# Icehouse Meteoric (Freshwater) Carbonate Porosity Evolution*

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Abstract

Icehouse carbonate diagenesis is complex. Prolonged subaerial exposure can impart a strong early meteoric-diagenetic signature through a carbonate platform, a consequence of high-frequency high-magnitude sea-level cycles. We have used CARB3D+ to forward-model the evolution of porosity in a generic platform using rates of diagenesis derived from hydrochemical studies of the modern Bahamas (high-stand island) and Guam (uplifted analogue for lowstand island).

There is an apparent contradiction between the significant net dissolution evident from calcium concentrations in modern carbonate groundwaters under all climates (at rates of up to several %/ky according to hydrochemical studies), and the prodigious amount of apparently meteoric cementation in the rock record (with reduction of depositional grainstone porosities of > 45% to limestone porosities of < 35% before burial diagenesis). Using modern rate data for subsurface diagenetic processes, a range of porosities can be simulated depending upon assumptions made regarding both hydrological routing of waters through the vadose zone and the character of freshwater-lens diagenesis. However, using most realistic scenarios, it is difficult to simulate pre-compaction porosity values of less than 60%. Only by specifying an external input of calcium carbonate at least equal to the amount discharged from the meteoric system can geologically reasonable porosities be modeled. The most plausible input into the open-system is calcium carbonate derived from land-surface dissolution, and we explore implications of reprecipitation within the vadose zone and freshwater lens. Because the source of this surface-derived carbonate is missing from the rock record, only by forward modeling and examining the rock record for evidence of missing section can we explore this process and its importance for subsurface porosity evolution.

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# Predicting <u>meteoric</u> carbonate diagenesis

## Hydrological Zones

### Current Paradigm

**Different meteoric hydrological zones can give different early diagenetic alteration products and rates**

We can forward-model hydrological zones and their associated rates to give us porosity prediction (and broader understanding) of carbonate platforms



VADOSE ZONE

Water Table

FRESH WATER PHREATIC

MIXING ZONE

MARINE PHREATIC
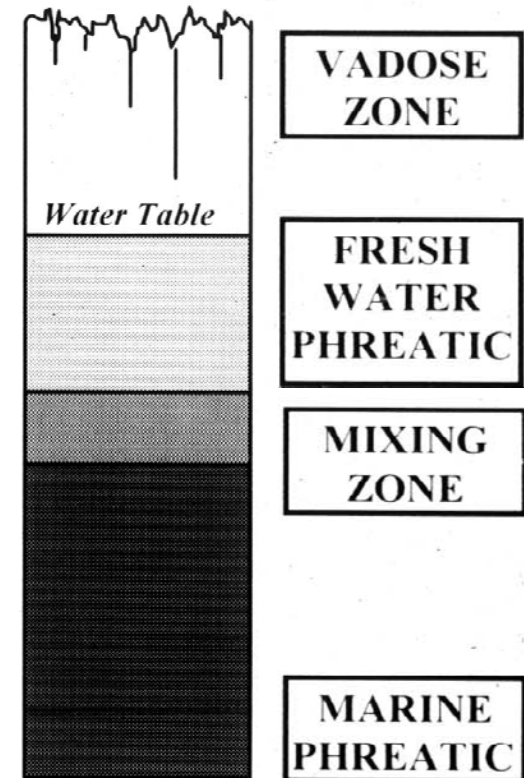
## CARB3D⁺ =

**PROCESS based forward model giving predictions of:**
- Depositional Facies
- Diagenetic Products
- **Porosity and Permeability**

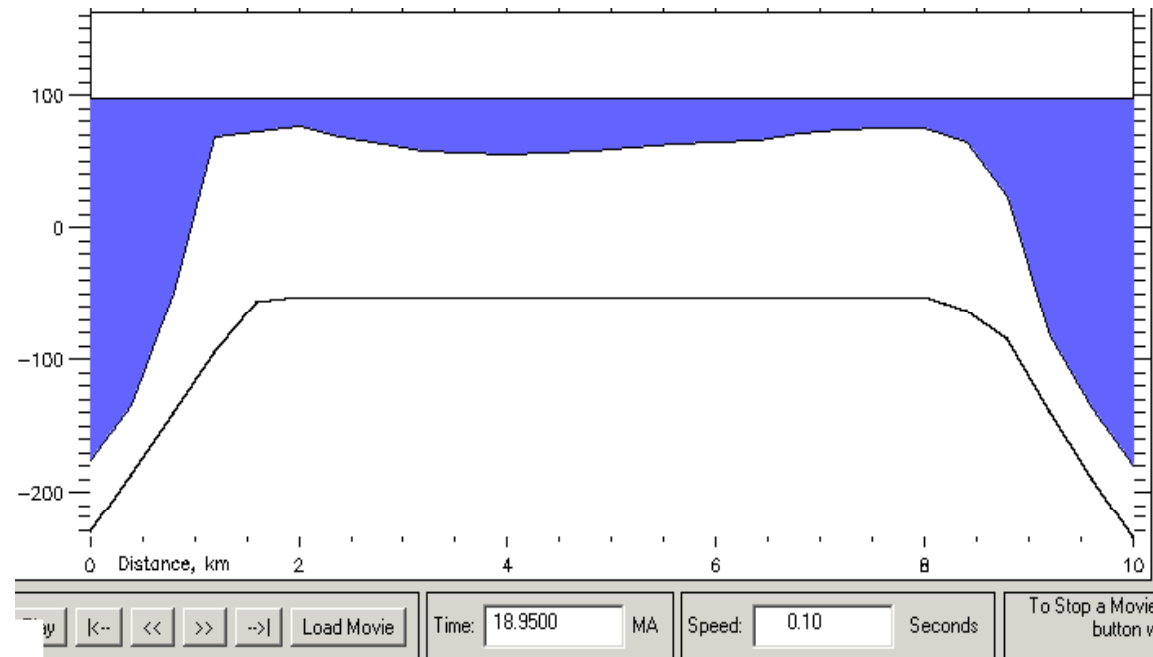# CARB3D⁺ fundamental diagenetic controls
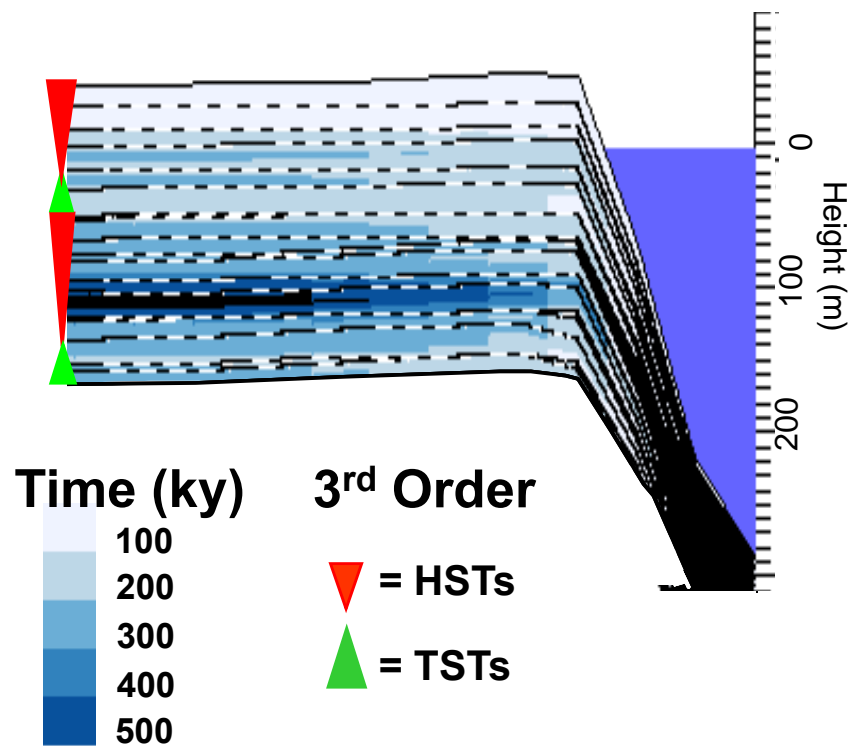
**Hydrozones are Dynamic**



