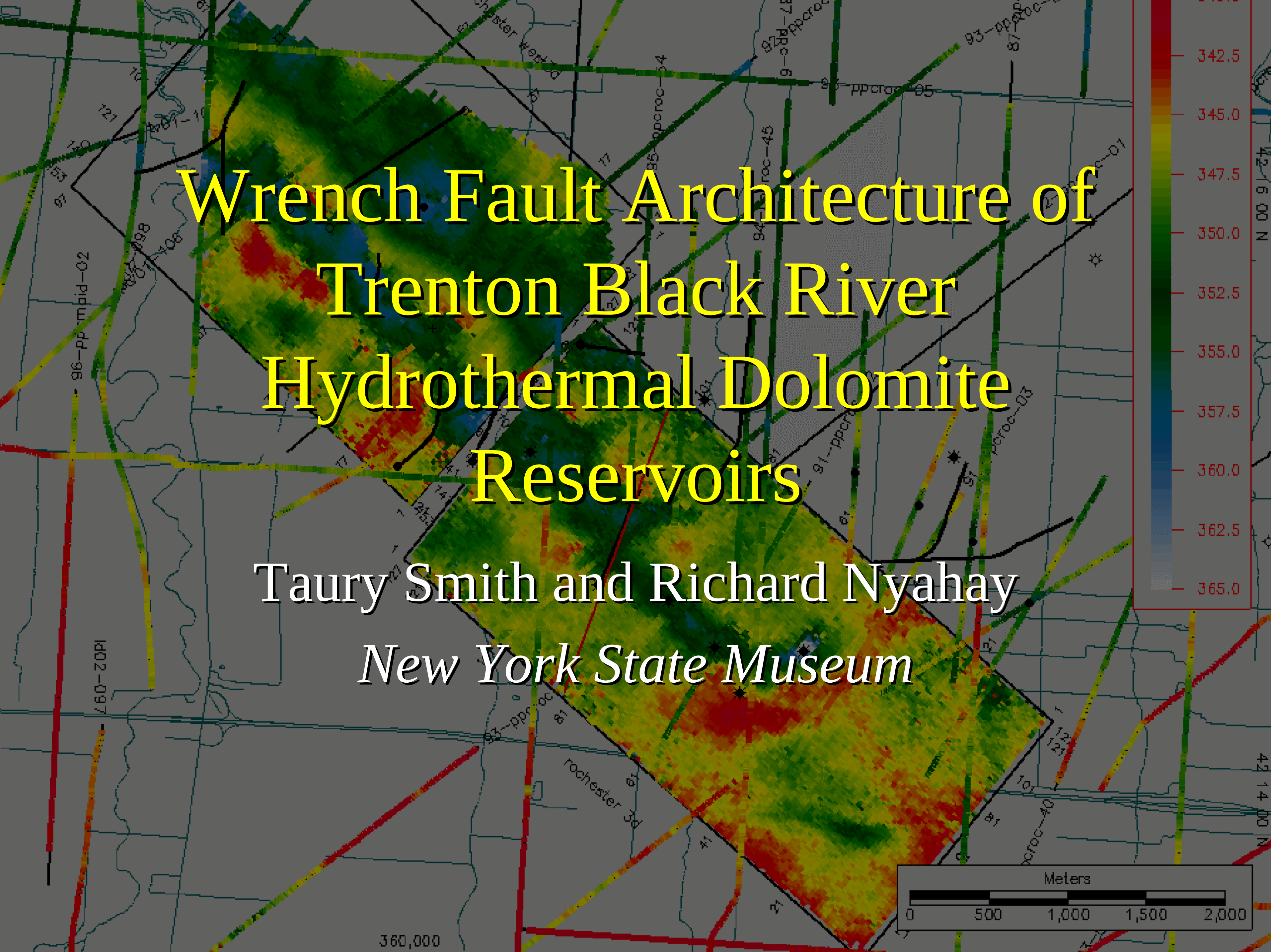
Wrench Fault Architecture of Trenton Black River Hydrothermal Dolomite Reservoirs

