

Widespread Hydrothermal Dolomitization of Trenton and Black River Groups, Eastern North America*

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Abstract

Trenton-Black River hydrothermal dolomite reservoirs of eastern North America formed when hydrothermal fluids (80-170 degrees C) flowed up active margin-bounding and transtensional faults and dolomitized the formations within the first 500 meters of burial. An unequivocal hydrothermal origin can be demonstrated where primary fluid inclusion homogenization temperatures from the dolomites exceed maximum ambient burial temperatures by at least 10 degrees C. Using these criteria, virtually all of the dolomite found in the Trenton and upper parts of the Black River in Kentucky, Ohio, Michigan, Wisconsin, and Ontario is of a hydrothermal origin. This is a very large volume of dolomite (hundreds to possibly thousands of cubic kilometers), that includes some areas of widespread, pervasive dolomitization.

An immense amount of fluid would be required to make that volume of dolomite, and new fluid flow models are required to solve the mass balance. These might include fault-driven forced episodic convection, recharge of basal aquifers that feed the faults by slowly descending saline brines sourced from seawater and/or mixing of hydrothermal fluids with in situ seawater at the site of dolomitization. Free convection in the absence of faults is not likely to play a significant role as permeability barriers would prevent hydrothermal conditions from developing. Additionally, there must be an element of fluid flow from the basement to explain fluid inclusion homogenization temperatures that commonly exceed the maximum ambient burial temperature for any part of the underlying sedimentary section.

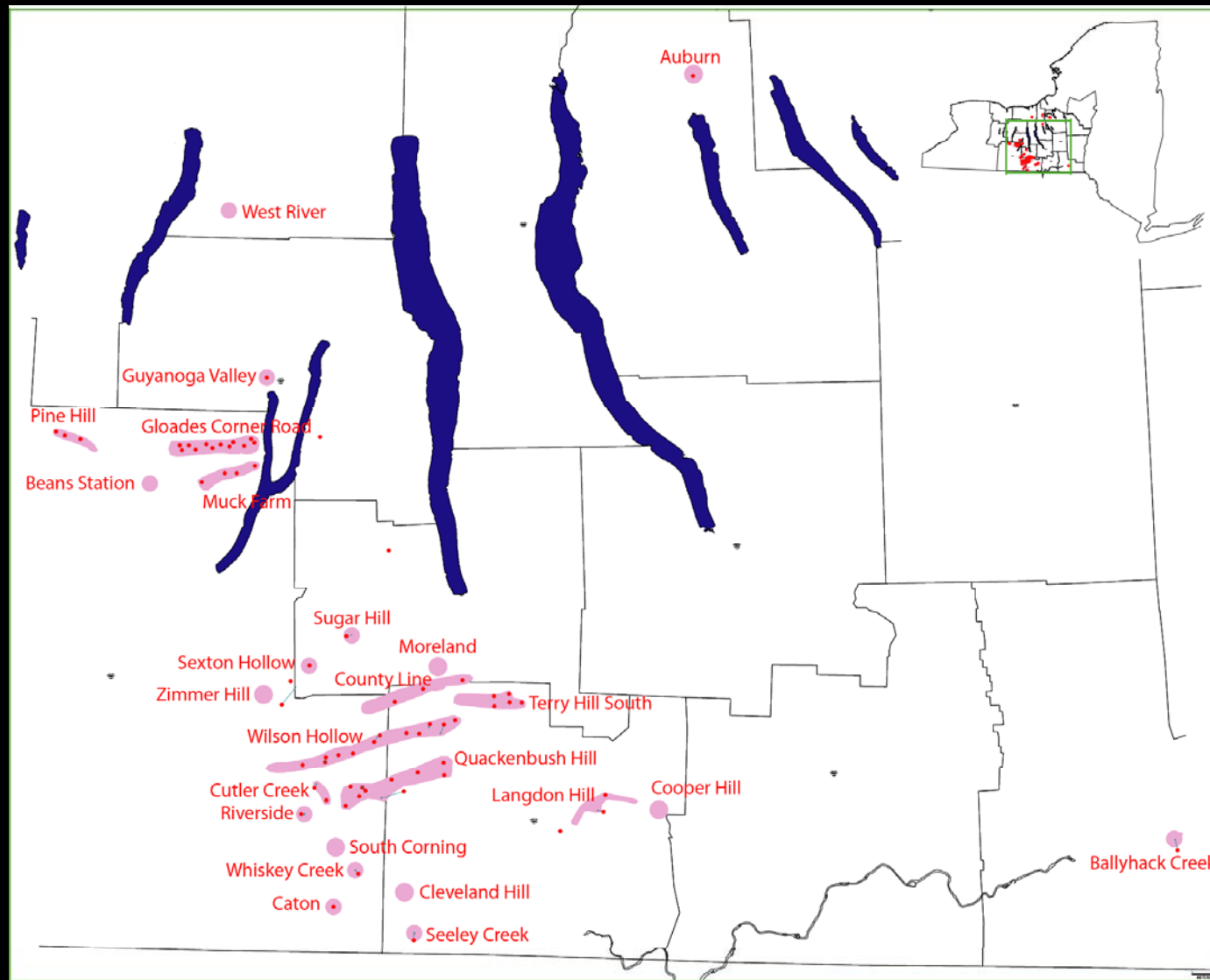
This example, along with others such as the dolomitized Jurassic and Cretaceous of northern Saudi Arabia, suggests that hydrothermal dolomitization can be widespread and pervasive and should be considered along with other models when interpreting the origin of dolomitized reservoirs.

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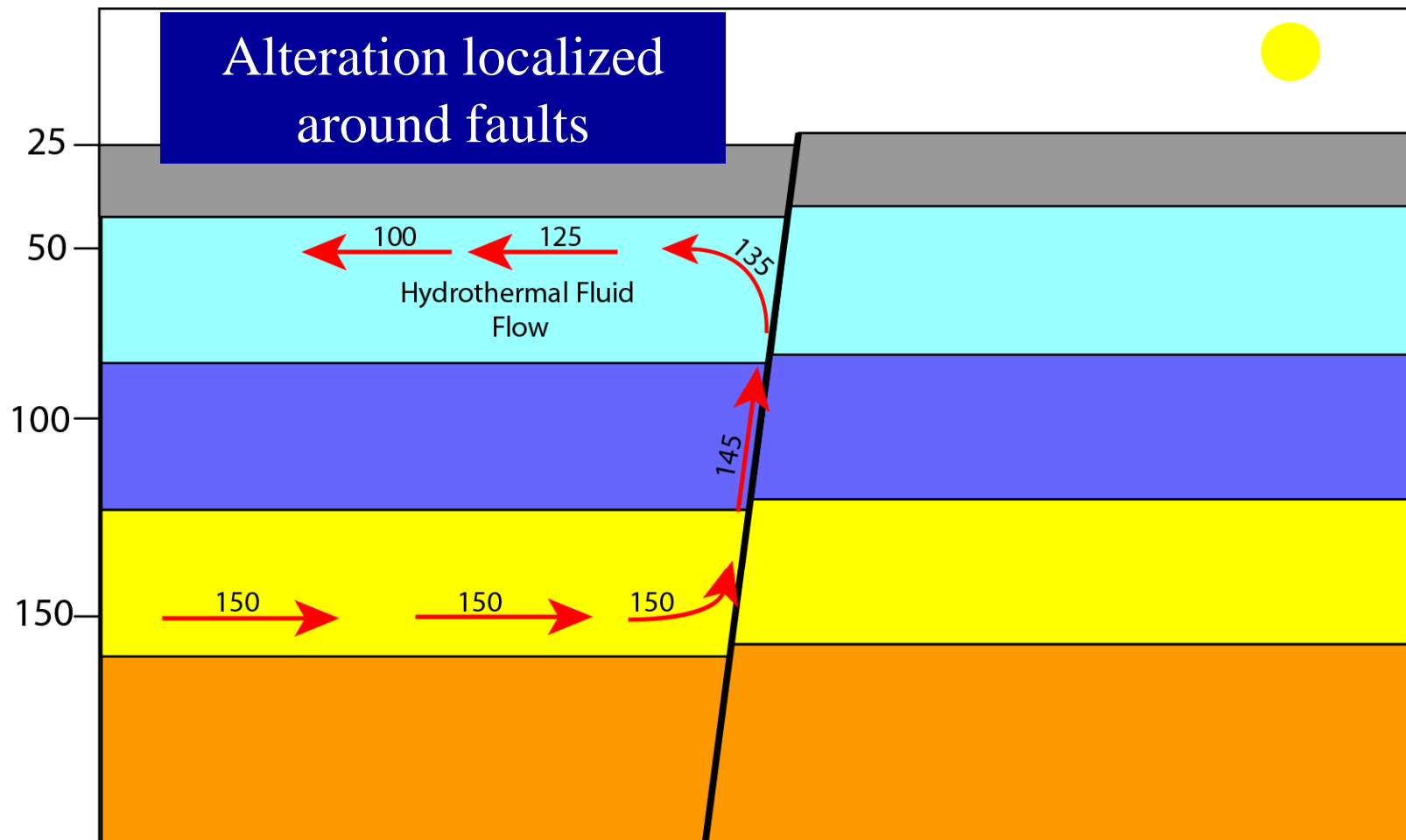


Snake Oil Salesmen?



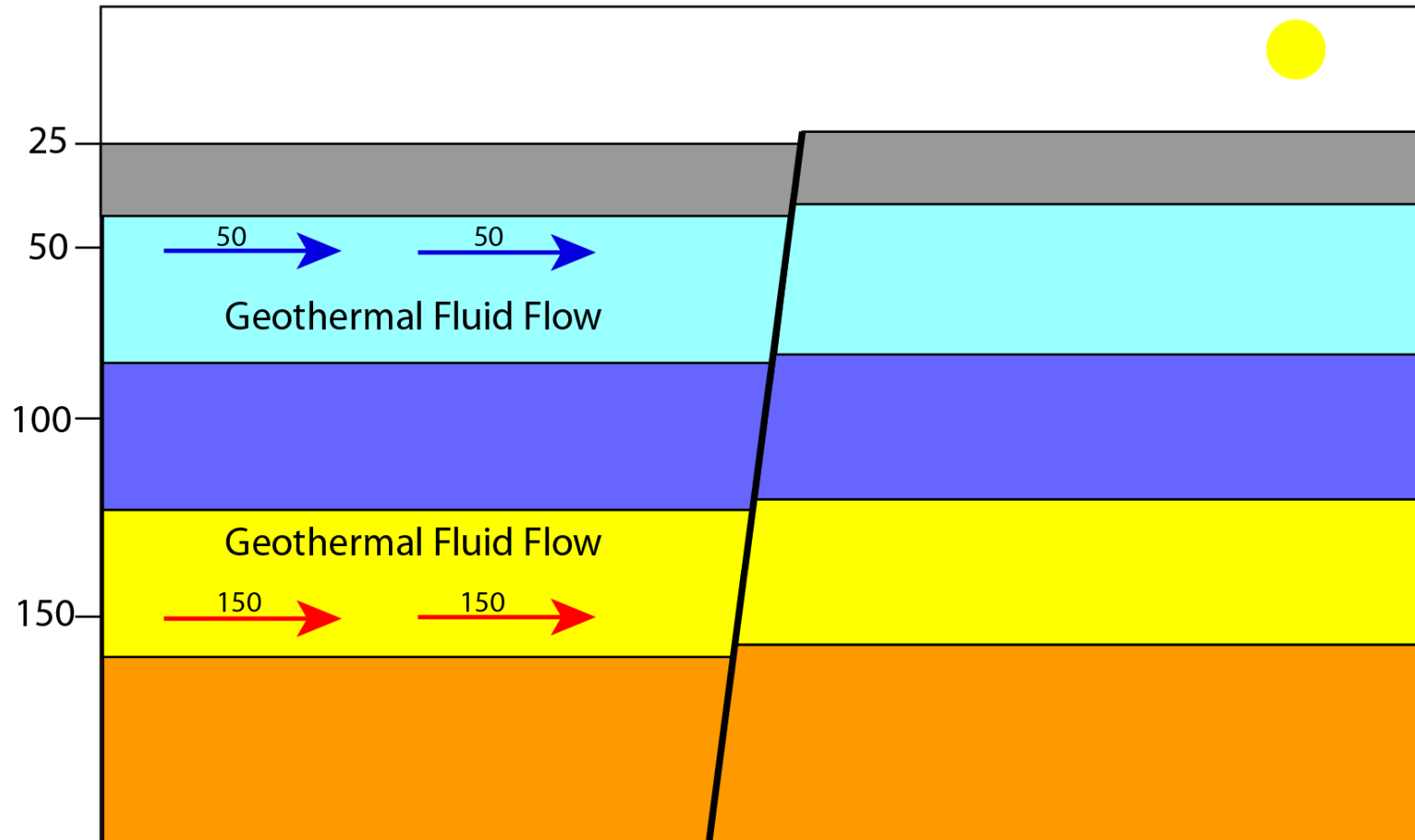
Fault-related hydrothermal dolomitization model has been used to find more than 34 fields in NY w/probable cum. production of >500 BCF

T(°C)

