A Sequence Stratigraphic Model for the Silurian A-1 Carbonate of the Michigan Basin*

Matt Rine[1], Jon Garrett[1], Stephen Kaczmarek[1], and William Harrison, III[1]

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Abstract

The Lower Salina A-1 Carbonate is the primary source rock for hydrocarbons in the Silurian (Niagaran) Reef Complex reservoirs, which are some of the most prolific reservoirs in the Michigan Basin. To date, State records from the Michigan Office of Oil, Gas and Minerals report that A-1 Carbonate hydrocarbon production occurs in 31 fields as the sole producing unit in that field or in combination with Niagaran or other Salina units. Nearly 3.3 million barrels of oil and 37.5 BCF of natural gas have been produced from the A-1 Carbonate throughout the MI Basin. Previous studies interpret the A-1 Carbonate as a shallow subtidal to supratidal deposit that sits on top of the reefs. Despite their close proximity and strong association in the hydrocarbon system, the sequence stratigraphic relationship between source and reservoir rock are poorly constrained.

To establish the timing and environments across the basin, fundamental sedimentological observations from cores are coupled with geochemical data collected with a handheld X-ray fluorescence spectrometer. One of the principal observations comes from an anhydrite unit called the "Rabbit Ear Anhydrite (REA)," which has been previously interpreted as a localized supratidal deposit that formed only around the periphery of paleo-topographic highs of the older Niagaran reefs. New observations from cores and wireline logs from deeper in the basin show that the REA is, instead, a basin-wide depositional unit which ranges from sabkha to deep-water settings and separates the A-1 Carbonate into an upper and a lower unit. This suggests that REA is a time-correlative unit across the basin and can be used to separate the A-1 Carbonate into upper and lower units.

Sequence stratigraphic correlations are further aided by lithofacies relationships and elemental trends (Mg, Ca, S, Fe, etc.), which point to four regionally extensive, fourth-order shallowing-upward cycles. Each shallowing-upward cycle exhibits

intervals of dolomite corresponding to the most regressive depositional facies. These dolomitic-prone intervals are correlated across the basin and should allow for more informed exploitation of resources with the A-1 Carbonate. In contrast, elements such as S, Fe, Si, Sr, and K are more prominent within maximum flooding zones

Selected References

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Eastern Section AAPG
September 27th, 2016

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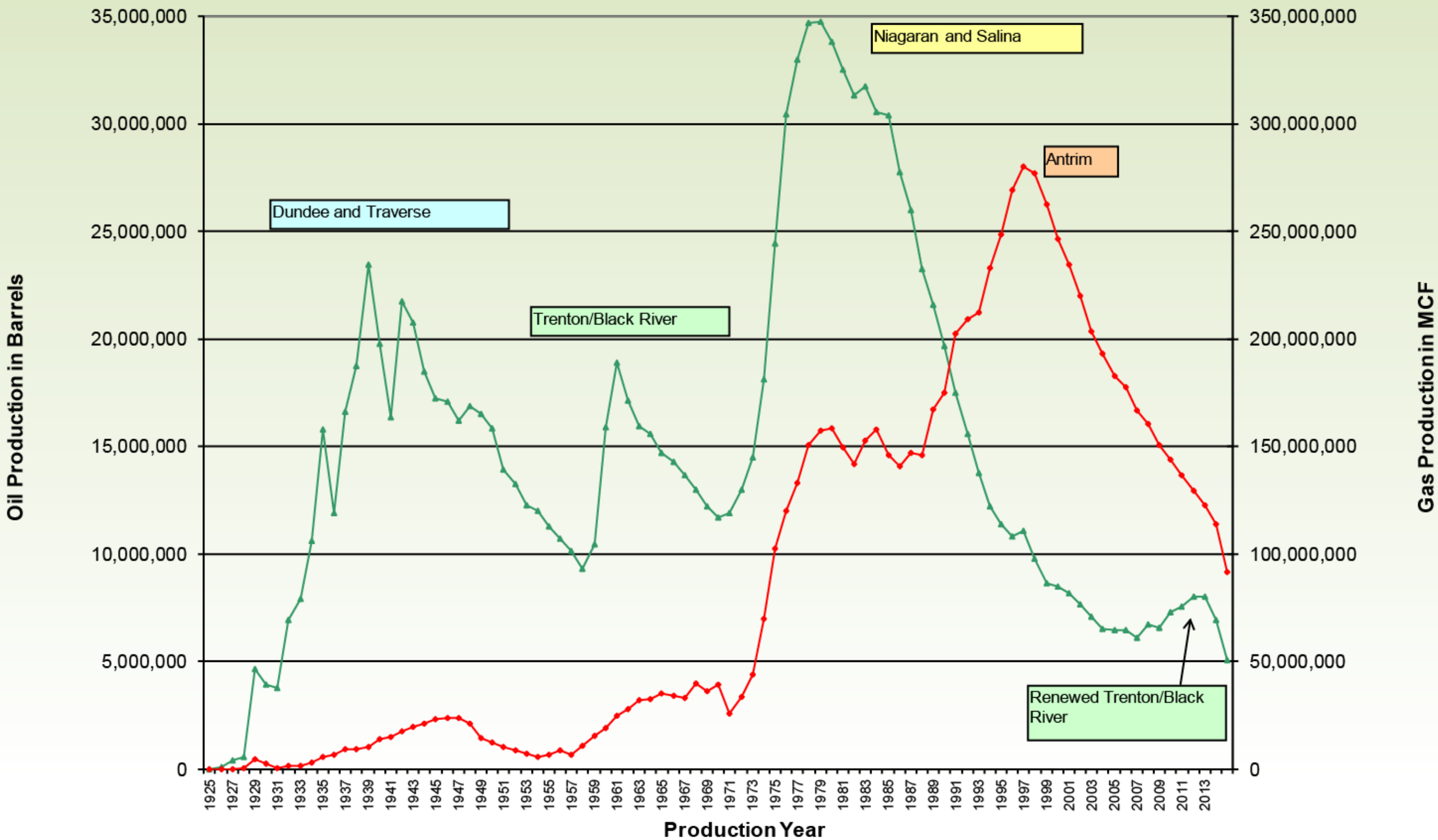
PURPOSE

- The **A-1 Carbonate is the source rock** for the Niagaran Reef Complex Reservoirs which are the most prolific reservoirs in the Michigan Basin

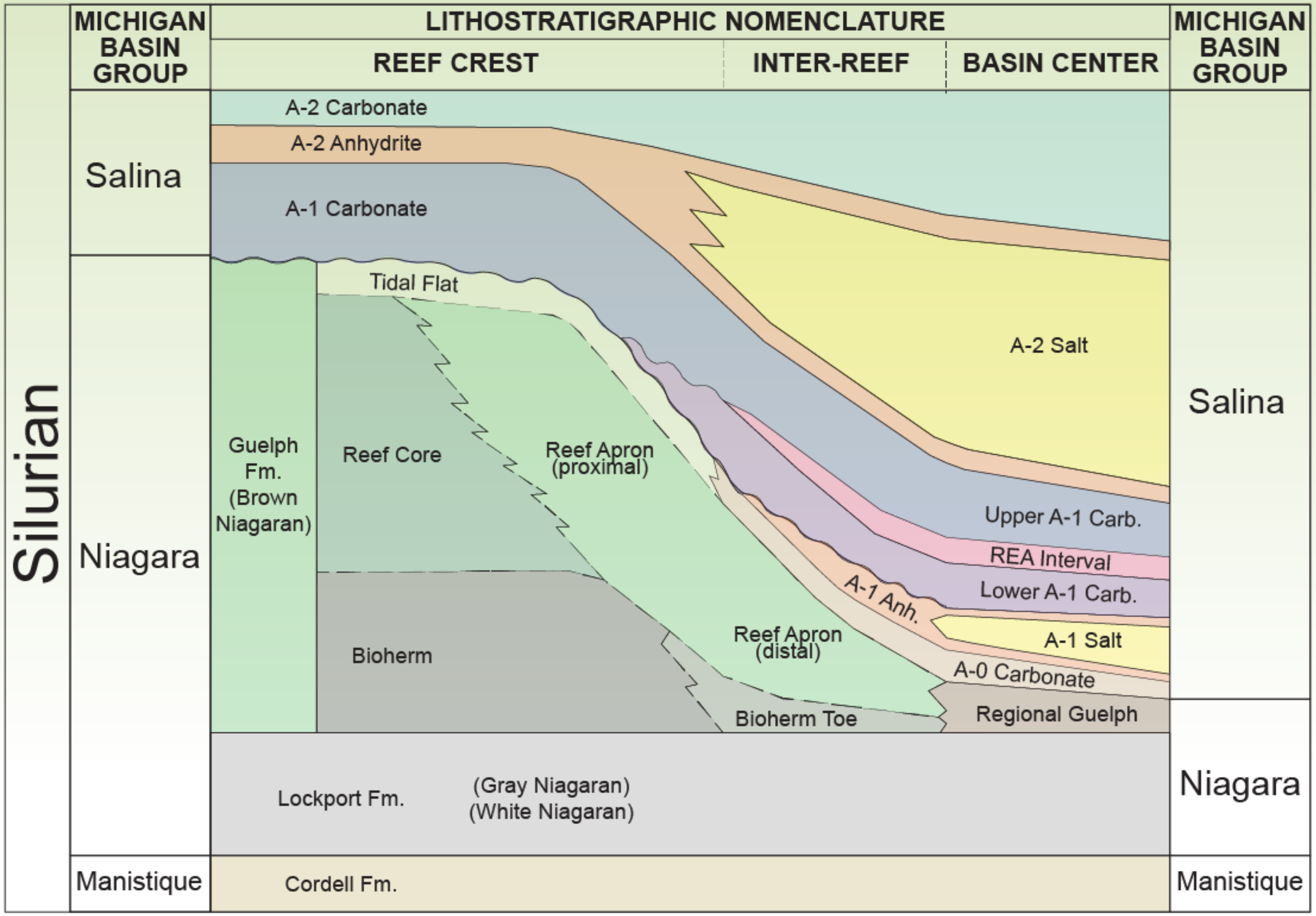


Niagaran/Salina Cum. Prod: >500 MMBO Oil; >3 TCF Natural Gas

PURPOSE

- The **A-1 Carbonate is the source rock** for the Niagaran Reef Complex Reservoirs which are the most prolific reservoirs in the Michigan Basin

However!
Due to close proximity to Niagaran Reefs, most A-1 Carb Production has been reported as Niagaran



PURPOSE

Geologic Problems:

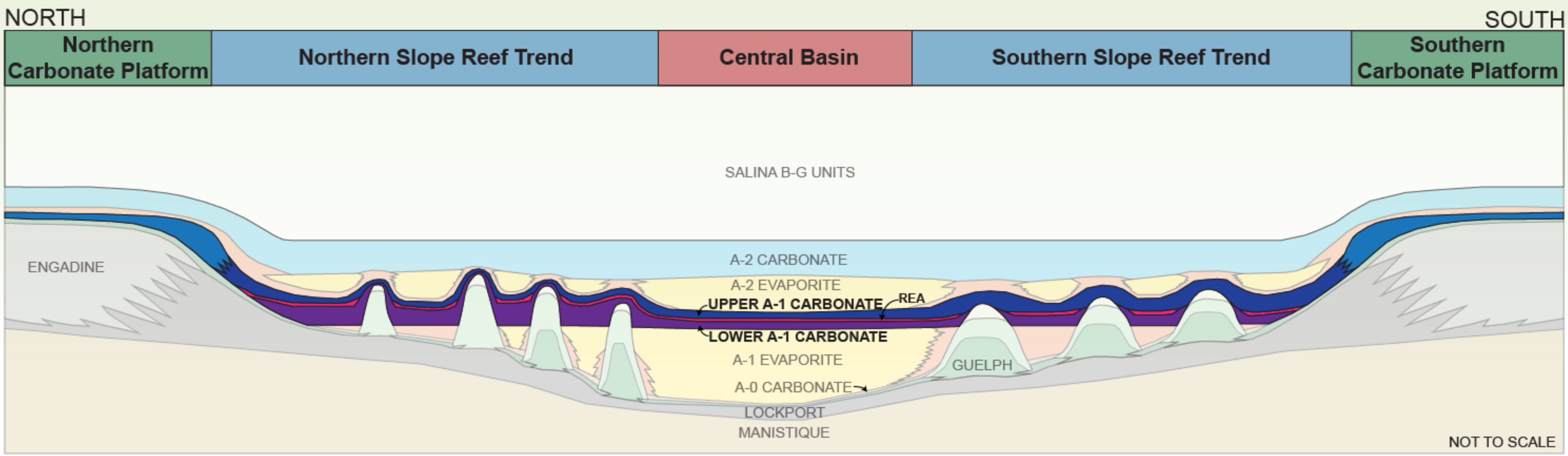
1) The entire A-1 Carbonate is **poorly understood sedimentologically**;
   *Difficult to interpret – subtle changes in carbonate mudstone

PURPOSE

Geologic Problems:

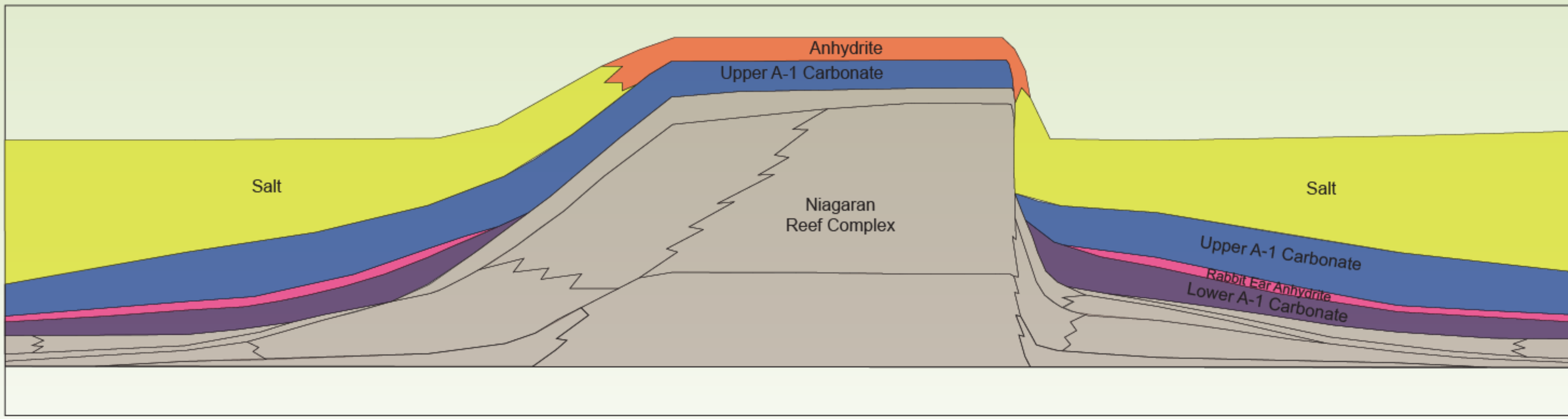
1) The entire A-1 Carbonate is poorly understood sedimentologically;
   *Difficult to interpret – subtle changes in carbonate mudstone

2) No attempt has been made to **correlate A-1 Carbonate basin-wide**



INDUSTRY QUESTIONS ?

1) **How much potential** does the A-1 Carbonate have as a **Conventional reservoir** adjacent to/atop Niagaran Reef Complexes?



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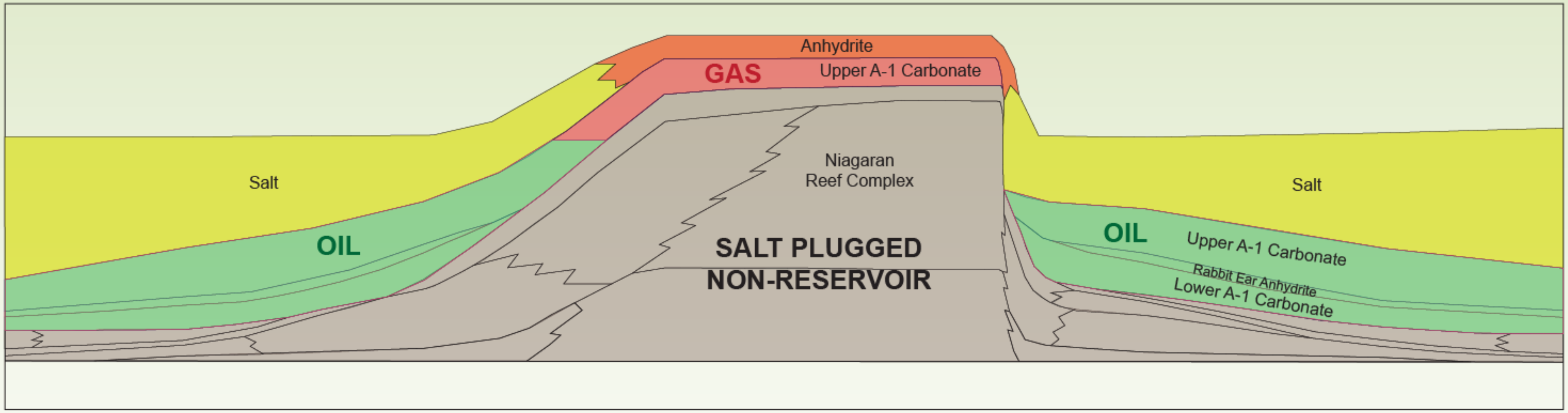


Adjacent to and atop reef crests, certain **A-1 Carbonate facies have:**

Porosities >15%

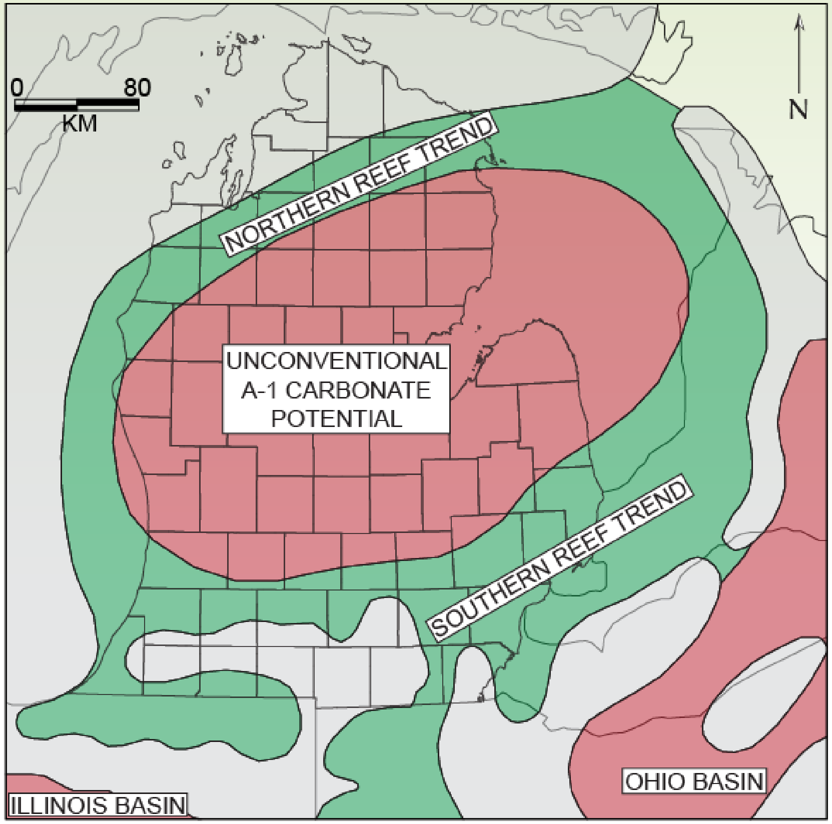
Permeabilities > 10mD

*Individual wells completed ONLY in the A-1 Carbonate have made **>1 Million Barrels of Oil**

INDUSTRY QUESTIONS ?

