

Characterization of Five Unconventional Diatomaceous (Opal-A) Reservoirs, Monterey Formation, San Joaquin Valley*

Dave Larue¹, Chris Hager², Tom Merrifield², Gena Evola², David Crane², and Phil Yorgensen²

Search and Discovery Article #11090 (2018)**

Posted June 25, 2018

*Adapted from oral presentation given at 2018 Pacific Section AAPG Convention, Bakersfield, California, April 22-25, 2018

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¹Chevron (retired), Bakersfield, California (endlessurfduke@gmail.com)

²Chevron, Bakersfield, California

Abstract

Unconventional Opal-A and Opal-CT diatomaceous reservoirs in the Monterey Formation of the San Joaquin Valley in California have been produced for more than 30 years. Although the reservoirs can be grouped into a single category as “diatomaceous reservoirs,” they are characterized by considerable heterogeneity in structural setting and style, lithology, 3D distribution of rock properties, and production character. Here, five diatomaceous reservoirs in the Monterey Formation are described, with locations at Lost Hills, Cymric, McKittrick and two at Midway-Sunset Fields, all in the San Joaquin Valley. Three occur in anticlinal traps (Lost Hills, Cymric, and Westates Anticline at Midway-Sunset), one occurs as a combined structural and stratigraphic trap (9C at Midway-Sunset), and one is present in a complex thrust belt (McKittrick). Characteristics of depth to reservoir, lithology, oil gravity api, porosity and oil saturation are described. Puzzling features of the diatomaceous reservoirs are considerable. Oil saturation is largely continuous through the reservoirs, indicating there are few or no “non-net” lithologies. Oil-water contacts for the diatomaceous reservoirs are poorly defined: only the 9C reservoir has a defensible oil-water contact. Strong 3D variations in oil saturation occur, and the edges of the reservoir appear wet at Lost Hills and for the Westates anticline, and possibly at Cymric 1Y. The transition from Opal-A to Opal-CT occurs at low formation temperatures, yet the fold amplitudes at Lost Hills, Cymric and Westates are thousands of feet, indicating that the crestal portions of these reservoirs have likely never been more deeply buried than they are today. The Opal-A to Opal-CT transition has been folded, but more gently than bedding.

In general, the best producing diatomaceous reservoirs have the best oil saturations (>45%, Cymric and McKittrick Field) or are thick (>1000 ft, Lost Hills Field). Negative characteristics are deeper reservoirs (>1500 ft) with lower oil saturations (<40%, Section 9C, Midway-Sunset Field), and reservoirs that are very shallow (<500 ft) (McKittrick Field). These insights provide general guidance about characterization of unconventional diatomaceous reservoirs, and the identification of factors that most dramatically influence performance.

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All of Chevron U.S.A. Inc., Bakersfield

Misconceptions About Opal A Diatomaceous Reservoirs....

- If you've seen one Opal A diatomaceous reservoir, you've seen them all
- All Opal A diatomaceous reservoirs will behave the same when produced
- Opal A diatomaceous reservoirs behave (or don't behave) like traditional reservoirs

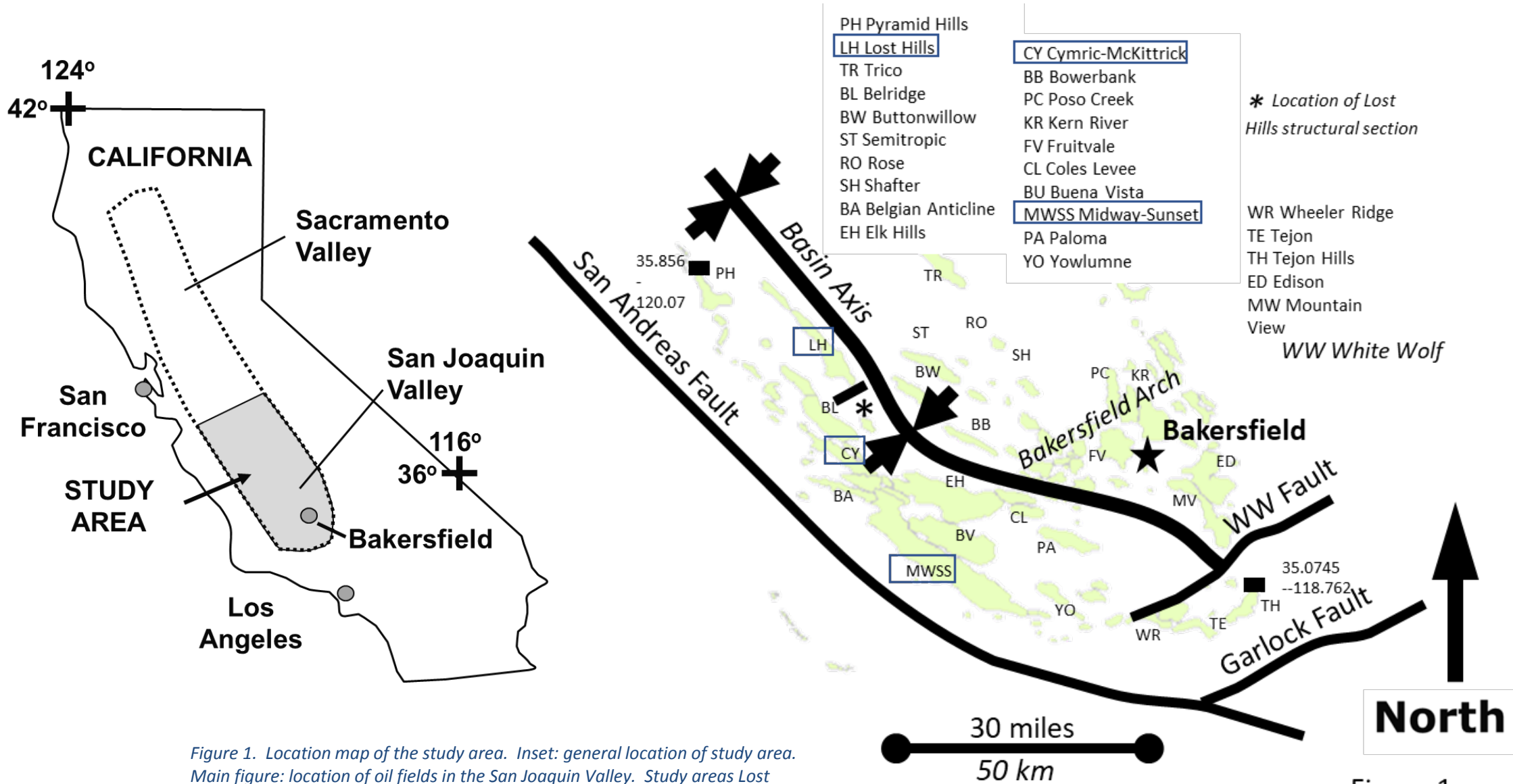


Figure 1. Location map of the study area. Inset: general location of study area. Main figure: location of oil fields in the San Joaquin Valley. Study areas Lost Hills, Cymric-McKittrick, and reservoirs in Midway-Sunset Field are shown in boxes. Figure modified from Larue et al. (2017).

Figure 1

Monterey Formation Stratigraphy

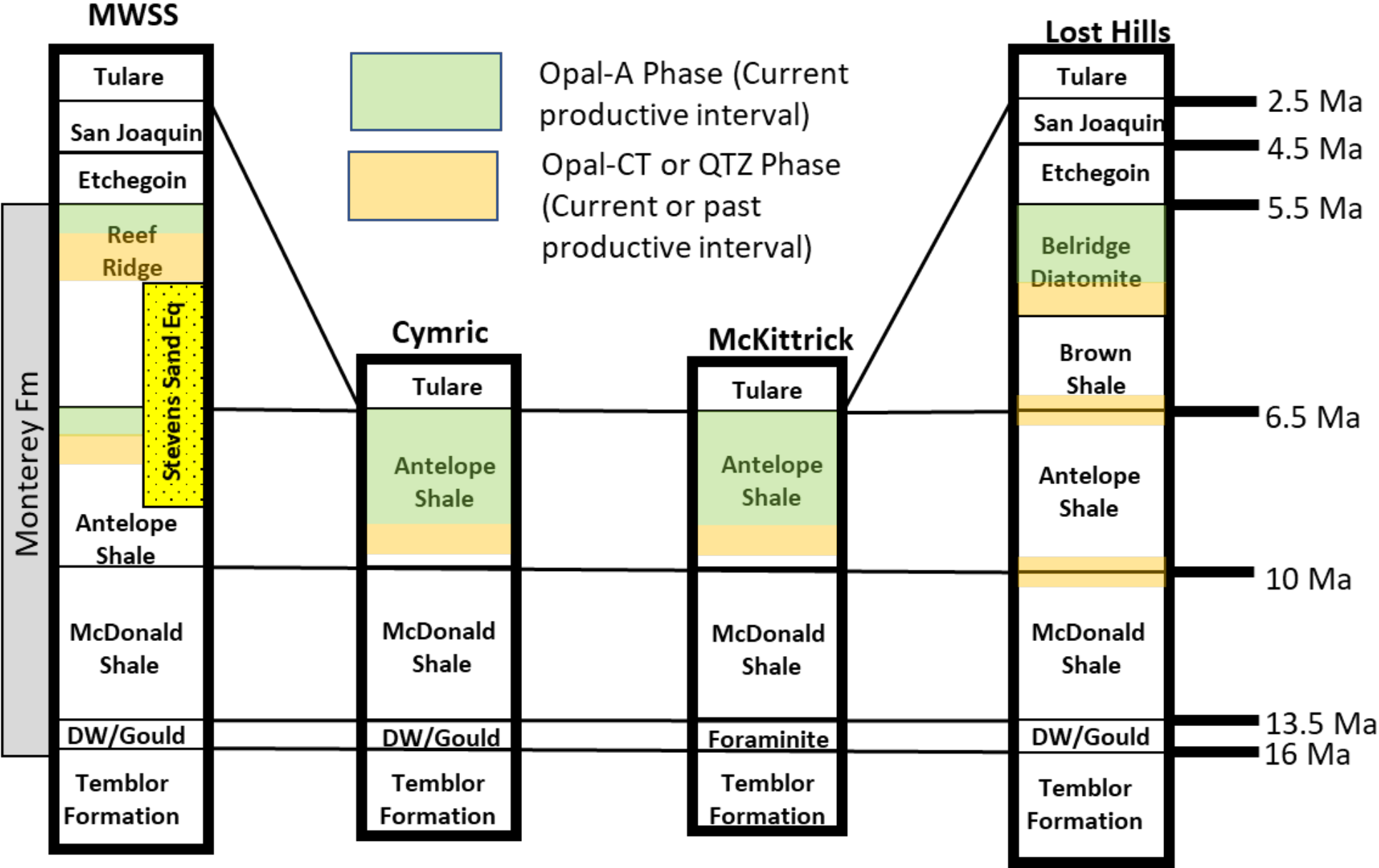
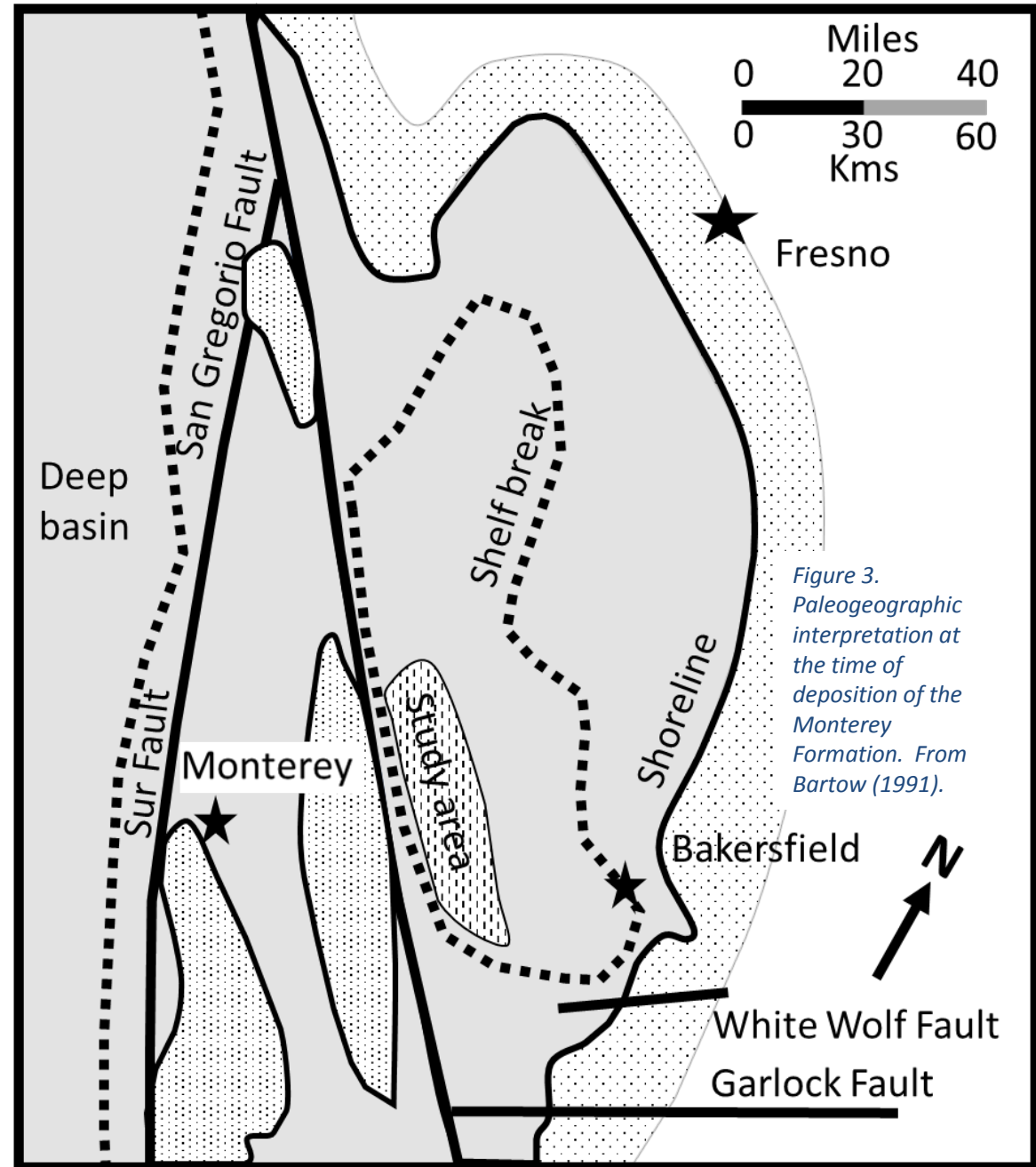


Figure 2. Stratigraphy of the Monterey Formation in the southern San Joaquin Valley. MWSS: Midway-Sunset Field. DW/Gould: Devilwater Gould member. Modified from an in-house report by Mike Morea.

DIATOMACEOUS RESERVOIRS

- Diatomaceous reservoirs contain rocks that are ***composed primarily of diatoms***.
- ***Diatoms are a major group of algae***, and one of the most common types of phytoplankton.
- ***Diatoms have a distinct silica cell wall***, termed a “frustule” made of amorphous opaline glass (Opal-A).
- ***Diatomaceous rocks are deposited by hemipelagic processes***, though resedimentation can and commonly does occur (as sediment gravity flows).
- ***Diatomaceous sediments can be mixed with terrigenous shales and sands***
- ***Diatomaceous reservoirs typically have porosities from 55-70% and very low permeabilities***



Diagenesis of Opal A

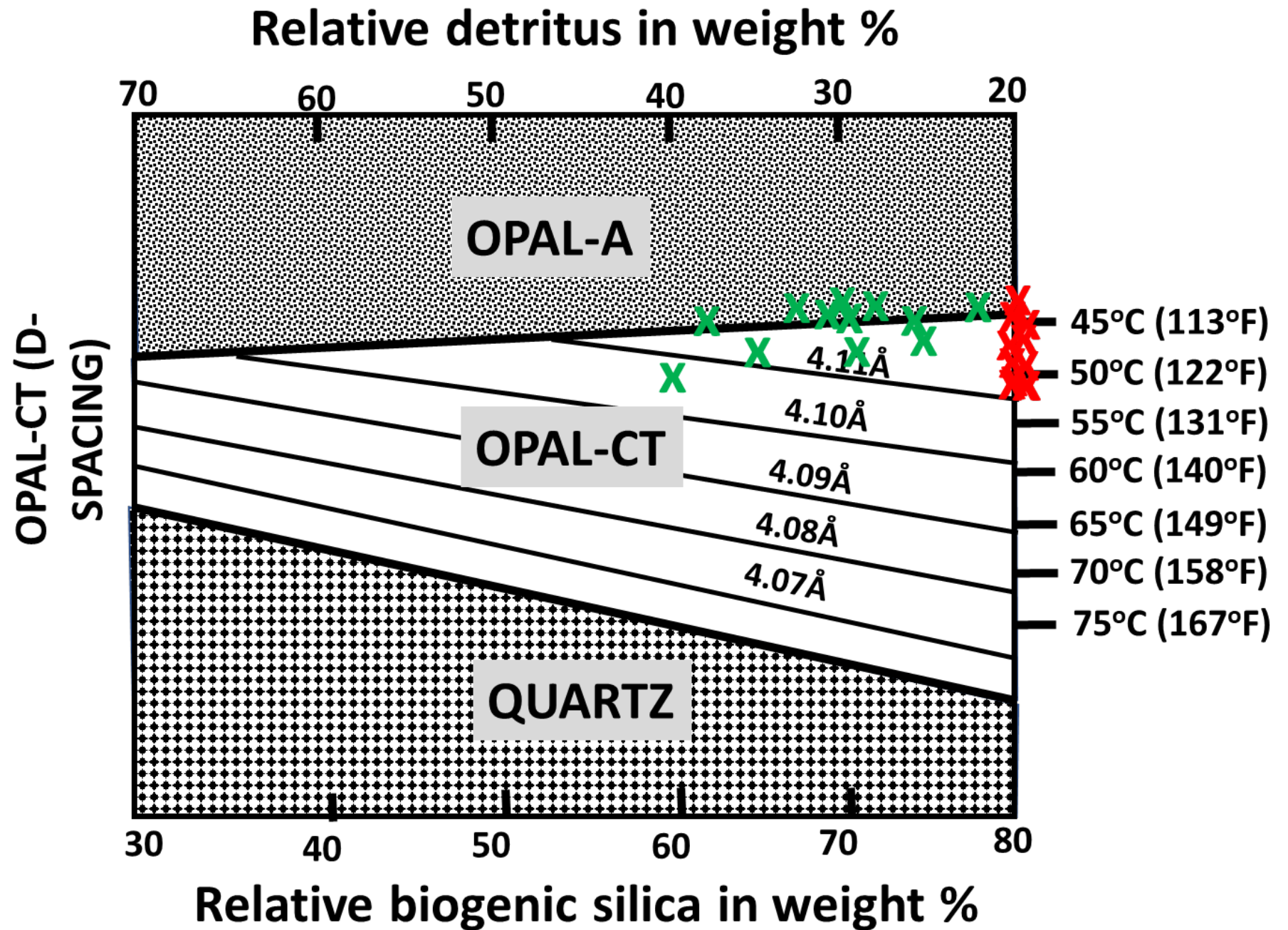
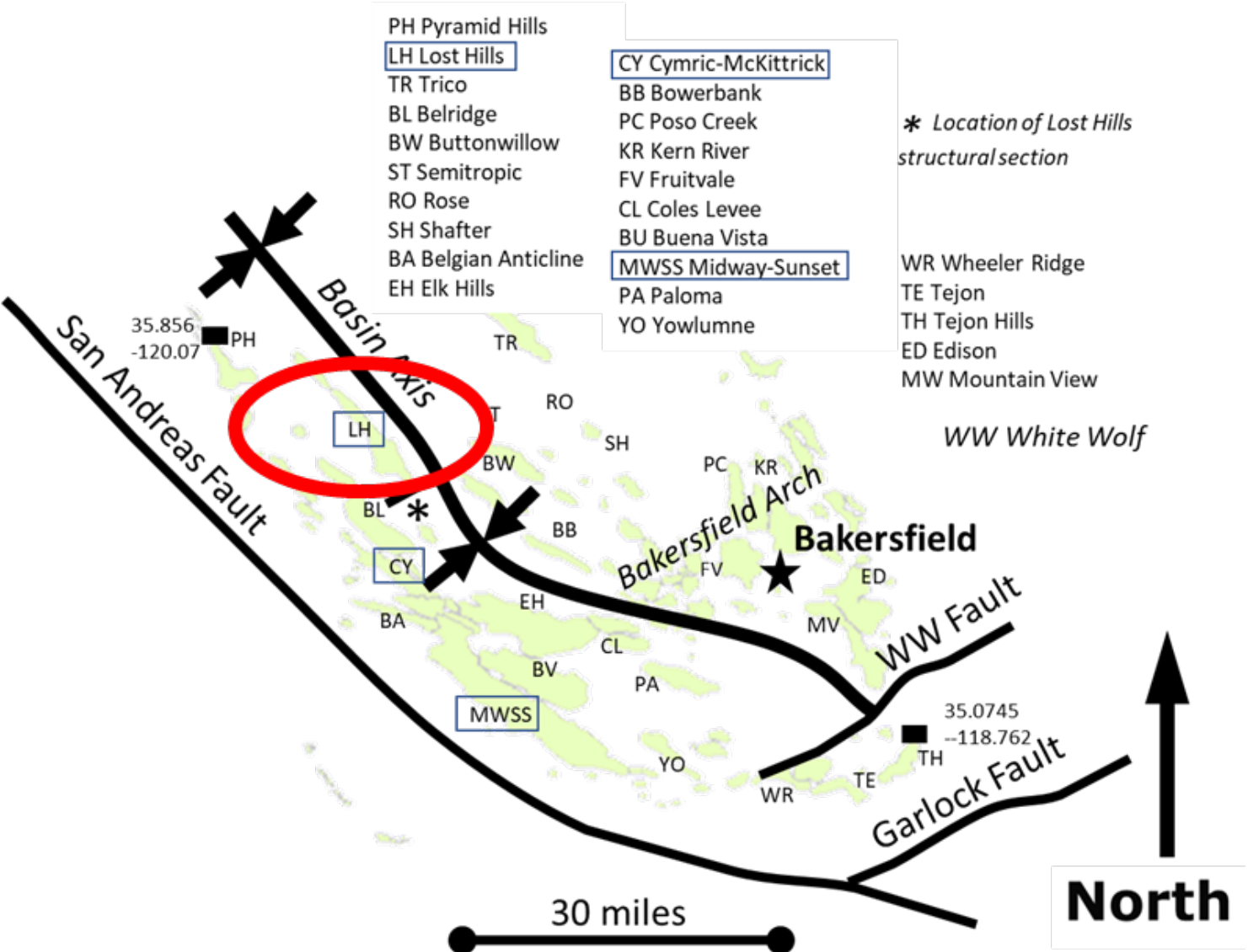


