

# **The Apparent Stratigraphic Concordance of Reflux Dolomite: New Insights from Synsedimentary Reactive Transport Models\***

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## **Abstract**

Understanding the distribution of dolomite in a sequence stratigraphic framework is a widespread method for interpreting synsedimentary dolomitization and constraining subsurface reservoir models. Early-formed stratiform dolomite bodies are often coincident with cycle caps and, by association, are interpreted to have been generated by equivalent time/space events. The present work shows that stratigraphic surfaces are not necessarily time-equivalent with the early dolomite bodies associated with them. We investigated stratigraphic dolomite patterns using the reactive transport simulator TOUGHREACT to: 1) evaluate the geological, hydrological and chemical controls on the reflux dolomitization of a high-frequency cycle, and 2) explore intra- and inter-cycle episodic brine reflux during the consecutive deposition of three high-frequency cycles.

Experiments were based on partially dolomitized cycles of a Cretaceous Glen Rose Formation outcrop in central Texas. Results demonstrate that refluxing brines, with salinities up to gypsum saturation, were capable of dolomitizing a high-frequency cycle to a depth of 1.5 m beneath the cycle top in 450 years; underlying cycles to a depth of 100 m were fully dolomitized in 2,500 years. Simulations of episodic brine reflux during the deposition of three high-frequency cycles revealed the potential for the complex evolution, migration and convergence of multiple dolomite fronts. The incomplete consumption of Mg along a flow path and the variable rate of dolomitization due to the dolomite “seed-effect” are primarily responsible for this phenomenon. These results suggest that the observed relationships between dolomite patterns and sequence stratigraphic surfaces may be casual, which has significant implications for correlating and building reservoir models. When correlating diagenetic geobodies, we should incorporate our understanding of the hydrogeologic and geochemical regime, as well as the stratigraphic framework.

# **THE APPARENT STRATIGRAPHIC CONCORDANCE OF REFLUX DOLOMITE: NEW INSIGHTS FROM SYNSEDIMENTARY REACTIVE TRANSPORT MODELS**

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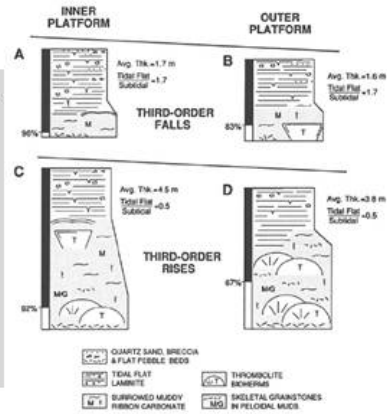
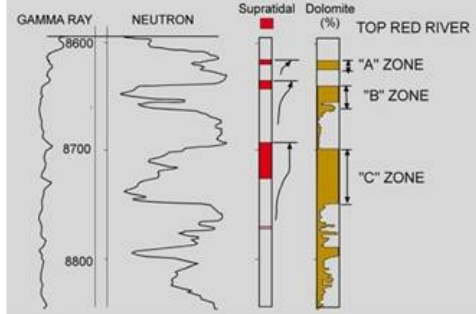
**TIANFU XU**  
*Lawrence Berkeley National Lab*



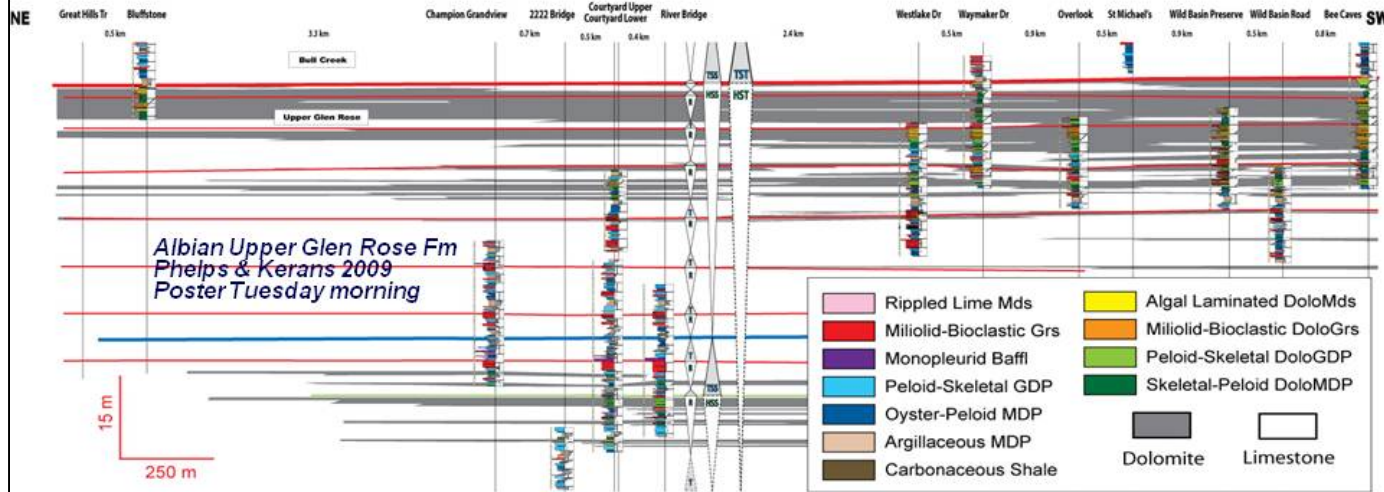
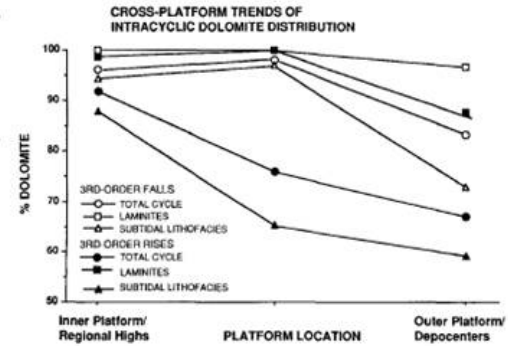
- Many hydrocarbon reservoirs are in dolomitized carbonates
- We use sequence stratigraphy to predict dolomite distribution and reservoir quality
- We are going to show that some of the predictive paradigms may be outdated, and propose new concepts that may help improve predictions

# Sequence stratigraphy and dolomitization

Mid Ordovician Red River Fm  
Clements 1985



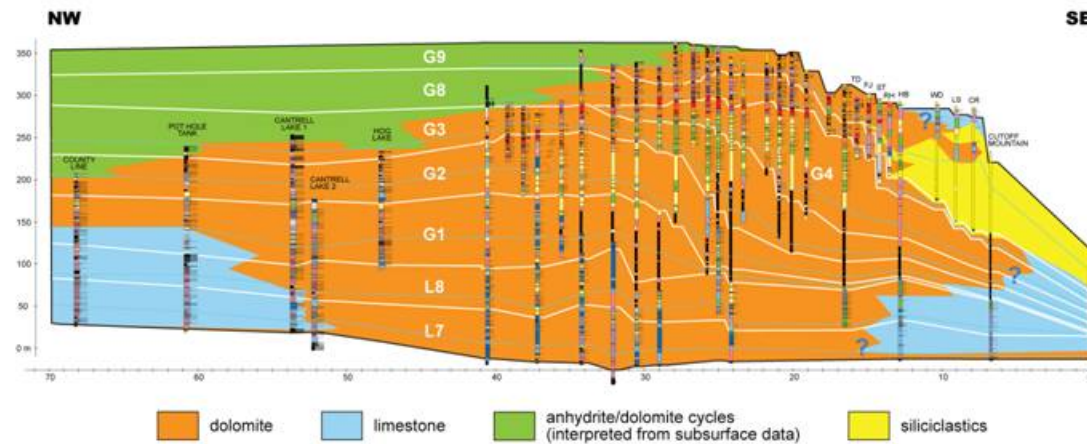
Ordovician Upper Knox Gp  
Montañez & Read 1992