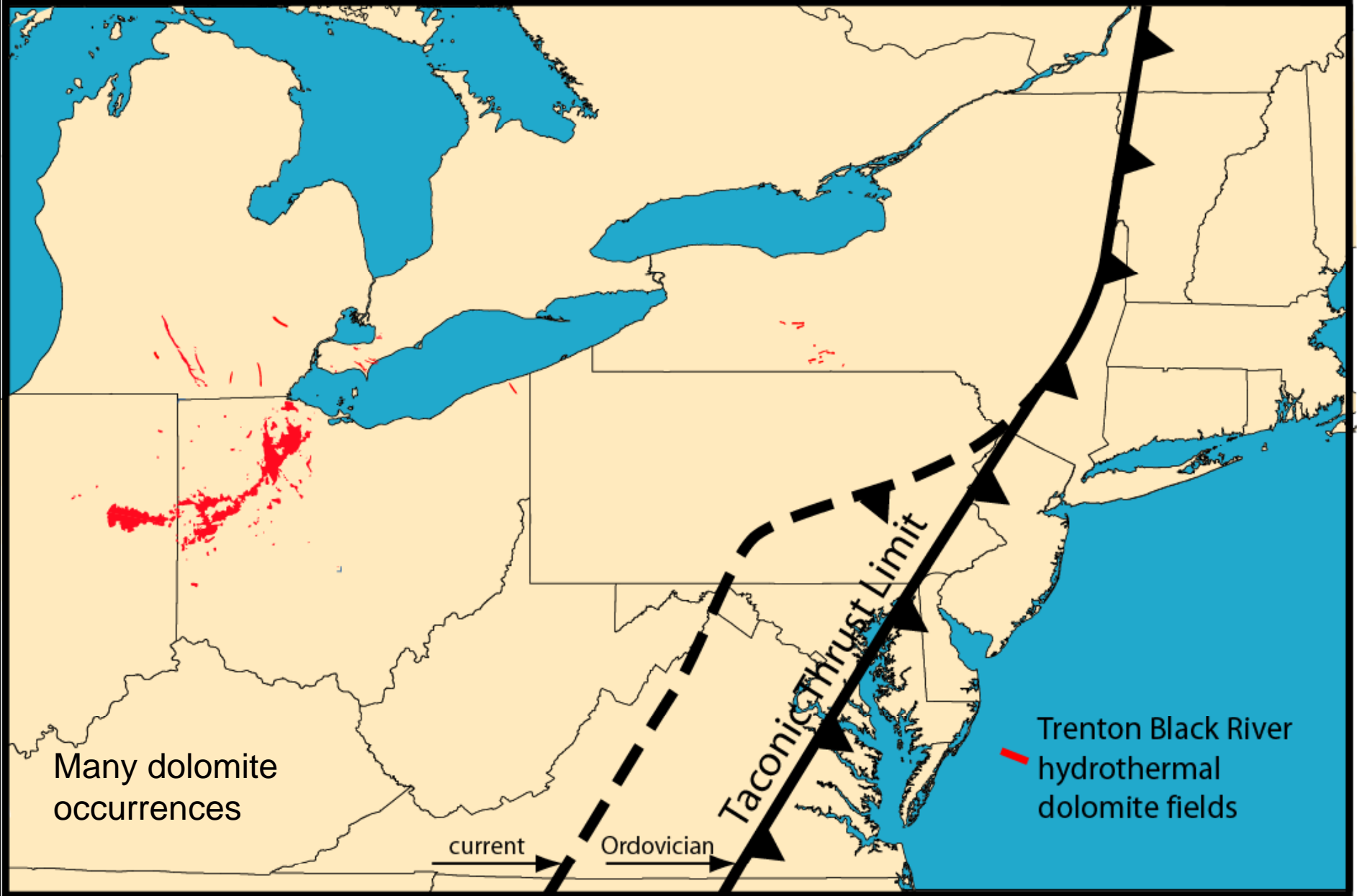


Hydrothermal fluid – fluid with temperature at least 5°C greater than ambient burial temperature at a given depth (generally requires a fault source) (Davies, 2001; Machel and Loney, 2002)

T(°C)



Geothermal fluid flow is mainly lateral flow, fluid is same temperature as ambient burial temperature



Trenton Black River hydrothermal dolomite reservoirs – hosted in limestone - also many occurrences of non-reservoir dolomite

Structural Settings of Dolomitization

- Laterally discontinuous dolomitized Trenton and Black River reservoirs occur around basement faults in two main settings
 - Around intra-platform negative flower structures that form when pre-existing basement faults are reactivated in a transtensional sense
 - Most with minor offset and faults that die out in Utica
 - Carbonate platform margin-bounding faults with shale basin (extensional or possibly transtensional)
 - Also found dolomite in positive flower structure

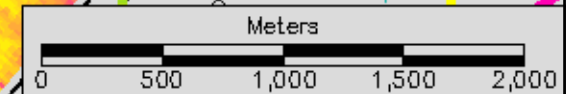
Top Trenton structure map from 3D seismic survey over Rochester Field in Ontario shows transtensional feature

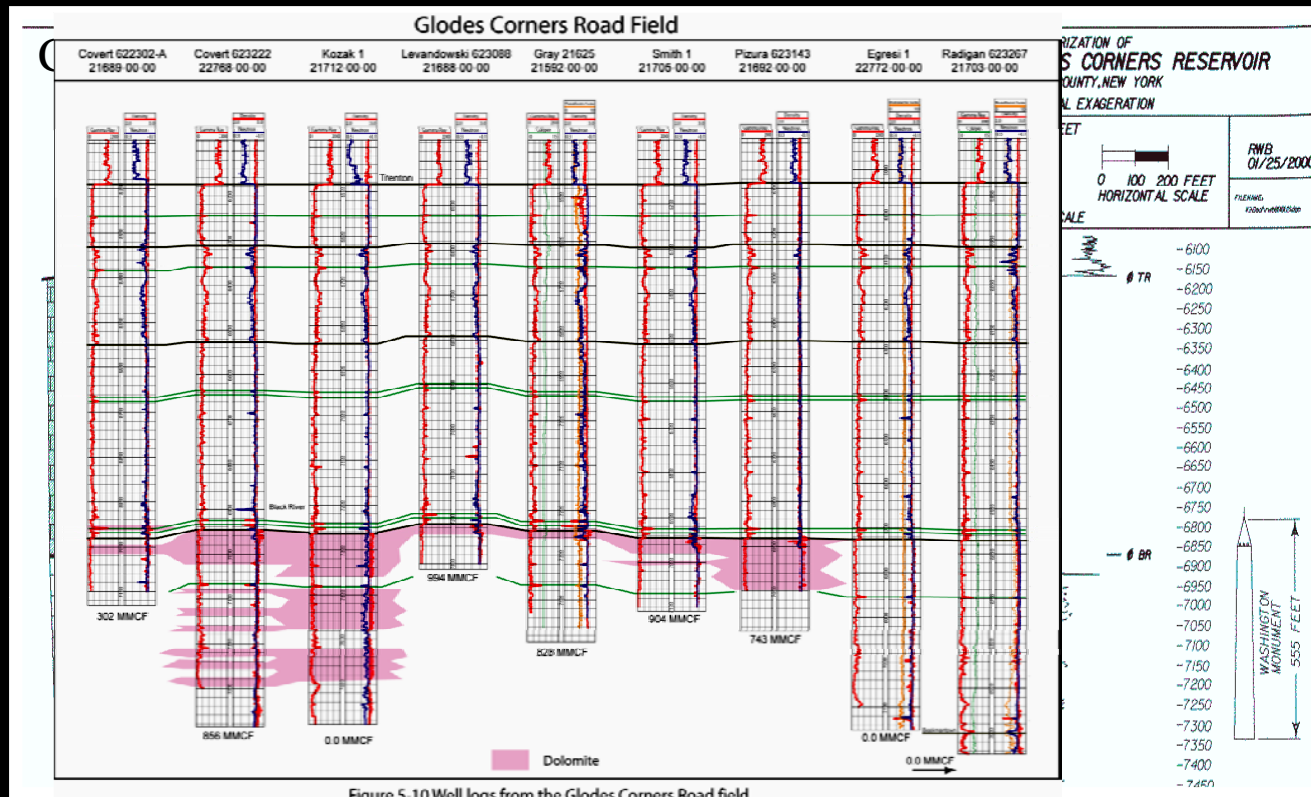
The map displays a complex geological structure with various faults and wells. A color scale on the right indicates elevations from 340.0 to 360.0. Blue arrows point to specific features on the map, including a large fault-bounded area and a smaller fault-bounded low.

Matrix dolomite, saddle dolomite-cemented breccias, vugs and fractures and hydrocarbons occur in fault-bounded lows, absent elsewhere – this is typical of TBR play

Tight limestone

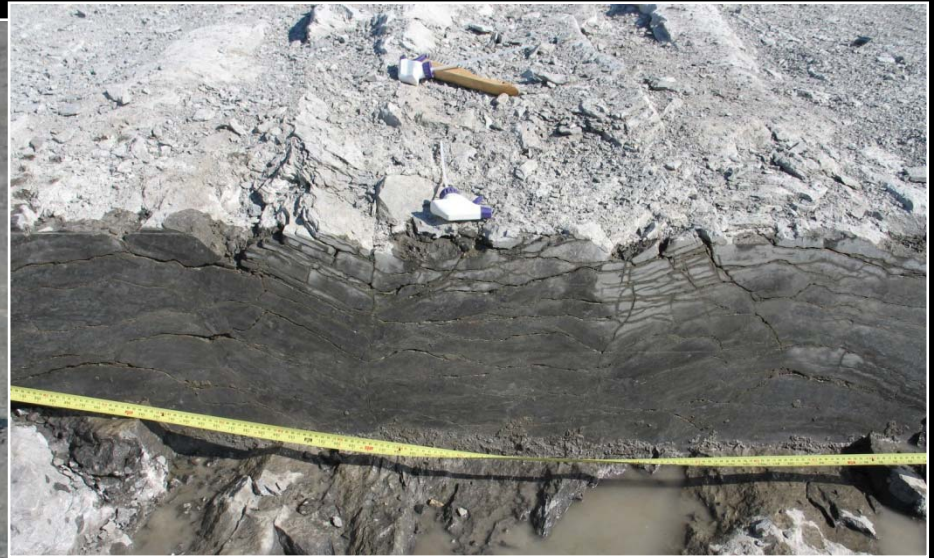
Courtesy Talisman



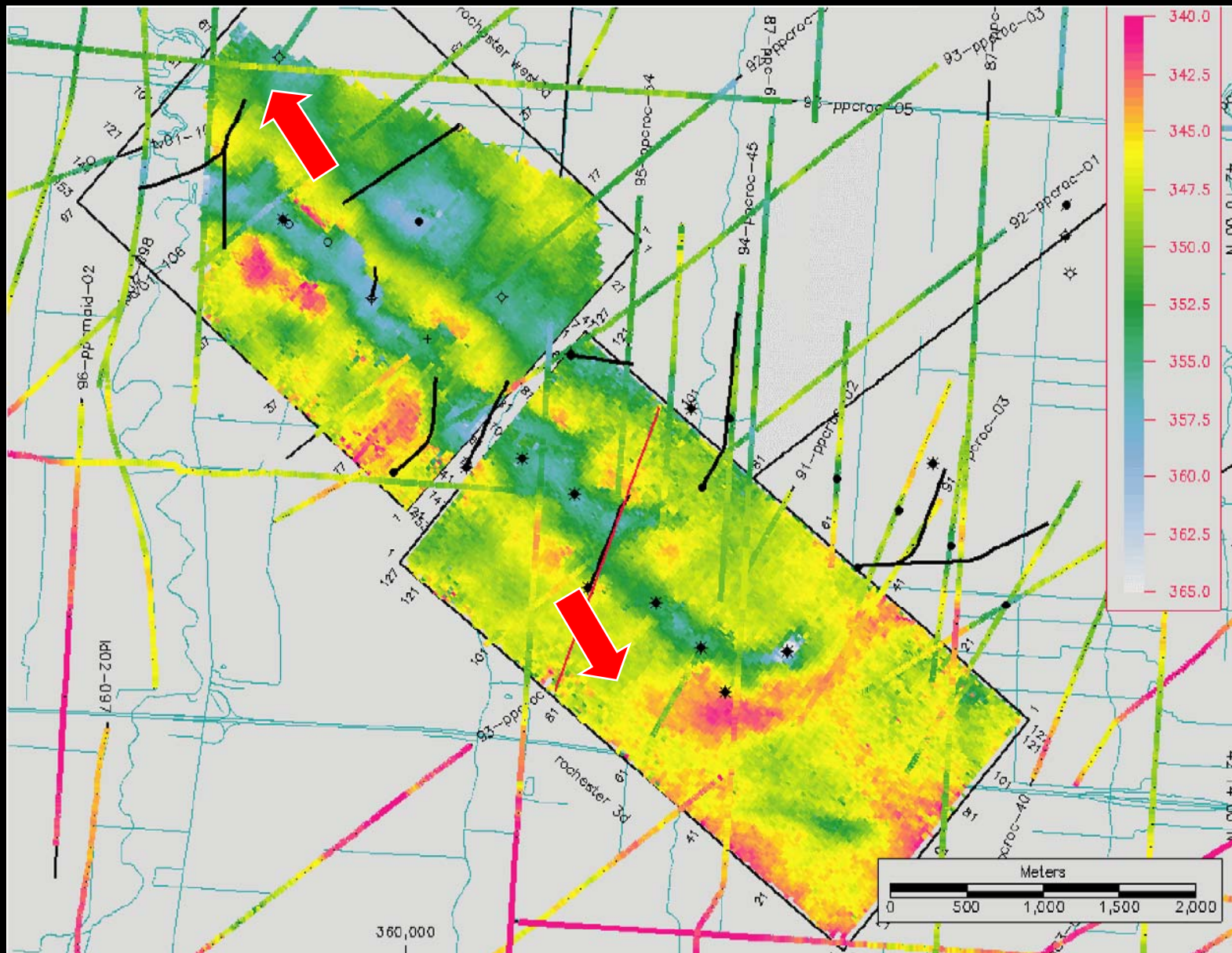


Matrix dolomite, fractures and vugs lined with saddle dolomite and hydrocarbons occur in “sags” formed by subtle faults visible on seismic surrounded by undolomitized limestone - >95% is matrix dolomite

