Evaporite Paleokarst on a Tectonically Enhanced Unconformity, Mississippian Madison Formation, Wyoming, USA*

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Abstract

Exploitation of hydrocarbons from strata with evaporite paleokarst development can be challenging due to tremendous permeability variability as a result of disrupted bedding, irregular pore types, allochthonous and autochthonous sediment fills and the development of persistent fractures throughout. Porosity networks and permeability barriers linked to evaporite paleokarst are critical elements of major hydrocarbon accumulations, such as the Madison Formation of the Bighorn Basin. The extensive suprastratal deformation can create substantial permeability heterogeneity, directly juxtaposed to the dissolution zones themselves that commonly form low-flow baffles or barriers. Despite these important and widespread characteristics, no systematic treatment of this style of carbonate reservoir heterogeneity exists and as a result of the "vanished" nature of the key controlling lithofacies, these systems are commonly controversial and poorly understood. The Upper Mississippian Madison Group offers a superb, if not spectacular, exposure of laterally continuous evaporite paleokarst zones. Many studies have described solution-enhanced zones within the Madison. The focus of this study is the reservoir-heterogeneity scale issues associated with this evaporite removal system. Thus, we build upon the impressive regional syntheses available for this Mississippian platform and treat a limited number of key localities in Wyoming and Montana in some detail. Observations from these localities have led to a list of criteria for recognition of evaporite paleokarst that, while based on the Madison, are also

present in other evaporite paleokarst systems. We interpret the timing of the paleokarst system, including the two distinct styles of paleokarst: end Madison subaerial exposure and the intrastratal solution collapse. We relate this to overall paleogeography and tectonic elements within the Late Mississippian. Finally, we highlight important observations regarding reservoir architectural elements that have significant implications for hydrocarbon development, especially in the form of highly fractured strata above the evaporite removal zone.

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Website

Laricina Energy Ltd., www.laricinaenergy.com. Website accessed October 2, 2015.

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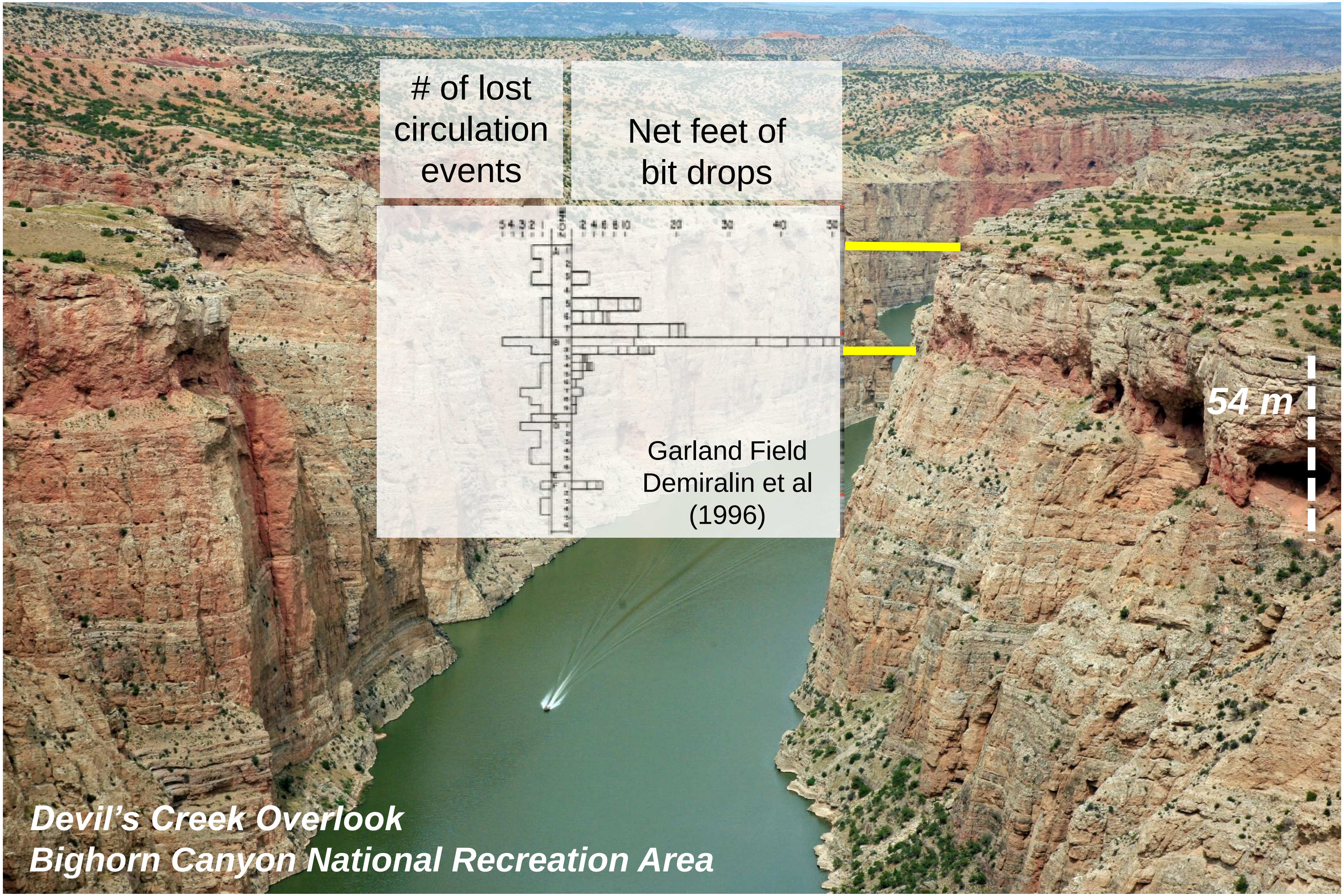
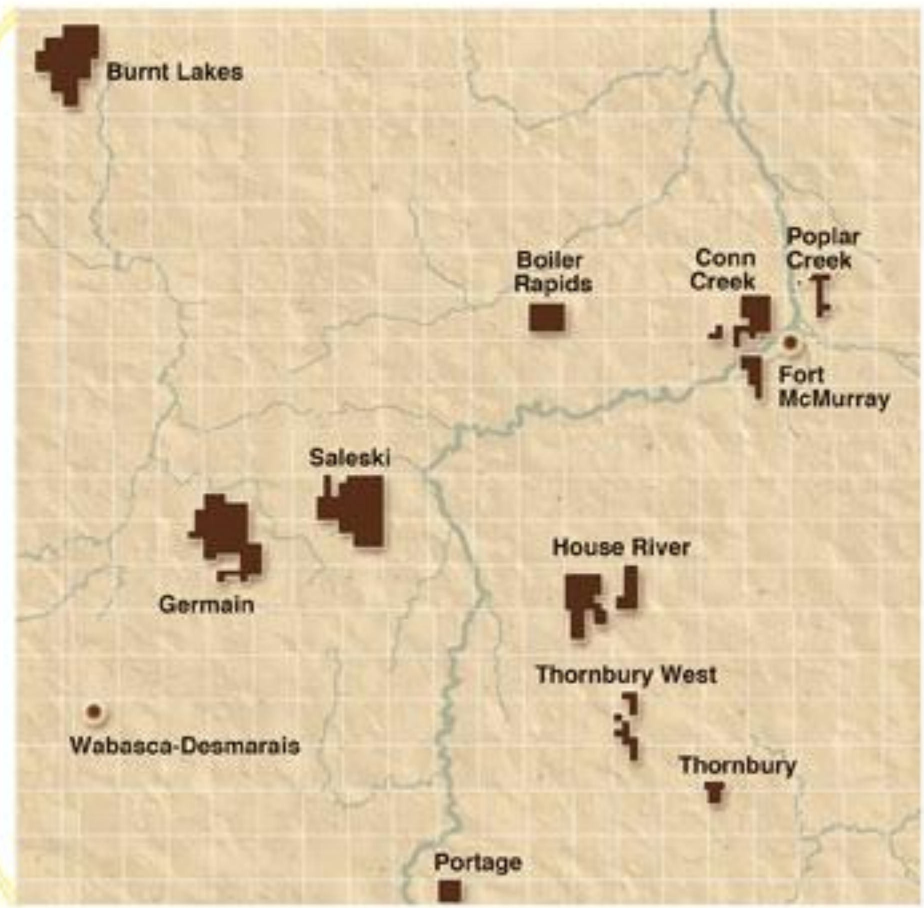
1 – Bureau of Economic Geology
2 - Department of Geosciences
3 – Now with Oxy Permian
4 - Now with Marathon Oil
5 - Now with EOG Resources

June 2015

Paleokarst – A Significant Reservoir Element



Challenged Reserves – Devonian Grosmont



Source: www.laricinaenergy.com

>500 billion barrels of heavy crude within Grosmont

Key general applications

- Knowledge of paleotectonics and paleogeography are essential elements in characterization of paleokarst

- Distinct criteria define evaporite-rich vs. epigenenic paleokarst systems

- Paleokarst systems, especially over broad areas, are complex and can be the result of multiple geologic processes

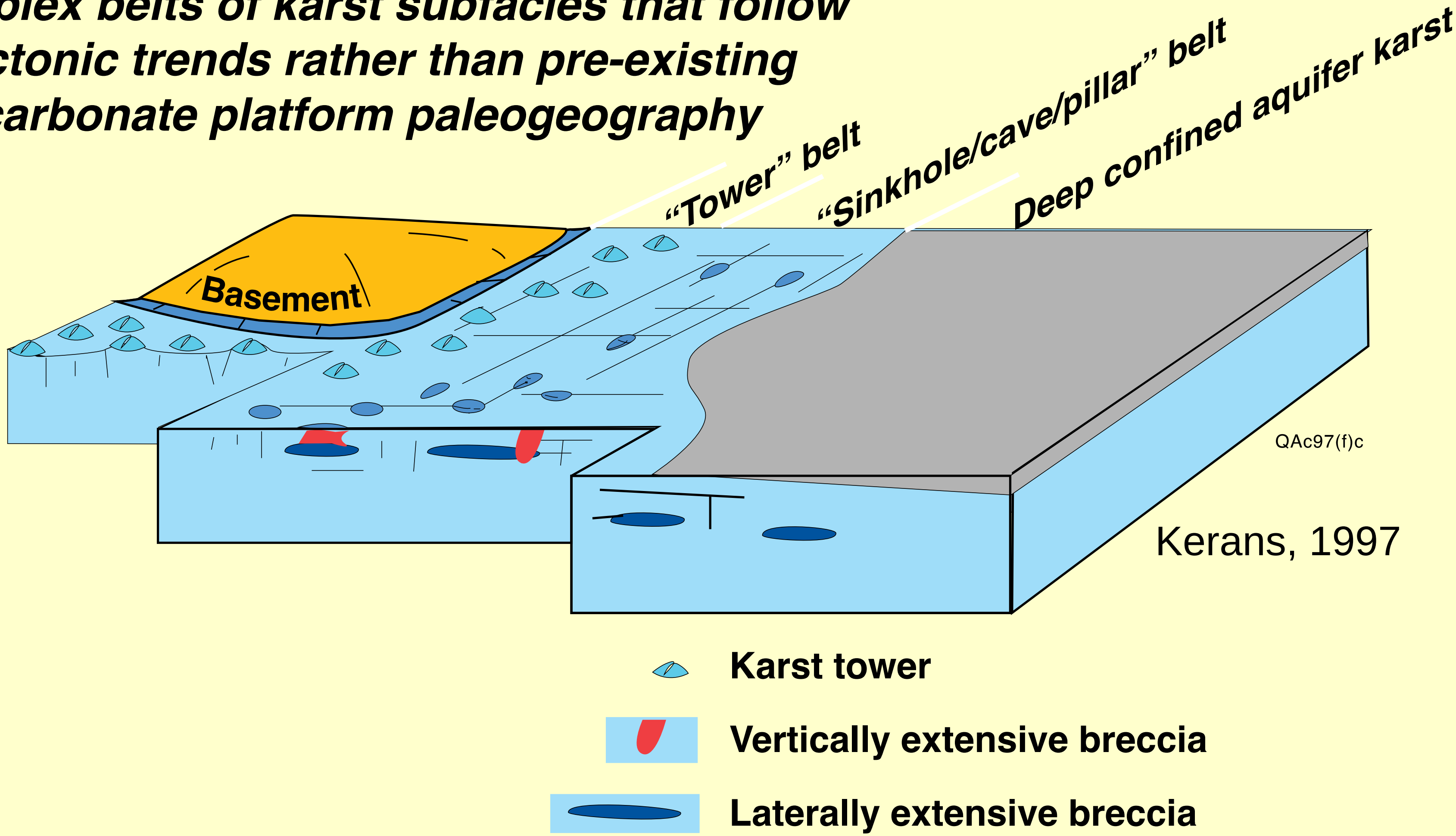
Paleokarst Classification by Unconformity Driver/Rank

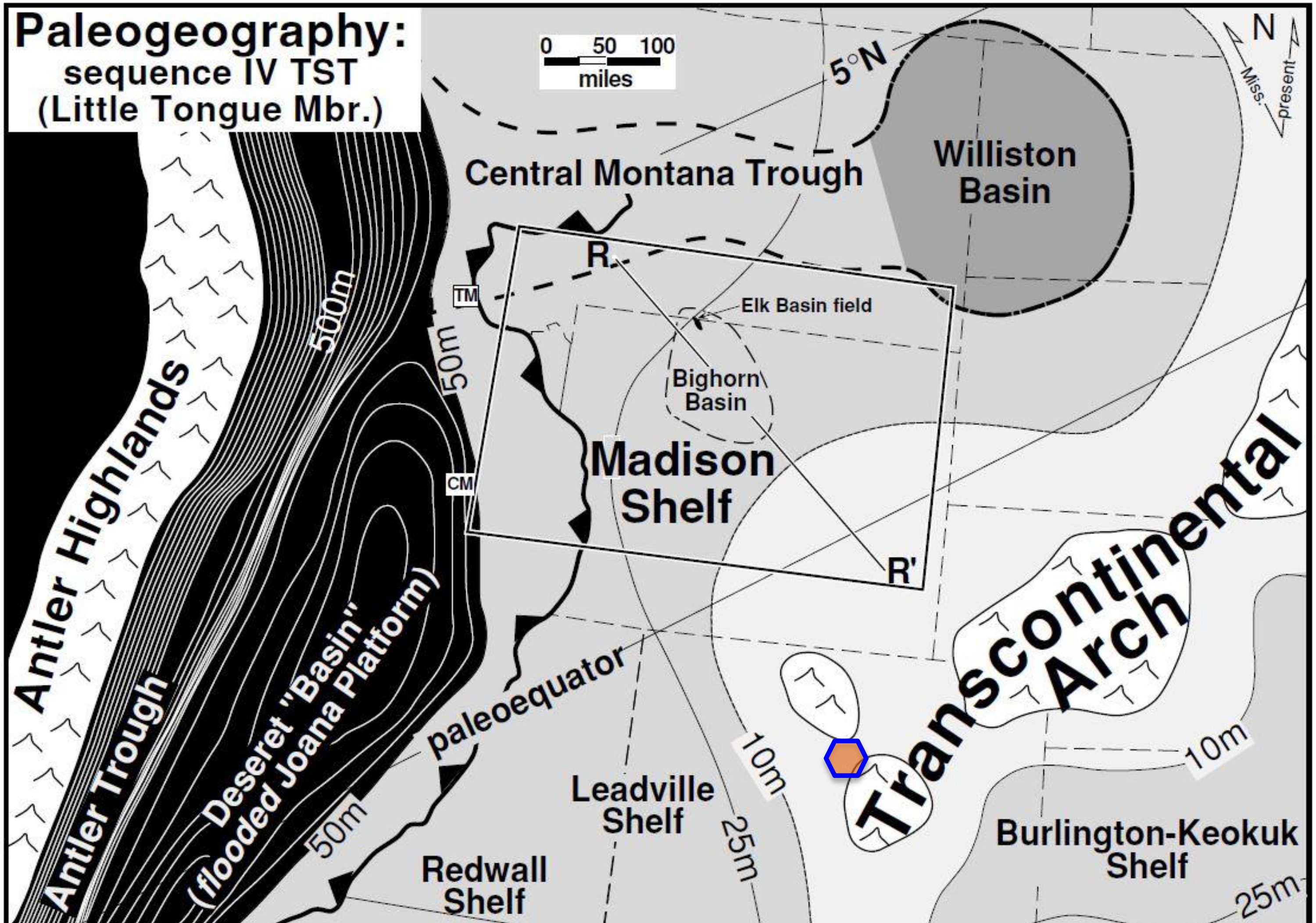
Order/ Rank	Tectonic/ Stratigraphic Unit	Base-Level Driver		Unit Duration	Unconf. Time Span	Reservoir Examples
1st*	Tectonic Element, Fold-Thrust Belt	Compressional tectonism, local or plate-wide	subsidence/ uplift	>20 my	20-500 my	Renqiu, Grosmont Casablanca, Rospo Mare, Golden Lane
2nd	Supersequence, Supersequence set	Tectono-eustacy		20-40 my	10-40 my	Ellenburger fields, Madison Elk Basin, Garland
3rd-4th	Composite Sequence, High-Frequency Sequence	Glacio-eustatic or tectono-eustatic	eustatic fall	0.1-3 my	<1 my	Devonian platforms, Permian margins ex. Kingdom,Yates, Hobbs, Cret. Shuaiba, Miocene Jintan
5th	High-Frequency Cycle	Glacio-eustatic		0.02-0.04 my	<0.1 my	Icehouse platforms, Sacroc, Salt Creek

Kerans, RCRL

2nd Order Supersequence - Paleokarst Characteristics

Complex belts of karst subfacies that follow tectonic trends rather than pre-existing carbonate platform paleogeography