- We use sequence stratigraphy to understand and predict the distribution of dolomite in formations and reservoirs
- We relate the location of dolomite bodies to time lines and facies boundaries
- Red River Fm example:
  - dolomite occurs below sequence boundaries
  - dolomite volume increases with increasing peritidal facies proportions
- Knox Gp example:
  - Dolomite volume increases in the inner ramp and in the HST, compared to the outer ramp and the TST
- U Glen Rose Fm example:
  - Illustrates the features summarized on the examples above
- This is the example we used on this study



# Sequence stratigraphy and dolomitization



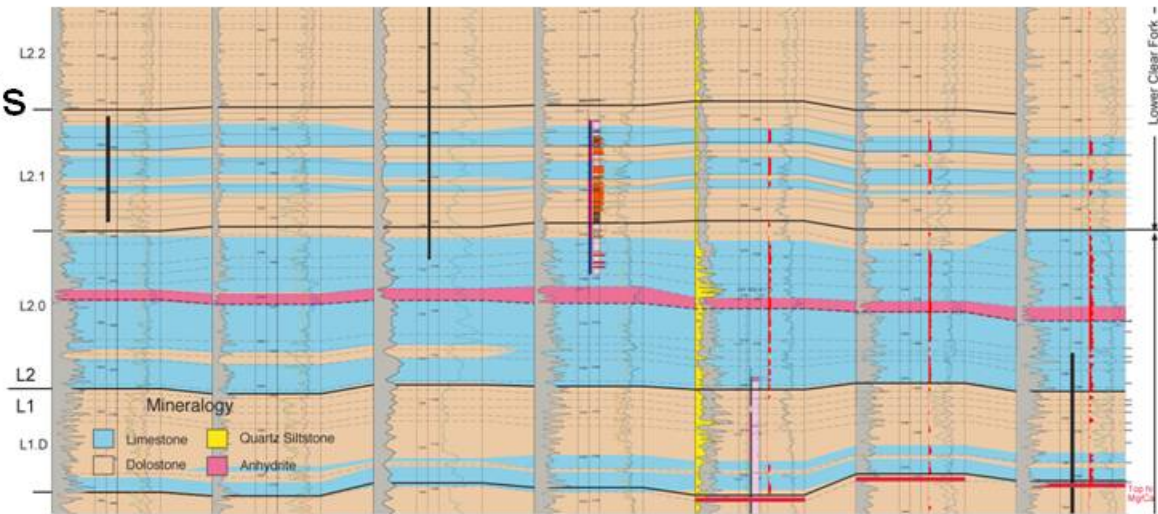
- Pervasively dolomitized

*Permian San Andres Fm,  
Algerita Escarpment, TX  
& NM*

*Garcia-Fresca, Lucia &  
Kerans, in preparation*

- Anhy-Lms-Dls succession!

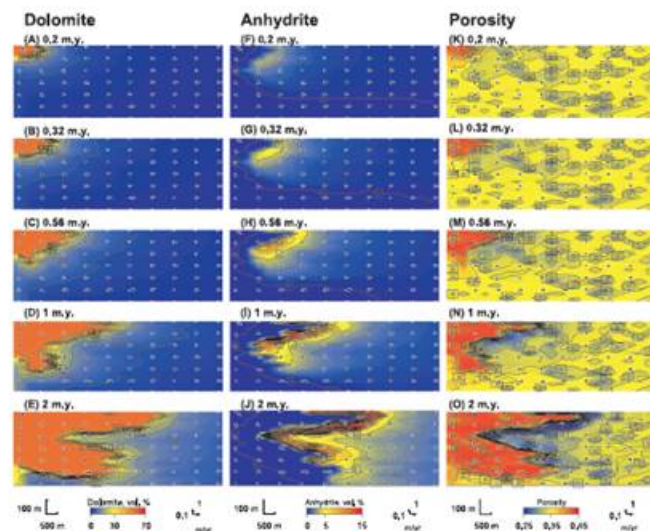
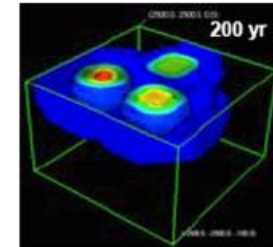
*Permian Clearfork Fm,  
Dollarhide field, TX  
S. Ruppel, BEG,  
unpublished data*



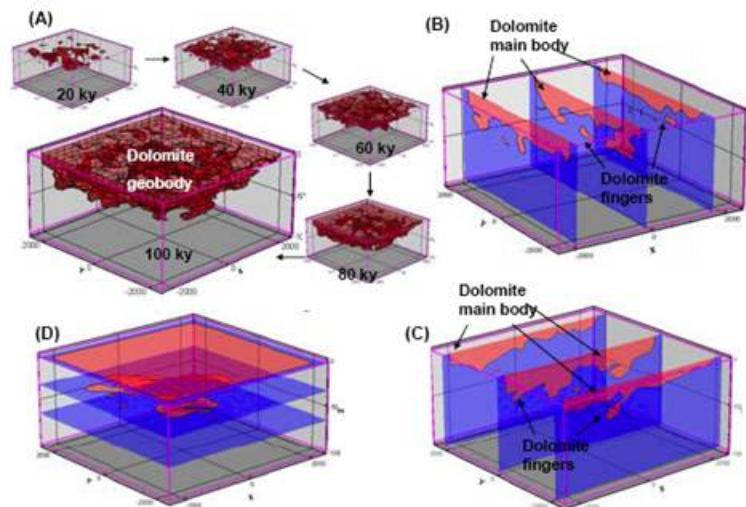
- But there are times where these simple rules are not helpful
  - San Andres Fm example: stratigraphy is pervasively dolomitized and we cannot discriminate the relation between dolomite bodies and stratigraphic surfaces
- Some distributions appear to violate the paradigm
  - Clearfork Fm example: anhydrite-rich deposits are often interpreted as the source of dolomitizing fluids, thus it doesn't make sense to find limestone below anhydrite in this partially dolomitized succession.
- We propose to explore these questions using PROCESS-BASED REACTIVE TRANSPORT MODELS

# Reactive Transport Models - previous efforts

- Explore
  - dolomite distribution
  - sulfate cements
  - porosity evolution
- Brine source at unique stratigraphic surface
- Generic stratigraphy/porophysical properties



Jones & Xiao 2005



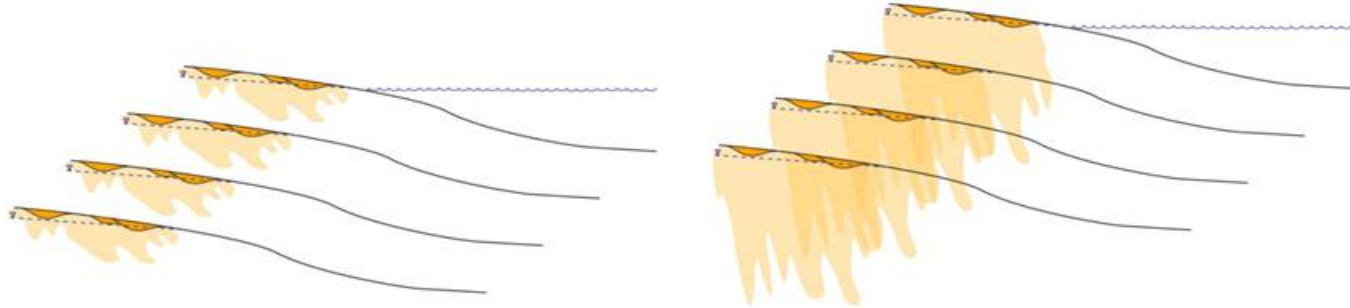
Xiao & Jones 2007

- RTM has been previously used to study reflux dolomitization to explore
  - Dolomite distribution
  - Sulfate cements
  - Porosity evolution
- These models were simple because
  - Brine source was constrained to a unique stratigraphic surface
  - Oversimplistic stratigraphy and distribution of petrophysical properties