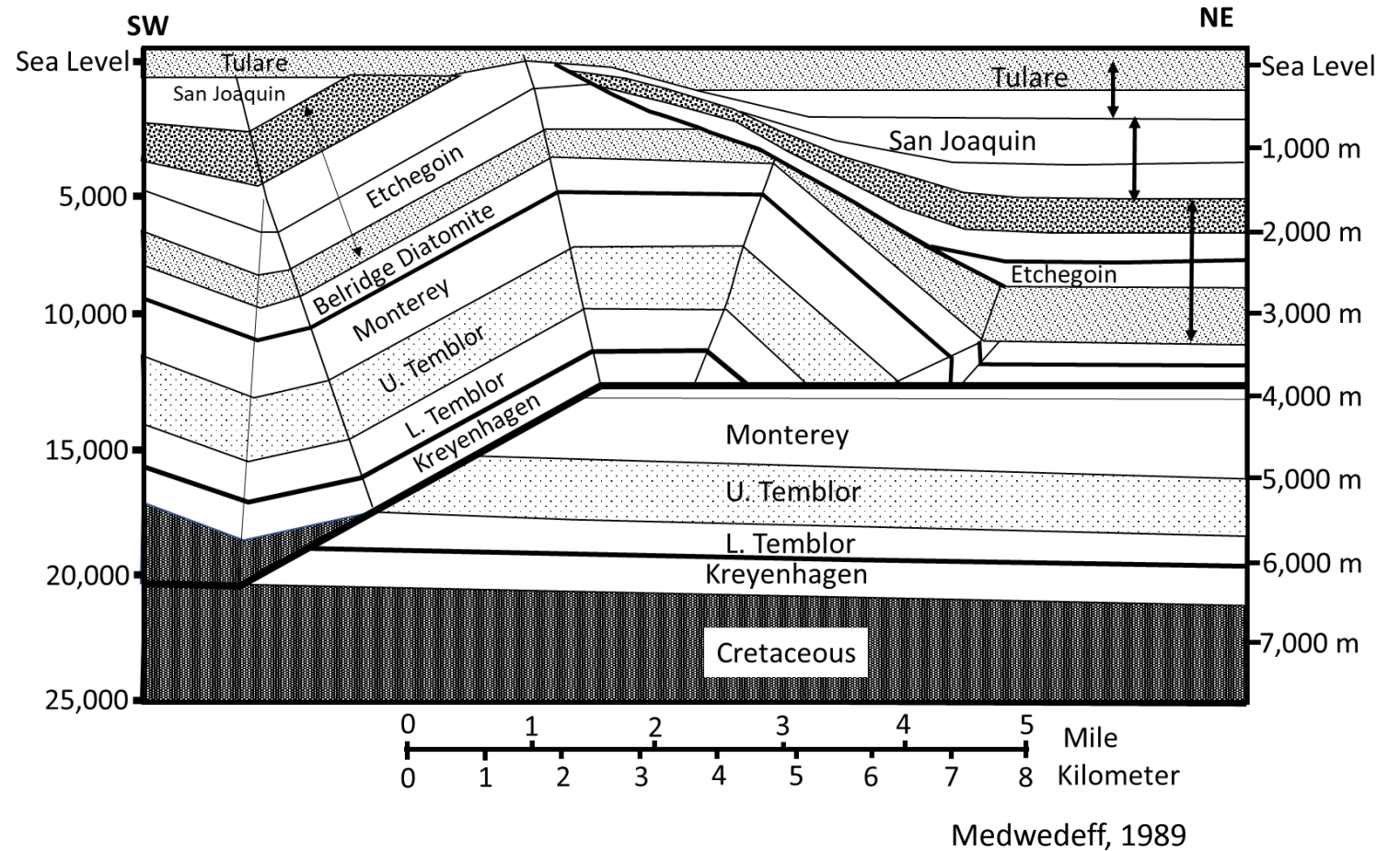
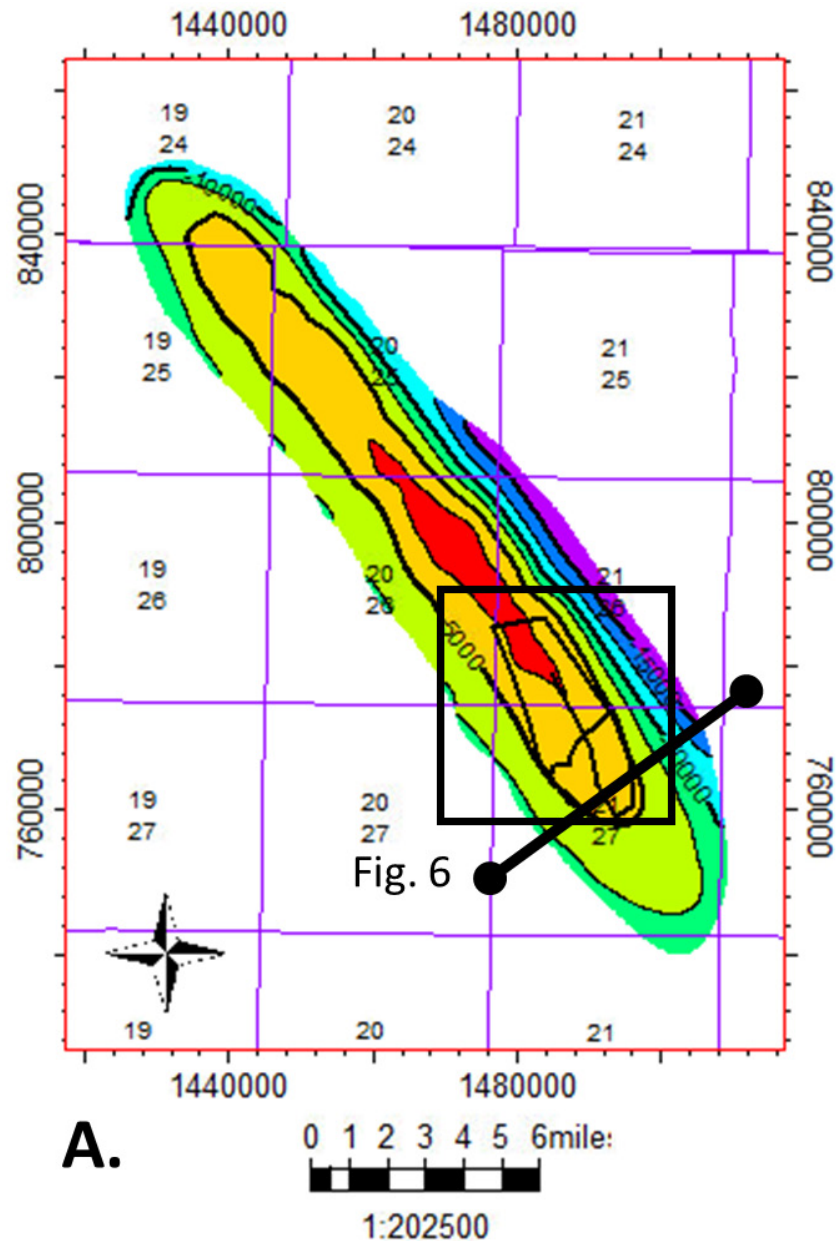
Figure 4. Keller and Isaacs (1985) plot showing the relationship between temperature, composition and silica phase. Opal-CT d(101) spacings are also shown. Green markings are Lost Hills samples with chemical analyses, red markings are Lost Hills samples where composition was approximated using well log (Vshale) data.

Field	Structural Style	Typical Reservoir Thickness	Approximate Area of Production (Chevron Portion)	Typical Core Porosity	Typical Core Oil Saturation	API Gravity	Produced by	Typical* Cumulative Oil Production Per Well (BO)
Lost Hills 1	Asymmetric anticline	1000 ft	3100 acres	50%	30%	19-23	Hydraulic fractures, waterflood	150,000
Midway-Sunset Section 9 (9C), T32N R23E 2	Homoclinal, sub-unconformity trap	200 ft	600 acres	54%	34%	21	Hydraulic fractures, waterflood	30,000
LIGHTER OIL								
Midway Sunset Westates Anticline 3	Asymmetric anticline	600 ft	400 acres	61%	42%	12-14	Cyclic steam	70,000
HEAVY OIL								
Cymric 1Y: T30S R21E 4	Complex disharmonic anticline	400 ft	500 acres	61%	44%	10-12	Cyclic steam	190,000
McKittrick 5	Thrust belt	500 ft	500 acres	65%	48%	12-15	Cyclic steam	50,000

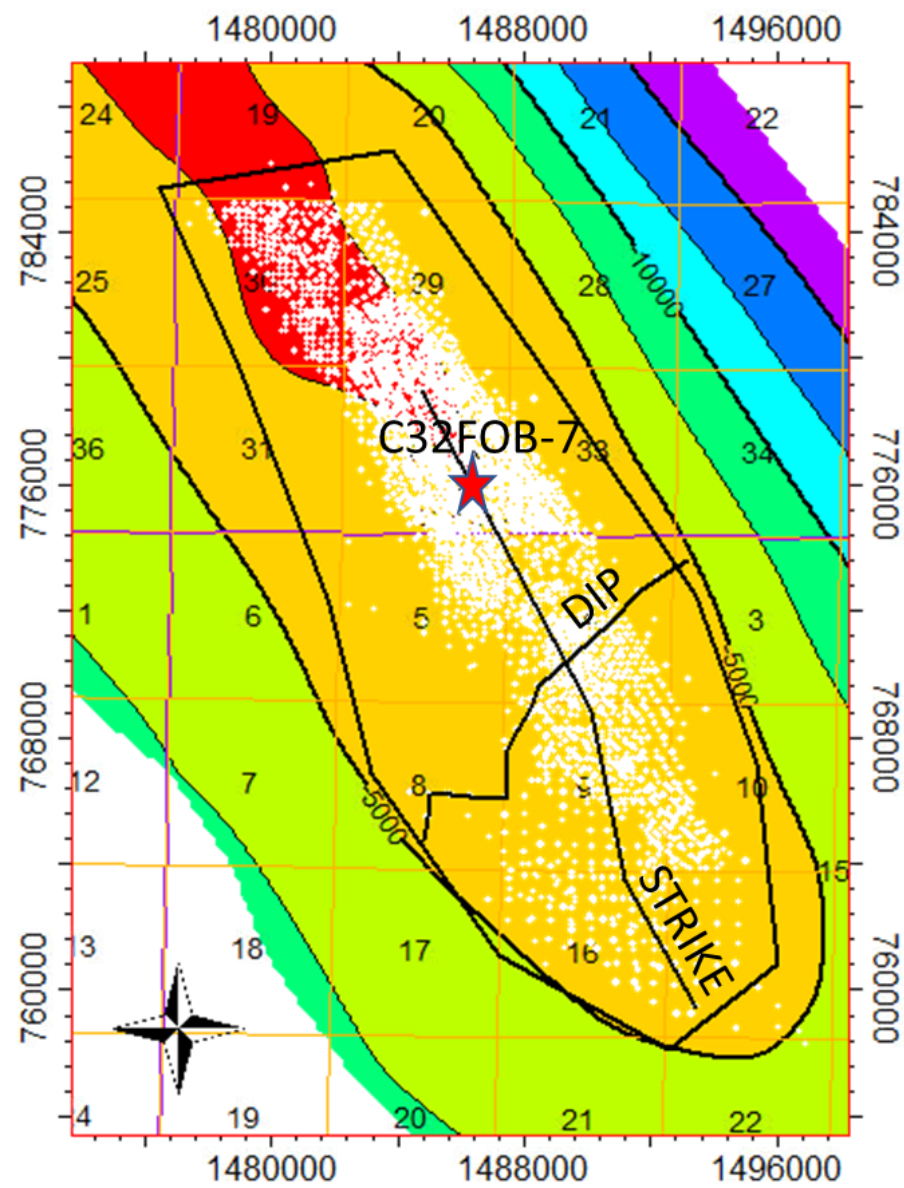
* DOGGR website

LOST HILLS





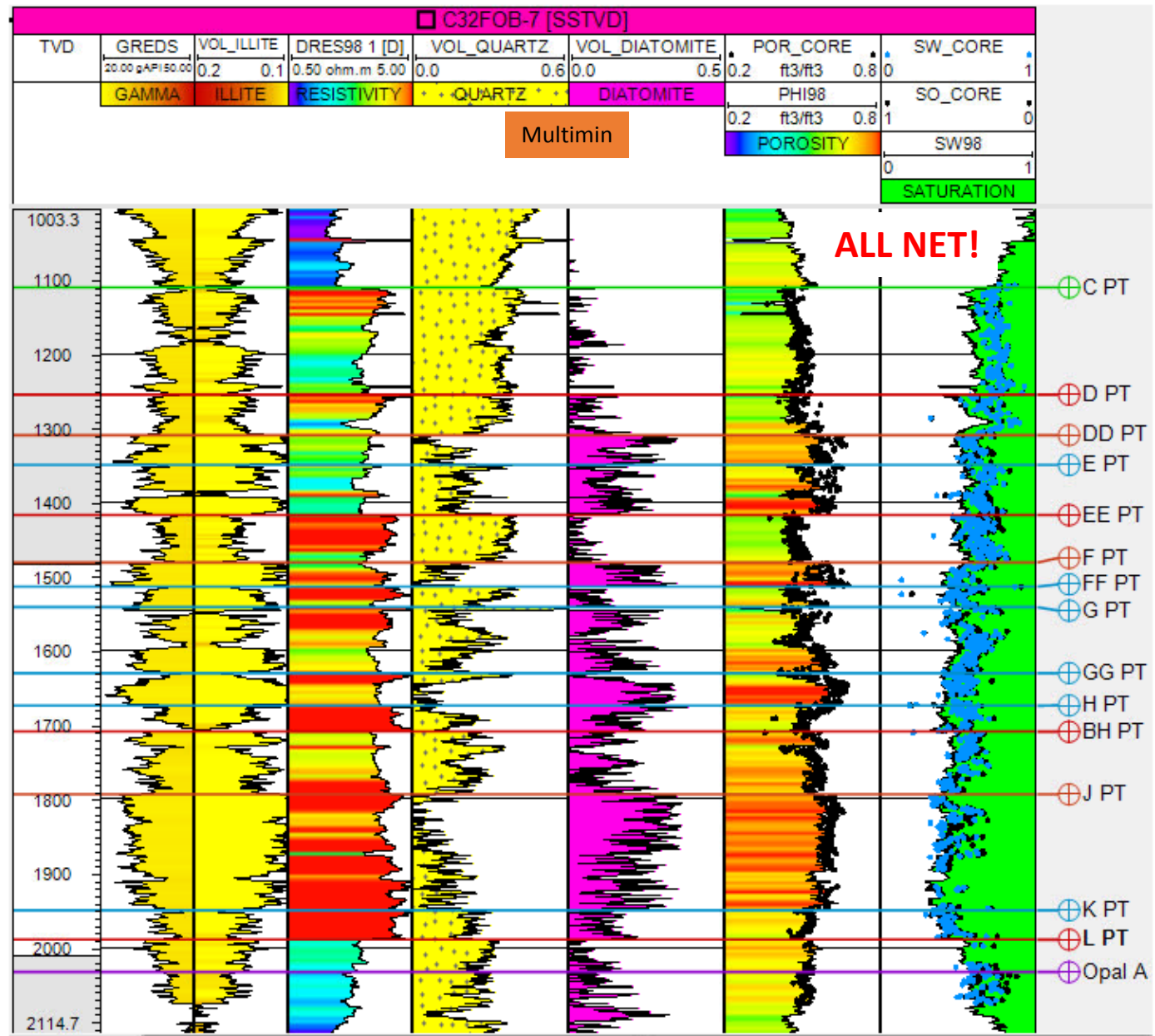
--preservation of Opal A diatomite in thrust belt
 --folding of Opal A/CT boundary is gentler than bedding