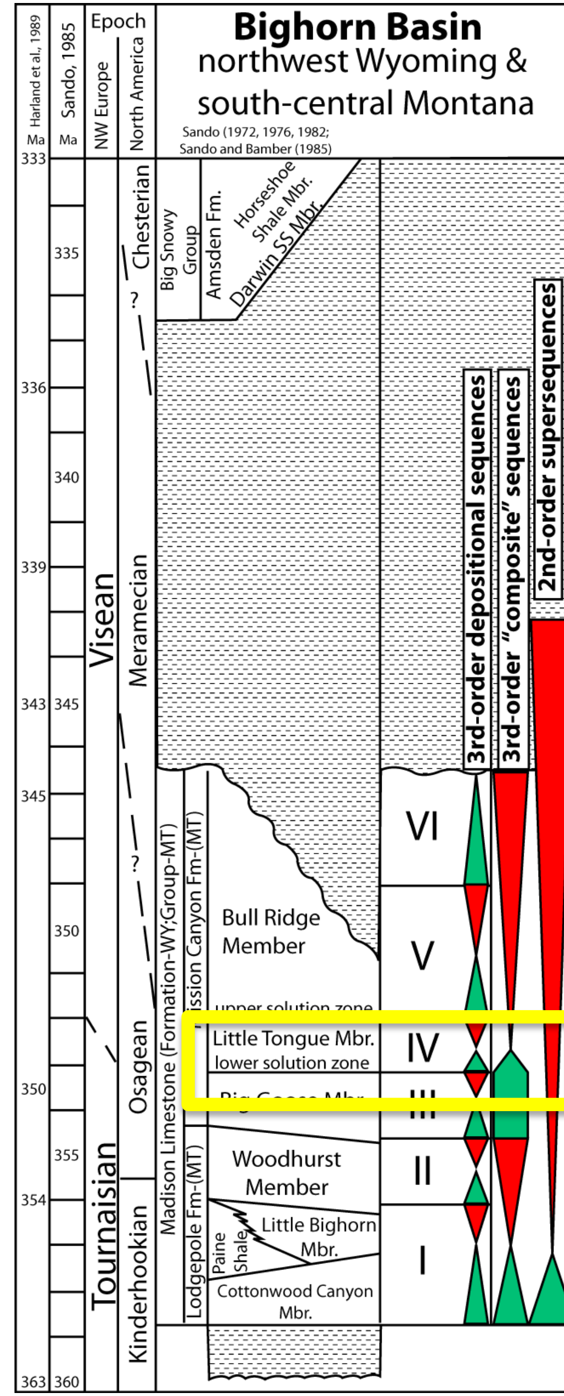


Modified from Gutschick and Sandberg (1983), Sonnenfeld (1996)

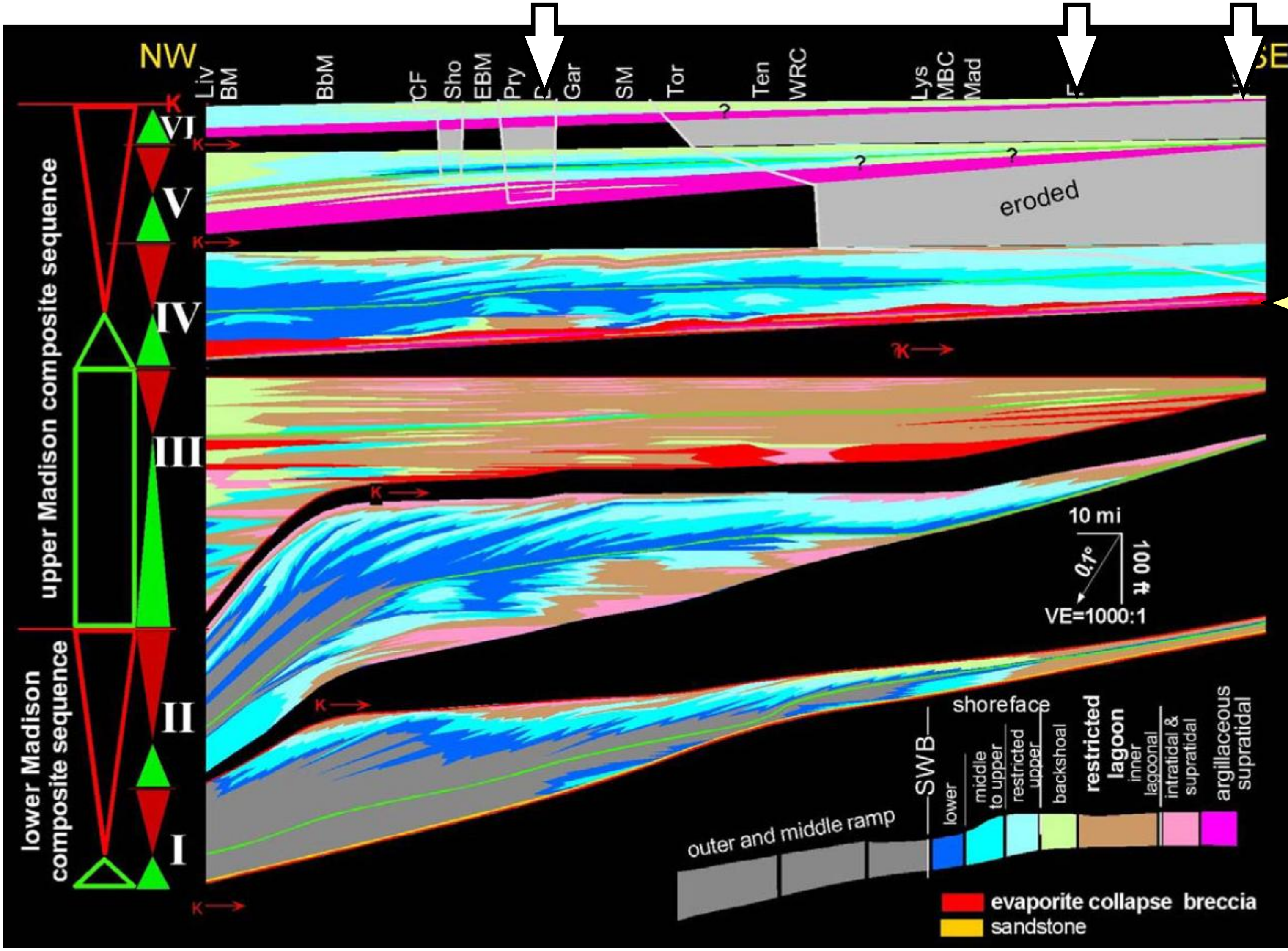
Stratigraphic zone of interest

Sando (1972) – Little Tongue Member / Lower Solution Zone

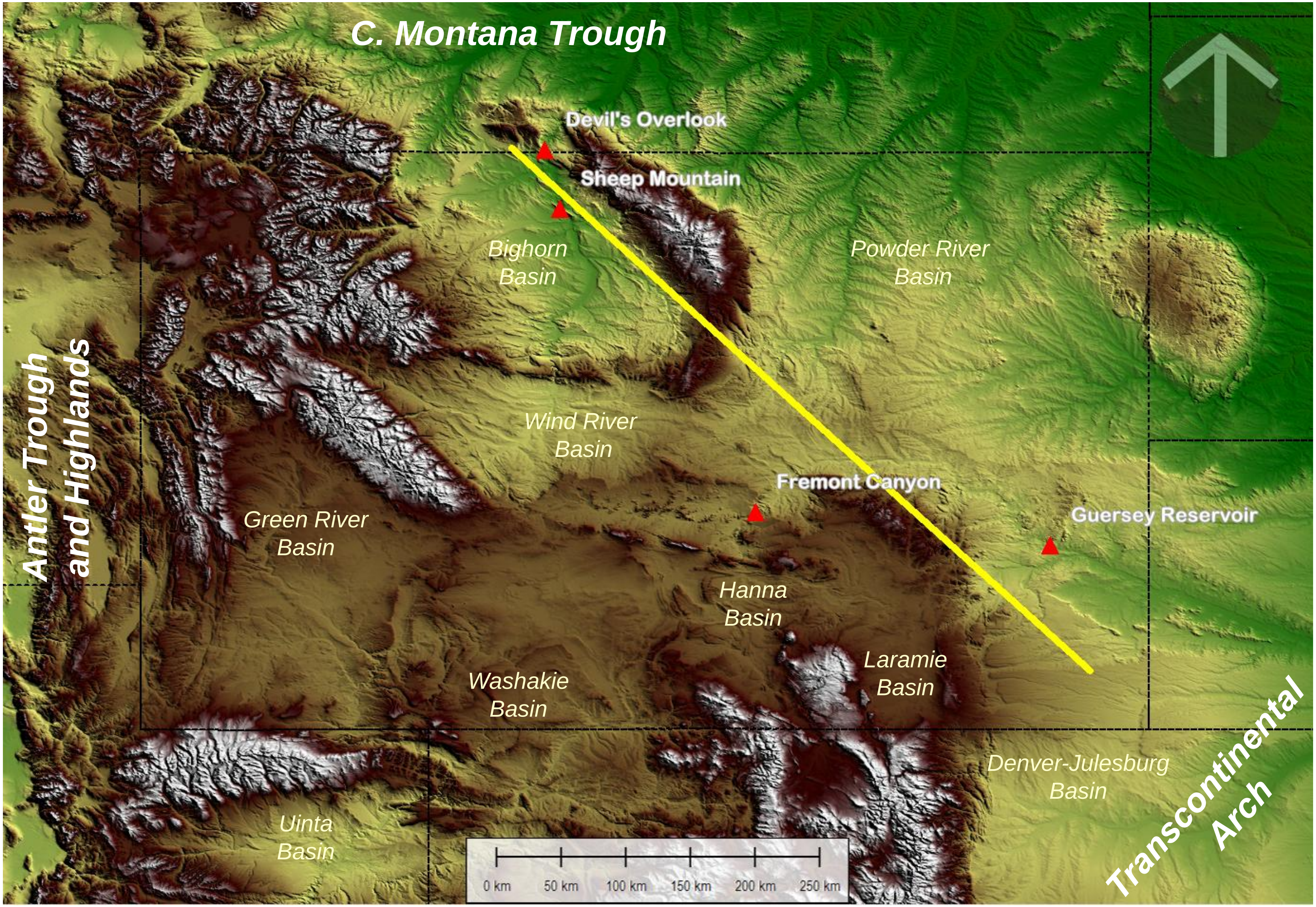
Sonnenfeld (1996) – Sequence IV



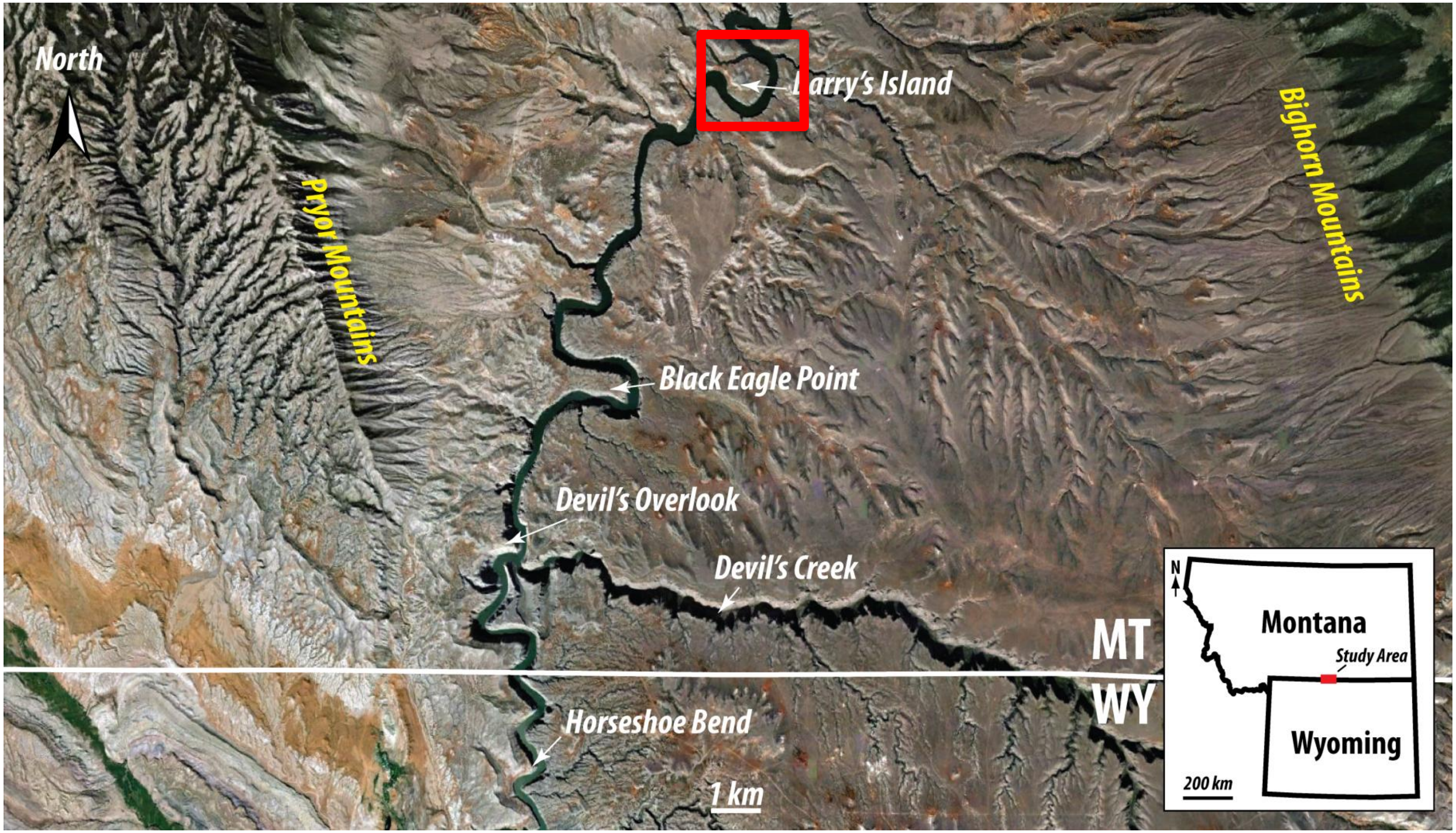
Madison Stratigraphy – Sonnenfeld, 1996



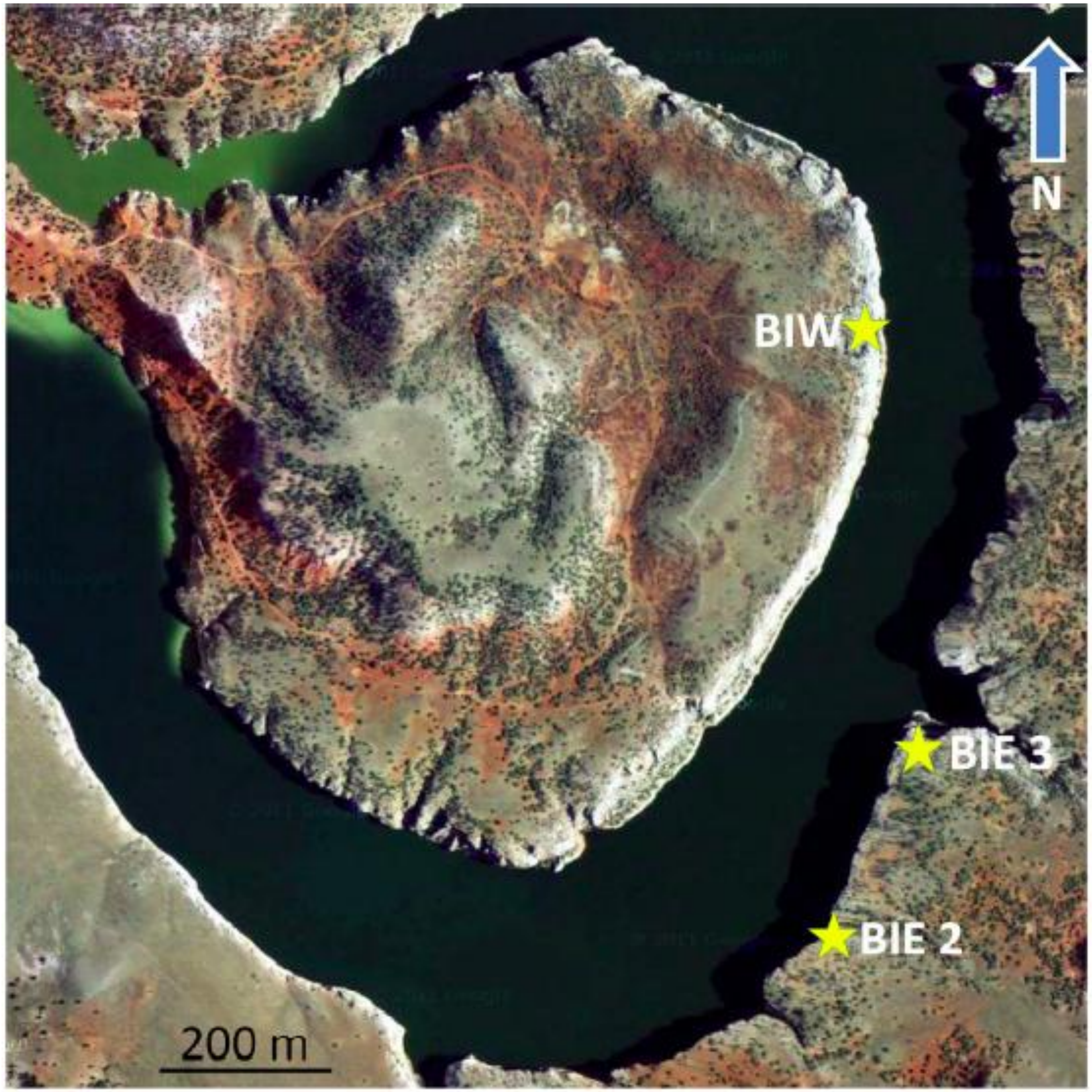
Regional evaporite near base of Seq. IV


C. Montana Trough
Devil's Overlook
Sheep Mountain
Bighorn Basin
Powder River Basin
Wind River Basin
Antler Trough and Highlands
Fremont Canyon
Guersey Reservoir
Green River Basin
Hanna Basin
Laramie Basin
Washakie Basin
Denver-Julesburg Basin
Uinta Basin
Transcontinental Arch
0 km
50 km
100 km
150 km
200 km
250 km