Taury Smith and Richard Nyahay

New York State Museum



Model for Hydrothermal Dolomitization

- Trenton Black River Hydrothermal Dolomite Reservoirs formed when hydrothermal fluids flowed up active faults, hit sealing strata in the basal Trenton (in NY) or the Utica (in OH, MI and ON) and flowed laterally into underlying permeable beds and leached and dolomitized the limestone

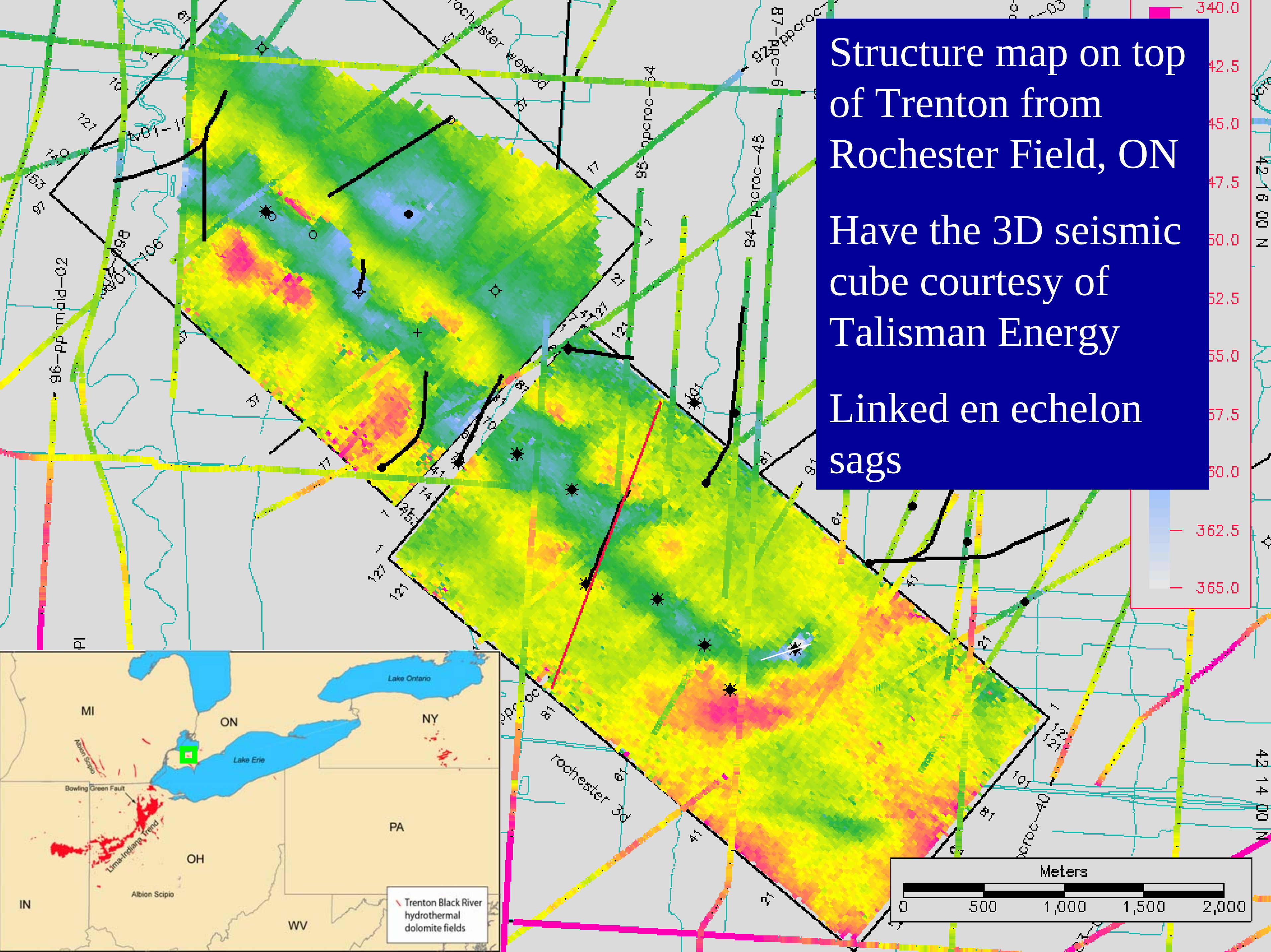
Structure

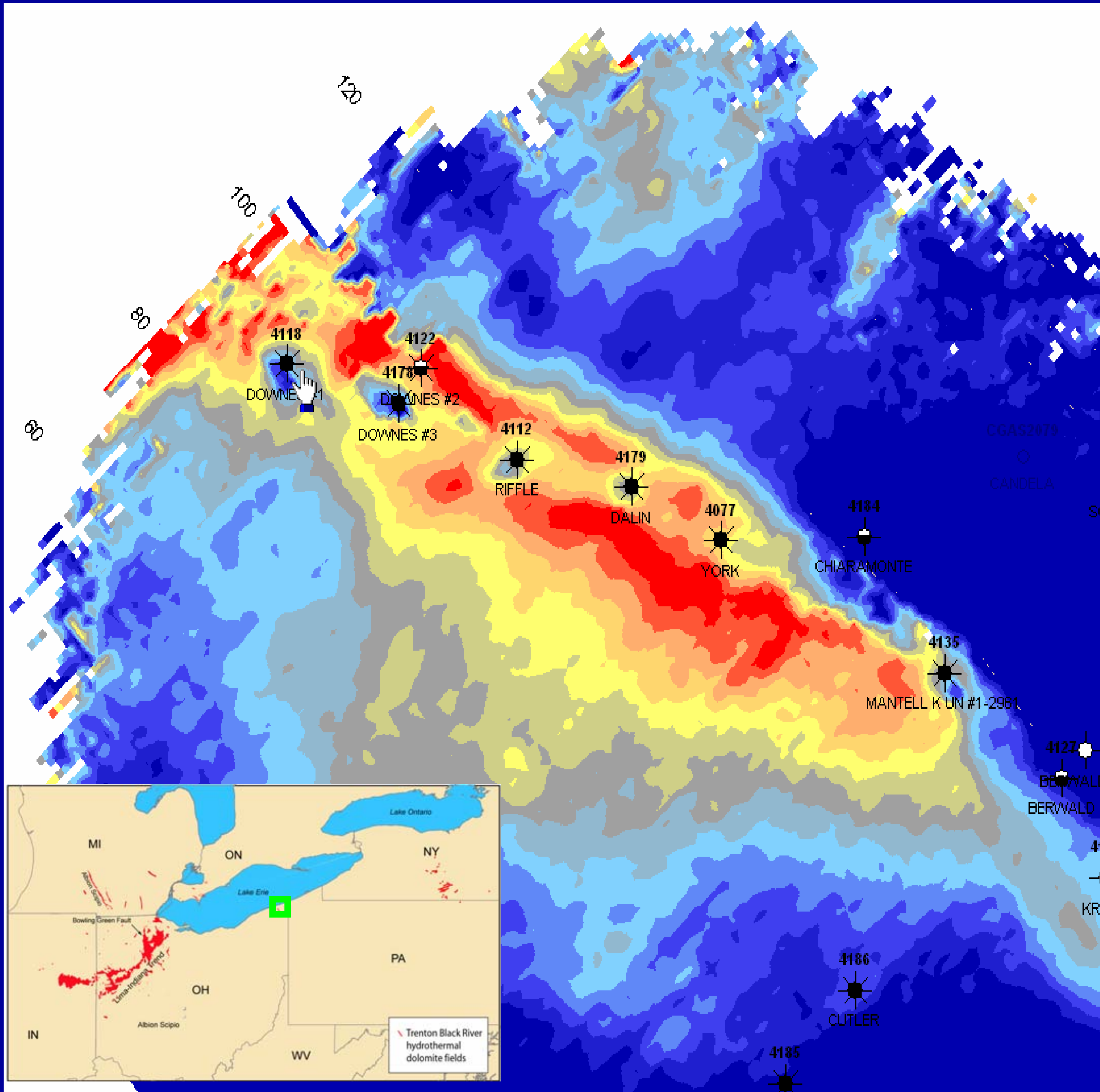
- We have good geochemical, petrographic and field mapping data to support this model
- One of the more complex aspects of the Trenton Black River story is the style or styles of faulting that is conducive to hydrothermal dolomitization – that is the focus of this talk
- Have studied this using 3D seismic from Ohio and Ontario
- This is a work in progress - results presented here are different than results presented in earlier talks and may change yet again with further research