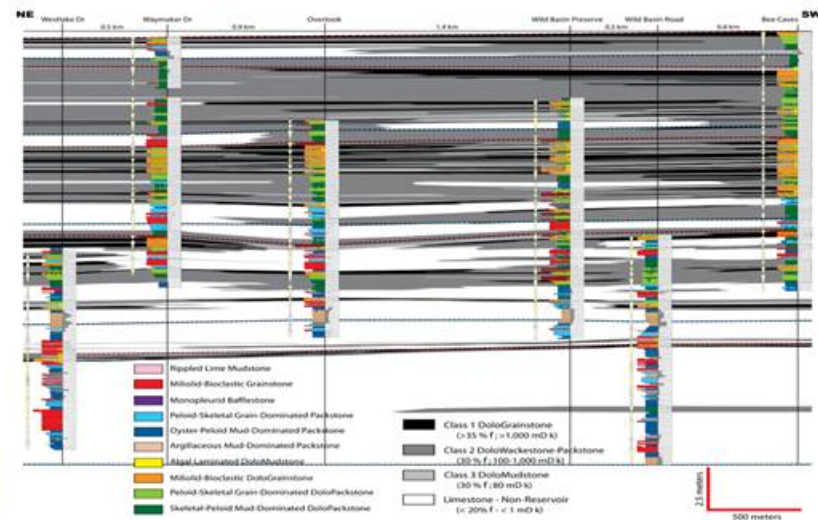
# Reactive Transport Models - this study

- Reflux at high-frequency cycle scale
- Cyclic sedimentation and brine reflux



- Real geologic model:  
Albian U Glen Rose Fm
  - Stratigraphic framework
  - Facies distribution
  - Petrophysical properties

Phelps & Kerans 2009  
Poster Tuesday morning



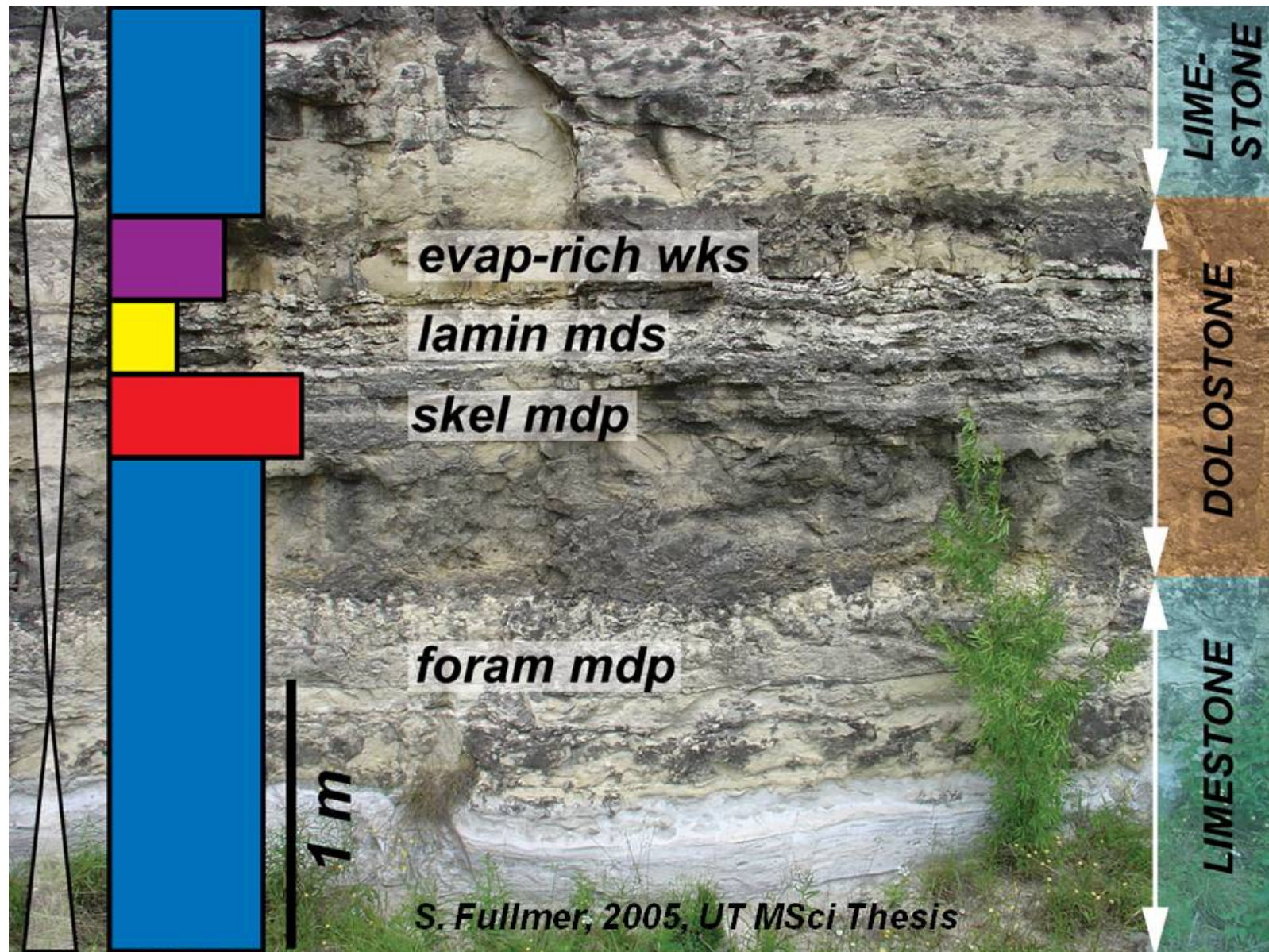
- This study is unique in the following ways:
  - Explores reflux dolomitization at the high-frequency cycle scale
  - Simulates cyclic sedimentation and brine reflux to explore the connection between stratigraphic surfaces and dolomite bodies
  - Uses a real geologic model to constrain boundary conditions, stratigraphic framework and the heterogeneous distribution of petrophysical properties
    - We use outcrop data of the Albian Upper Glen Rose Fm in central TX
    - Point out area covered by this study, partially dolomitized





- This is the particular outcrop covered by this study
- Color banding corresponds to limestone and dolostone intervals
- It has been most recently studied by my colleagues Shawn Fullmer and Ryan Phelps