Period simulated in movie

Sea Level Height (m)
Subsidence (m)
Time (My)
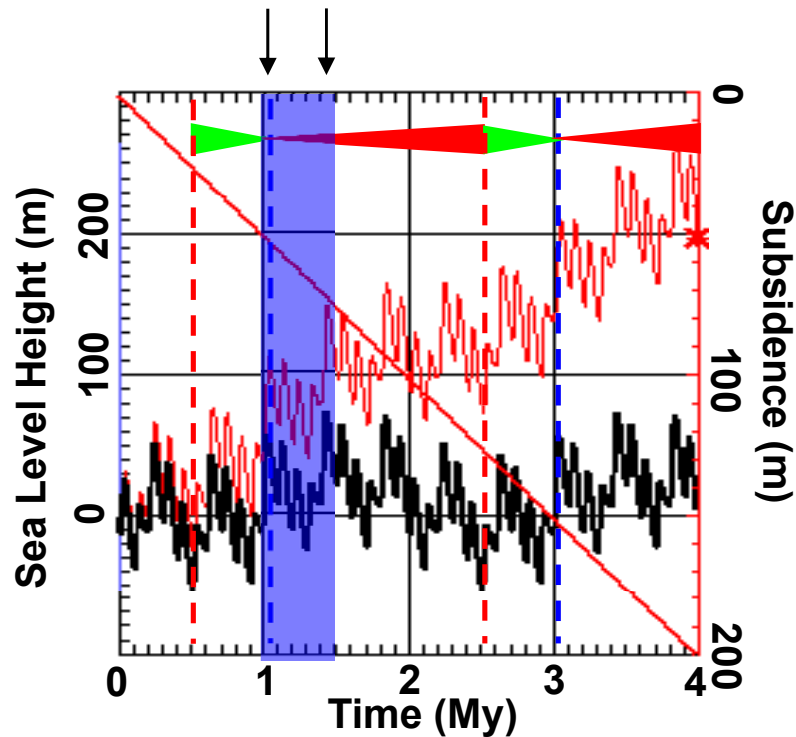
3rd Order
▼ = HSTs
▲ = TSTs

**Early Diagenetic Overprinting**

# CARB3D⁺ fundamental diagenetic controls

**Cumulative Freshwater Lens**
**Residence Time (ky)**



Height (m)

0

100

200

**Time (ky)**

**3ʳᵈ Order**

100
200
300
400
500

▼ = HSTs

▲ = TSTs

**Hydrozone
Residence
Time**

X

**Diagenetic
Rate
of Alteration**

**Diagenetic Modification
Porosity & Permeability**

# How do you measure the rates?



| Rain Water | Soil Water | Cave Drips | Freshwater Lens | Coastal Seep |

**Progressively sample water through the hydrological system**
**Here we are using Guam**

$$Ca_{XS} = Ca_{Sample} - \left( \frac{Ca_{Seawater} \times Cl_{Sample}}{Cl_{Seawater}} \right)$$

**Measure Ca$_{XS}$ from water sample (derived from water/rock interactions)**

**Change in Ca$_{XS}$ × Fluid Flux = Rate of porosity change**
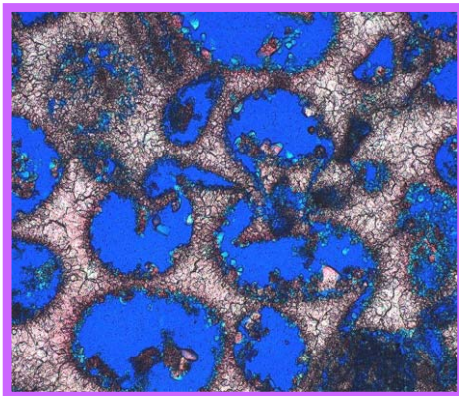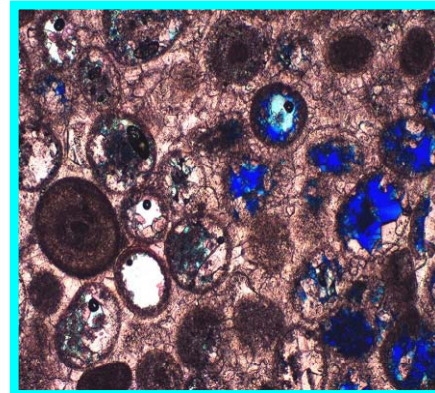
# How Ca$_{XS}$ relates to the rock record