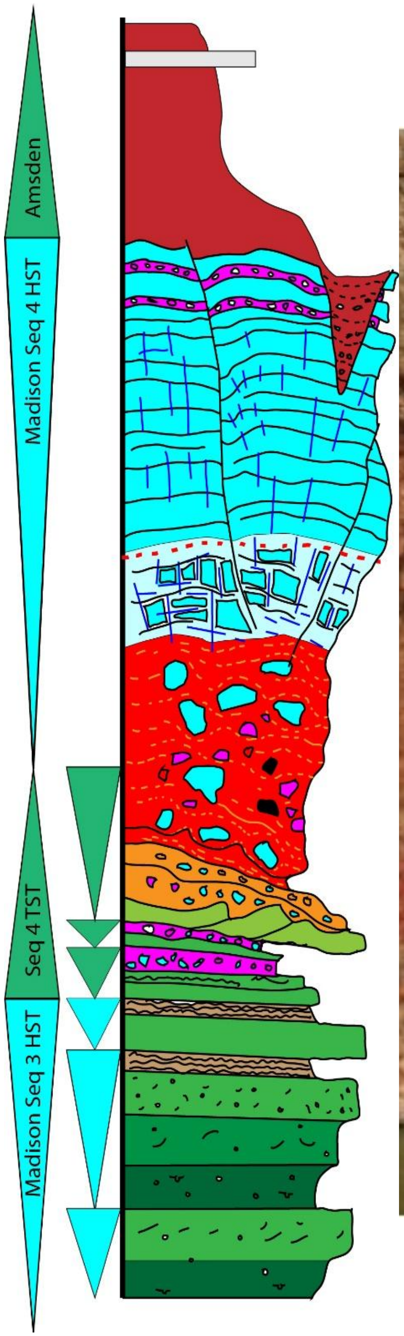
Bighorn Canyon – Localities of Interest

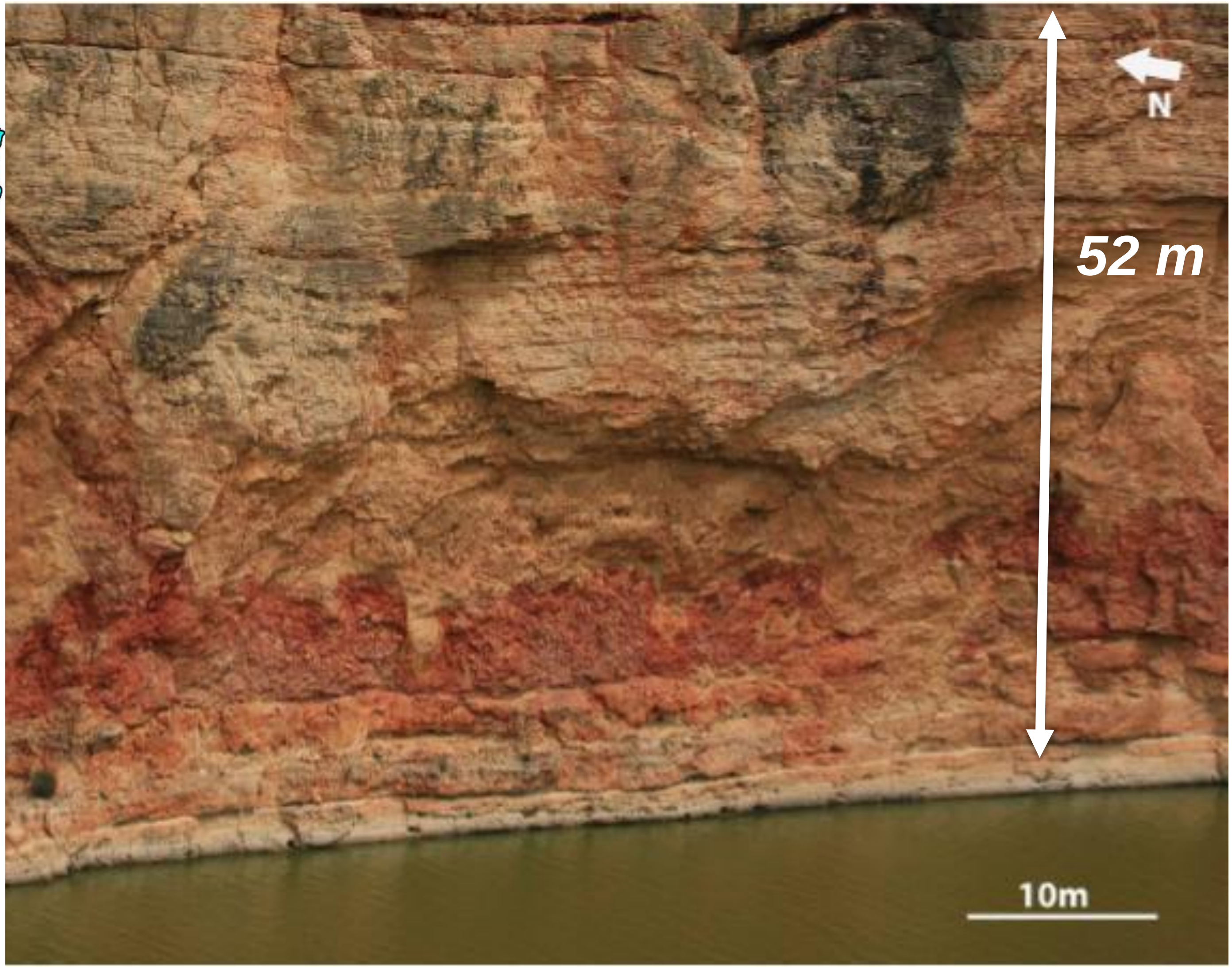


Barry's Island Outcrop Locality – Measured Section

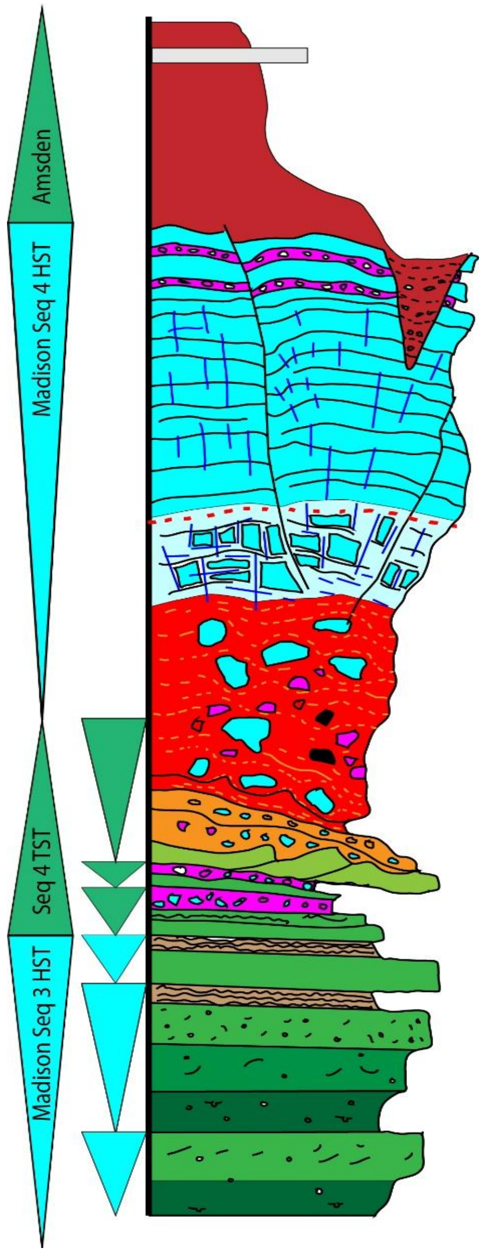


Sequence IV dissolution stratigraphy





Paleokarst Stratigraphy – Barry's Island Section



F – Fracture breccia

D – Mosaic breccia

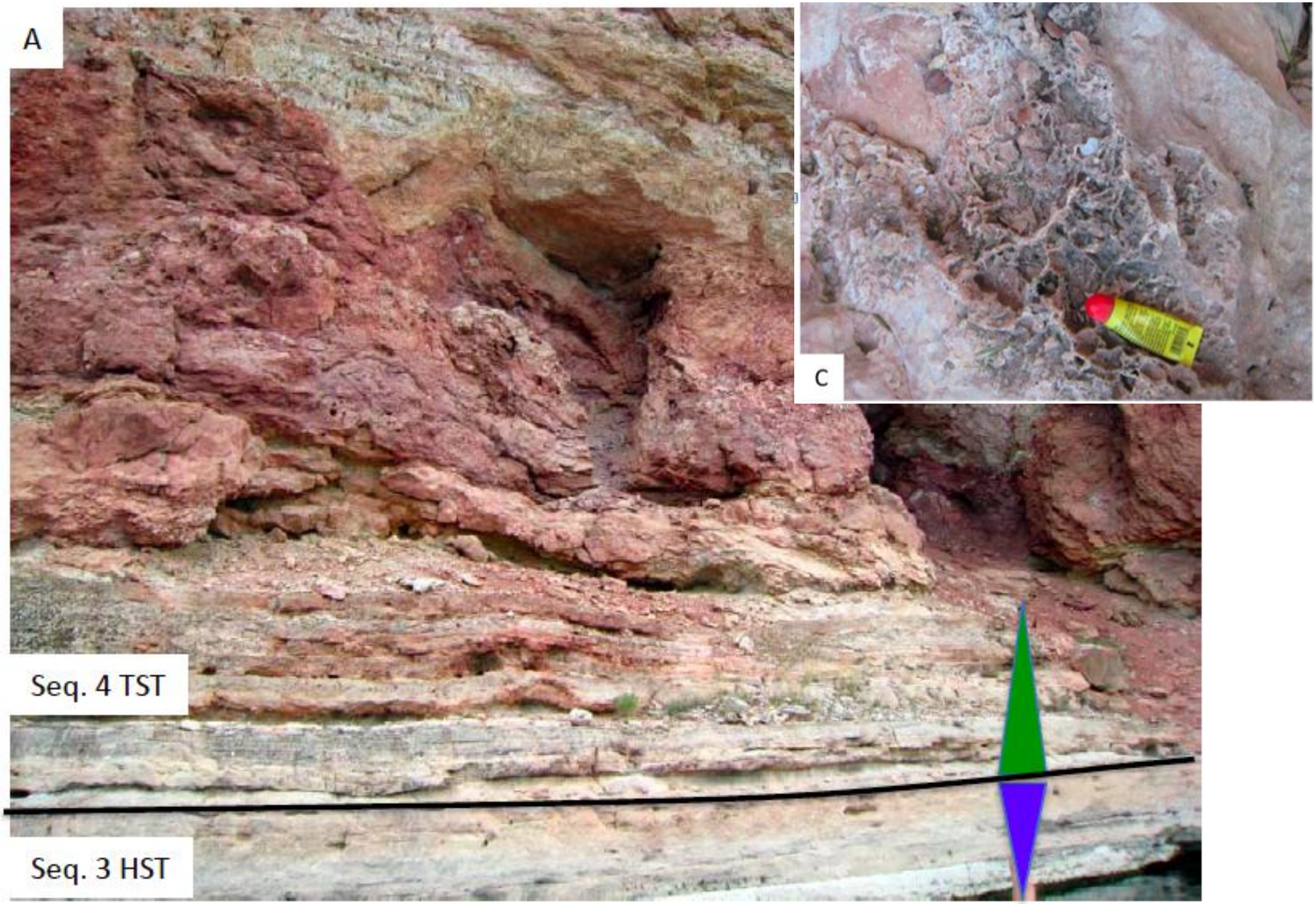
C_2 – Clast and matrix-supported limestone breccia