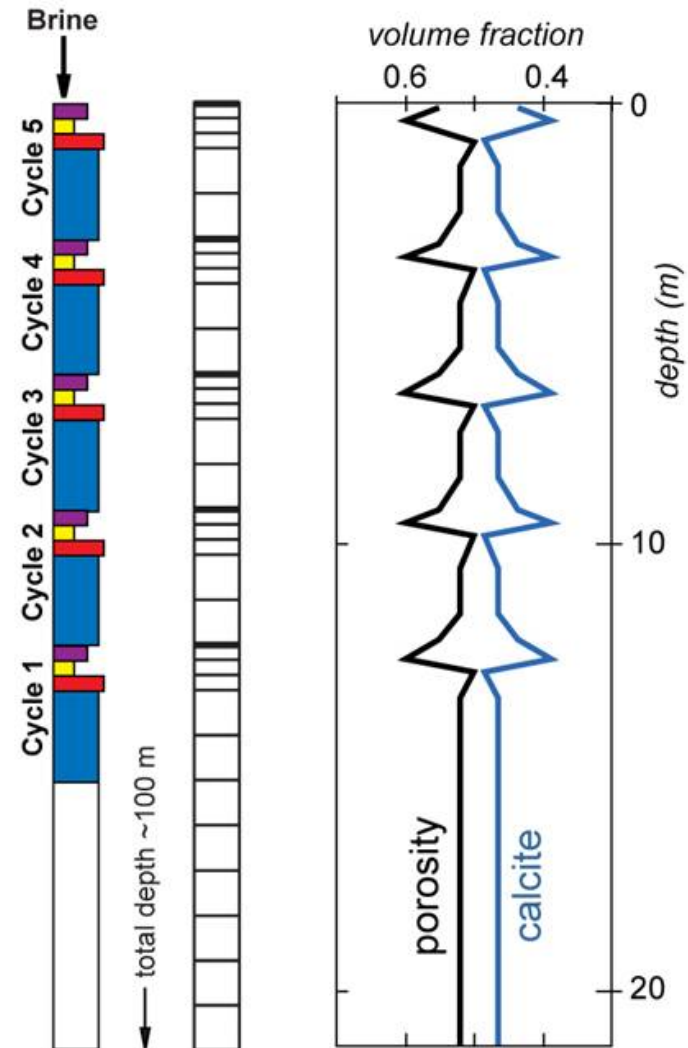


- This particular HFC was the object of study by Fullmer for his MS thesis
- It is approximately 3 m thick and the upper ½ is dolomitized
- It is a succession of muddy facies, ranging from shallow subtidal to peritidal
- The HFC is capped by a evaporite-rich supratidal wackestone that is interpreted as the source of dolomitizing fluids
- Fullmer reconstructed the petrophysical properties of the different facies to their depositional values, based on a rock fabric approach
- Boundary conditions for timing based on bed thicknesses and sedimentation rates



# 1D TOUGHREACT Model

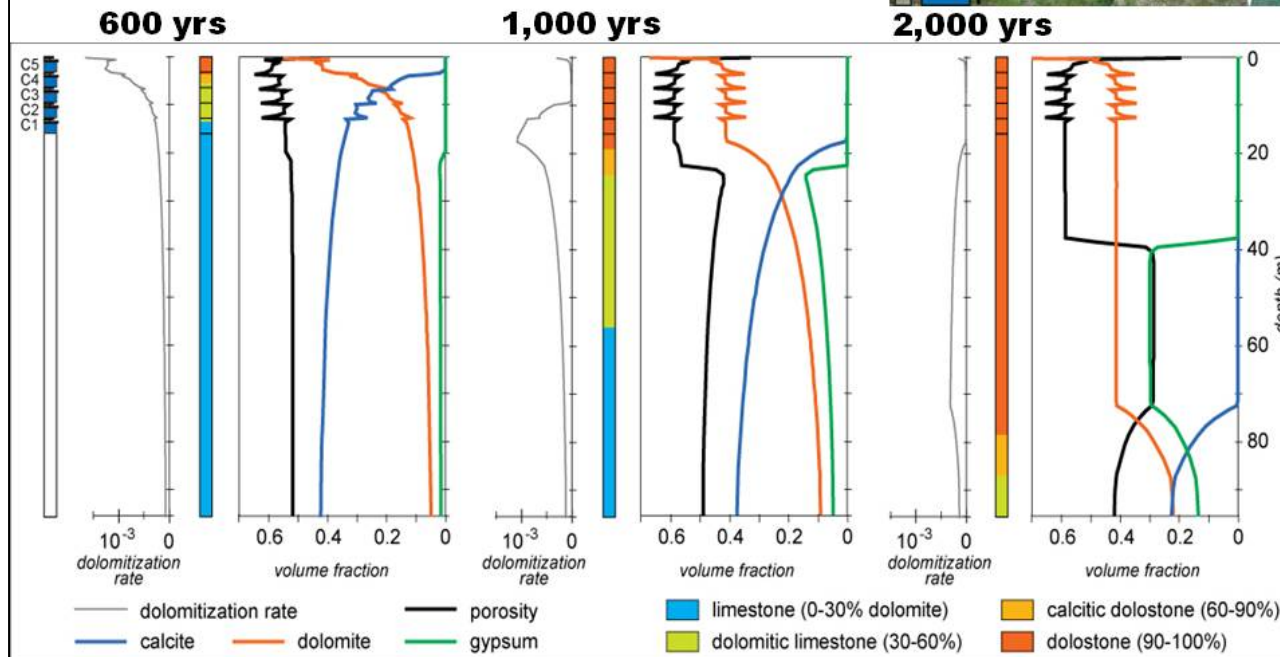
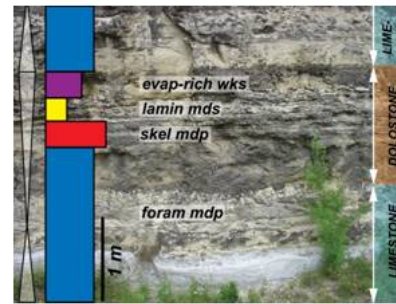
- Grid: 100 cell,  $\sim 1 \times 1 \times 1$  m
- Initial mineralogy
  - 97% calcite
  - 2% dolomite
  - 1% gypsum
- Heterogeneous properties
  - Initial porosity: 0.5-0.6
  - Initial perm: 0.26-2.8 darcy
- Initial pore fluid: seawater in equilibrium with cal, dol & gyp
- Brine: seawater evaporated 4x, unlimited supply
- Flow outlet at bottom
- Isothermal system
- Density-dependent fluid flow
- Por/perm feedbacks



- The model consists of five ideal Glen Rose Cycles, the lower part is a generic limestone
- Grid is arranged based on facies thicknesses
- It is a limestone composed mainly of calcite, saturated with seawater
- Properties are reconstructed by Fullmer
- Muddier facies have higher porosity and smaller volume of calcite.
- The brine enters at the top and has seawater composition, evaporated 4 times

# TOUGHREACT Results

- 1.5 m dolomitized in ~450 yr
- Replacive dolomite increases porosity (5% avg)
- Sulfate cements precipitate/dissolve/precipitate