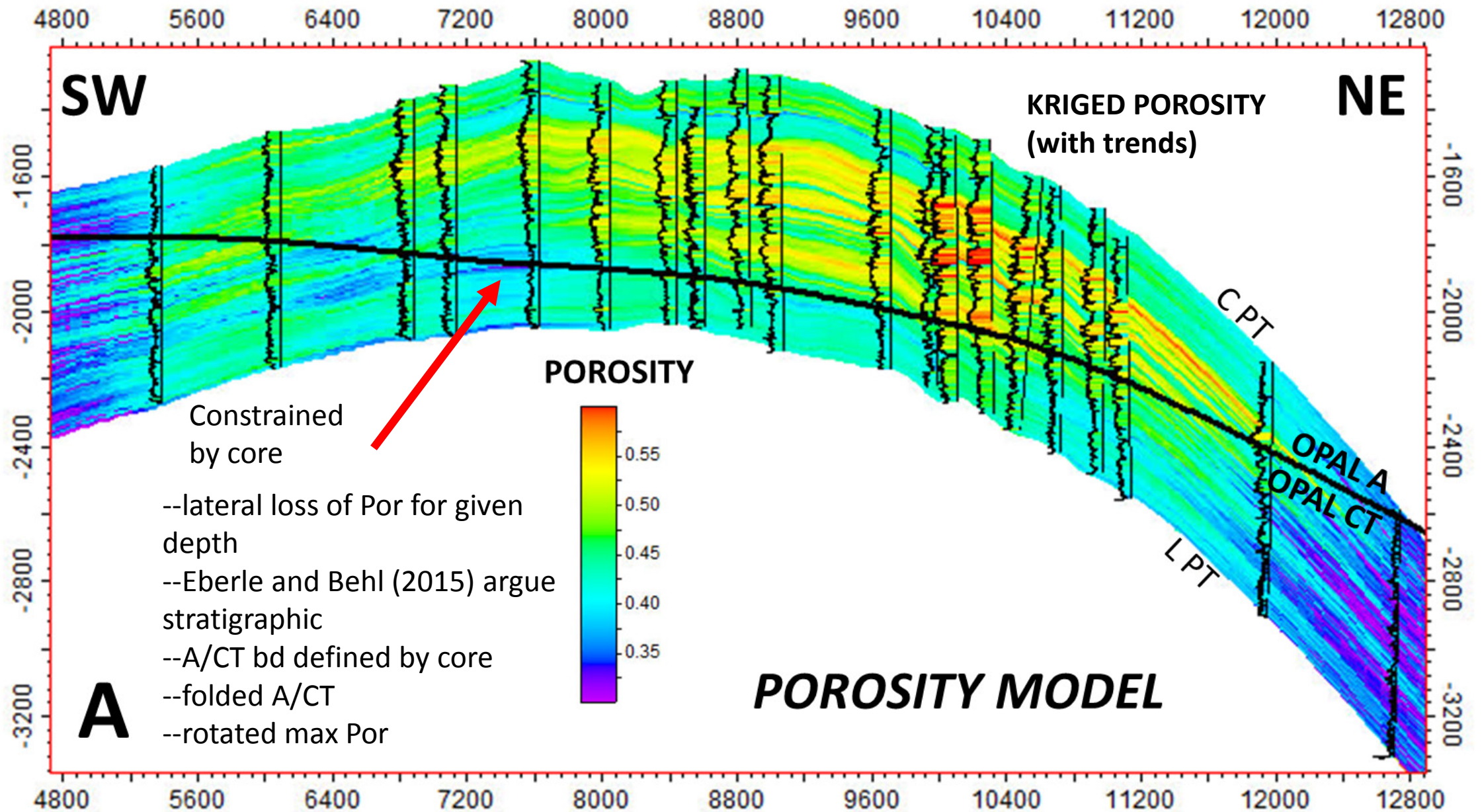
B.

0 0.5 1mile
1:50000

1000 ft!

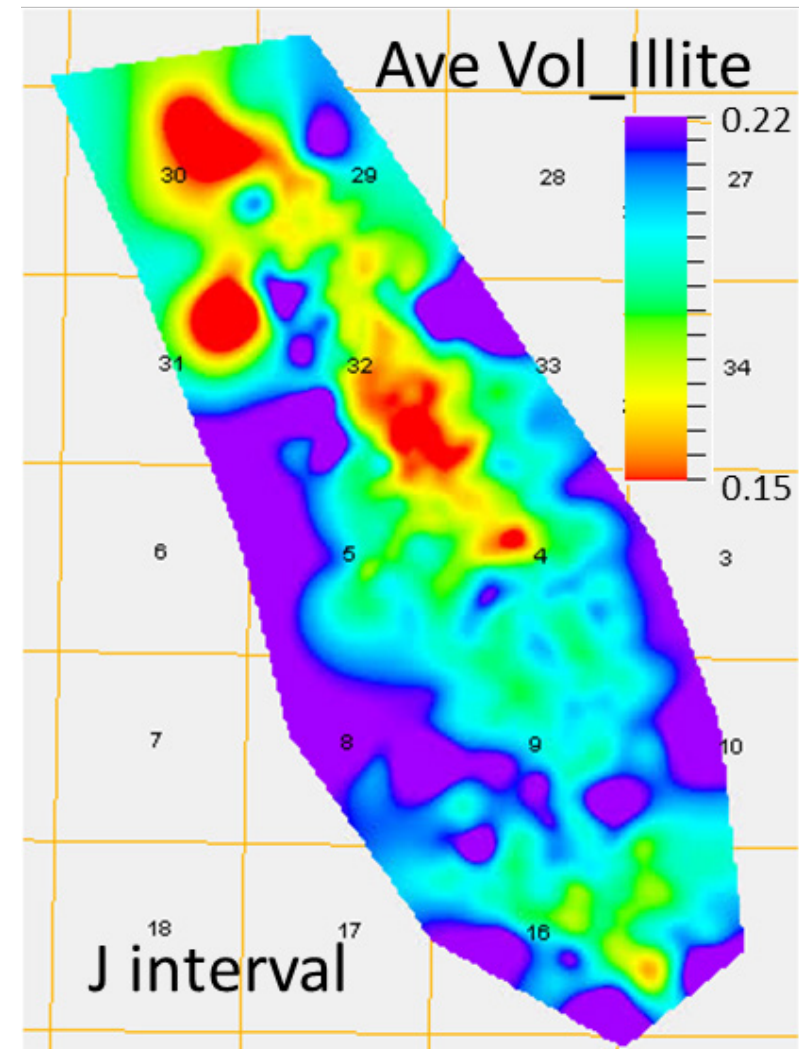


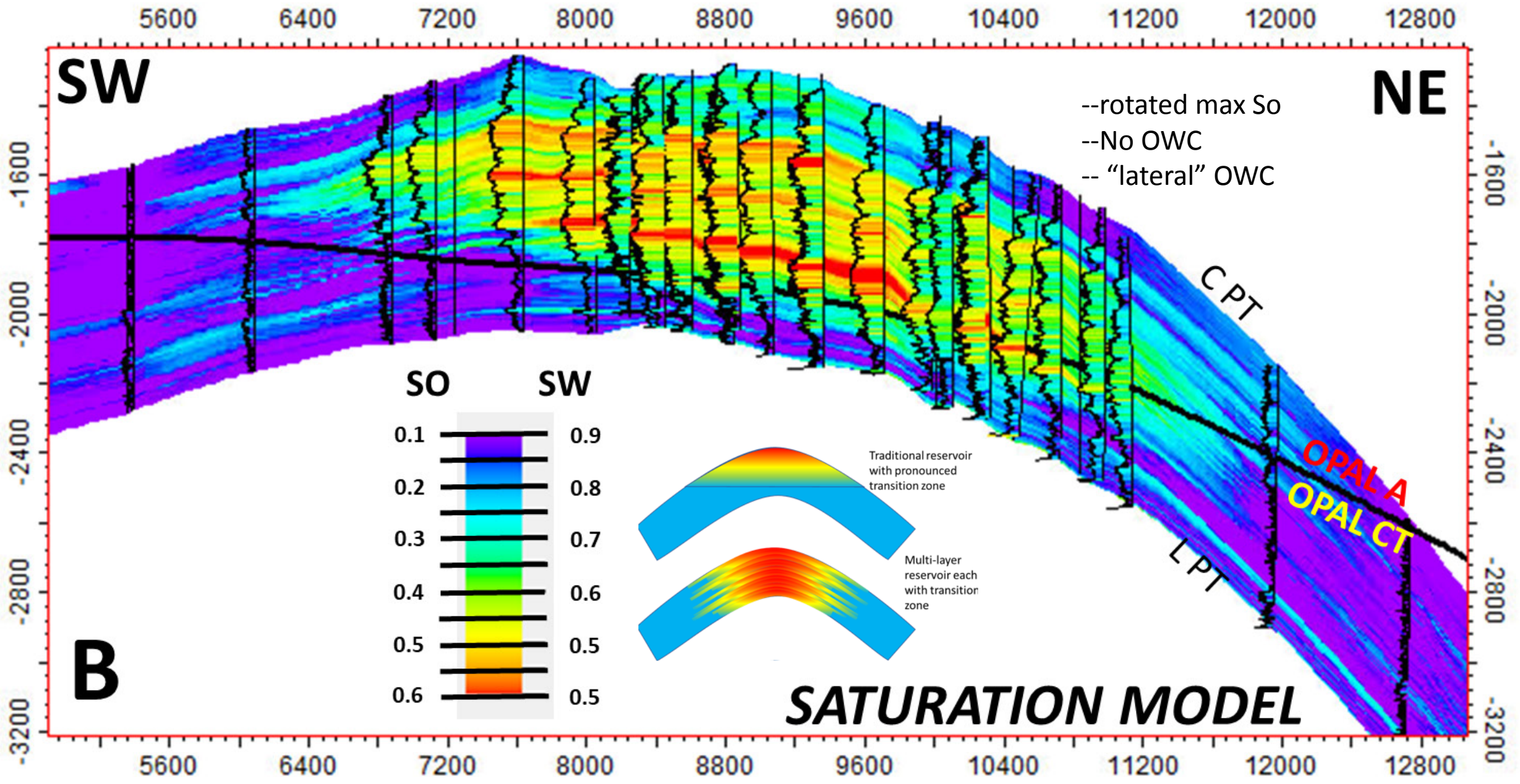
Type log for Lost Hills, well C32FOB-7.



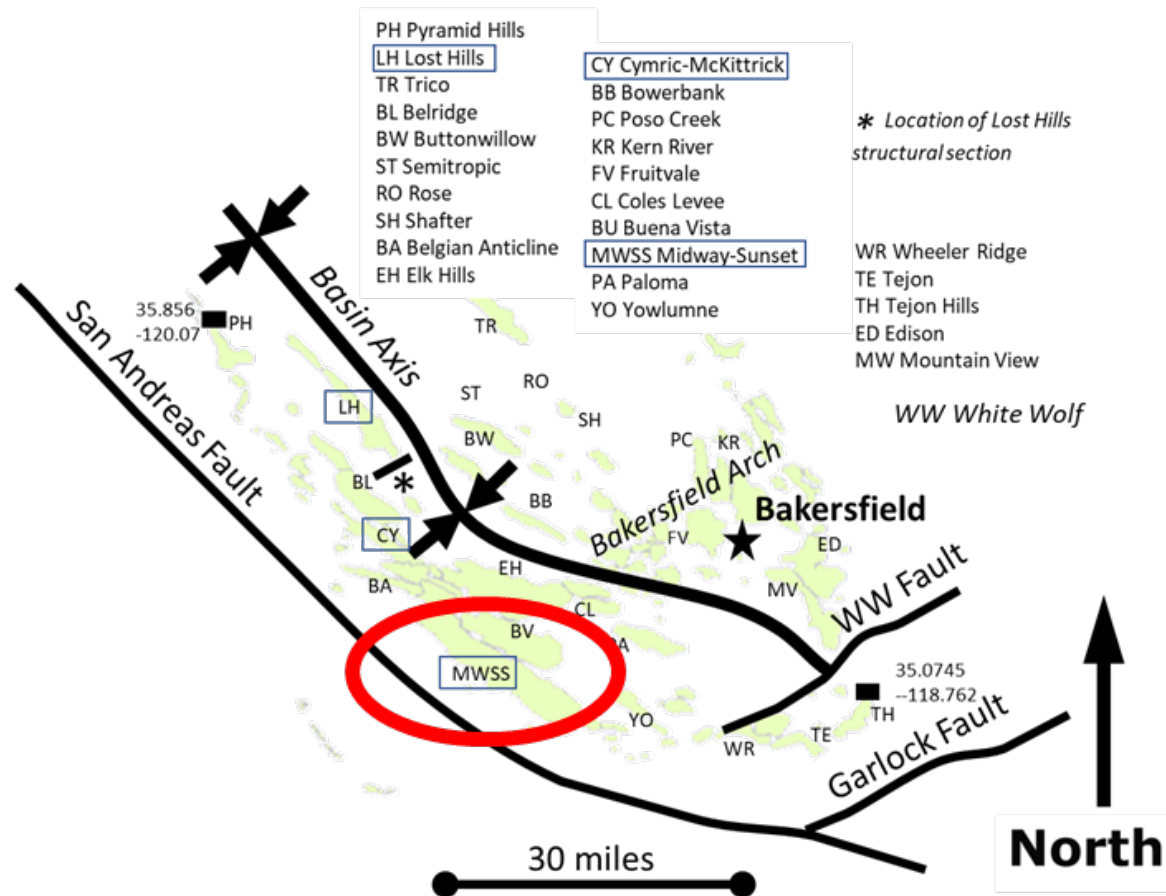
Supporting the Eberle/Behl (2015) Hypothesis

- Limited published studies on the Midway-Sunset, Buena Vista, Elk Hills, Belridge, and Lost Hills fields show *a gradation of lithofacies from more highly siliceous sediments at the top of anticlinal paleobathymetric highs to the surrounding lows* where biogenic or diagenetic silica is diluted with detritus.