**Grainstone Example**
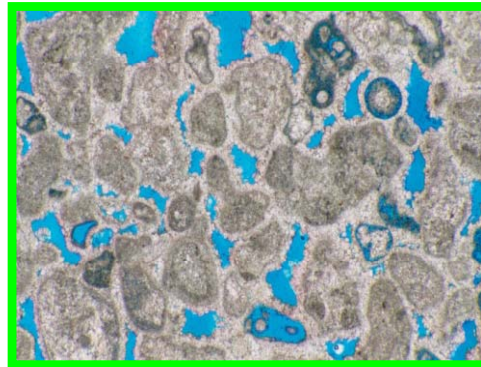


**Near Depositional**

**Δ Increase in Ca$_{XS}$ = dissolution**

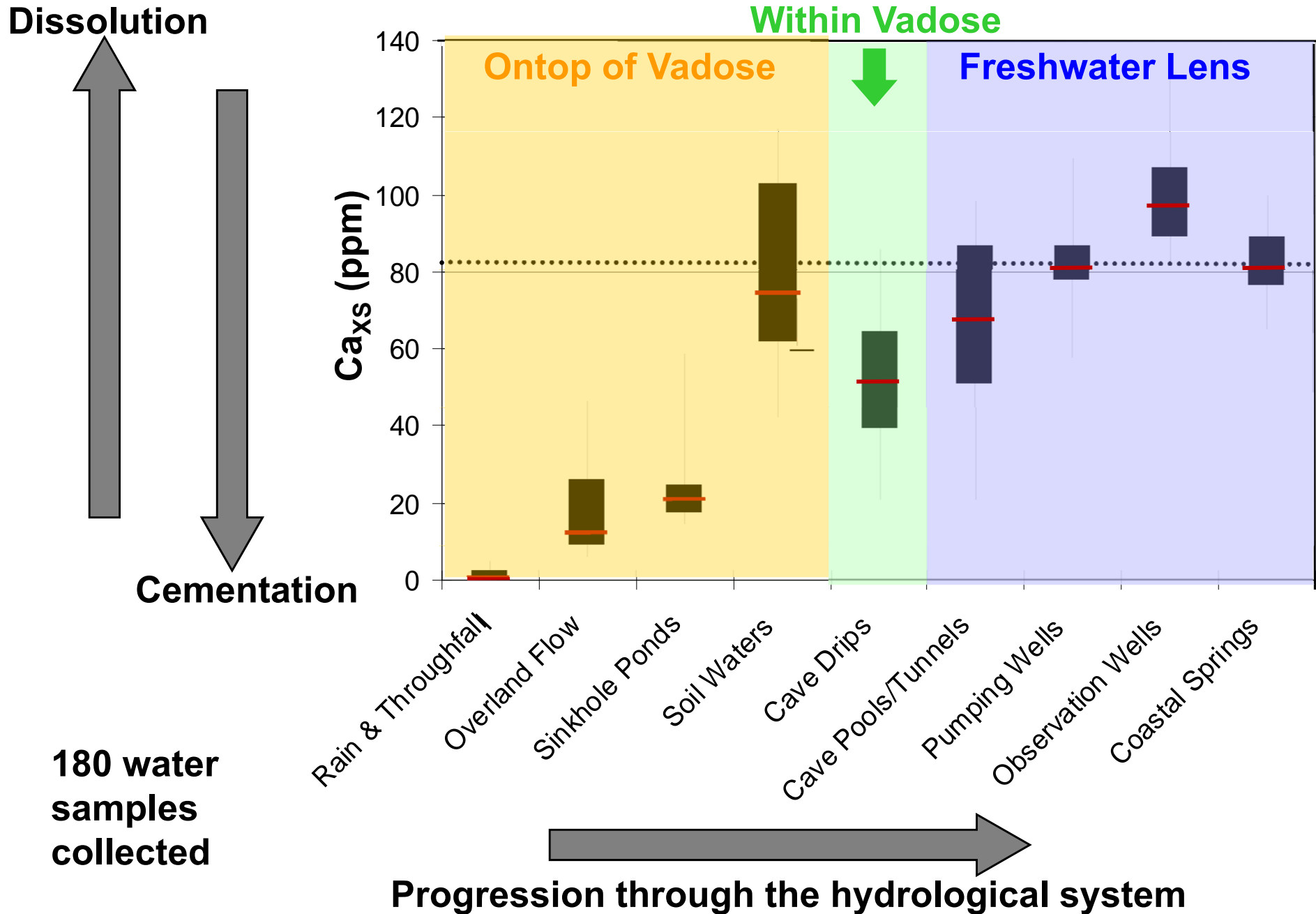**Δ Decrease in Ca$_{XS}$ = cementation**
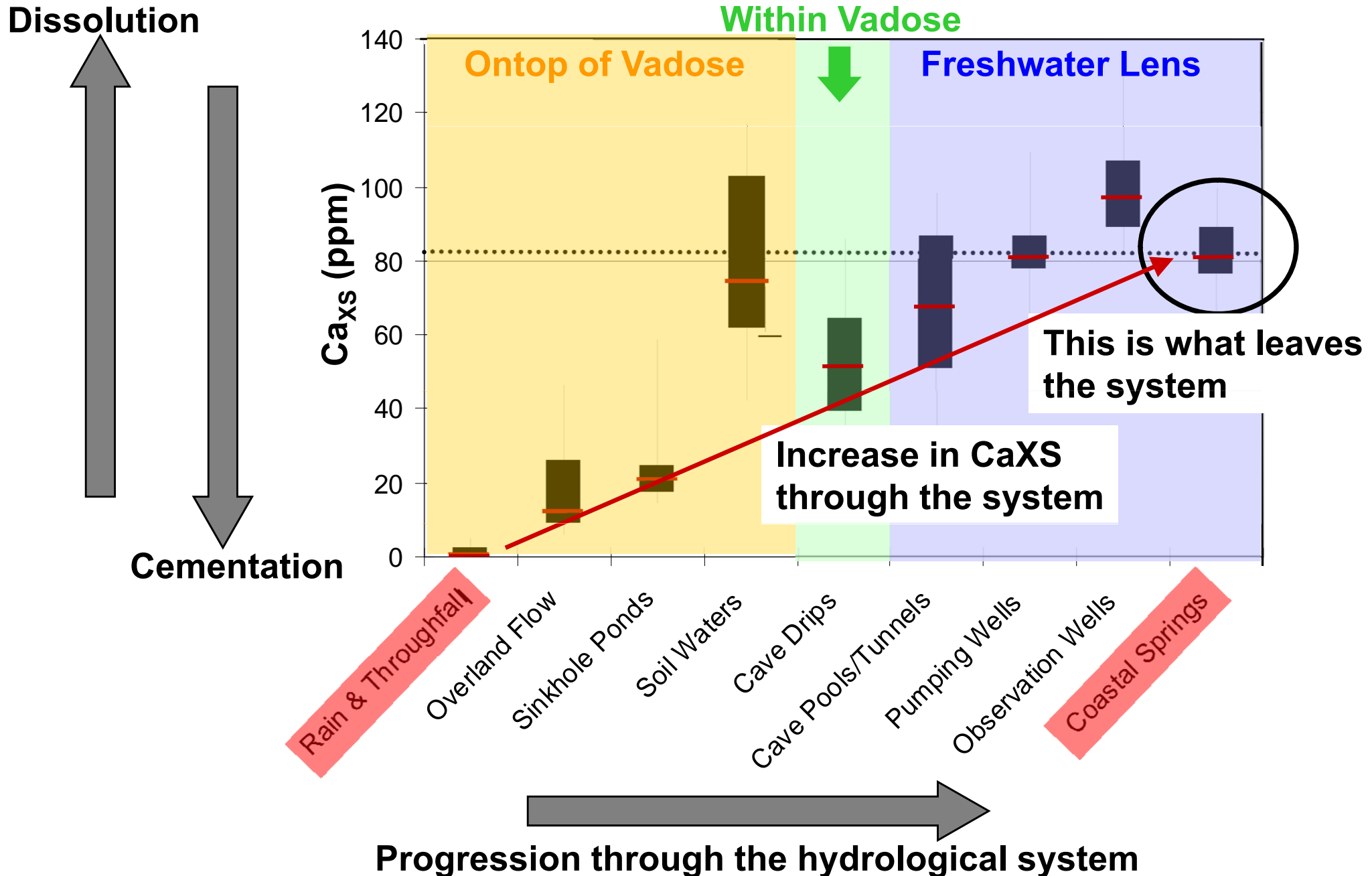


**Heavily Dissolved**



**Heavily Cemented**

**Over time the delta change in Ca$_{XS}$ will reflect porosity change**

# The calcium budget through the system (Guam)

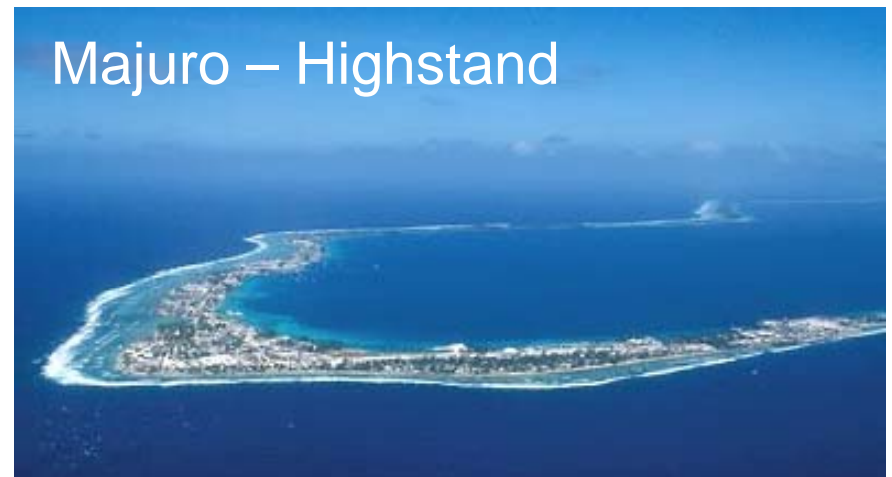# The calcium budget through the system (Guam)

# The calcium leaving the system

| | Guam | Majuro |
|---|---|---|
| Net Ca$_{XS}$ (ppm) | 83 ± 20 | 82 ± 36 |
| Recharge (m/a) | 1.735 | 1.780 |
| Vadose thickness (m) | 60 – 180 | 1 – 3 |
| Net Dissolution (m³/km²/a) | 189 ± 46 | 192 ± 84 |