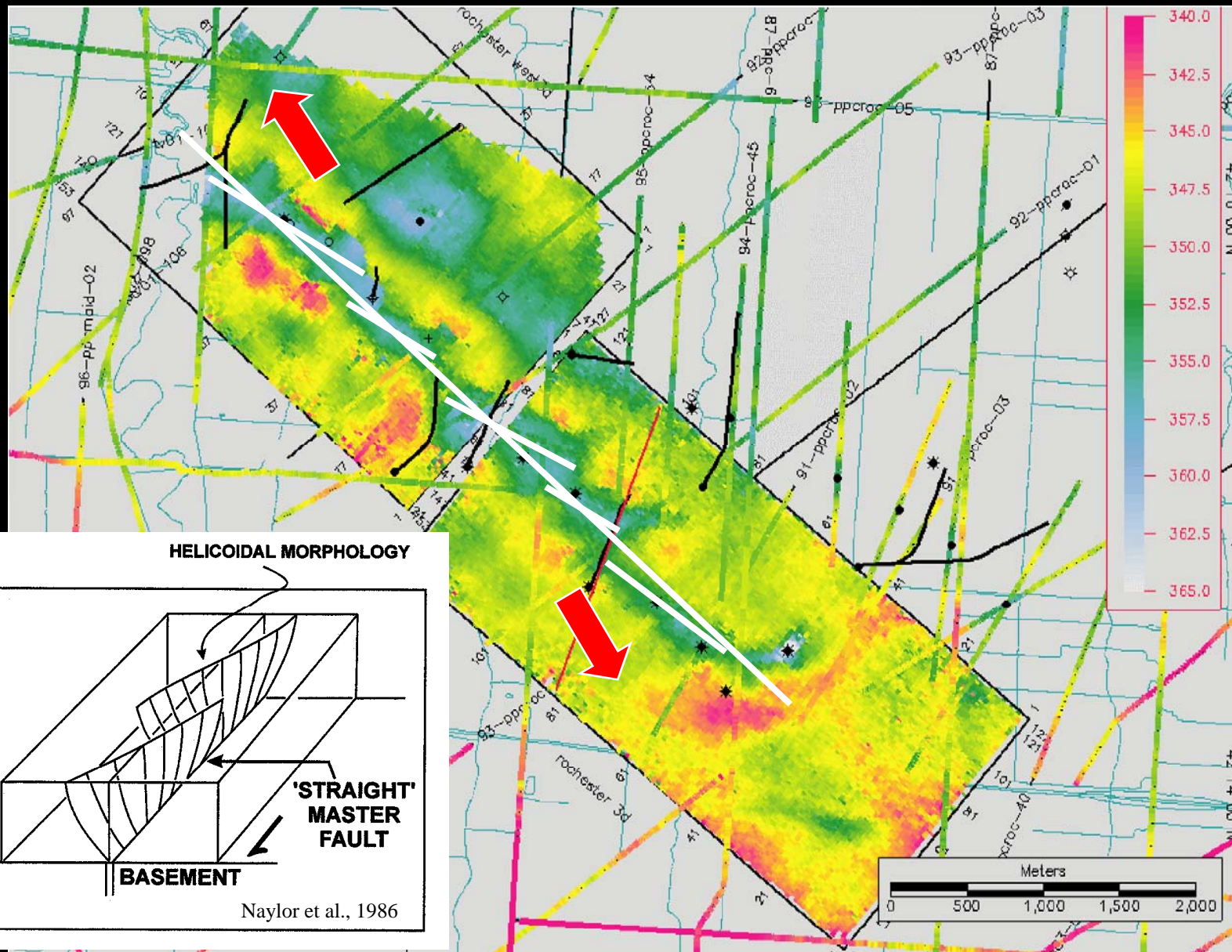




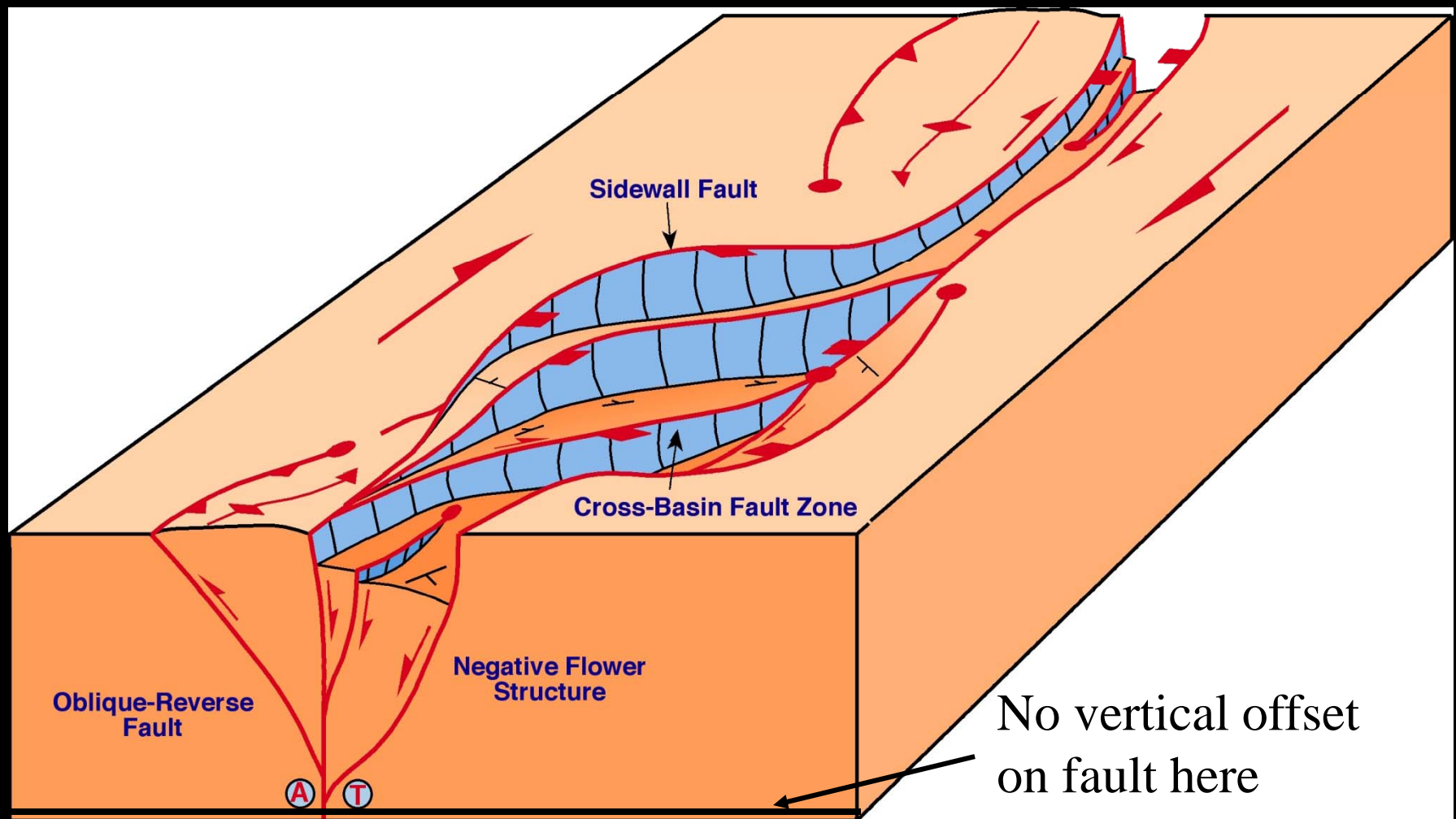
Outcrop analog in Ordovician of
Mohawk Valley, NY confirms
interpretations



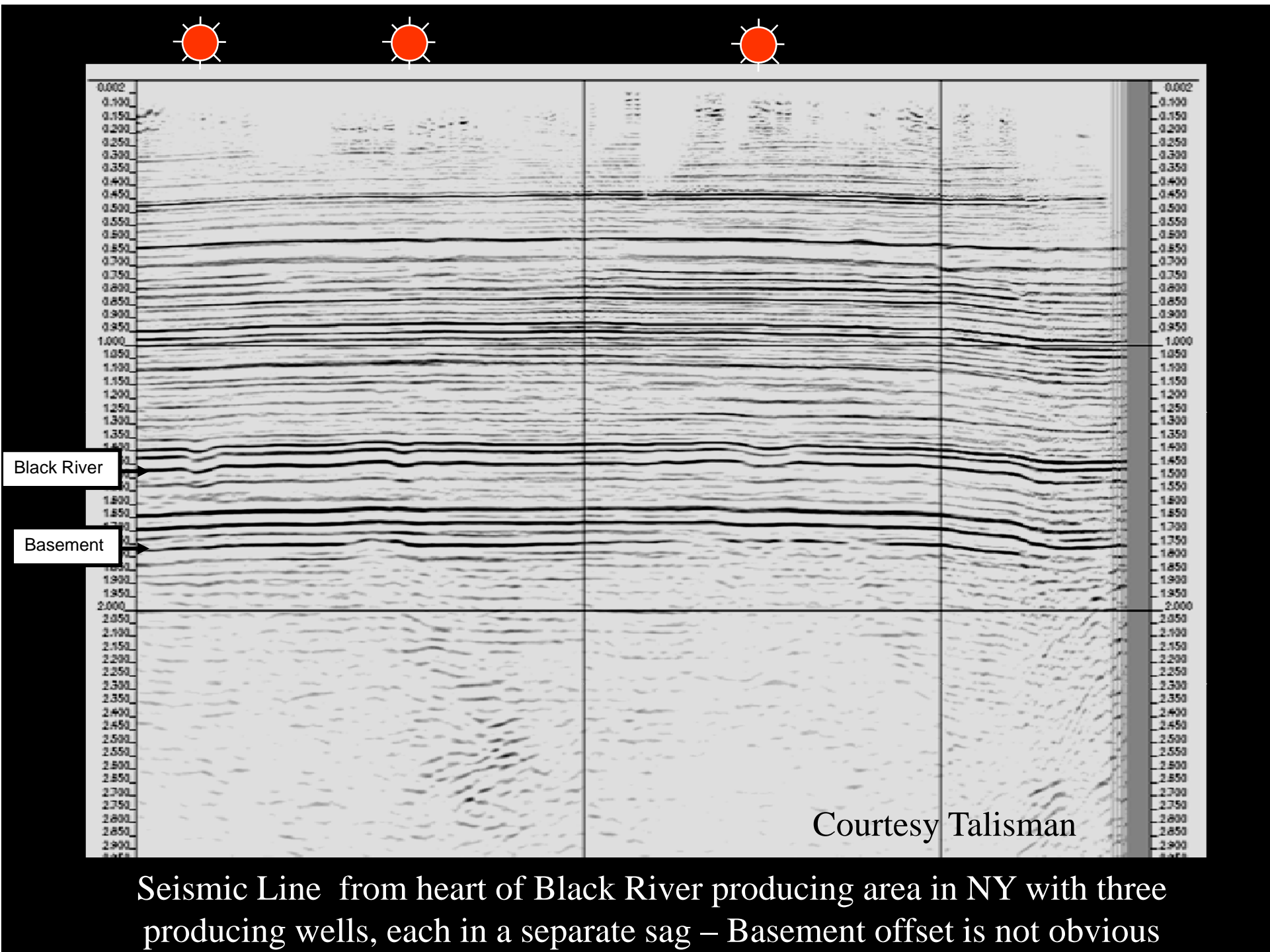
The ~continuous nature of the sag suggests that it formed from NNW-SSE oblique divergent slip (transtensional)

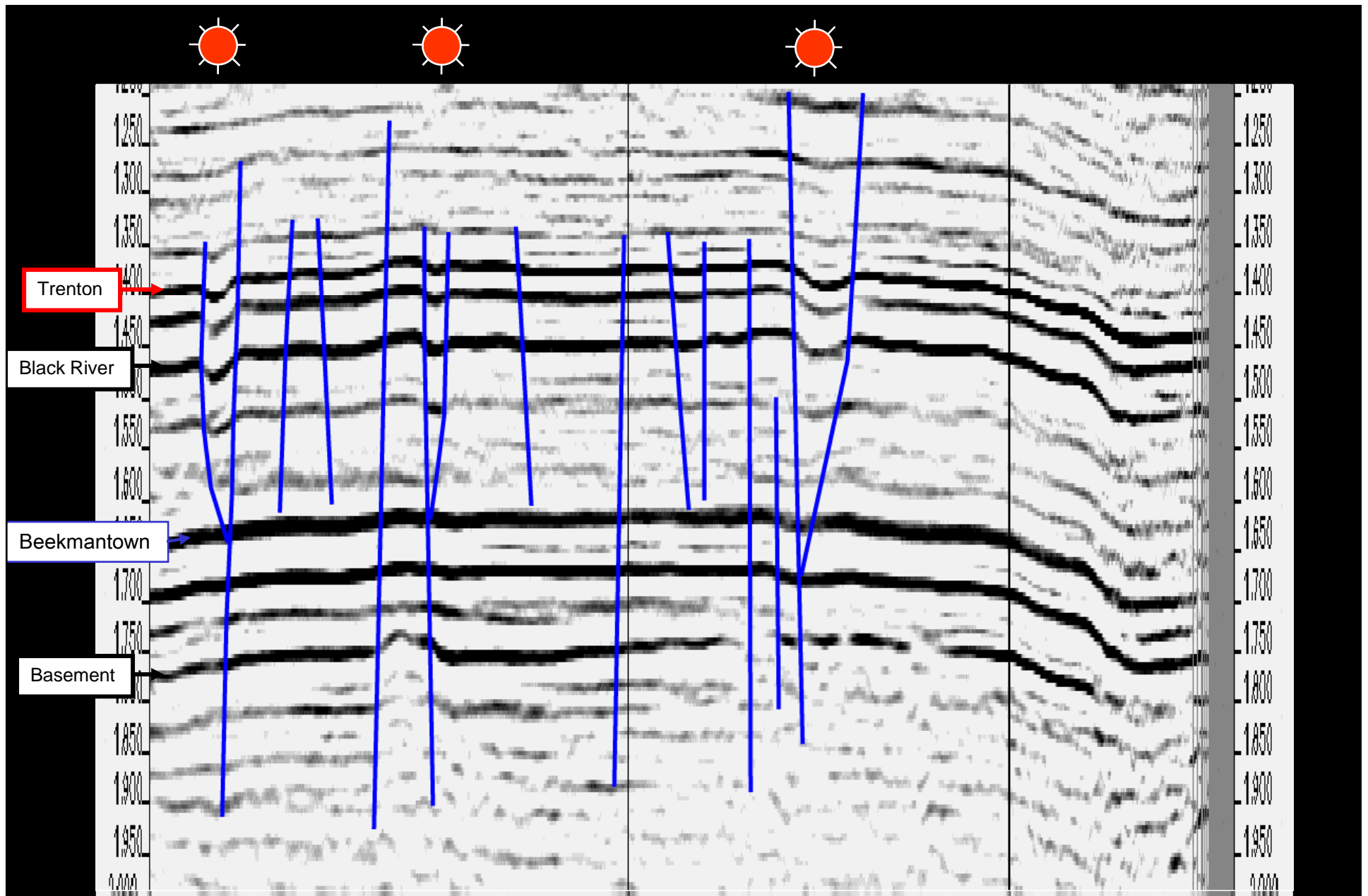


Each sag occurs in a negative flower structure formed on a synthetic shear fault (Reidel) that is linked to an underlying left-lateral master fault