Midway-Sunset



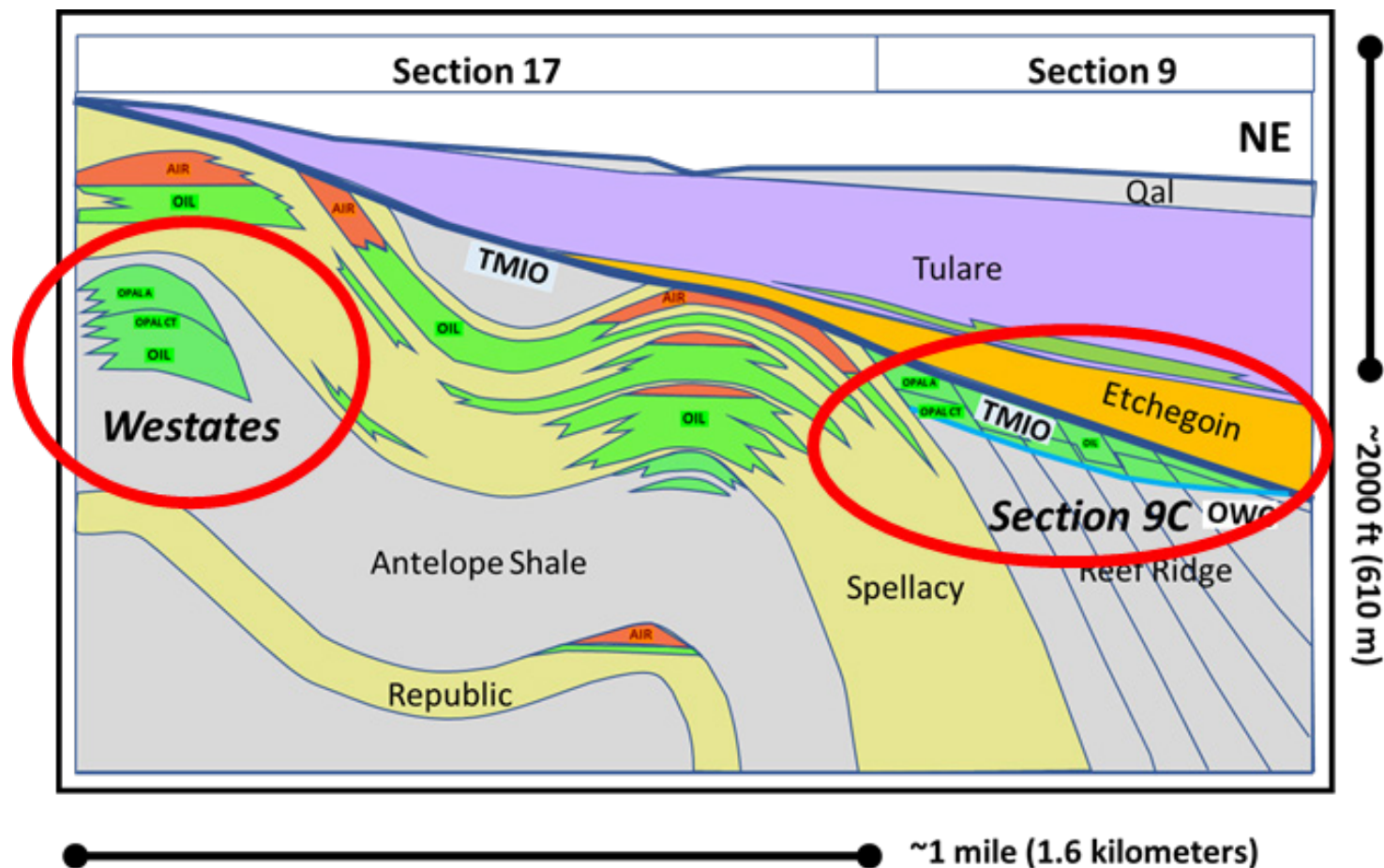
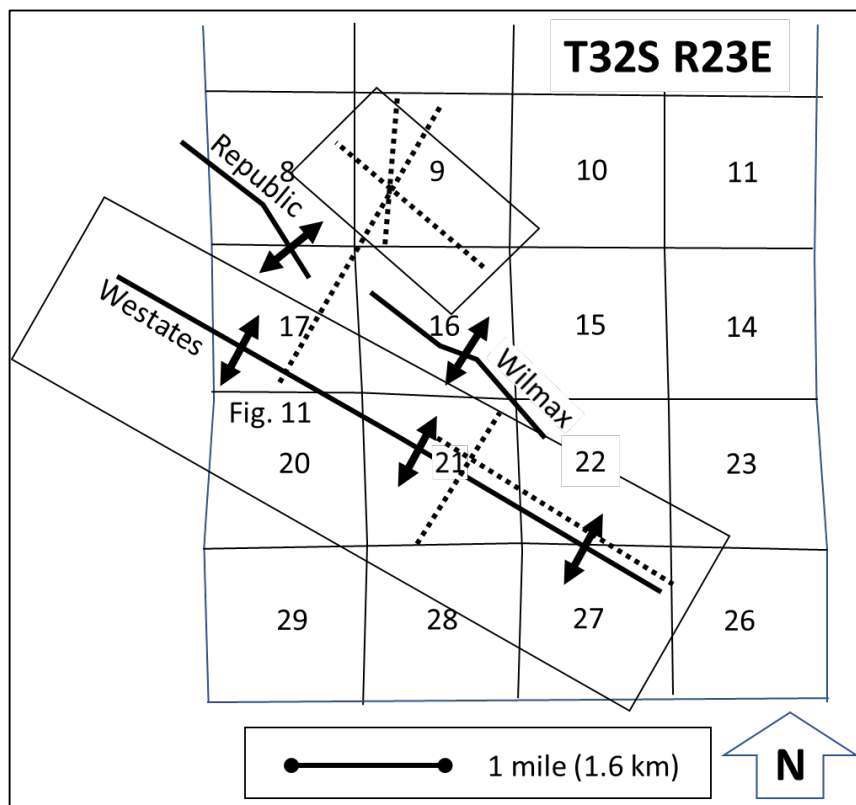
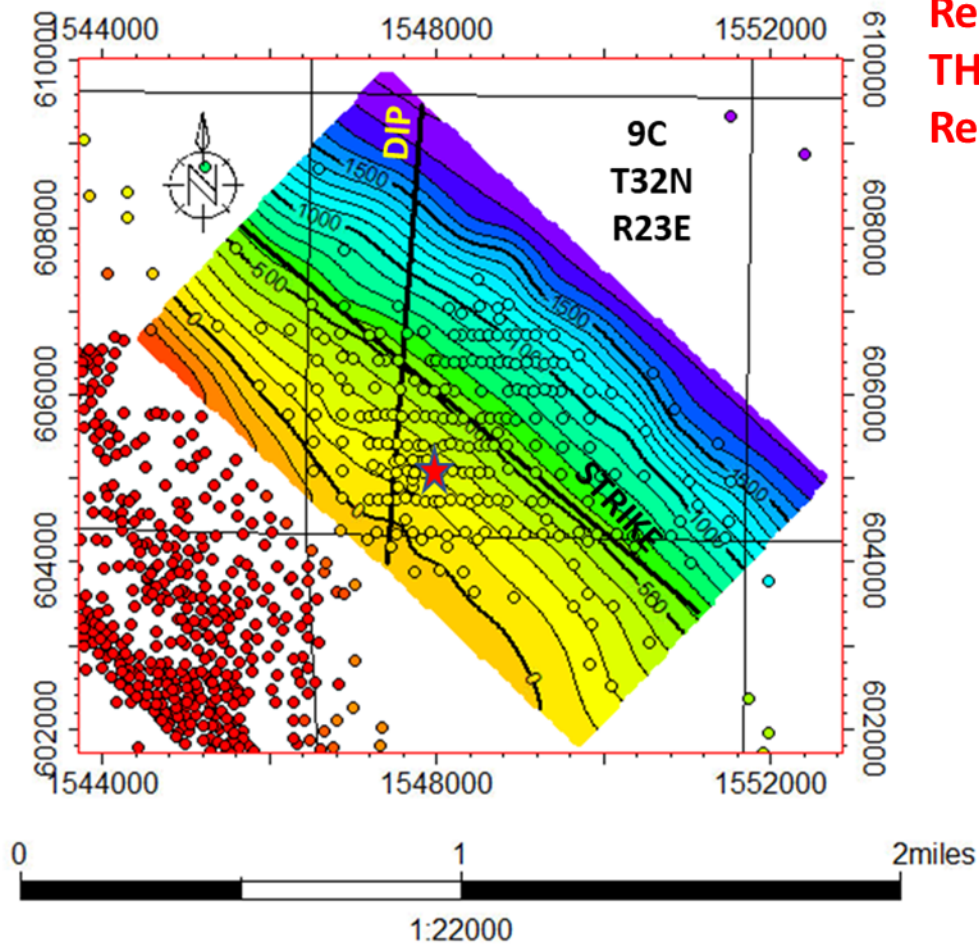
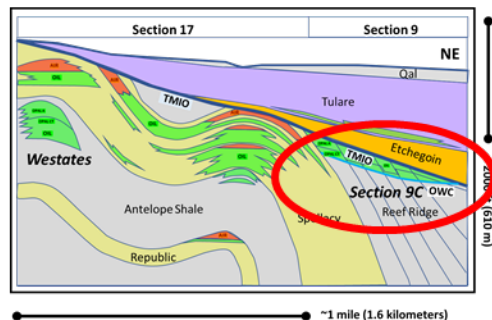
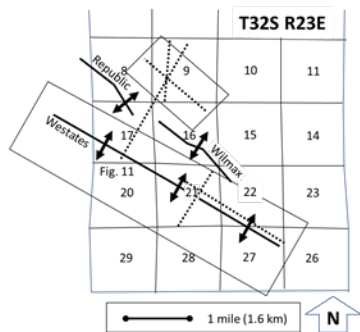
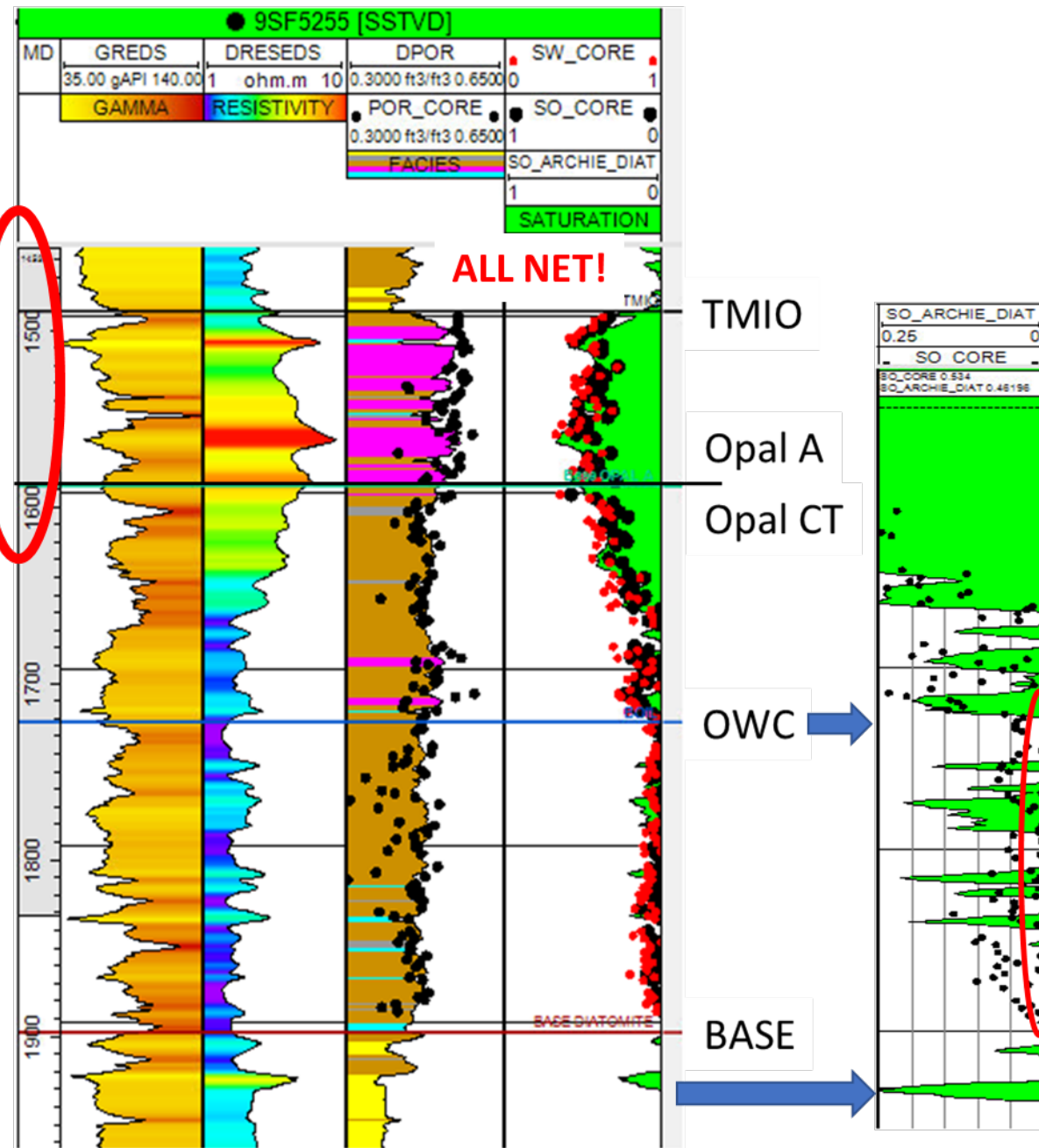


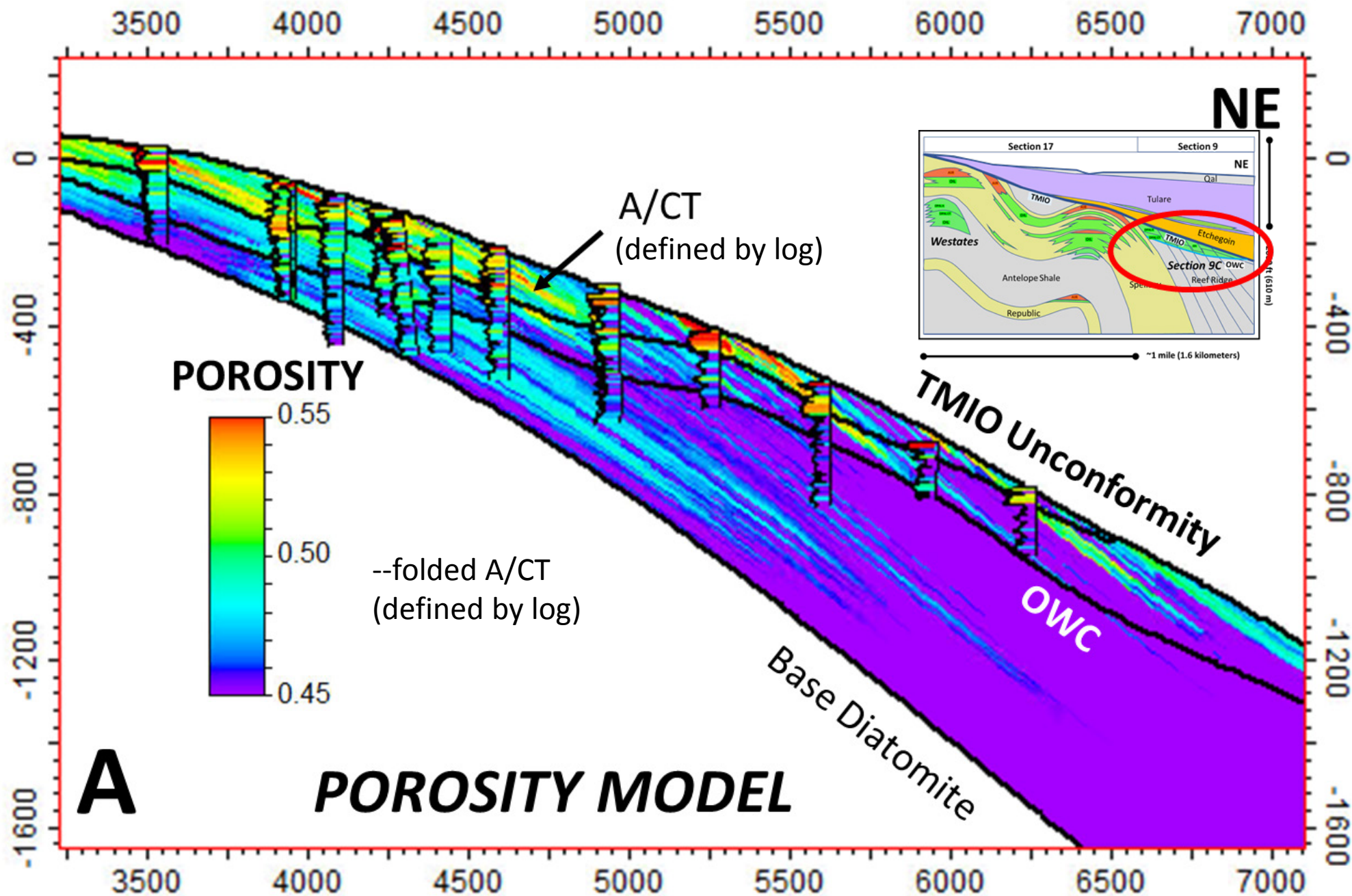
Figure 11. Schematic cross section between Sections 17 and 9 on Figure 10. The figure has been used internally in Chevron for years, of uncertain origin.

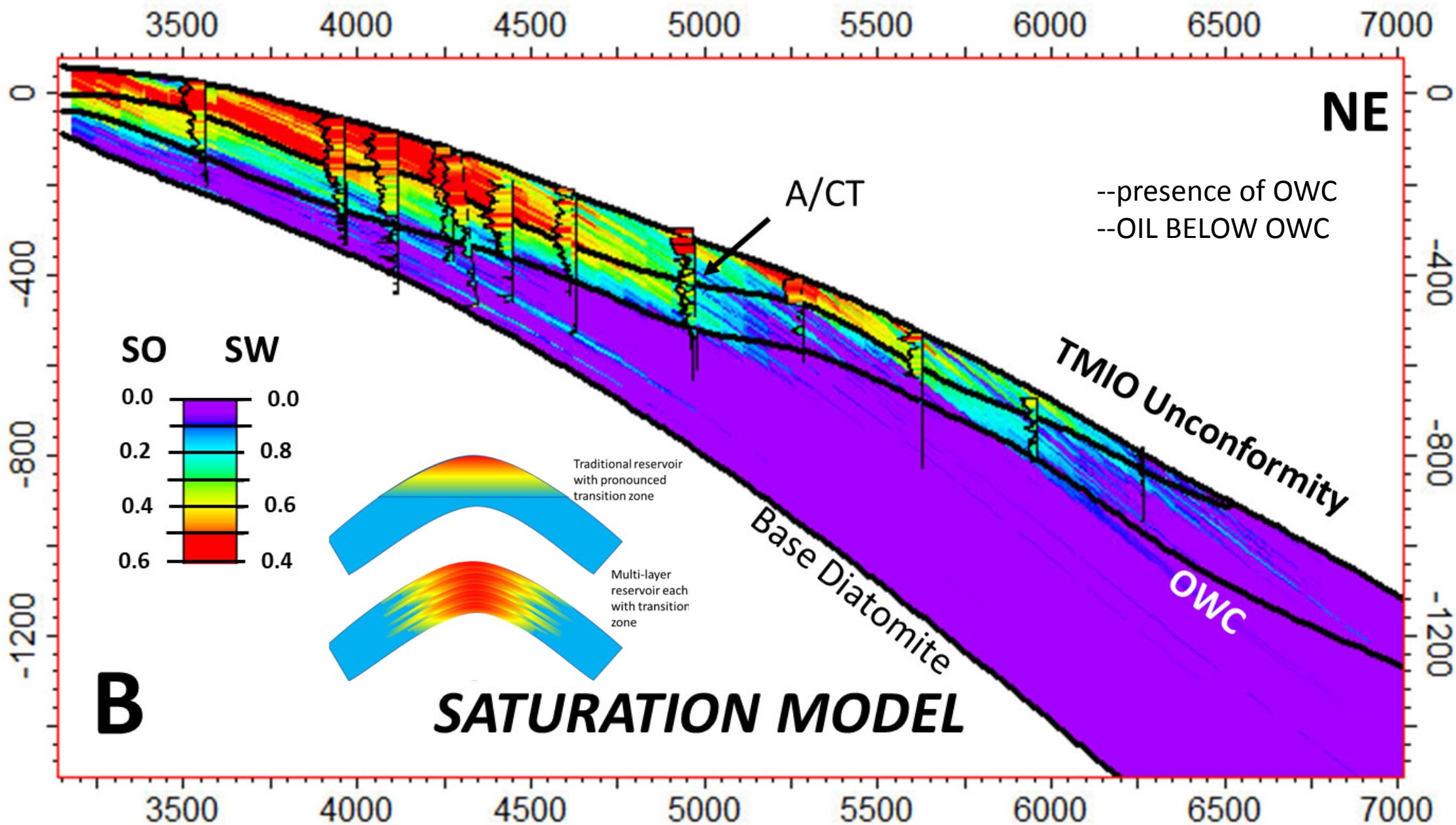
Figure 10. Location map of the two diatomite reservoirs described in Midway-Sunset Field, located in T32S R23E. The locations of the Westates, Republic and Wilmax anticlines are indicated (from Gregory, 2001). Dashed lines show cross-sections described here.

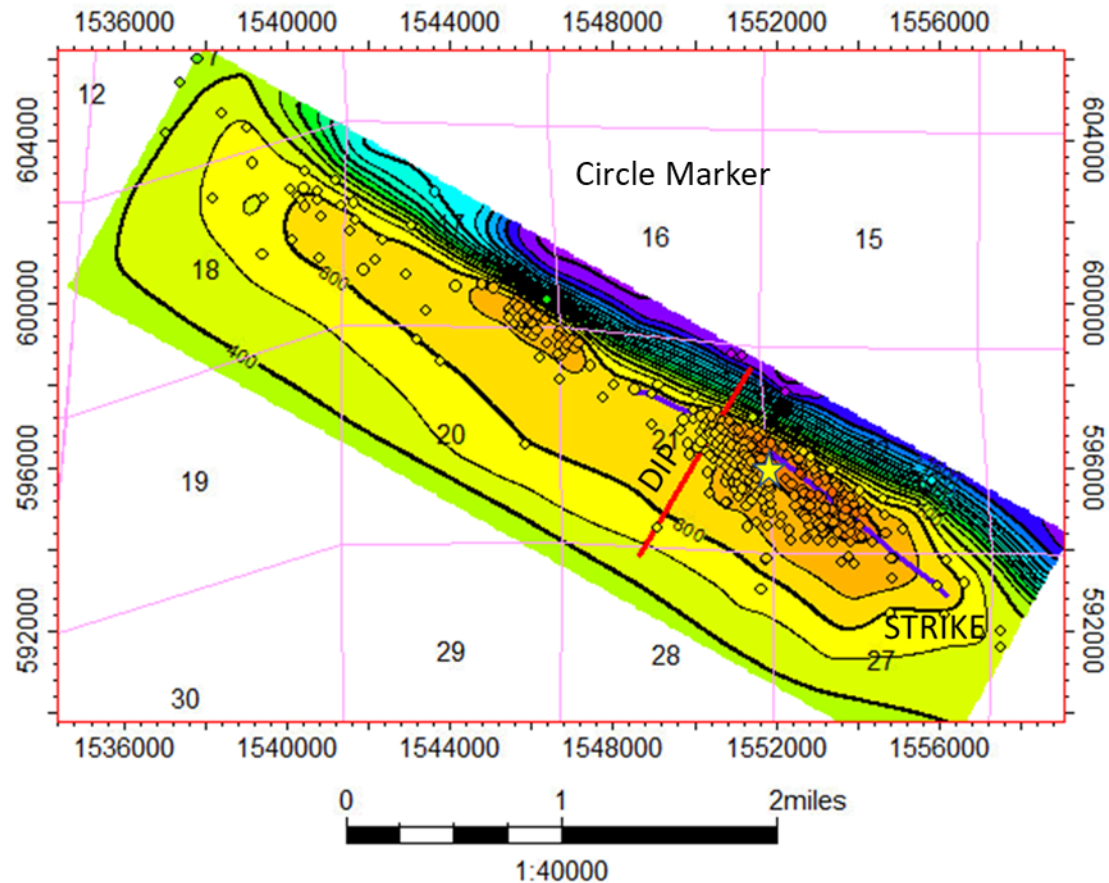
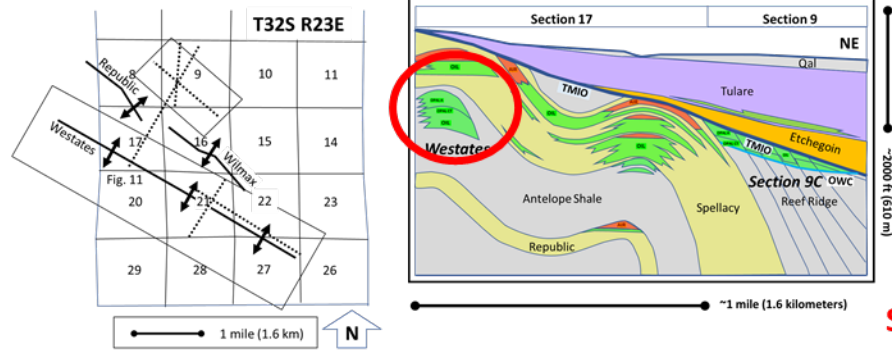


