

Using Modern Cave Systems as Analogs for Paleokarst Reservoirs*

Chip Feazel¹

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**Adapted from 2008-2009 AAPG Distinguished Lecture.

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Abstract

Karst processes, hydrology, dimensions and architecture are useful in understanding karsted rocks that serve as reservoirs for oil and natural gas. Three-dimensional cave surveys can be used to assign properties to “karst” cells in geocellular models. Surveys of long karst passages (e.g., Yucatan flooded caves) can be used to infer connectivity (i.e., how many “karst” cells can be neighbors?).

Karst processes ranging from surface weathering to deep burial dissolution have affected numerous karst intervals that host petroleum accumulations. Recognition and prediction of subsurface paleokarst from seismic or borehole information involves addressing the following concerns:

- Does the layer in question consist primarily of carbonate rocks?
- Is there evidence to suggest subaerial exposure of the carbonates?
- Can a humid paleoclimate be documented?
- What was the paleo-relief?
- Does the tectonic history include episodes of jointing, faulting, or fracturing that would focus flowing water in the paleo-hydrologic setting?
- Is there reason to suspect burial dissolution?
- Did karst dissolution pre-date petroleum migration?
- What differences would karsting make to wellbore deliverability, well spacing, drilling operations, injection strategies, and production profiles?

Analogues and regional studies incorporating the elements of this list can be used in the exploration and production workflow to identify potential problems and opportunities, to constrain geo-model input, and to improve communication of subsurface risks and uncertainties.

References

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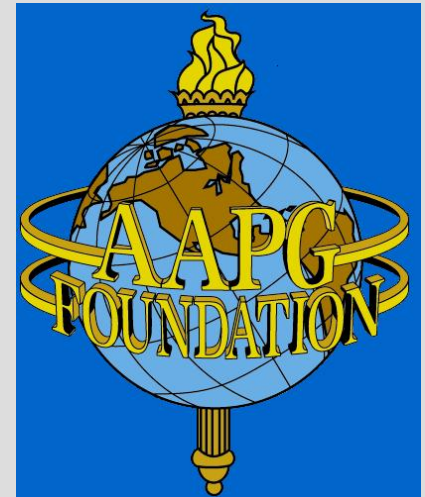
USING MODERN CAVE SYSTEMS AS ANALOGS FOR PALEOKARST RESERVOIRS

Chip Feazel
Subsurface Technology



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Special thanks to:

Ira Sasowsky, Rich Aram, Bob Loucks – karst discussions & images

Paul Valasek – seismic modeling

AAPG Foundation / Distinguished Lecture program

ConocoPhillips

Numerous colleagues -- photos

OUTLINE

What is paleokarst?

How did it form?

How is it recognized?

Can paleokarst be predicted in the subsurface?

**Using modern cave architecture and distribution
to interpret paleokarst reservoirs**

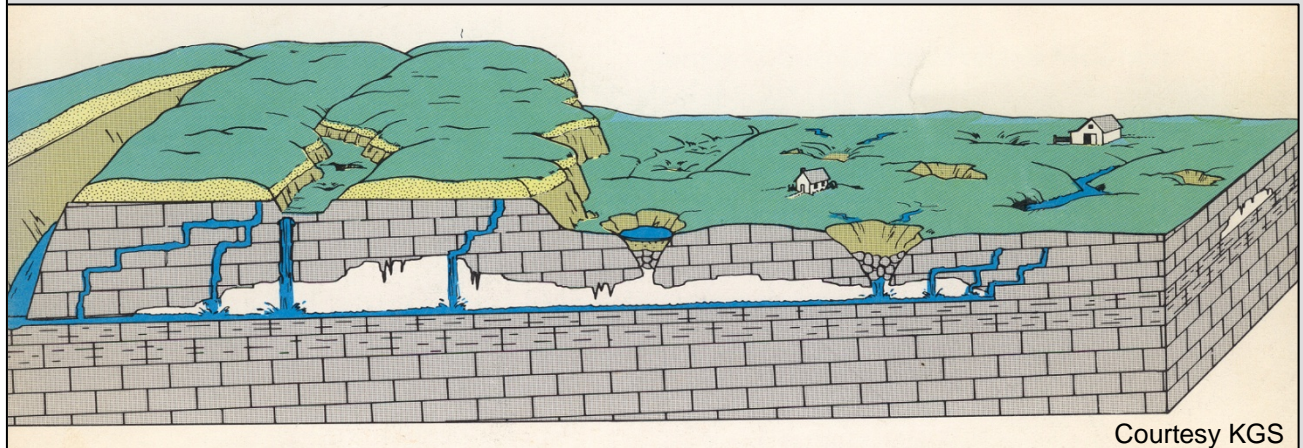
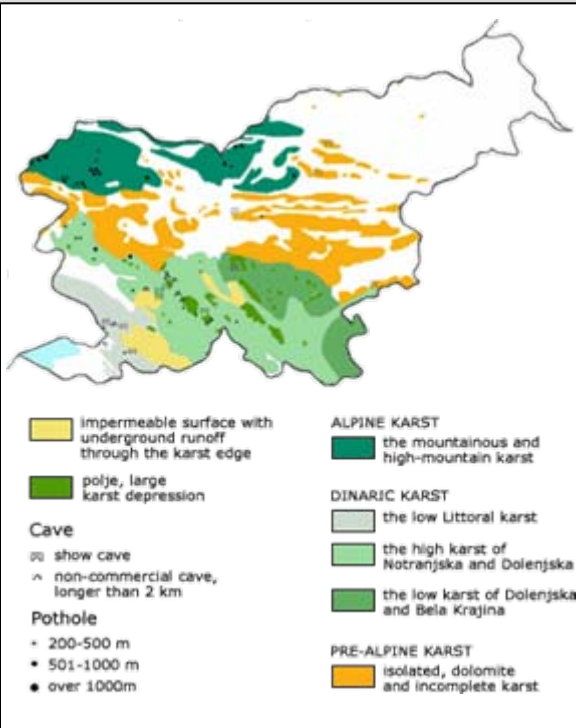
Consequences to drilling & production

How to incorporate karst in geomodels

Conclusions

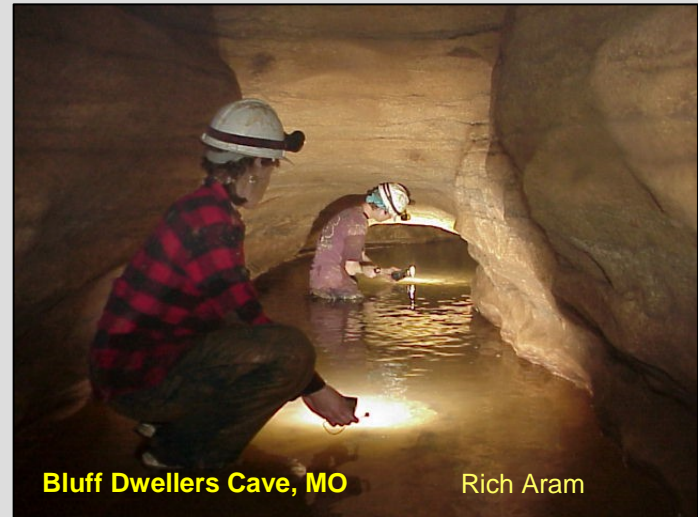
What is karst?

- Originally a geomorphic term for part of present-day Slovenia



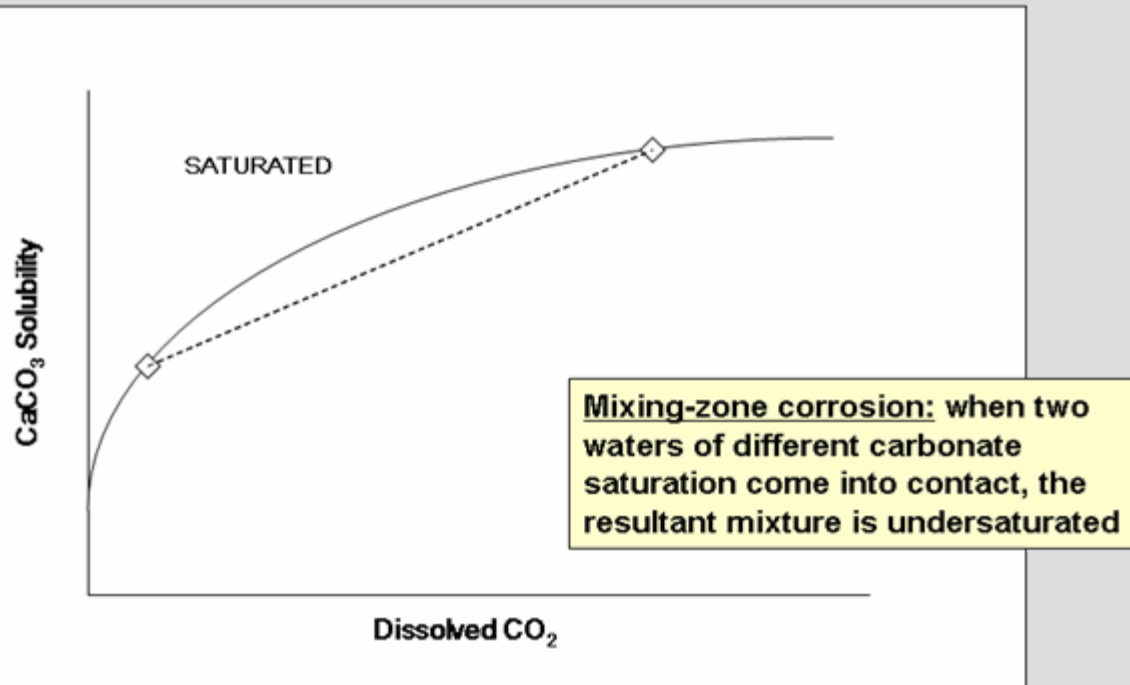
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- More inclusive approach:
 - Traditional karst -- denudation varies directly with precipitation



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 - Coastal mixing-zone karst (salinity cycles)



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 - Hydrothermal karst (high P_{CO_2})



Sitting Bull Crystal Caverns, SD

What is karst?

- Originally a geomorphic term for part of present-day Slovenia
- More inclusive approach:
 - Traditional karst -- denudation varies directly with precipitation
 - Coastal mixing-zone karst (salinity cycles)
 - Hydrothermal karst (high P_{CO_2})
 - Sulfuric acid karst (sulfur, nitrogen & carbon redox, significant microbe role)
- Many karsts are polygenetic



Isl

Lecheguilla Cave

Platonsko polje

Ira Sasowsky

Why should petroleum geologists be interested?

Yates #30A flowed **204,672 BOPD**
from San Andres Fm. paleokarst (1930)

Yates Field contains 1556 documented caves,
intersected by 582 wells.

- Stafford et al. (2008)

The most productive well in history (Cerro Azul-4) flowed **260,000 BOPD**
from a paleokarst zone in the Golden Lane trend, Veracruz, Mexico (1916)

- Viniegra and Castillo-Tejero (1970)



**And we can't assume it happened a long time ago,
and is now inert...**

- **Renqiu oilfield, China, in buried hill karst**
 - **dolomitic reservoir, >400 wells**
 - **paleo-hills 4x18 km**
 - **surficial karst, starting mid-Ordovician**
 - **burial karst – before oil entry**
 - **“conservation karst” during hydrocarbon charge and storage**
 - **“development karst” during 35 yrs of production**
 - **fresh & produced water injection (containing SRB)**
 - **corrosion of calcite, dolomite & ankerite**
 - **pyrite dissolution**
 - **gypsum precipitation**

- Han & Zhu (2008)

Evolving concepts:

Dominant themes
at this meeting,
June'08, Rapid City SD

- **Structure – process – time**
 - Especially in sequence stratigraphic context
- **Widespread nature of hypogenic (deep-origin) karst**
 - Usually recognized by lack of internal sediment
 - “Karst” originally described landforms generated near-surface
 - Some “buried karst” may never have experienced meteoric dissolution
 - May be unrelated to sequence stratigraphy
- **Biogenic origin of some karst (microbial contribution to dissolution)**
- **Karst studies across scales ranging from microscopic to global**



What is paleokarst?

Is it simply “old karst”?

- at the surface
- a buried, inert surface
- fossil, relict, covered, exhumed, reactivated, rejuvenated
- how to distinguish from deep-origin (hypogene) karst?