1) **How much potential** does the A-1 Carbonate have as a **Conventional reservoir** adjacent to/atop Niagaran Reef Complexes?

2) Could new basin-wide insights create opportunities for an **Unconventional A-1 Carbonate Play?**



Areal Extent: 16,000 km^2

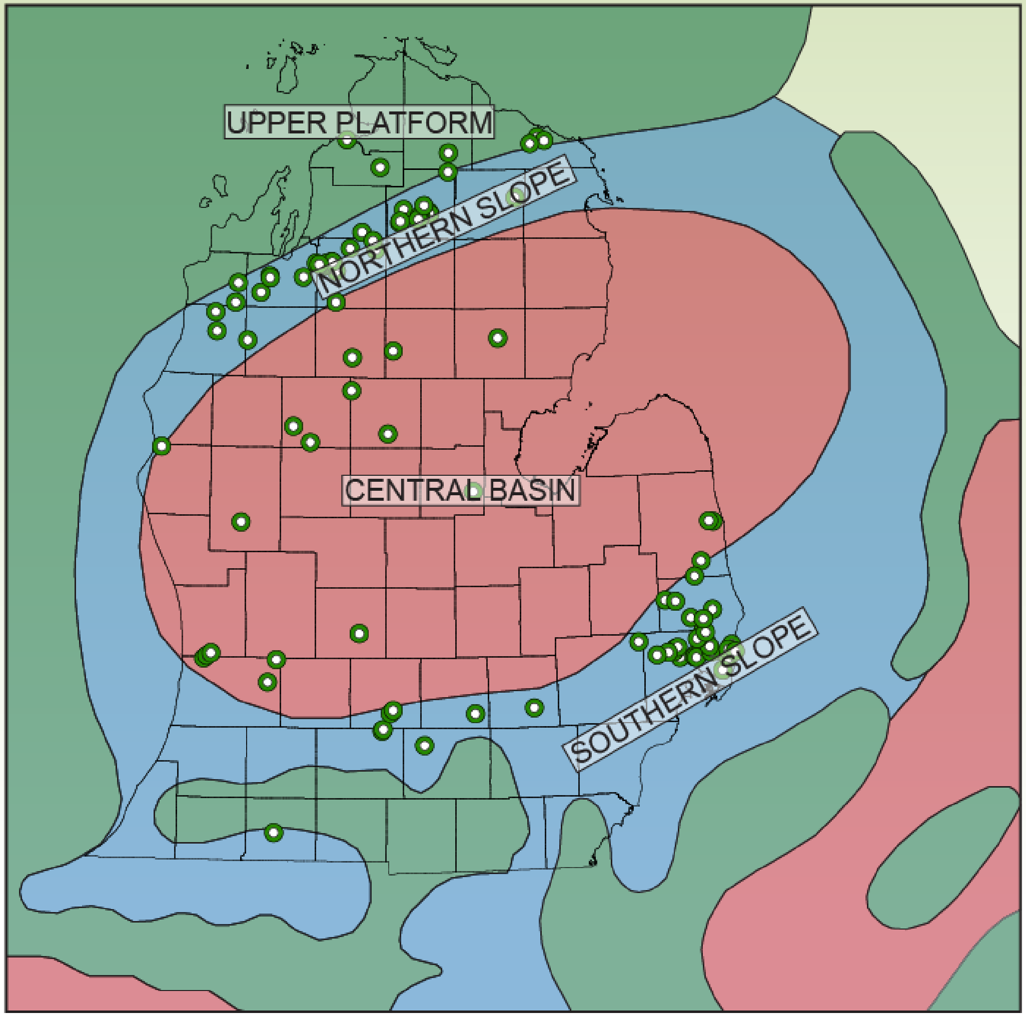
Thickness: 15-35 m

TOC: 0.5 – 3.5%
(marine Type II Kerogen)

(Obermajer et al. 2000)

METHODS/TOOLS

I) Core Analysis – Lithofacies Descriptions (MGRRE Core Facility)



A-1 Carbonate Core Distribution

105 Total Cores

This Study:

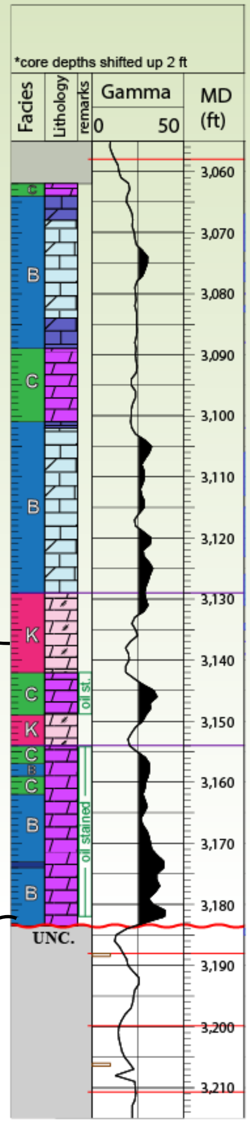
- **2 Northern Slope**
- **1 Basin Center**
- **4 Southern Slope**

METHODS/TOOLS

II) Core-to-Log Correlation

Nodular anhydritic mudstone

Normally graded mudstone



METHODS/TOOLS

III) Elemental Data – Handheld XRF

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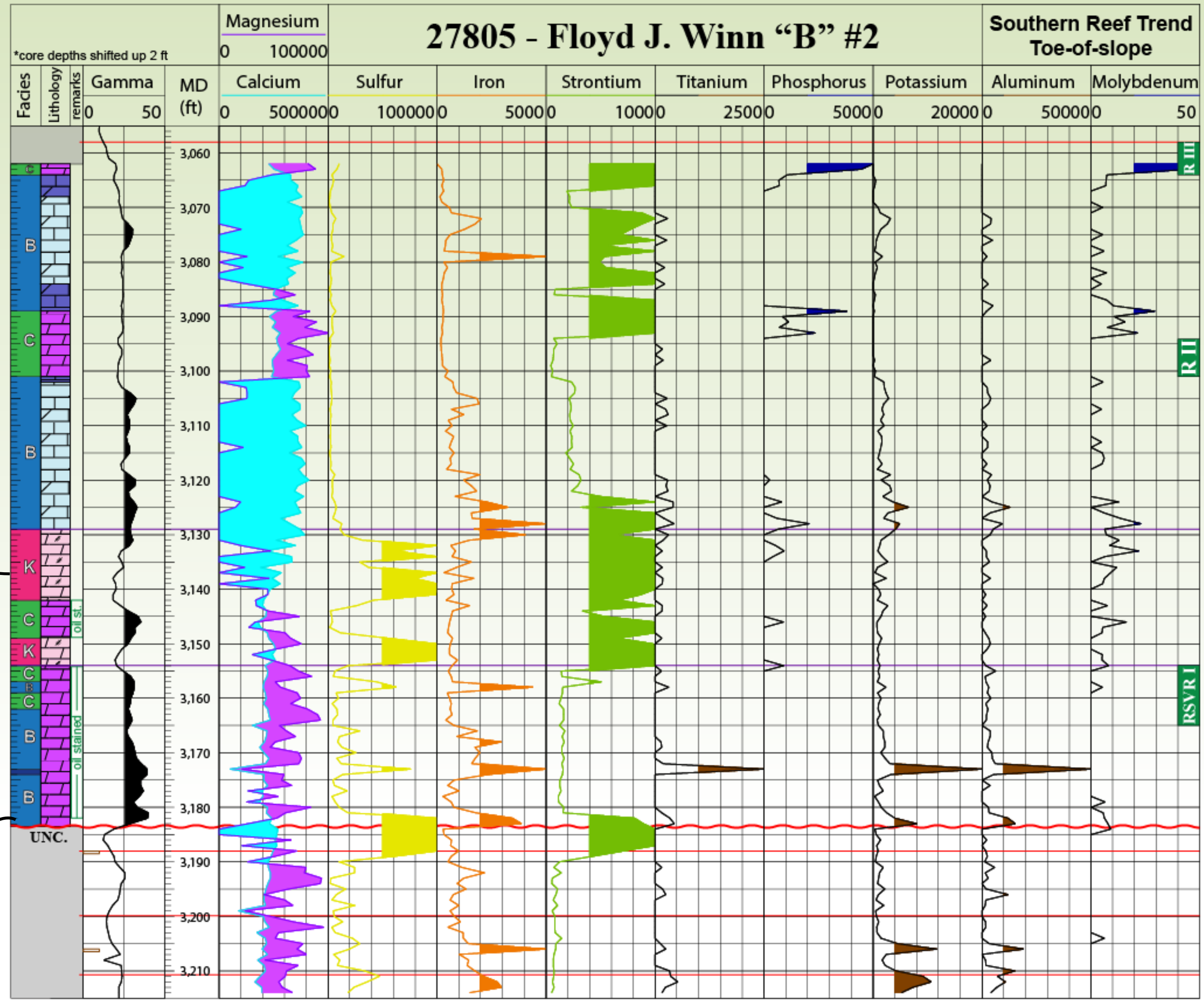

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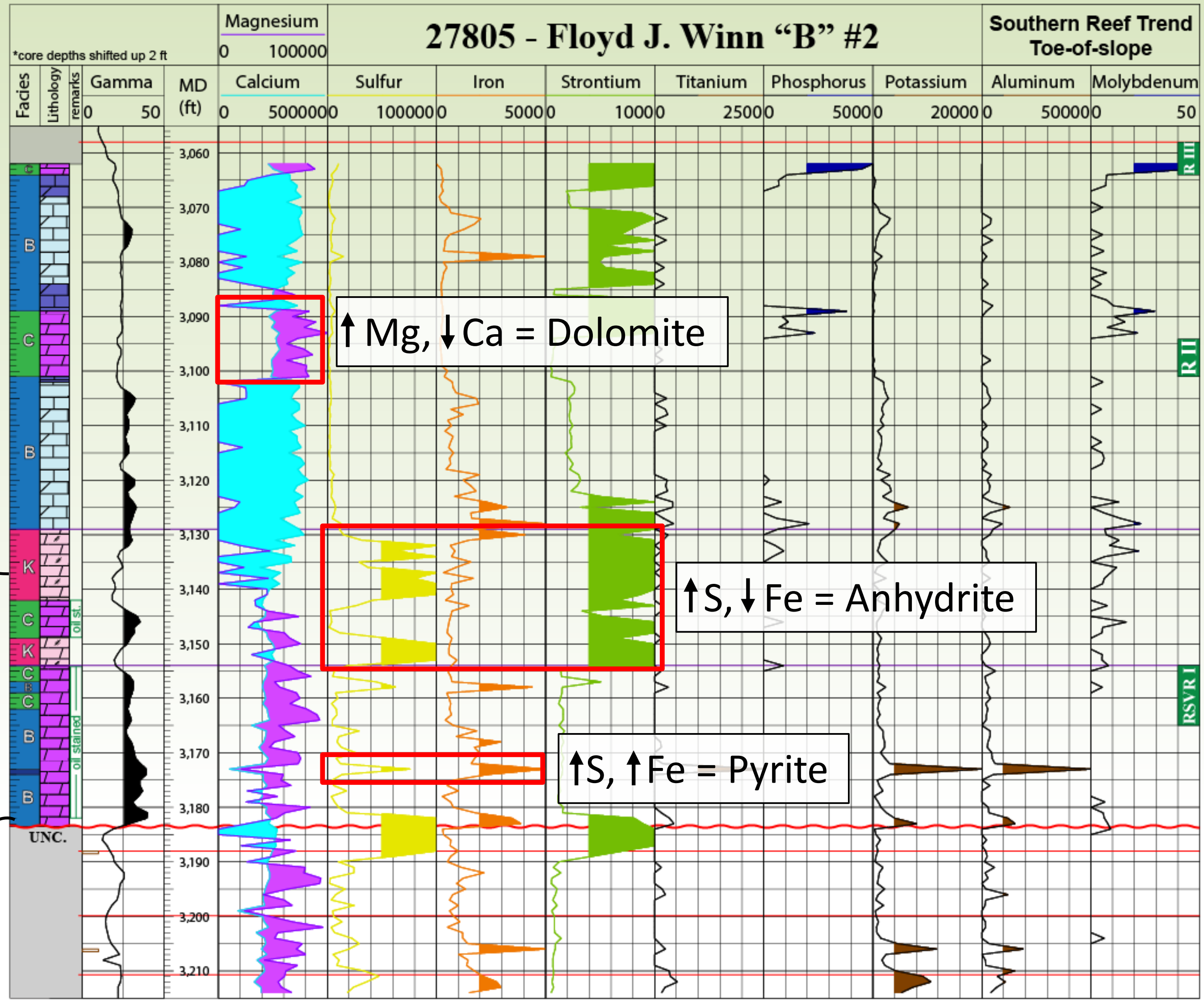

Methods/tools

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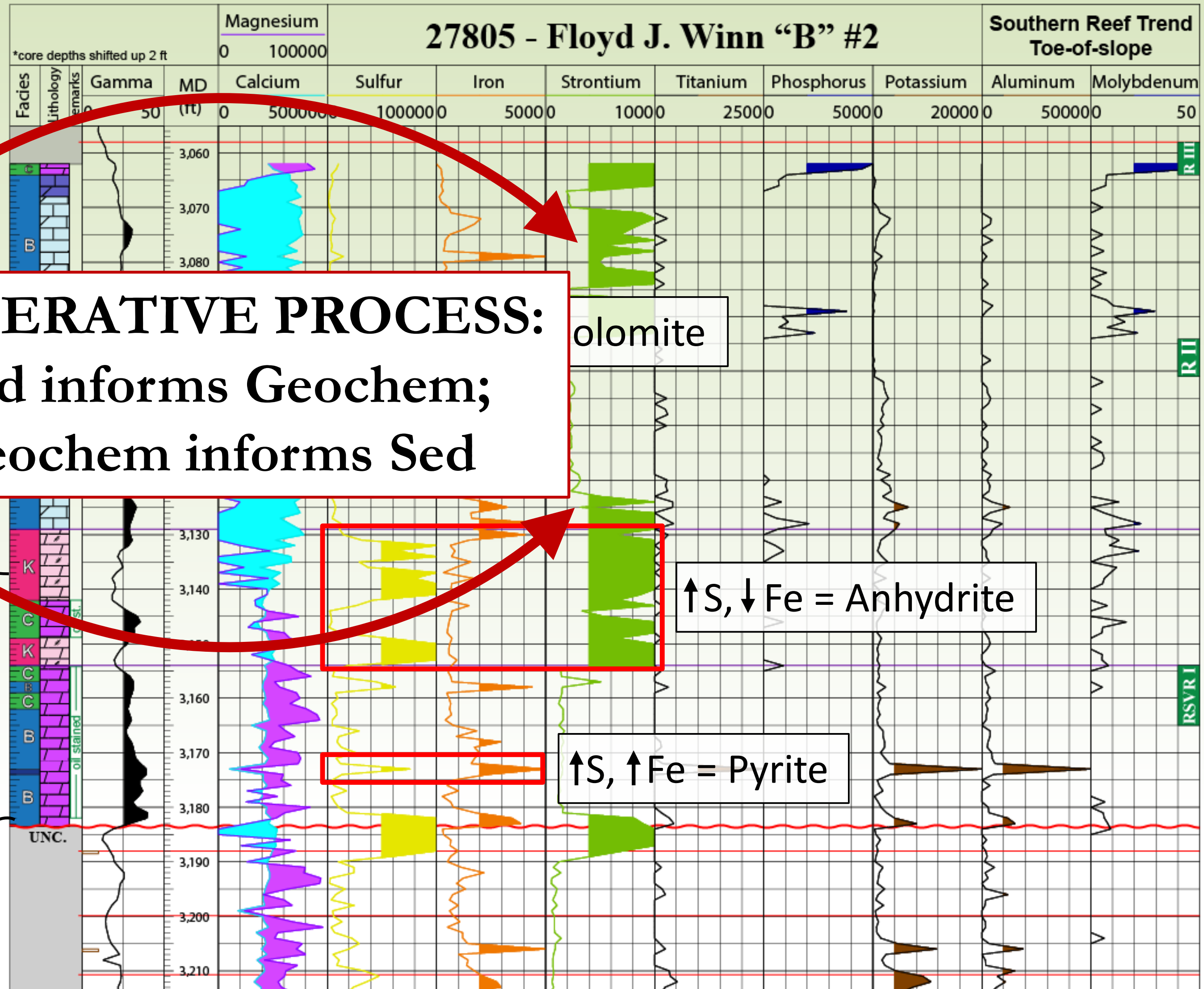

ITERATIVE PROCESS:
Sed informs Geochem;
Geochem informs Sed

METHODS/TOOLS

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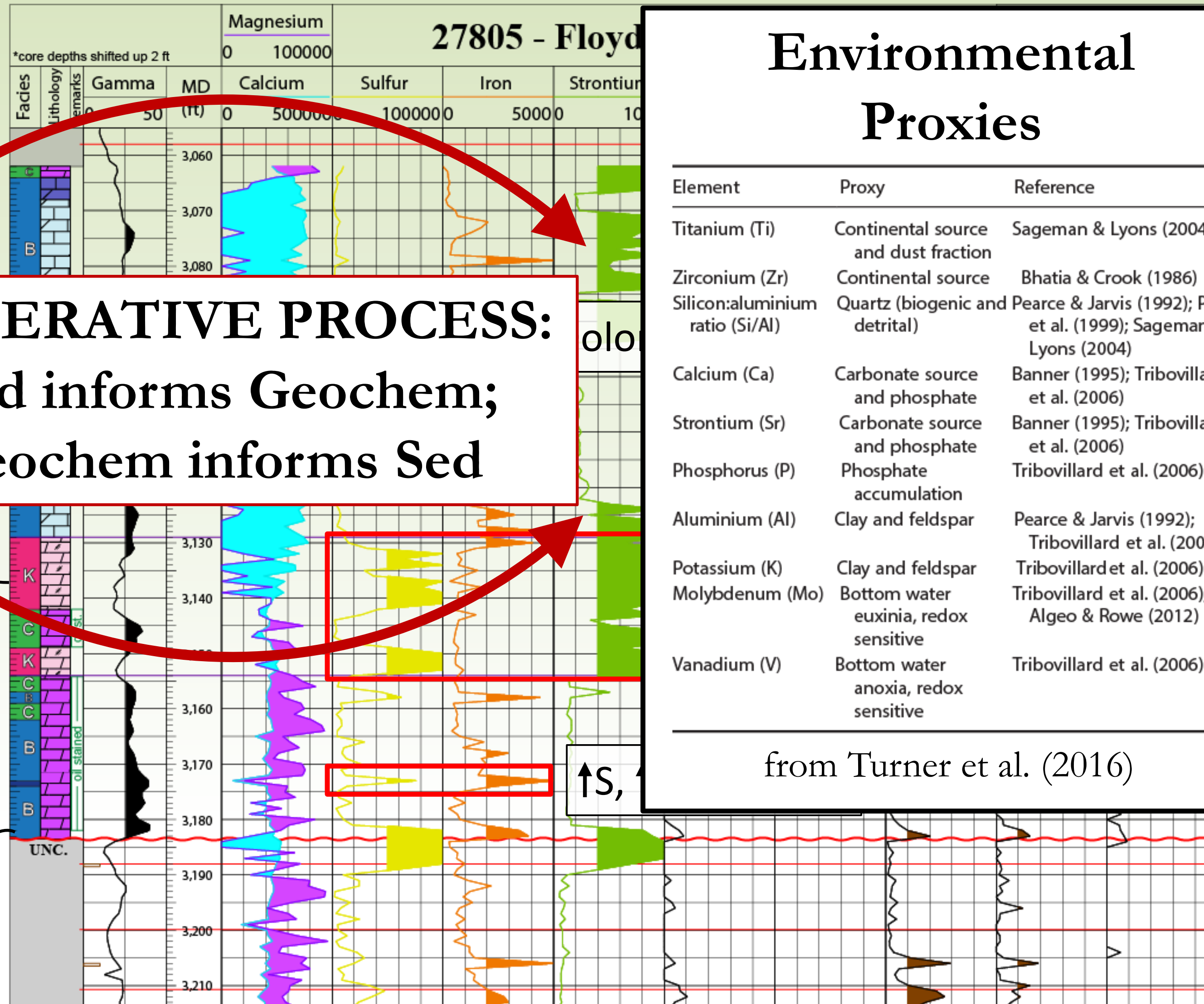


