies having been deposited during Sequence 1 and Sequence 2, respectively.

Conclusions

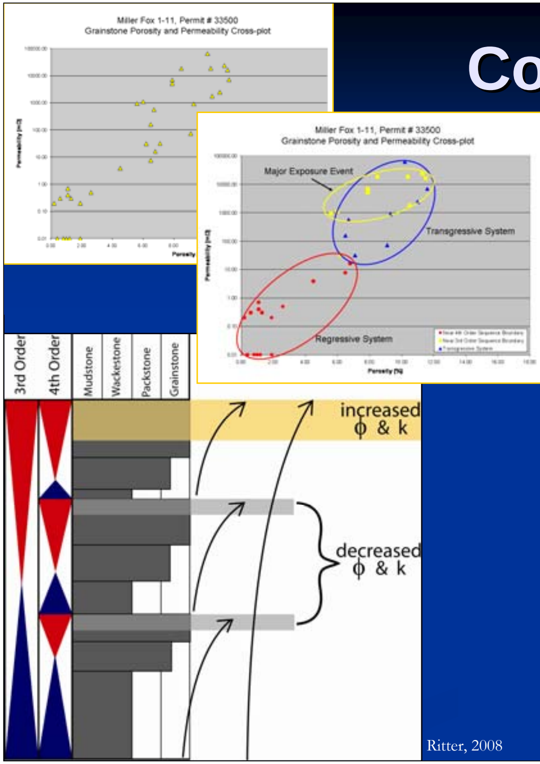


Modified from Gill, 1973



Ritter, 2008

- Sequence stratigraphic frameworks more accurately capture vertical and lateral continuity between facies



Conclusions

- Facies close to 3rd order sequence boundaries have higher porosity and permeability
- Facies positioned near 4th order HFS boundaries have lower porosity and permeability

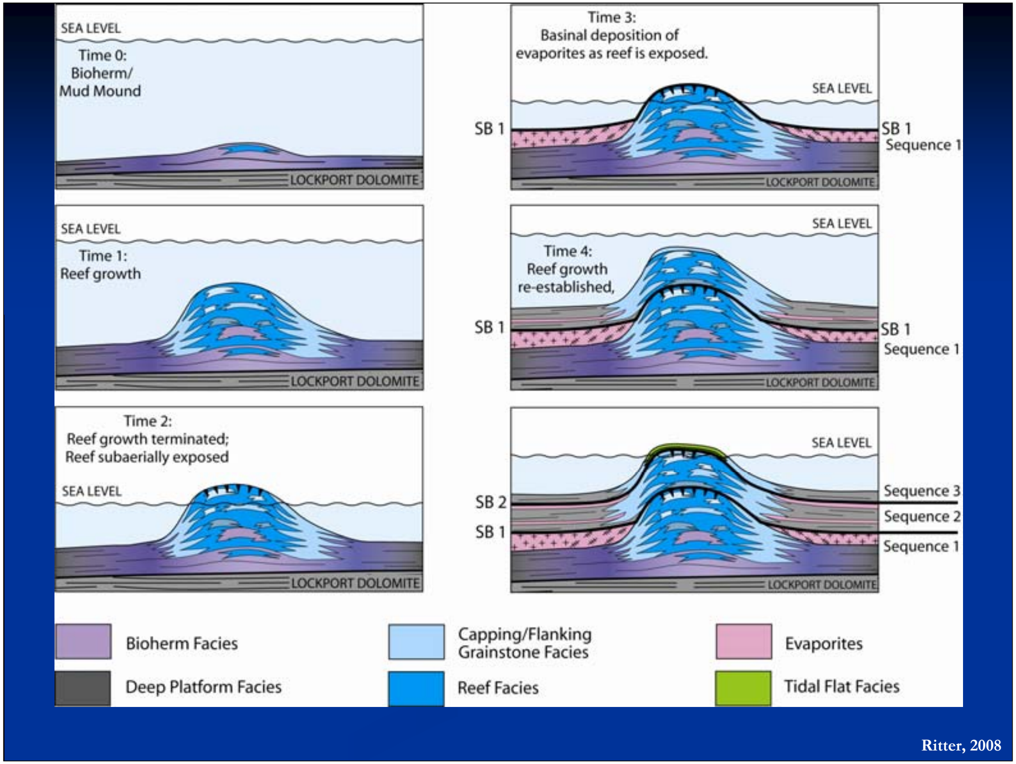
Ritter, 2008

Presenter's Notes: In conclusion, we found that the sequence stratigraphic framework controls reservoir distribution in which 3rd order sequences, stacking patterns of 4th order, high-frequency sequences and possibly 5th order cycles dictate the vertical variability (compartmentalization) of reef reservoirs.

Additionally, facies close to 3rd order sequence boundaries have higher porosity and permeability values due to preferential dissolution and porosity enhancement associated with well developed exposures. In contrast, facies positioned near 4th order HFS boundaries have lower porosity and permeability values due to early submarine cementation and porosity occlusion.