Wind Cave, SD

**Pennsylvanian-age karst breccia
exposed in ceiling of a more recent cave**

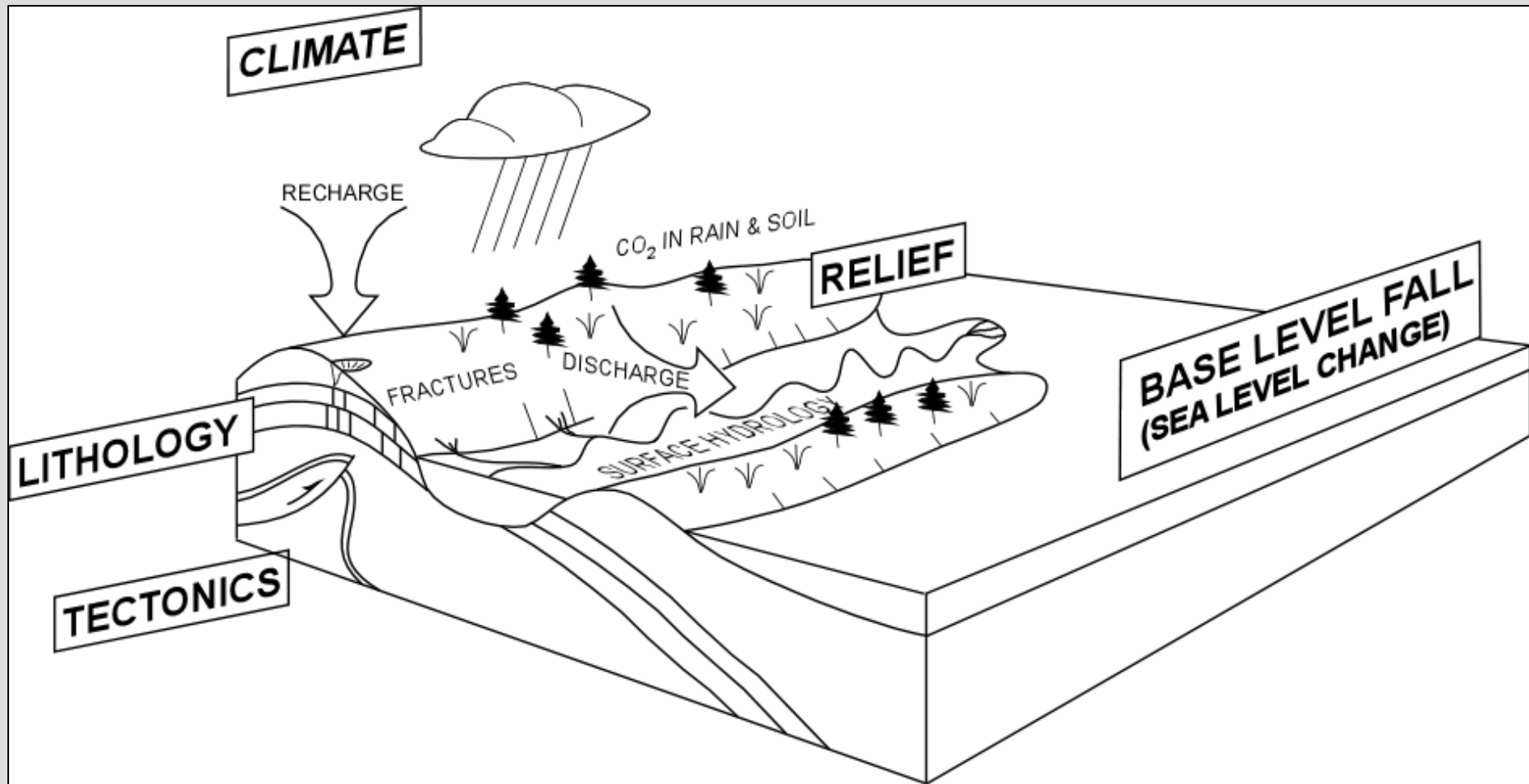


Indian Cave, Middle Caicos, BWI

Ira Sasowsky

Breached cave roof

What forms karst?



Meteoric (epigene) karst processes respond to a variety of drivers

How do we recognize paleokarst?

In outcrops



Paleo-sinkhole with infill



Calcite-cemented paleokarst breccia

Black Hills, SD



Breccia in paleo-sinkhole

How do we recognize paleokarst?

In outcrops

**Diagnostic: dissolution
scalloping of clast margins**



Middle Caicos, BWI

How do we recognize paleokarst?

In outcrops

In cores

What was dissolved?



Black Hills, SD



1 inch

Paleokarst in core

Classification of Paleocave Facies

Undisturbed Strata
Facies
(Undisturbed Host
Rock)

Disturbed Strata
Facies
(Disturbed Host
Rock)

Highly Disturbed Strata
Facies
(Cave-Roof and
Cave-Wall Collapse)



Sediment-Fill
Facies
(Cave-Sediment Fill)

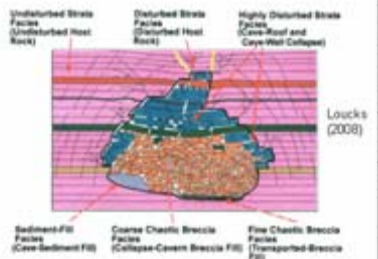
Coarse Chaotic Breccia
Facies
(Collapse-Cavern Breccia Fill)

Fine Chaotic Breccia
Facies
(Transported-Breccia
Fill)

Loucks
(2008)



Classification of Paleocave Facies



Loucks (2008)

HOST ROCK

CAVE ROOF BRECCIA

CAVE FILL BRECCIA

BASE OF CAVE

HOST ROCK

Schematic vertical succession in collapsed Ellenburger paleocave



Criteria for recognition of karst in core:

- Chaotic heterolithic breccia clasts (commonly weathered, solution-rounded or scalloped)
- Between clasts: multi-stage cements and internal sediments
- Difficulty of distinguishing internal sediment from cement
- Karst independent of lithofacies
- Vertical sequence: mosaic breccia with cement overlies chaotic breccia with sediment
- Near-vertical fractures, increasing in width and abundance upward
- Fracture-filling sediment and multi-generational cement
- Low abundance of stylolites (stress relief by cave collapse?)



How do we recognize paleokarst?

In outcrops

In cores

What was dissolved?

What might it be confused with?

- Fault breccia

- Sedimentary breccia



How do we recognize paleokarst?

In outcrops

In cores

What was dissolved?

What might it be confused with?

- Fault breccia

- Sedimentary breccia



How do we recognize paleokarst?

But it can get tricky...

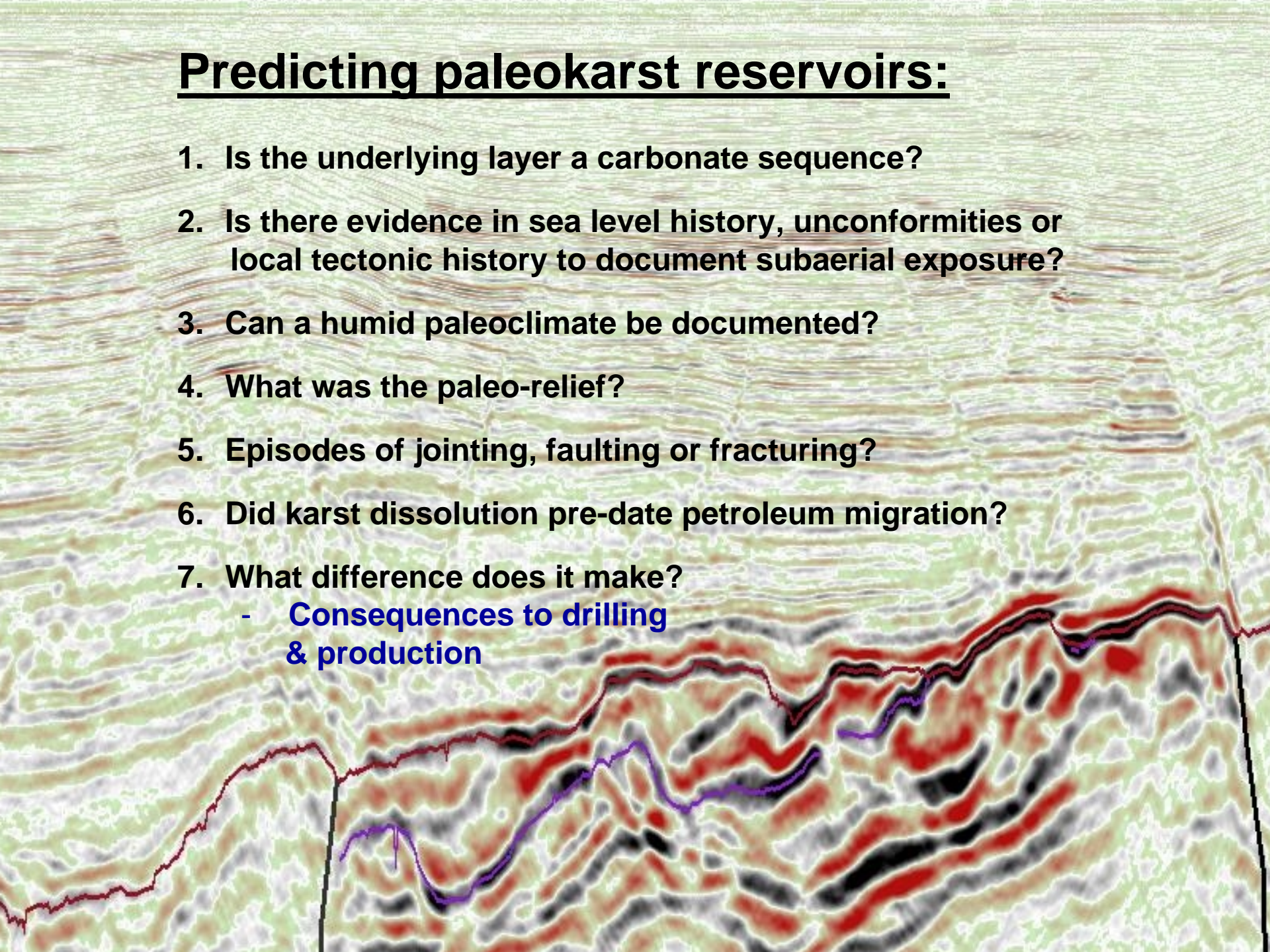


Pete D'Onfro

Fault breccia in Morrison Fm., Arches National Park

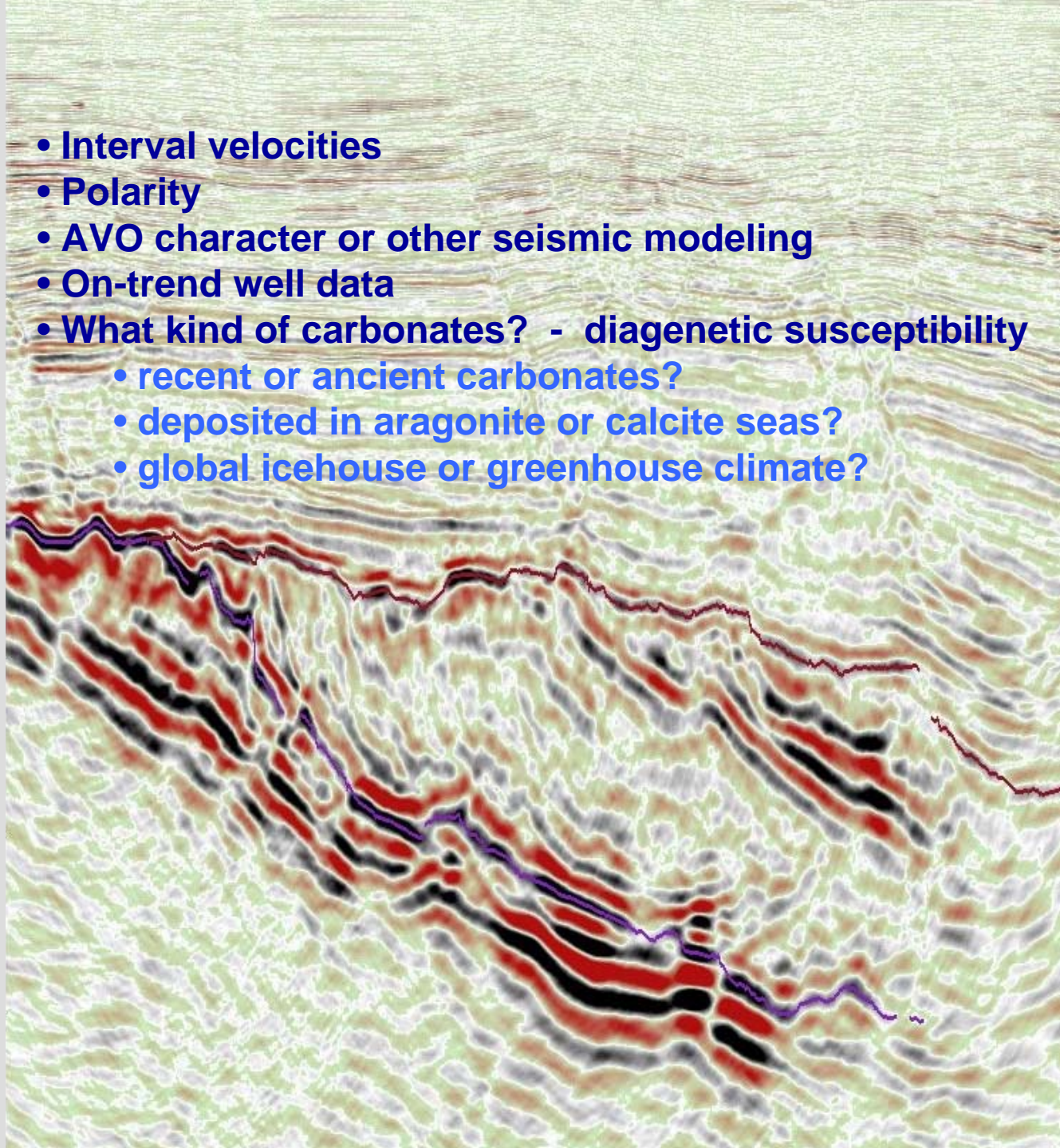
Predicting paleokarst reservoirs:

1. Is the underlying layer a carbonate sequence?
2. Is there evidence in sea level history, unconformities or local tectonic history to document subaerial exposure?
3. Can a humid paleoclimate be documented?
4. What was the paleo-relief?
5. Episodes of jointing, faulting or fracturing?
6. Did karst dissolution pre-date petroleum migration?
7. What difference does it make?
 - Consequences to drilling & production