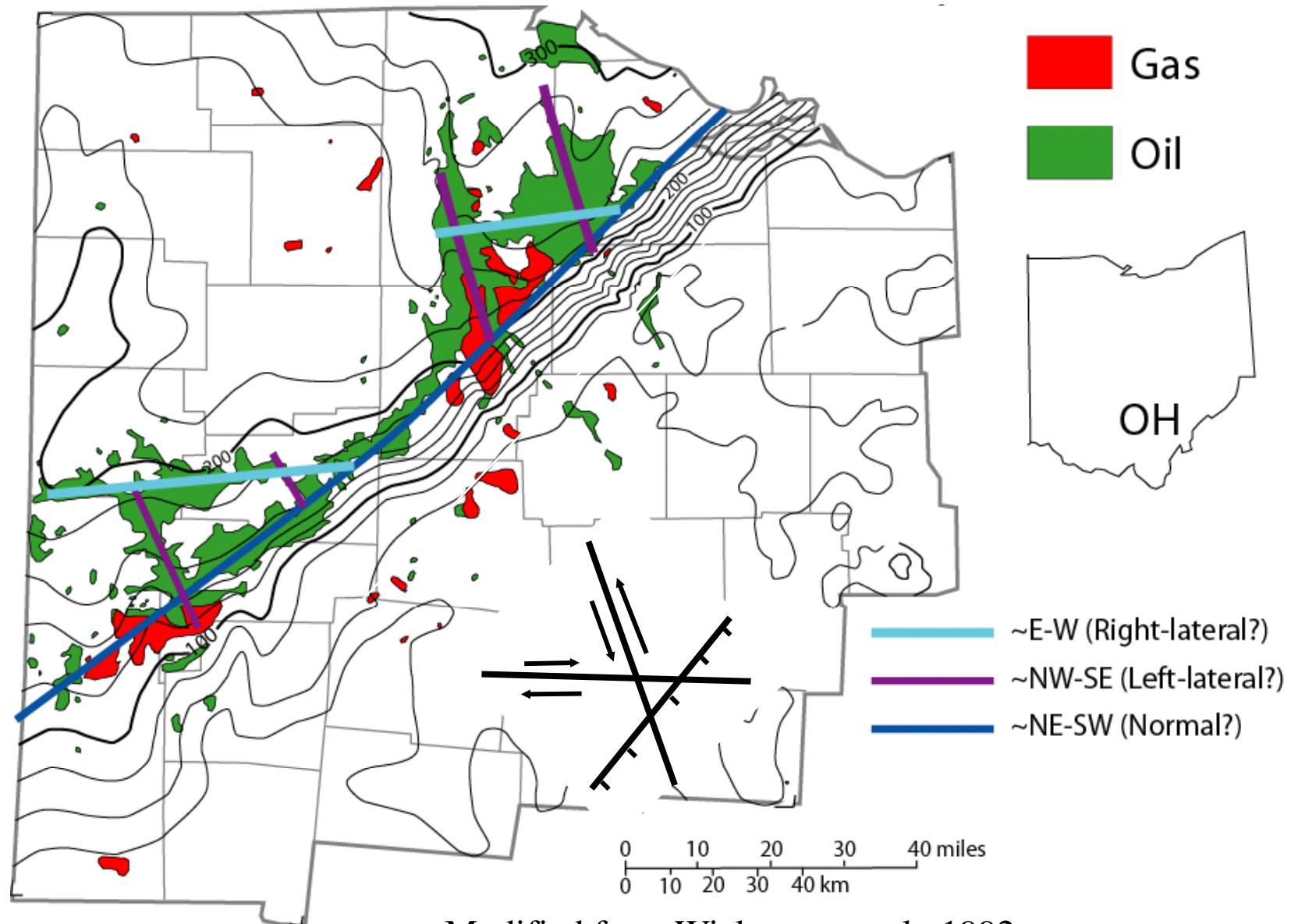


Block Model for transtensional pull apart – Dooley and McClay, 1997 -
Note in cross section view that either side of fault zone is not vertically displaced but that significant thinning occurs within fault zone



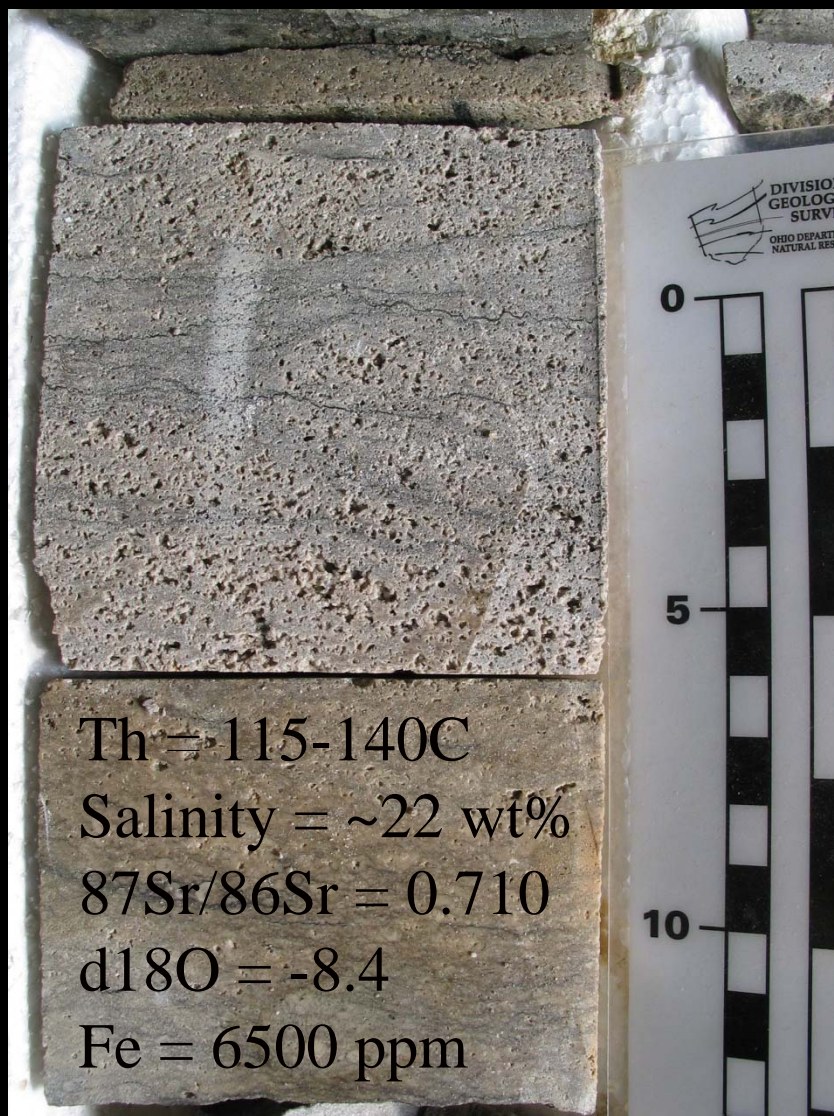


When stretched vertically, basement control becomes clear; sags almost all accommodated in overlying shale suggesting early faulting and alteration