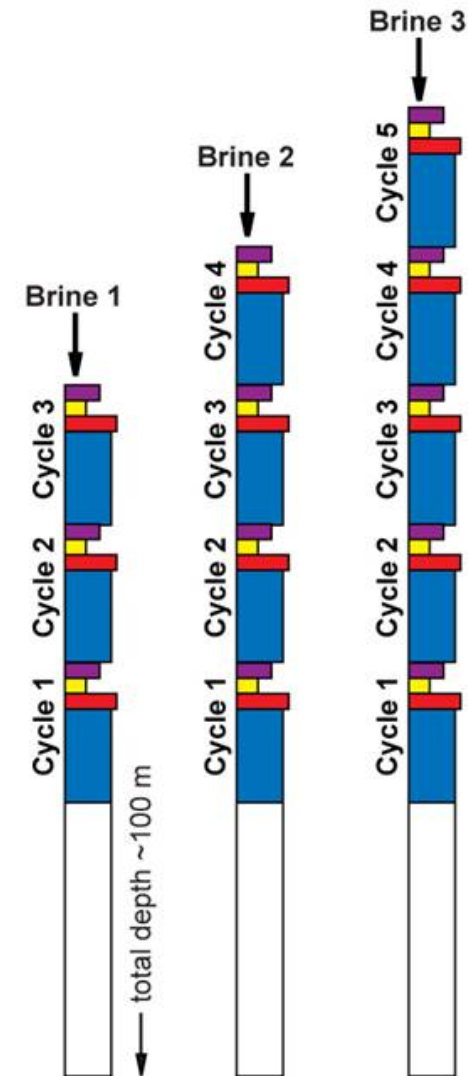
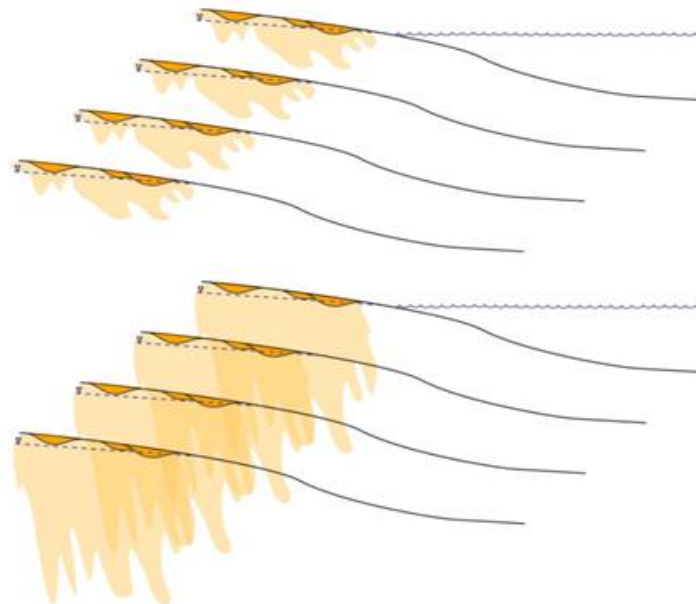
- Three snapshots of the progression of dolomitization
- First diagram represents the conceptual model
- The thin line represents dolomitization rate as the change on the volume of dolomite per year
- The color column represents the percentage by volume of dolomite. Blue is limestone, green is dolomitic limestone, yellow is calcitic dolostone, orange is dolostone
- The colored lines represent abundance by volume fraction of porosity (black), calcite (blue), dolomite (orange), and gypsum (green).
- After 600 yrs of reflux:
  - Top of column dolomitized
  - Fastest dolomitization rates at the very top, exponential decay with depth
  - Calcite has been consumed at the top of the column, replaced by dolomite; cal and dol show a mirror image exponential decay as one is forming at the expense of the other

- Porosity slightly increases with dolomitization
- Some sulfate begins to appear at depth
- After 1,000 yrs of reflux:
  - The very top is 100% dolomitized as expressed by zero dolom rate
  - Highest dolomitization rates occur at the dolom front
  - Cal and dol show a similar mirror image evolution
  - Gypsum cements are prevalent at depth and dramatically affect porosity
- After 2,000 yrs of reflux:
  - Most of the column is dolomitized and thus rates decline
  - Cal and dol show mirror image evolution
  - Gypsum cements have migrated downward, increased in volume, and occlude  $\frac{1}{2}$  porosity in the center of the column



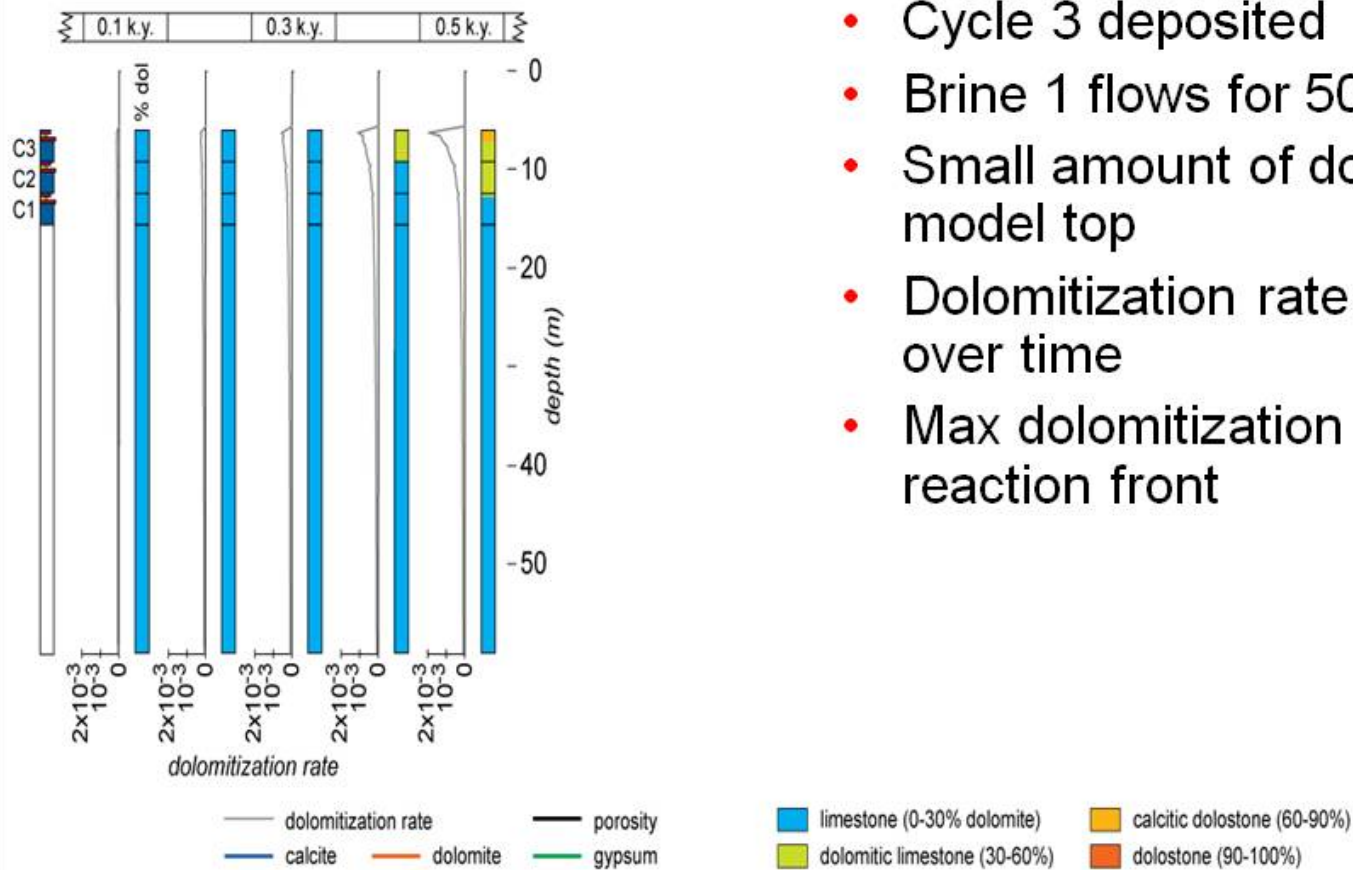
# Dynamic stratigraphy TOUGHREACT model

- Cyclic sediment deposition and brine reflux
- Explore relationship between seq strat surfaces and dolo bodies
- Recreate partially vs. fully dolomitized cycles



- Now we will explore the role of cyclic sedimentation and brine reflux
- We do that by progressively adding a HFC at the top of the model and letting a brine circulate before adding another HFC
- We will try to recreate fully and partially dolomitized cycles, in order to explore the relationship between stratigraphic surfaces and adjacent dolomite bodies.