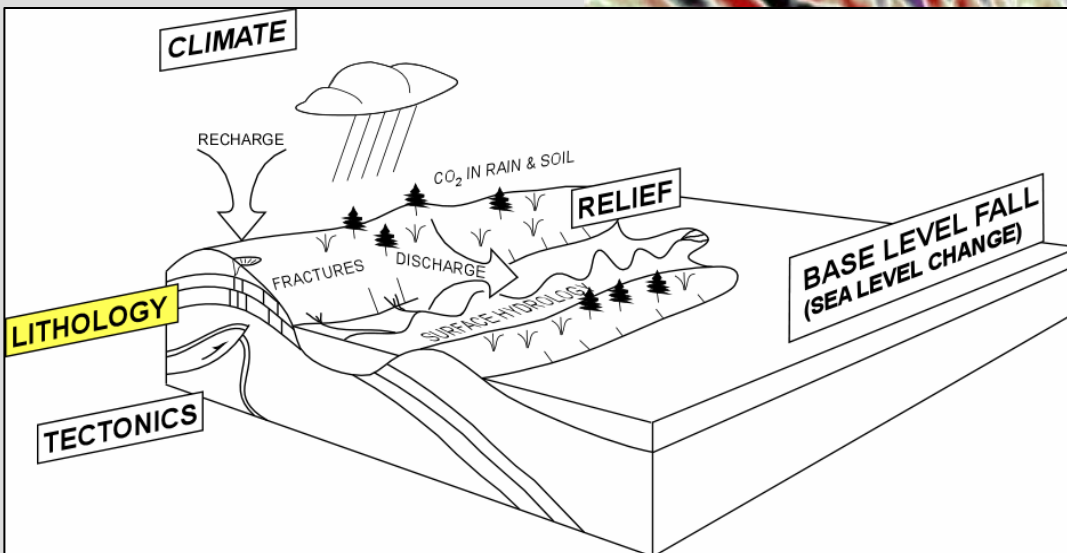
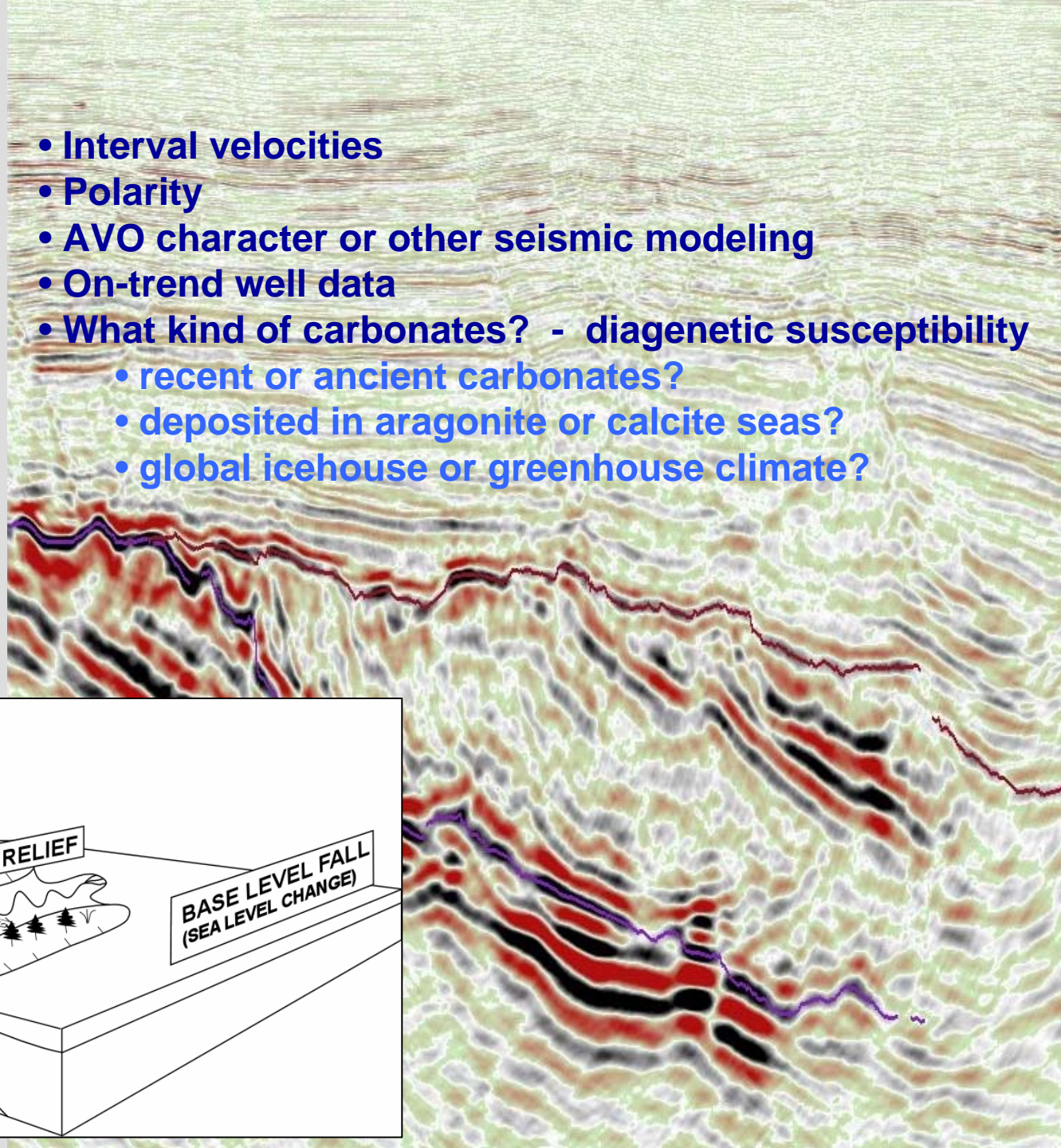
**1. Is the
underlying layer
a carbonate
sequence?**

- Interval velocities
- Polarity
- AVO character or other seismic modeling
- On-trend well data
- What kind of carbonates? - diagenetic susceptibility
 - recent or ancient carbonates?
 - deposited in aragonite or calcite seas?
 - global icehouse or greenhouse climate?

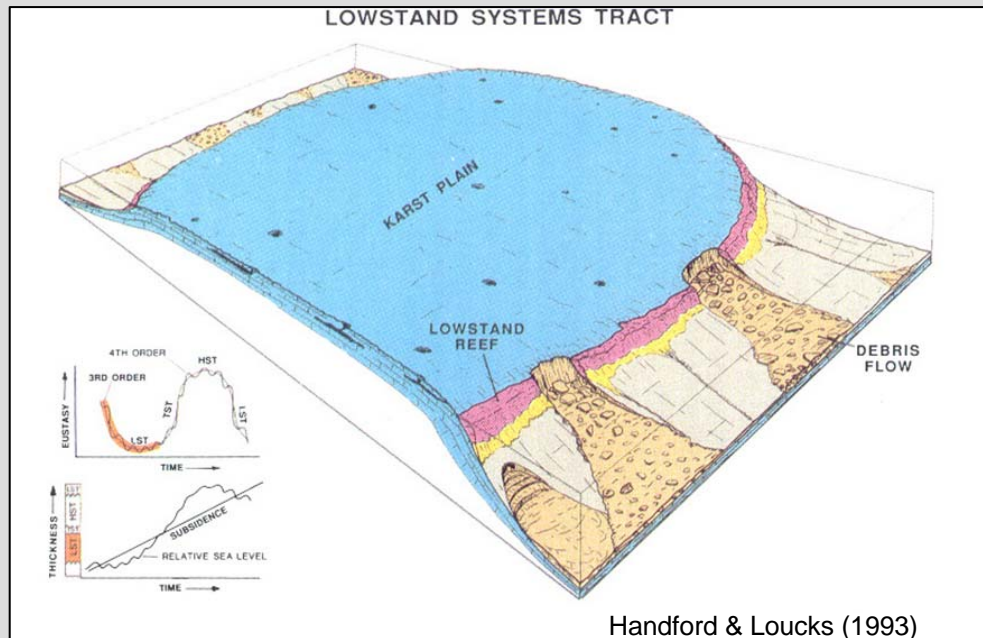
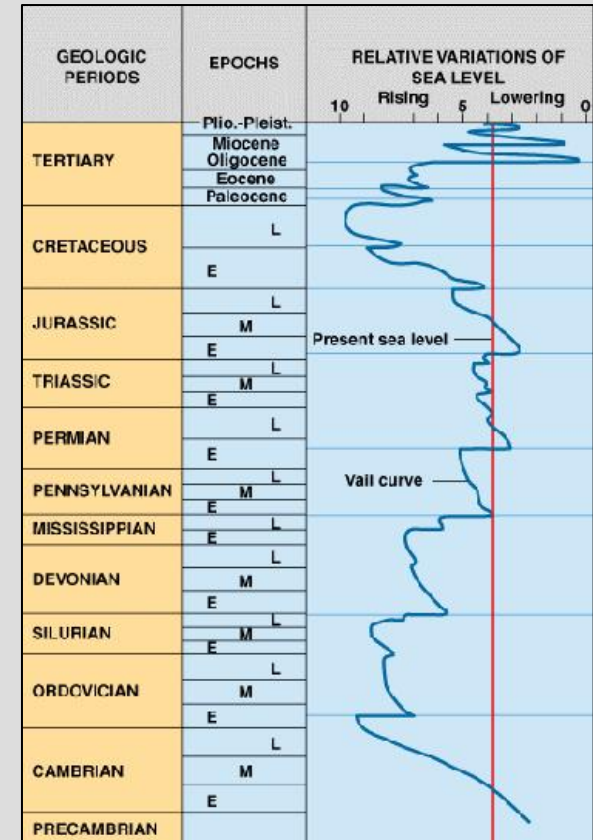
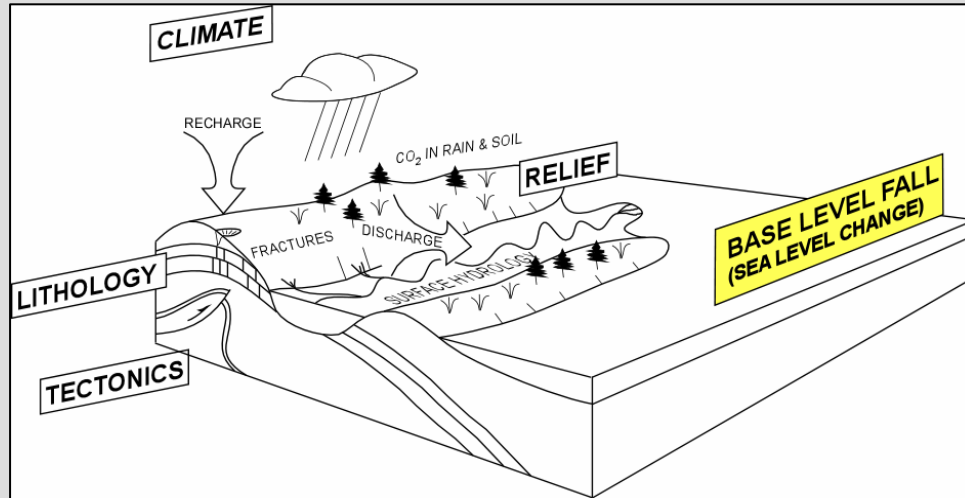


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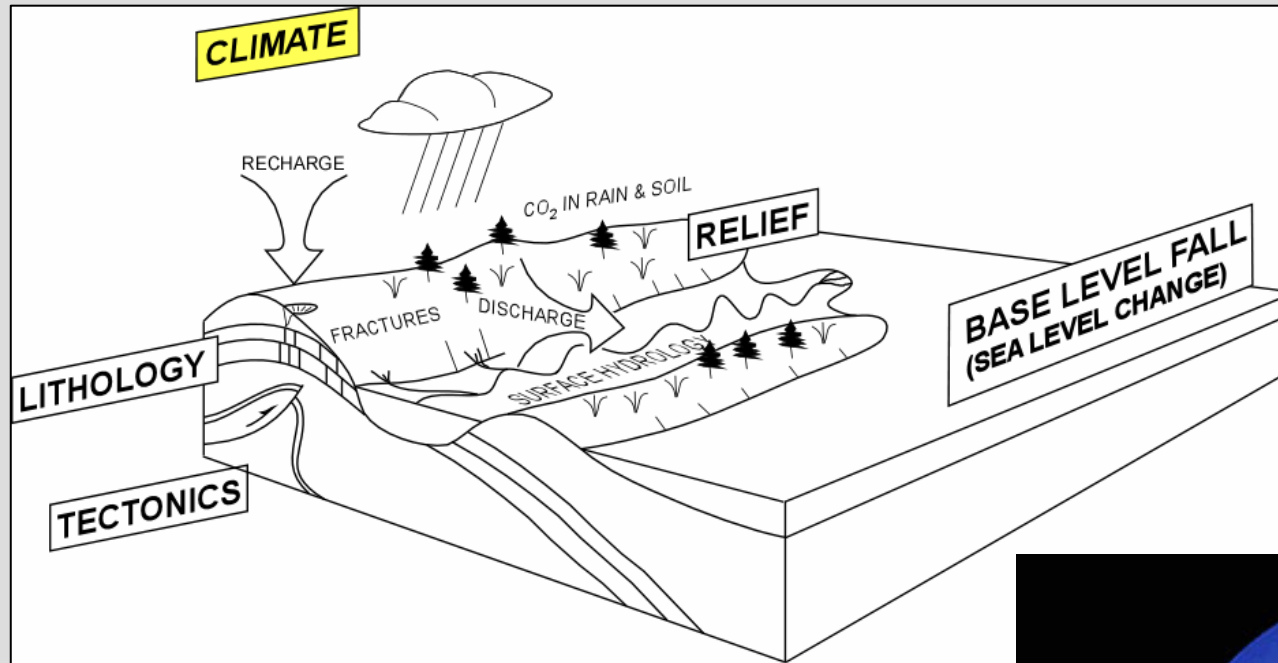


2. Is there evidence in sea level history, unconformities or local tectonic history to document subaerial exposure?



Handford & Loucks (1993)

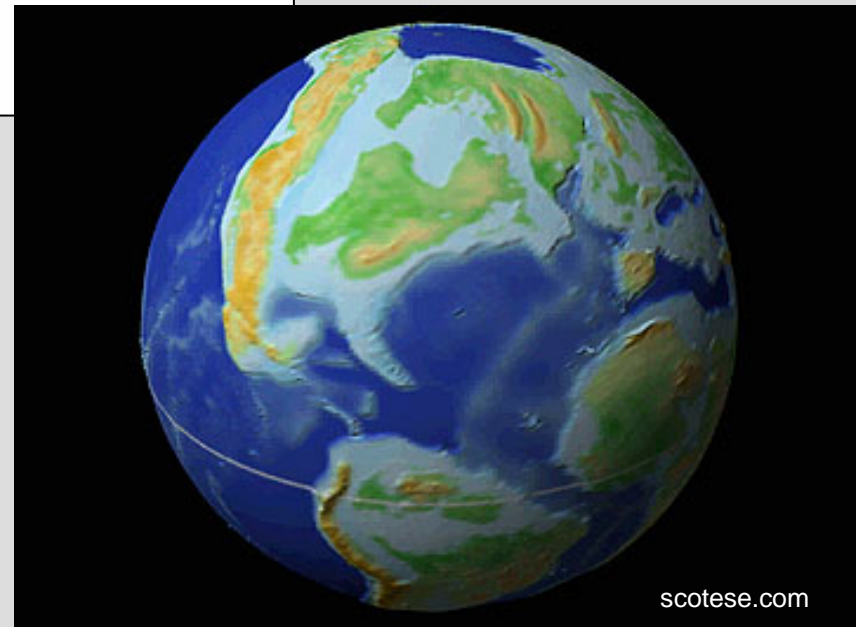
3. Can a humid paleoclimate be documented?