Guam Data: Whitaker et al. 2006
Majuro Data: Anthony et al. 1989


Guam – Lowstand Analog
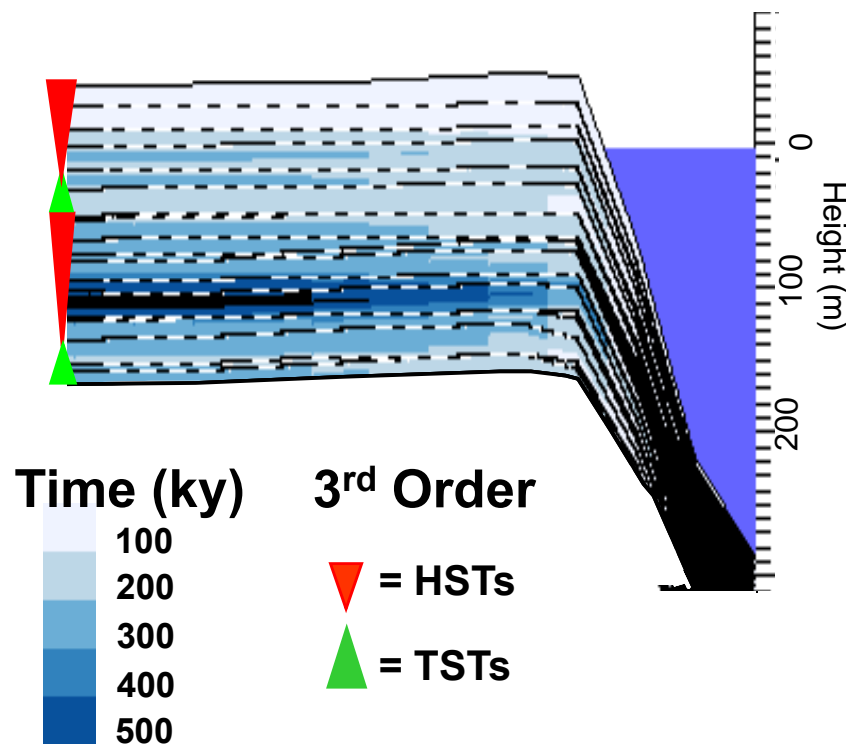

Majuro – Highstand

**Total dissolution on both carbonate islands is large and is independent of sea level change!**

# CARB3D⁺ fundamental diagenetic controls

**Cumulative Freshwater Lens**
**Residence Time (ky)**



Height (m)

0
100
200

**Time (ky)**

| | |
|---|---|
| 100 | |
| 200 | |
| 300 | |
| 400 | |
| 500 | |

**3rd Order**

▼ = HSTs
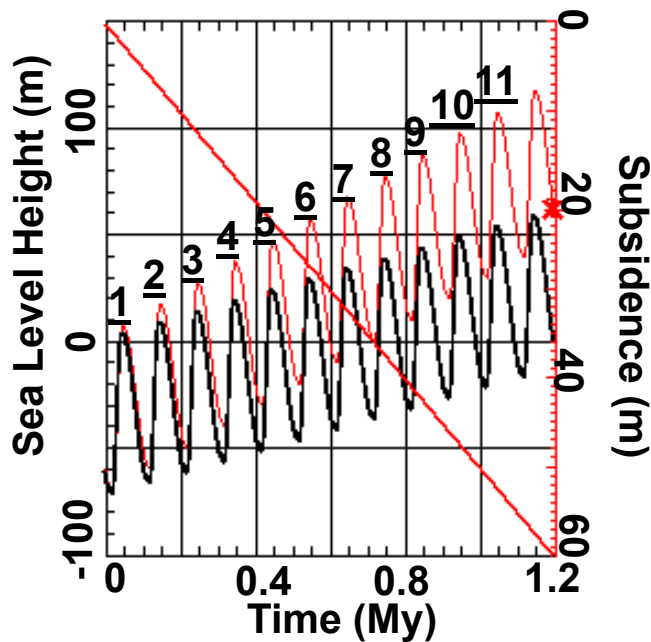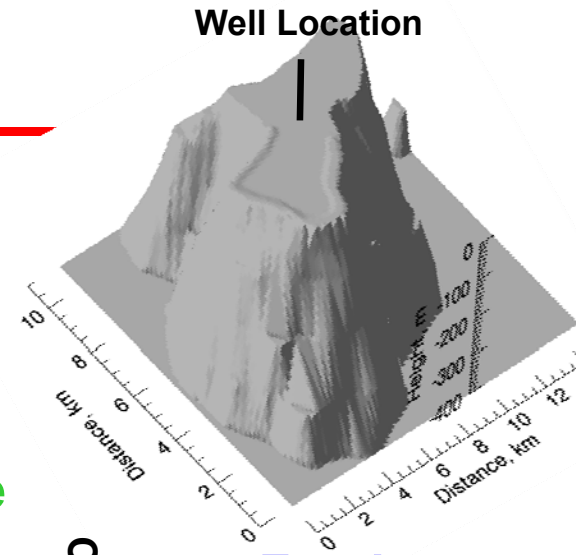
▲ = TSTs

**Hydrozone Residence Time**  **X**  **Diagenetic Rate of Alteration**

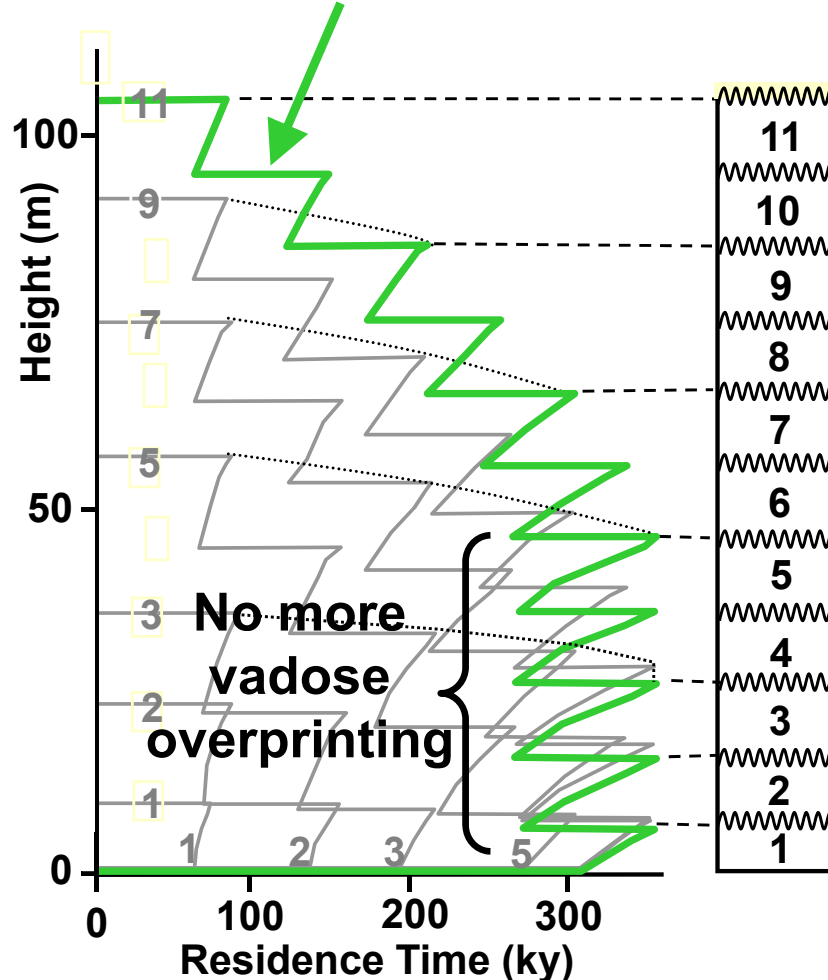**Diagenetic Modification**
**Porosity & Permeability**

# How cumulative hydrozones work

For very simple case, each sequence has 80 ky subaerial exposure, but 350 ky total VZ exposure and 200 ky total FWL exposure