ITERATIVE PROCESS:
Sed informs Geochem;
Geochem informs Sed

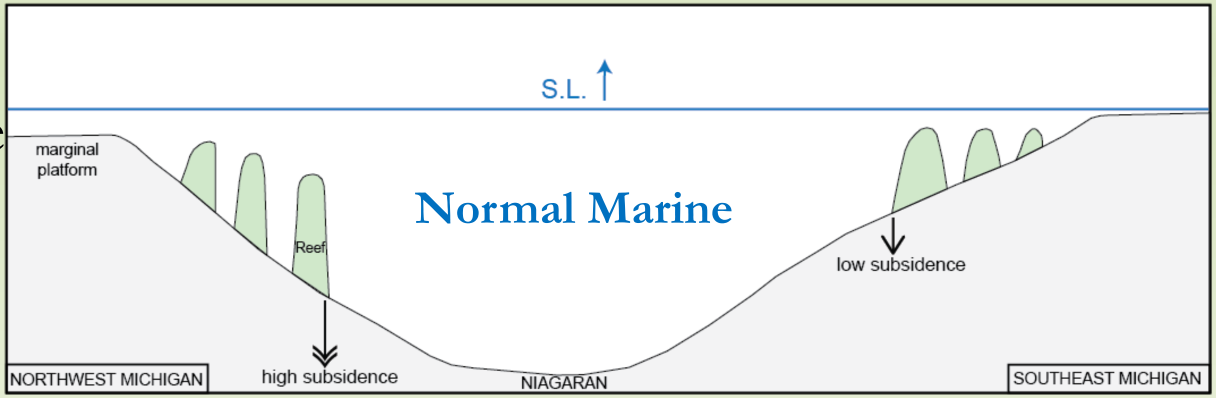
Environmental Proxies

Element	Proxy	Reference
Titanium (Ti)	Continental source and dust fraction	Sageman & Lyons (2004)
Zirconium (Zr)	Continental source	Bhatia & Crook (1986)
Silicon:aluminium ratio (Si/Al)	Quartz (biogenic and detrital)	Pearce & Jarvis (1992); Pearce et al. (1999); Sageman & Lyons (2004)
Calcium (Ca)	Carbonate source and phosphate	Banner (1995); Tribovillard et al. (2006)
Strontium (Sr)	Carbonate source and phosphate	Banner (1995); Tribovillard et al. (2006)
Phosphorus (P)	Phosphate accumulation	Tribovillard et al. (2006)
Aluminium (Al)	Clay and feldspar	Pearce & Jarvis (1992); Tribovillard et al. (2006)
Potassium (K)	Clay and feldspar	Tribovillard et al. (2006)
Molybdenum (Mo)	Bottom water euxinia, redox sensitive	Tribovillard et al. (2006); Algeo & Rowe (2012)
Vanadium (V)	Bottom water anoxia, redox sensitive	Tribovillard et al. (2006)

from Turner et al. (2016)

GEOLOGIC BACKGROUND

Niagaran: Normal Marine Pinnacle Reef Growth



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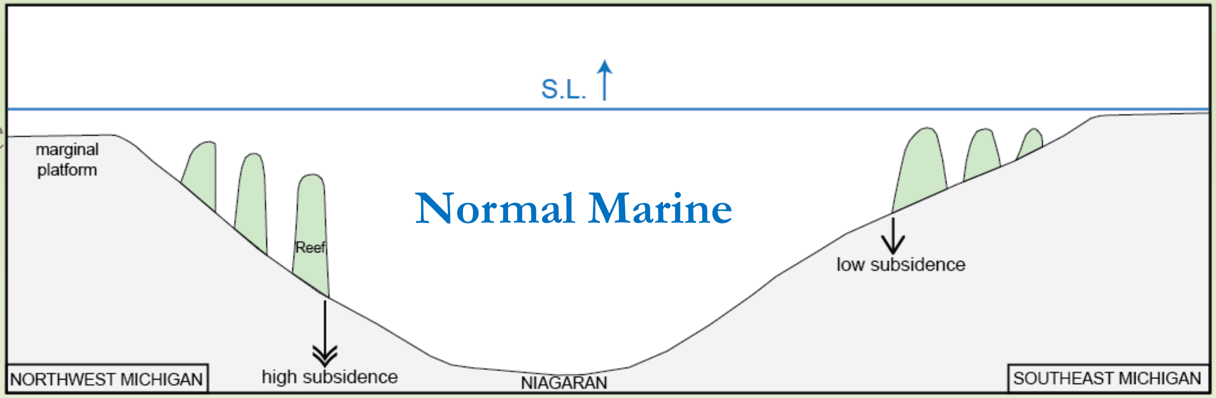
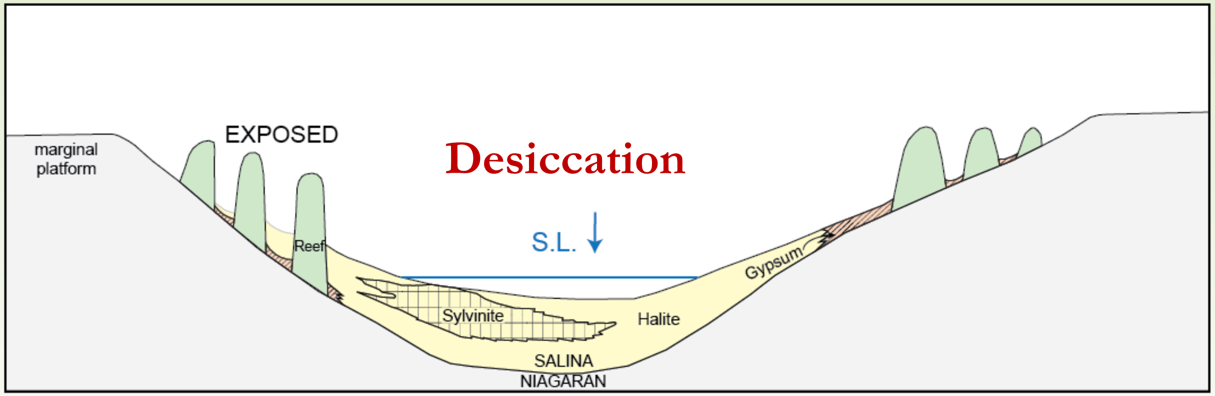


Humid Tropics

Arid Belt



Salina A-1 Evap:
Basin Desiccation
Gypsum → Halite → Sylvinite

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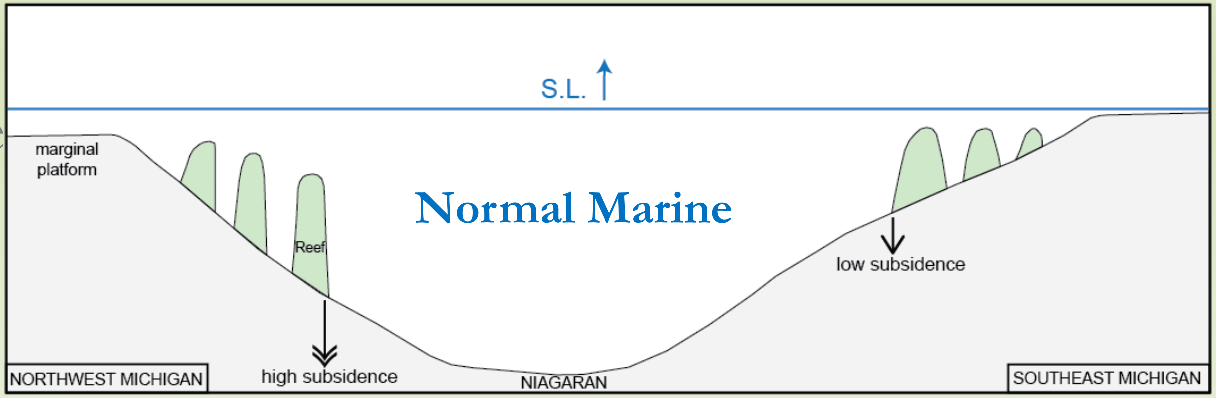

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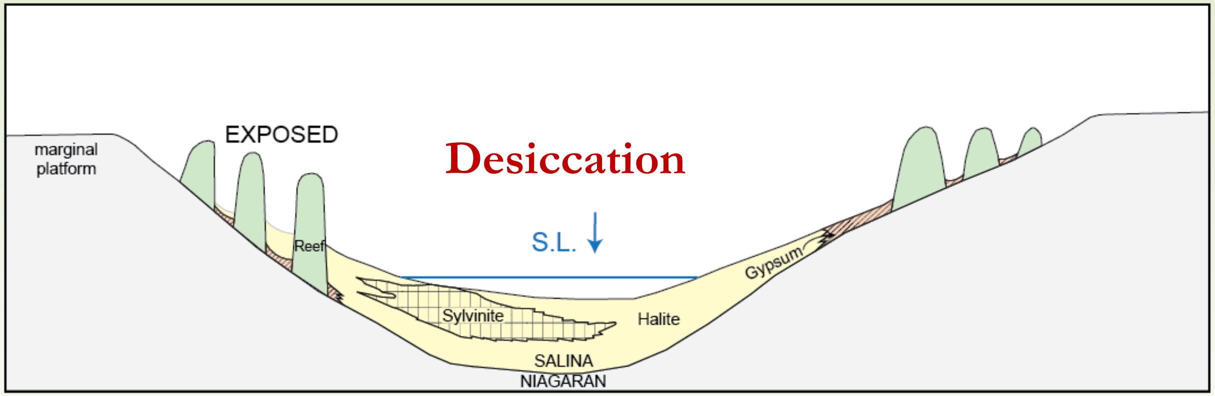
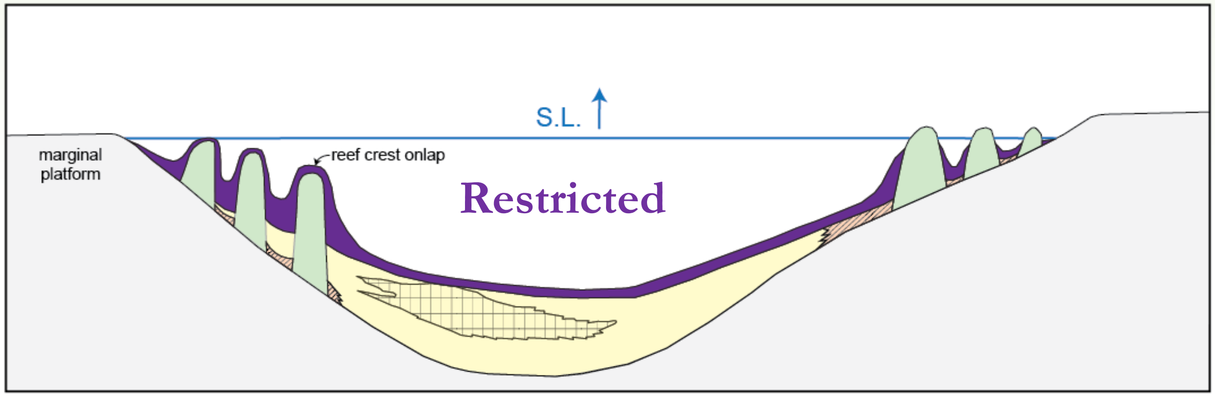


Salina A-1 Carb:
Restricted Carbonate
(microbial) deposition



PREVIOUS WORK

Budros & Briggs (1976), Gill (1977), Coniglio (2004)

- All 3 studies interpreted A-1 Carbonate facies to reflect **shallow subtidal to intertidal environments**

- The "Rabbit Ear Anhydrite" unit is the result of **localized sabkha environments**

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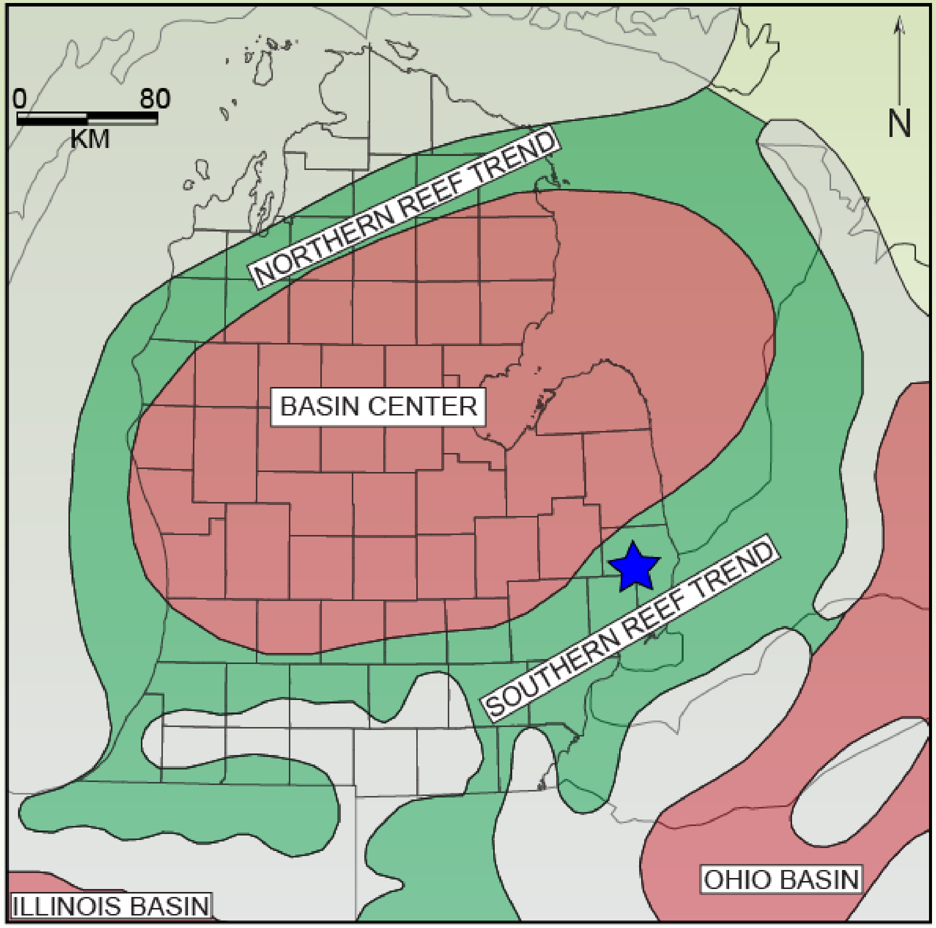
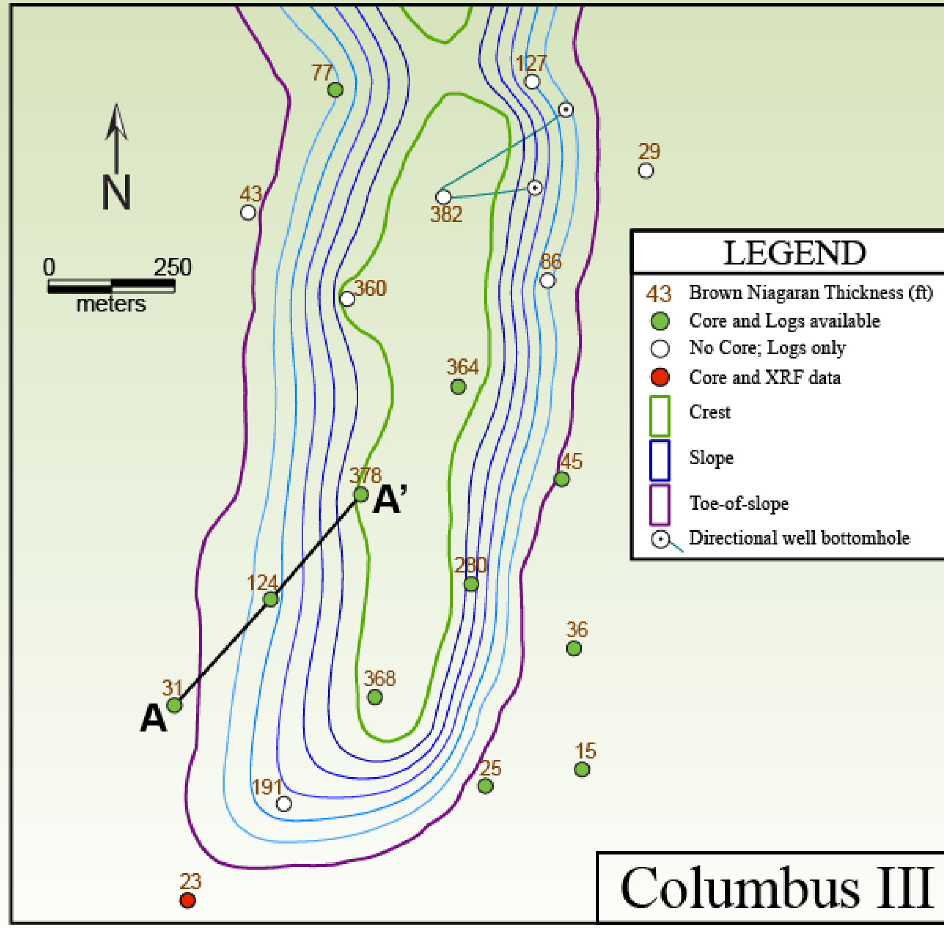
KEY FINDINGS (this study):

- The majority of A-1 Carbonate facies were deposited in **deep water**
- The "Rabbit Ear Anhydrite" unit is a **time significant event** that resulted in basin-wide restriction and gypsum deposition