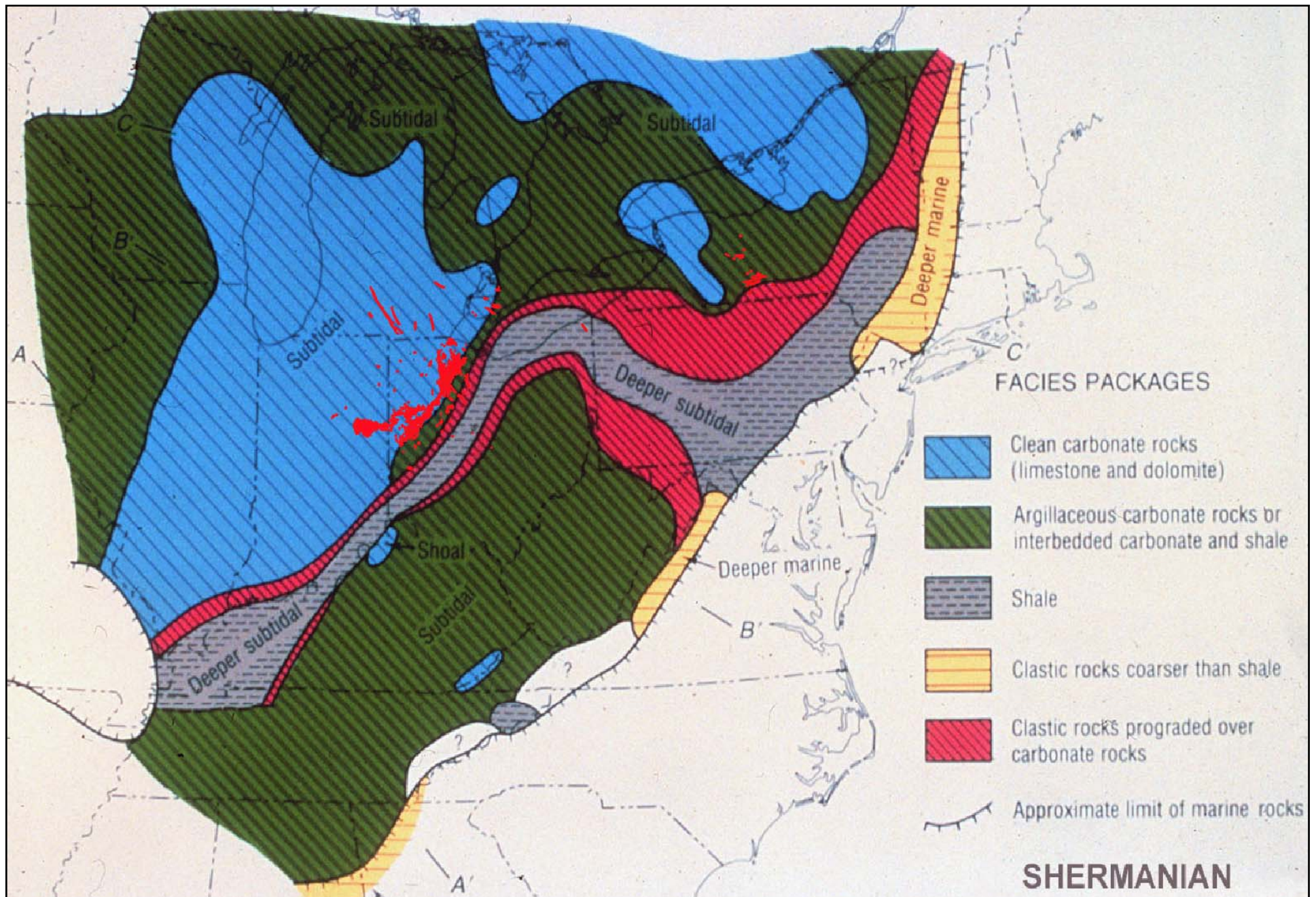


Modified from Wickstrom et al., 1992

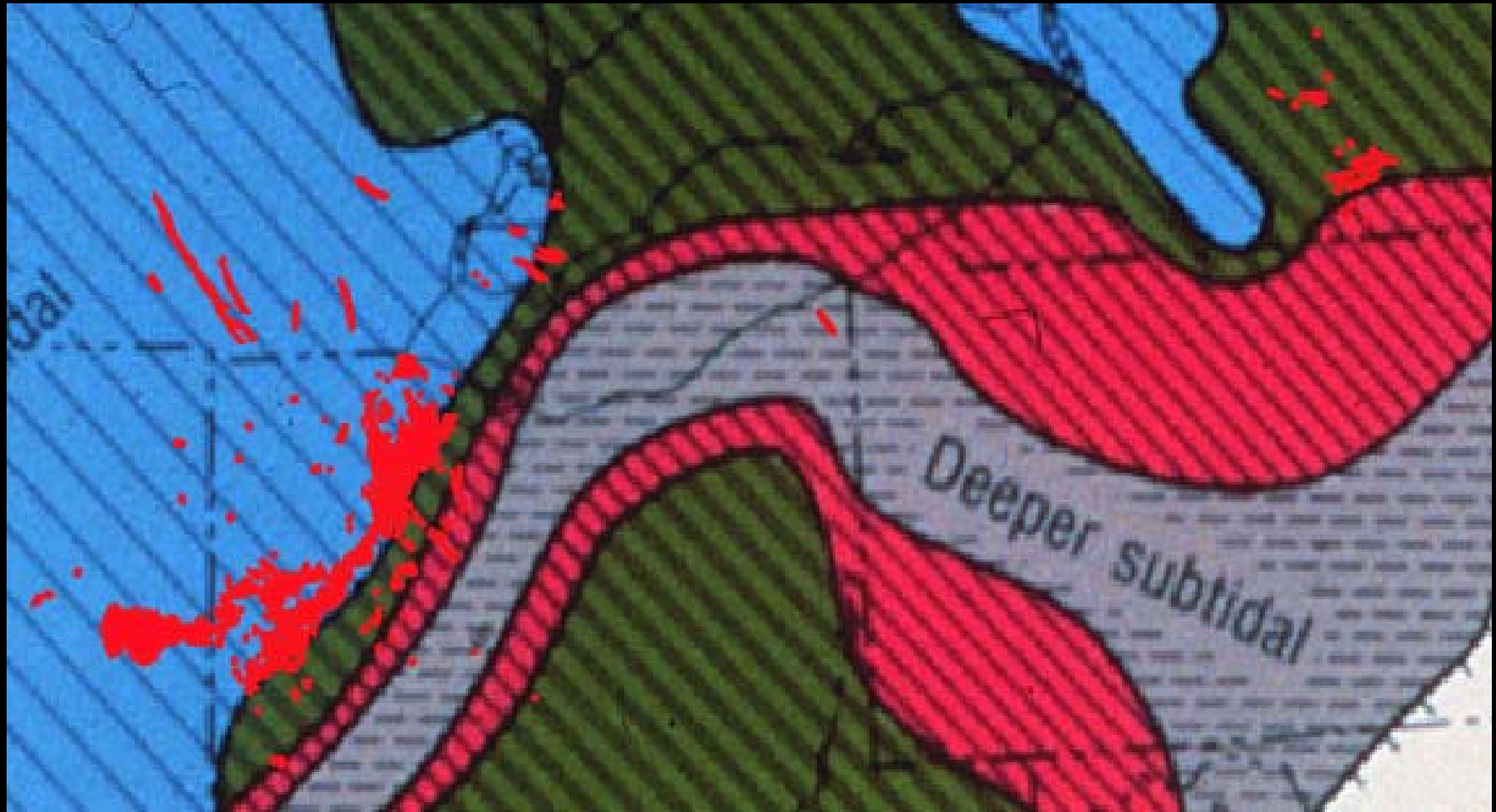
Dolomitization in Trenton occurs along margin with shale basin, around intraplateform wrench faults and at fault intersections



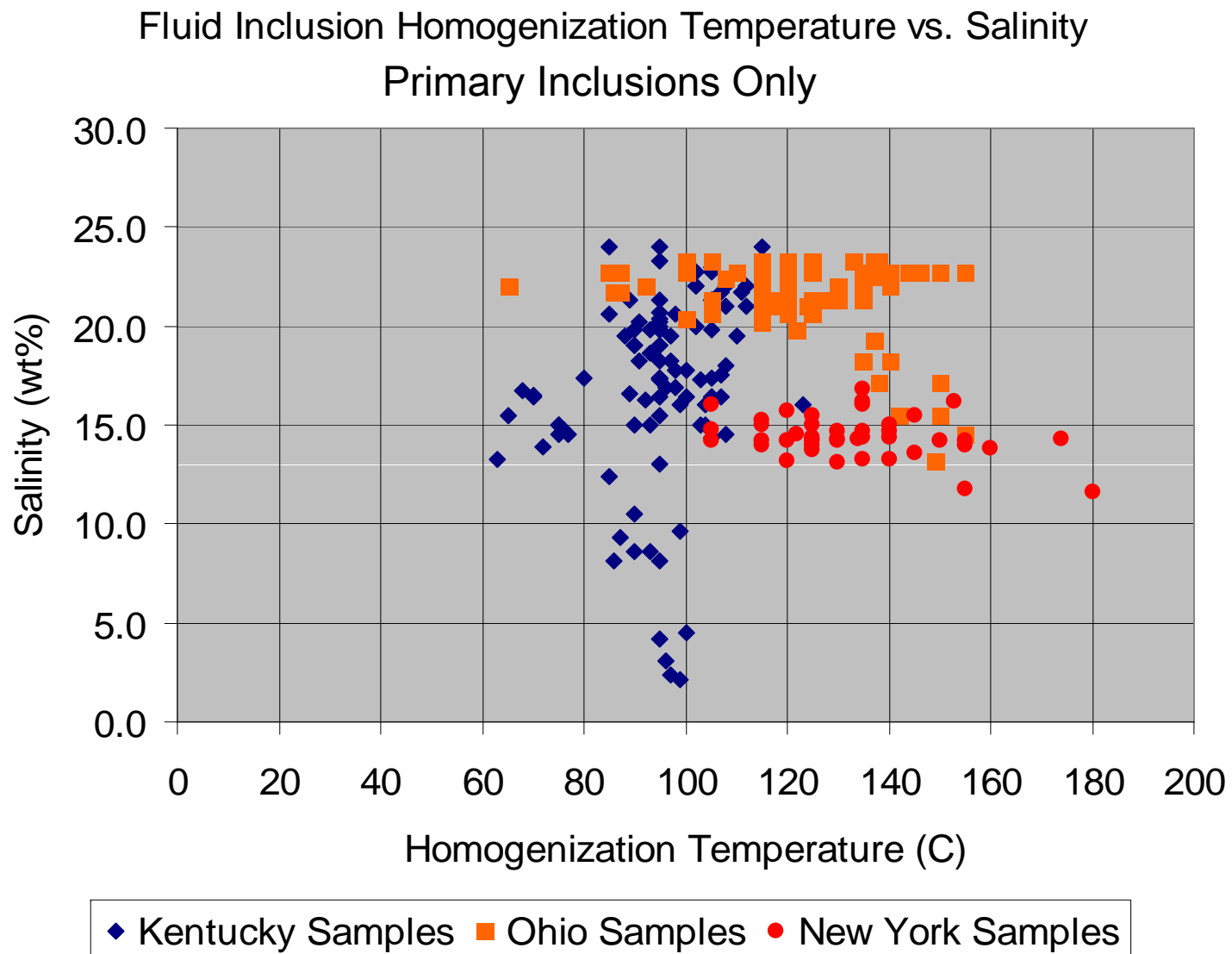
“Facies” Dolomite –occurs along margin of Seebree Trough in OH and IN, matrix porosity, little obvious vug- or fracture-filling white saddle dolomite



Trenton Depositional Environments with Fields (map from Keith)



Based on this map, it looks like many of the fields occur parallel to the margin of the Seebree Trough. Fields are not confined to the margin, however, and occur both in the Trough and back on the platform – These are commonly oriented at an angle to the margin
Faults that set up the margin were conduits for later fluids



Most of the dolomite formed between 85-160C and all of it formed above surface temperatures – most salinities between 13 and 24 wt%

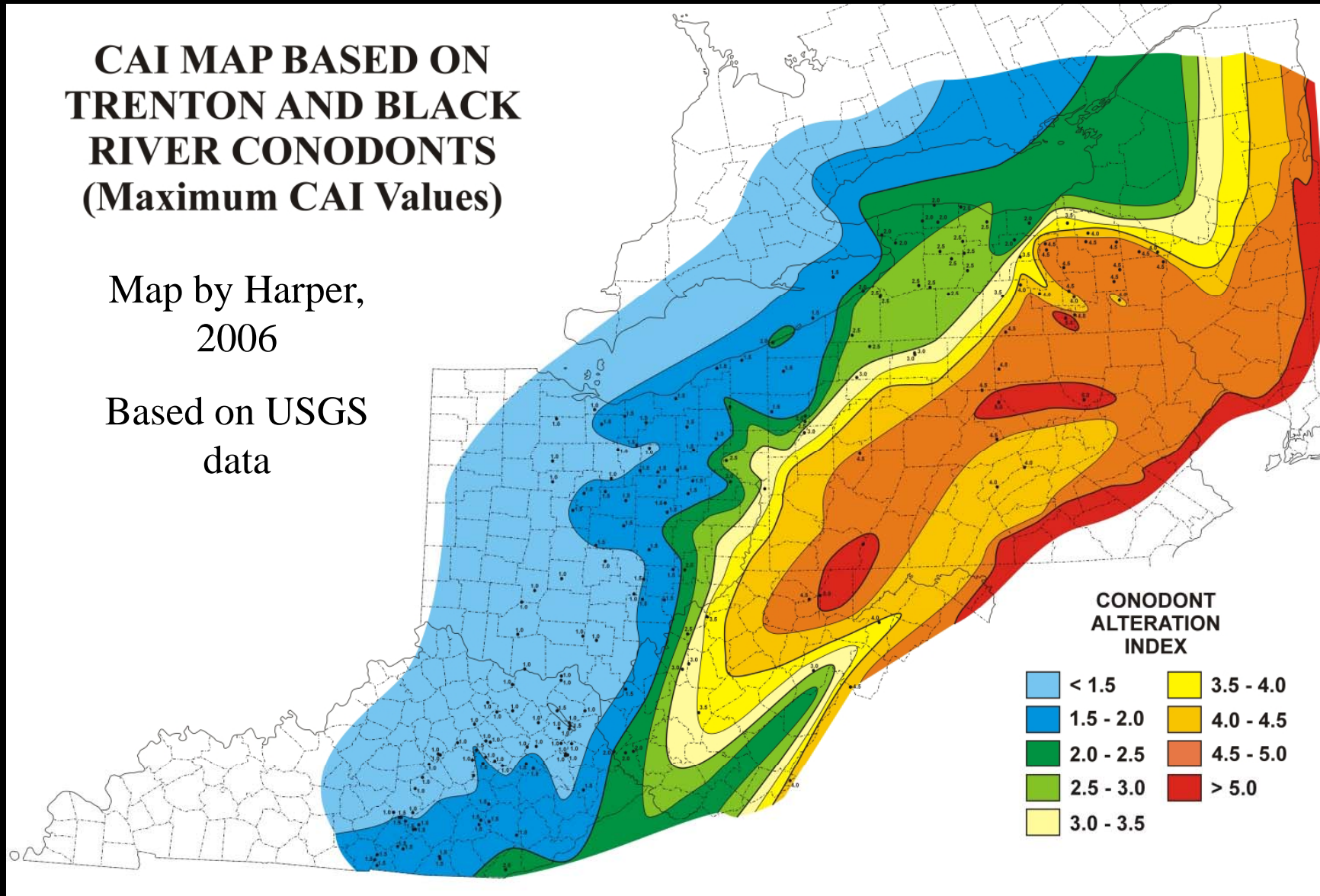
Geochemistry Summary

- Strontium isotopes radiogenic relative to Late Ordovician seawater
- Stable isotope values depleted relative to what one would expect for seawater dolomites
- Dolomites enriched in Fe and Mn
- Fluid inclusions, stable isotopes, strontium isotopes and trace elements all support a hot, subsurface origin for all the dolomite in the TBR
- The fluid that made the dolomite was hot, saline, +2 to +4 $\delta^{18}\text{O}$, Fe- and Mn-rich and passed through basement rocks or immature siliciclastics prior to making the dolomite
- The link to faults suggests a hydrothermal origin

CAI MAP BASED ON TRENTON AND BLACK RIVER CONODONTS (Maximum CAI Values)

Map by Harper,
2006

Based on USGS
data



Can use CAI (conodont alteration index) values to determine burial
history (regional USGS study)

**Conodont Color Alteration Index Temperatures for Geological
Heating Durations of 10-100 m.y.**

CAI	Minimum Temperature (°C)†	Maximum Temperature (°C)‡	Temperature Range (°C)™	Calculated Depth of Burial (km)®
1	20±5Ⓞ	20±5Ⓞ	20±5	0.00±0.20
1.5	30±5	52±7	37±22	0.68±0.88
2	35±7	106±10	72±44	2.00±1.76
2-2.5*	35±7	146±6	90±62	2.80±2.48
2.5	88±9	146±6	116±36	3.82±1.46
3	127±6	160±6	144±22	4.94±0.90
3-3.5*	127±6	206±8	168±56	5.92±2.24
3.5	142±6	206±8	175±39	6.20±1.56
4	187±8	254±9	221±42	8.04±1.68
4-4.5*	187±8	354±1	267±88	9.88±3.52
4.5	236±9	354±1	291±64	10.84±2.56
5	337±1	>400	368±32	13.92±1.28

Using temperature ranges calculated experimentally by Hulver, 1997

CAI MAP BASED ON TRENTON AND BLACK RIVER CONODONTS (Maximum CAI Values)

with interpreted maximum burial
temperatures and primary fluid inclusion
homogenization temperatures