Acknowledgements

- Contributing Author: Dr. G. Michael Grammer
- Dr. W. B. Harrison III
- Dr. Robb Gillespie
- Linda Harrison, MGRRE Administrator
- Michigan Geological Repository for Research & Education (MGRRE) Facility
- Colleagues: Jennifer Schulz, Jessica Wold, Amy Noack, Heather Qualman, & Tony Sandomierski

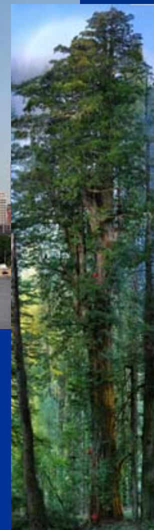


Presenter's Notes: This reef-growth schematic model illustrates reef evolution, relative timing and general heterogeneity of the deposits based on the sequence stratigraphic framework. Previous models have shown continuous reef growth with deposition of the Salina "A" Formations representing the end of Niagaran reefs based on "stromatolite" rip-ups and breccias of reef rubble from the uppermost interval of Niagaran deposits found in the A-0 Carbonate. In this model, off-reef deposits of mud are interpreted as the Salina A-0 Carbonate (Sequence 1) and A-1 Carbonate (Sequence 2 and 3) and the brecciated clasts are interpreted as reef rubble with void-filling cements, not stromatolites from the tidal flat deposits. Additionally, as the reef was exposed (3rd order), basinal deposition of evaporites (A-1 Evaporite) occurred as part of a 4th order high-frequency sequence.

Relative Scale

- St. Louis Arch is over 600 ft in height
- California Redwoods are 300 feet in height
- Northern Trend Pinnacle Reef is 300-600 feet in height

Photograph by: Buphoff, 2007



~300 ft

Problems in Stratigraphic Nomenclature

- The end of Niagaran reef deposits has historically been picked based on gamma-ray log “spikes”
  - Sequence Boundary 2 does not coincide with the pick
  - High gamma-ray signatures do not accurately represent evaporites
- Salina “A” Formations were considered post-reef deposits
  - Based on the sequence stratigraphic framework, it is not reasonable to consider the deposits as post-reef but as “quasi-contemporaneous”
  - A-0 Carbonate and A-1 Carbonate are the off-reef, basinal muds and inter-reef facies, deposited during Sequence 1 and Sequence 2, respectively.

Cyclicity	Duration	Thickness	Controls
1st Order	200 to 300 m.y.		Major tectonic activity
2nd Order	10 to 50 m.y.	100's to 1,000's of meters	Tectonics and changes in ocean volume
3rd Order	500,000 yrs to 5 m.y.	10's to 100 m	Changes in global ice volume (50 m change)
4th Order	< 20,000 to 400,000 yrs	10 to 40 m	Climatically driven –
5th Order	< 20,000 to 400,000 yrs	1 to 10 m	Changes in continental ice volume

Ritter, 2008

Assumptions for Correlation of Relative Sea-Level Changes

- **Basin Subsidence Rates** – are considered minor, and relatively consistent, in the tectonically stable, intracratonic setting of the Michigan Basin with thicker sequences in cores from the Northern trend compared to cores from the Southern trend. This may be attributed to more accommodation space available in the north as a result of the asymmetrical tilt of the Michigan Basin (Howell & van der Pluijm, 1999) or possibly deeper water initiation of bioherm growth .

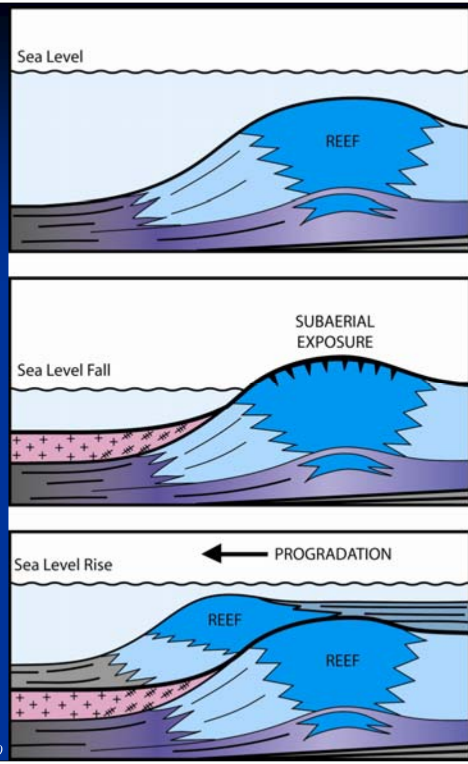
- **Sedimentation Rates** – Framework reefs, at least in the Neogene, can grow significantly faster vertically (i.e., aggradational growth) and have higher sedimentation rates (50-82 ft/m.y; 15-25 m/m.y.) than other facies (6.5-13 ft/m.y.; 2-4 m/m.y.) as recorded from Pliocene to mid-Pleistocene deposits of Little Bahama Bank, Bahamas (McNeill et al., 1998).

- **Rock Type** – For example, off-reef deposits are generally mud-dominated and more susceptible to compaction by the overlying deposits than framework reefs (Jodry, 1969).

Belle River Mills

Reef Geometry

- Reef development during the TST/HST
- Evaporites were deposited
- Reef development re-established, and offset from the original reef



Modified from Eberli & Ginsburg, 1989

Presenter's Notes: This is a schematic representation of the Belle River Mills reef progradation based on core observations and correlations between reef-core and off-reef wells.

During the transgressive/highstand system tracts, a well developed reef complex was established. A dramatic fall in sea level exposed the reef, and subaqueous evaporites were deposited in the basin. This major exposure represents an estimated 150-foot (50-60-meter) sea-level drop based on reconstruction of reef height and off-reef wells. Reef development was re-established during the following transgressive systems tract (TST) (i.e., beginning of Sequence 2) and offset from the original reef (progradation).