Rain + soil CO₂ = dissolution



Arid = caliche

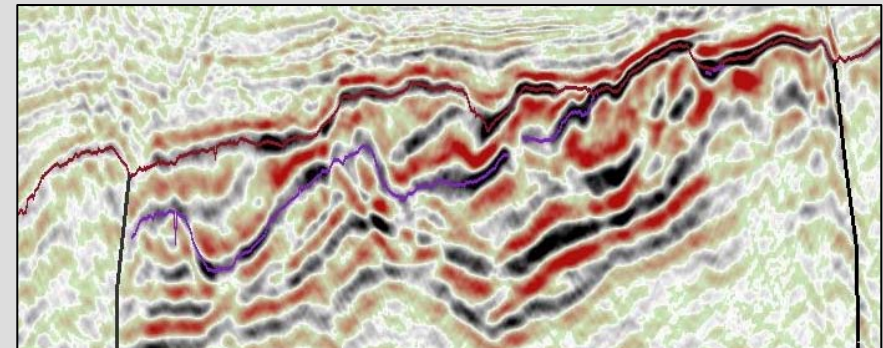
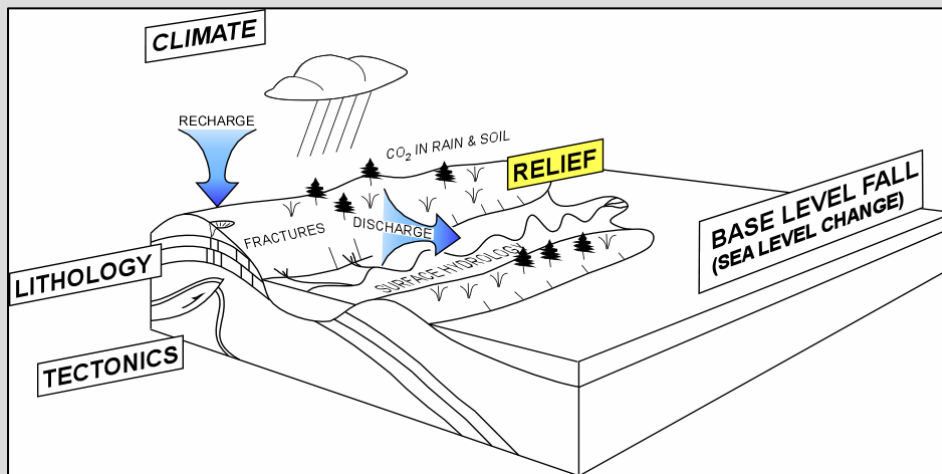


4. What was the paleo-relief?

Determines depth of meteoric influence

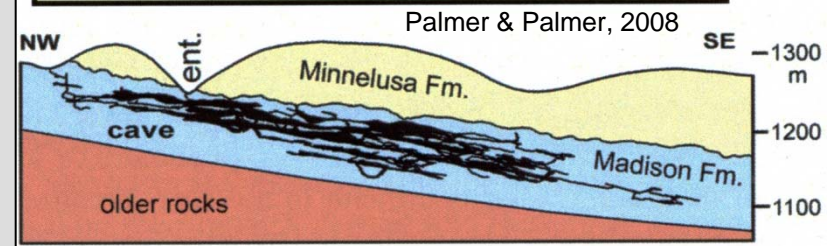
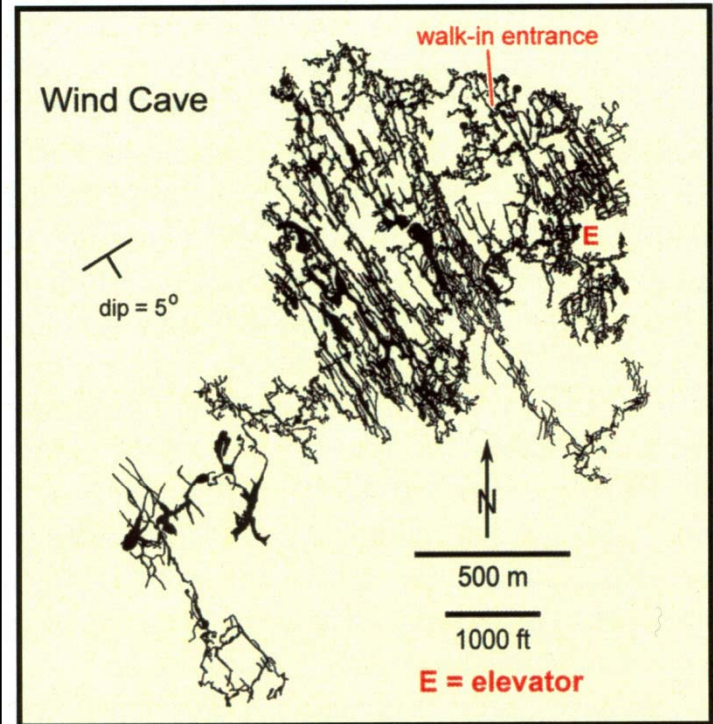
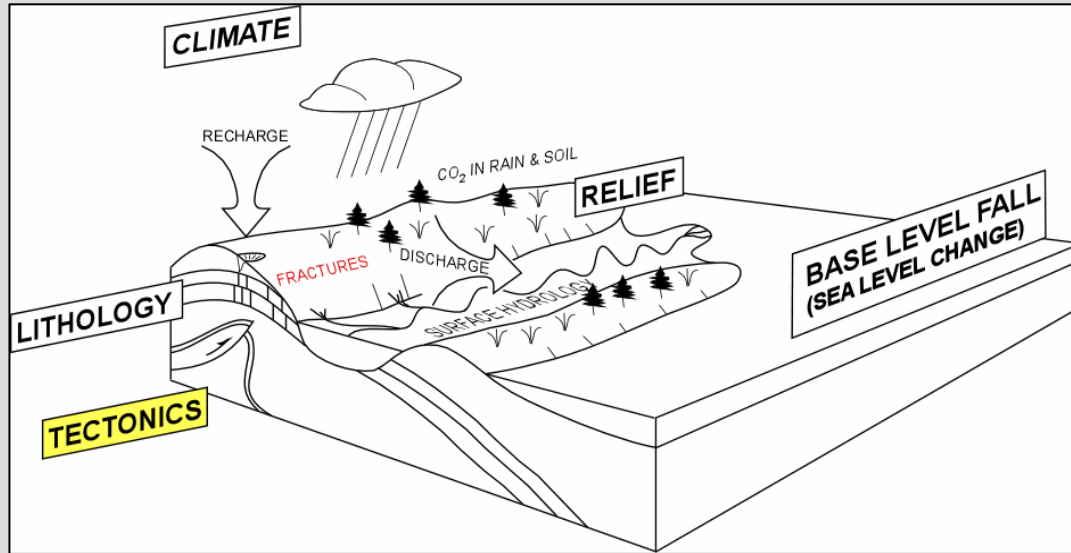


Karst may extend downward only
1-2m (epikarst) or reach deeply into the terrain



Meteoric karst hydrology requires recharge and discharge
– karst may extend no deeper than the deepest valley on the erosion surface

5. Episodes of jointing, faulting or fracturing?



Many caves display strong structural control

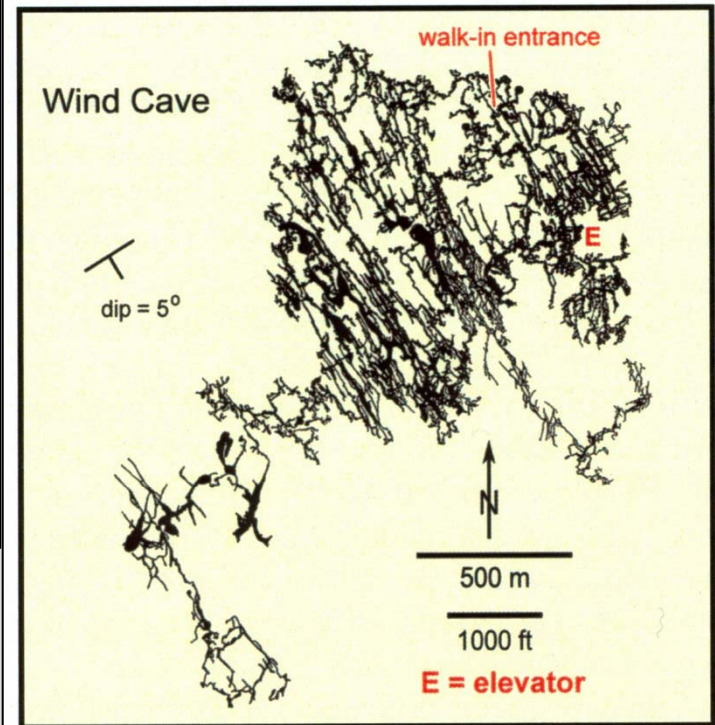
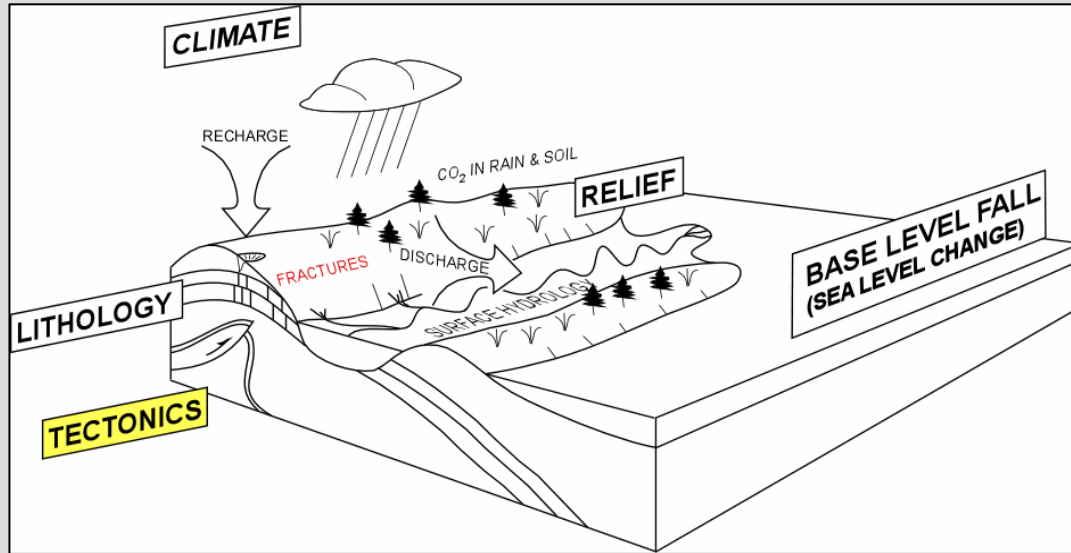