FACIES DISTRIBUTIONS

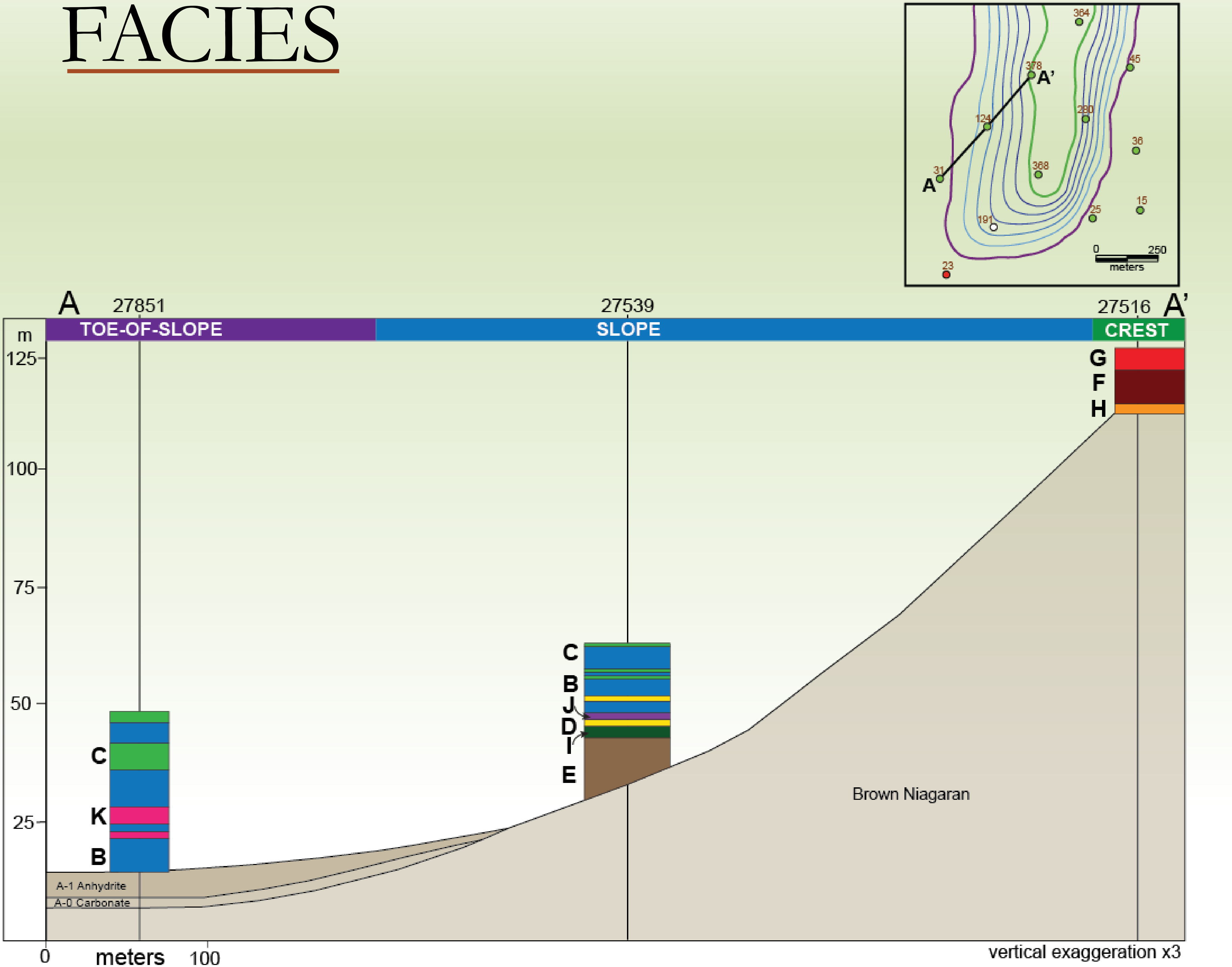




Southern Trend **Data-Rich Field** – Columbus III – 300 m core spacing

A-1 Carb Facies controlled by **Niagaran Reef Complex Paleotopography**

FACIES



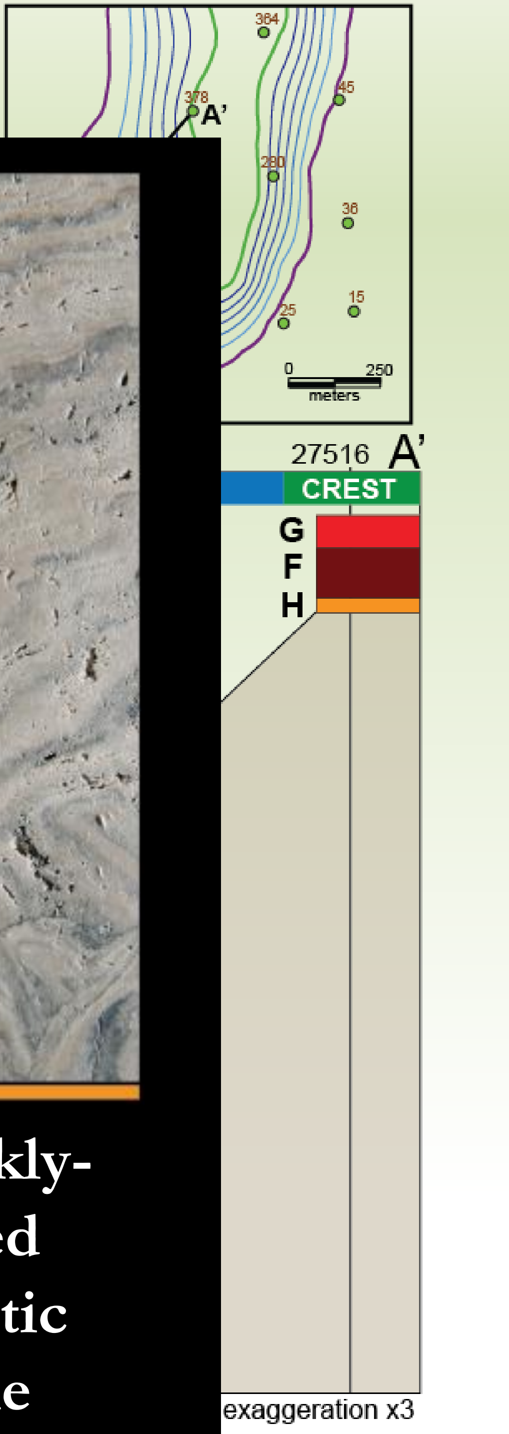
A
A'
27851
27539
27516
TOE-OF-SLOPE
SLOPE
CREST
m
125
100
75
50
25
G
F
H
C
B
J
D
I
E
C
K
B
A-1 Anhydrite
A-0 Carbonate
Brown Niagaran
0
meters
100
vertical exaggeration x3
384
45
378
280
124
36
368
31
15
25
191
23
0
250
meters

FACIES (OBSERVATIONS)

Thrombolitic Bindstone

Laminated Peloidal Stromatolitic Bindstone

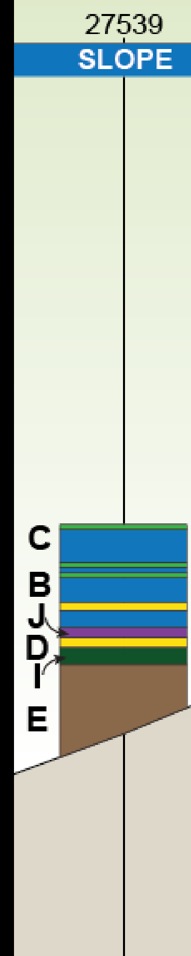
White Crinkly-Laminated Stromatolitic Bindstone



FACIES (OBSERVATIONS)

Enterolithic Anhydrite

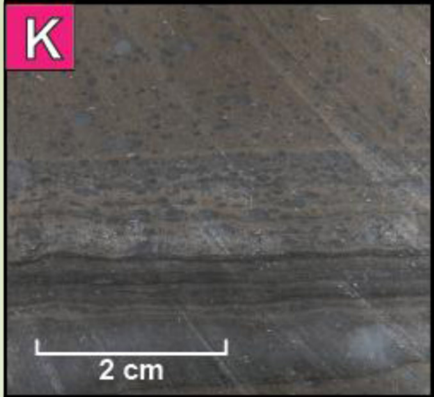
Peloidal Wacke-Packstone



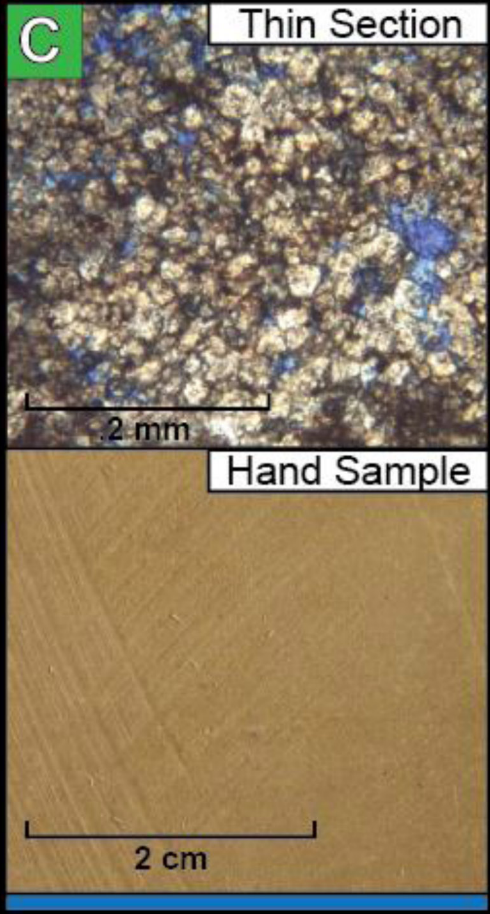
Stromatolitic Rudstone

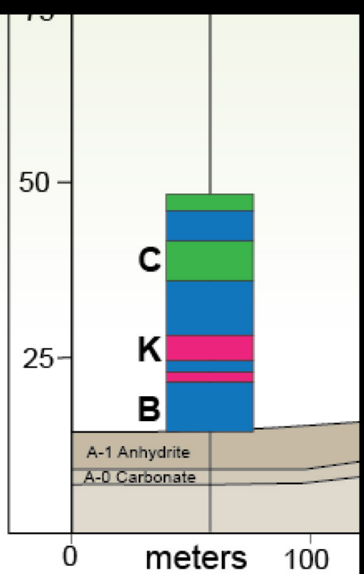
Stromatolitic Floatstone

FACIES (OBSERVATIONS)



Nodular Anhydritic Mudstone





Laminated Peloidal Wackestone

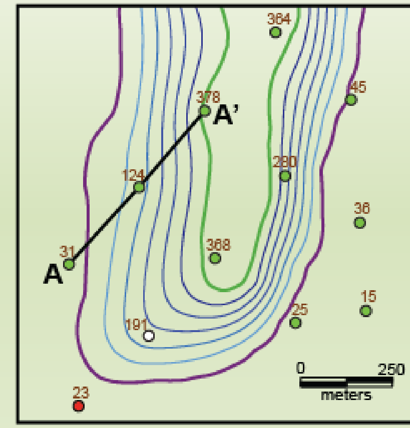
Normally Graded Mudstone

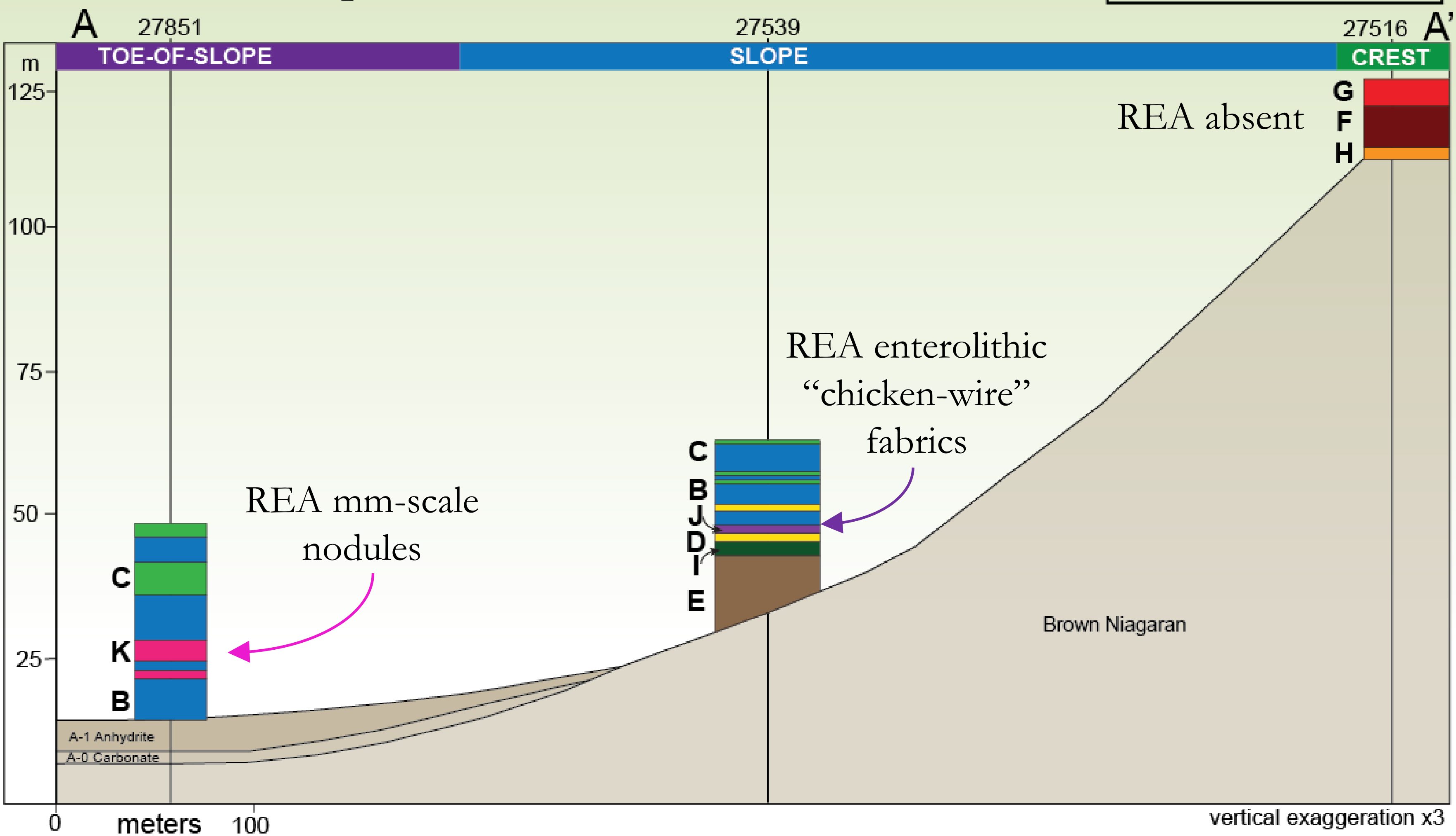
Crystalline Dolomite

FACIES

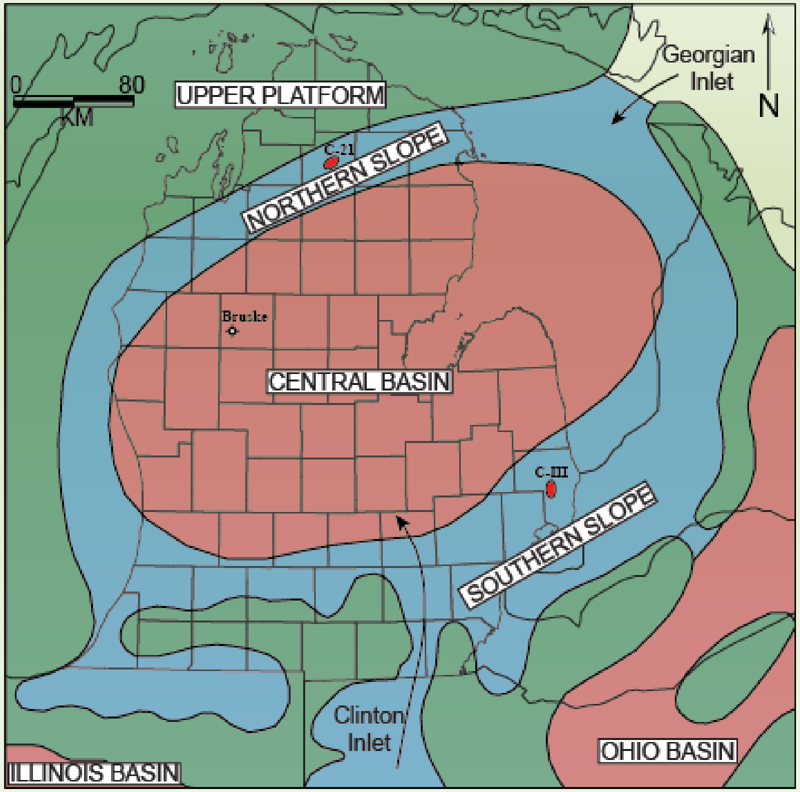
General Observations:

1) Increase in microbial carbonates up-slope
2) Increase in laminated "poker chip" mudstones down-slope & into basin interior



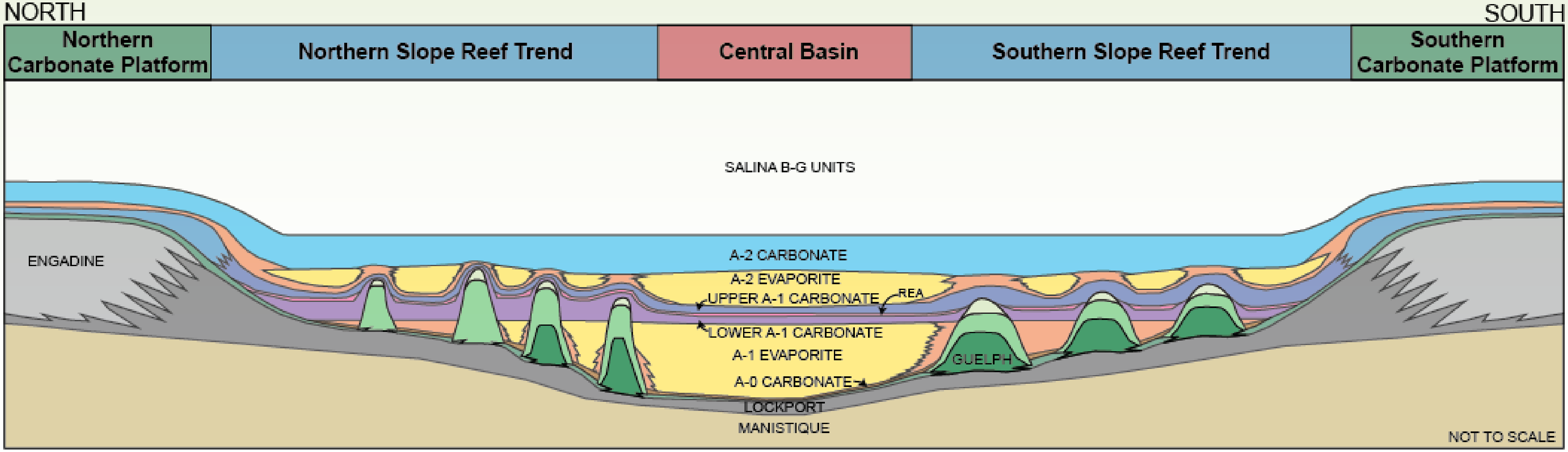


BASIN-WIDE OBS.