DEEP
Reservoir
THIN
Reservoir



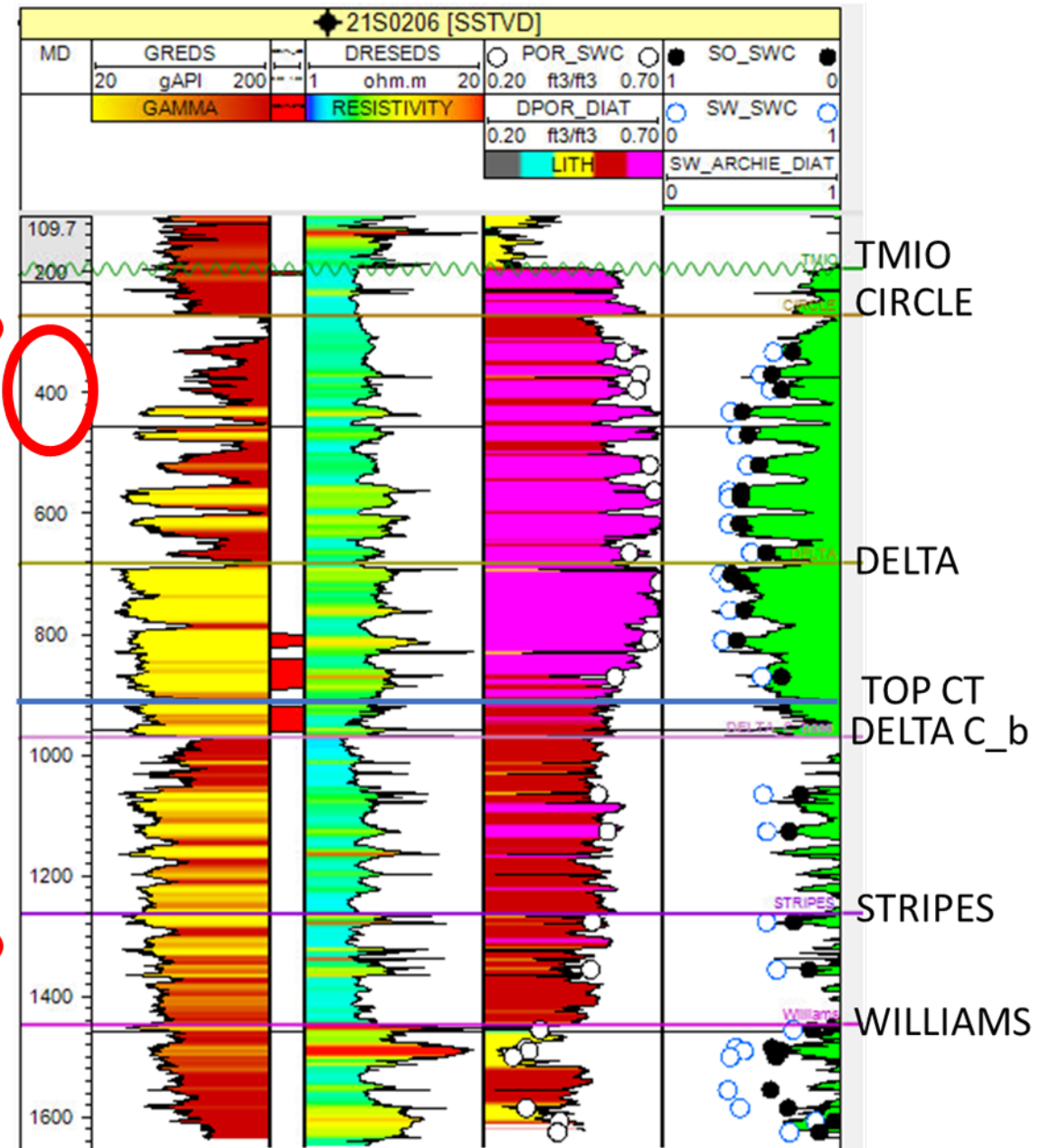




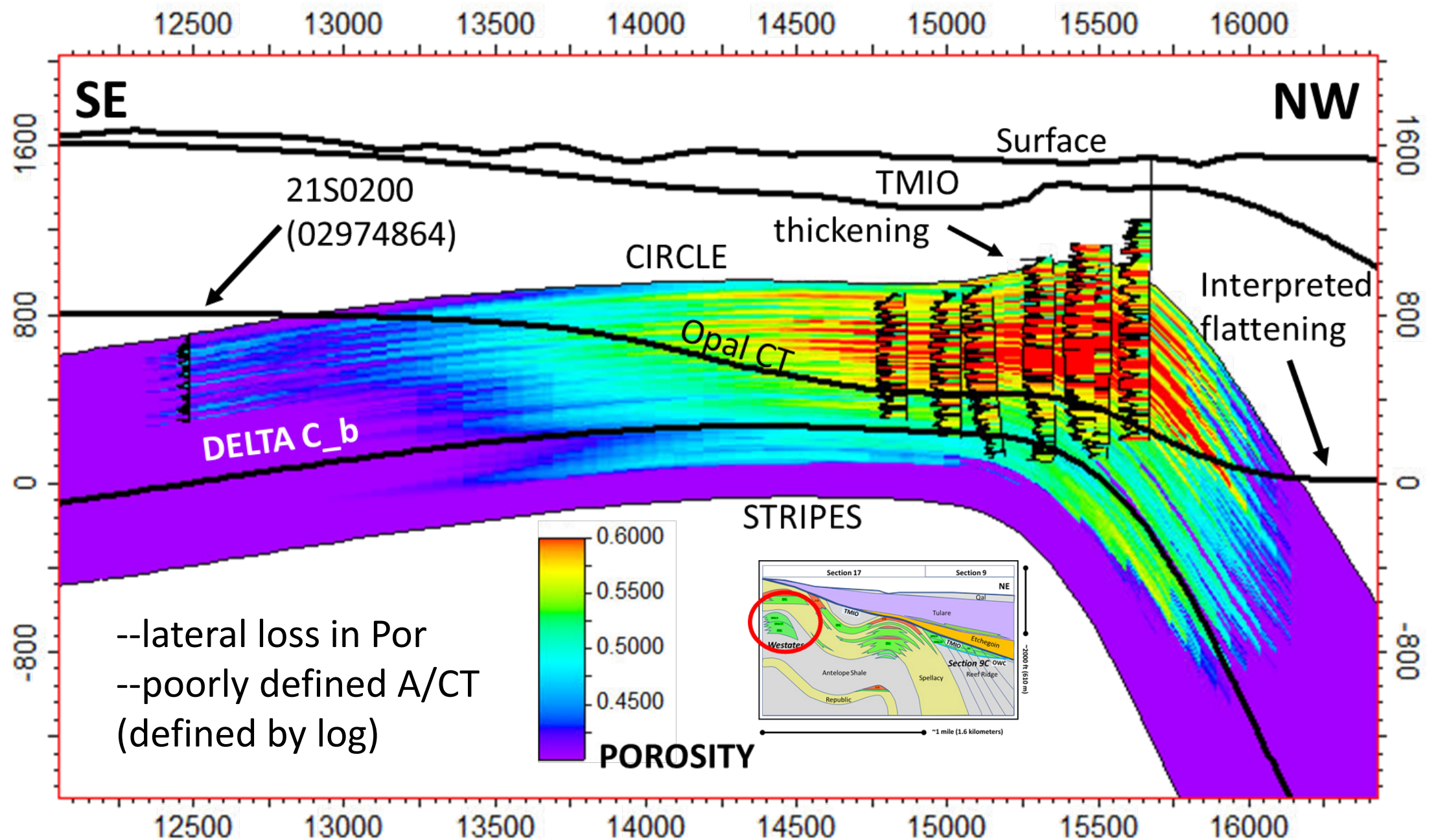


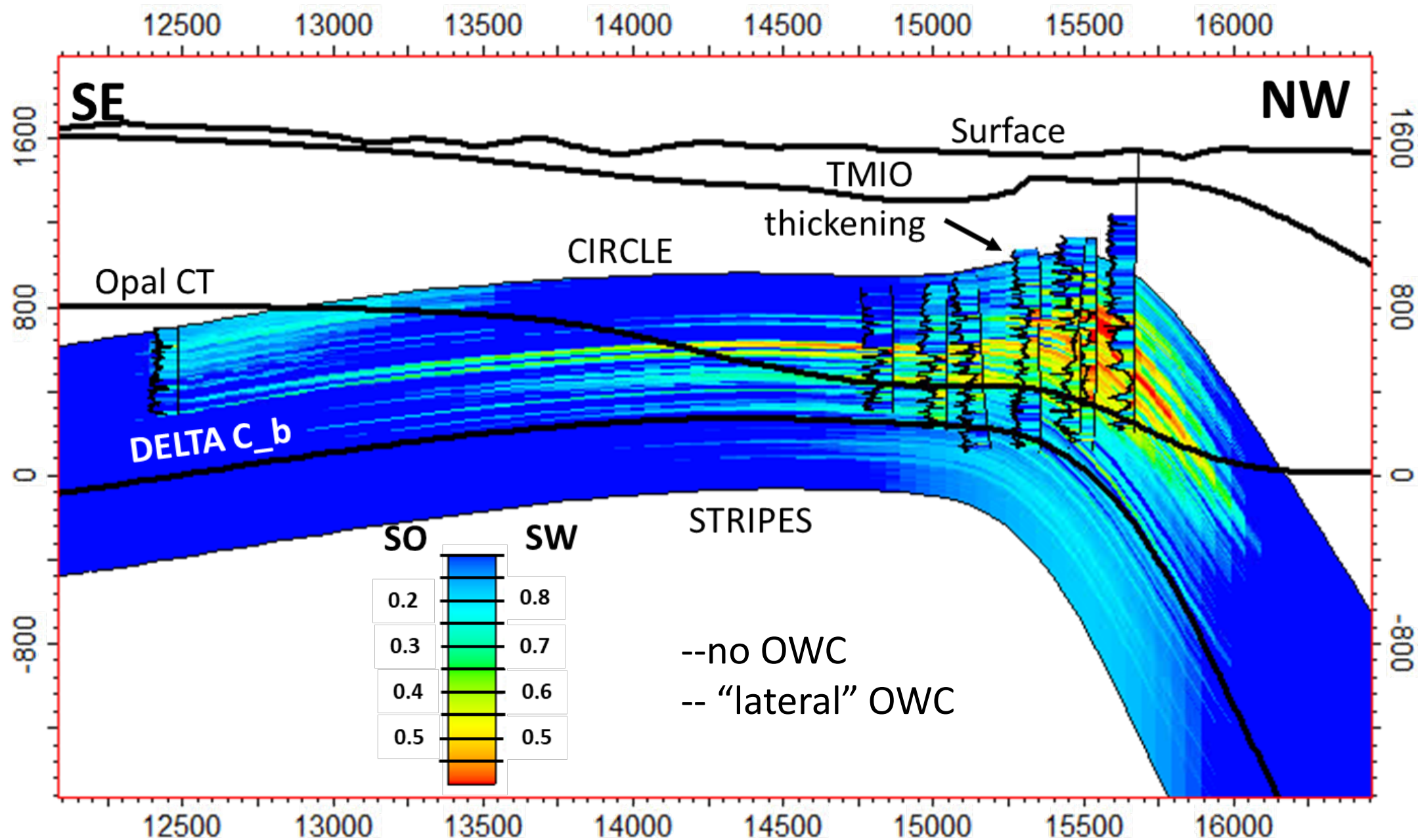
SHALLOW
reservoir
THICK
reservoir

1000 ft

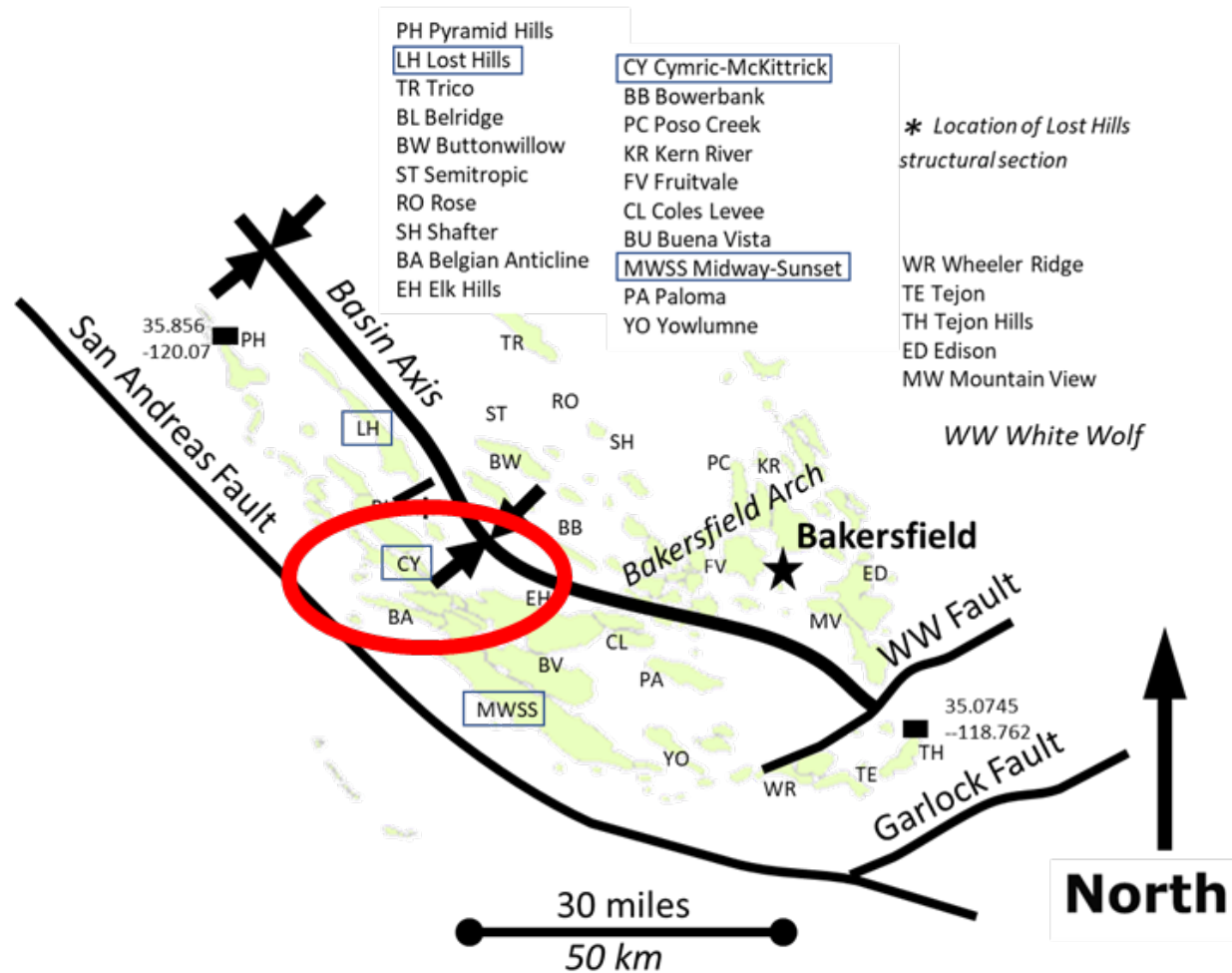


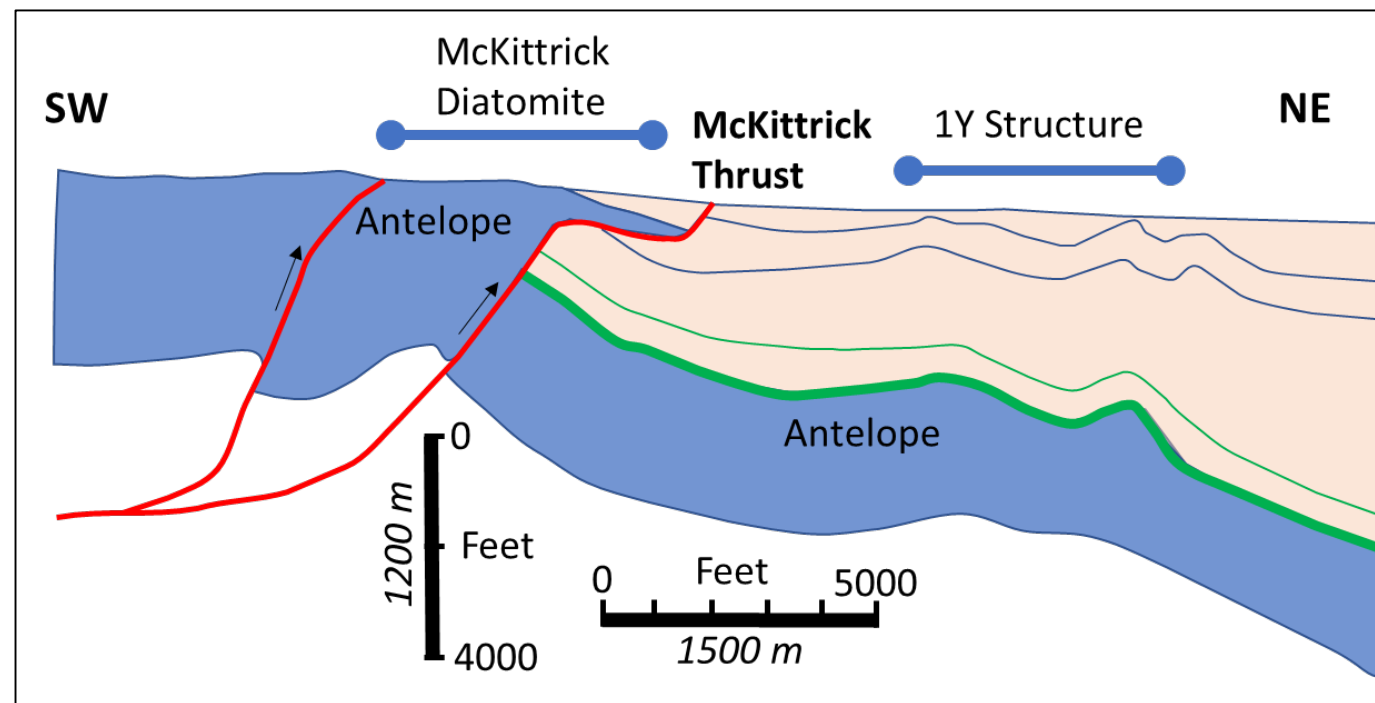
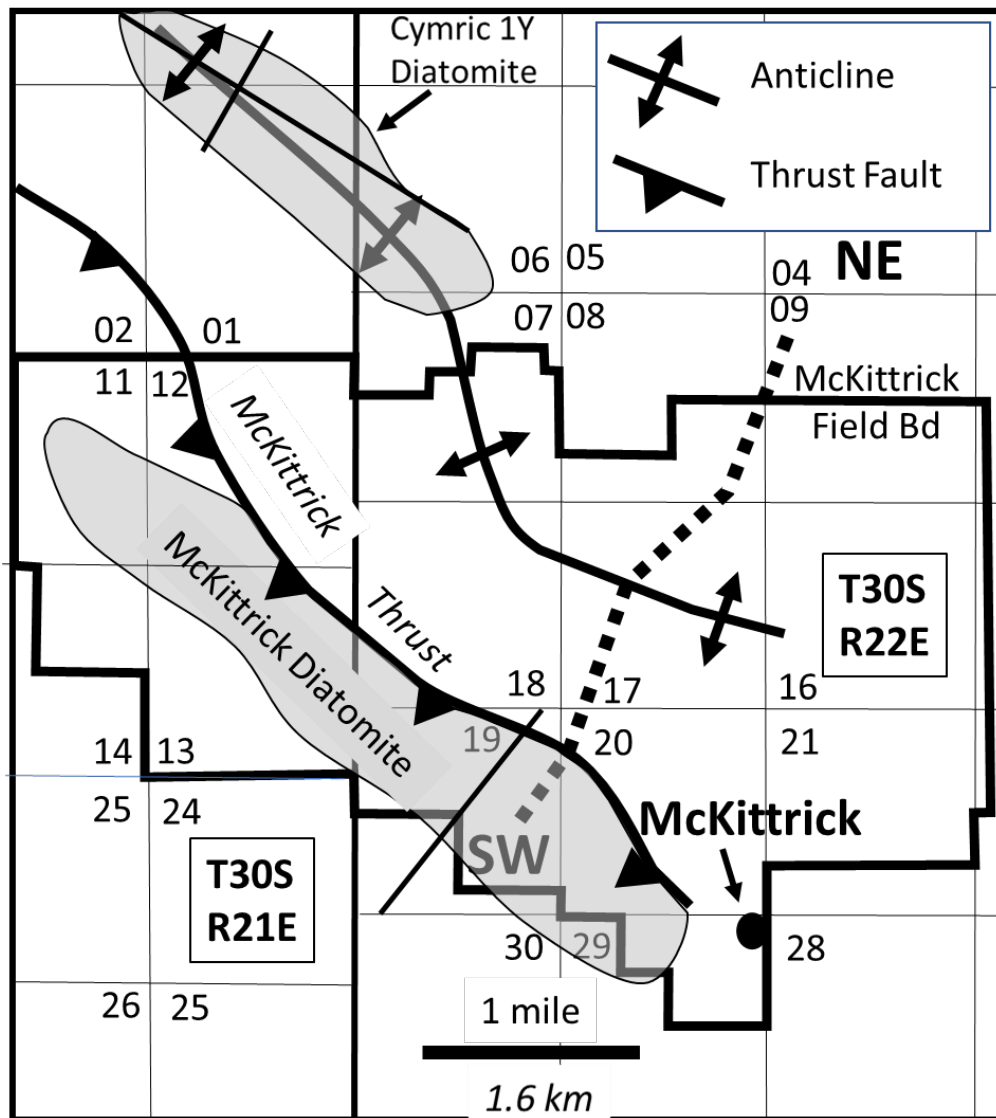
pink, Opal-A diatomite; brown, Opal-CT; yellow, sandstone; blue, cemented tight zones (carbonate) and gray, clay-rich mudstone.