## Cycle 3 - 500 yr brine reflux

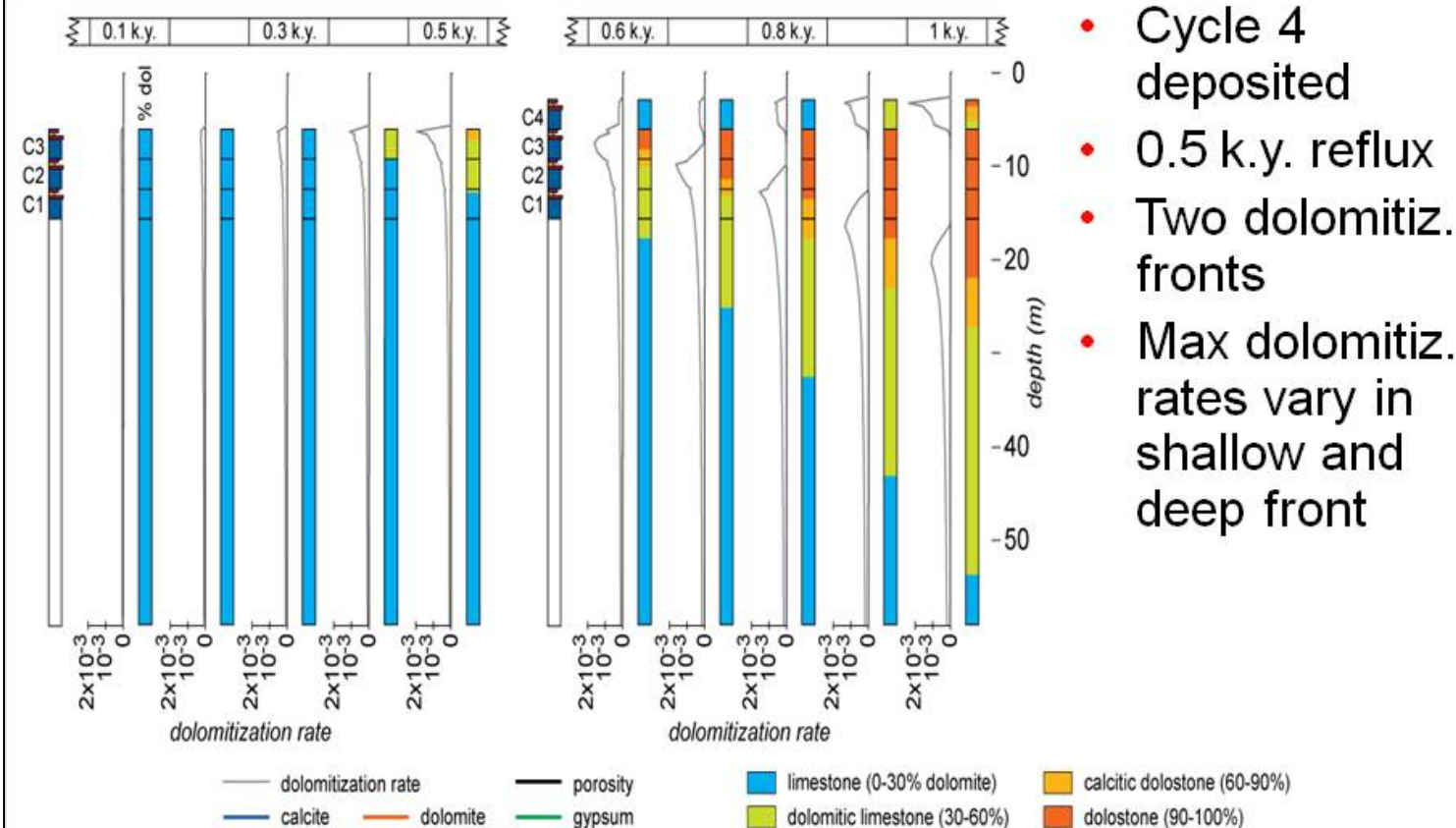


- Cycle 3 deposited
- Brine 1 flows for 500 yr
- Small amount of dolomite on model top
- Dolomitization rate increases over time
- Max dolomitization rate at reaction front

- Diagrams show dolomitization rates (gray curve) and dolomite percentage (color column)
- Cycle 3 is deposited and a brine circulates for 500 years
- At the end of 500 yrs, a bit of dolomite has formed at the top of the model
- Dolomitization rates increase over time, as the dolomite abundance increases and there are more nucleation surface for new dolomite to form.
- At any point in time the maximum dolomitization rate is found at the dolomitization front



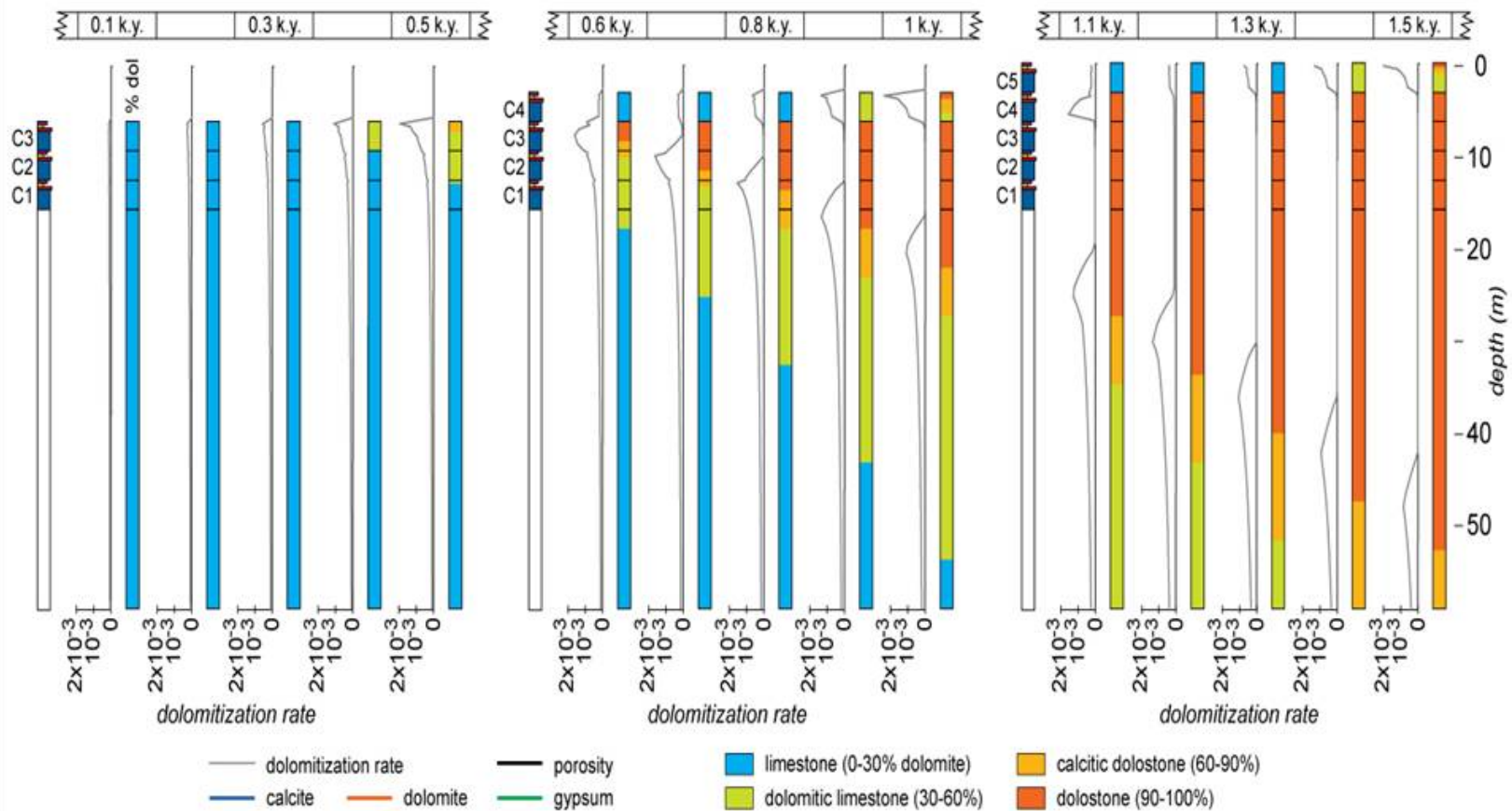
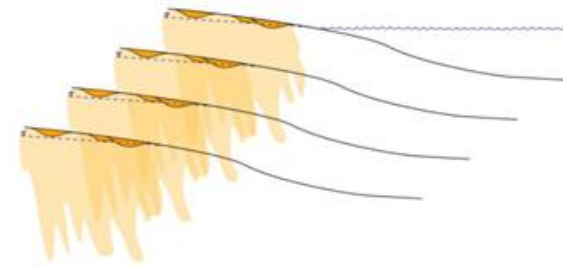
# Cycle 4 - 500 yr brine reflux