Well Location

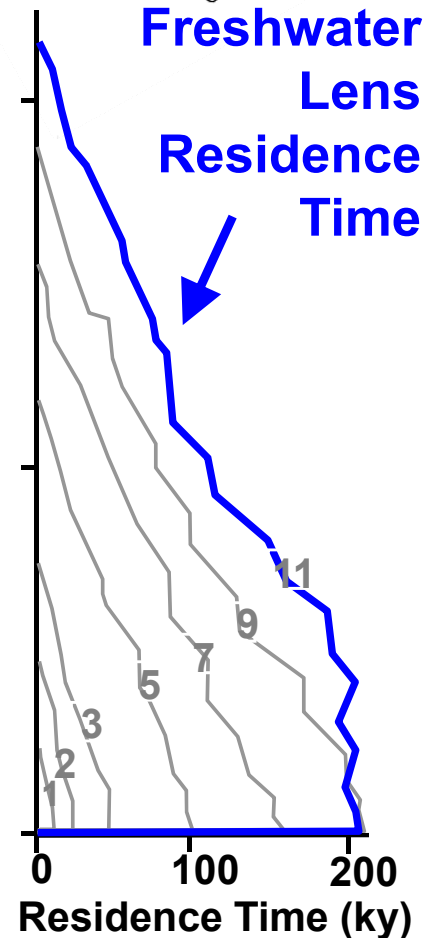Vadose Zone Residence Time

No more vadose overprinting

Sea-level cycles (4th order) 75 m magnitude 100 ky frequency

cf: Paterson et al. 2008

CARB3D+ Interior Platform Pseudo Well-Log

Freshwater Lens Residence Time

Residence Time (ky)

Residence Time (ky)

# The calcium budget via overland flow
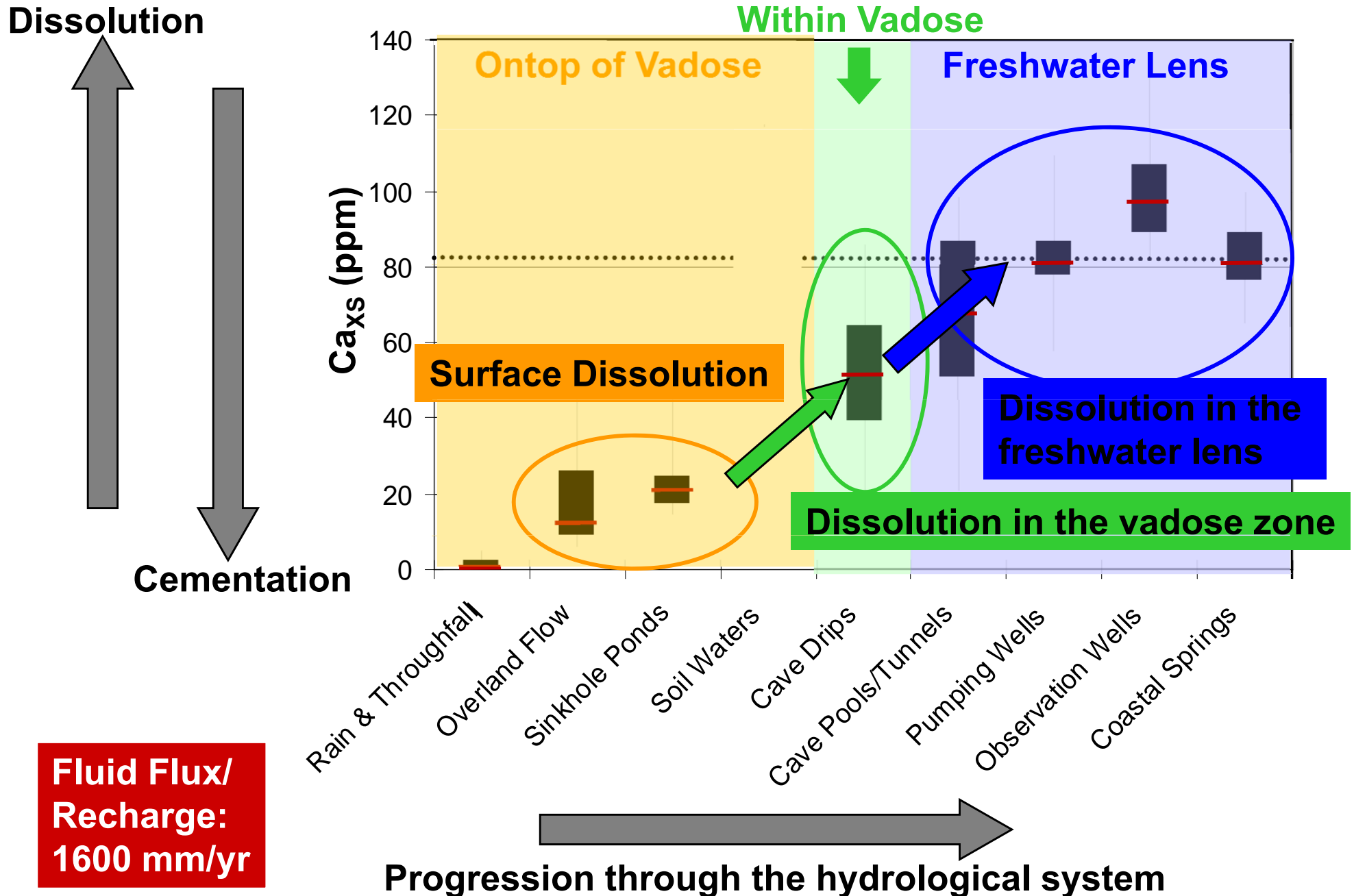
# Guam rate data – recharge removing CaXS

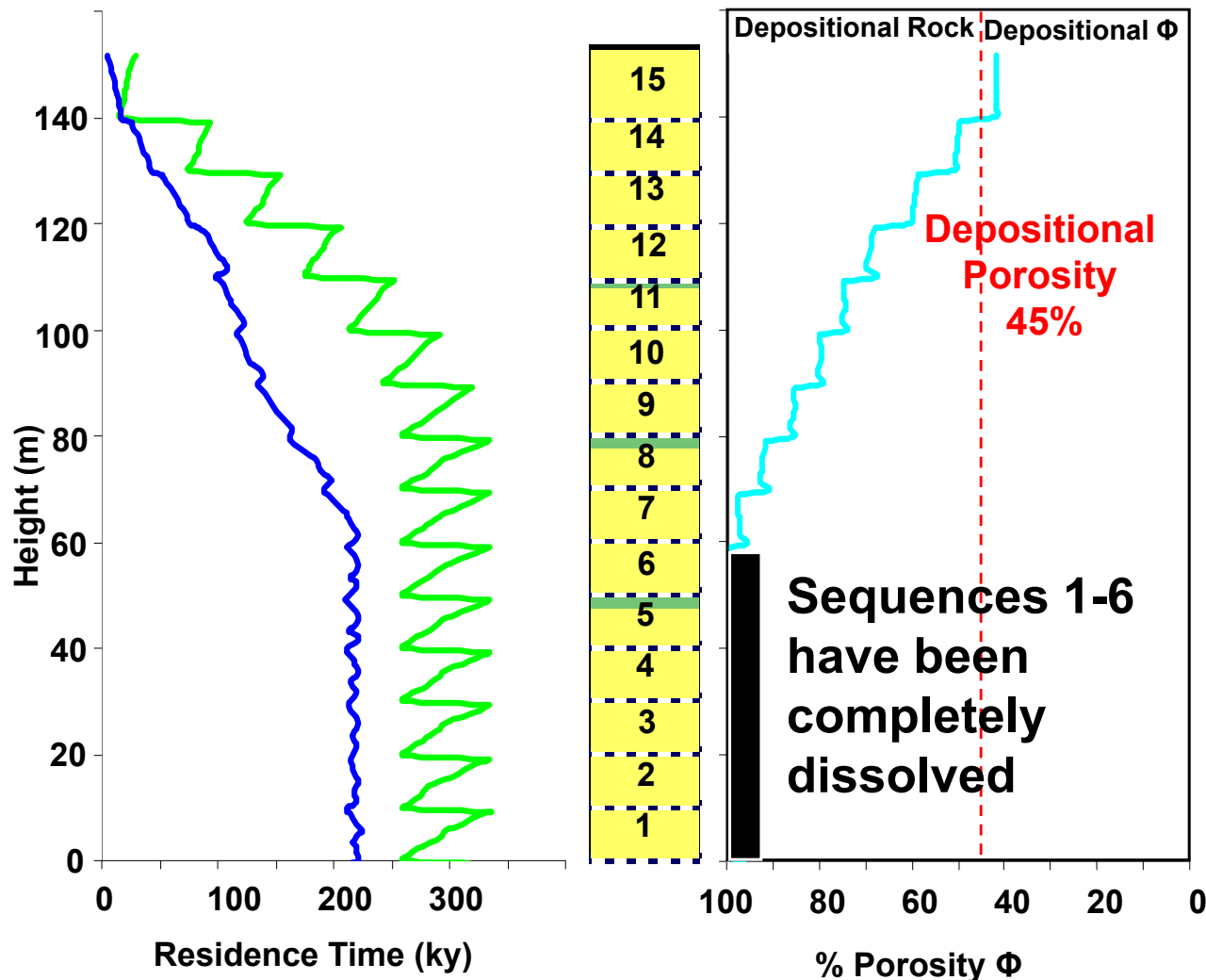**43** mm/ky Surface Dissolution

**Rates are in %/ky**

| | Dissolution | Precipitation |
|---|---|---|
| Vadose Zone | 0.065 | - |
| Freshwater Lens | 0.19 | - |