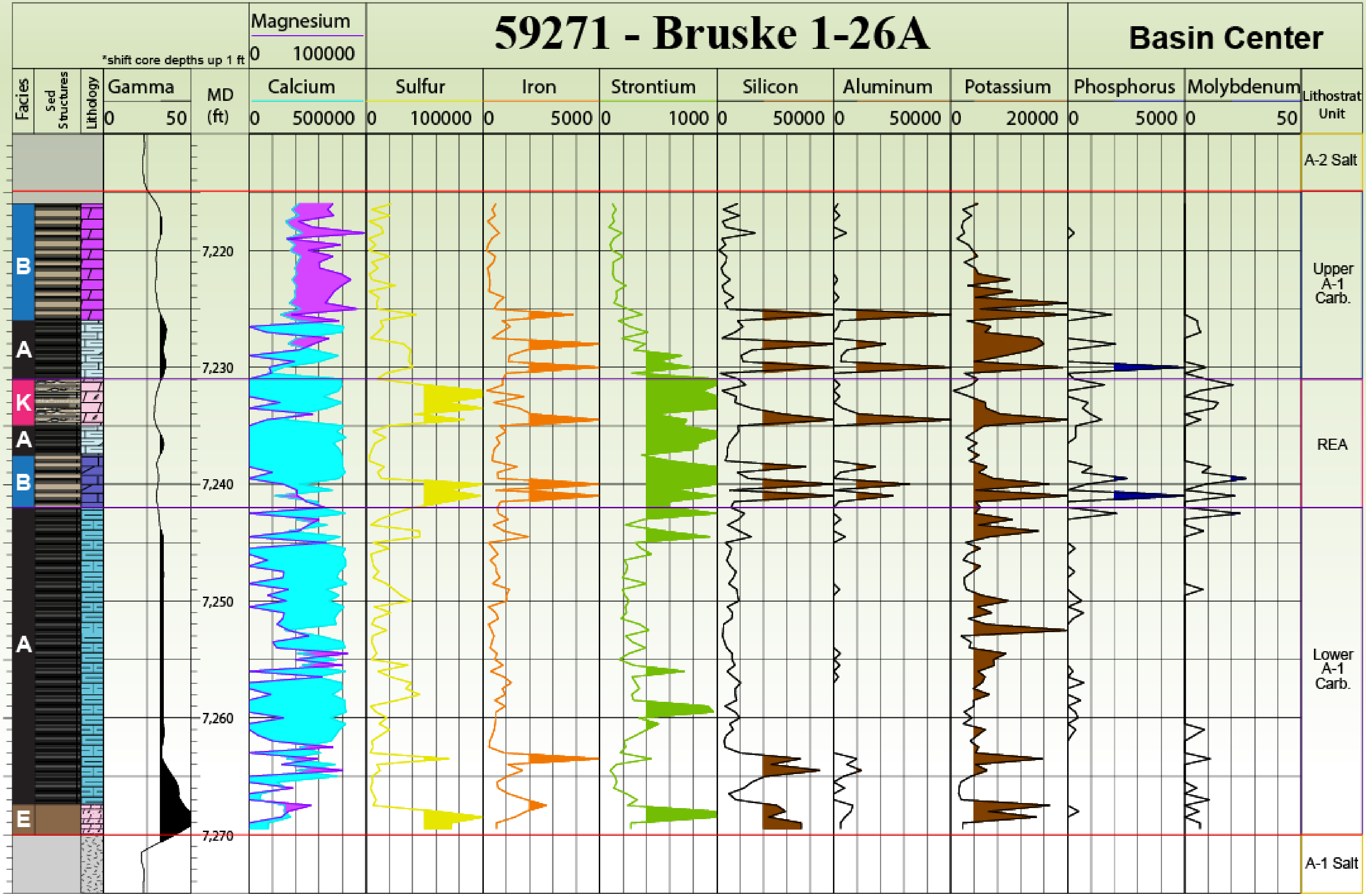


1) Northern trend crest to slope facies relationships very similar to South

2) Basin center cores composed mostly of laminated “poker chip” carbonate mudstone facies



XRF ELEMENTAL DATA



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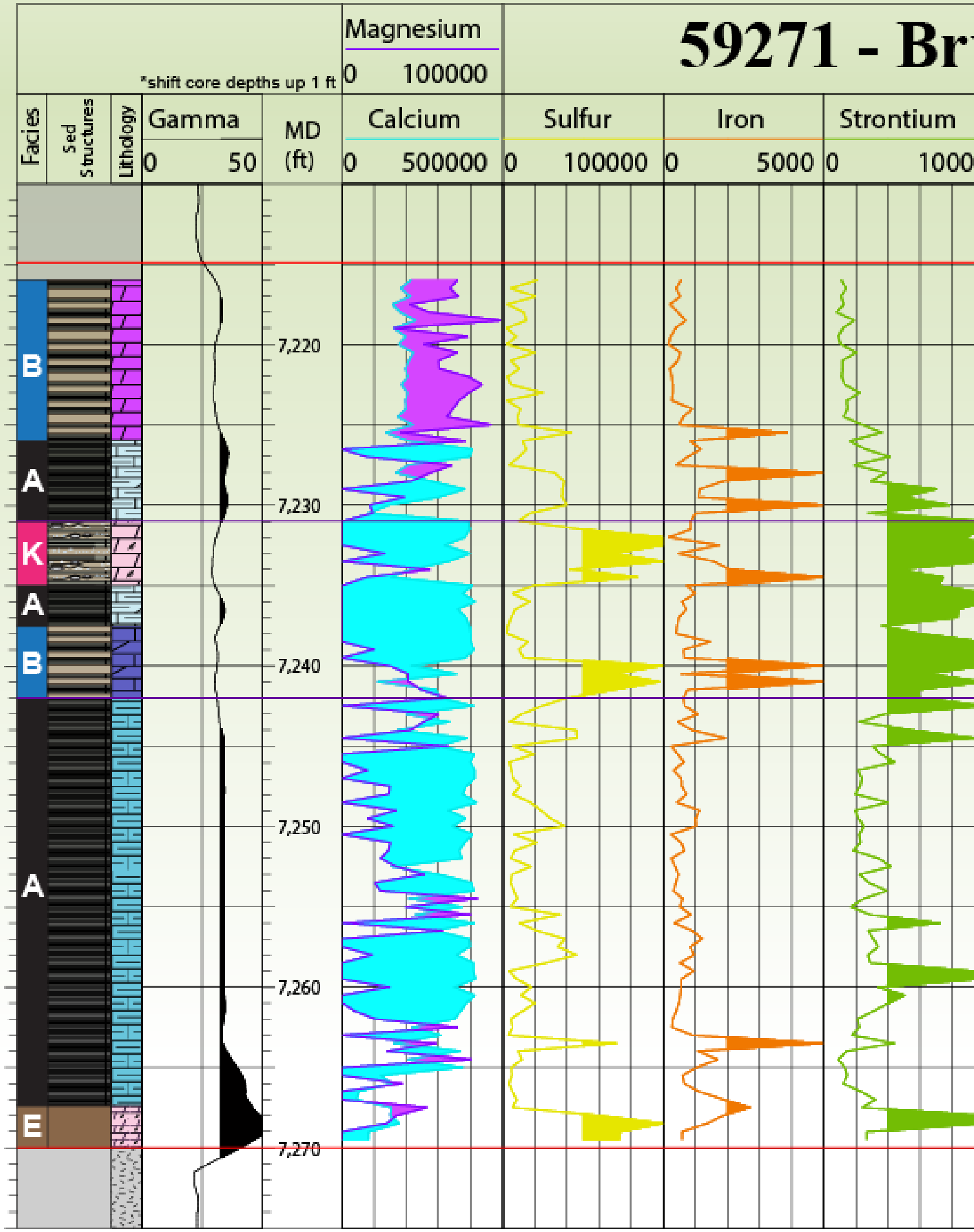
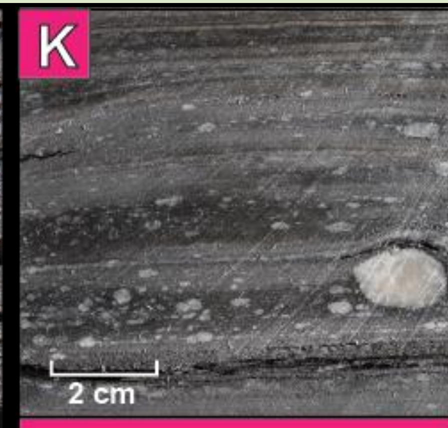
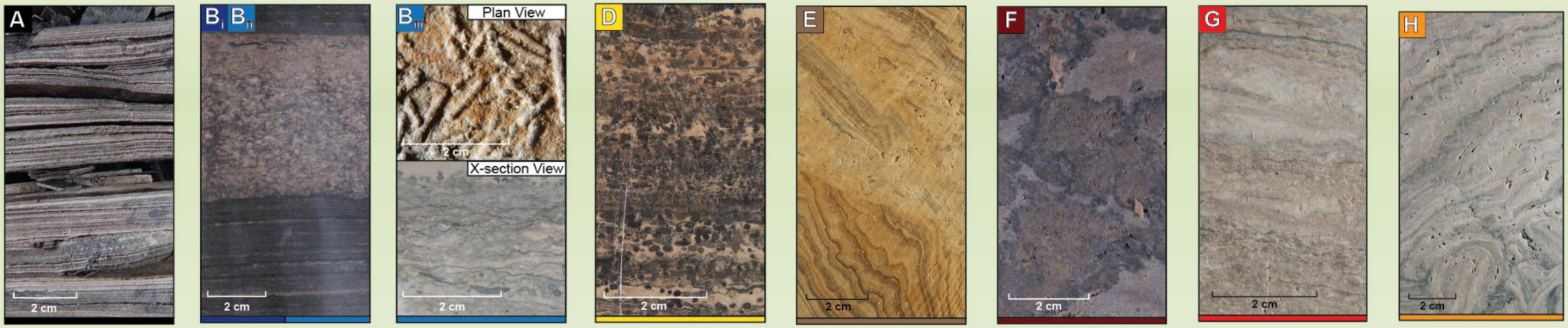


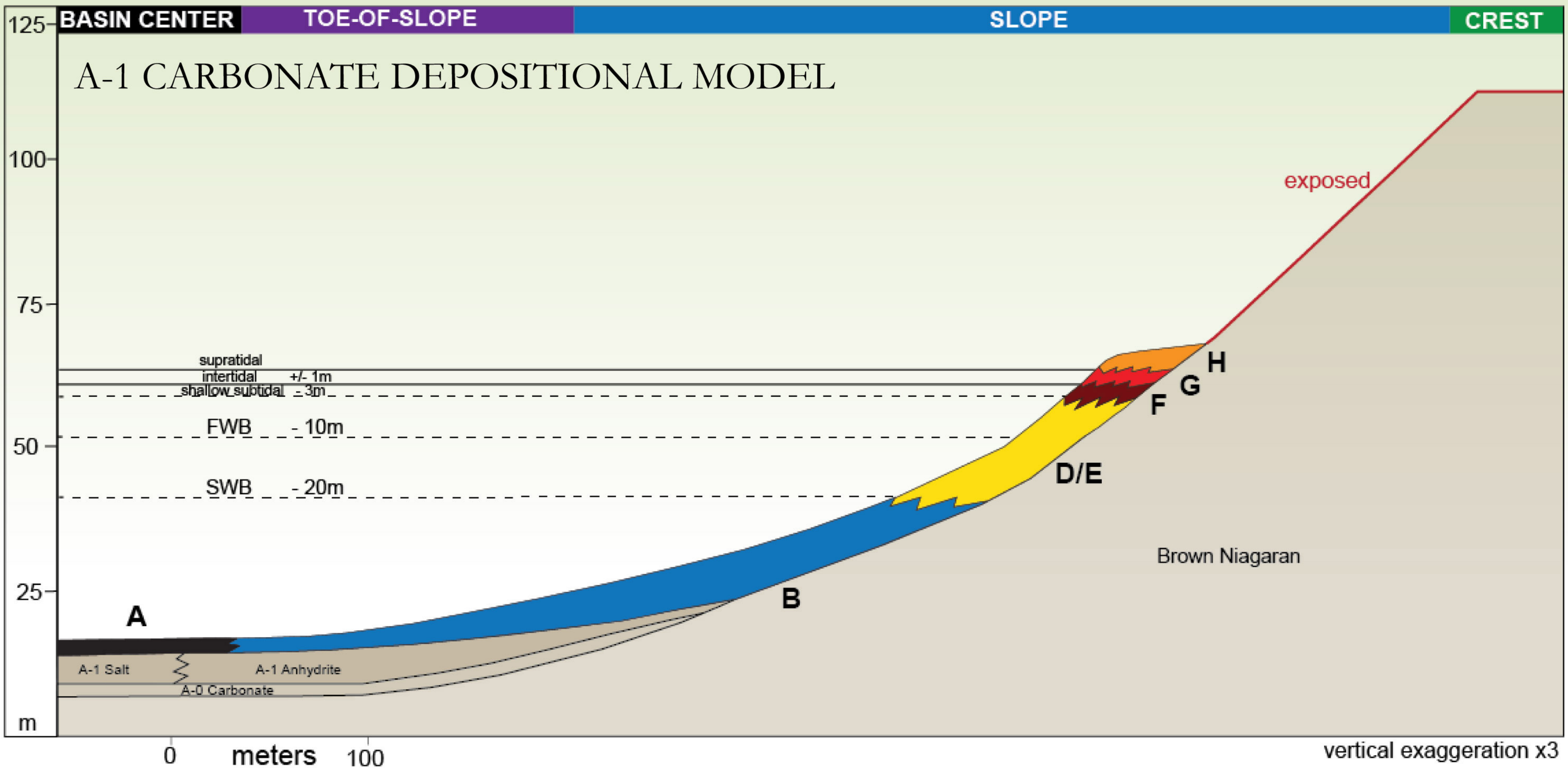
Thinly Laminated "Poker Chip" Mudstone



Nodular Anhydritic Mudstone

FACIES INTERPRETATIONS





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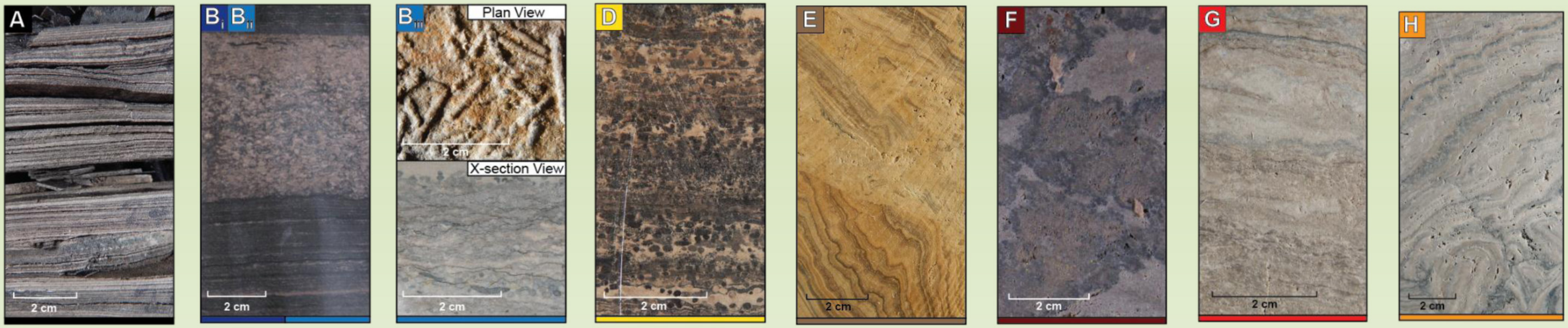
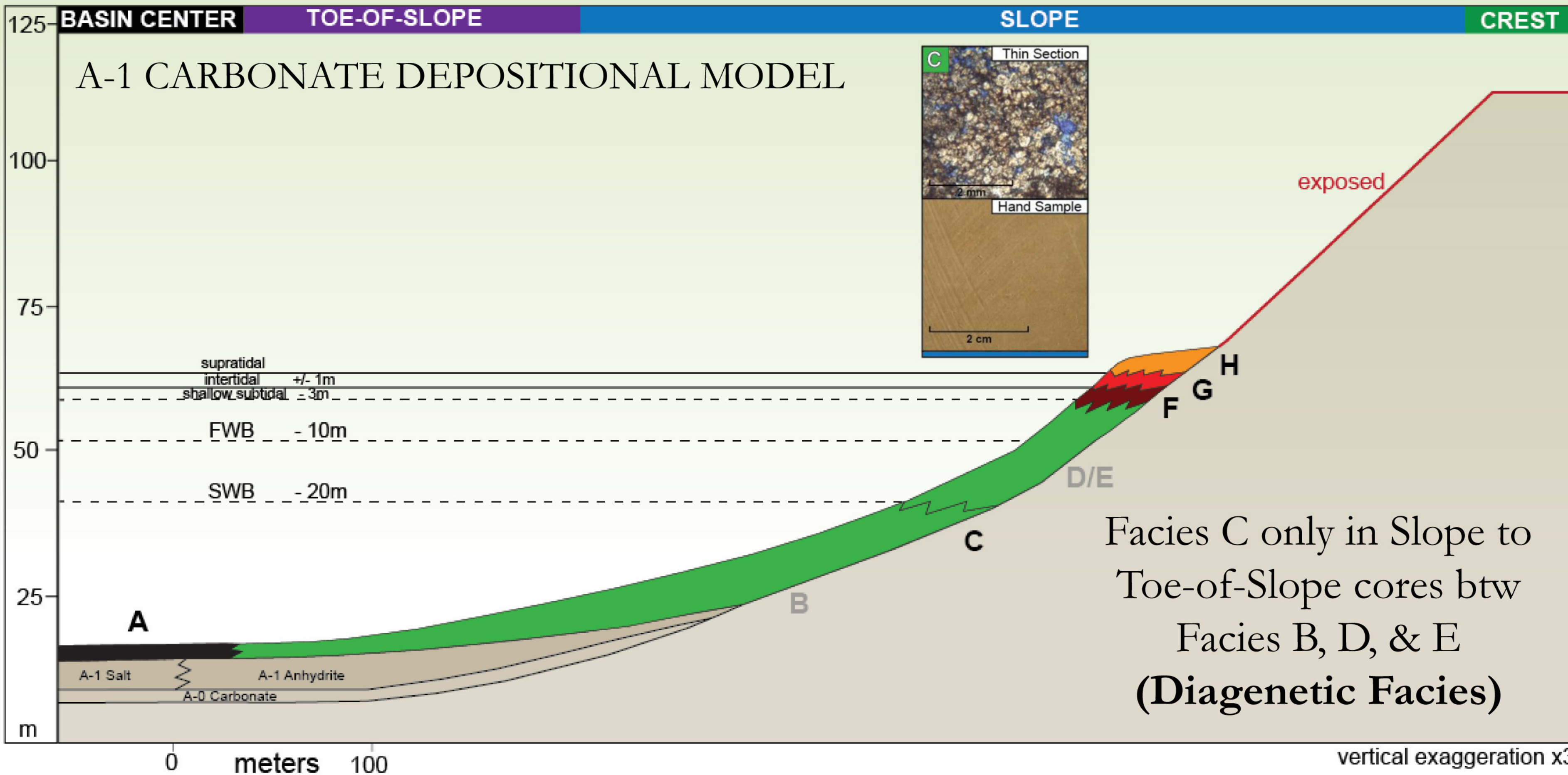
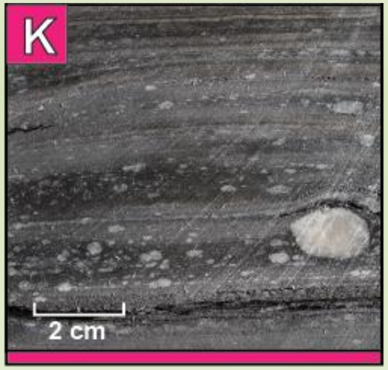