- Cycle 4 deposited
- 0.5 k.y. reflux
- Two dolomitiz. fronts
- Max dolomitiz. rates vary in shallow and deep front

- Cycle 4 is deposited: all blue → limestone
- A brine circulates for 500 yrs
- As reflux progresses two dolomitization fronts develop
- Early on fastest rates are found at the deepest dolomitization front
- Later on fastest rates are found at the shallow front
- Dolomite continues to precipitate at depth by the second brine

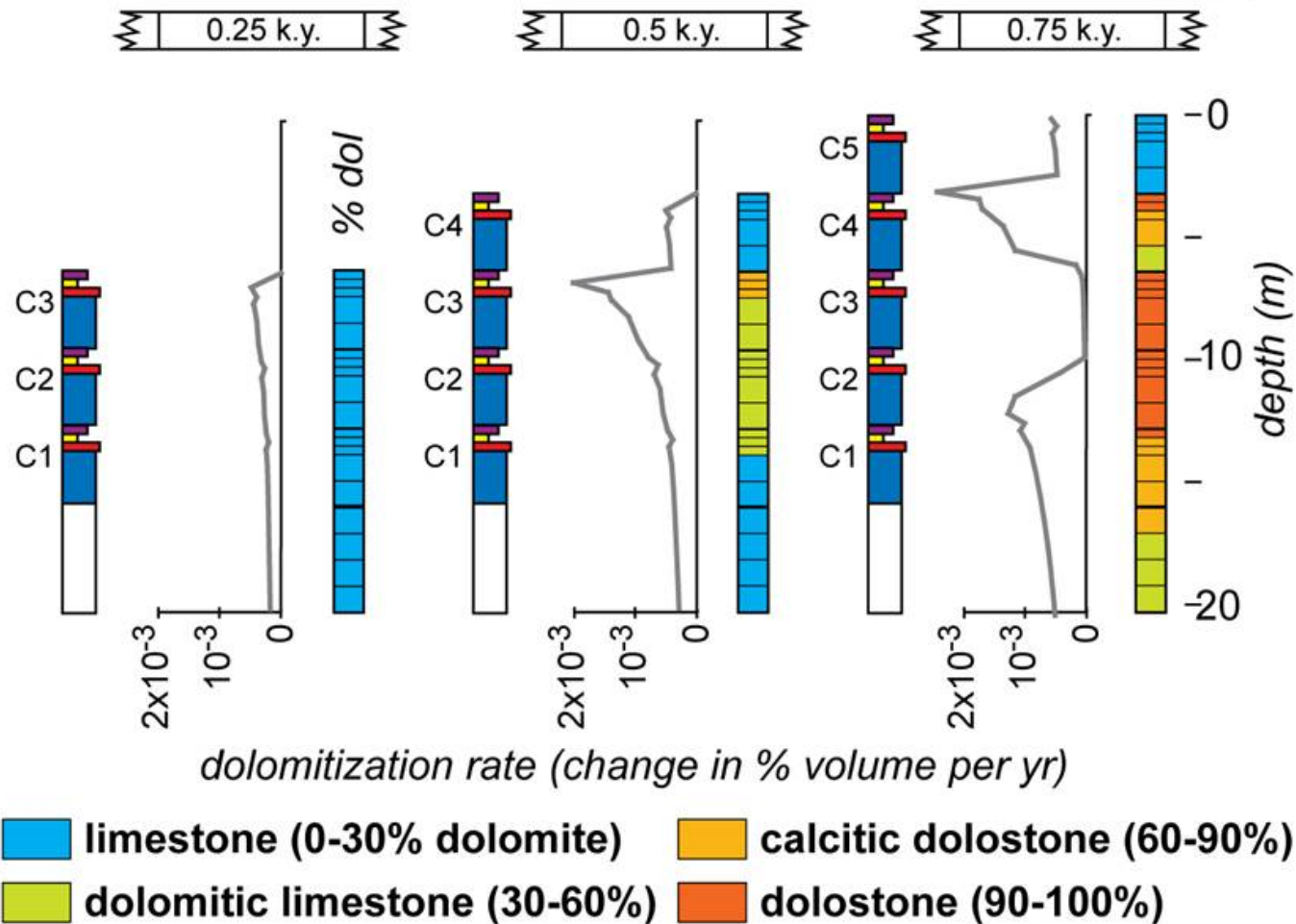
## Cycle 5 - 500 yr brine reflux



- Cycle 5 is deposited
- Brine circulates for 500 yrs
- As reflux progresses we again find two dolomitization fronts
- The deep front seems to be spreading and losing gas as dolomitization progresses
- At the end of the experiment we managed to have a fully dolomitized succession