C_1 – Matrix-supported dolomicrite and matrix-supported gravity flows

B – basal thrust faults

A – Seq. III HST shallow subtidal

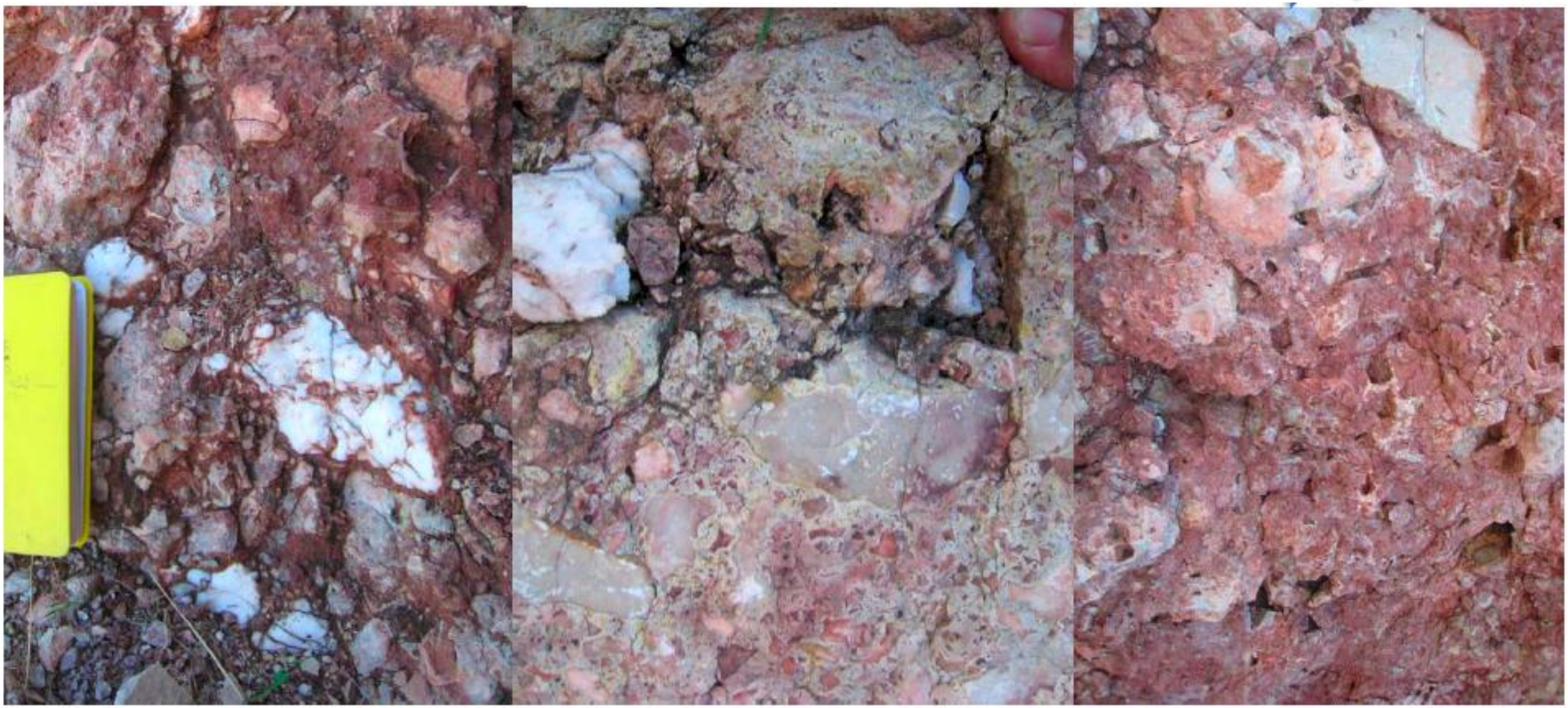
Basal evaporite-bearing cycles



Intrastratal deformation – lower collapse

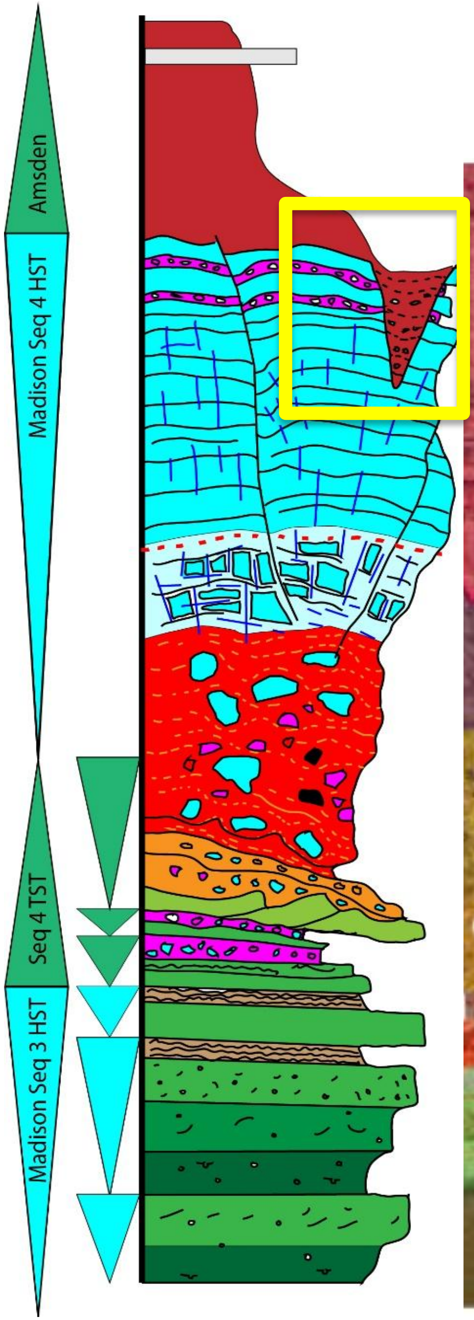
Evidence of evaporite removal

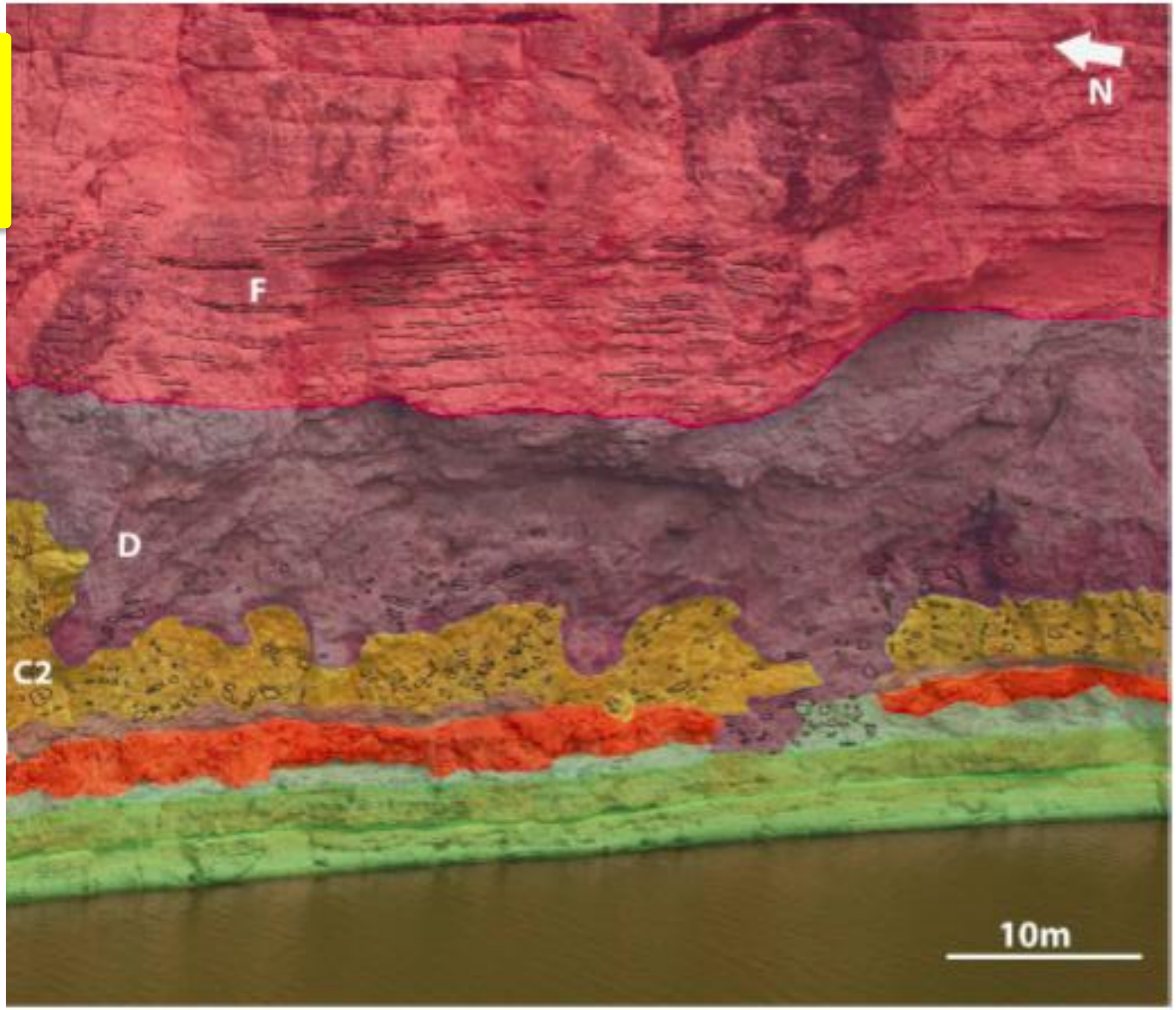
Progressive evaporite removal



C_1 basal sediment infill

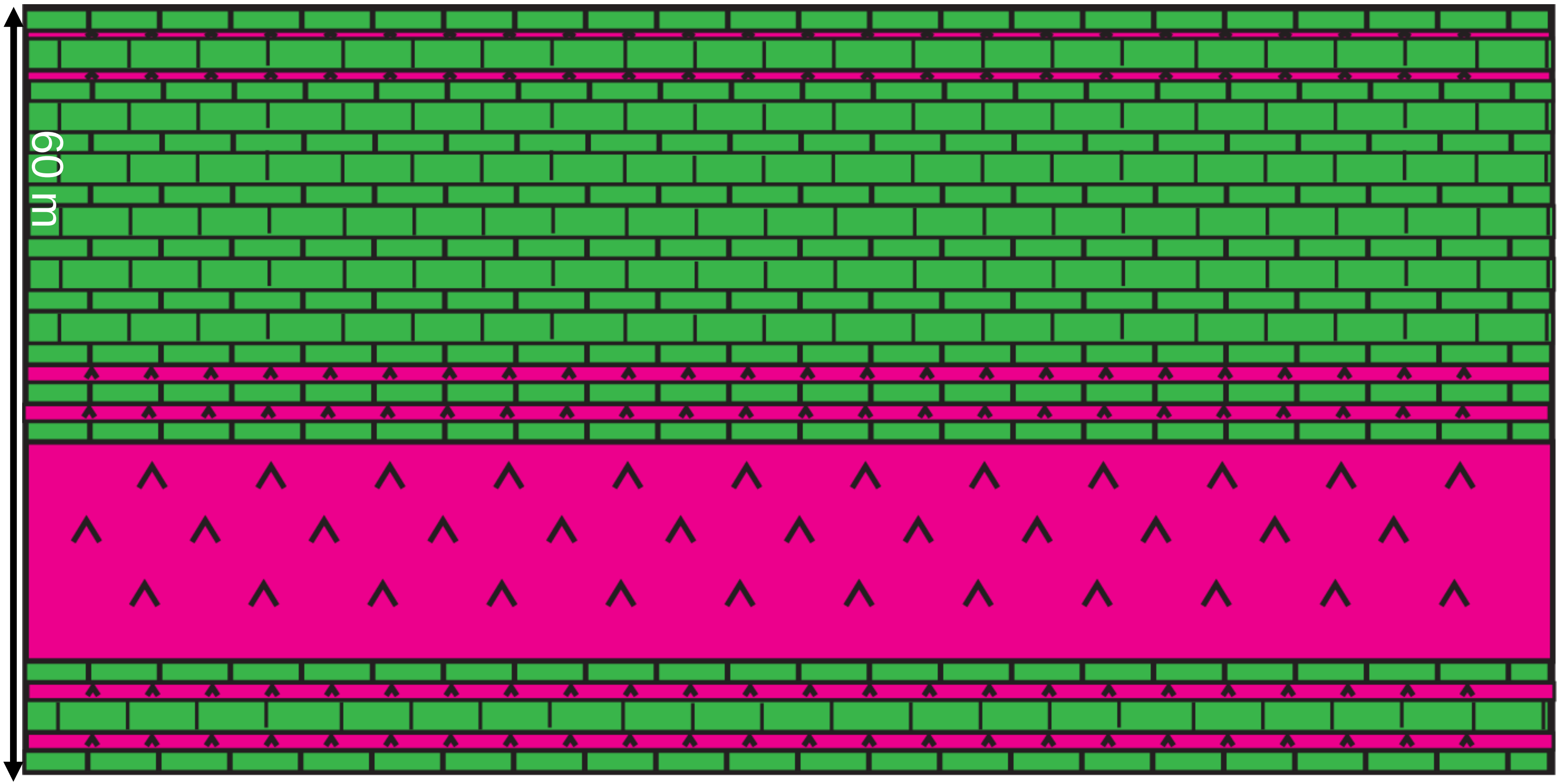
Interpreted Outcrop Photo



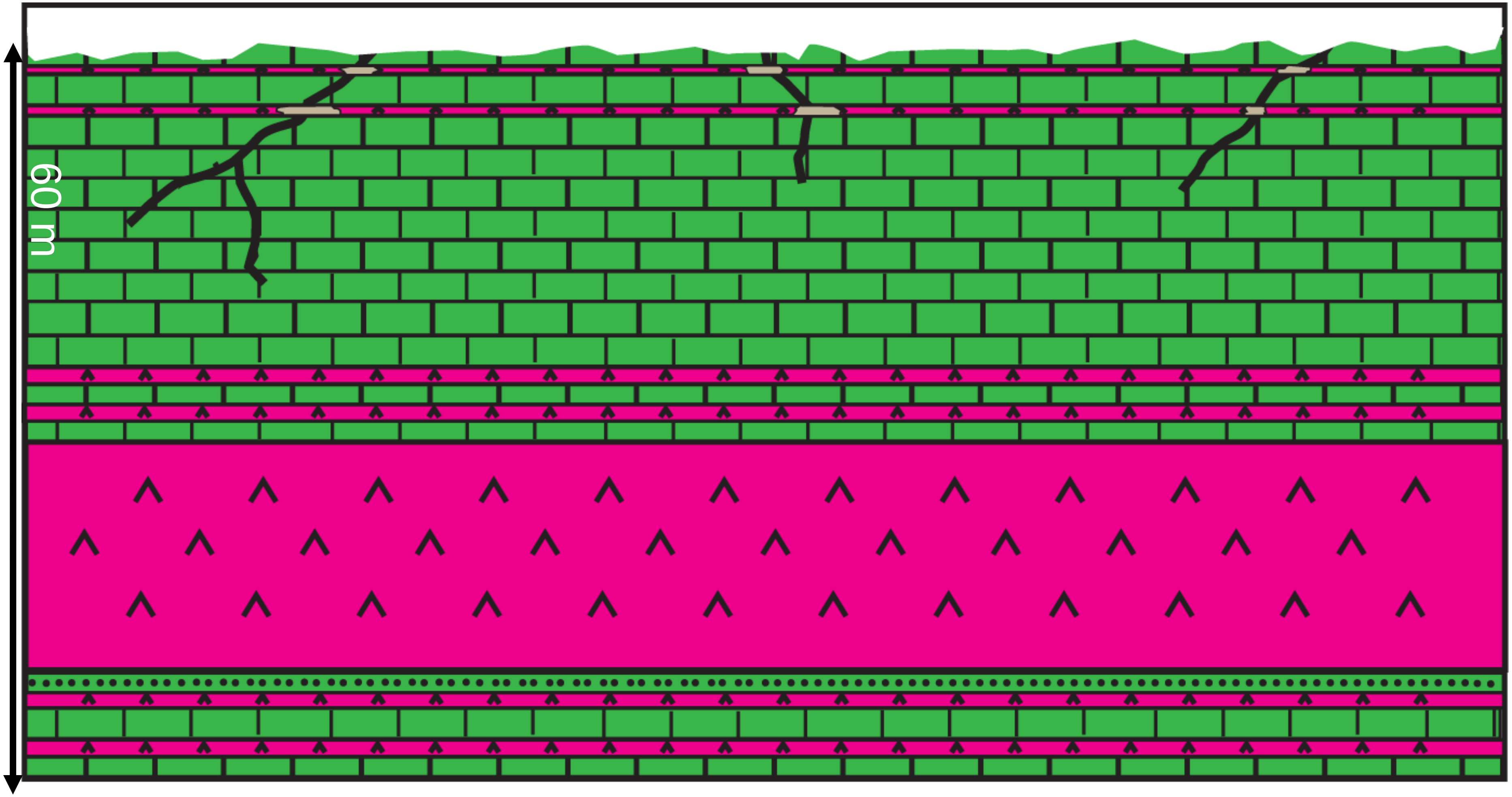


20-mile Dissolution Pipe and Fill

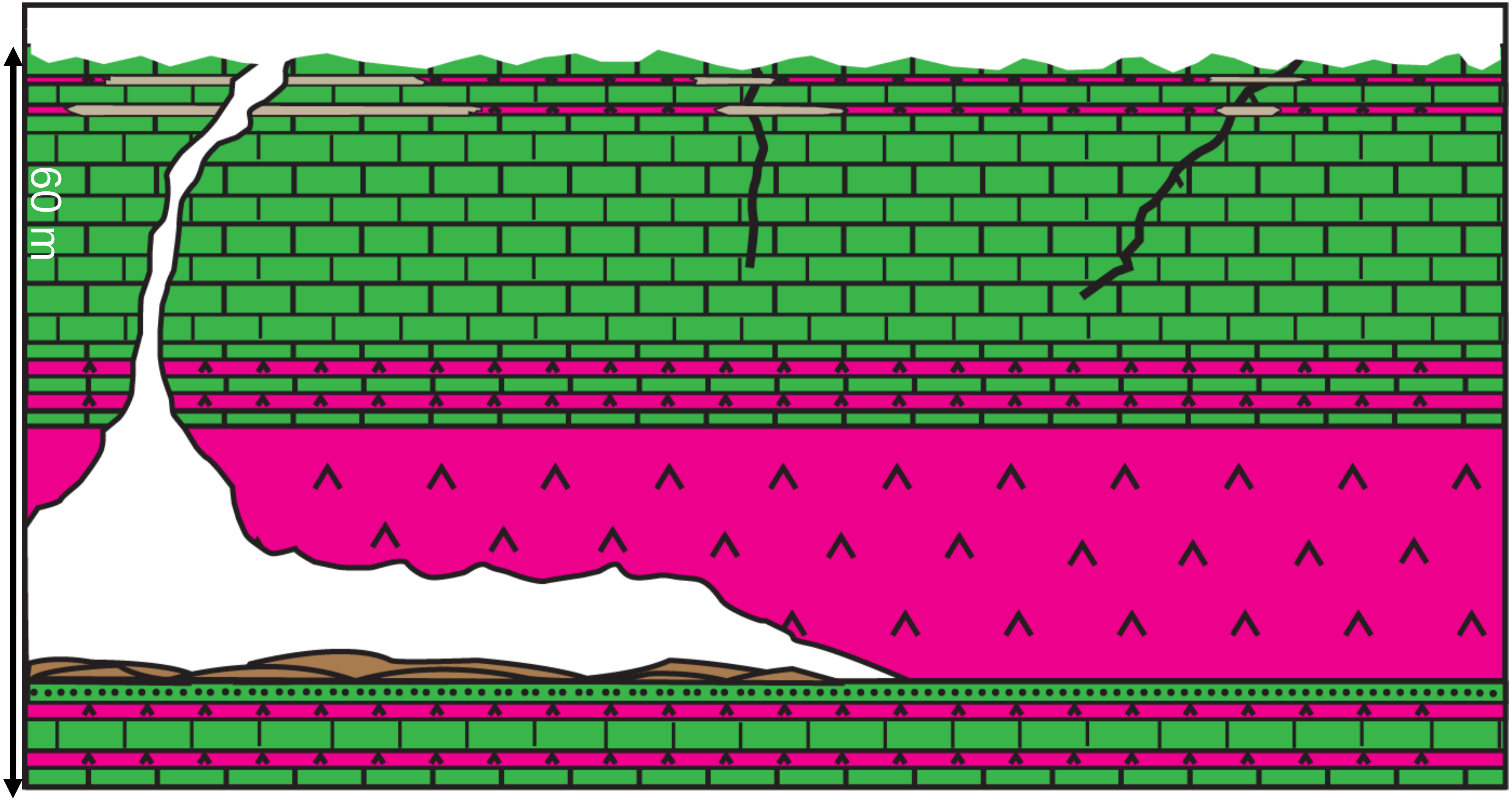
Stage I (Protolith)