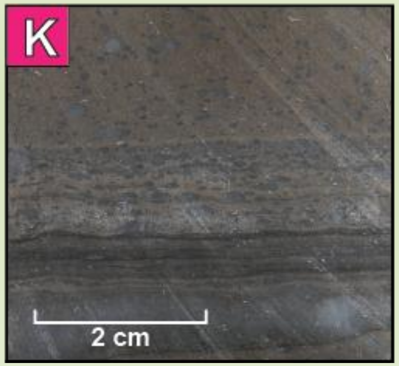


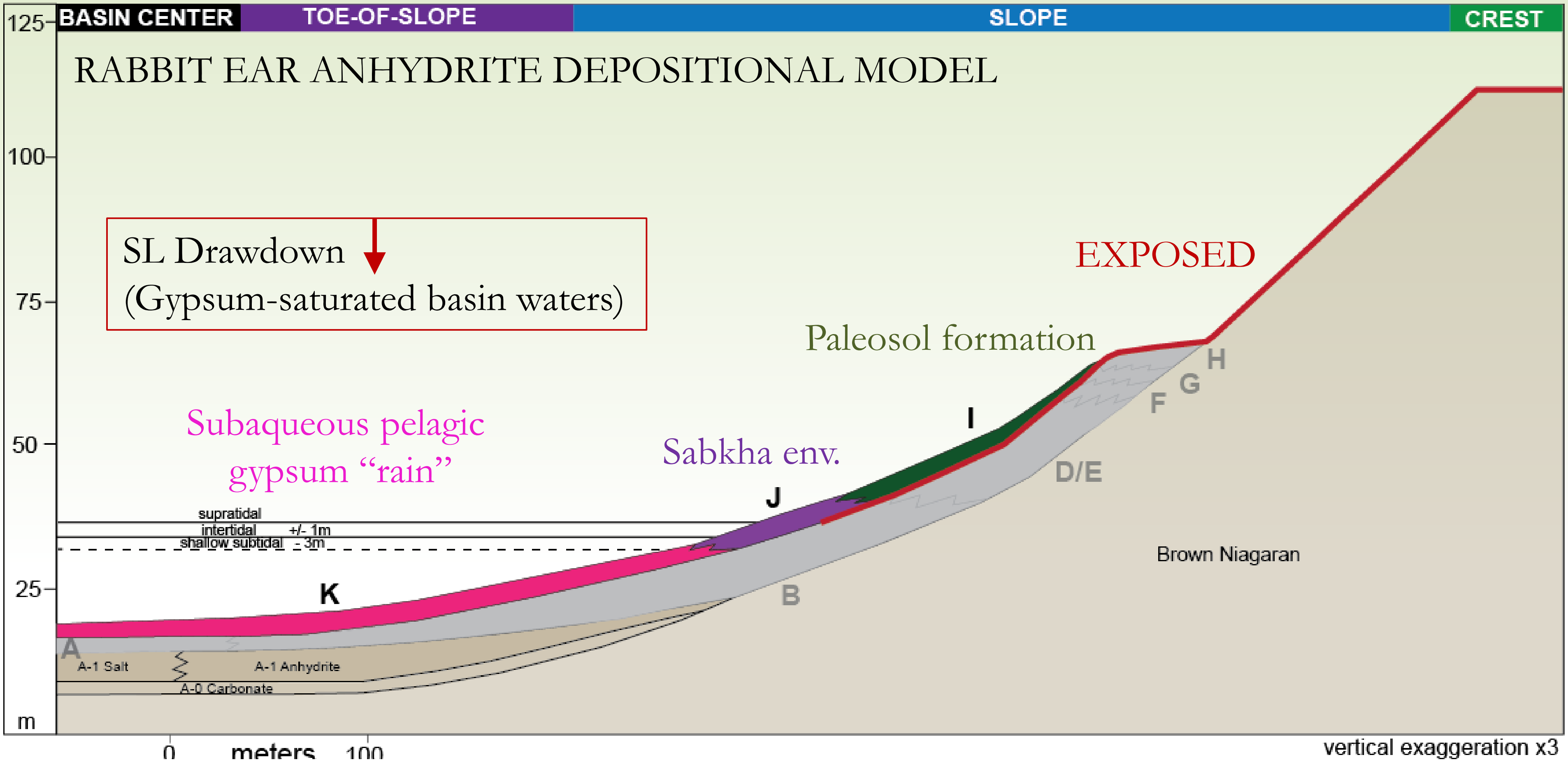
Facies C only in Slope to Toe-of-Slope cores btw Facies B, D, & E

(Diagenetic Facies)

FACIES INTERPRETATIONS



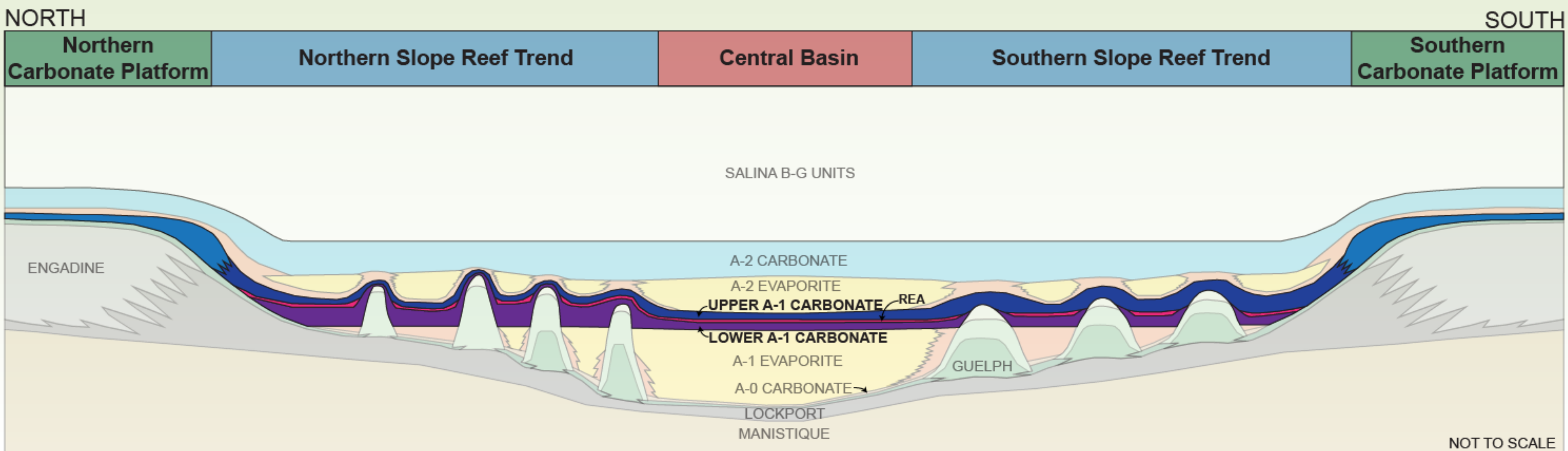




REA IMPORTANCE

1) Identification of REA interval in every A-1 Carbonate core in the basin (including basin center) leads to new interpretation

2) The REA is a time correlative event (4^{th} order drawdown) that resulted in increased gypsum saturation/deposition



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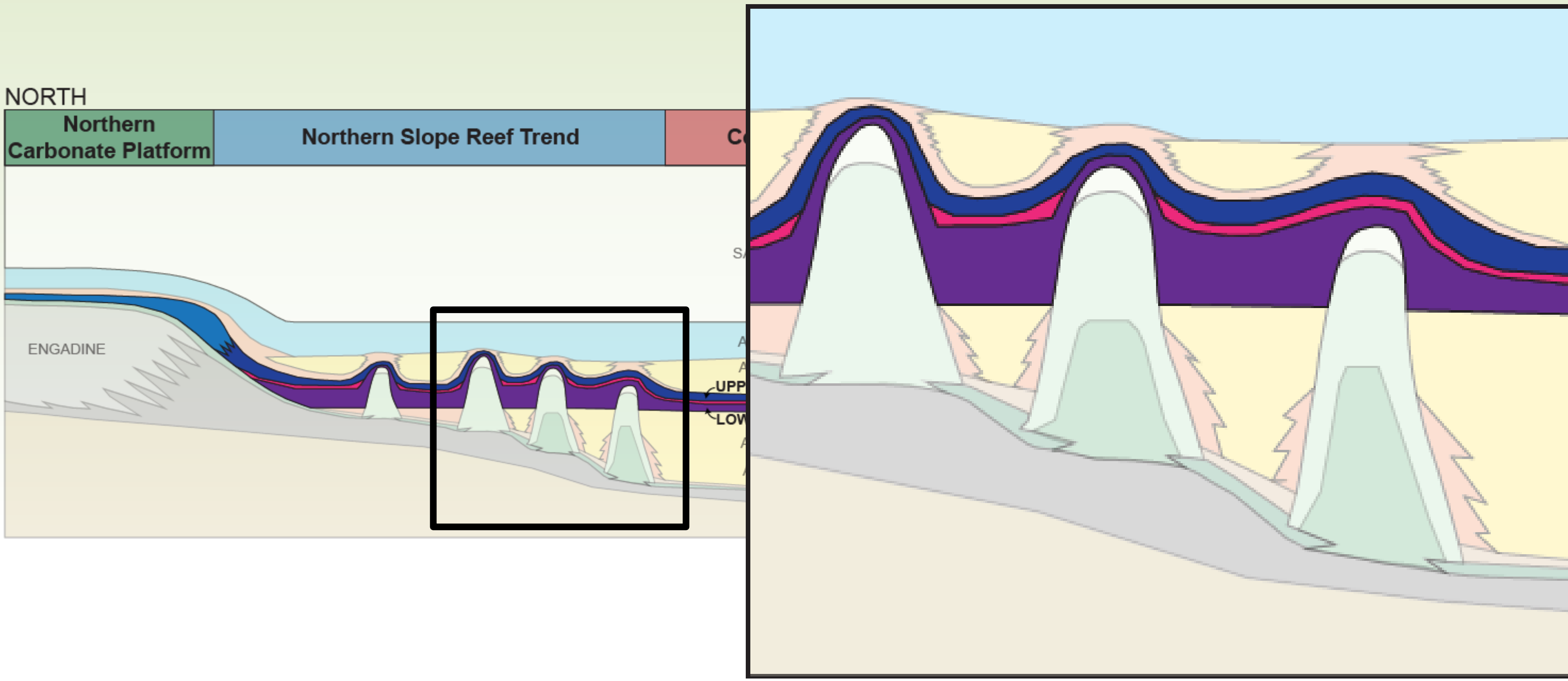
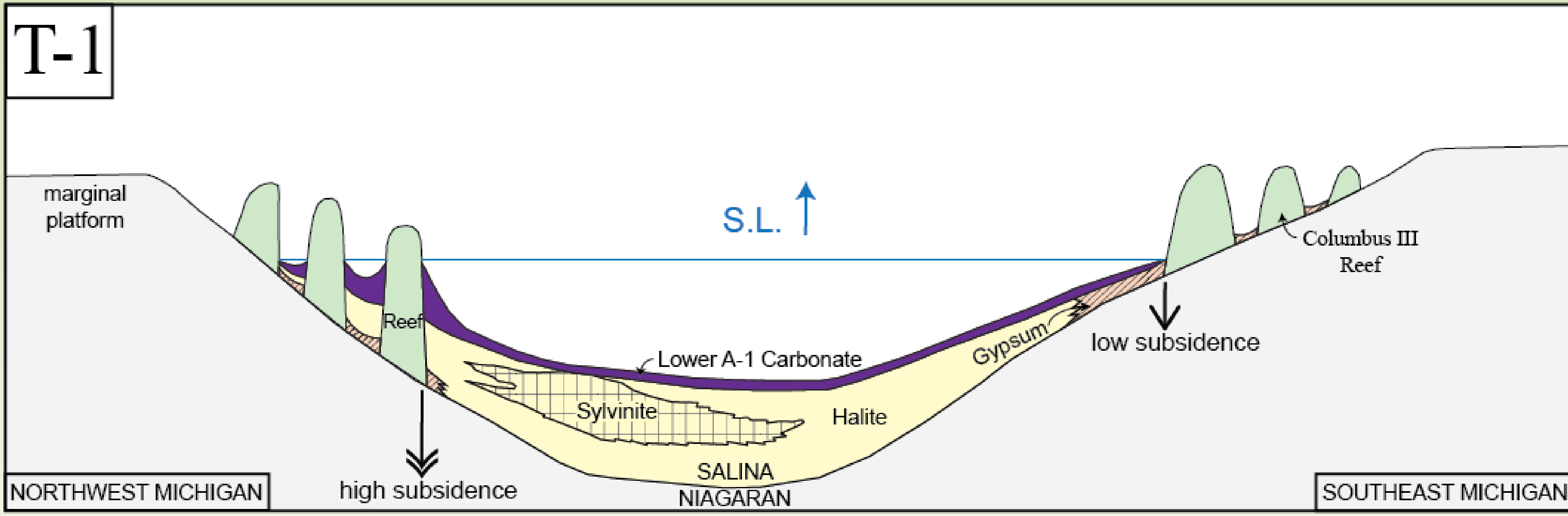
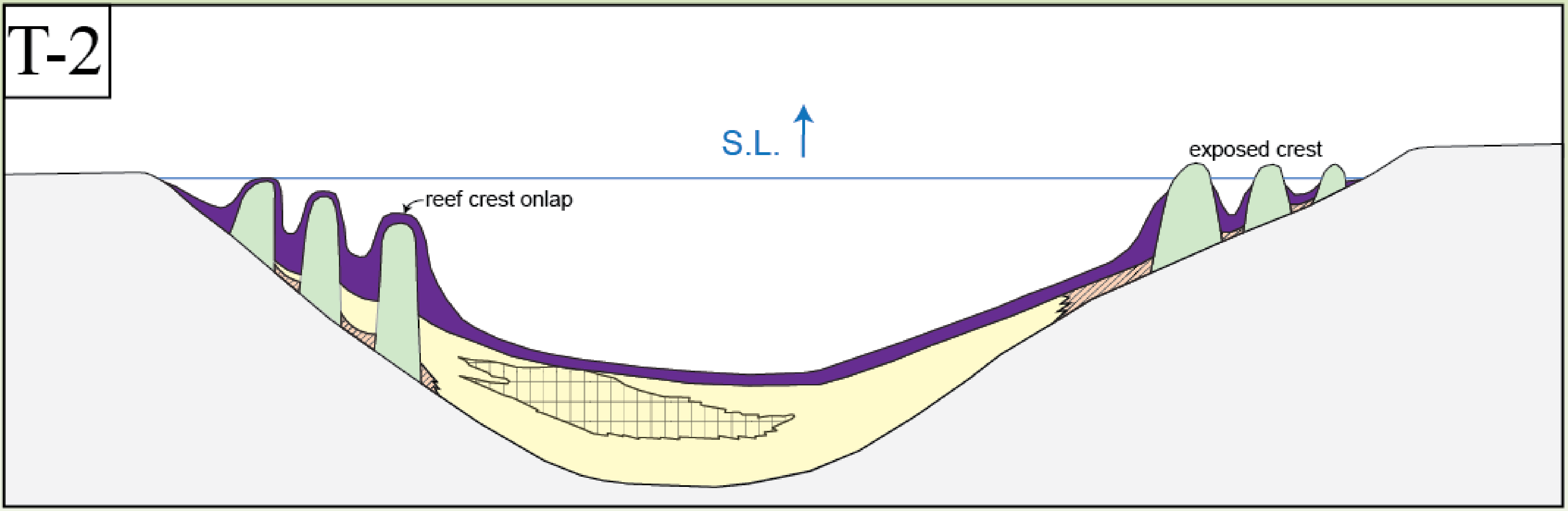


SEQ. STRAT. MODEL



- First A-1 Carbonate deposition occurs in Basin Center in the form of cyanobacterial mats and associated clasts
- Microbial carbonate factory established on flanks of Northern Trend Reefs; Southern Trend Reefs remain exposed

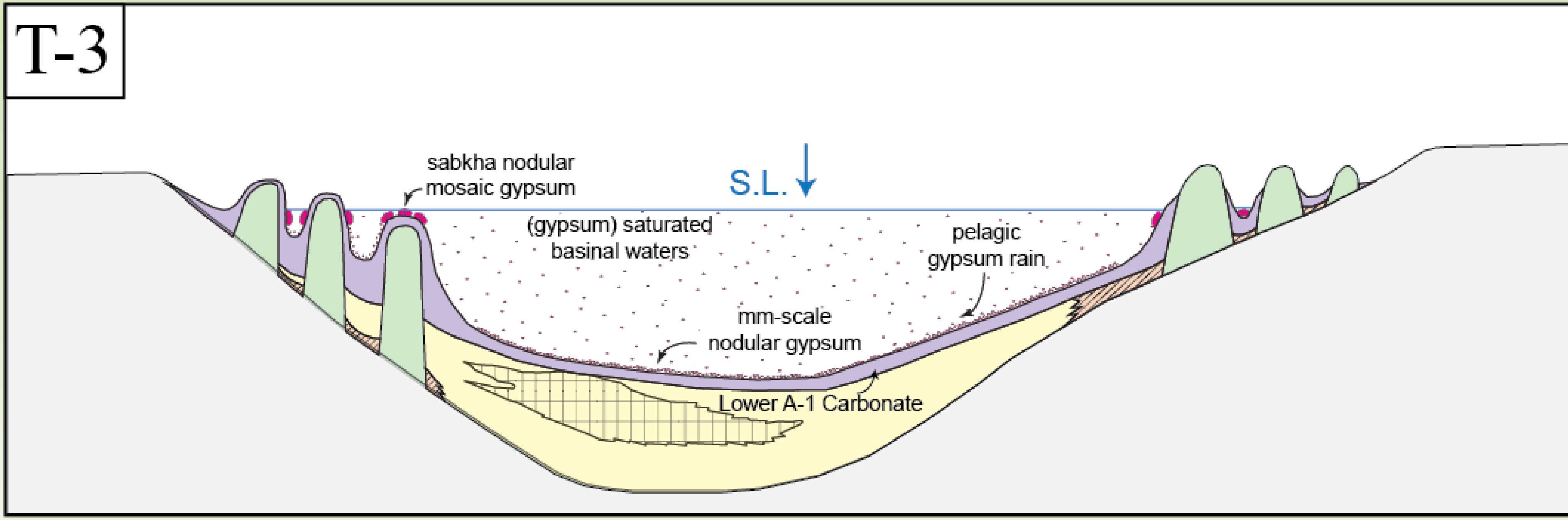
SEQ. STRAT. MODEL



- Maximum transgression during Lower A-1 Carbonate results in onlapping of Northern Trend Reef crests; Southern Trend Reef crests remain exposed (differential subsidence)

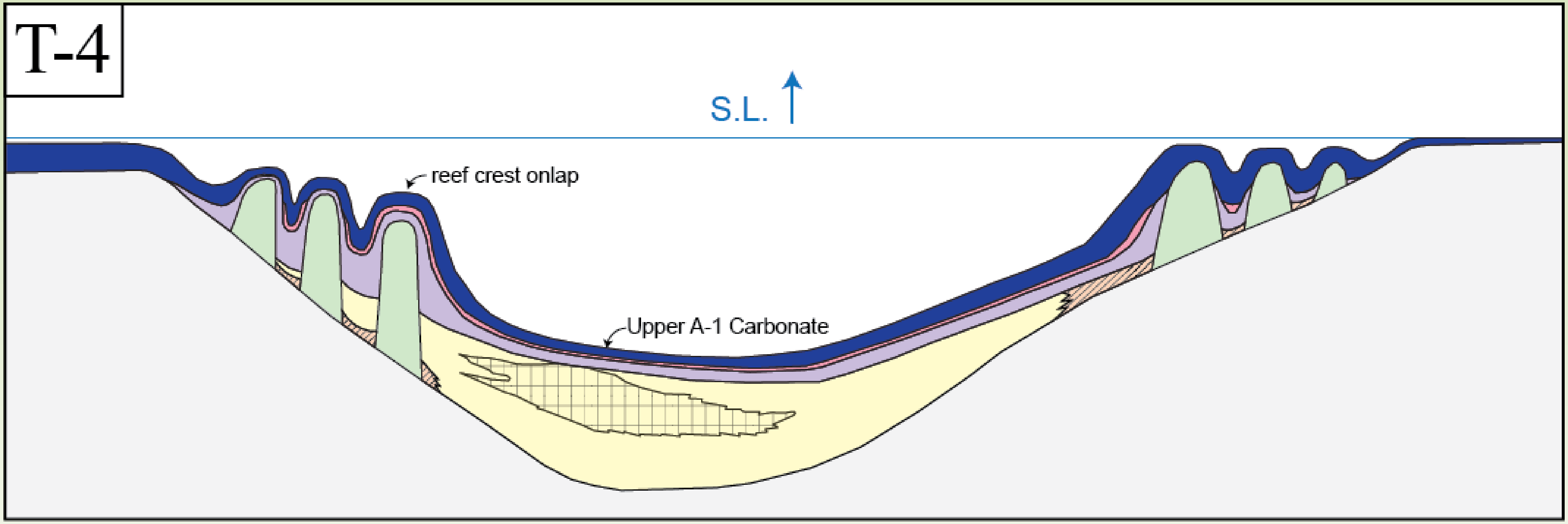
- Deep-water carbonate laminites being deposited in inter-reef and basin-center localities (possible anoxic bottom waters – High TOC)