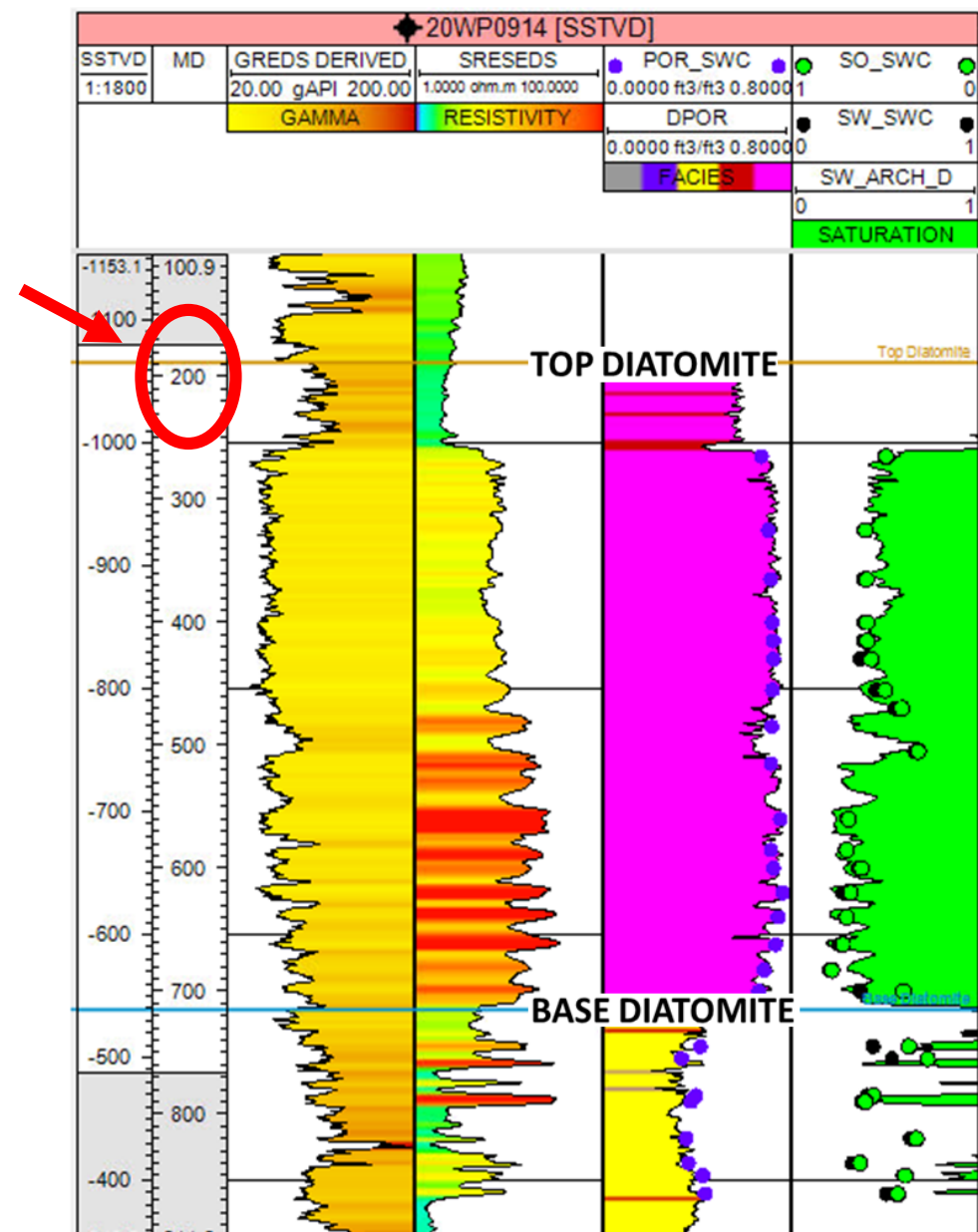
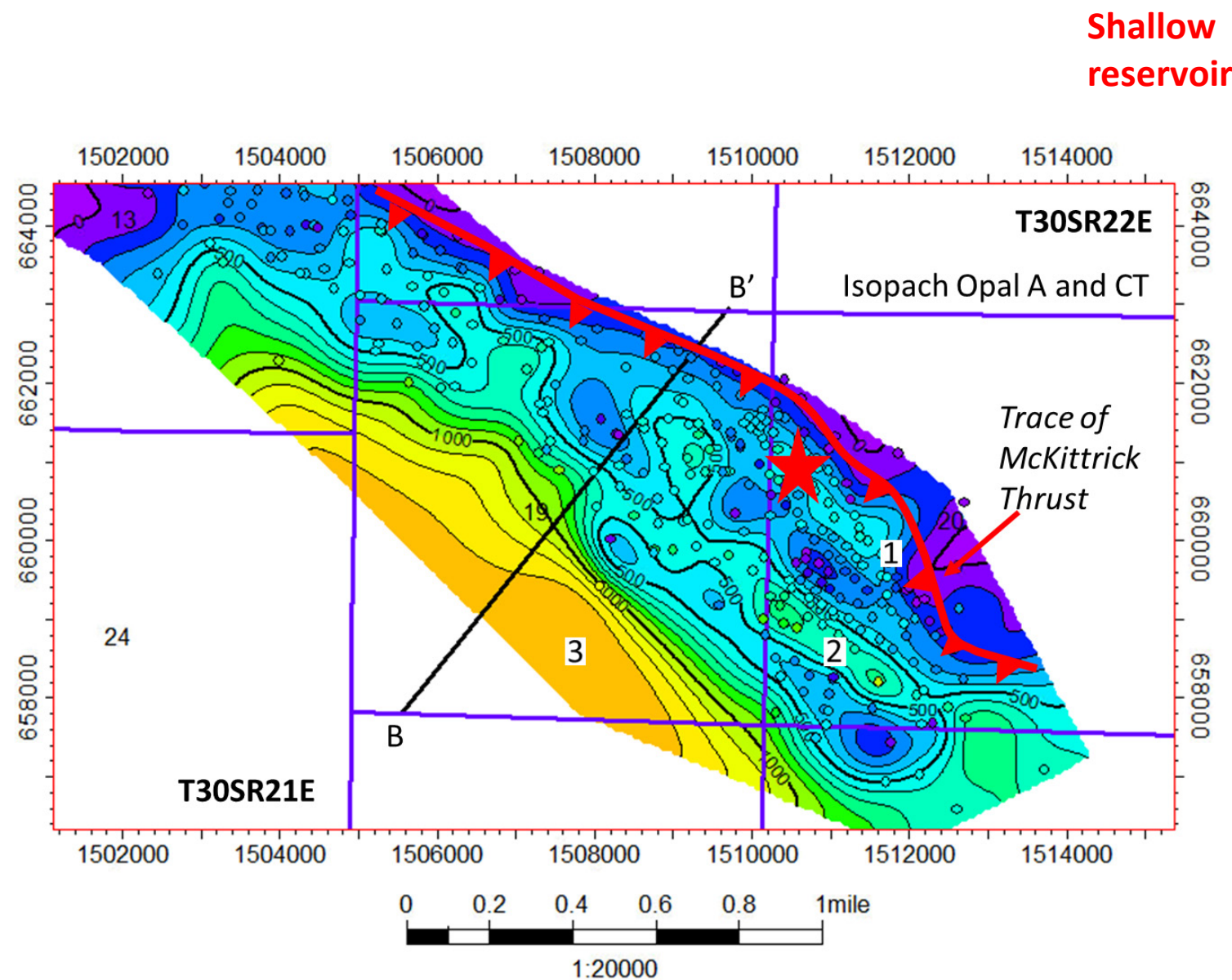


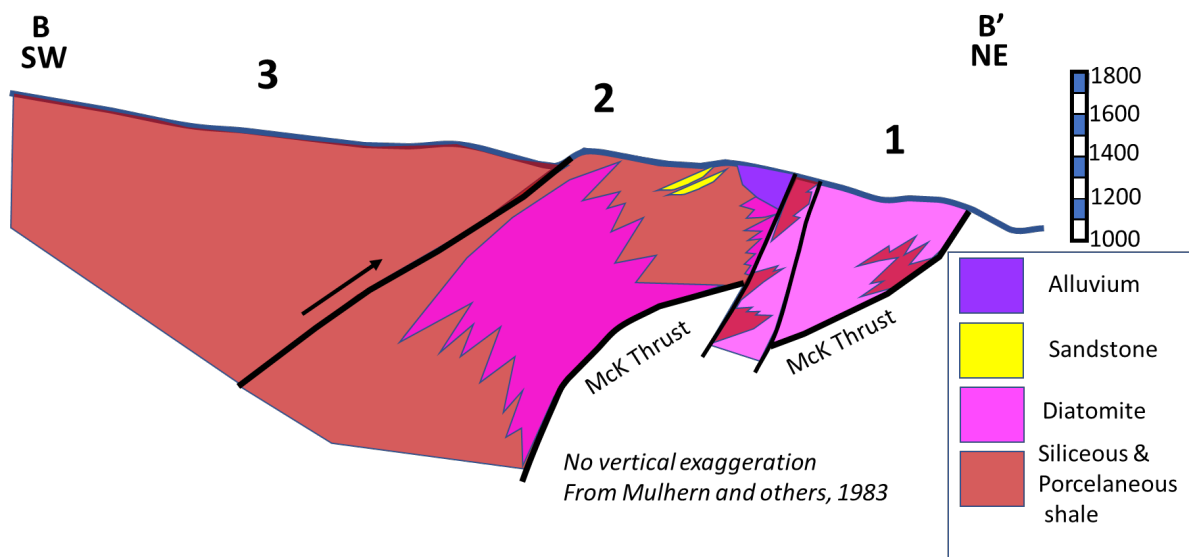
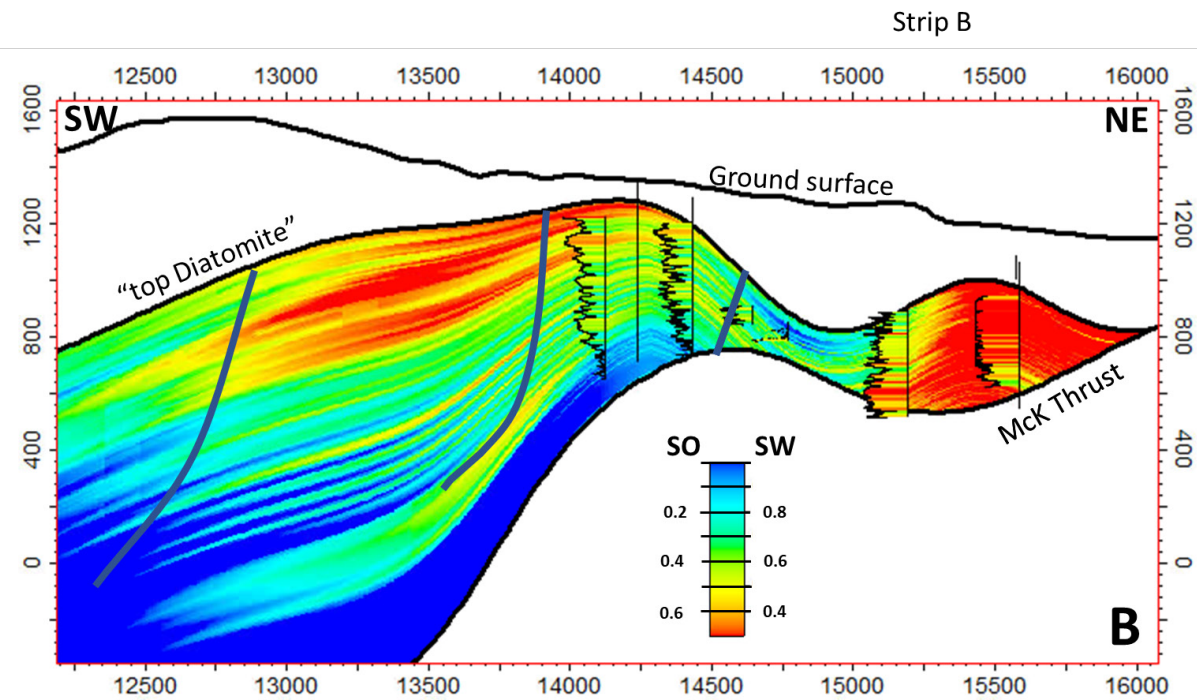
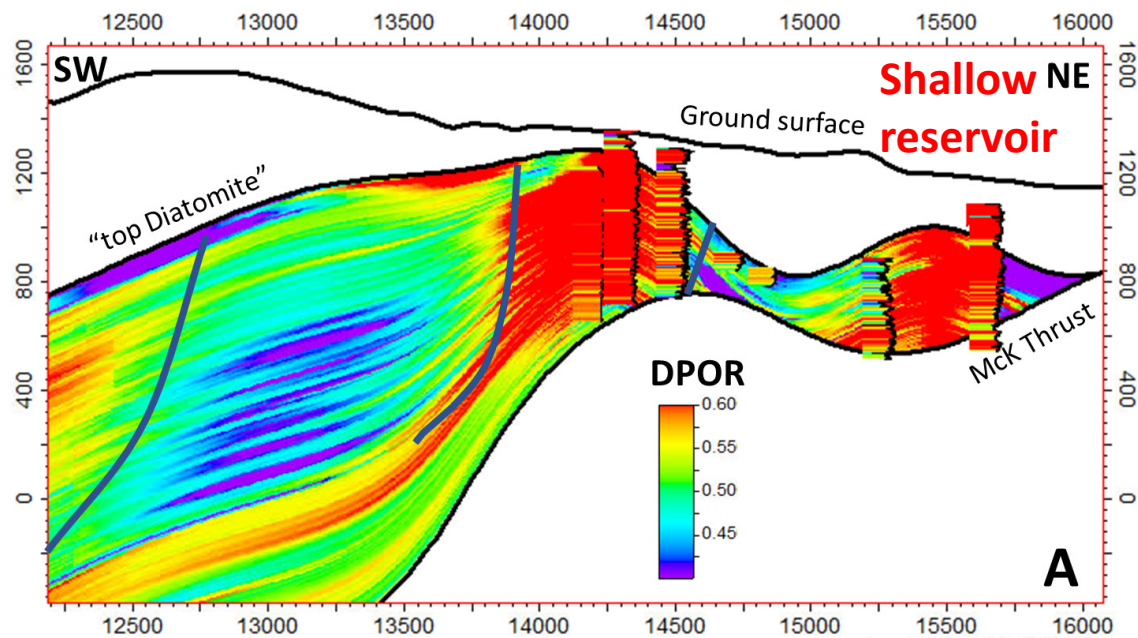