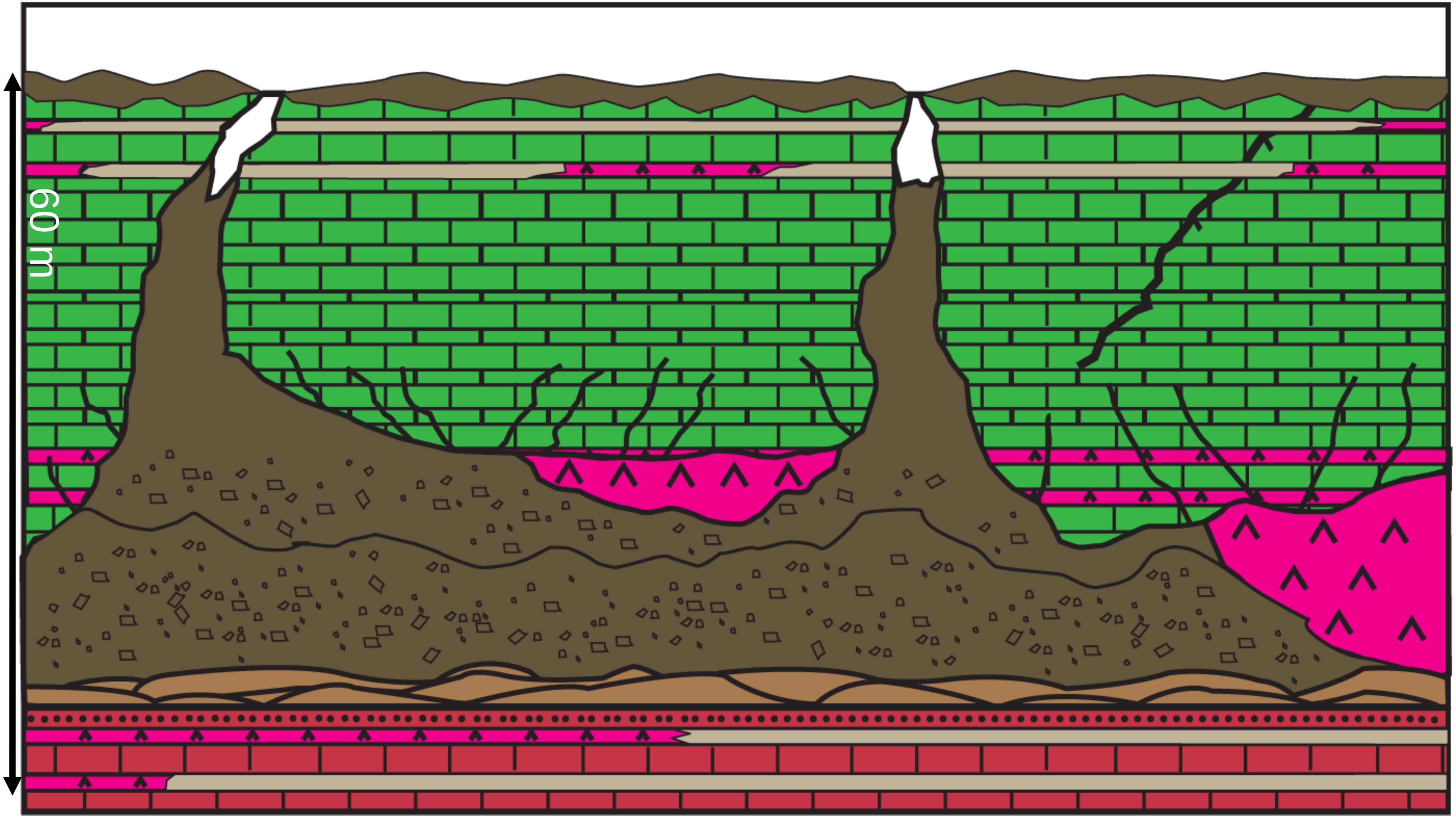
Stage II



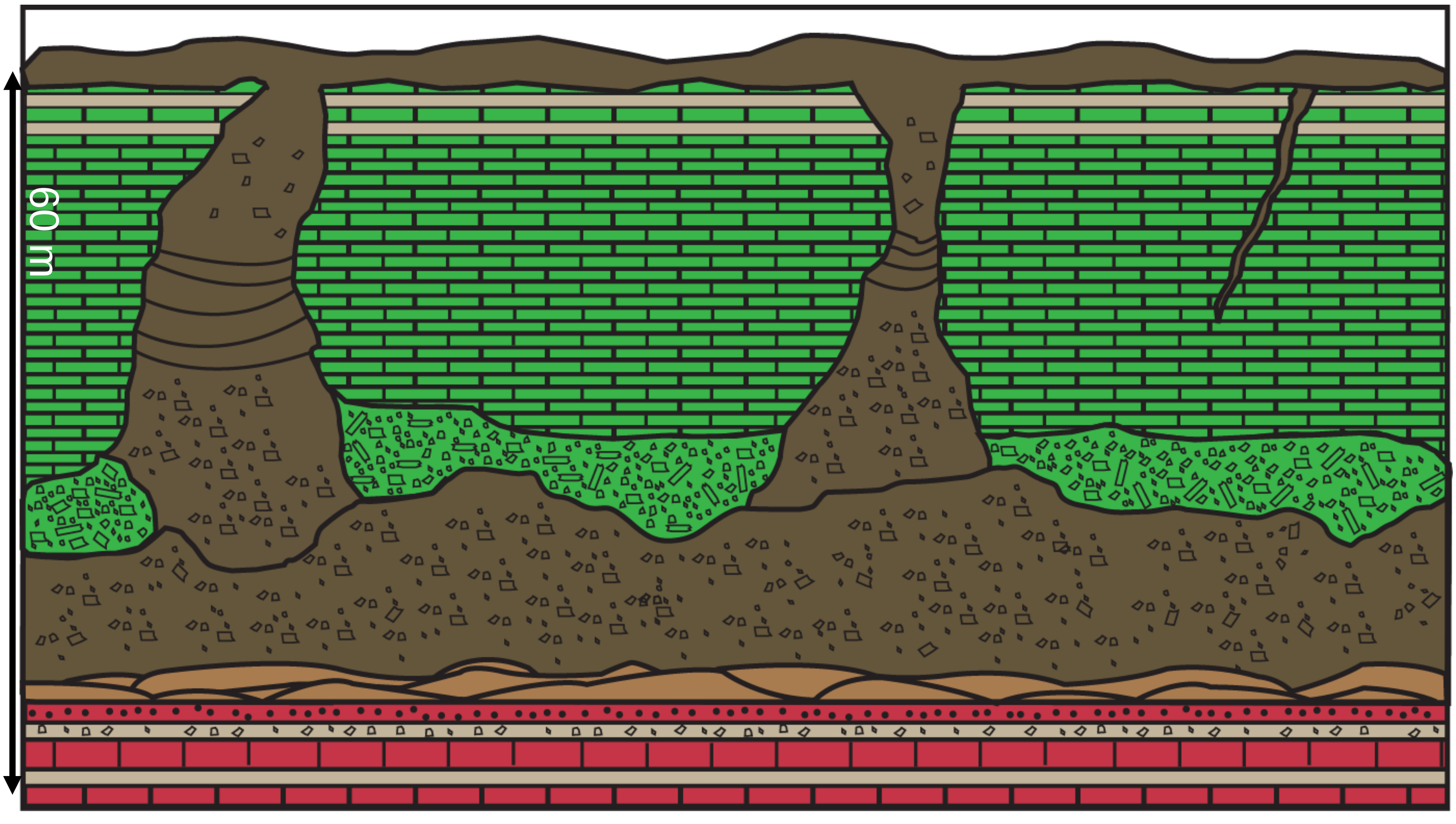
Stage III



Stage IV

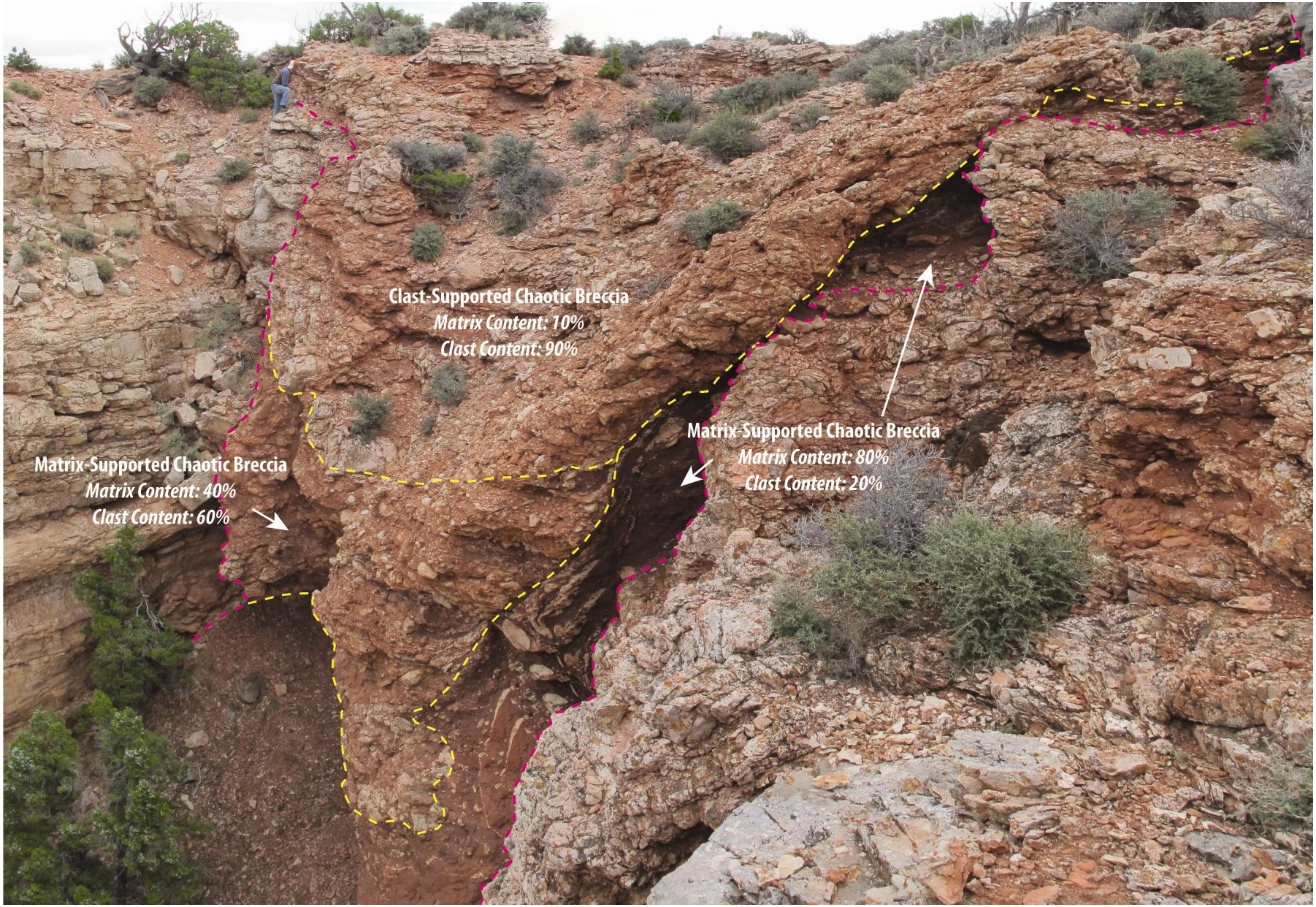


Stage V



Large Dissolution Features

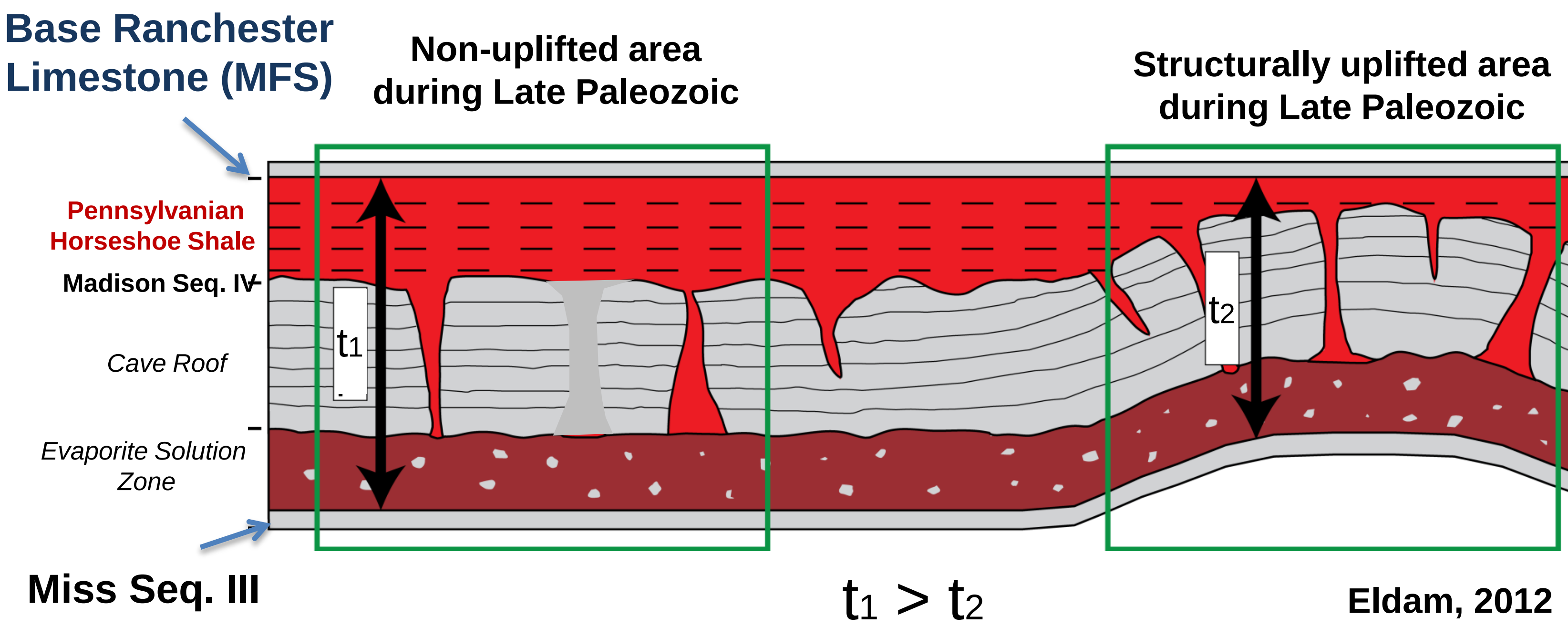
Lenticular Doline with Multiple Breccia Fills



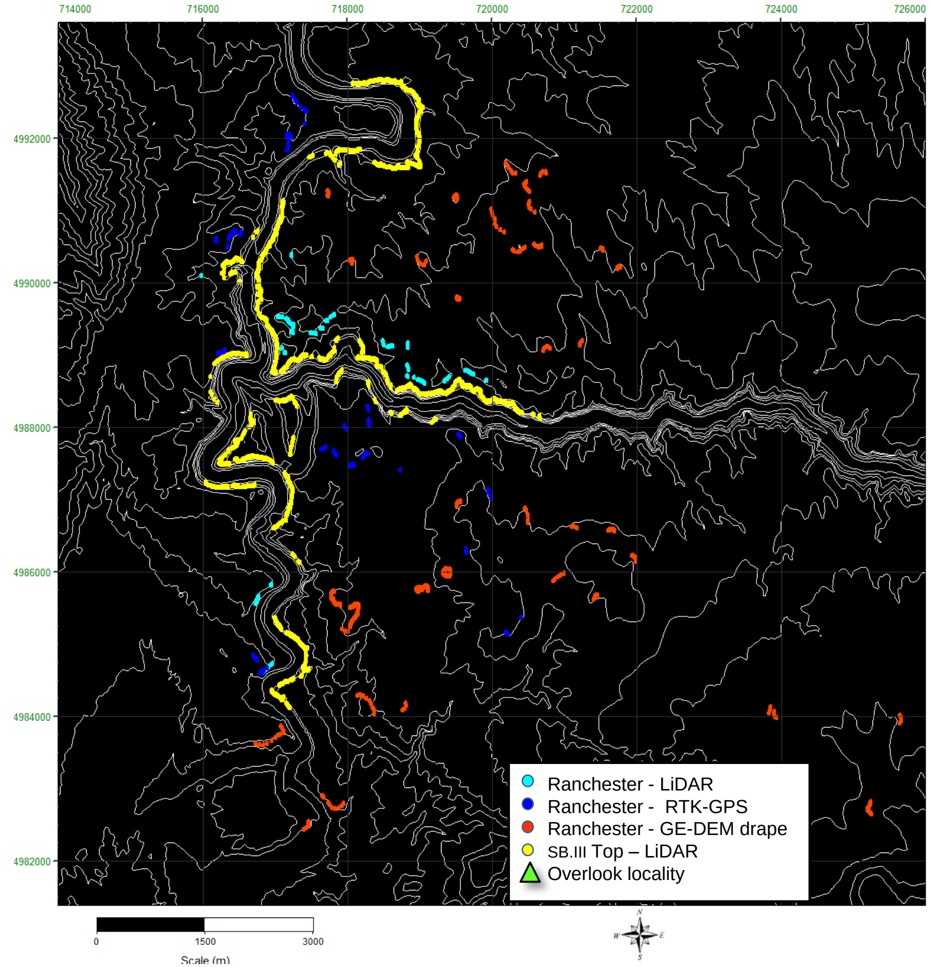
Comparison (abbreviated) Between Epigenetic and Evaporite Paleokarst

Feature	Surface Epigenetic	Evaporite
Lateral continuity of breccia / cave body	Breccia bodies vertically extensive with thickness/width ratio of 1:1 to 10:1	Breccia bodies extend for 100s of km with thickness/ width ratio 1:1000
Stratigraphic position	Follows aquifer boundaries, not lithostratigraphic units	Strata-bound by position of former evaporite
Lower contact	Diffuse, complex, and dependent on exposure	Sharp, little disruption below, chaotic within zone
Remnant anhydrite	Absent	Present as slabs, clasts of anhydrite, or molds
Lateral compressive structure	Rare	Common, esp. at base of stratiform breccia

Increased Solution-Widened Fracture Intensity Related to Paleostructure



Data Acquisition



<u>Input data for structure contour model:</u>

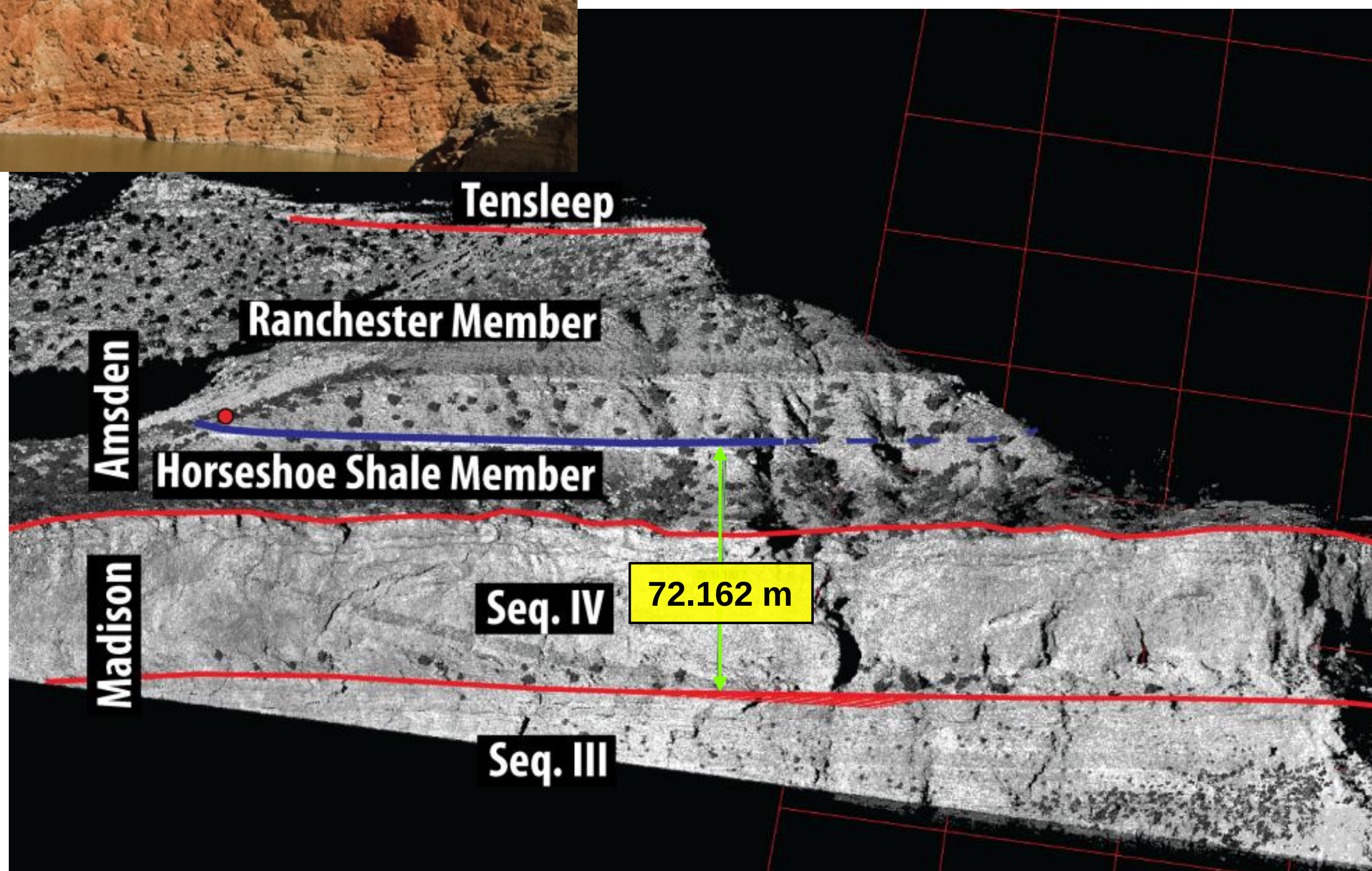
-Terrestrial lidar

-RTK-GPS

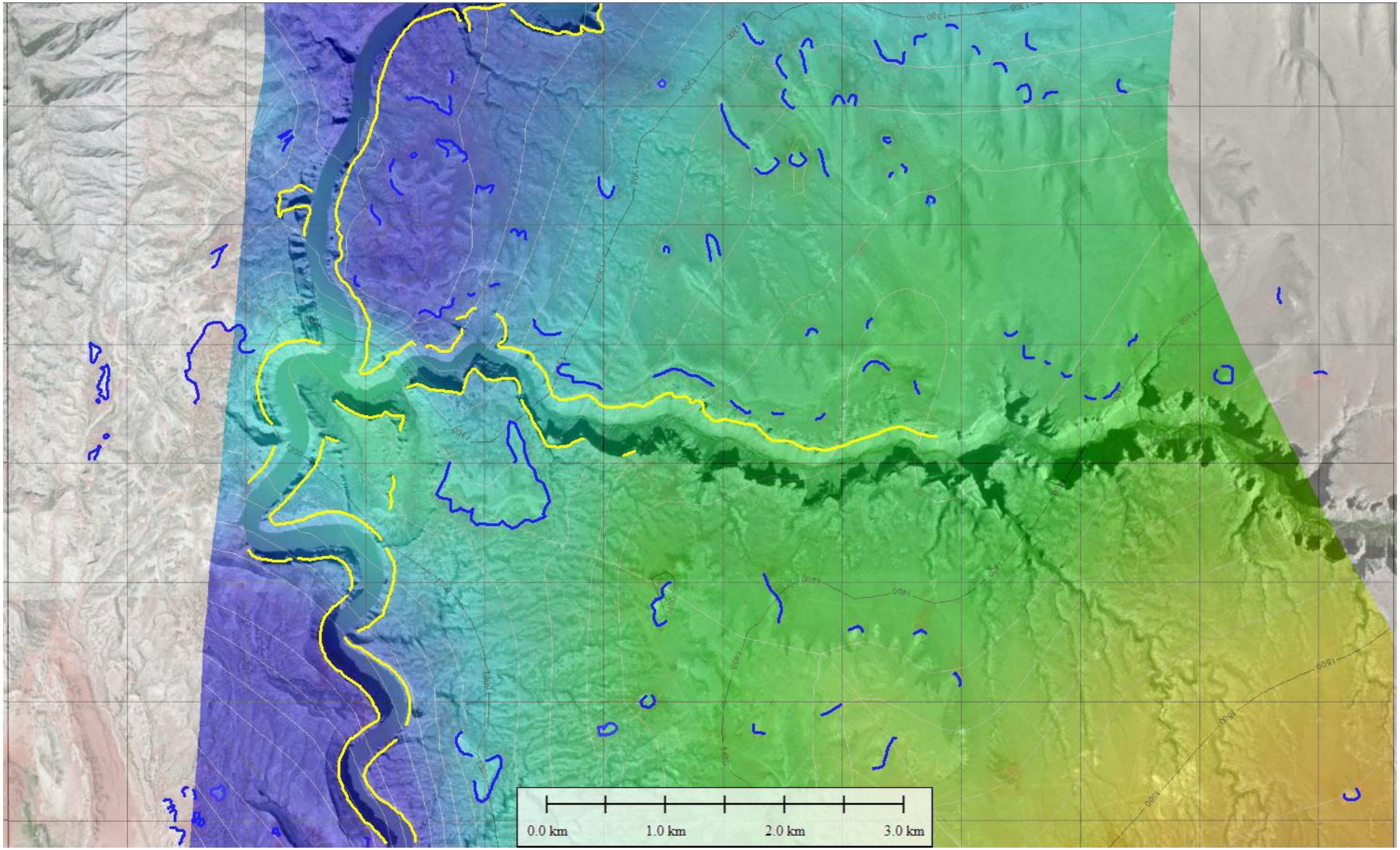
-Aerial photo interpretation of contacts