Anhalt quarry, TX

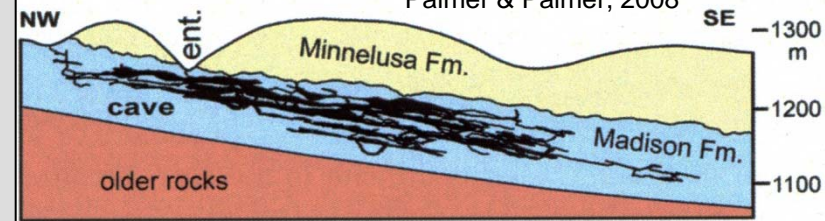
Chris Zahm

Faults & fractures focus flowing water that dissolves rock

5. Episodes of jointing, faulting or fracturing?



Palmer & Palmer, 2008



Many caves display strong structural control

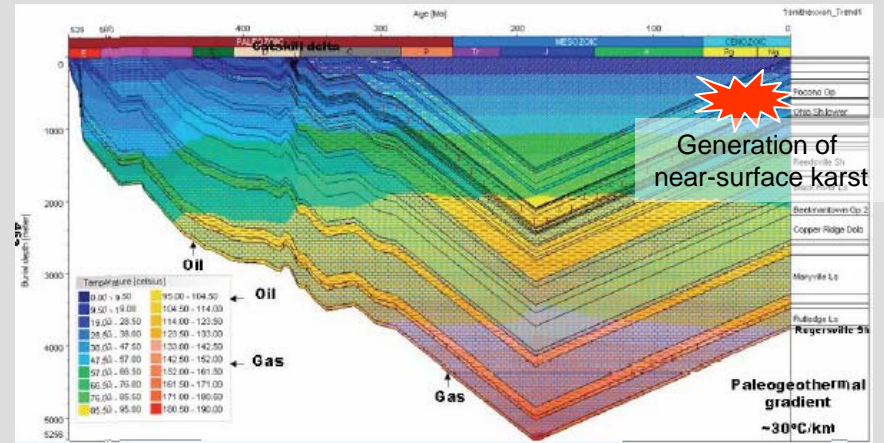
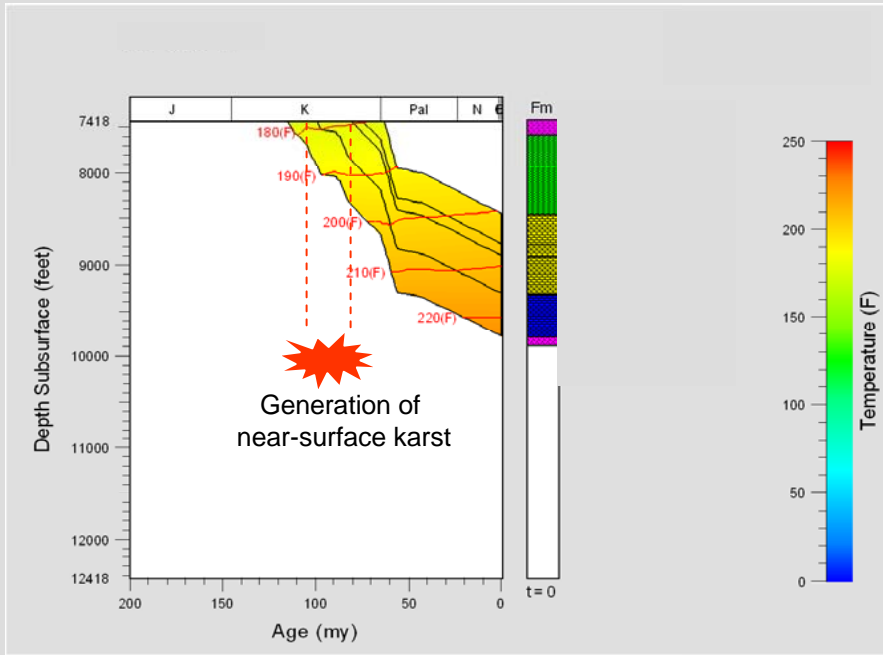


Anhalt quarry, TX

Chris Zahm

Faults & fractures focus flowing water that dissolves rock

6. Did karst dissolution pre-date petroleum migration?



Burial history plots reveal earliest possible oil & gas generation & migration

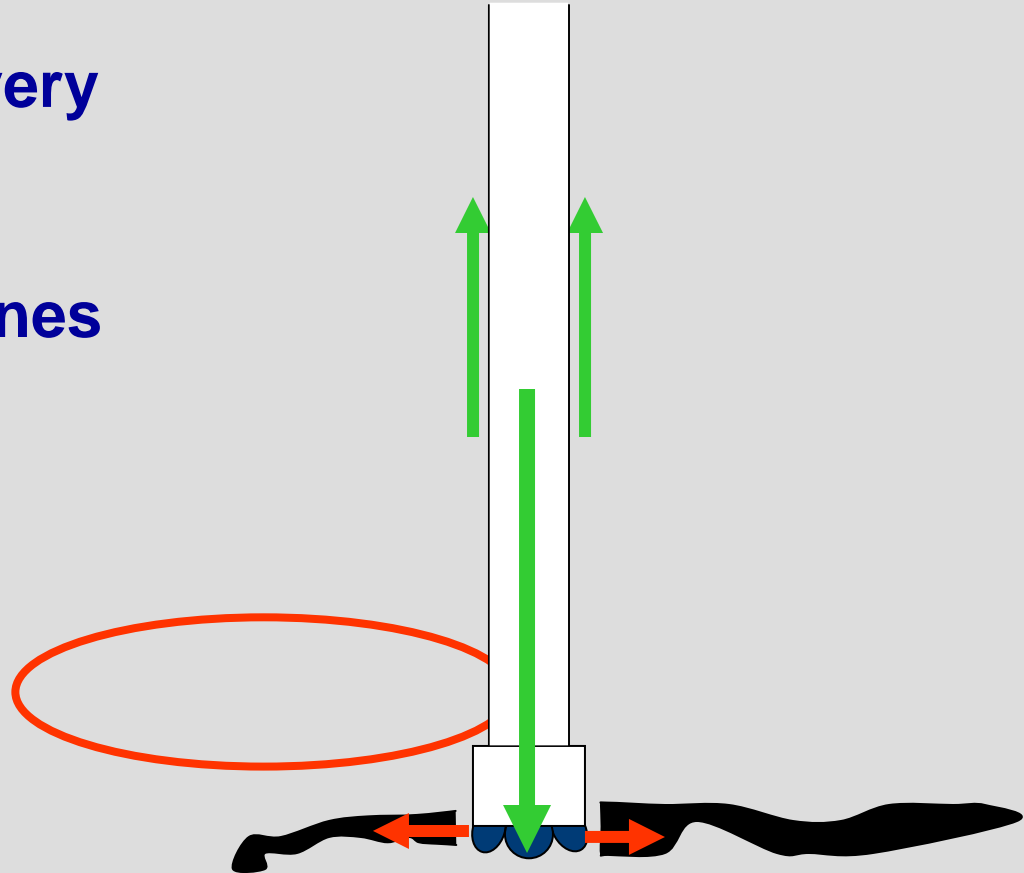
- karst created after petroleum has migrated to traps is ineffective as a reservoir
- but voids created long ago have had many opportunities to become cemented or sediment-filled, and may be ineffective as a reservoir



7. What difference does it make?

Consequences to drilling & production:

- Bit drops
- Incomplete core recovery
- Poor logs
- Lost-circulation zones
- Super-permeability zones



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Consequences to drilling & production:

- Bit drops
- Incomplete core recovery



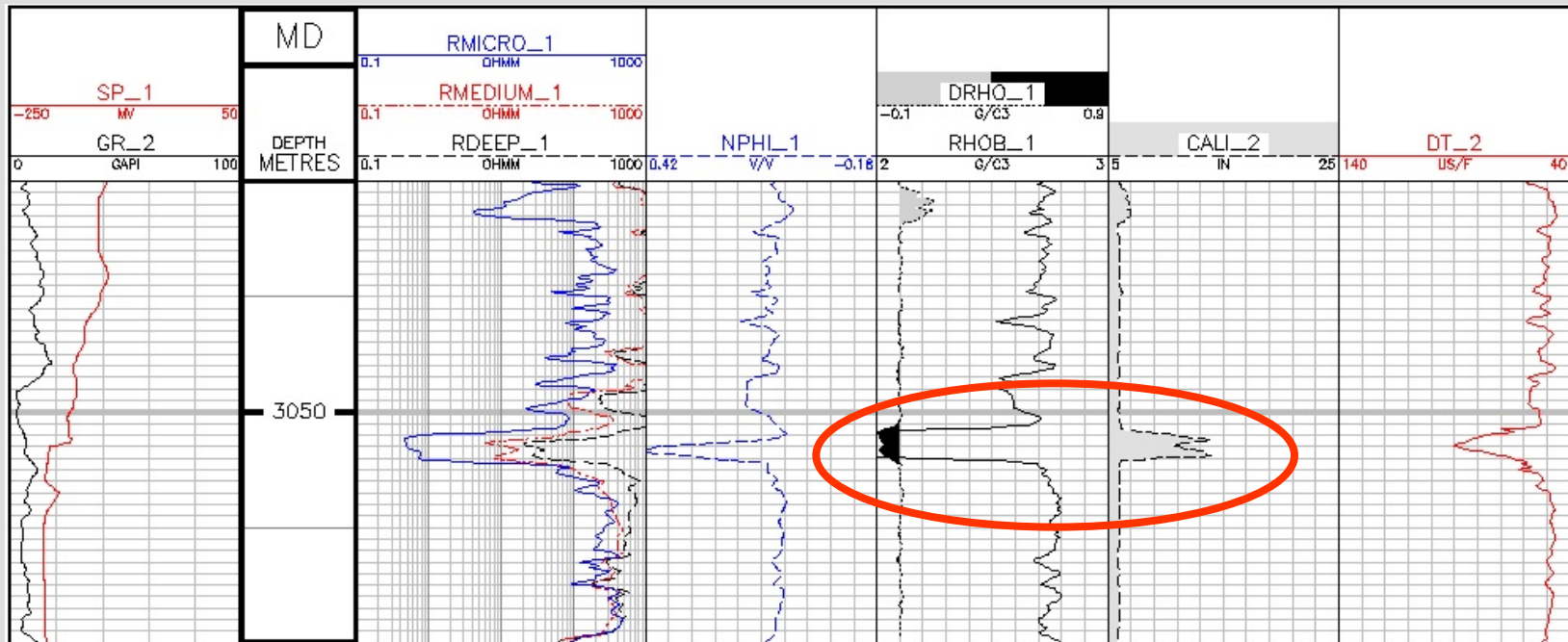
Scott Hollow Cave, WV

Ira Sasowsky

7. What difference does it make?

Consequences to drilling & production:

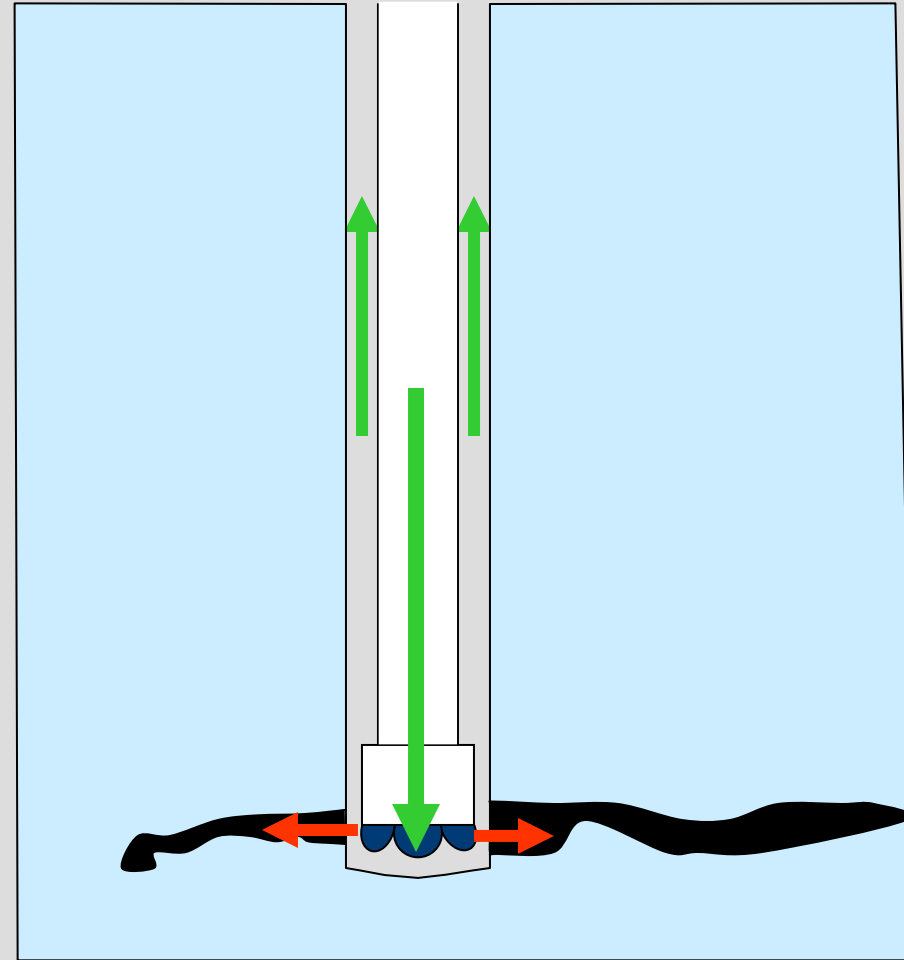
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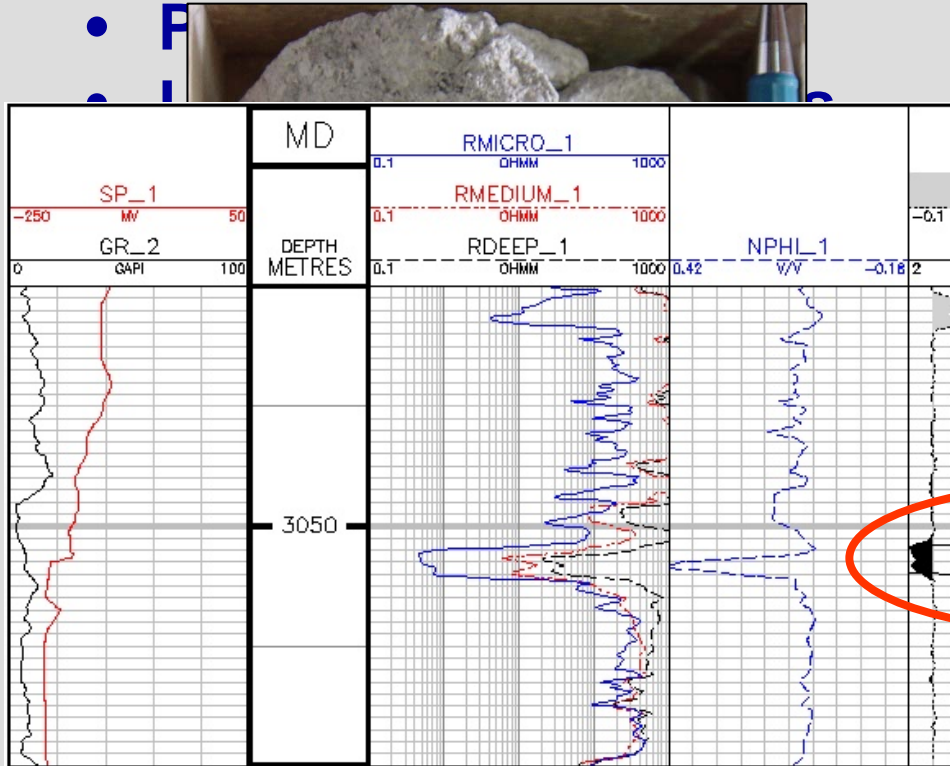
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Consequences to drilling & production:

- Bit drops
- Incomplete core recovery
- F
- I



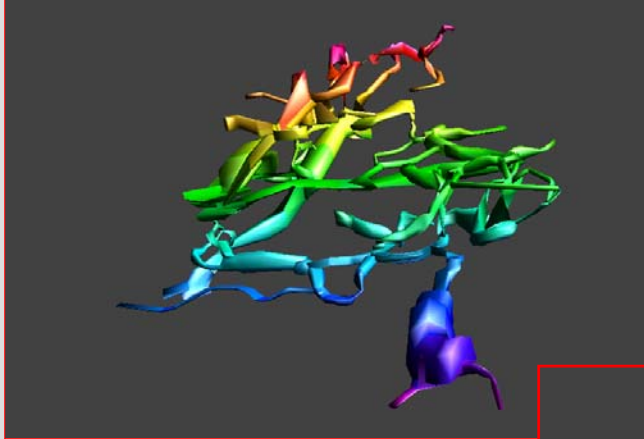
What about non-meteoric karst?

- H_2S , organic acid or hydrothermal origins
- May be disconnected from surface hydrology
- Commonly discordant to stratigraphy
- Deep, hot, late?
- Petroleum-associated fluids?
- Commonly lacks internal sediment
- Needs pathways – faults, fractures (and drive mechanisms)
- May have seismic expression, otherwise difficult to predict
- May host economically valuable minerals
- Gaining recognition as a significant karst-generating process

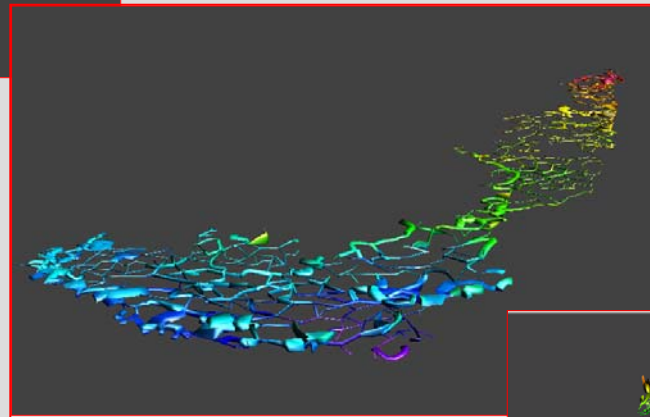


Early to late diagenesis, Jewel Cave

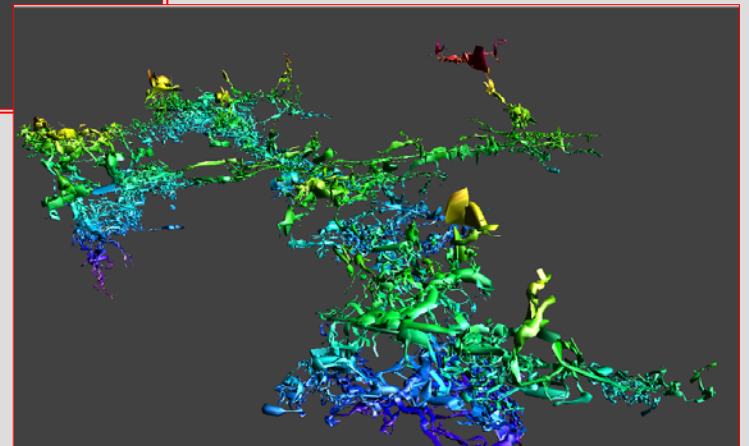
Using modern caves as input to geo-models



From simple...



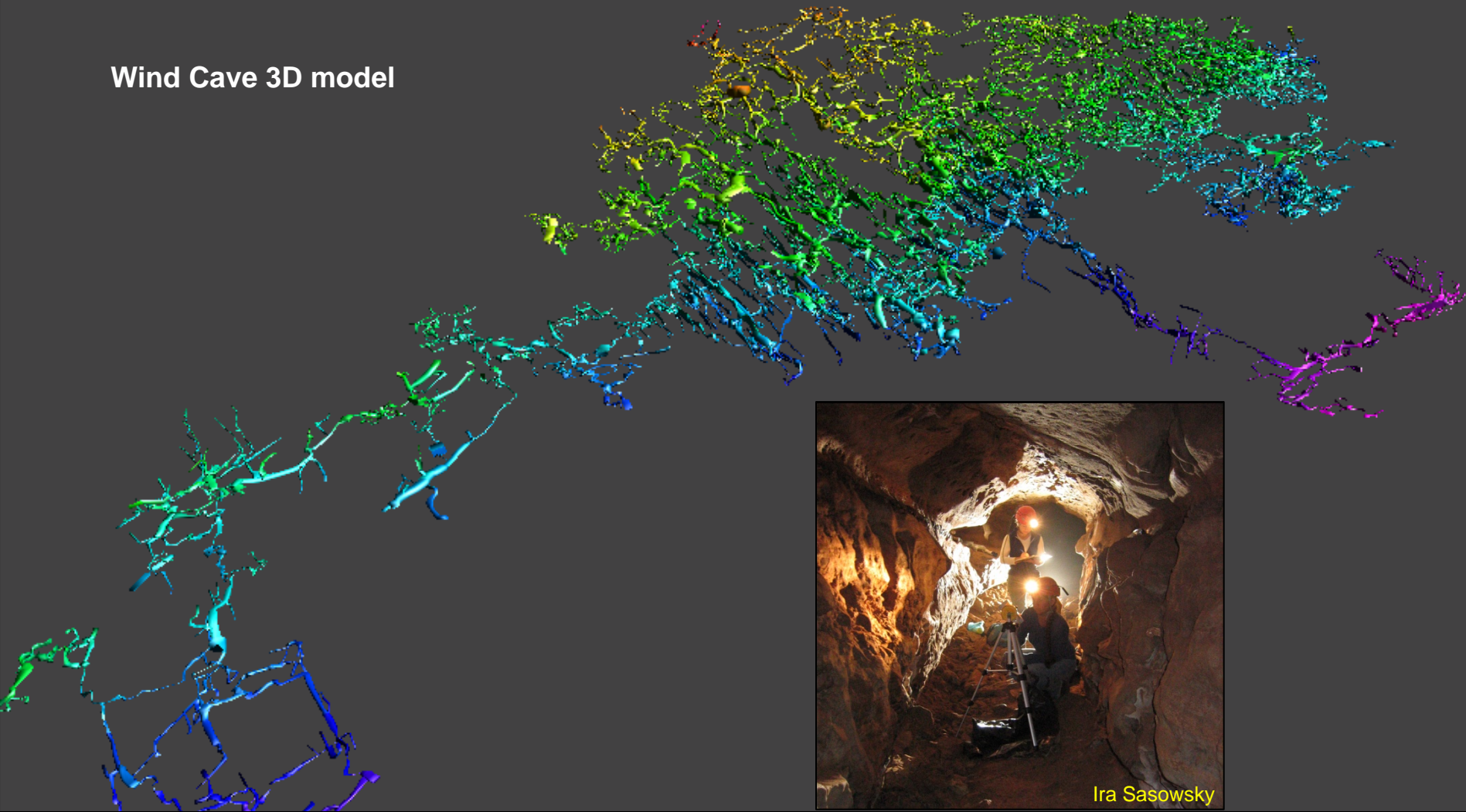
...to complex



Cave surveys can be used to:

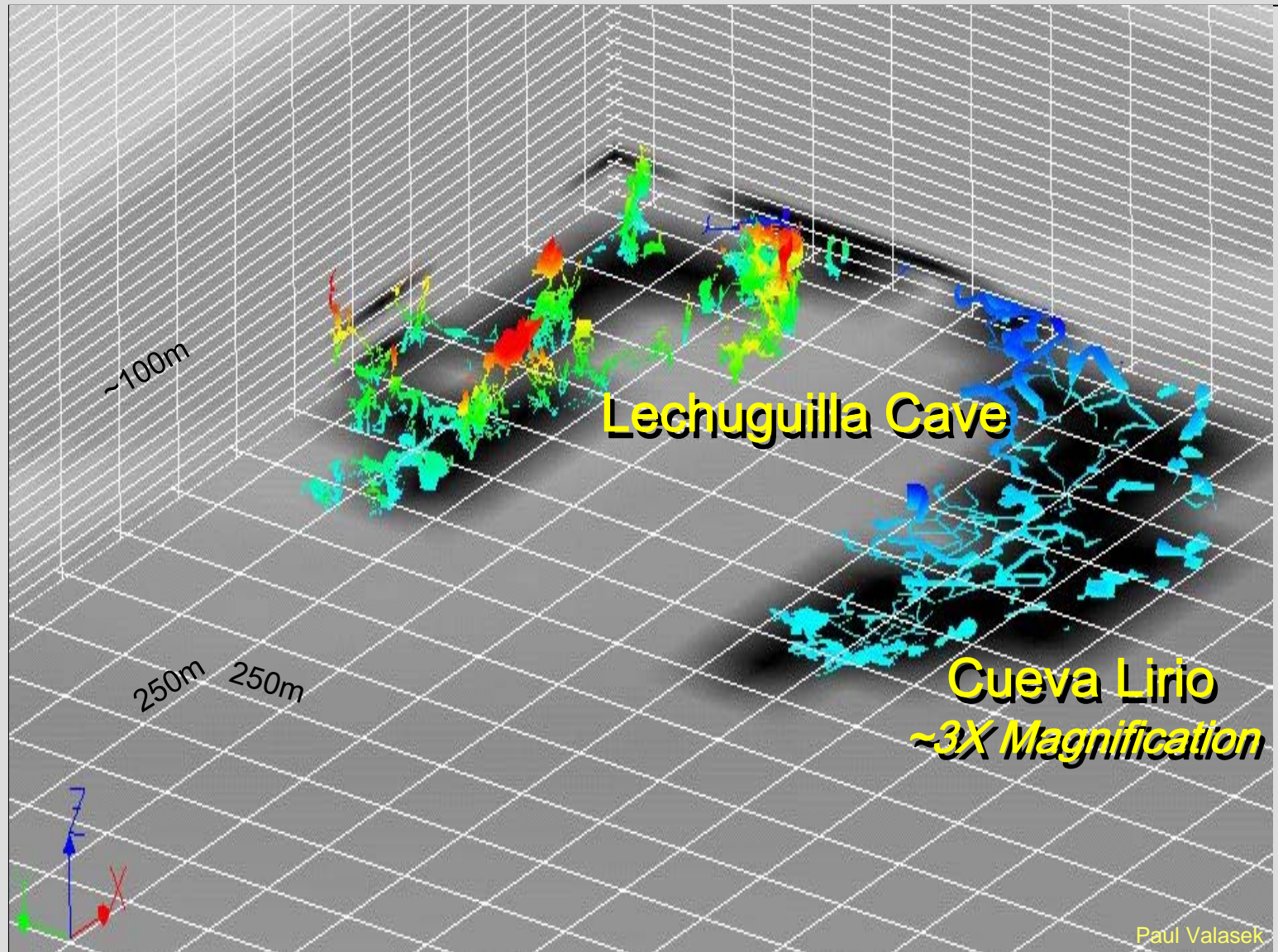
- Assign properties in geocellular models of karsted reservoirs
- Forward model paleokarst seismic response
- Distribute transmissibility in fluid flow-simulation models