● >max burial temp

● <max burial temp

Cap dolomite

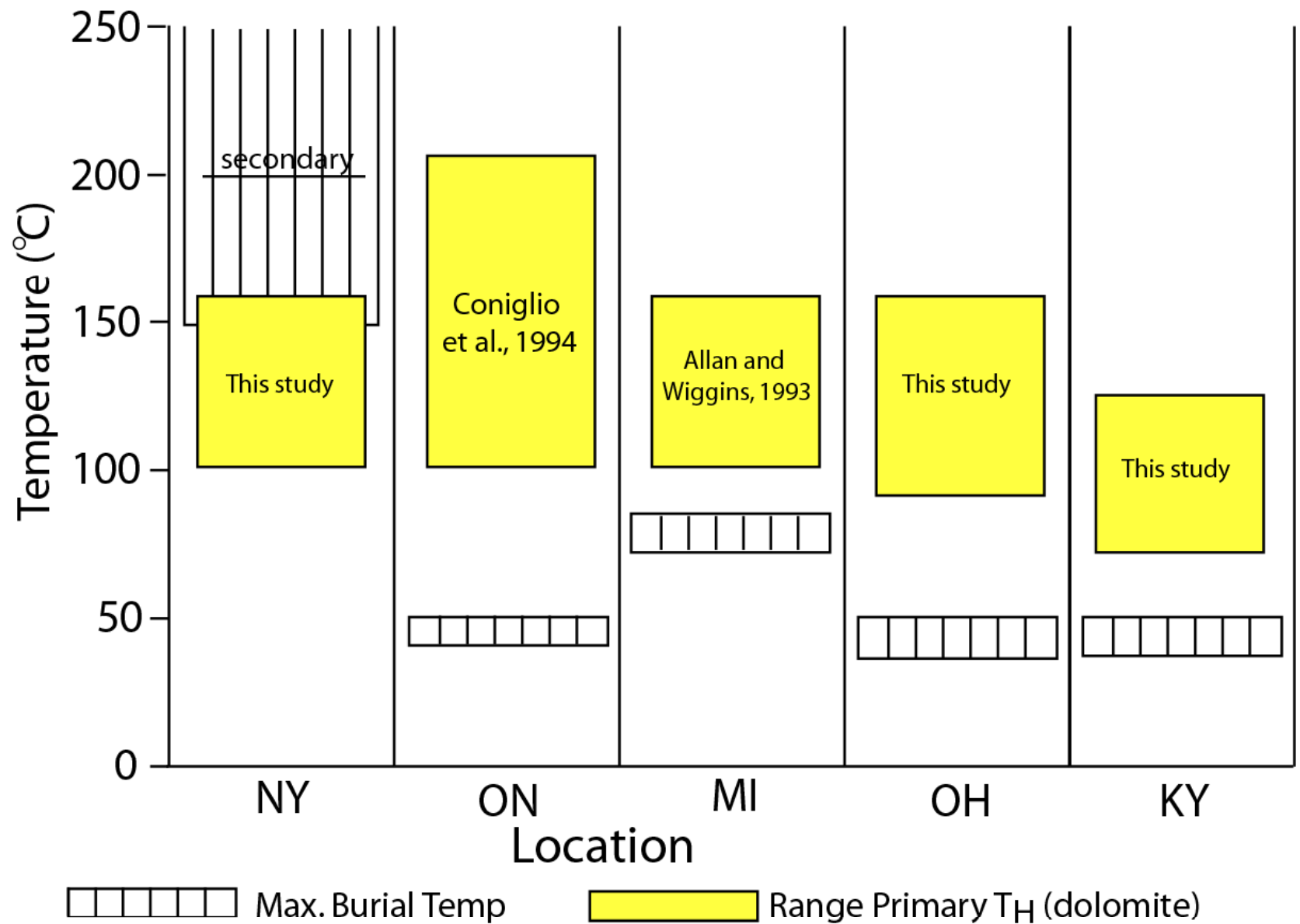
Facies dolomite

Jeptha Knob

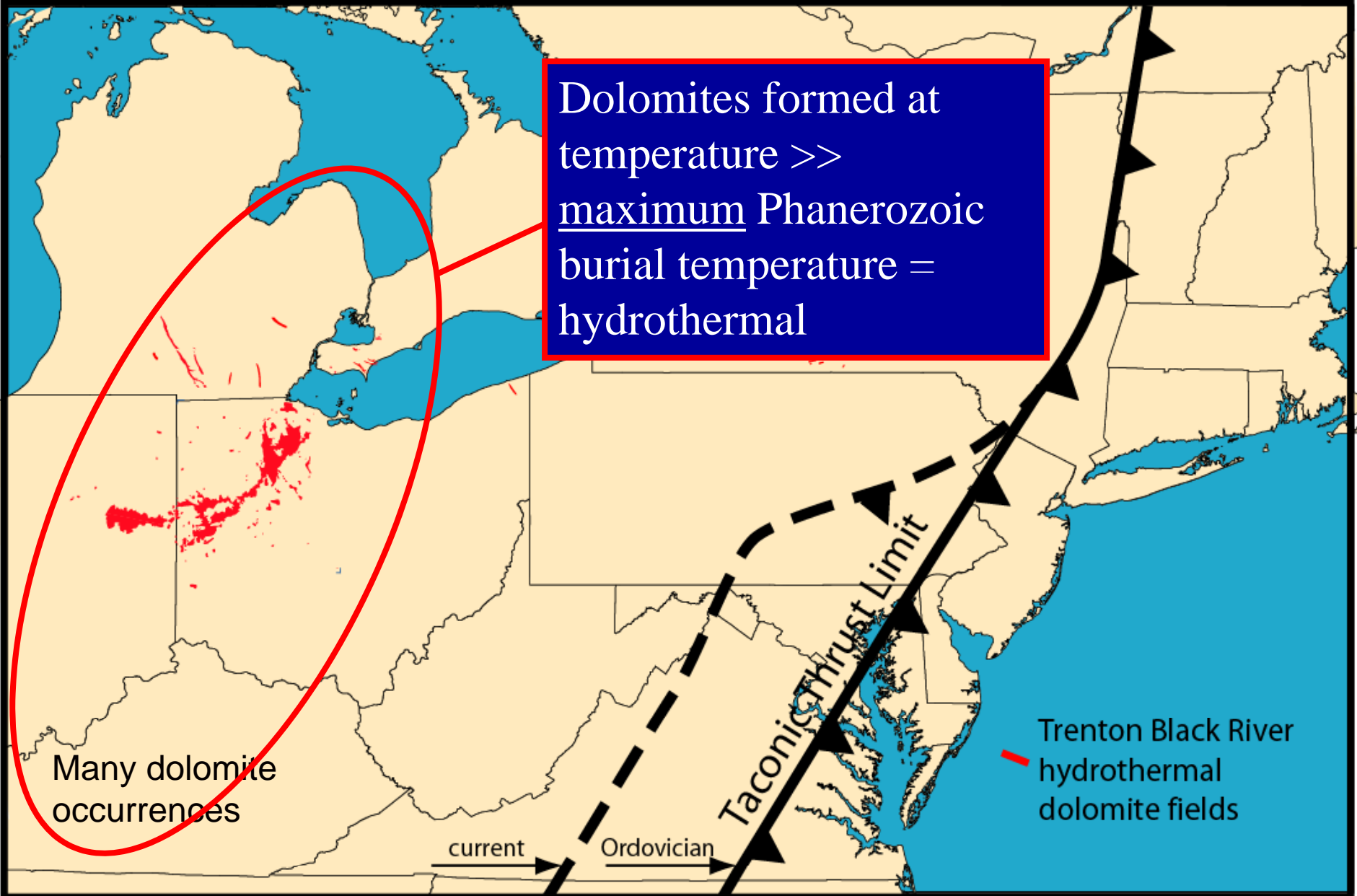
Interpreted Maximum Burial
Temperature (°C) from CAI (Hulver, 1997)



Fluid inclusion homogenization temps vs. maximum burial
temperatures - unequivocally hydrothermal at red dot locations



In all locations except NY, fluid inclusion homogenization temperatures exceed maximum ambient burial temperatures



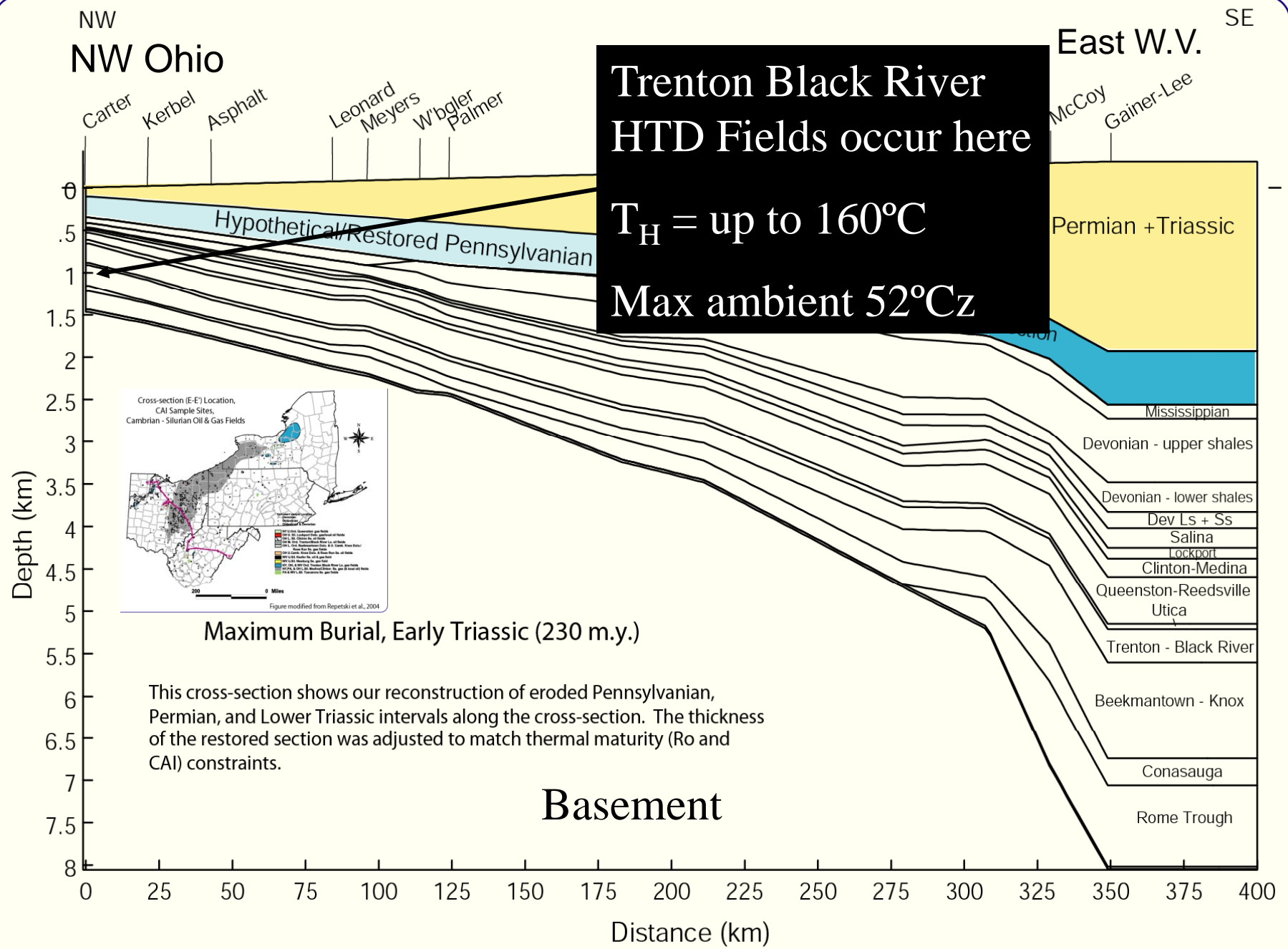
Dolomites formed at
temperature >>
maximum Phanerozoic
burial temperature =
hydrothermal

The map shows the Appalachian region with a red circle highlighting dolomite occurrences in the western part. A dashed line labeled 'Taconic Thrust Limit' runs diagonally from the bottom left to the top right. Red lines indicate hydrothermal dolomite fields in the Black River area. Arrows at the bottom indicate 'current' and 'Ordovician' directions.