Data Interrogation

- •lidar scan outcrop
- •GPS mapping

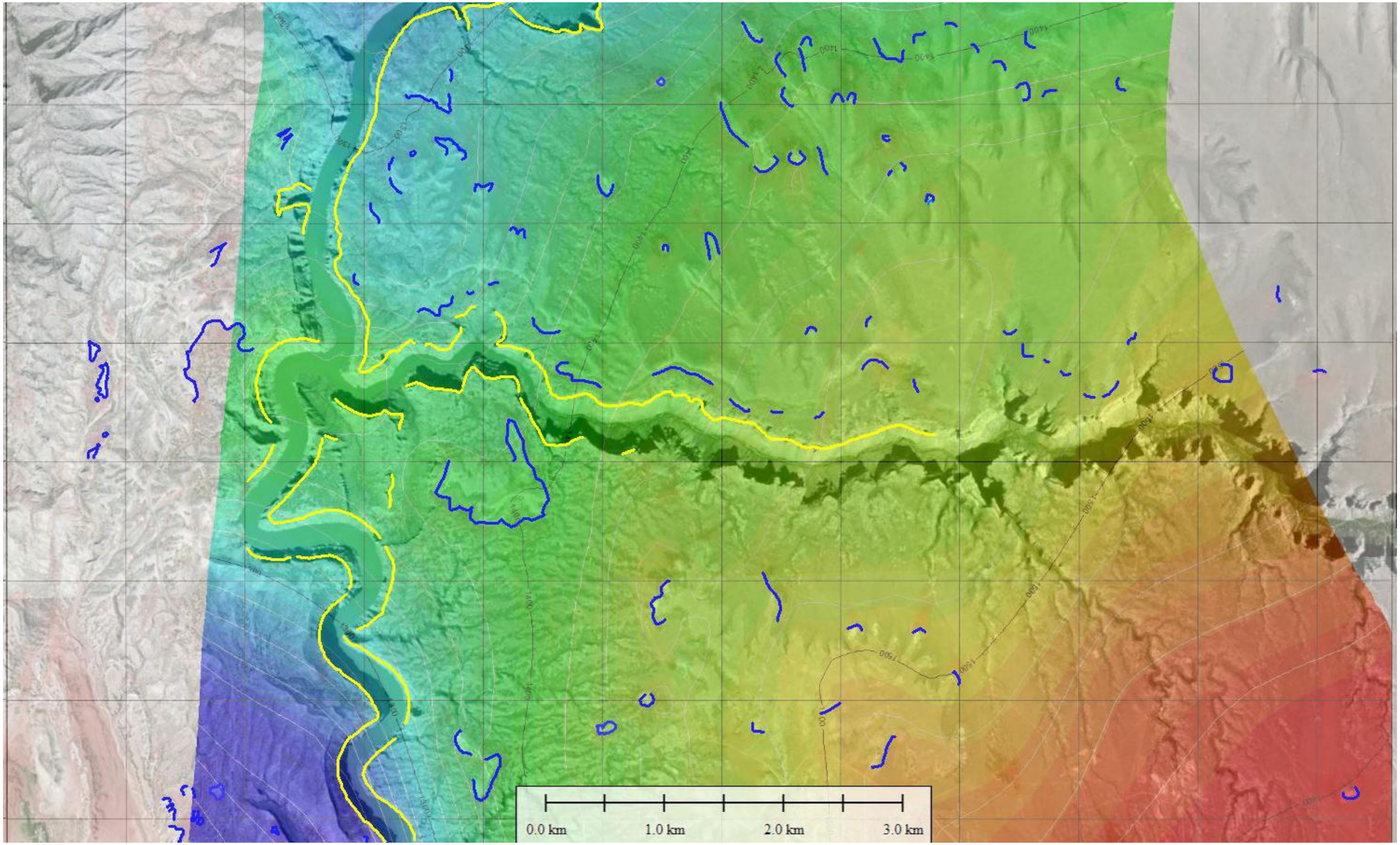


Structure Contour and Data Control - Top Seq. III (Miss.)



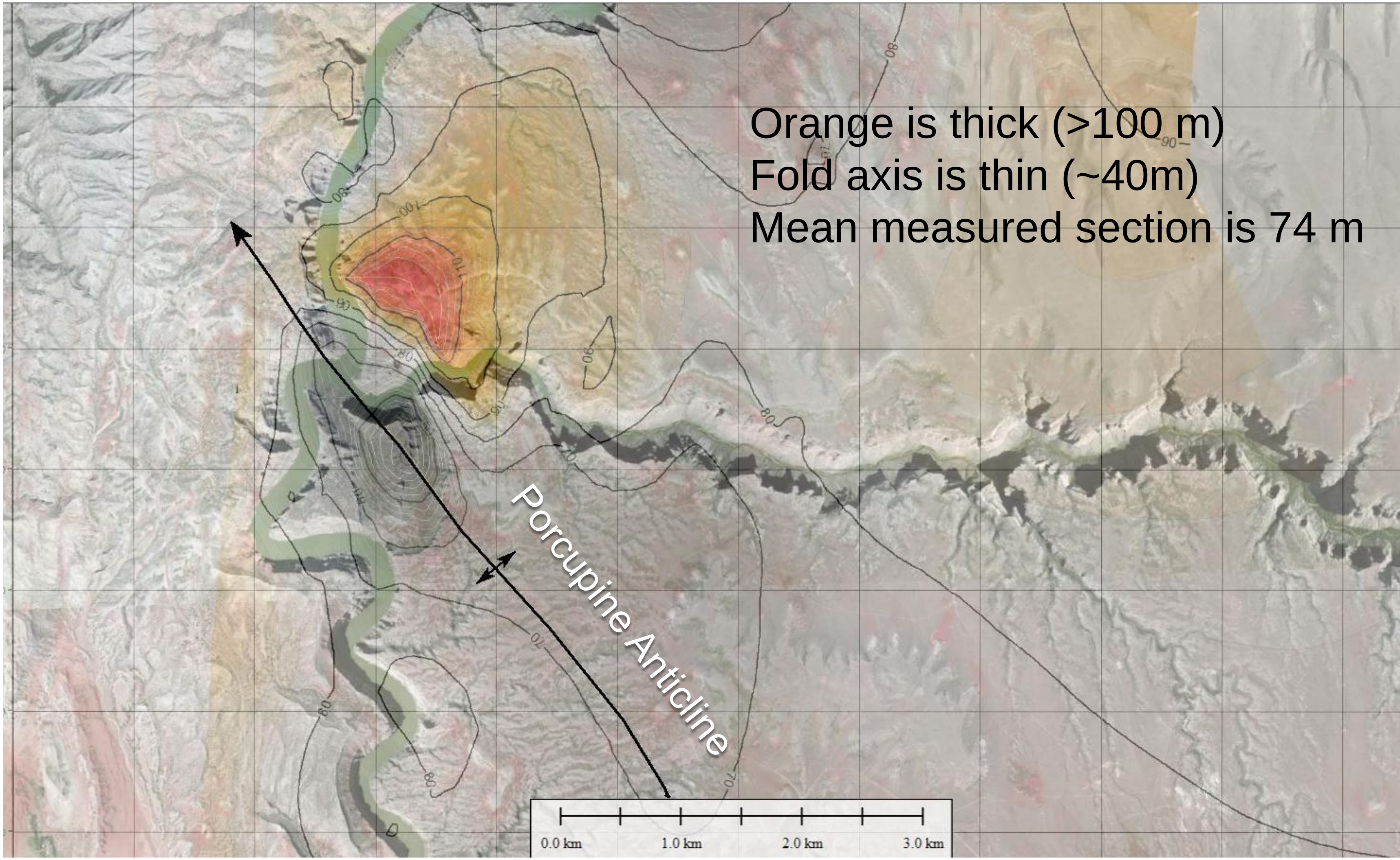
*yellow line is lidar data; blue line is aerial photo interpretation

Structure Contour and Data Control - Top Ranchester (Penn.)



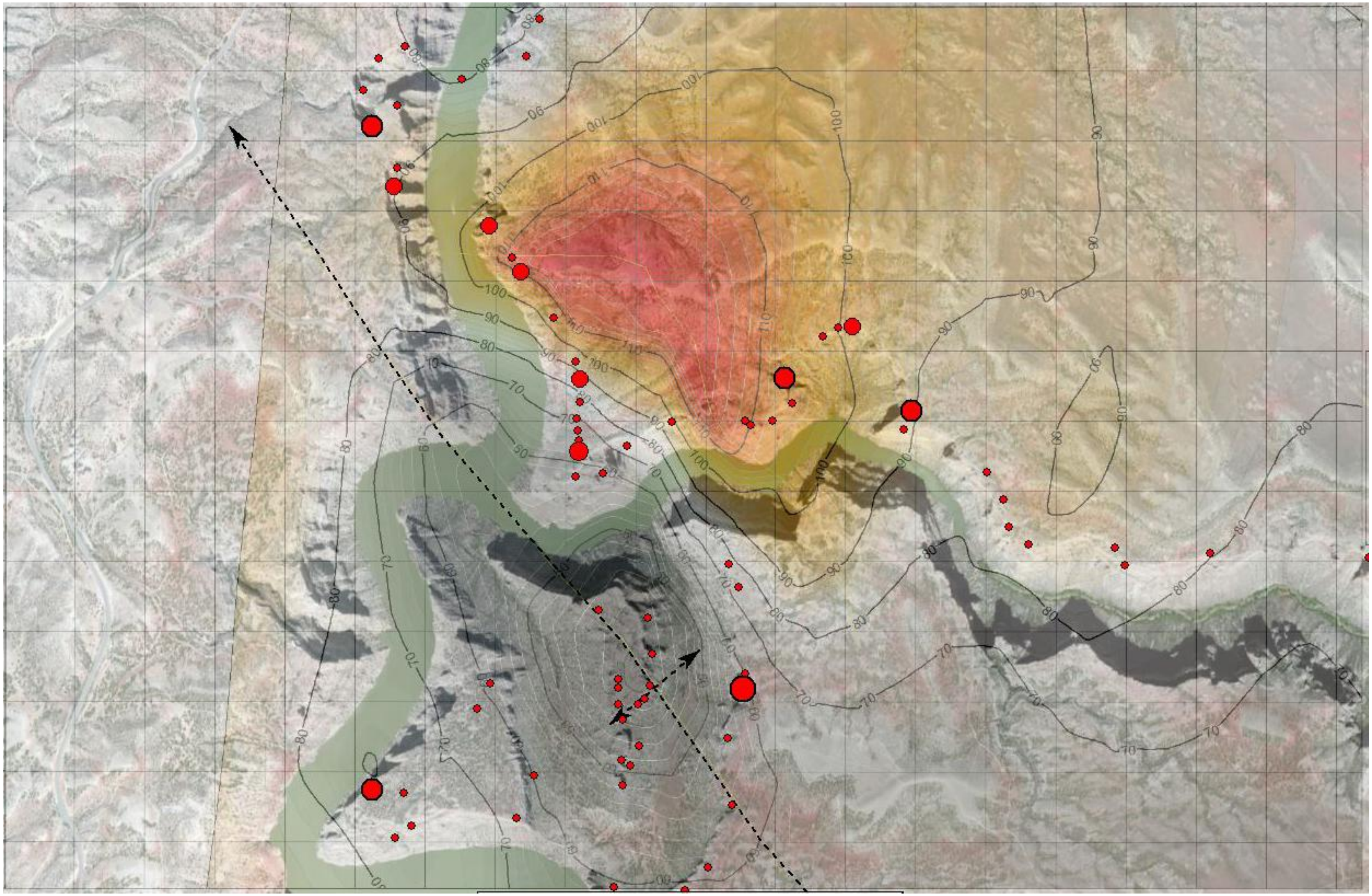
*yellow line is lidar data; blue line is aerial photo interpretation

Isopach of Ranchester (Penn.) to Madison Seq. III (Miss.)



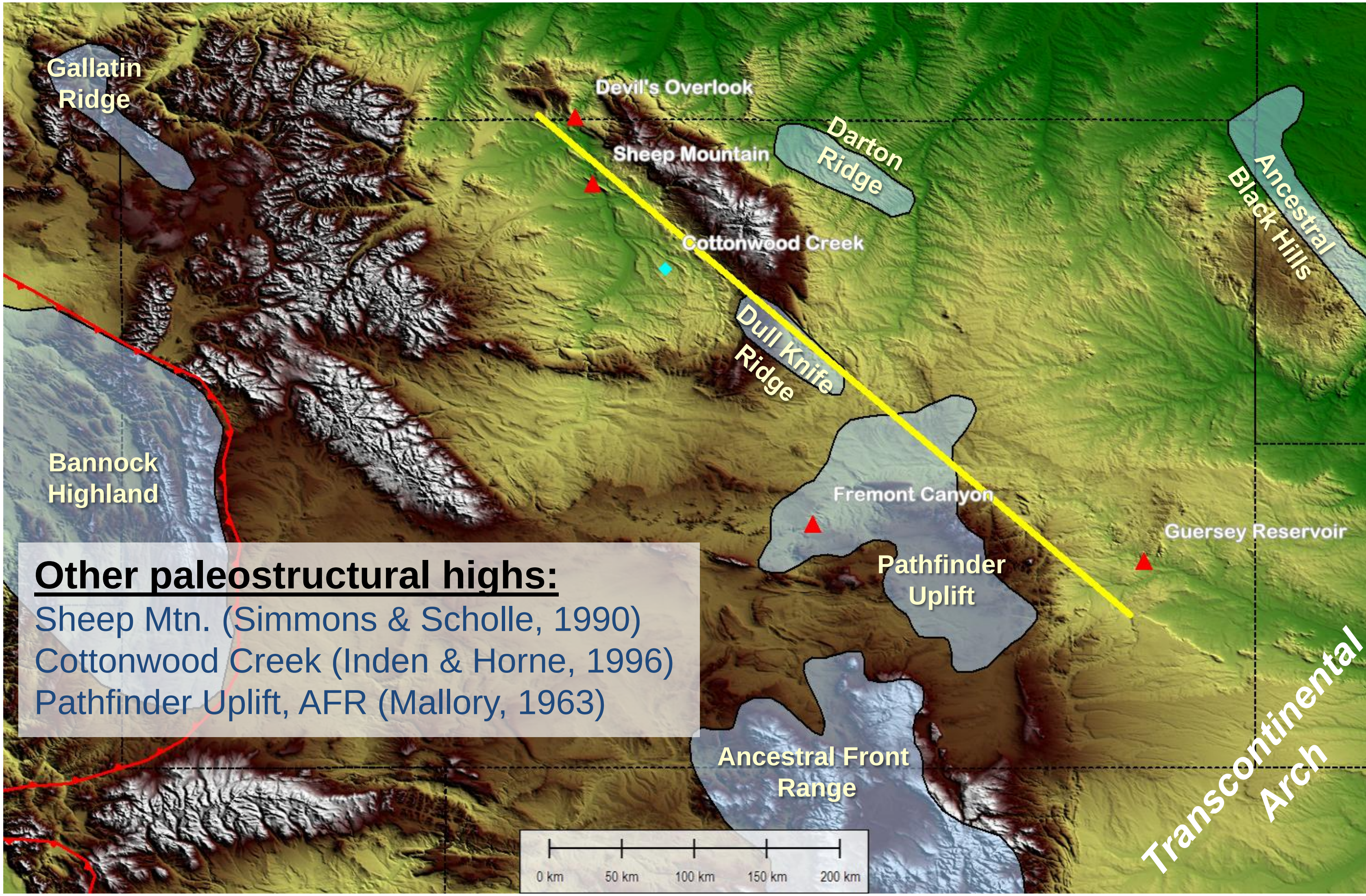
Porcupine Anticline of the BCRA is a paleostructural high

Paleostructure and solution-widened features



Red dots are mapped solution-widened fractures (dot size scales—largest is 40 m wide)

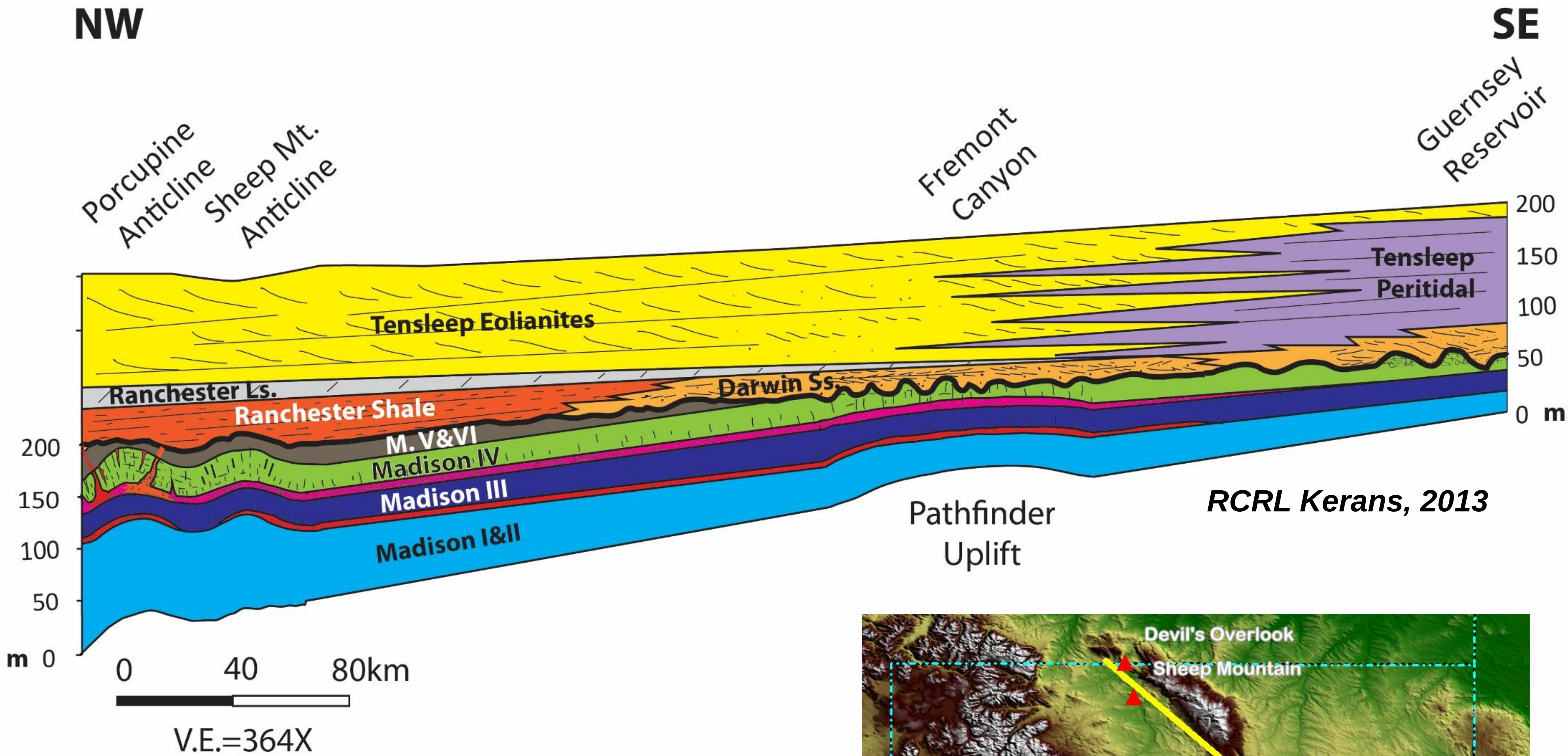
Ancestral Rockies Uplifts, Ridges or Highs – Maughan, 1993