Structure map on top of Trenton from Rochester Field, ON

Have the 3D seismic cube courtesy of Talisman Energy

Linked en echelon sags





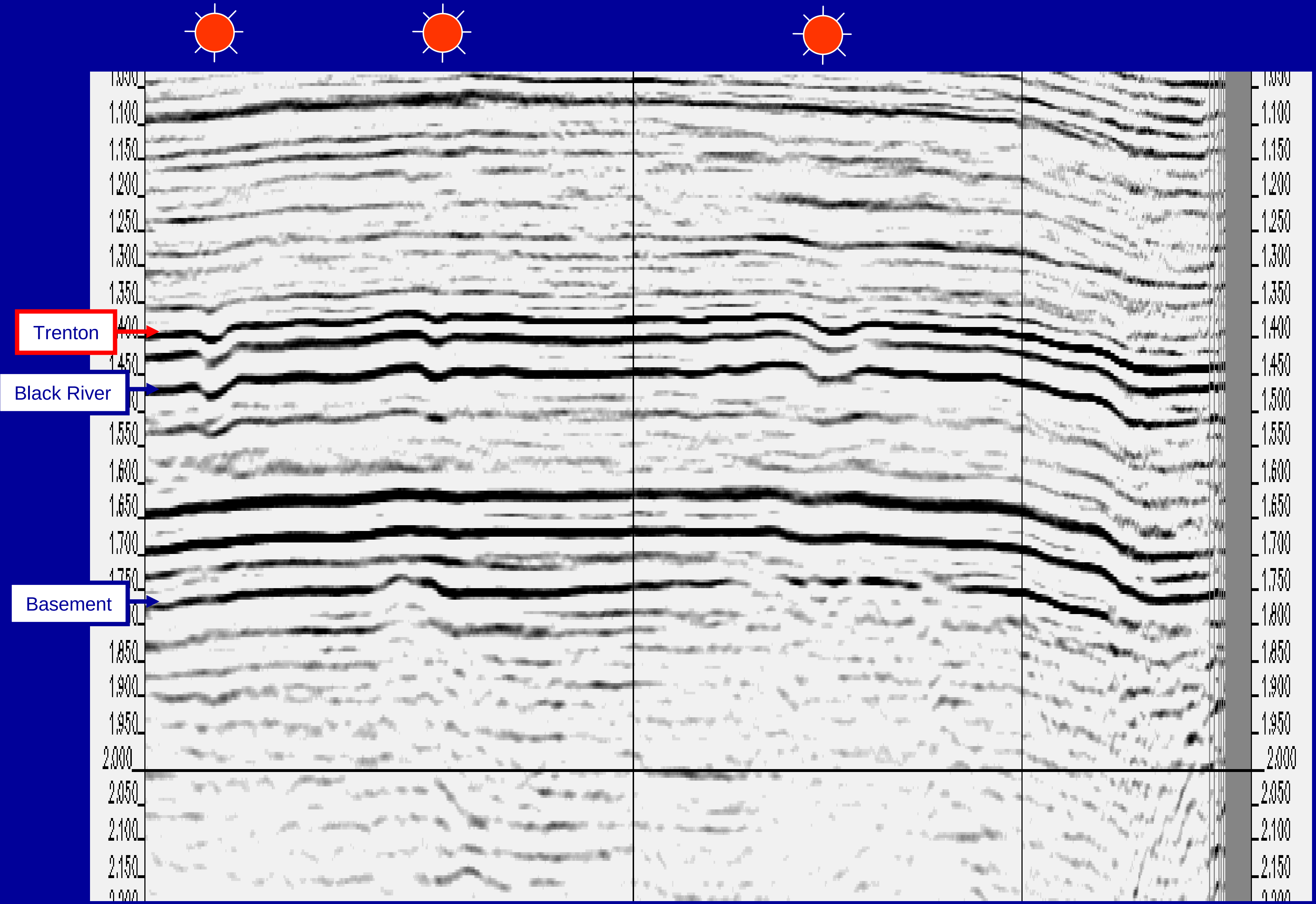