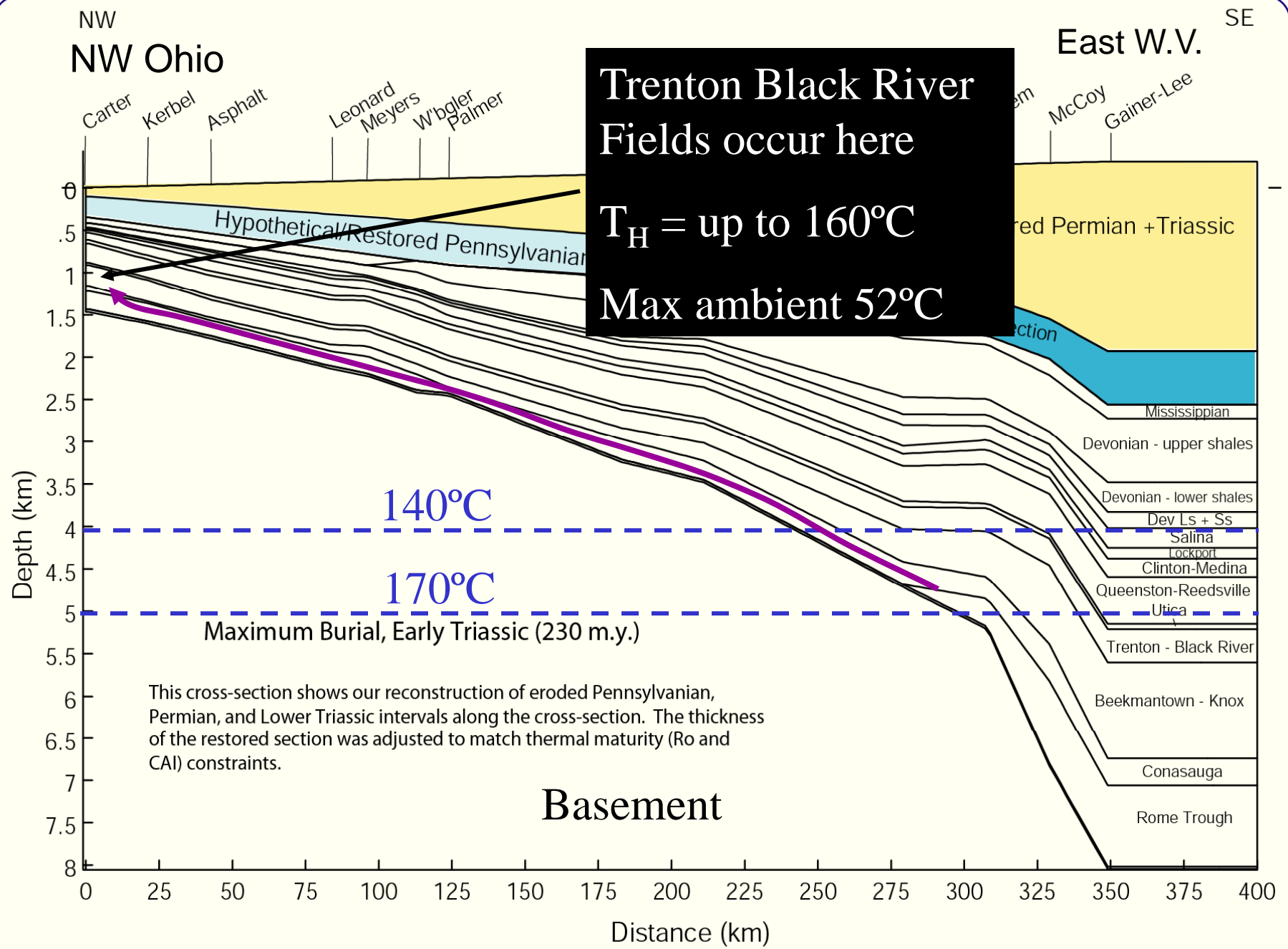
Many dolomite
occurrences

Trenton Black River
hydrothermal
dolomite fields

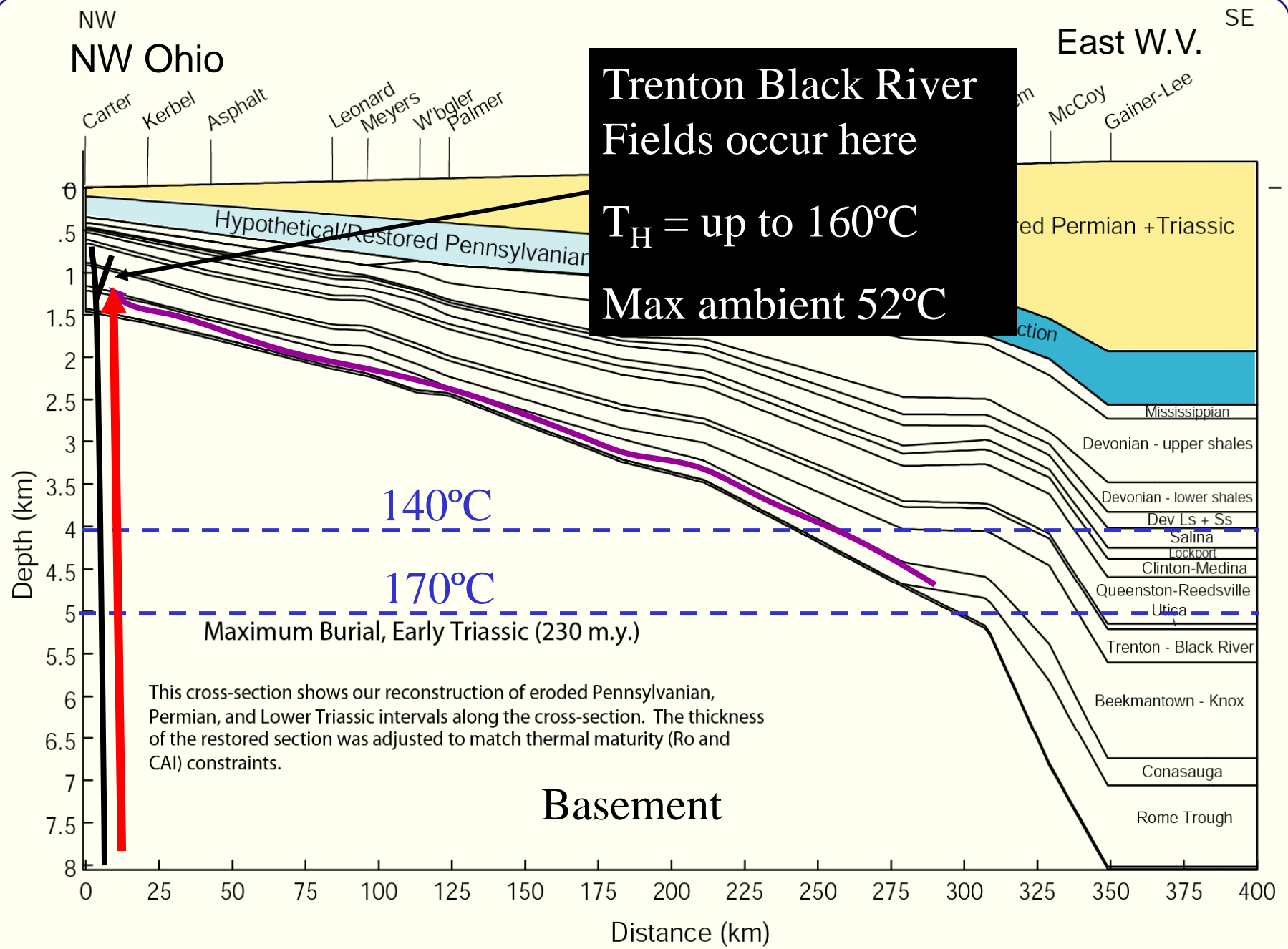
Matrix and saddle dolomites in red circle have fluid inclusion
homogenization temperatures >> maximum ambient burial temperature



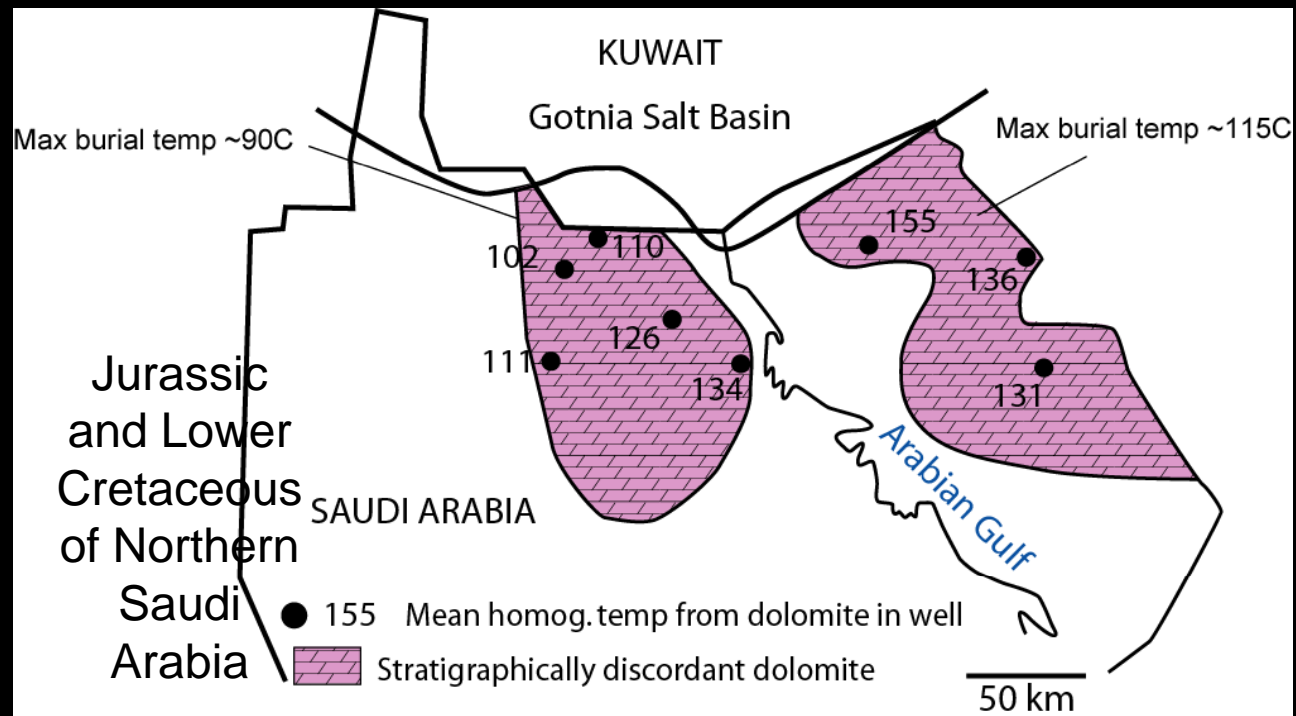
Burial History for Appalachian Basin from Rowan et al., 2004



Unlikely that temps achieved by lateral flow – fluids would cool

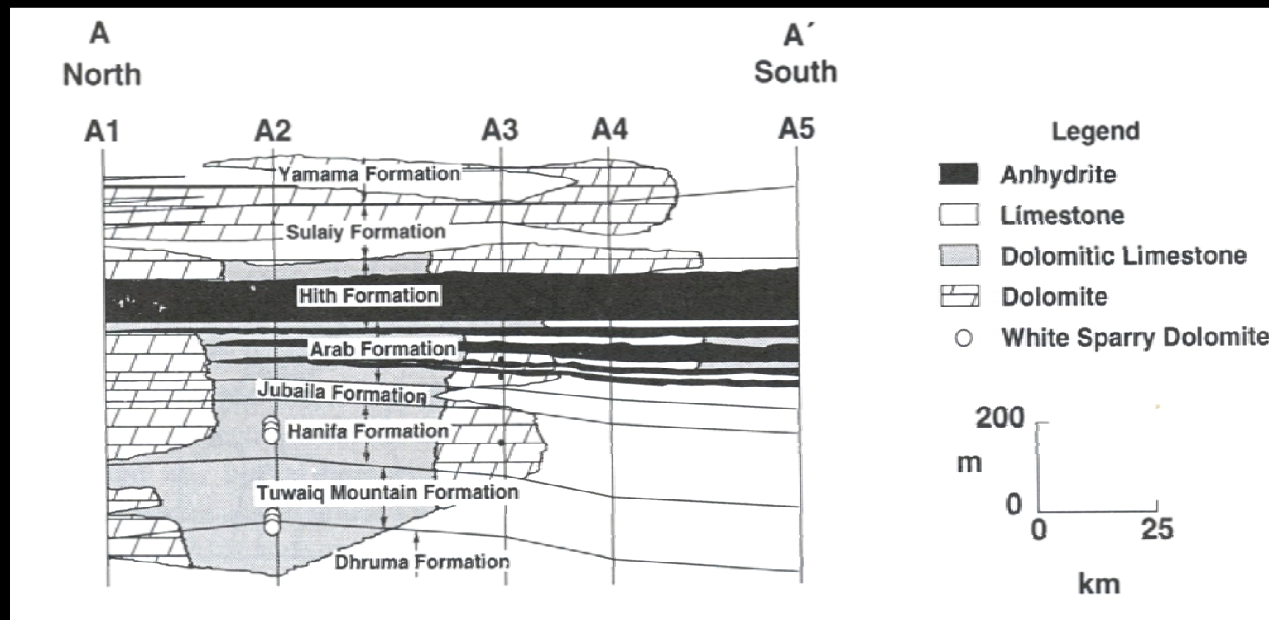


Must have vertical flow out of basement to achieve high temps

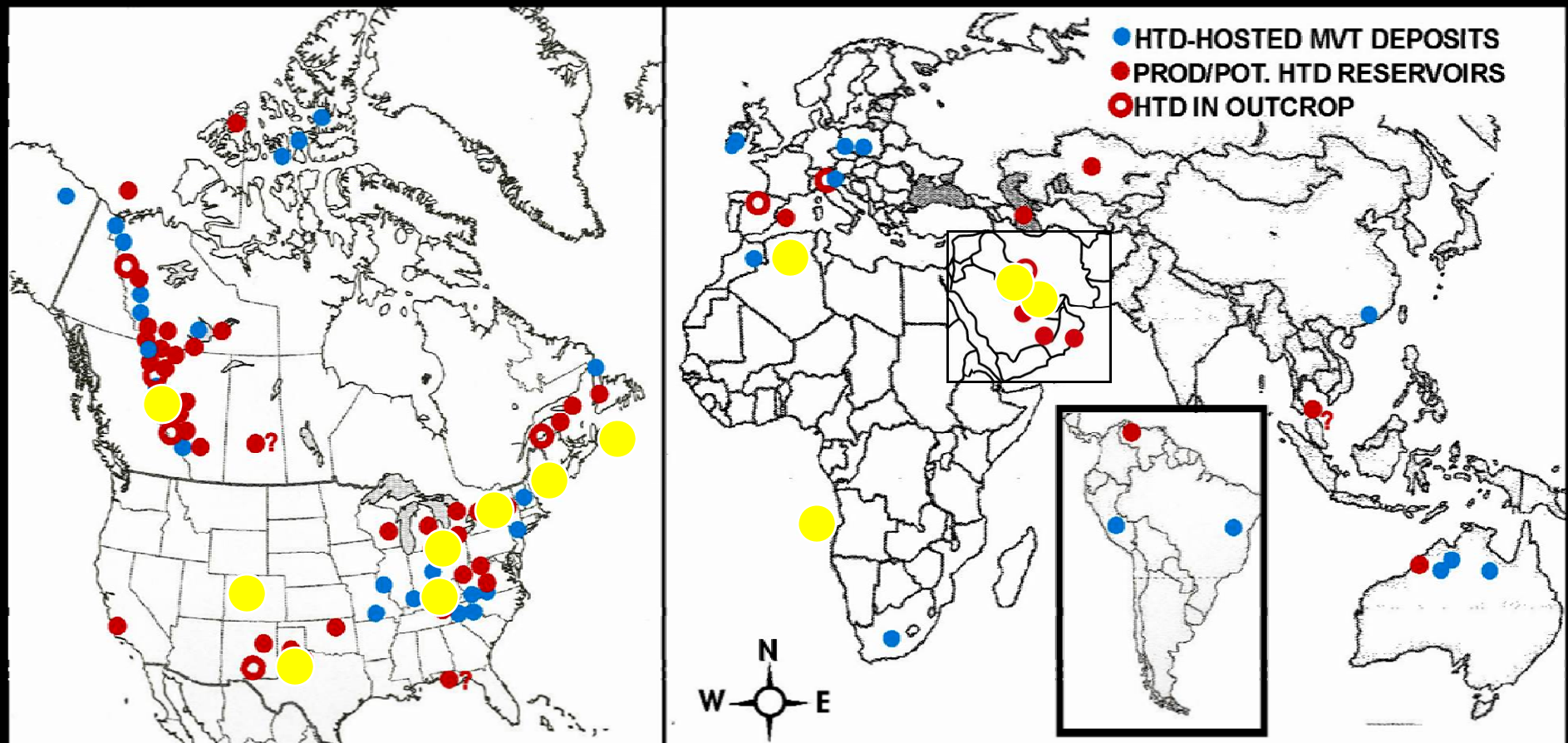


Hydrothermal dolomitization can be widespread and volumetrically significant given the right facies and fluid flow scenario