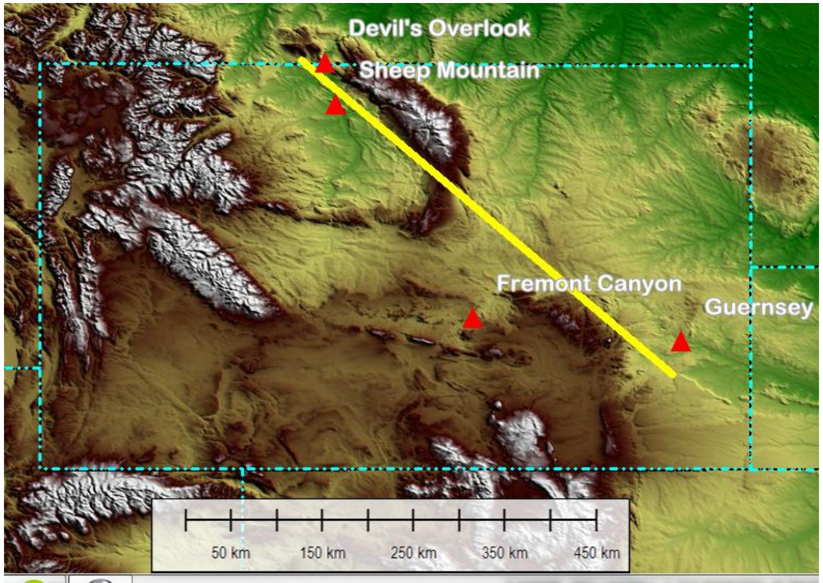
<u>Other paleostructural highs:</u>

Sheep Mtn. (Simmons & Scholle, 1990)
Cottonwood Creek (Inden & Horne, 1996)
Pathfinder Uplift, AFR (Mallory, 1963)

Madison Paleokarst System



RCRL Kerans, 2013

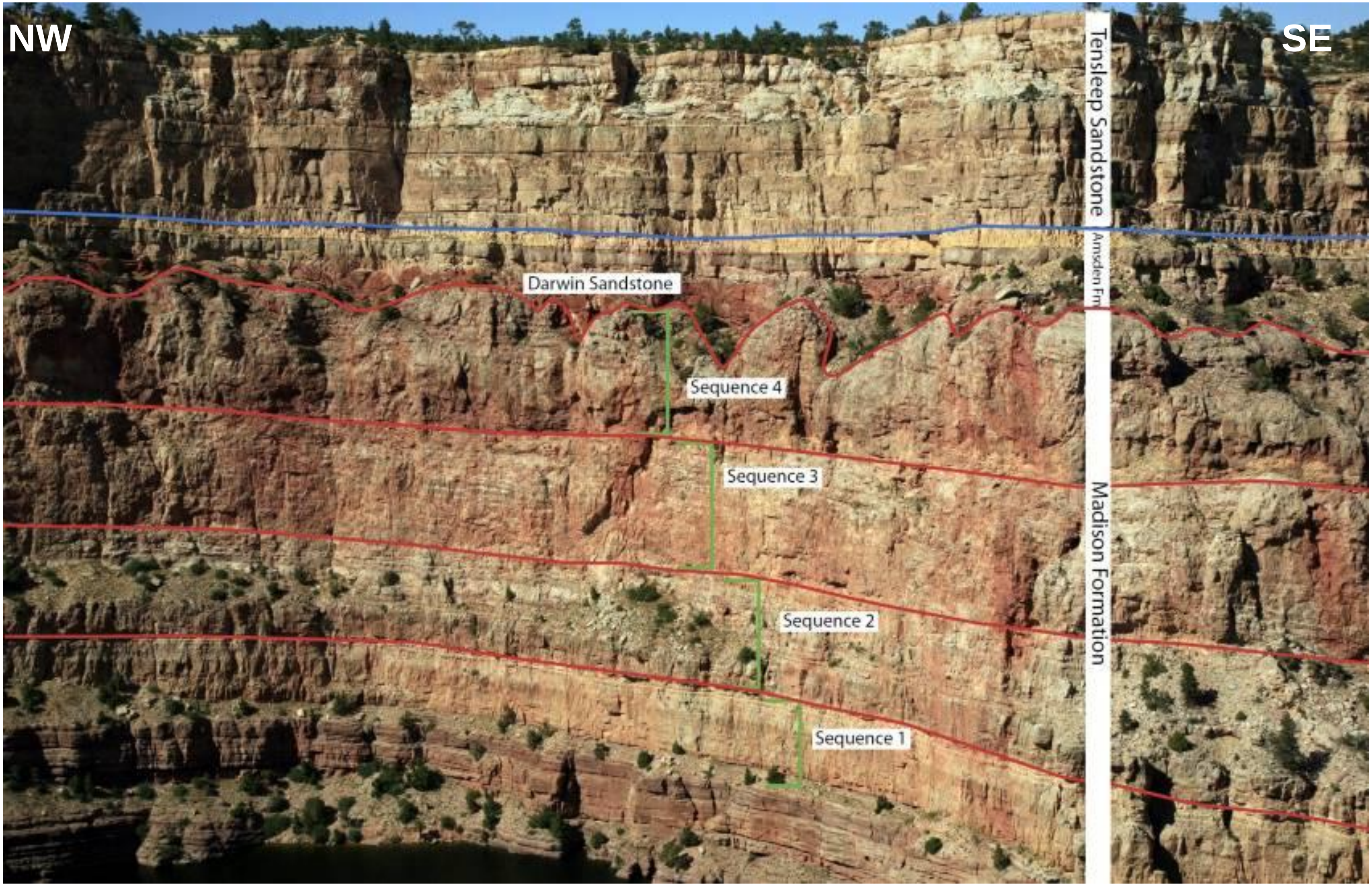


Fremont Canyon:

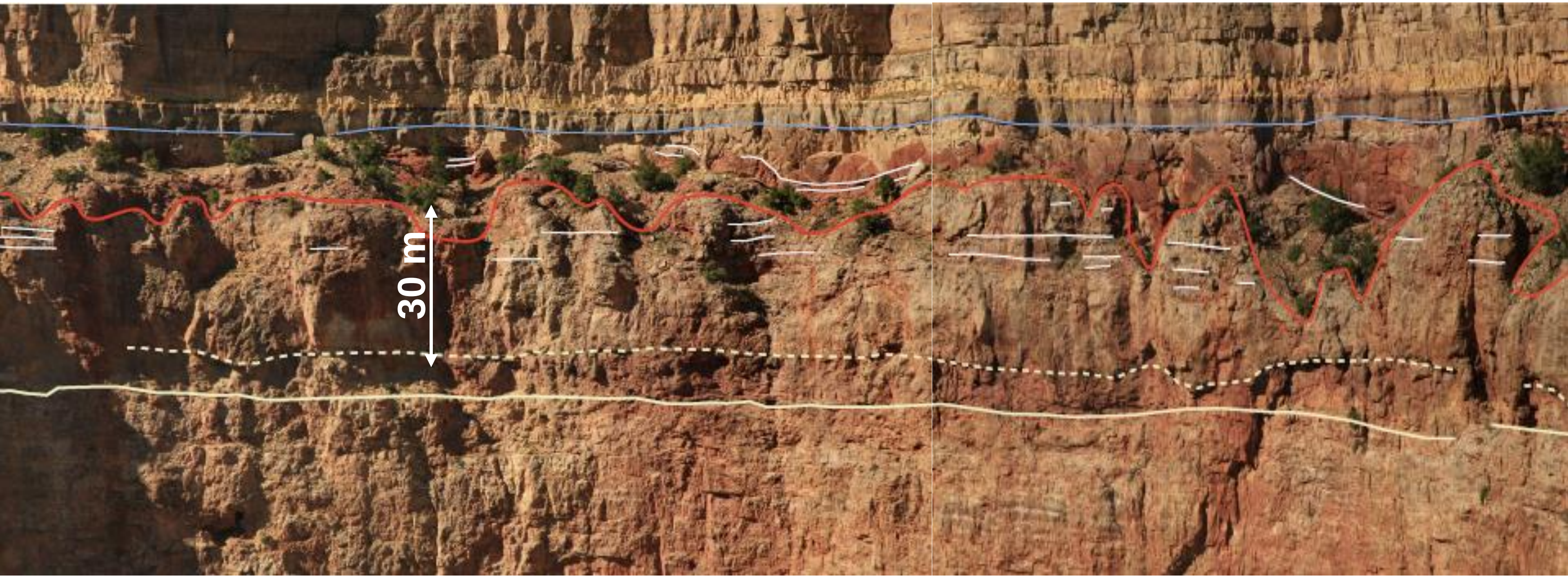
2nd Order Karst + evaporite dissolution + paleostructural high

View to the west – Laramide-age homocline

Fremont Canyon Formations and Sequences



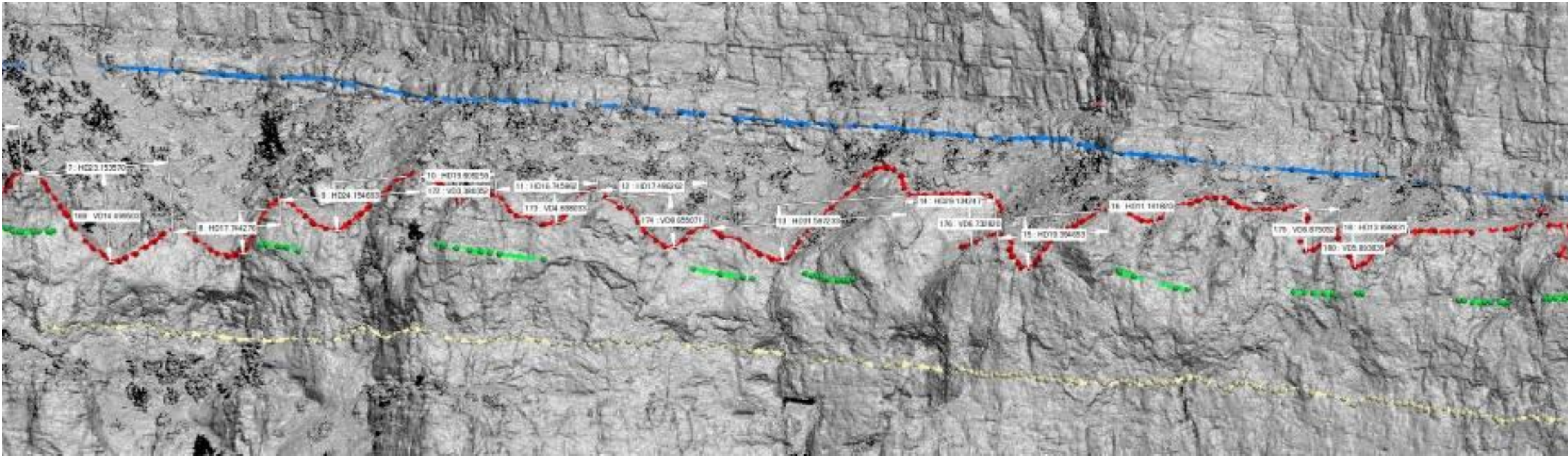
Combined paleokarst drivers



Low-relief karst pinnacles

Paleokarst facies– 2nd order + evaporite + paleostructural

LiDAR scanning of the top paleokarst surface



LiDAR scan utilized to developed quantified mapping of paleokarst surface

Outcrop morphology allows for areal statistics to be determined

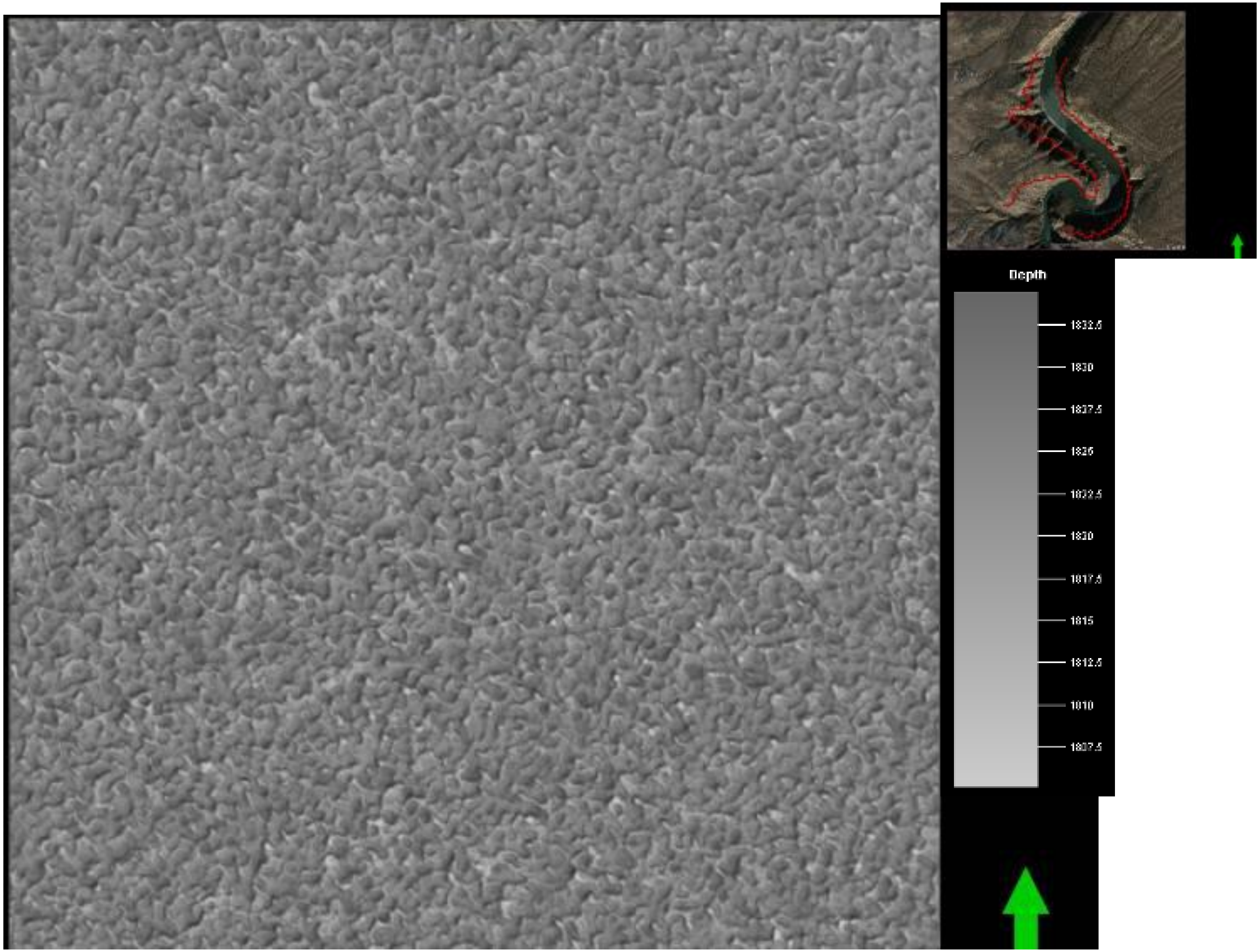
Paleokarst Topography: Combined Effects

Grid Size
2Km x 2Km

Grid
Increment
2x2 m

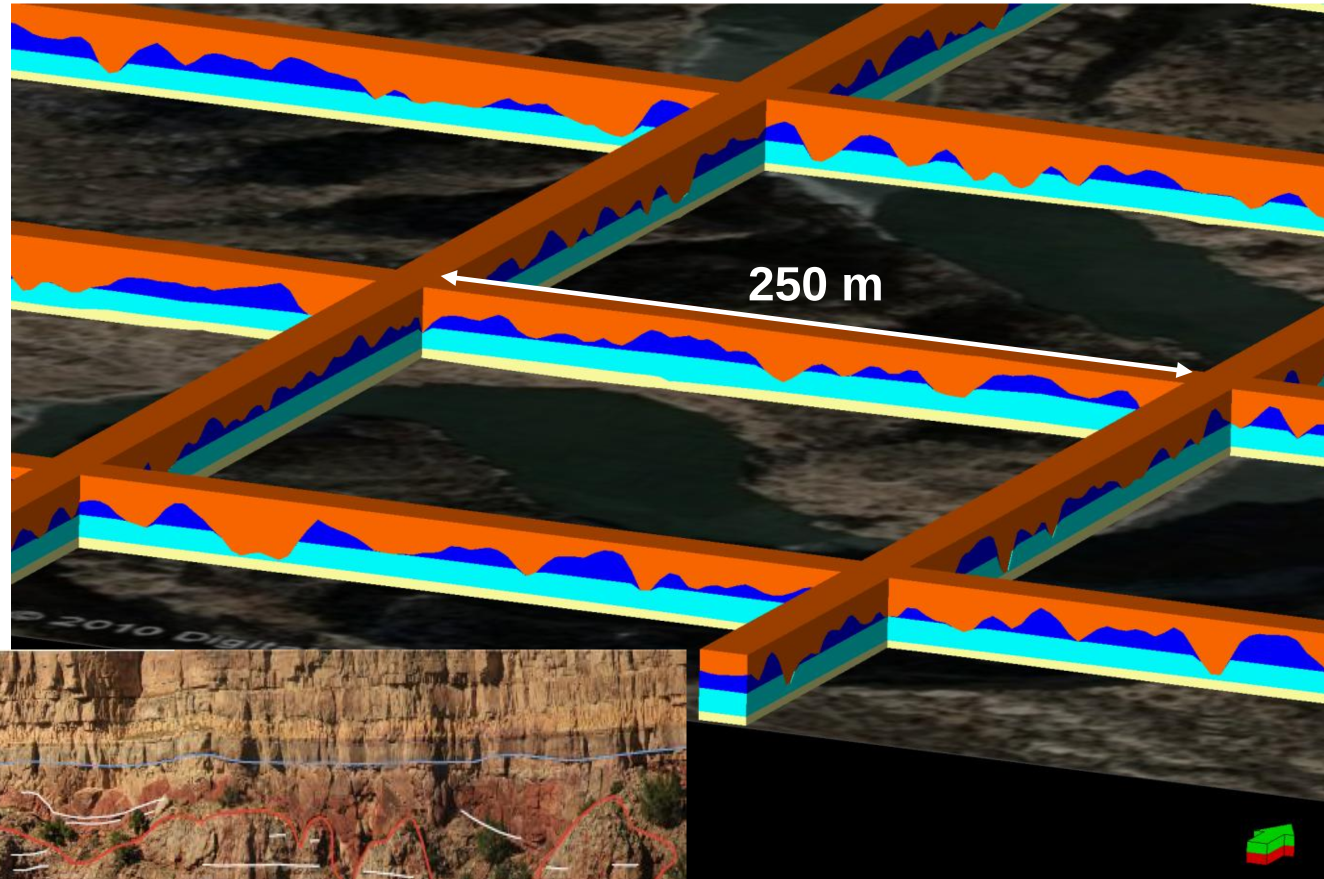
Min 1805m
Max 1834m
Delta 29m

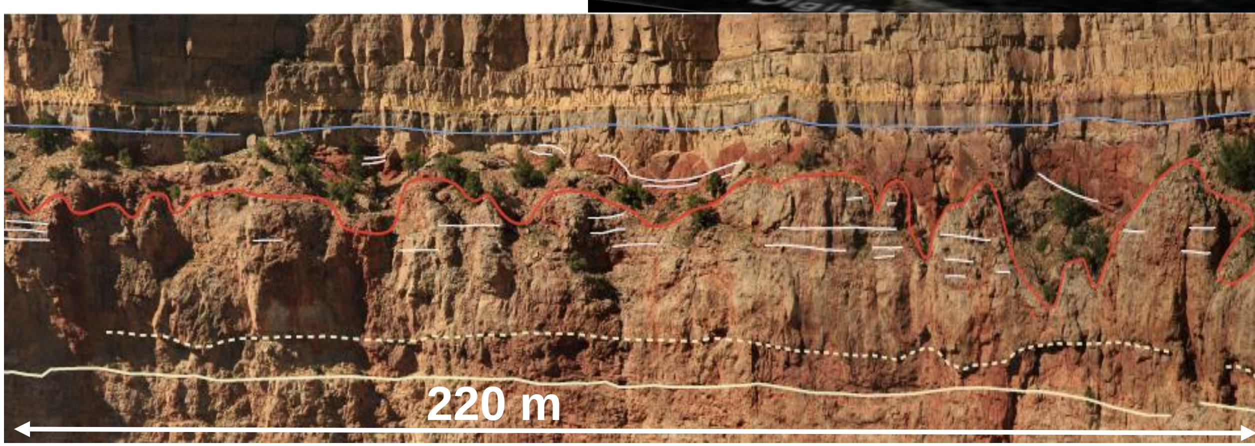
Method: SGS
Nugget: 0.005
Major: 25
Minor: 25
Azimuth: 0