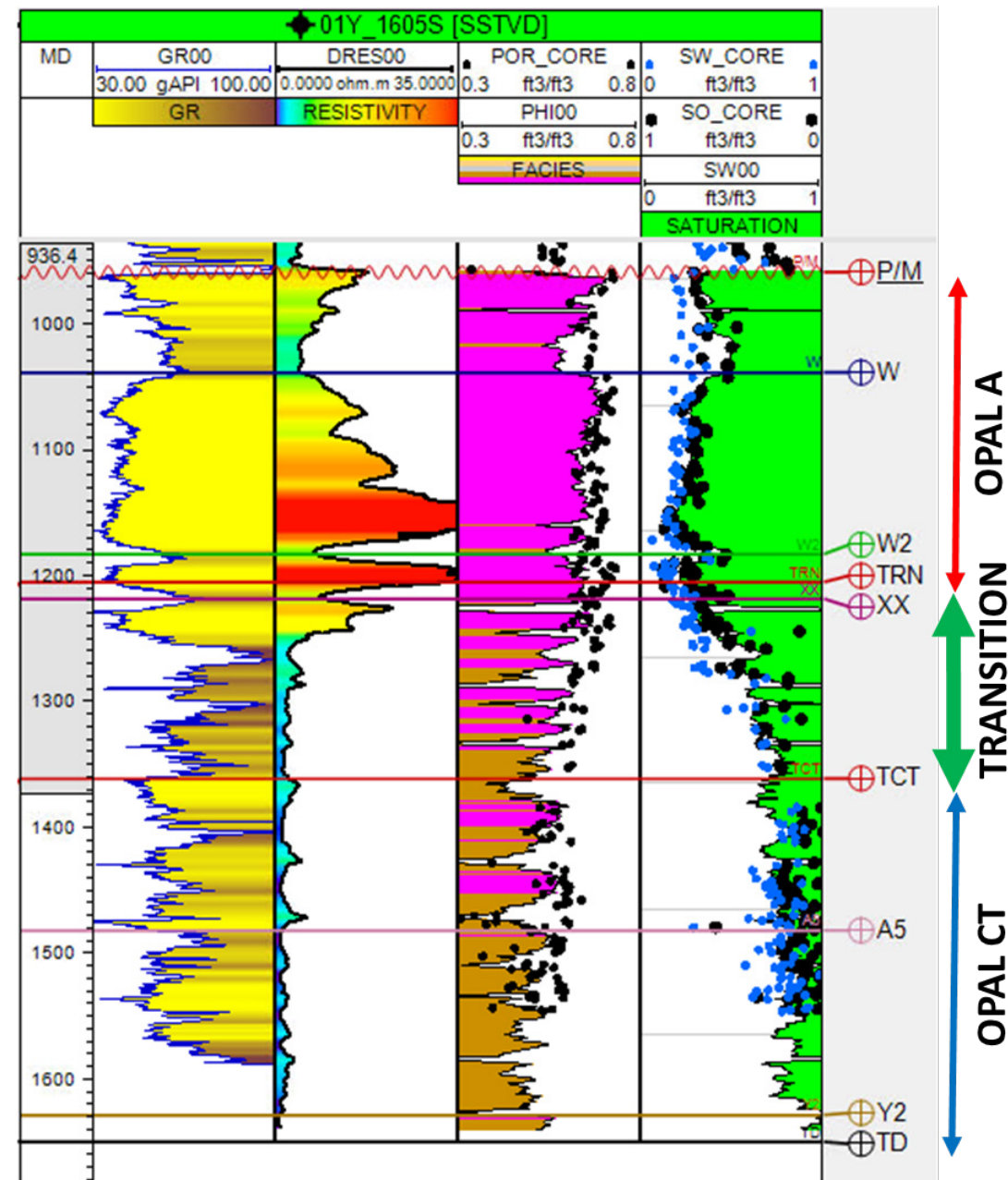
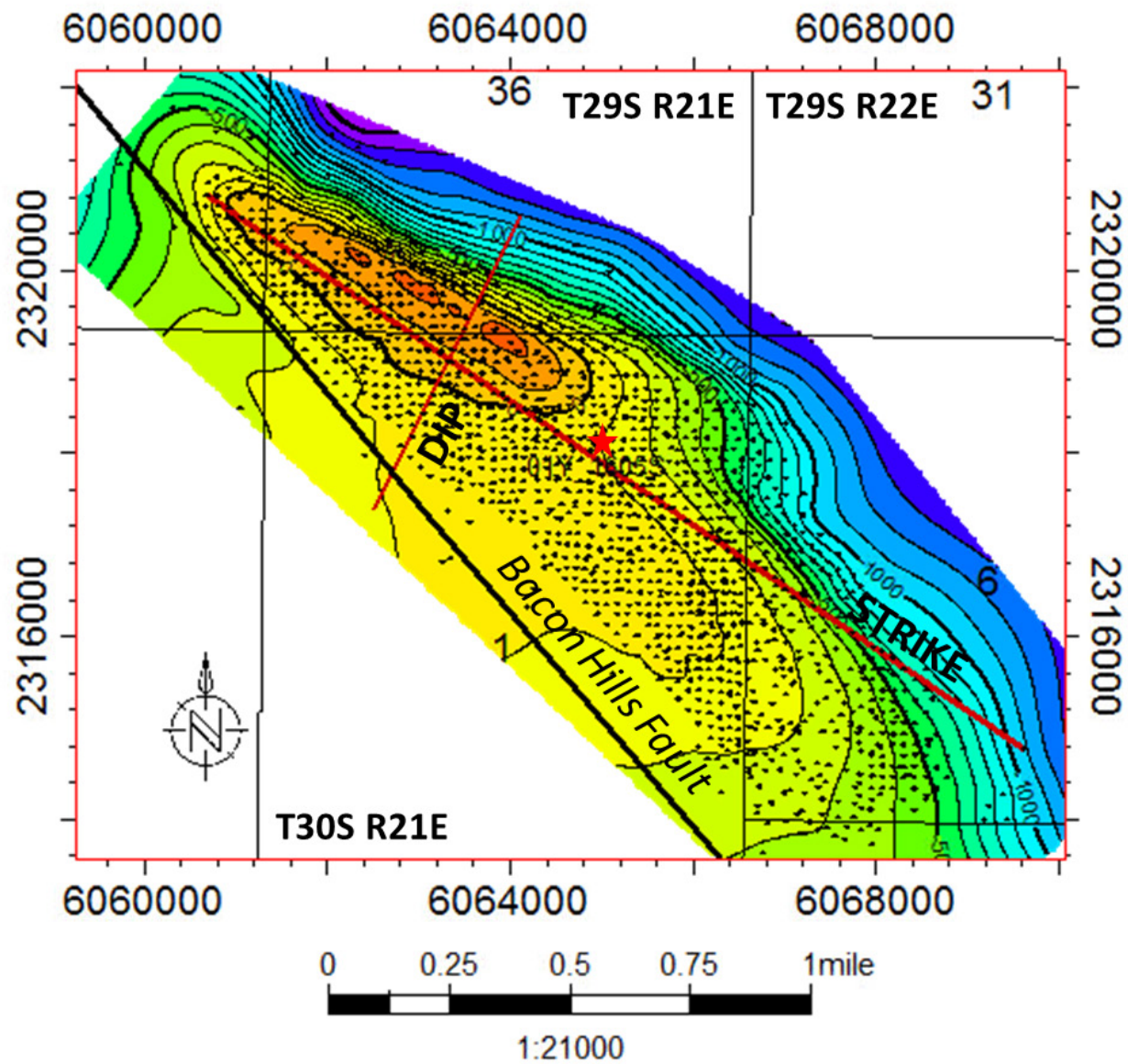
Cymric-McKittrick

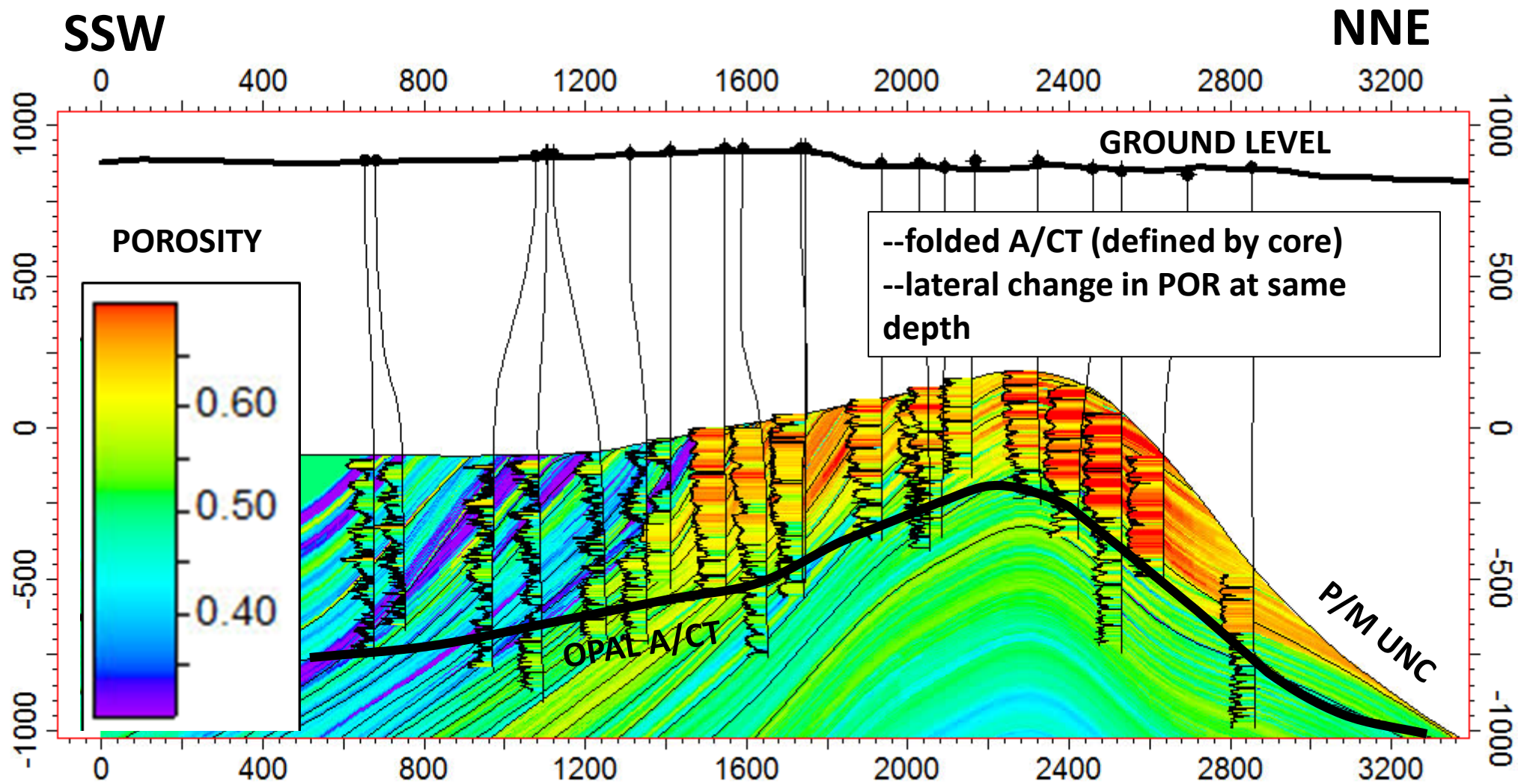


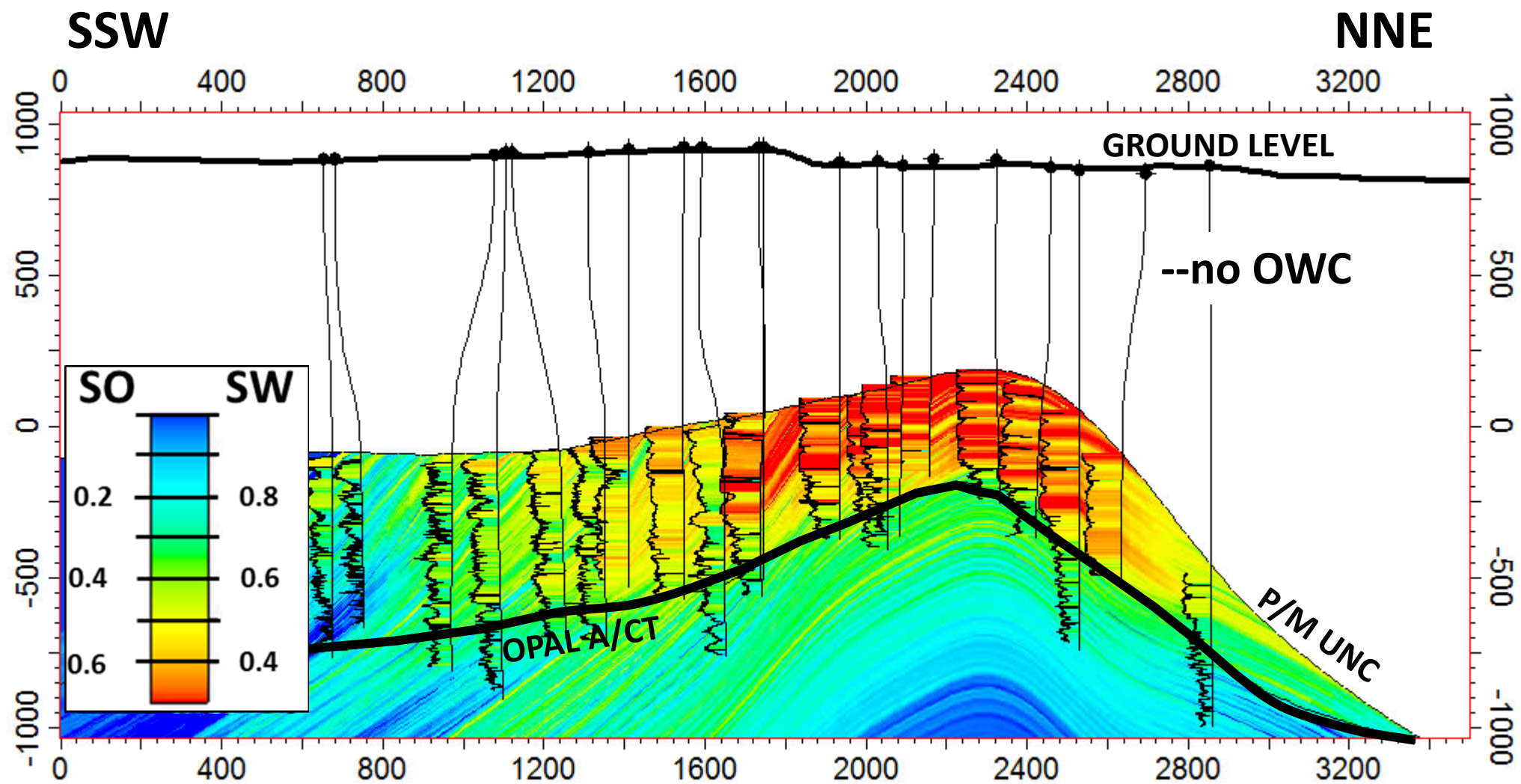






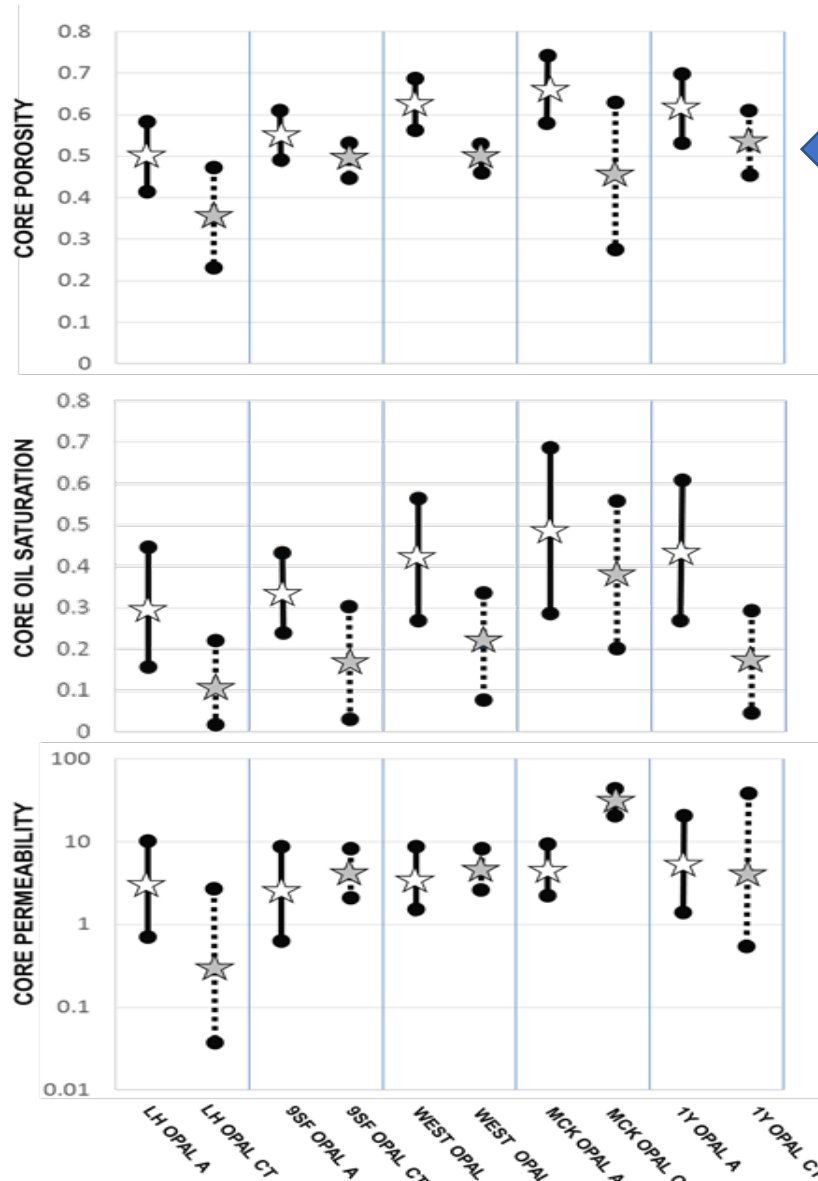






Summary Points

AVERAGE CORE PROPERTIES



- OPAL A HAS BEST POR AND SO
- OPAL CT HAS WORSE POR AND SO (But some, look producible!)
- Cymric/McKittrick Best POR AND SO
- Lost Hills/9C Worst

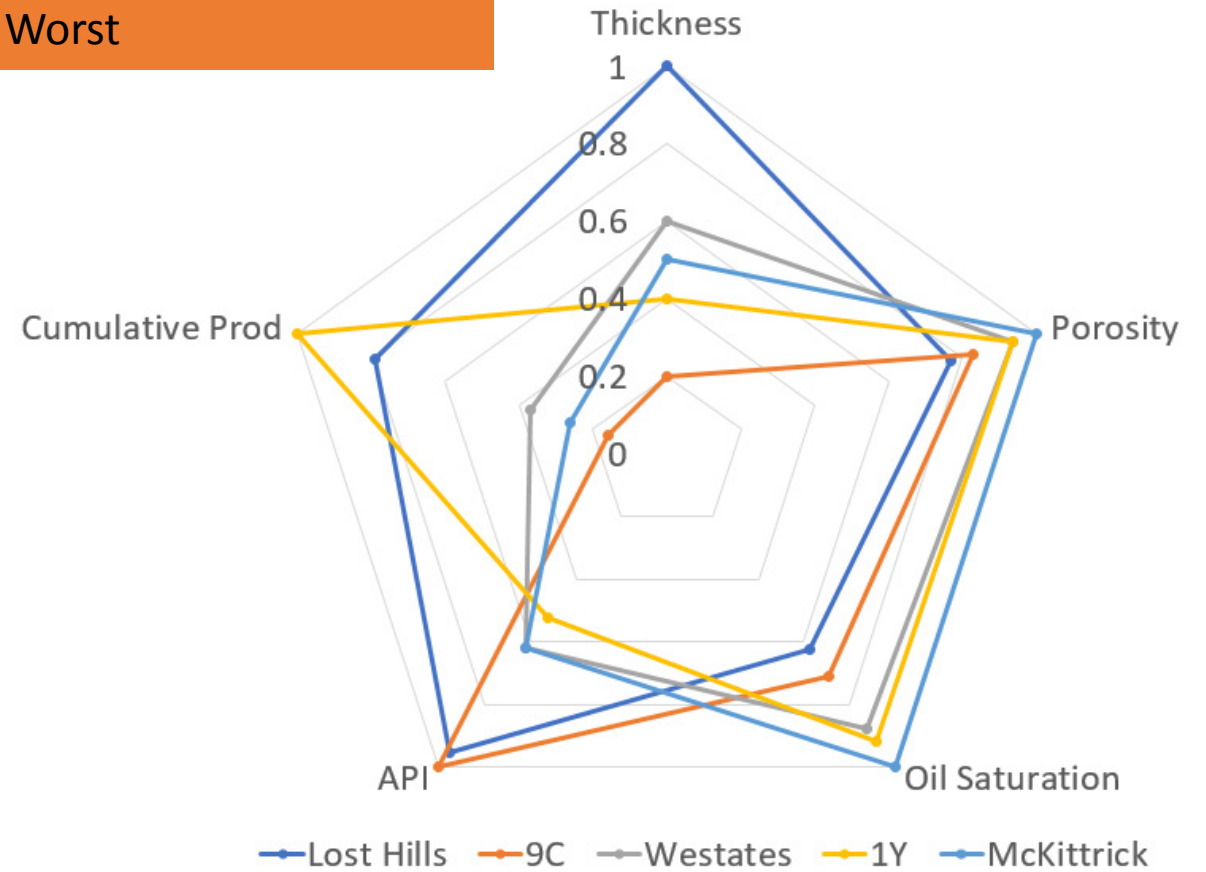
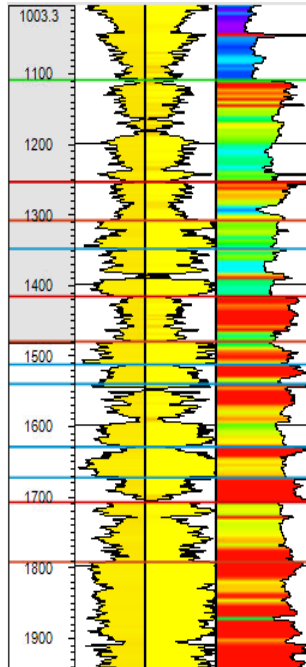


Figure 35. Spider diagram showing normalized rock properties for the different Opal-A diatomaceous reservoirs studied here.

Average whole or sidewall core data (star) plus or minus 1 standard deviation.