Depositional Rock

Depositional Φ

**Depositional Porosity 45%**

**Sequences 1-6 have been completely dissolved**

**Height (m)**

**Residence Time (ky)**

**% Porosity Φ**

**Overall dissolution and removal of the platform (over geological time scales – 1.5 m.y. run ≈ 0.5 m.y. of meteoric Interaction)**
**1) Little from surface**
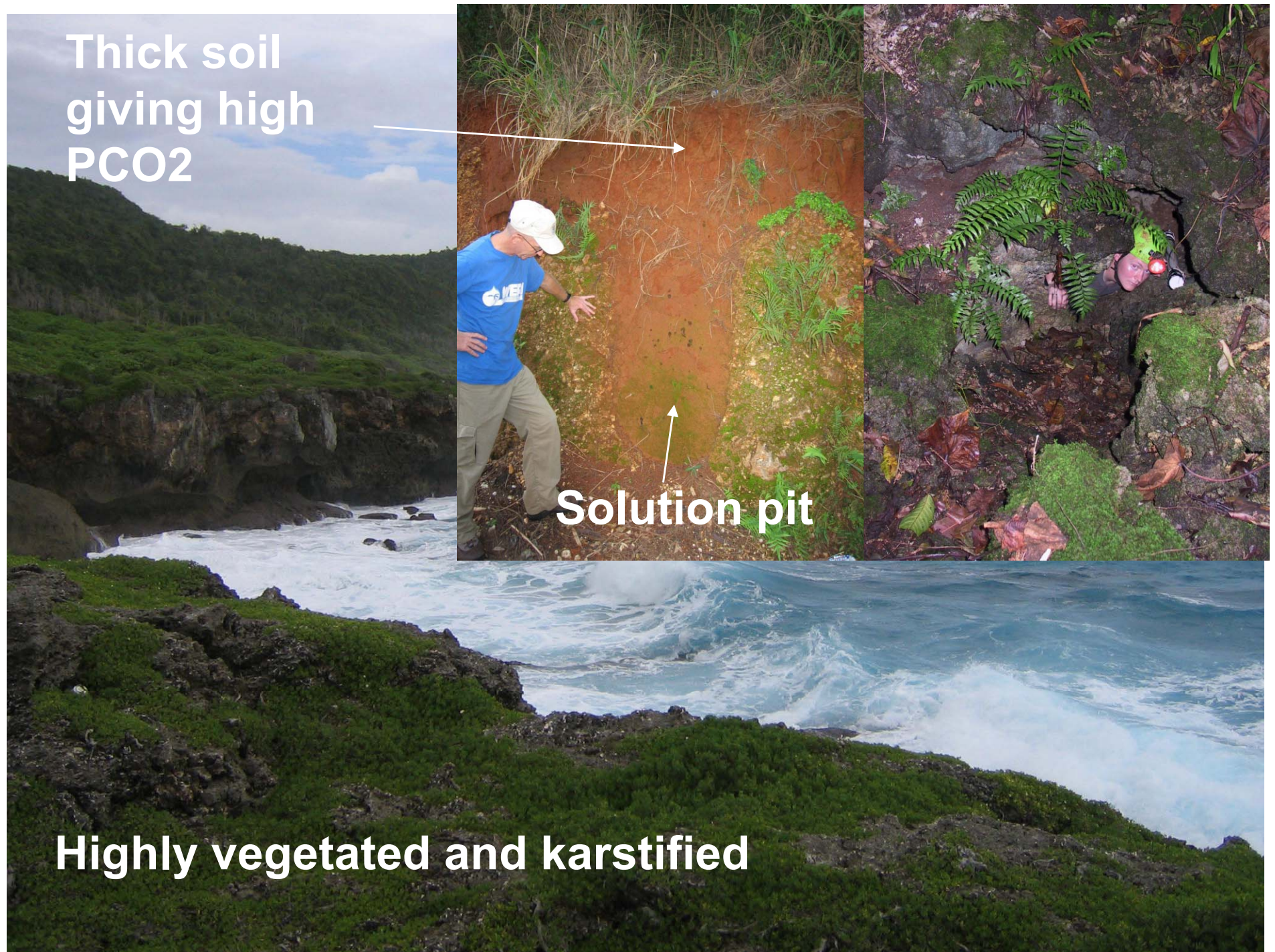**2) Lots from subsurface**