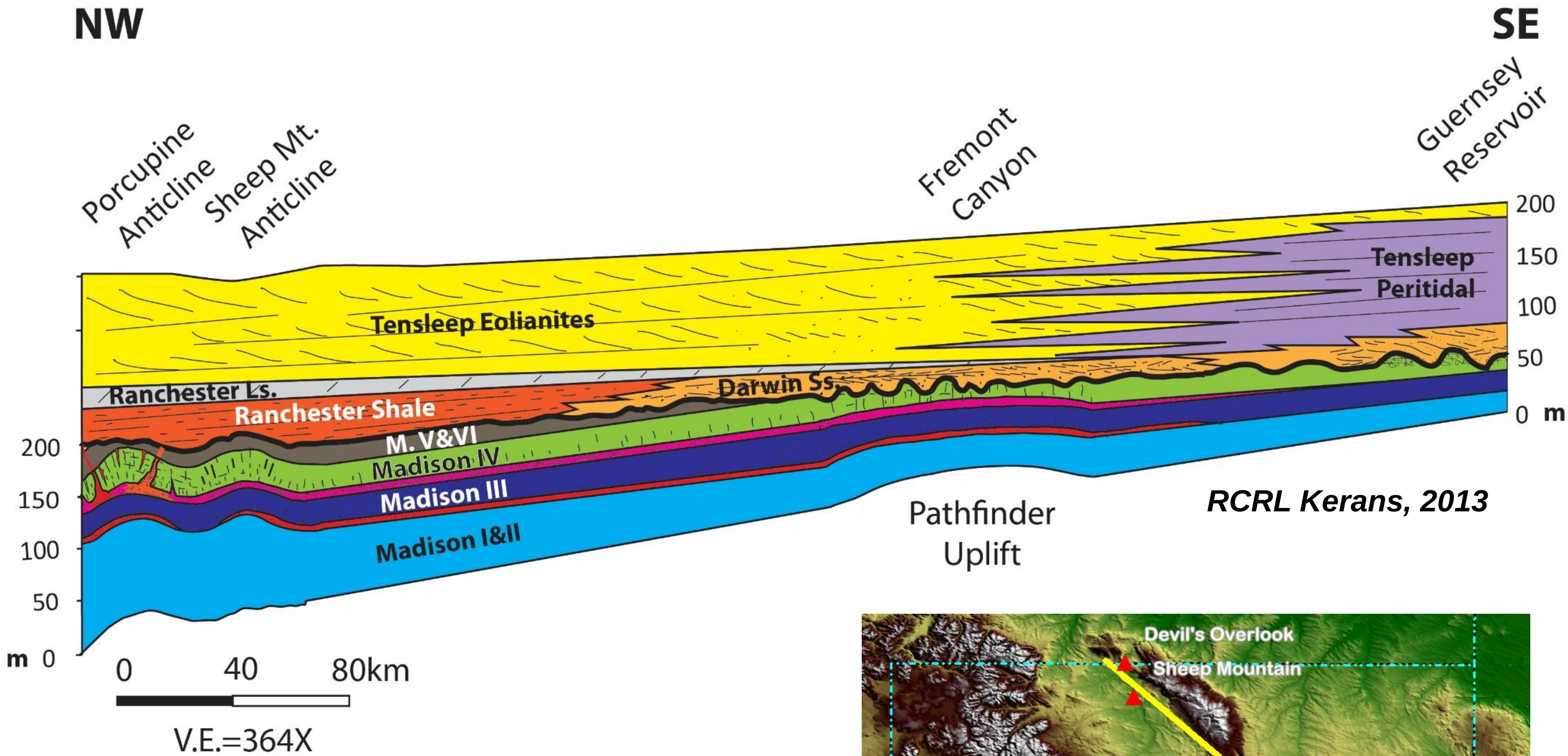
Outcrop To Model

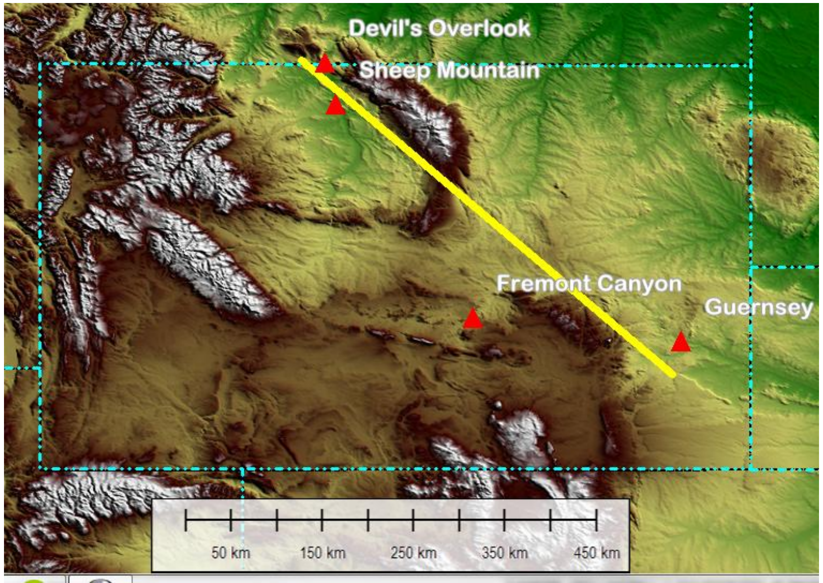
3 zones are modeled to represent the Madison Seq. IV





Madison Paleokarst System



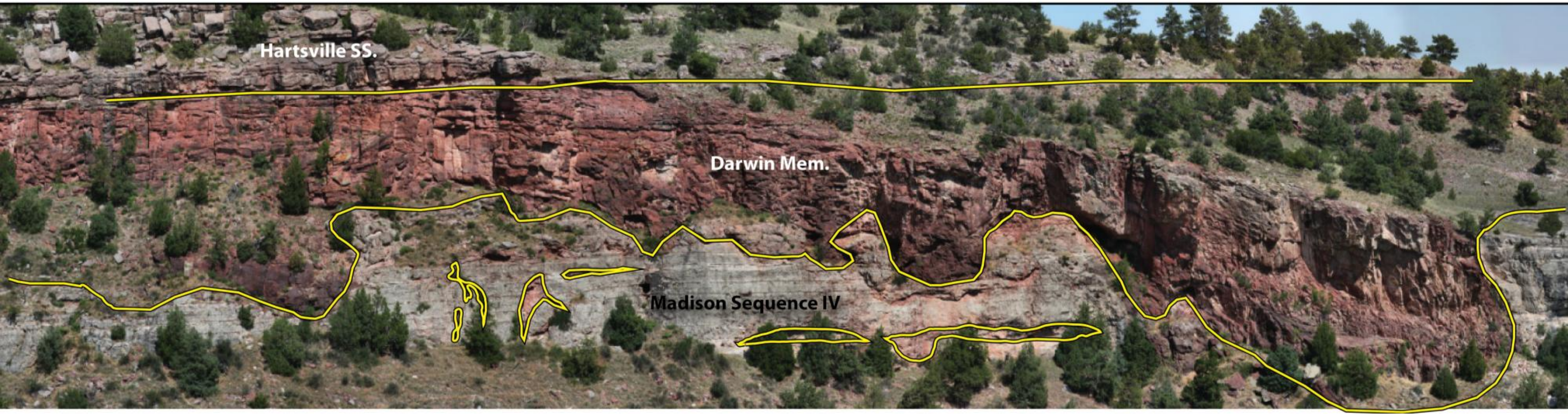


RCRL Kerans, 2013

Hartsville Canyon / Guernsey Reservoir

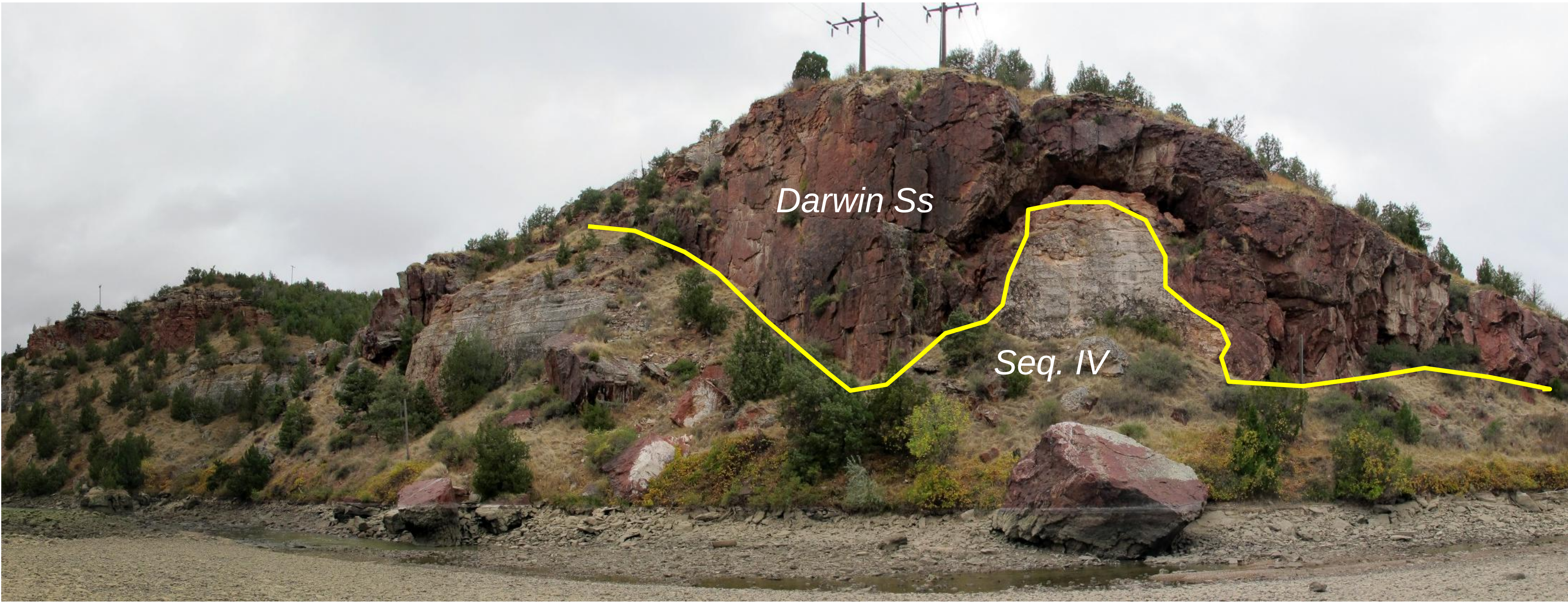
Top-Madison Dissolution and Fill

Paleokarst – paleogeography + evaporite + 2nd order



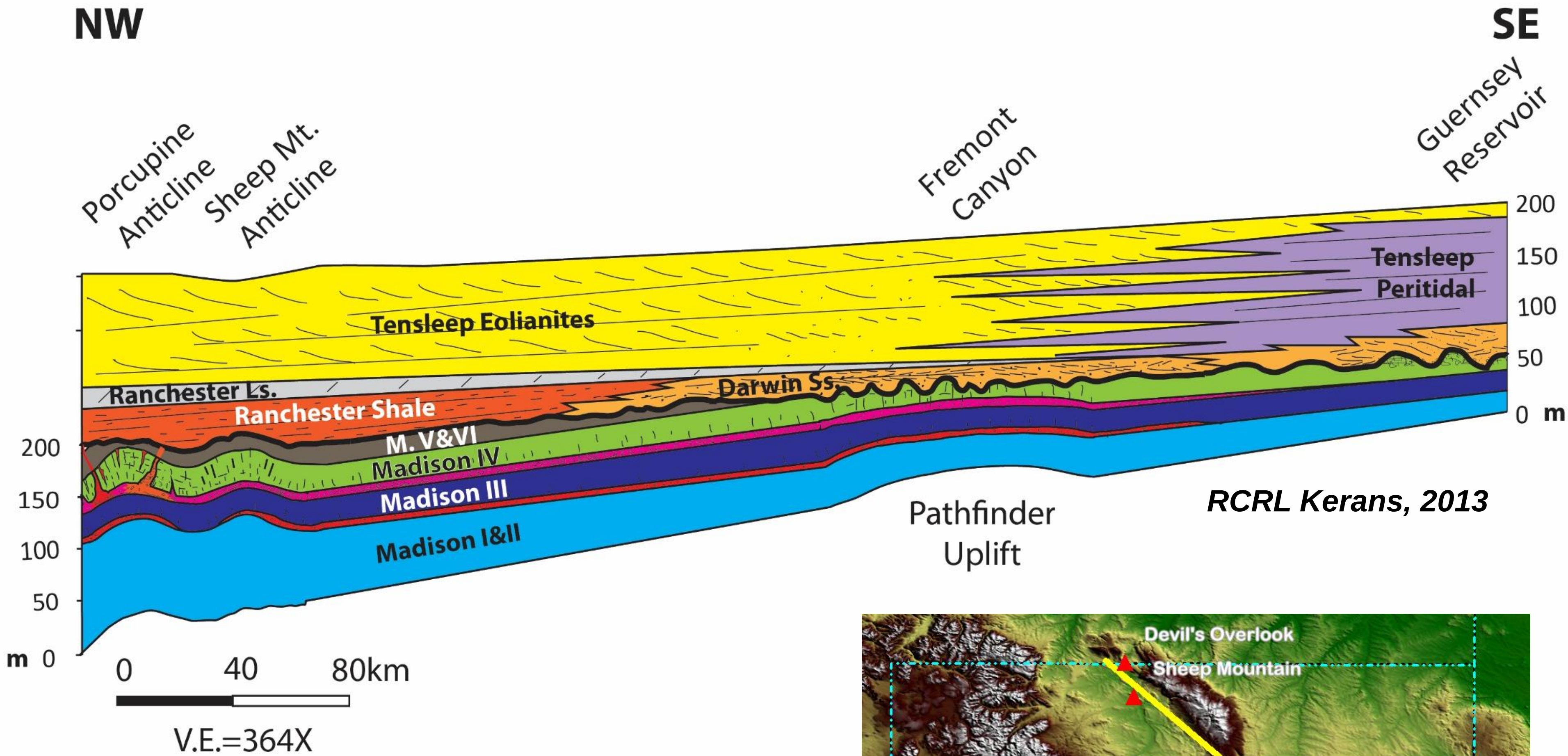
High-relief karst pinnacles and towers

Paleokarst – paleogeography + evaporite + 2nd order

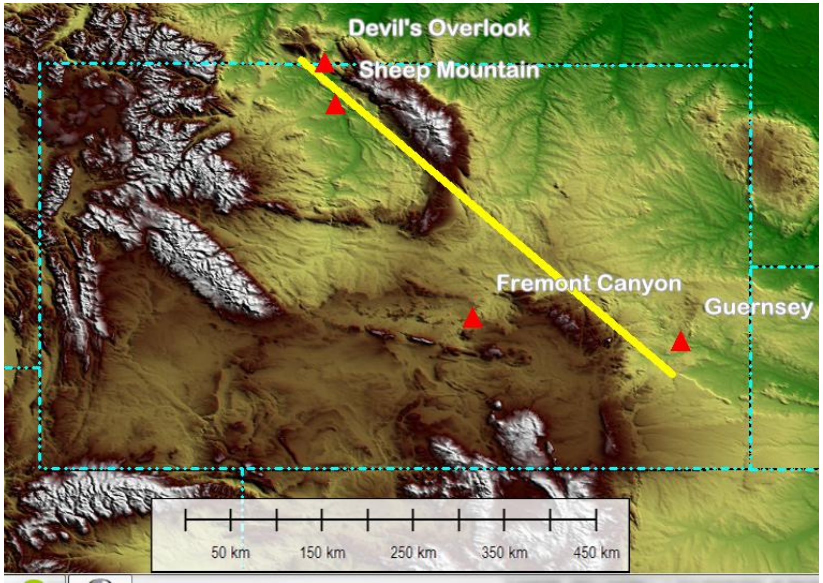


High-relief karst pinnacles and towers

Madison Paleokarst System



RCRL Kerans, 2013



Key general applications

- Knowledge of paleotectonics and paleogeography are essential elements in characterization of paleokarst

- Distinct criteria distinguish evaporite-rich vs. epigenenic paleokarst systems

- Paleokarst systems, especially over broad areas, are complex and can be the result of multiple geologic processes

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