Top Trenton time-structure map

We have several screen dumps from a PowerPoint presentation courtesy of CGAS

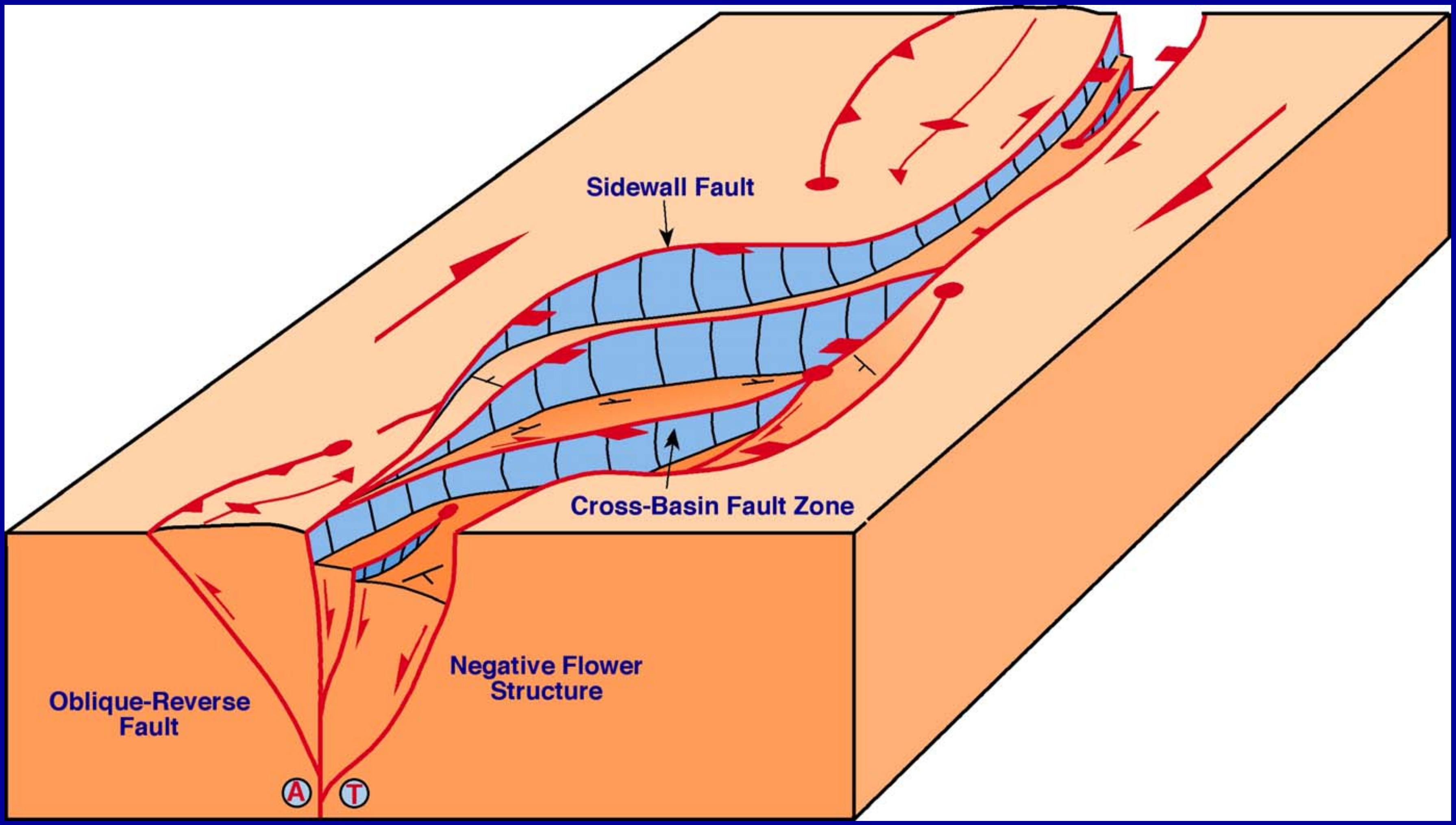
~continuous low on high with subcircular “holes”