This example modified from Broomhall and Allan, 1987 and Allan and Wiggins, 1993

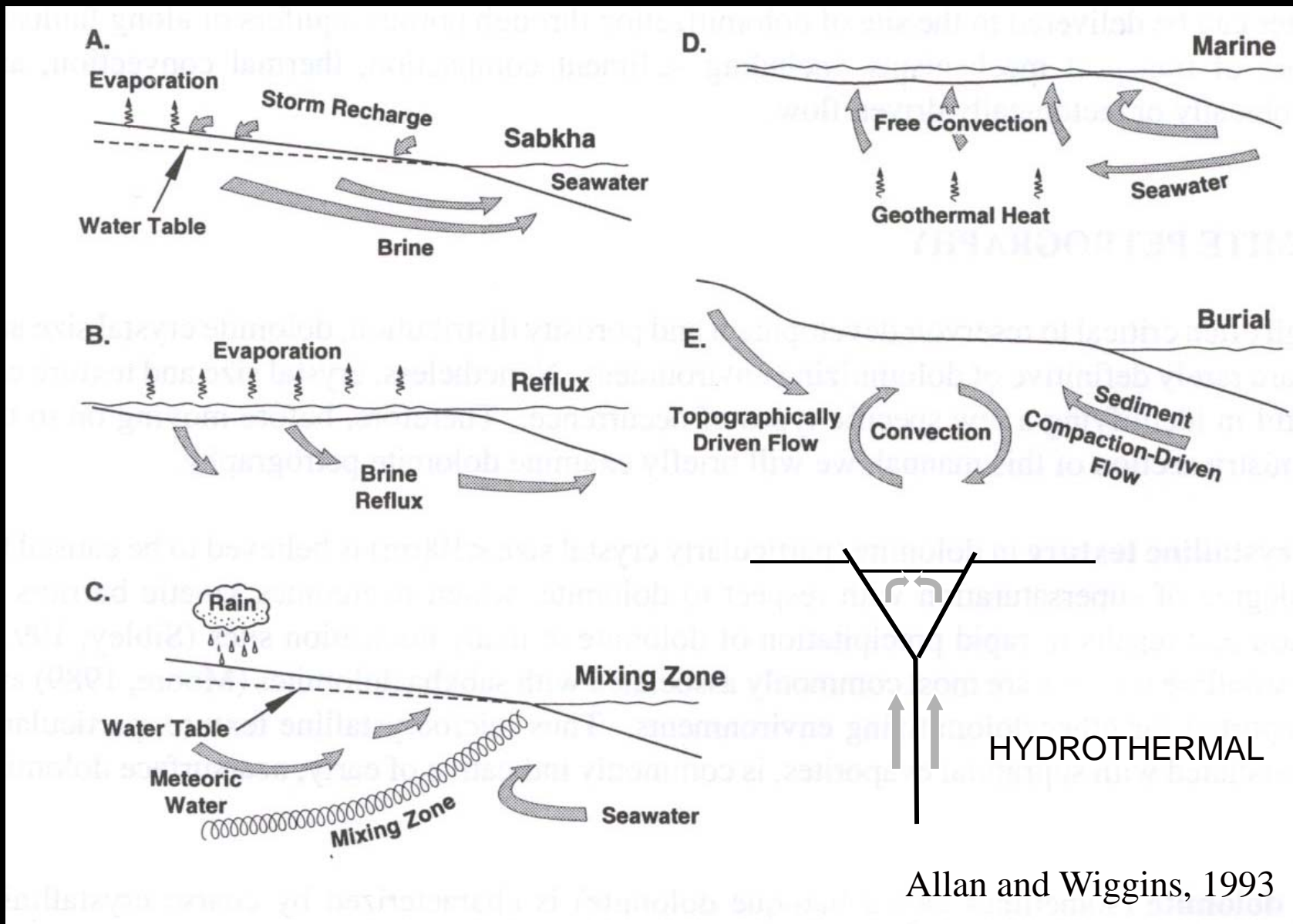


HTD FACIES: GLOBAL DISTRIBUTION



FROM SANGSTER (1990), DAVIES (2001)

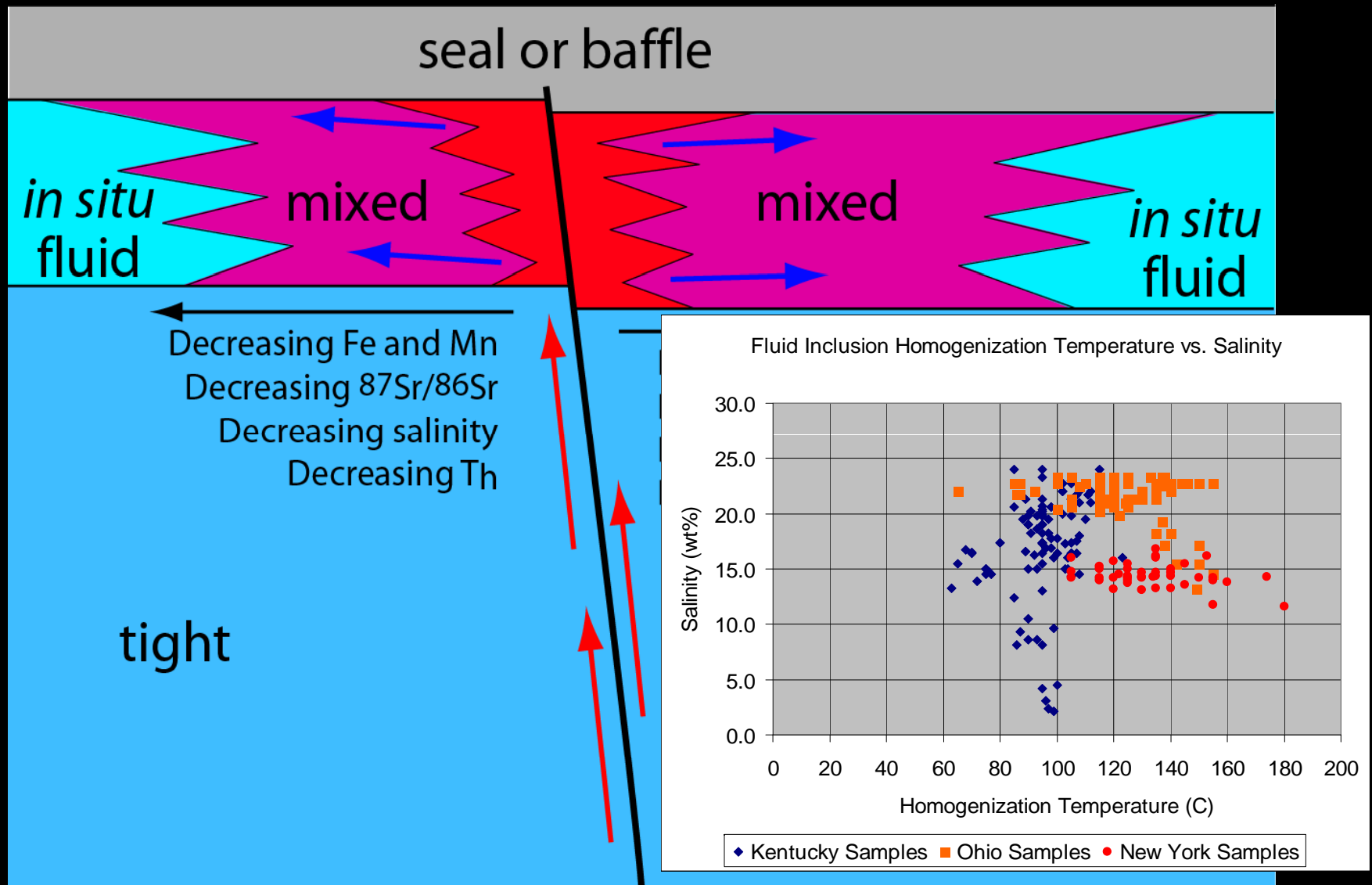
Documented examples of some HTD reservoirs and associated MVT deposits from around the world, likely a small fraction of the actual number – yellow are examples/places I have seen or worked on



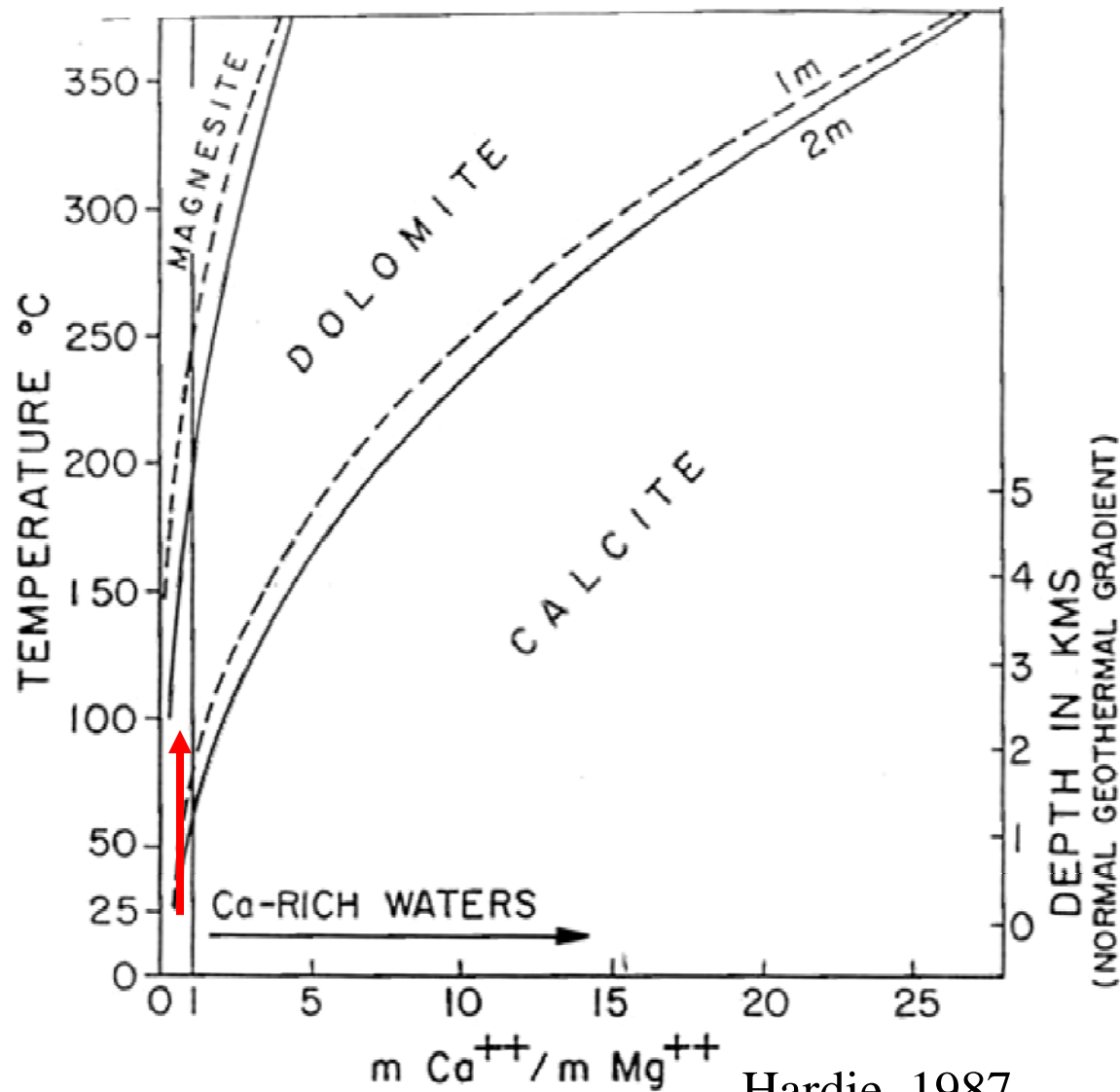
Given the widespread occurrence of hydrothermal dolomite here and elsewhere, this model should always be considered as a possibility

Mass balance

- Large amounts of fluid and magnesium are required for this (or any other dolomite) to form
- Ideas for fluid:
 - Mixing with *in situ* marine phreatic fluids (mainly seawater – this provides Mg as well) (Salas et al, 2007)
 - Recycling in fault zone
 - Broad recharge, focused discharge
- Ideas for magnesium:
 - Mixing with *in situ* marine phreatic fluid
 - Some could be leached from underlying early dolomites
 - Basement source?



Mixing with in situ seawater or marine phreatic fluid in altered zone –
Work by Salas et al, 2007 shows that in some cases dolomitization
could occur from mixing of hydrothermal and in situ fluids



Hardie, 1987

“Above 60°C there is no dolomite problem” – Hardie, 2004

Seawater has about 5 times more magnesium than calcium so even if the hydrothermal fluid is Ca-rich, the mixed fluid might still make dolomite

Conclusions

- Fault-related hydrothermal processes are capable of producing large quantities of reservoir-quality dolomite and should be considered with other models when interpreting the origin of dolomites
- Must be a component of fluid flow out of basement (at least in some cases), which may be why these reservoirs only occur around basement-rooted faults
- Mass balance problems may be overcome through mixing with *in situ* marine phreatic fluids, fluid recycling in fault zone, cannibalization of early dolomite, other models
- Similar process appears to produce leached limestone which may be even more common in reservoirs

Selected References

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