**Rock Properties**
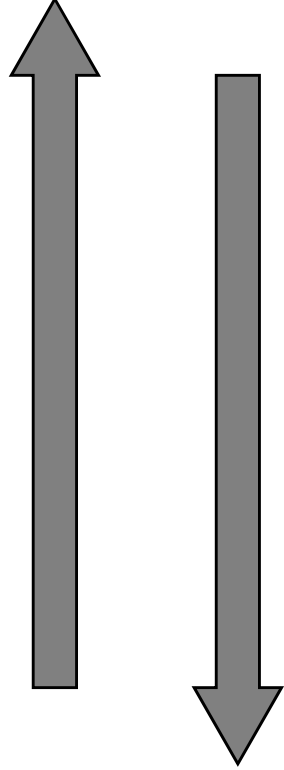— Porosity

**Hydrozones**
— Vadose
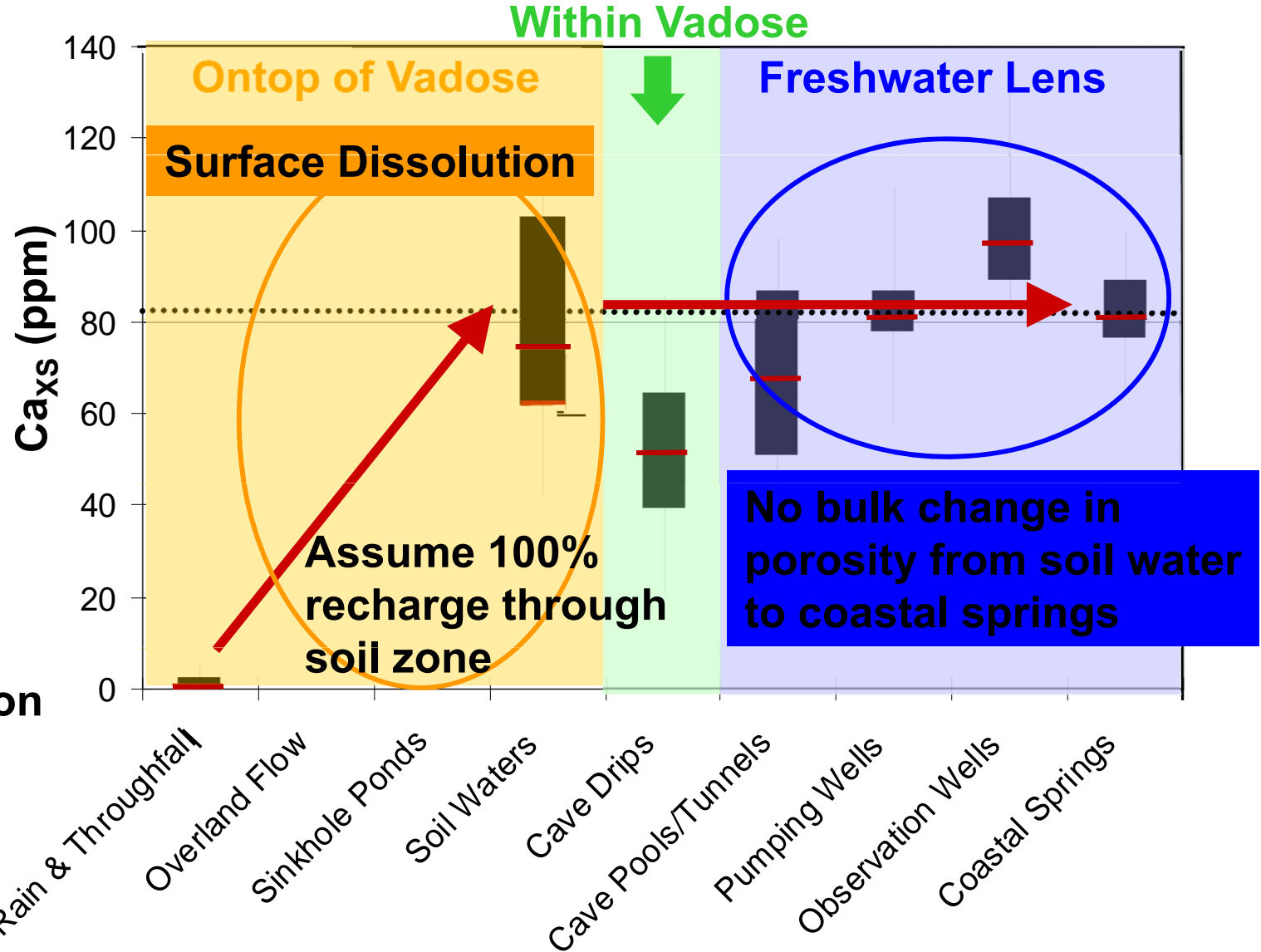— FW Phreatic

# Guam's surface dissolution is high



Thick soil giving high PCO2

Solution pit

Highly vegetated and karstified

# The calcium budget via the soil zone

# The calcium budget via dual recharge
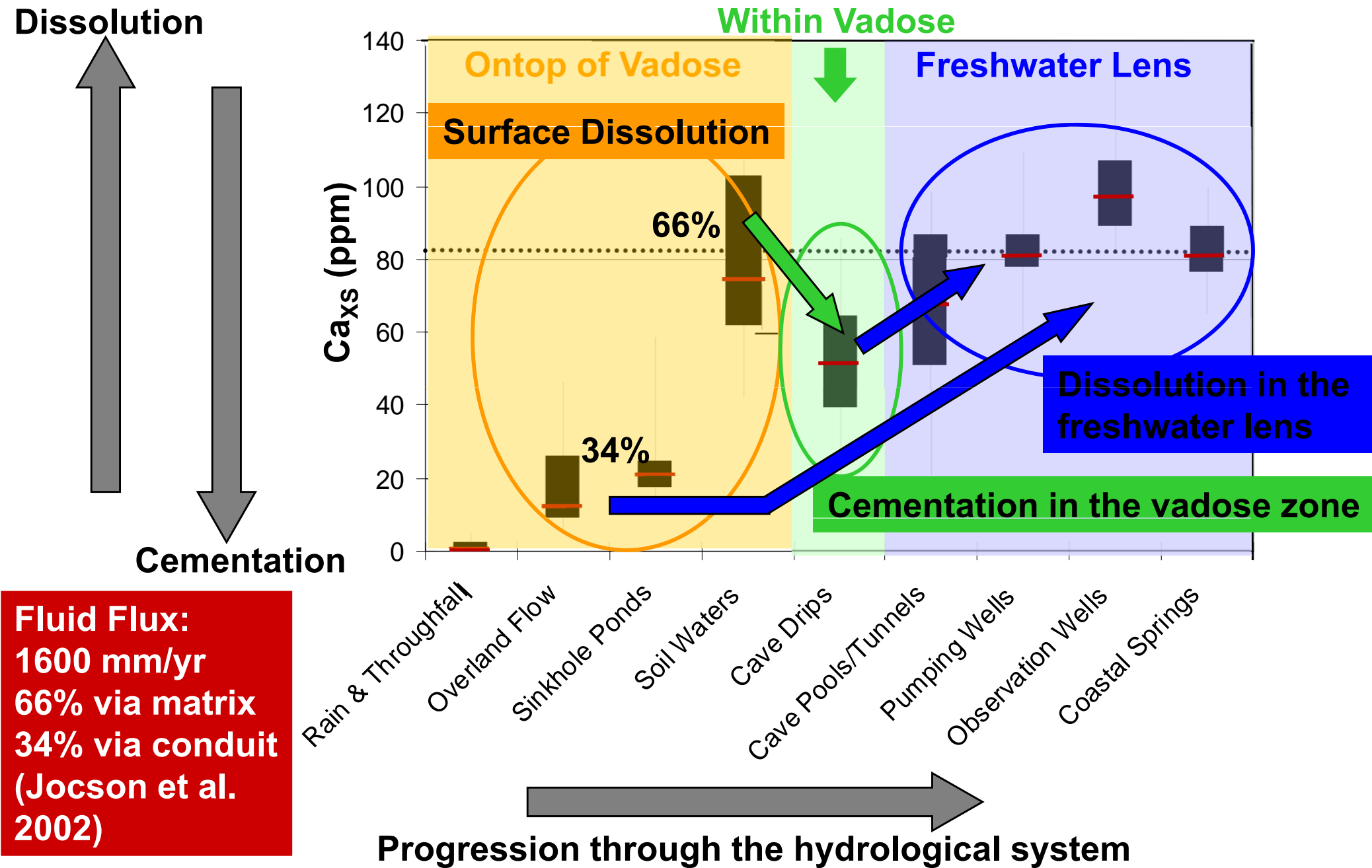
# Guam rate data – Input of soil-zone derived CaXS