Sags

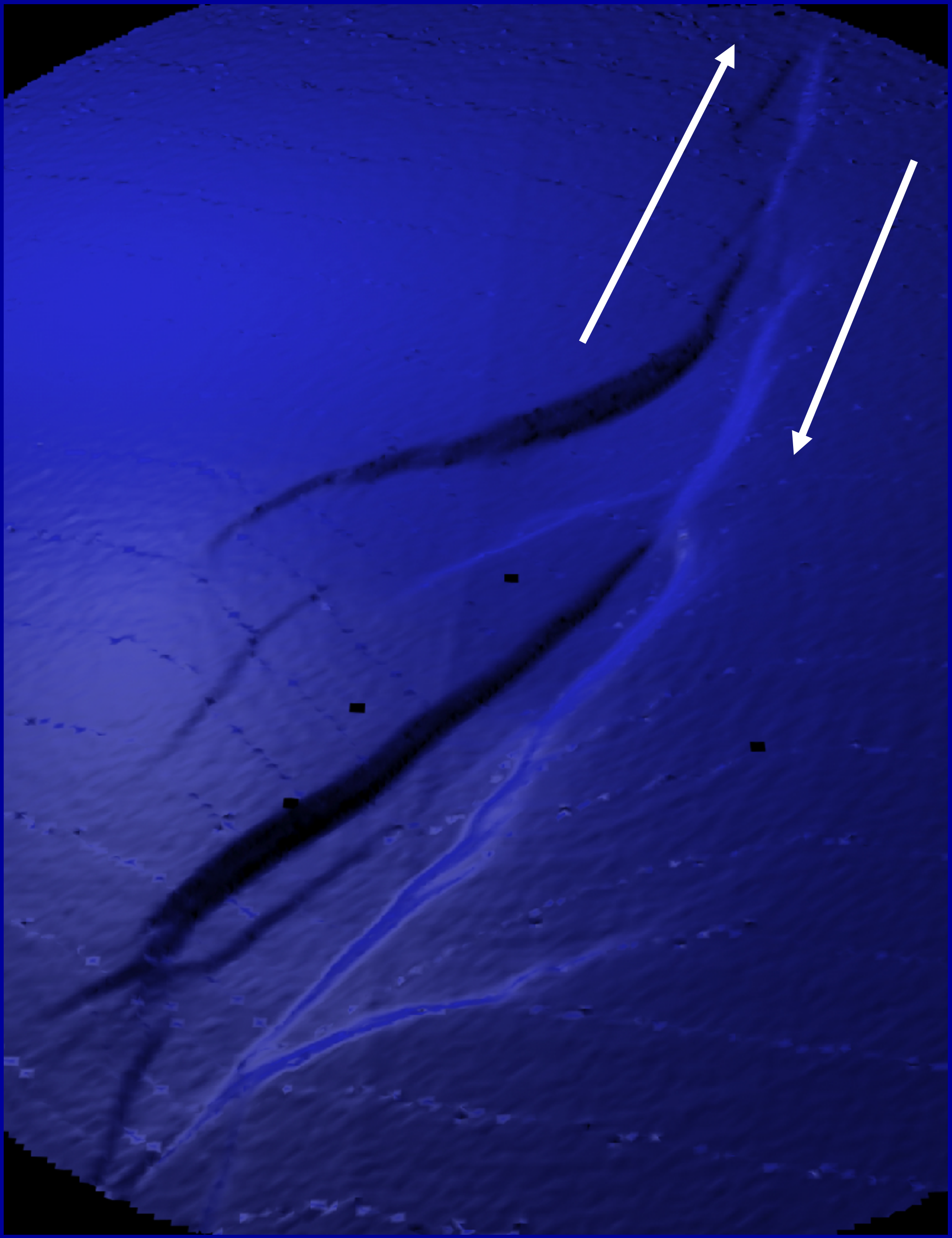
- Most TBR hydrothermal dolomite reservoirs occur in and around structural sags
- Sags may be produced by the following
  - Negative flower structures and extensional tectonics
  - Dissolution of limestone and dolomite
  - Dolomitization of limestone and associated volume reduction
  - Combination of Above



Sags dolomitized and produced gas from Ordovician Black River - subtle basement-fault control? – Seismic Line courtesy of Fortuna Energy



Block Model for negative flower structure – Dooley and McClay, 1997 - Note that either side of fault zone is not vertically displaced but that significant thinning occurs within fault zone