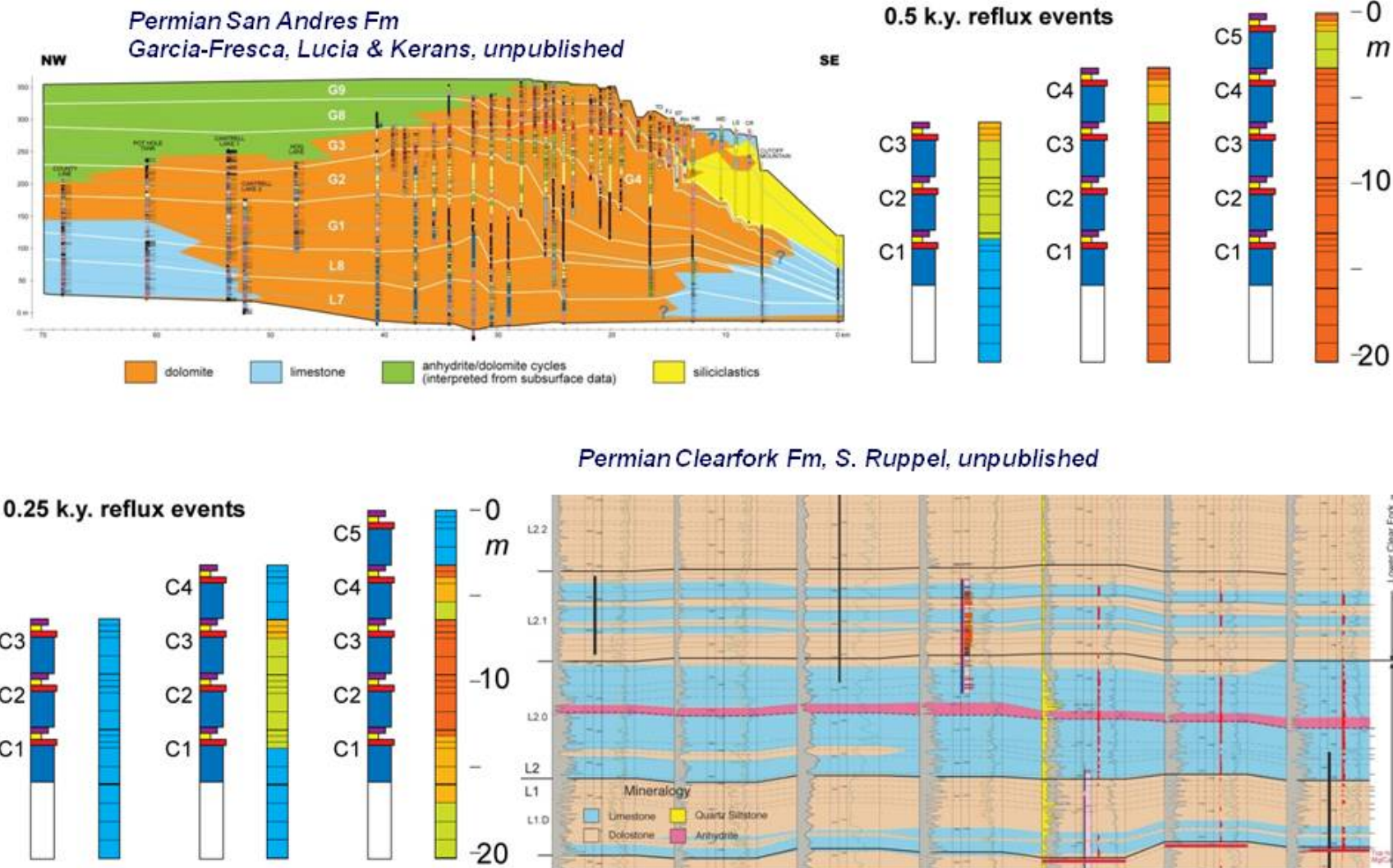


## 3 x 250 yr brine reflux



- We repeated the experiment with shorter reflux events of 250 yr
- At the end of the simulation we observe three dolomitization fronts
- A brine may circulate through the rock without fully dolomitizing it, and yet generate dolomite farther down the section
- We manage to generate partially dolomitized succession
- A HFC may be dolomitized by brines associated with younger cycles
- Field relationships between stratigraphic surfaces and dolomite bodies may be casual and deceiving

# Improve predictions with RTM

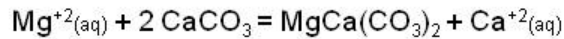


- San Andres Fm example: These experiments allow us to explain the obscure relationship between stratigraphic surfaces in a pervasively dolomitized succession
- Clearfork Fm example: these new concepts allow us to understand partially dolomitized successions and “abnormal” lithology relationships

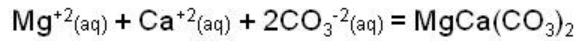


# Dolomitization

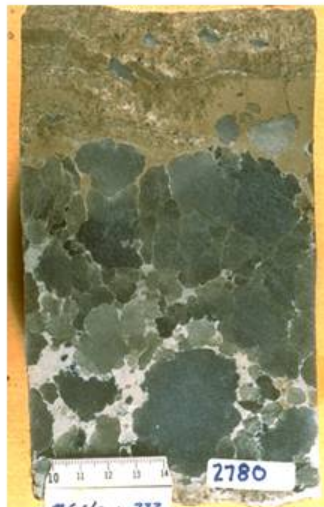
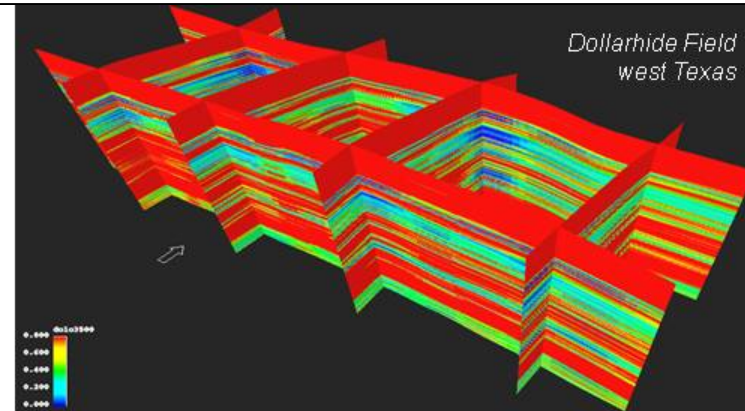
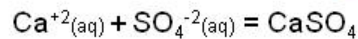
**Replacive dolomite – creates porosity**



**Dolomite cementation – reduces porosity**



**Sulfate cementation – reduces porosity**



nodular anhydrite in dolomite  
San Andres-Grayburg Fm  
(Scholle, 1999)

**PRECURSOR:  
LIMESTONE**

Sedimentology  
Sequence stratigraphy  
Petrography  
Petrophysics  
Geochemistry

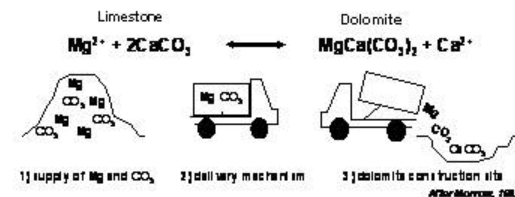
**FLUID/ROCK  
INTERACTION**

**PRODUCT:  
DOLOSTONE**

**FLUID**

Hydrodynamics  
Hydrochemistry

## • Process-based Reactive Transport Models



- Dolomite distribution may be complicated, as in the example of Dollarhide field.
- Dolomitization affects reservoir quality: it may increase or decrease porosity.
  - Dolomite replaces calcite: porosity increases
  - Dolomite cement: decreases porosity
  - Sulfate cements: decrease porosity
- Where does porosity increase and where decrease?
- When studying dolomitization, sometimes we focus on sed, seq strat, petro, petrophysics and geochemistry; but to understand the process as a whole, we need to incorporate the delivery mechanism, the fluid and its interaction with the rock
- Process-based reactive transport models allow us to do this

# Conclusions

- Sequence stratigraphy STILL provides the framework to predict carbonate diagenesis, HOWEVER:
- **Observed relationships between dolomite and stratigraphic surfaces may be casual**
  - A reflux dolomite body may be generated by several brines that flow across time lines and facies boundaries
  - Incomplete consumption of  $Mg^{2+}$  along flow paths cause multiple dolomite fronts to propagate and coalesce into a discrete dolomite body
  - Variations on dolomitization rate are controlled by dolomite abundance or “seed effect”
- Complexity expected to increase in 2D and 3D

### **Selected References**

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