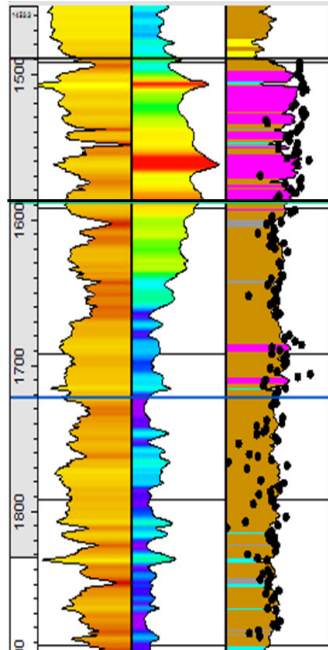
Variation in Stacking Patterns

Lost Hills



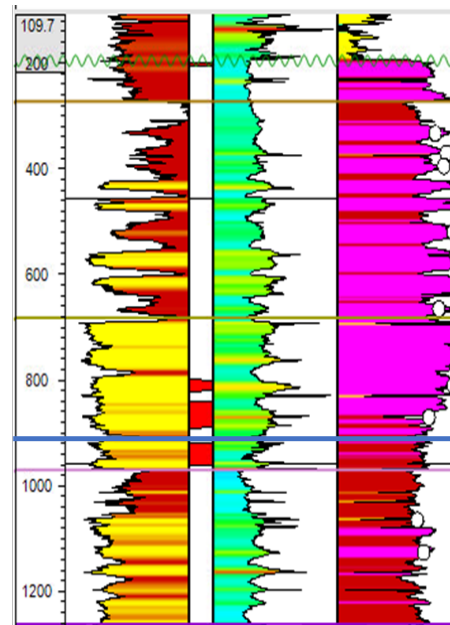
- Discrete packages
- Interbedded with sandy diatomites

MWSS 9C



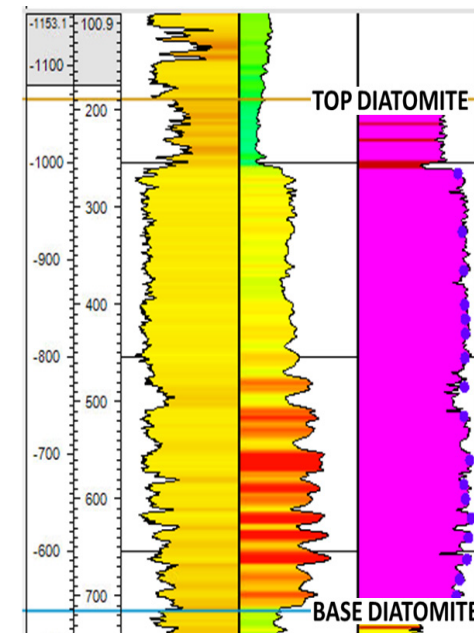
- Discrete packaging of units

MWSS Westates



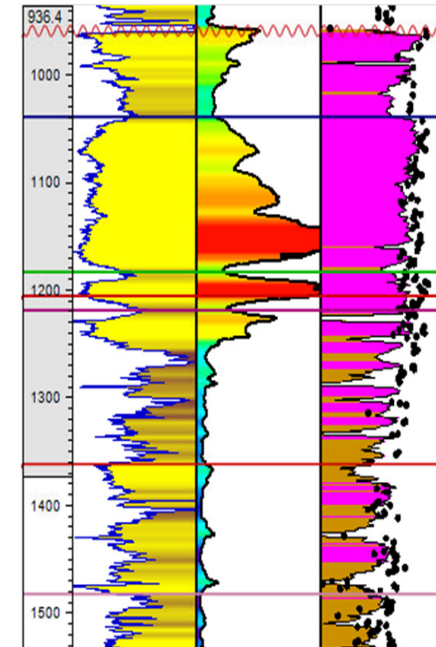
- Strong cyclicity
- Variation in cyclicity

McKittrick



- Locally homogeneous but with subtle cyclicity

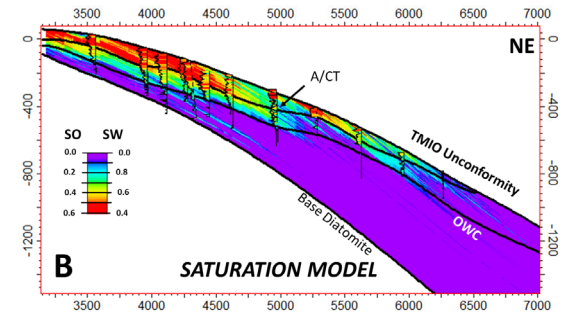
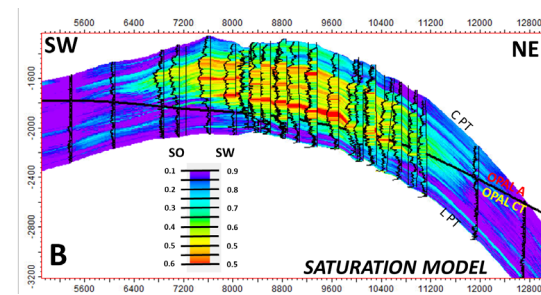
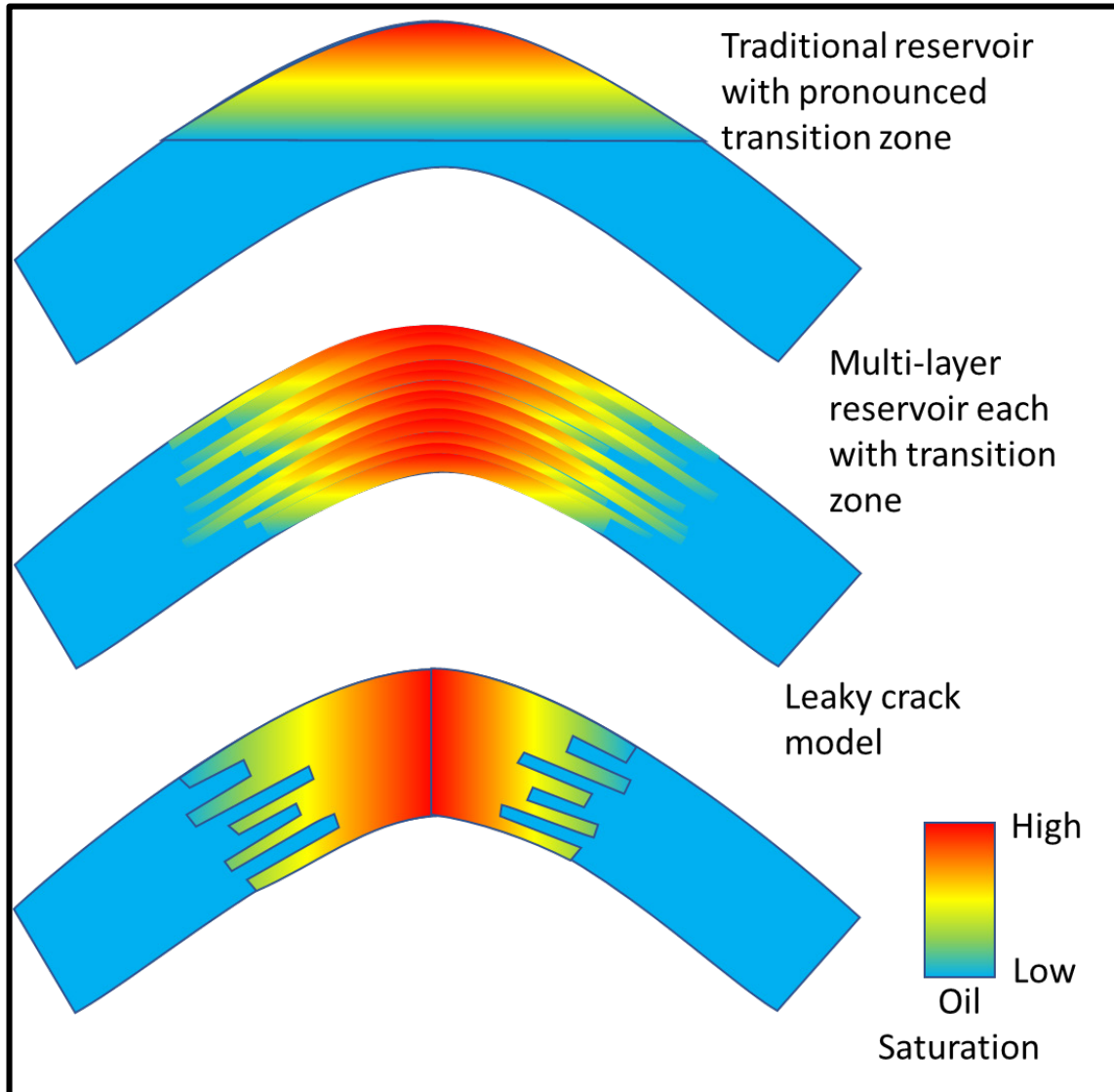
Cymric



- Discrete packaging of units
- Interbedded with sandy diatomites

What is the significance of the different diatomaceous stacking patterns?

Why The Rarity of Oil-Water Contacts But Presence of Lateral Contacts?



Doesn't match geology!

Con: lack of obvious compartment boundaries

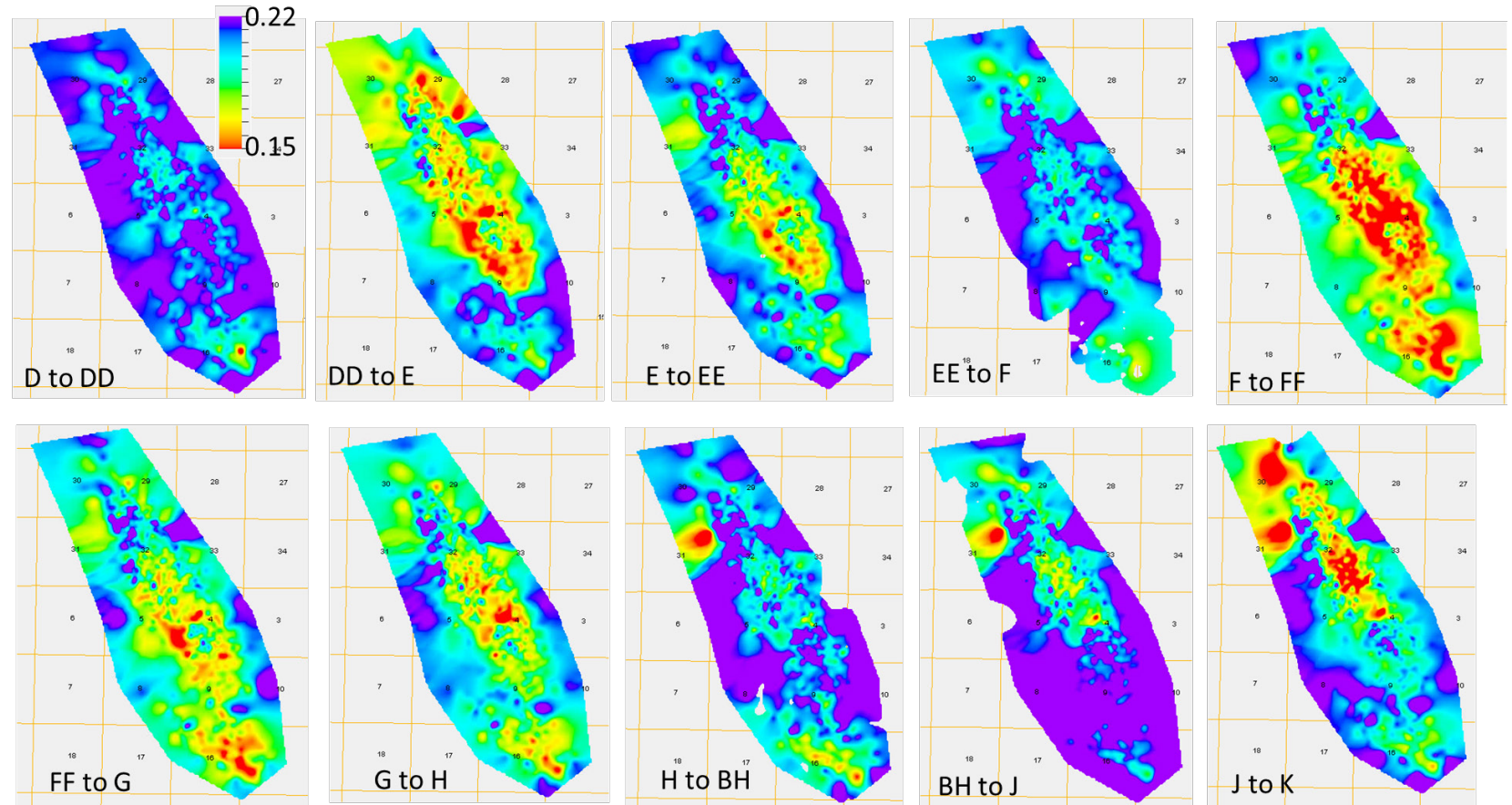
Pros:

- explains geometries
- geochemical studies indicate different compositional families of oils

Speculative

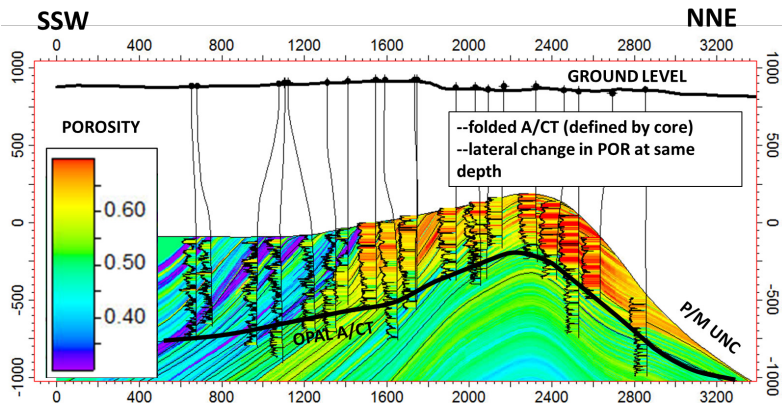
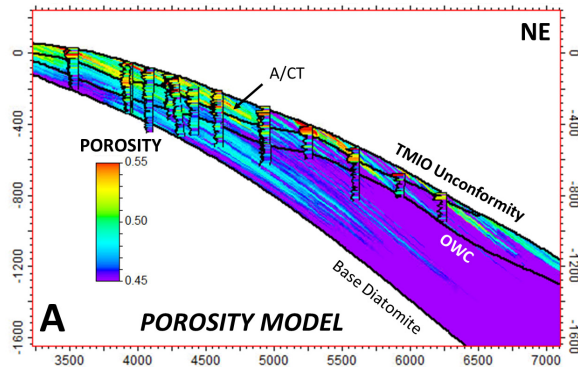
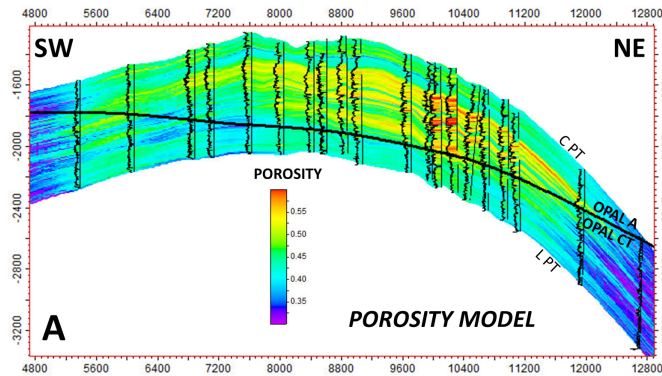
Support for the Eberle/Behl Hypothesis

Limited published studies on the Midway-Sunset, Buena Vista, Elk Hills, Belridge, and Lost Hills fields show *a gradation of lithofacies from more highly siliceous sediments at the top of anticlinal paleobathymetric highs to the surrounding lows* where biogenic or diagenetic silica is diluted with detritus.

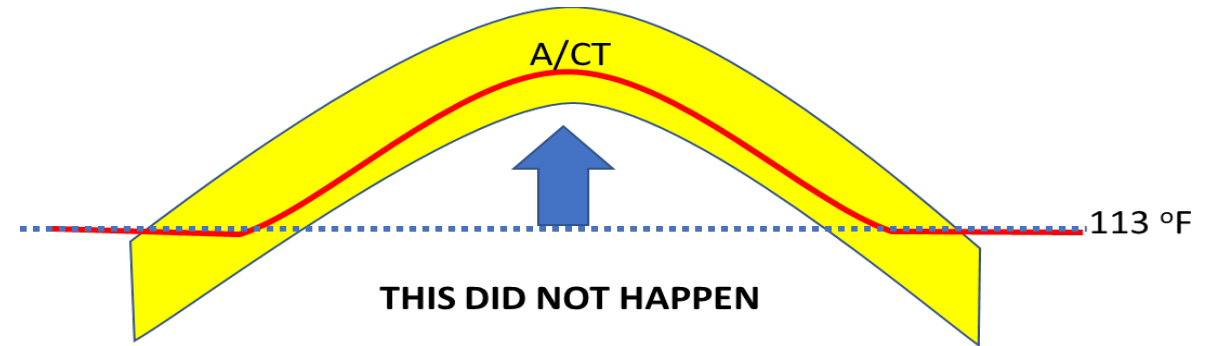


Kriged Vol_Illite Intervals for Lost Hills

Folded A/CT Contact

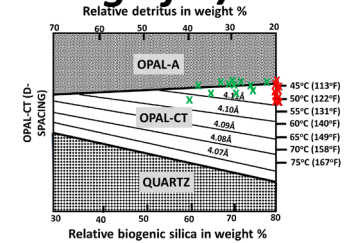
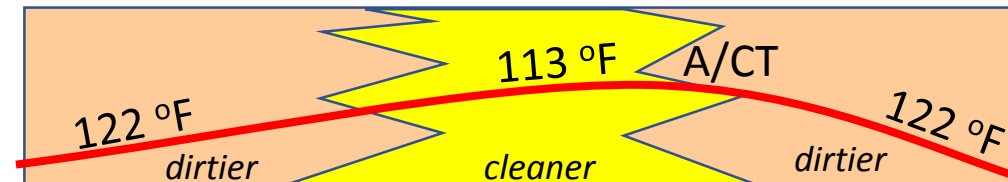


The A/CT boundary is NOT folded as tightly as bedding!

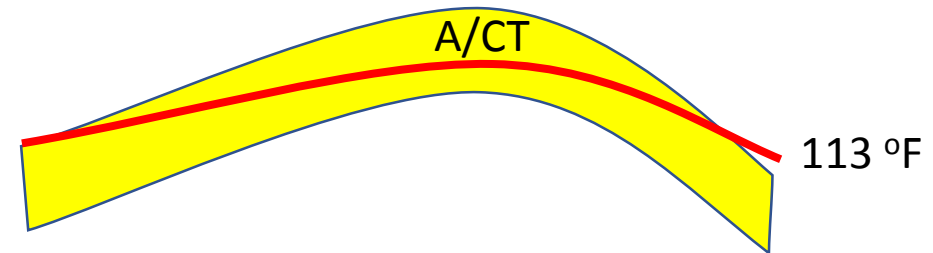


A/CT boundary folds and moves upward, but the A/CT transition flattens at the depth corresponding to 113°F for the Opal A/CT transition

Lateral variations in lithology does NOT help explain folding of A/CT!



Eberle/Behl Hypothesis



Geotherms not folded as tightly as bedding?

Conclusions

- Reservoir characterization studies for five Opal-A diatomaceous reservoirs has been provided.
- These low permeability reservoirs are all considered to be unconventional because they require stimulation for economic production.
- Although the reservoirs are all diatomaceous, and occur in the same basin and are of similar age, considerable diversity in character is observed, including structural setting and trapping style, reservoir depth, api oil gravity, reservoir stacking patterns, reservoir porosity, permeability and oil saturation as well as means of production (hydraulic fracturing, waterflooding and cyclic steam injection).
- Observations include:
 - preservation of Opal A in complexly deformed region,
 - Folding of the Opal A/CT contact gives information on kinematic constraints
 - rarity and complexity of oil-water contacts