SEQ. STRAT. MODEL



- 4th-order regression results in development of subaerial exposure, sabkha environments, and subaqueous pelagic gypsum rain
- Stratigraphic position of the REA unit and identification of anhydrite fabrics allows for better understanding for SL position

SEQ. STRAT. MODEL

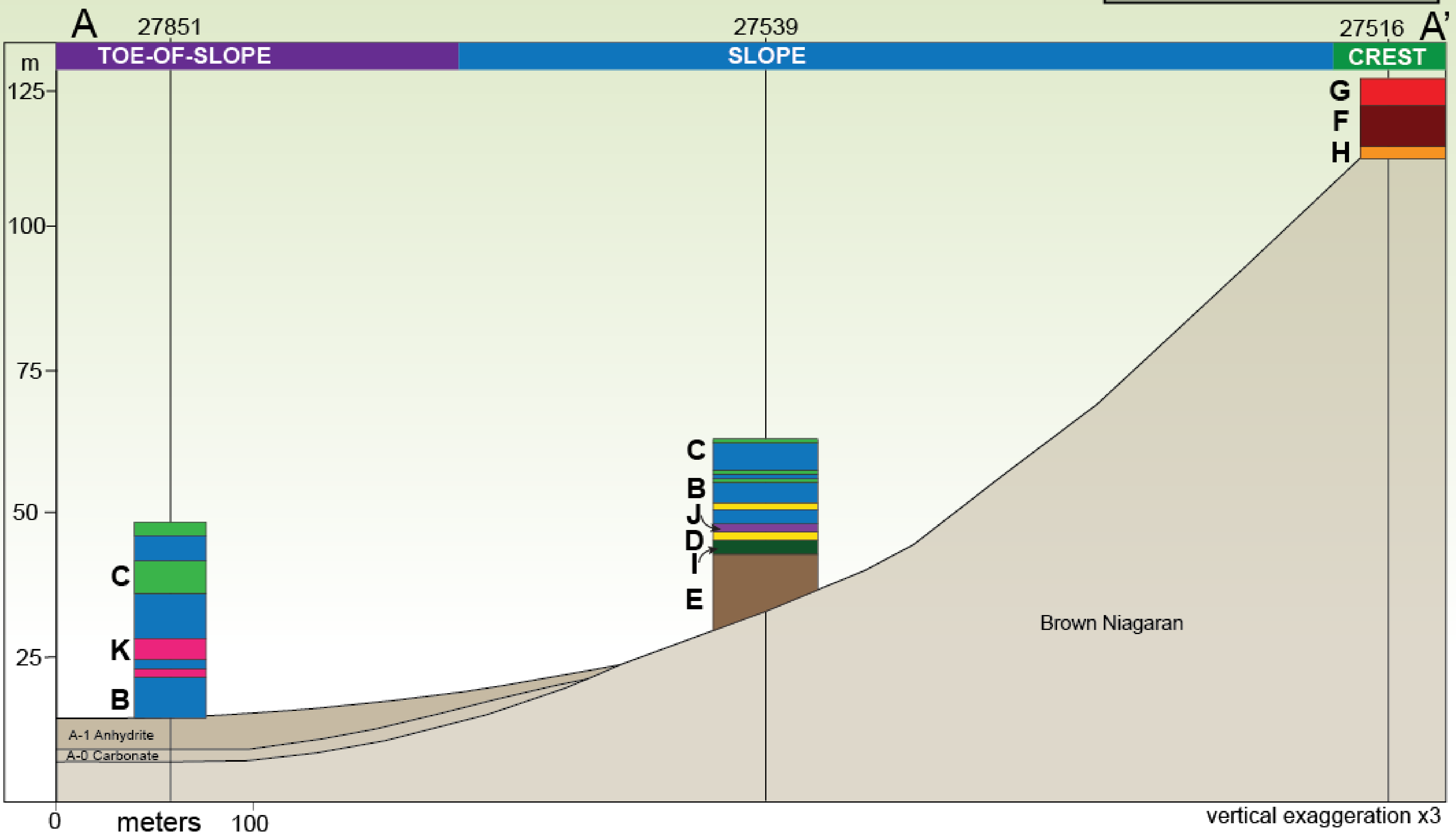


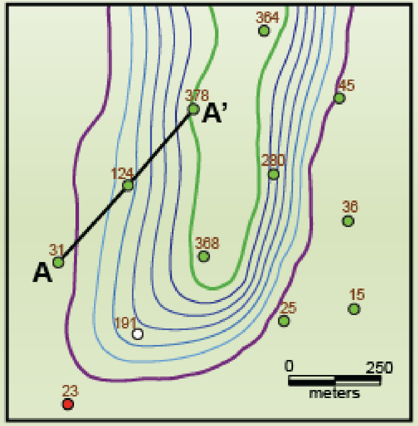
- During Upper A-1 Carbonate deposition, microbial carbonate factory onlaps all reef crests

- Basinal waters have returned as close to normal marine after the end of reef growth time; abundance of peloids, brachiopods, stromatolites

RESERVOIR FACIES

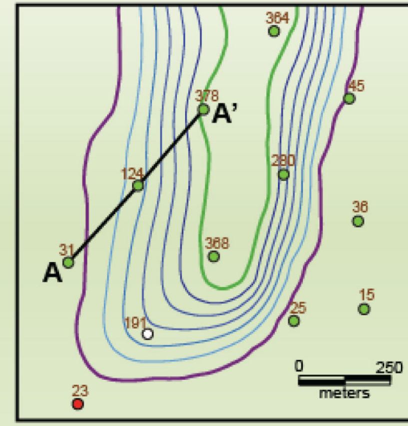
Depositional Facies Stacking



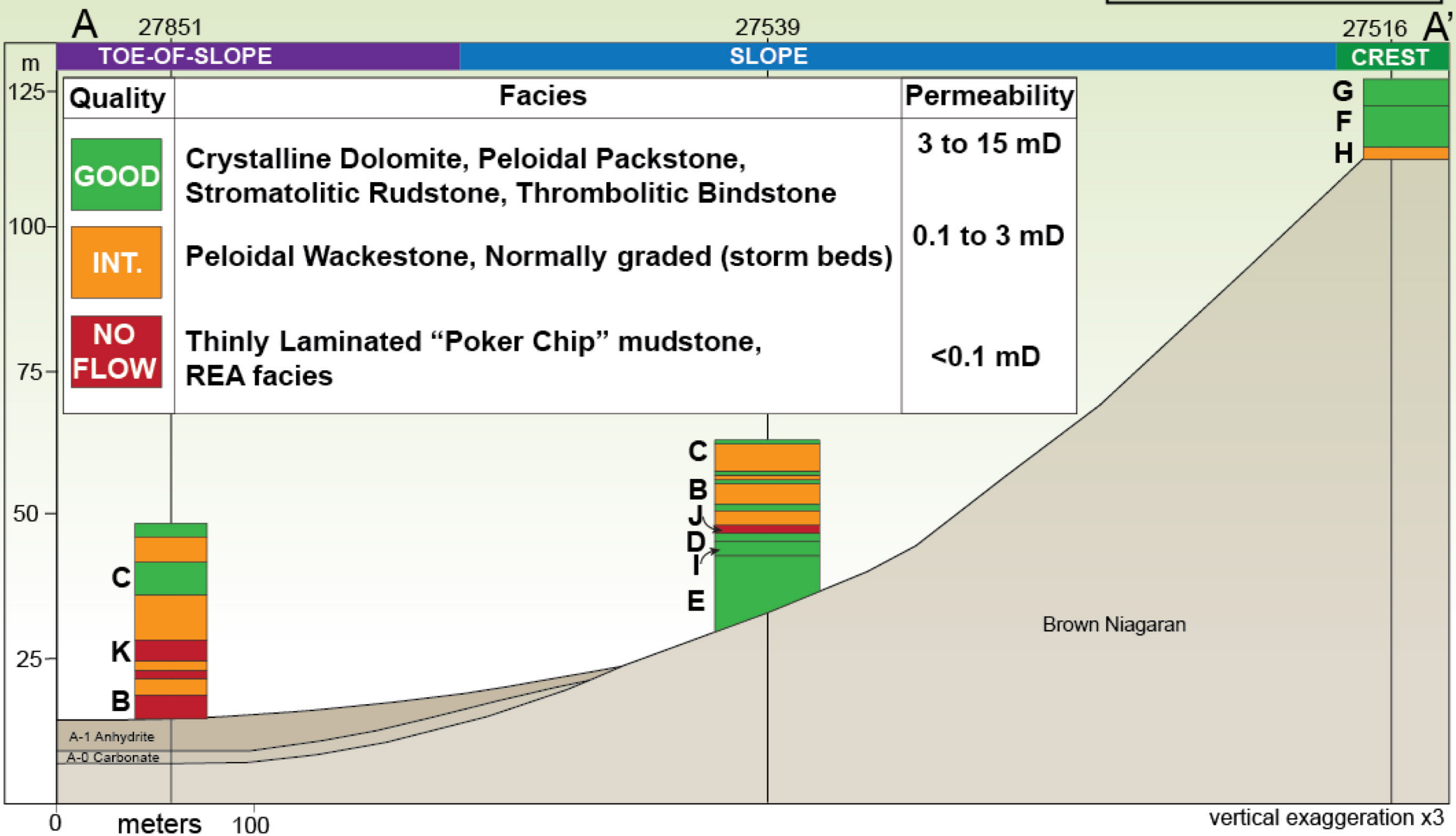


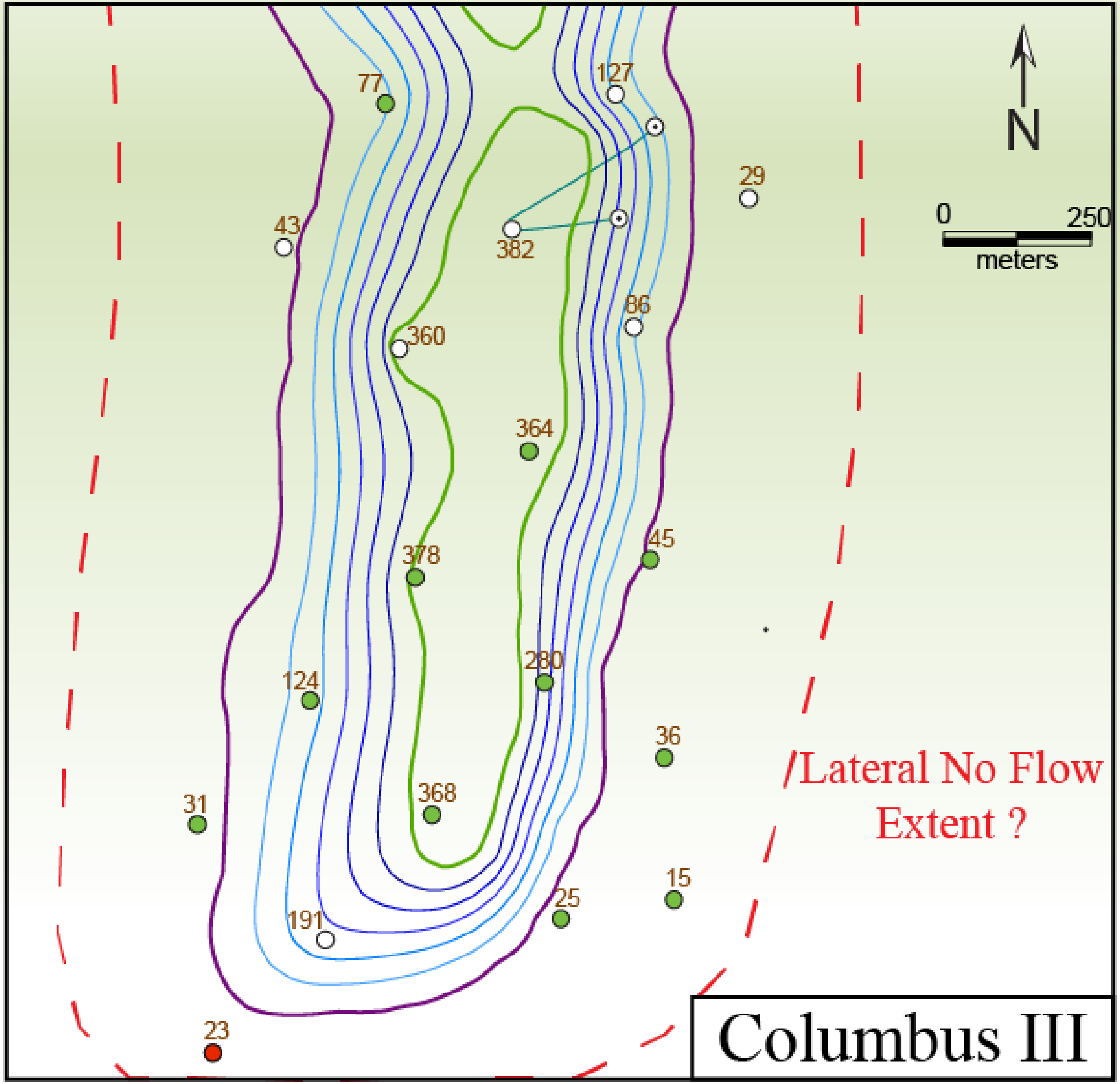
RESERVOIR FACIES

Petrophysical Facies



Quality	Facies	Permeability
GOOD	Crystalline Dolomite, Peloidal Packstone, Stromatolitic Rudstone, Thrombolitic Bindstone	3 to 15 mD
INT.	Peloidal Wackestone, Normally graded (storm beds)	0.1 to 3 mD
NO FLOW	Thinly Laminated "Poker Chip" mudstone, REA facies	<0.1 mD

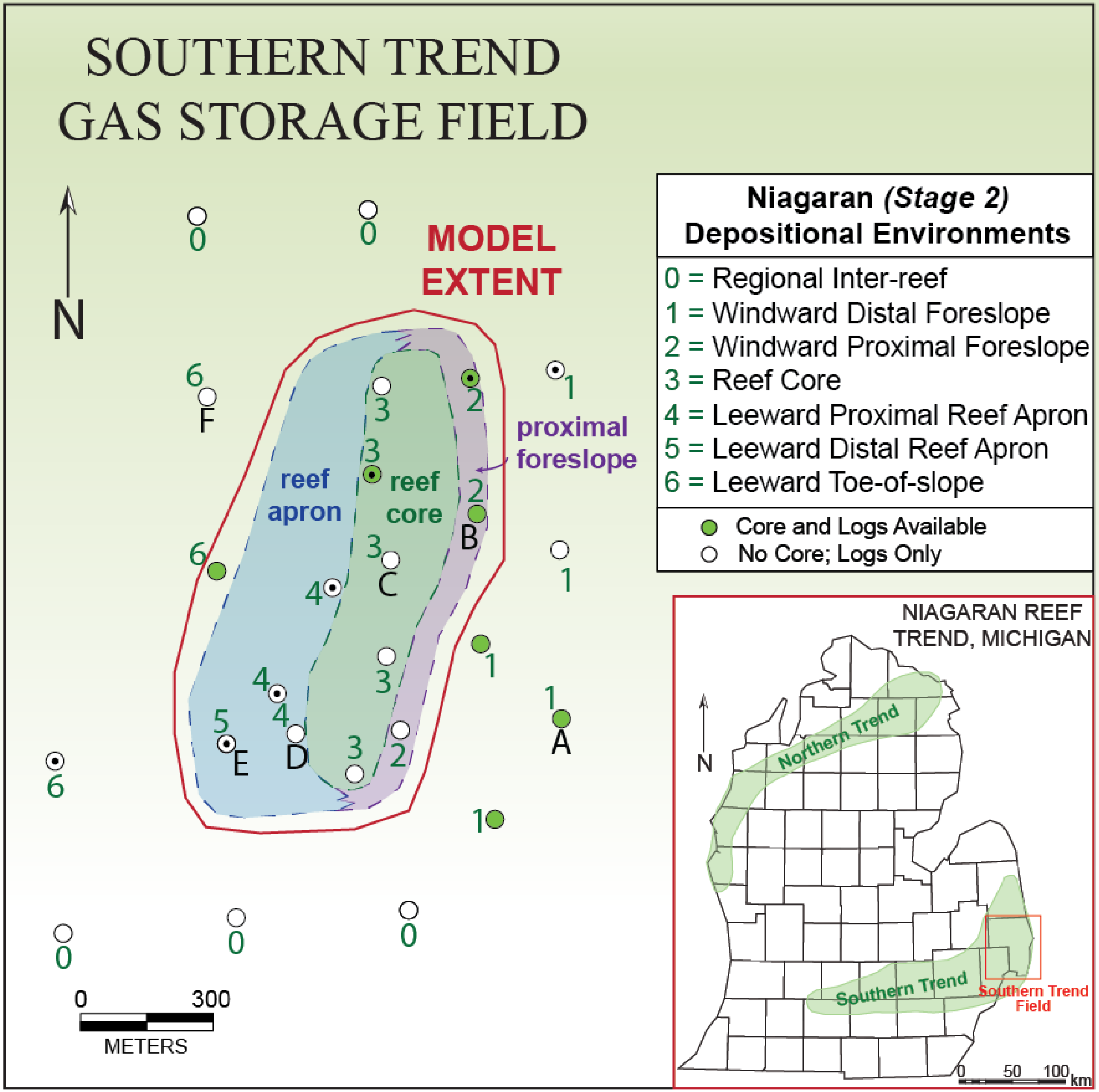




Reservoir Facies pinch-out laterally; difficult to identify due to poor well control