Wind Cave 3D model



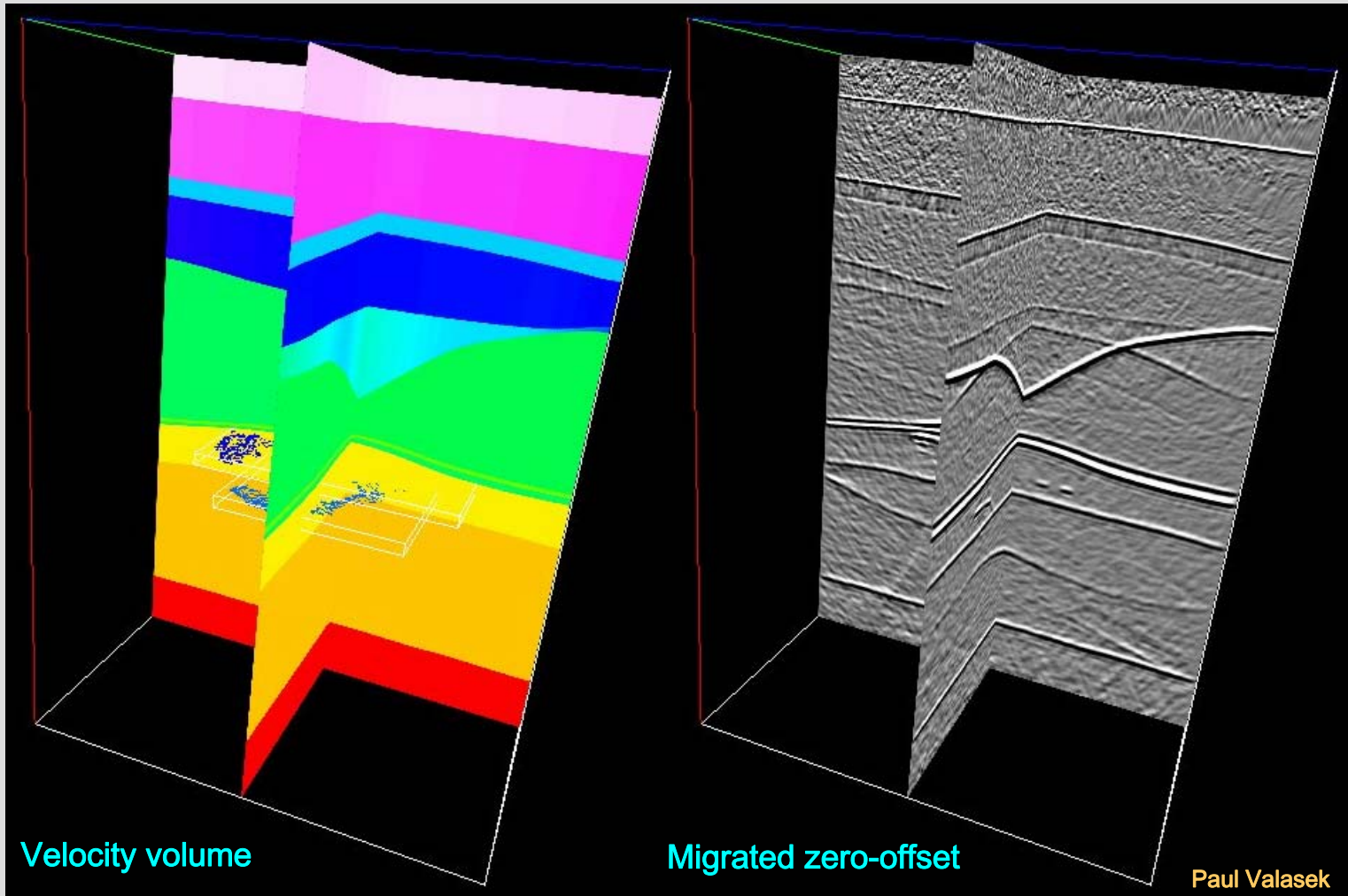
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Seismic Velocity Model



Forward seismic modeling

- Embed 3D cave surveys in seismic velocity model
- Determine sensitivities to cave size, cave-fill properties, and acquisition parameters
 - define thresholds at which caves become detectable

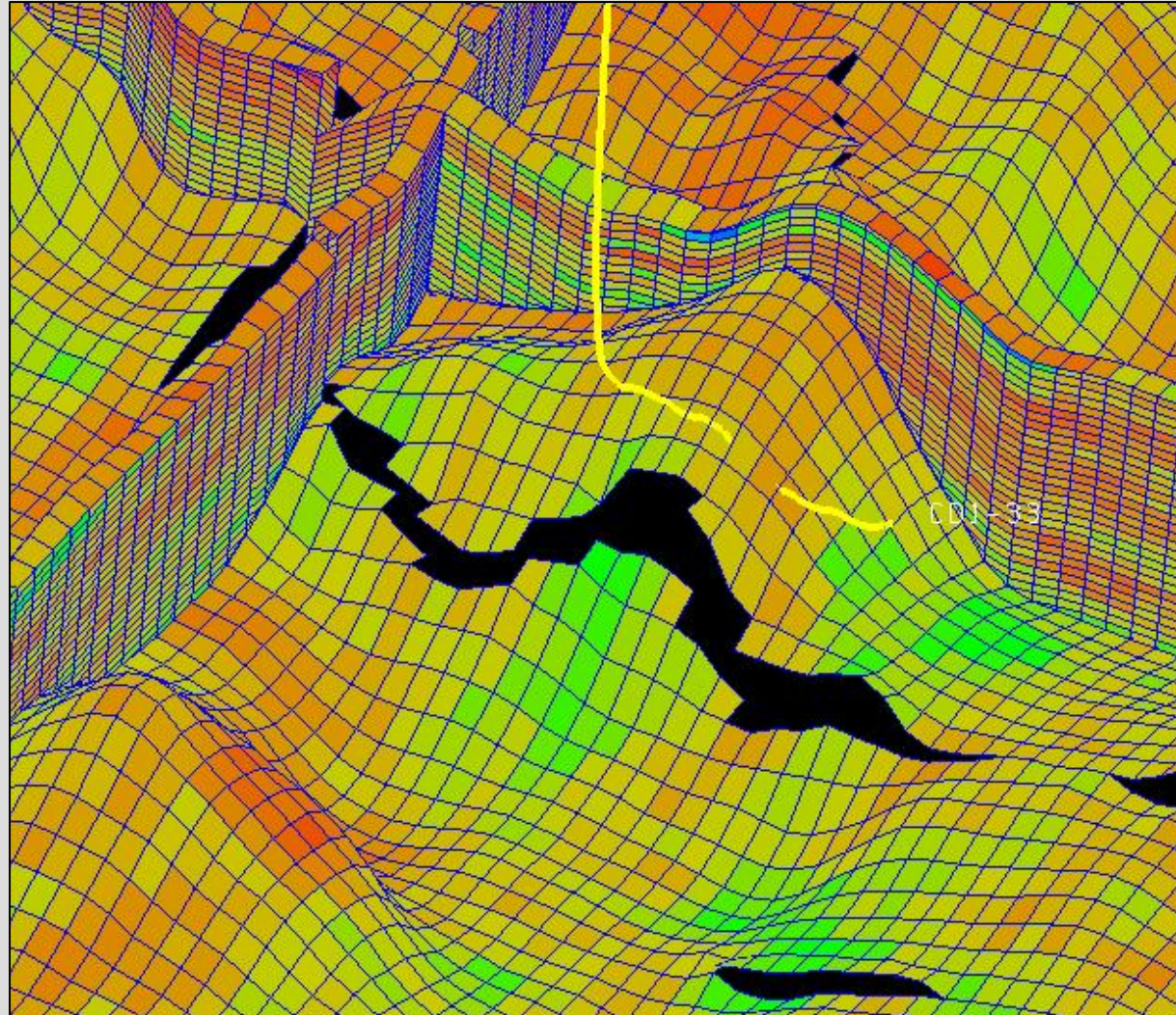


Geocellular modeling:

1. What properties to assign to “karsted” cells?
2. Connectivity: how many “karsted” cells can be neighbors?

For both questions, analogs are useful:

- A small cave that fits inside one model cell
- A large cave network



MODERN CAVE ANALOG

Bluff Dwellers' Cave, Missouri



Low-case cave
(joint-controlled) fits entirely
within one model cell

25 m

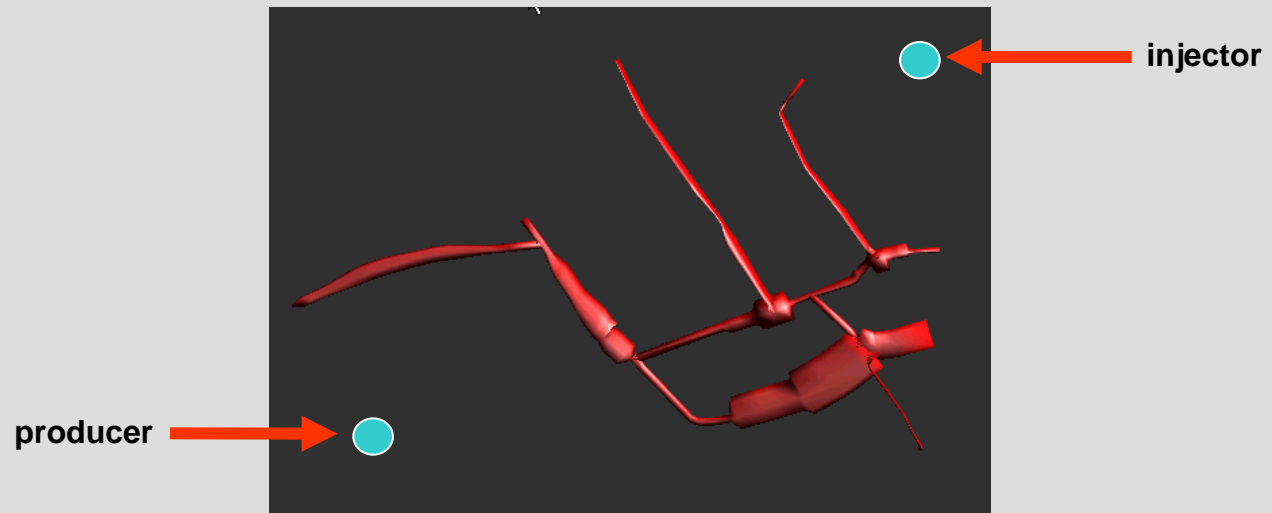


Cave passages = 8% of cell volume
Fractures = additional 7% of volume

Total cell porosity = 0.15 (100%) + .85 (matrix porosity)

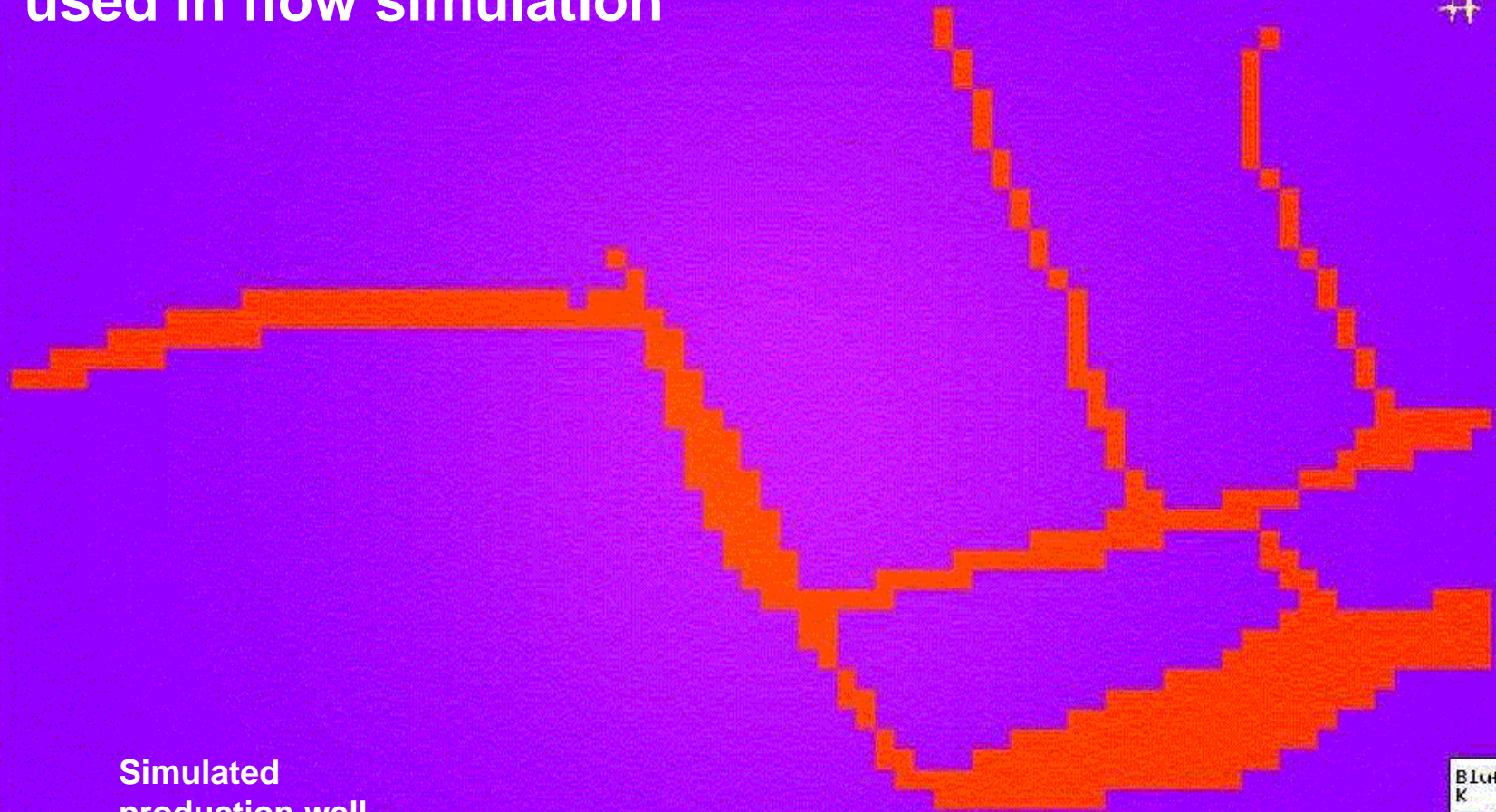
The effect on porosity is minimal, but the changes in permeability can be significant.

Consider an injector-producer pair in the cell containing the Bluff Dwellers' Cave model...