103 mm/ky Surface Dissolution

Rates are in %/ky

|  | Dissolution | Precipitation |
|---|---|---|
| Vadose Zone | - | 0.079 |
| Freshwater Lens | 0.19 | - |
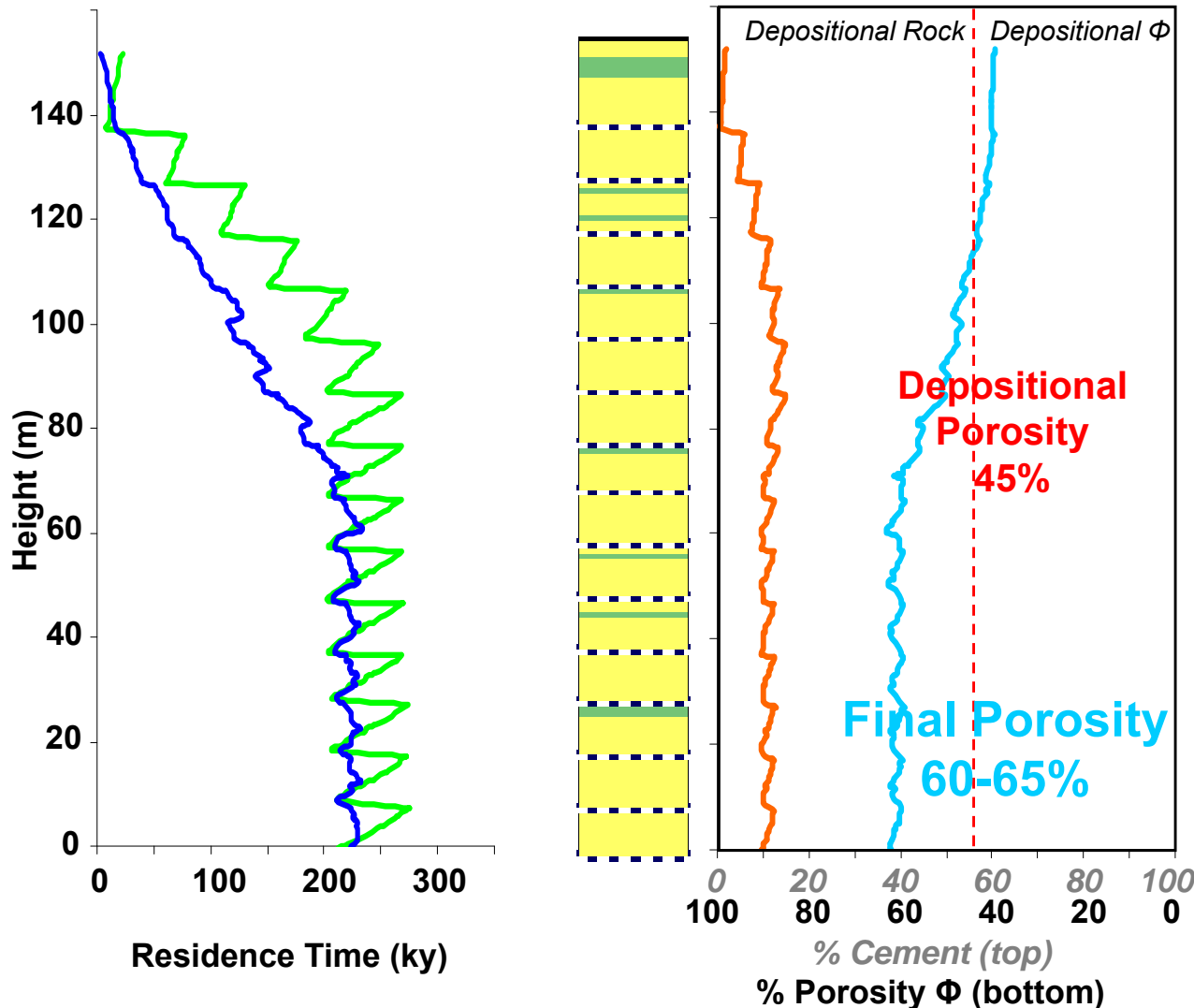


**Overall net dissolution**
**1) Lots from surface**
**2) Some from subsurface**
**3) Some cementation**
**In subsurface**

Depositional Rock   Depositional Φ

Depositional Porosity 45%

Final Porosity 60-65%

## Rock Properties
— Porosity
— Calcite Cement

## Hydrozones
— Vadose
— FW Phreatic

Height (m)

Residence Time (ky)

% Cement (top)
% Porosity Φ (bottom)

# So what are we seeing?

**Ontop of Vadose**

Surface Dissolution CaXS

**Within Vadose & Freshwater lens**

Complex array of dissolution and cementation reactions within the subsurface Dual recharge is important

**Output from Freshwater Lens**

Output of CaXS at the coast

The CaXS in the hydrological system needs to be near balanced:
The large amount of carbonate removal from the system (output) can be in large part sourced from surface dissolution (input)
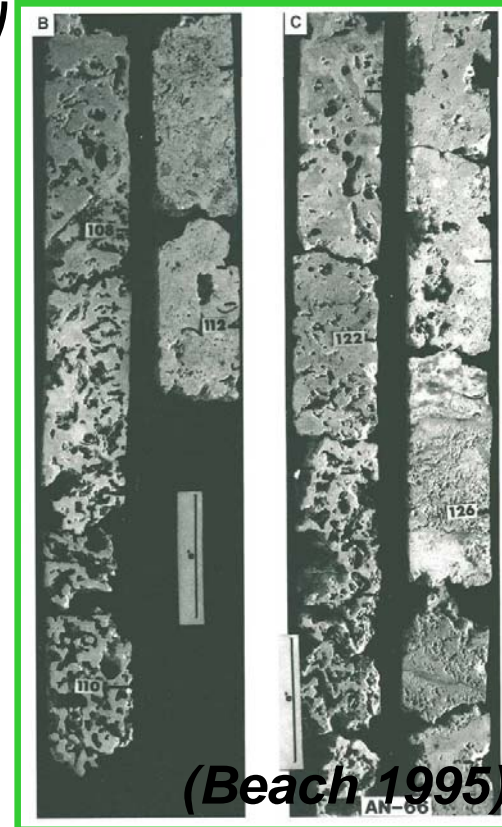


*(Beach 1995)*

# Conclusions

➢ **Forward modelling using rate data from hydrochemical process based studies gives insight into carbonate diagenesis**

➢ **Relative rates of surface and subsurface dissolution (and cementation) are critical in determining rates of porosity evolution**

➢ **Future studies should focus on surface and subsurface processes and include the effects of dual recharge**

➢ **Industry needs to understand cements and the calcium source of those cements if they want processes based reservoir predictability**
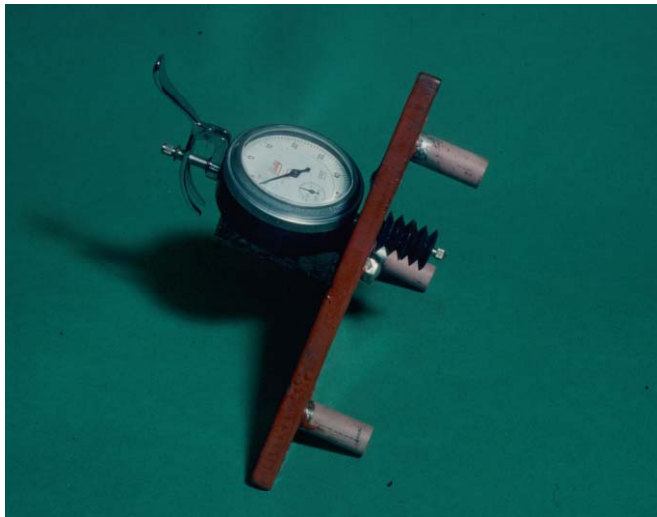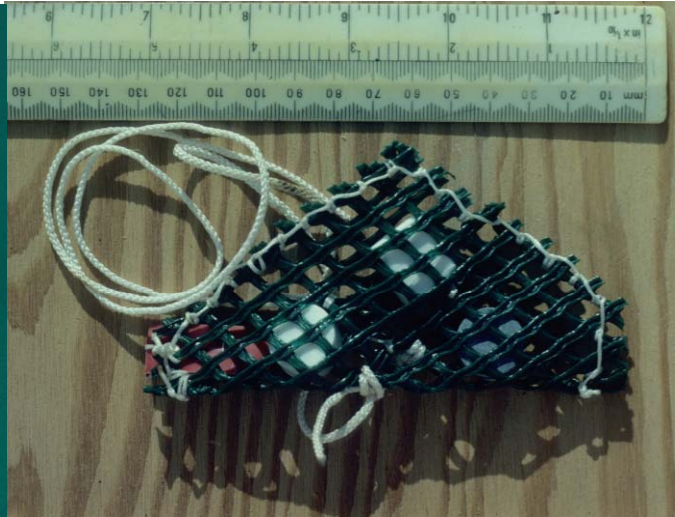
Fieldwork Over!

Any Questions

# Surface dissolution rates

| Method | Rate (mm/ka) | Study Area | No. of Refs |
|---|---|---|---|
| Field Experiments | 352 ± 305 (n=11) | Global – From Israel to Bikini Island | 8 |
| Hydrochemical | 75 ± 62 (n=5) | Global – From Bahamas to Guam | 4 |
| Historical | 74 ±70 (n=10) | Global – From Enewetak to S.E. Australia | 5 |



**Micro Erosion Meters**          **Dissolution of CaCO3 pills**          **Water Chemistry**

# Reference

Richard J. Paterson, Richard J., Fiona F. Whitaker, Peter L. Smart, Gareth D. Jones, and David Oldham, 2008, Controls on early diagenetic overprinting in icehouse carbonates: Insights from modeling hydrological zone residence tmes using CARB3D: Journal of Sedimentary Research, v. 78, p. 258-281.