IMPLICATIONS

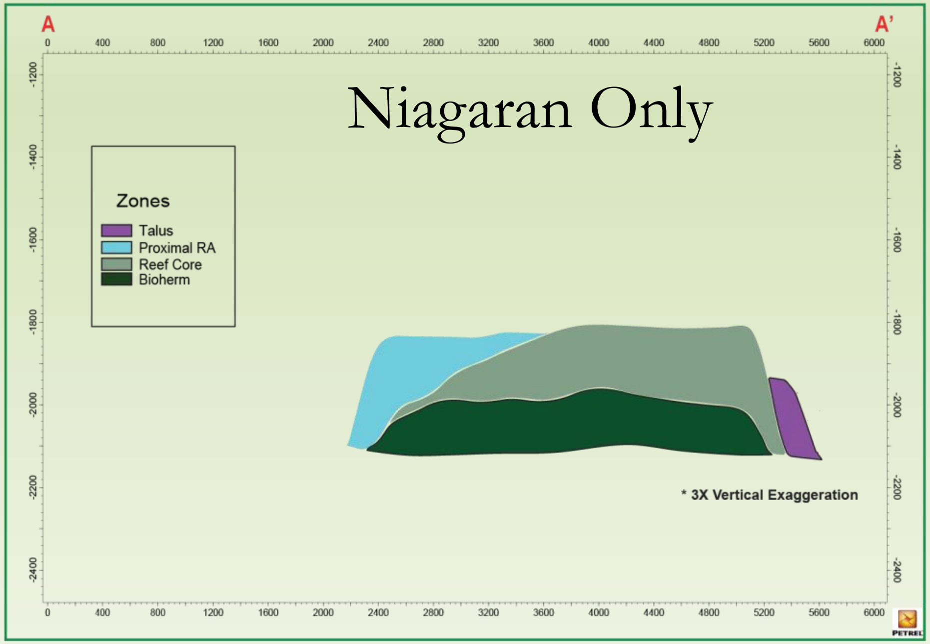
Case Study #1: Gas Storage

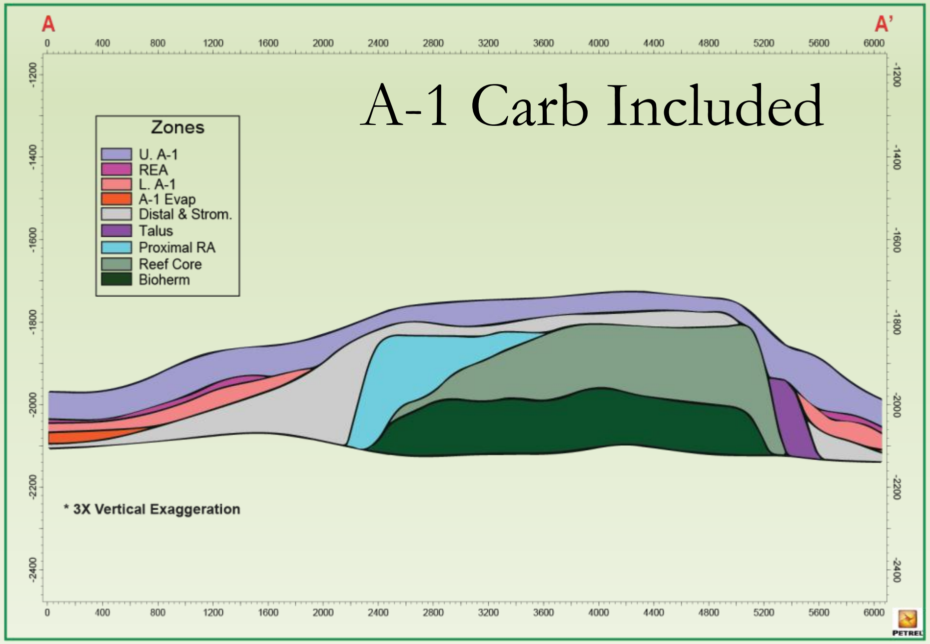


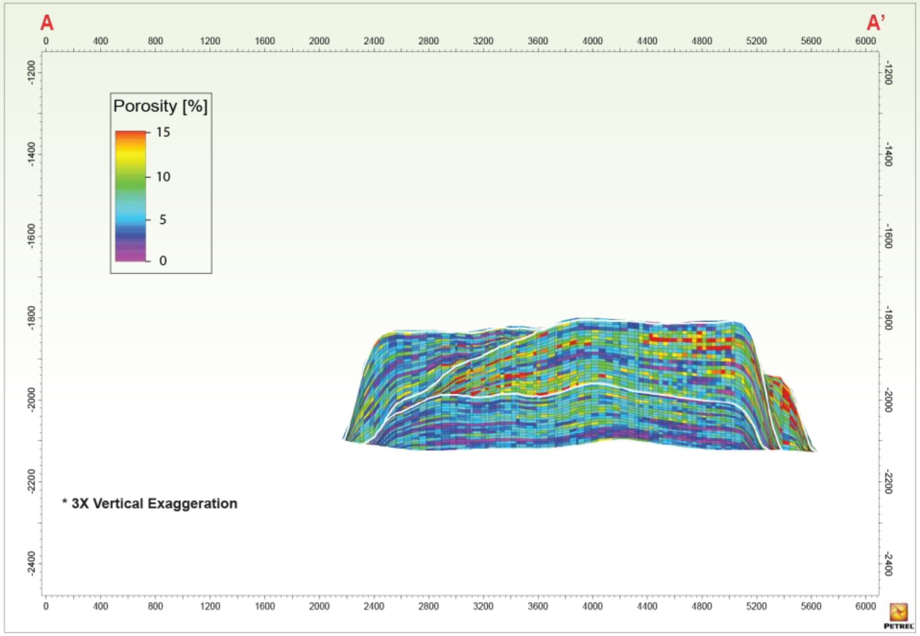
Original modeling
Efforts only included
Niagaran Reef
Complex Units

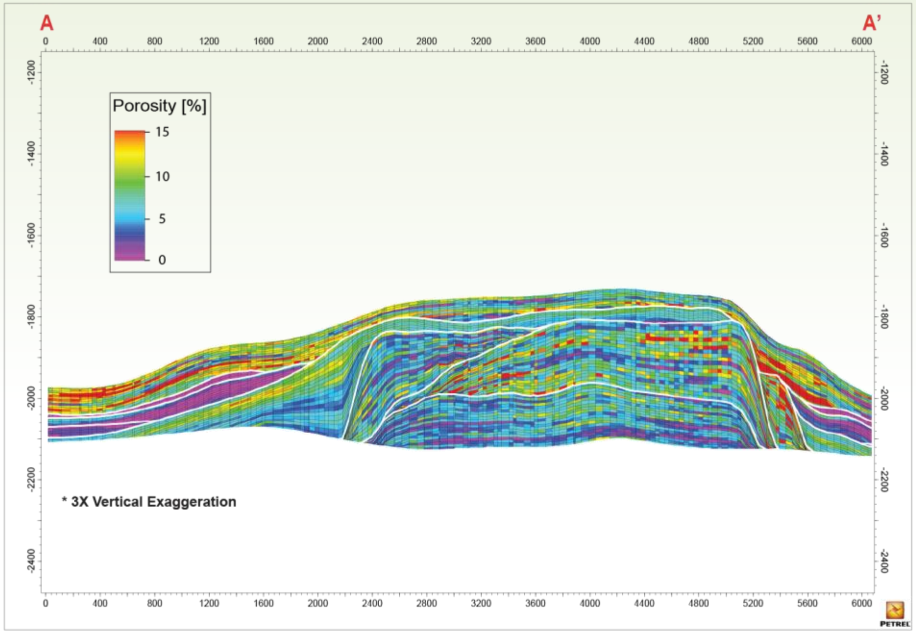
IMPLICATIONS

Case Study #1: Gas Storage



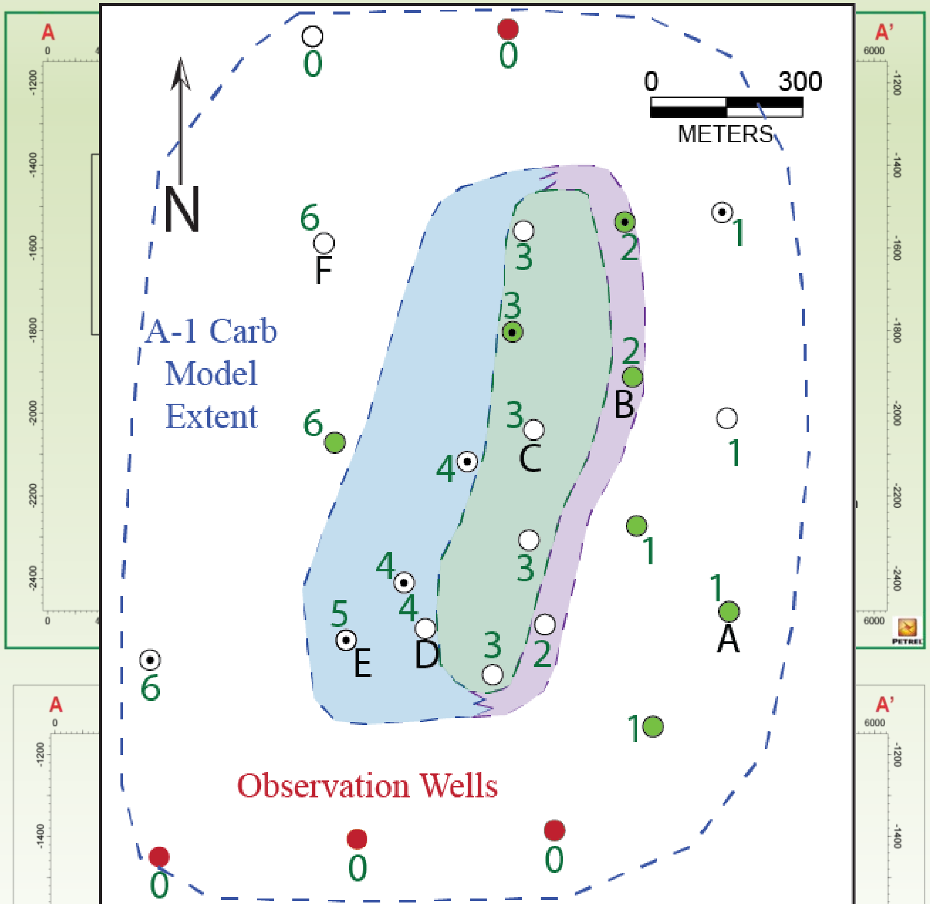


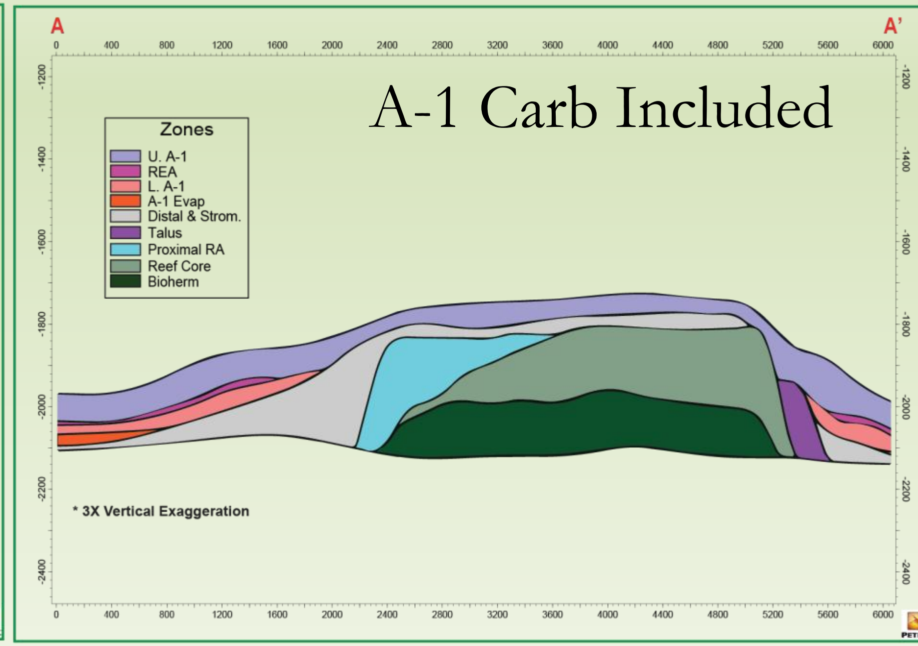


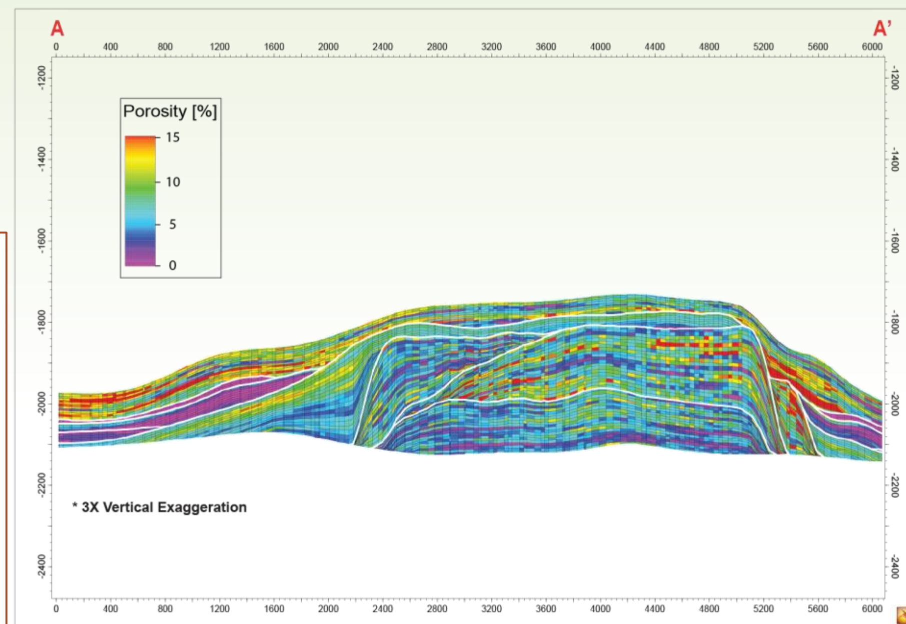


IMPLICATIONS

Case Study #1: Gas Storage







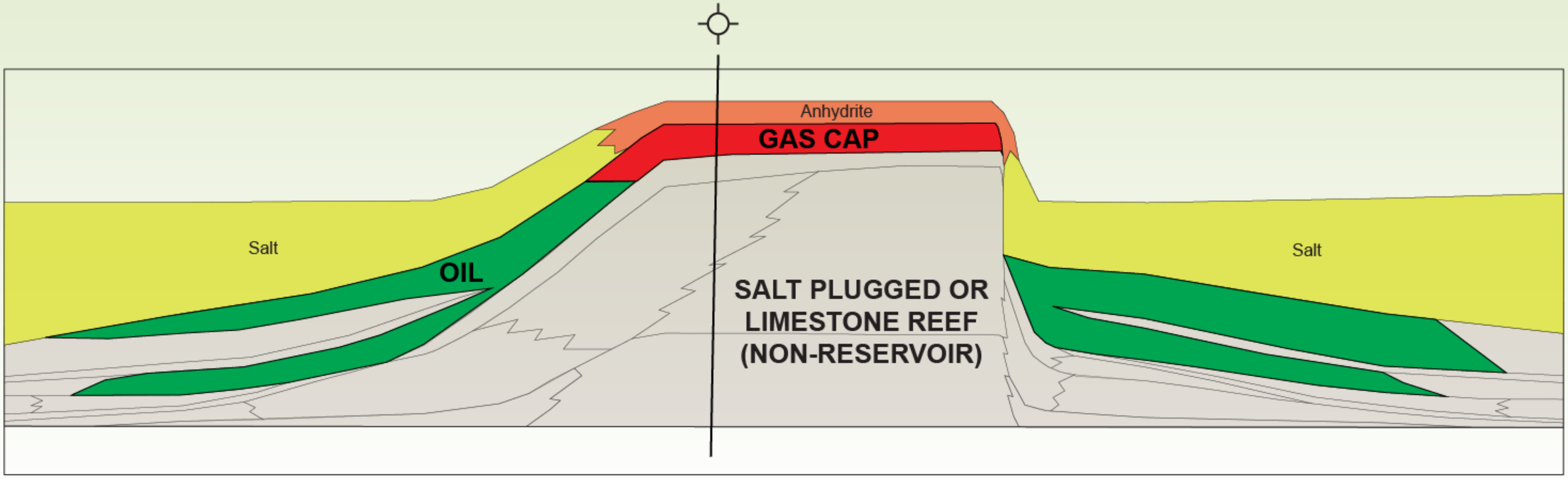
A-1 Carbonate Model still underestimates total pore volume of reservoir when compared to known base and working gas volumes

IMPLICATIONS

Case Study #2: A-1 Conventional

Ex.) Original exploration attempts drill reef crest and only have gas shows in A-1 Carb

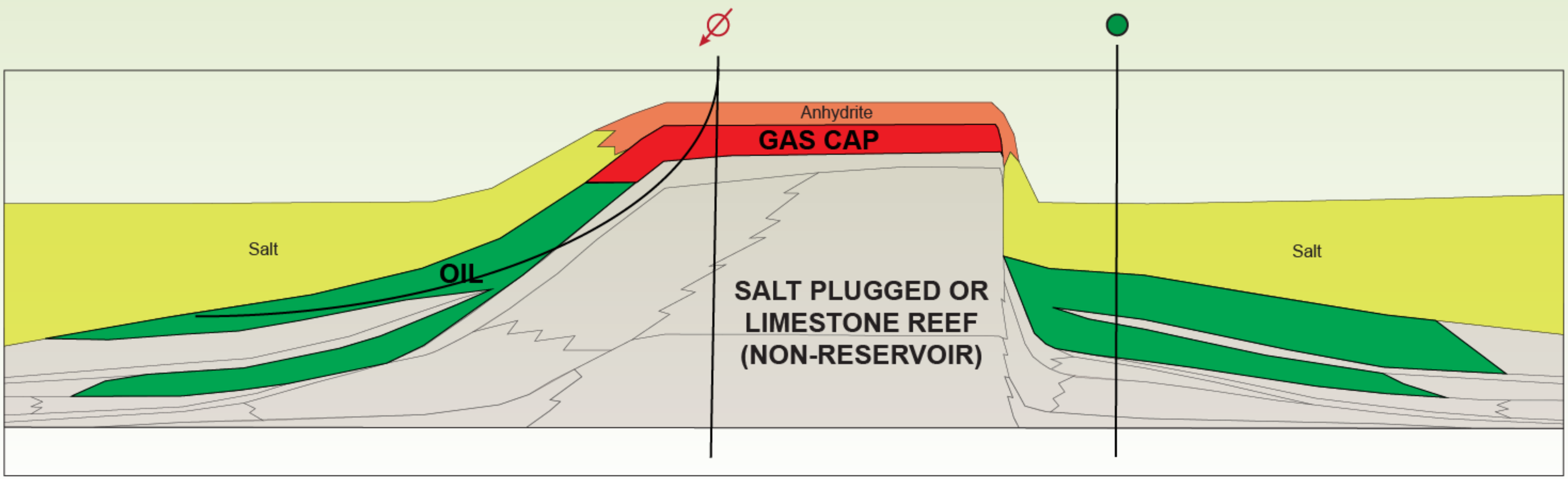
Result: Label entire reef complex as tight limestone, gas reef; Abandon



IMPLICATIONS

Case Study #2: A-1 Conventional

- Potential for banked oil in dolomitized A-1 Carb facies flanking reefs
- Opportunities to use existing boreholes: kick-off, convert to injector



Also potential to explore A-1 Carbonate in inter-reef and basin center localities as an unconventional play

CONCLUSIONS

1. While intertidal to shallow subtidal microbial facies do exist in the A-1 Carbonate, the majority of A-1 Carbonate deposition is **deep water**

2. The "Rabbit Ear Anhydrite" unit is a **time significant event** that resulted in basin-wide restriction and gypsum deposition

3. The A-1 Carbonate is an important reservoir unit within the entire Niagara-Lower Salina Reef Complex Reservoirs and has more potential for **conventional and unconventional exploration**

Thanks

Questions?