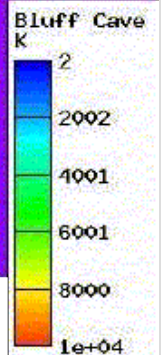


Geocellular model of paleo-cave used in flow simulation

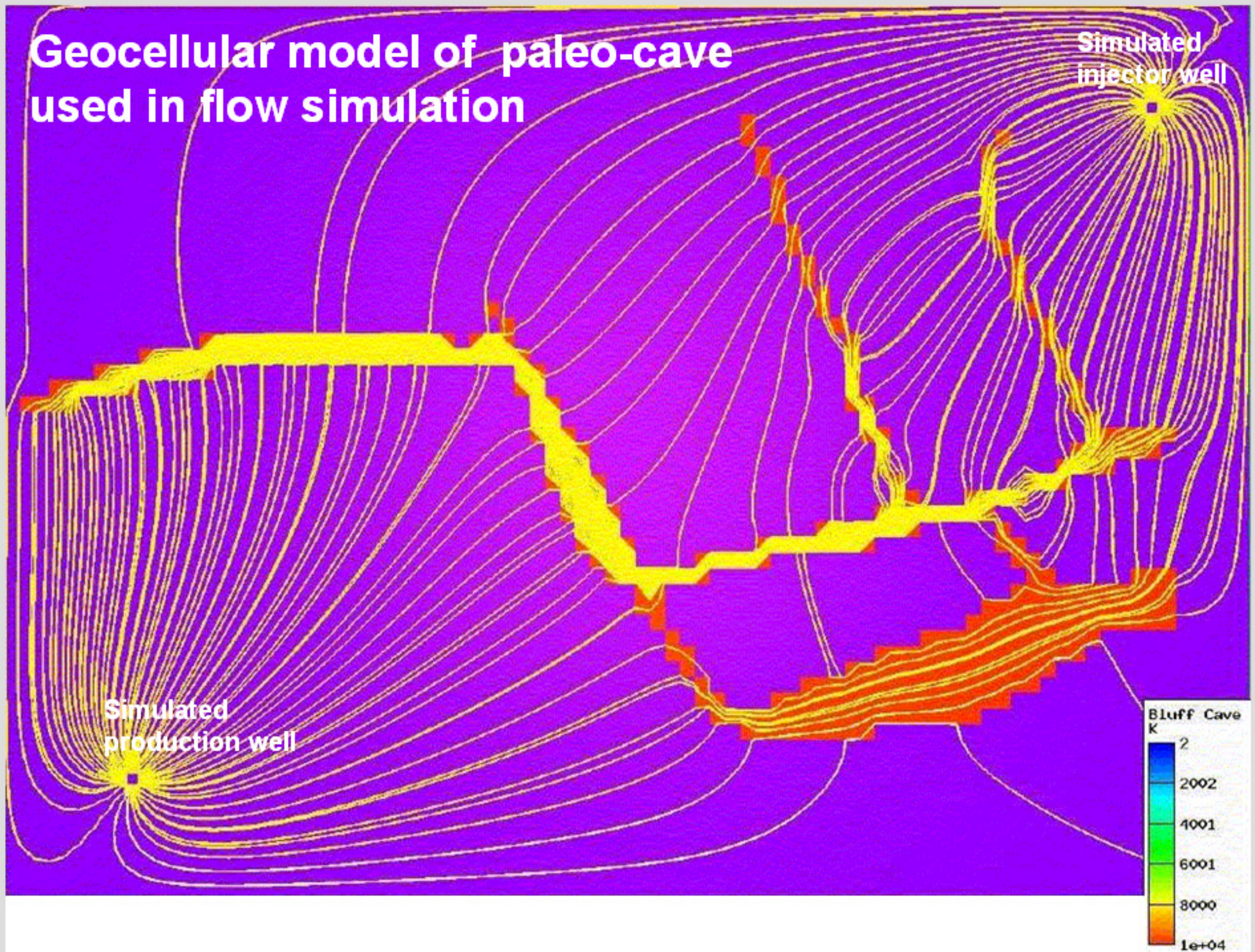
Simulated
injector well
#



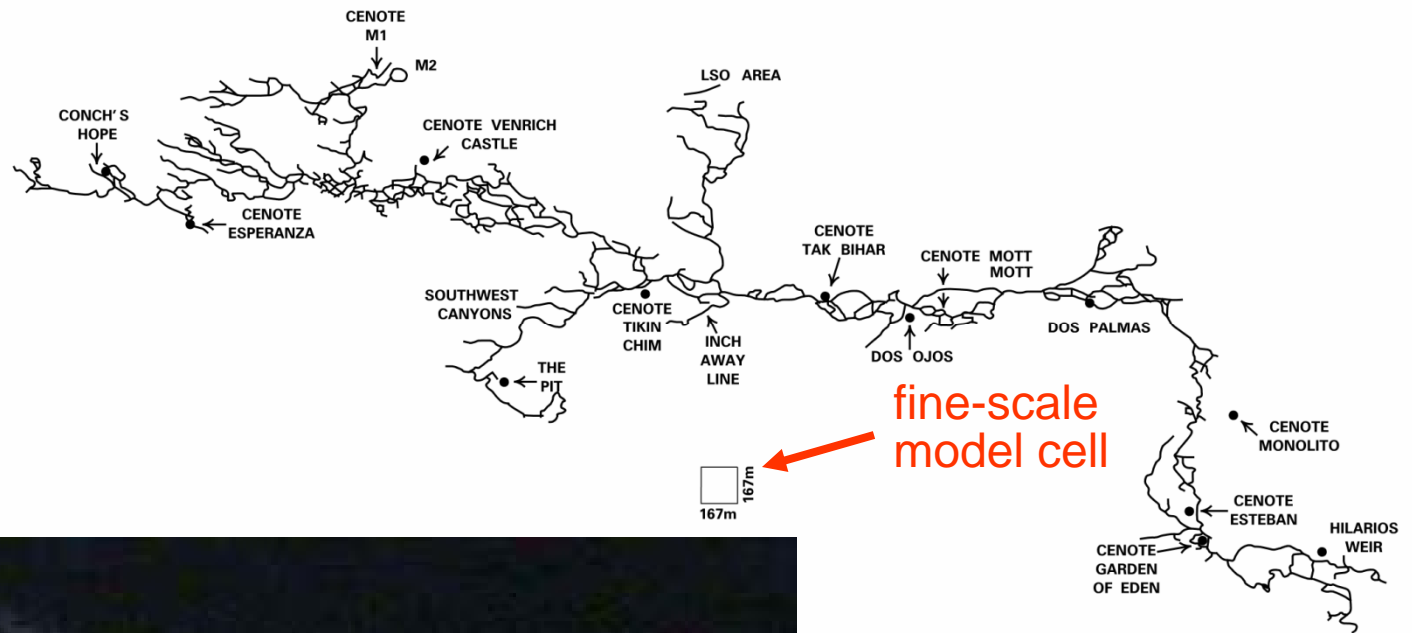
Simulated
production well



Geocellular model of paleo-cave used in flow simulation



**High case:
karst connectivity
is patterned on
flooded Yucatan
cave system,
Mexico**

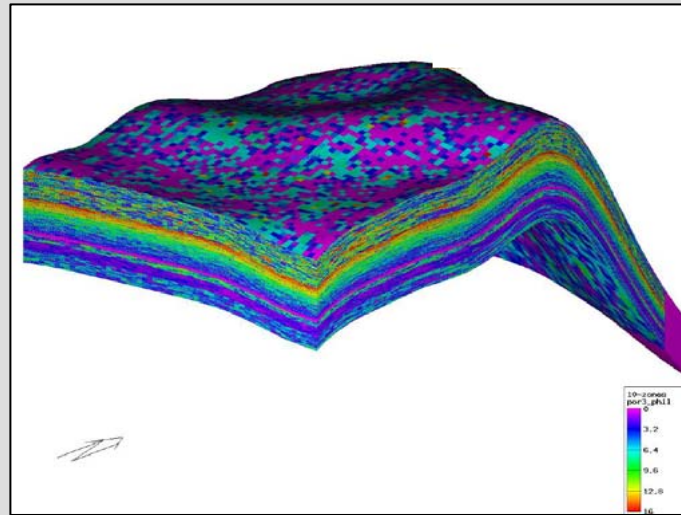


MODERN CAVE ANALOG

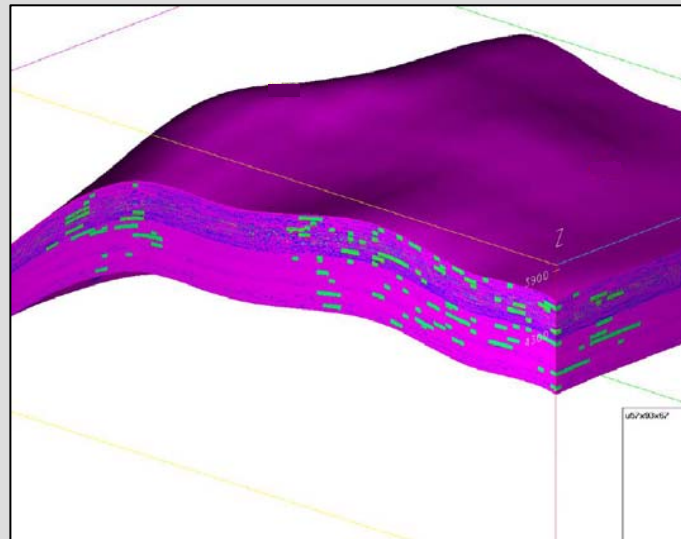
**Dos Ojos Cave System,
Quintana Roo, Mexico**



Incorporating karst in geocellular models

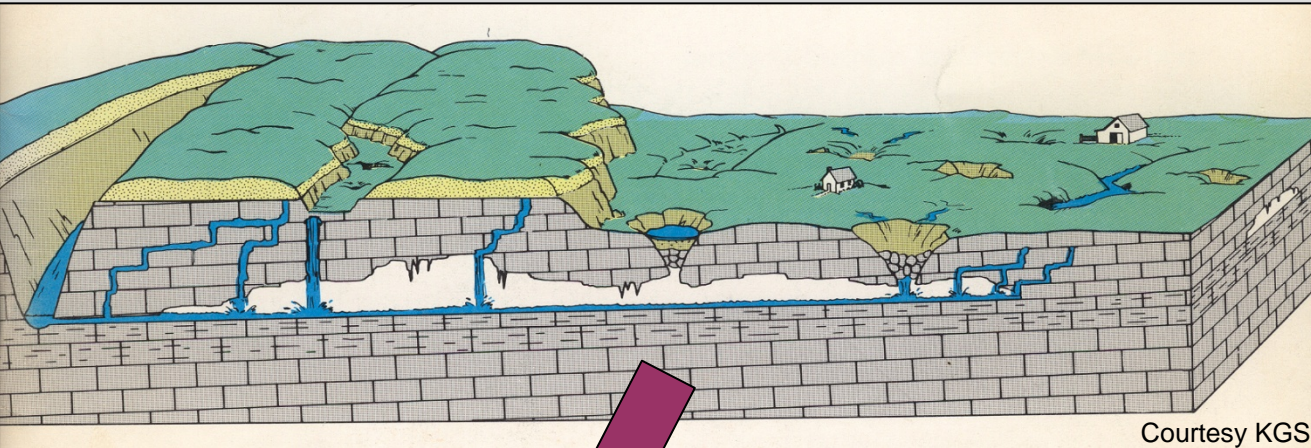


Matrix porosity in geocellular model



“Karsted” cells in geomodel

During burial, cave passages collapse and coalesce



Courtesy KGS

Classification of Paleocave Facies

Undisturbed Strata
Facies
(Undisturbed Host
Rock)

Disturbed Strata
Facies
(Disturbed Host
Rock)

Highly Disturbed Strata
Facies
(Cave-Roof and
Cave-Wall Collapse)



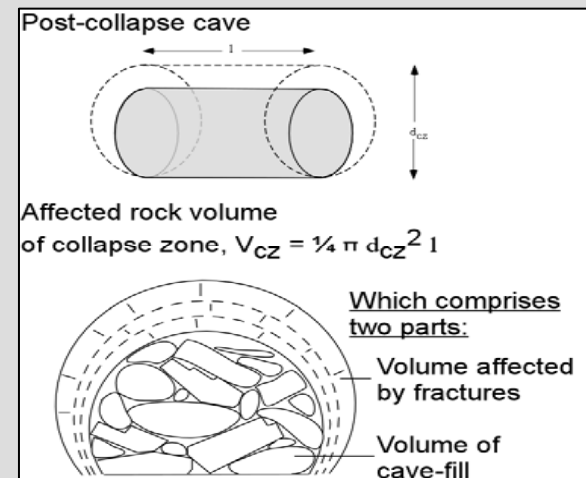
Loucks
(2008)

Sediment-Fill
Facies
(Cave-Sediment Fill)

Coarse Chaotic Breccia
Facies
(Collapse-Cavern Breccia Fill)

Fine Chaotic Breccia
Facies
(Transported-Breccia
Fill)

The exploration target enlarges:
We don't need to drill into
a former cave passage,
just into fractures that are
in pressure communication



CONCLUSIONS

- Karsted reservoirs can be prolific oil & gas producers
- Karst processes are complex, but not random, and respond to
 - Lithology
 - Climate
 - Tectonics
 - Relief
 - Sea-level fluctuation
- Paleokarst can be recognized in
 - Seismic volumes
 - Cores
 - Drilling histories
 - Logs
- Maps and models of modern caves facilitate understanding (mapping, modeling & predicting) of paleokarst reservoirs

QUESTIONS?