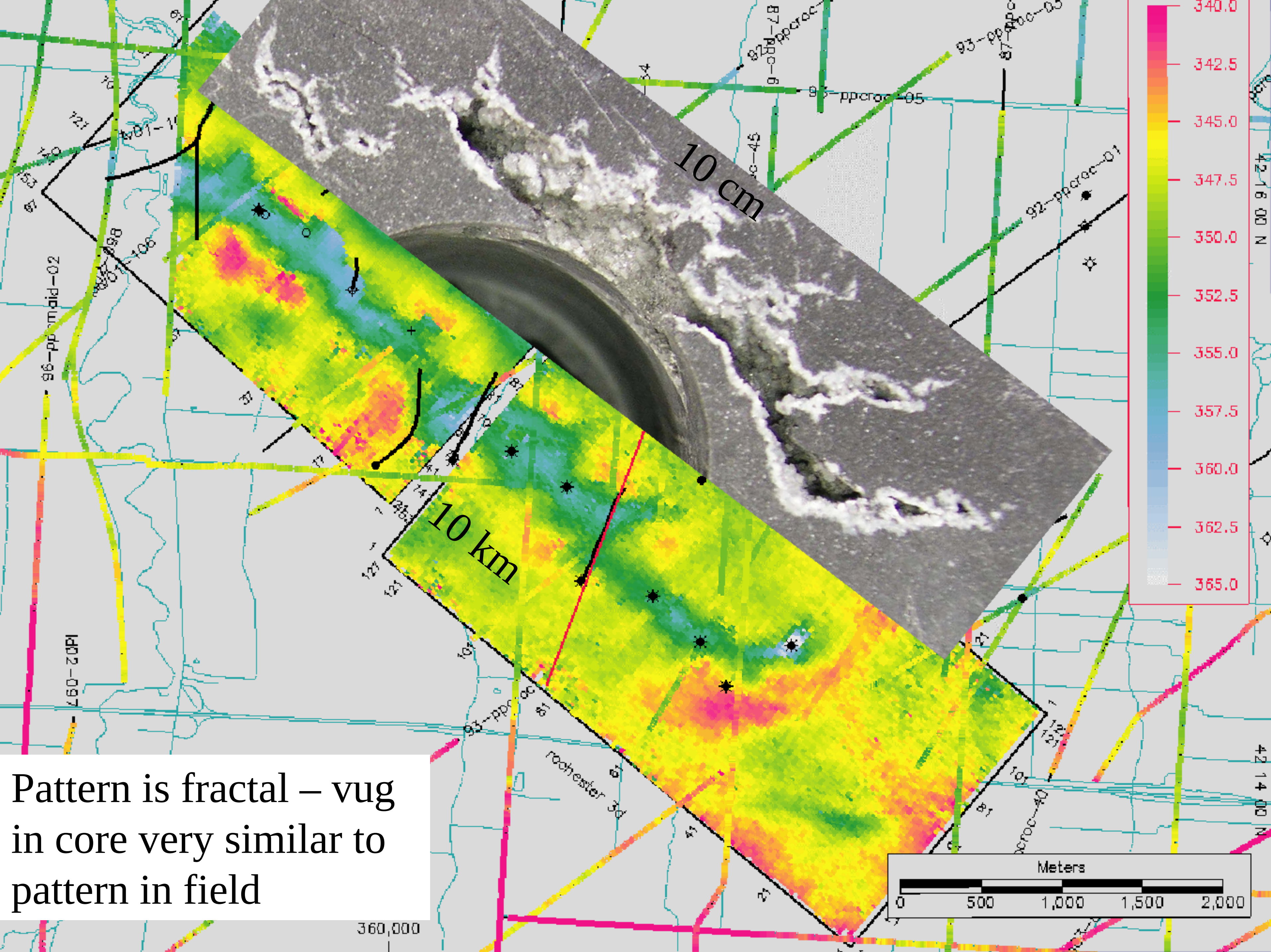


Sandbox model (Dooley and McClay, 1997) of “pull-apart” structure shows “sag” or “graben”

The orientation of the fingers tells us the direction of movement on the fault

Hydrothermal fluid flow and alteration thought to be most intense around downthrown portions of sags

Dissolution- vuggy porosity
Requires dissolution of limestone and/or dolomite
The questions is, can enough volume be removed by dissolution to create sags visible on seismic?

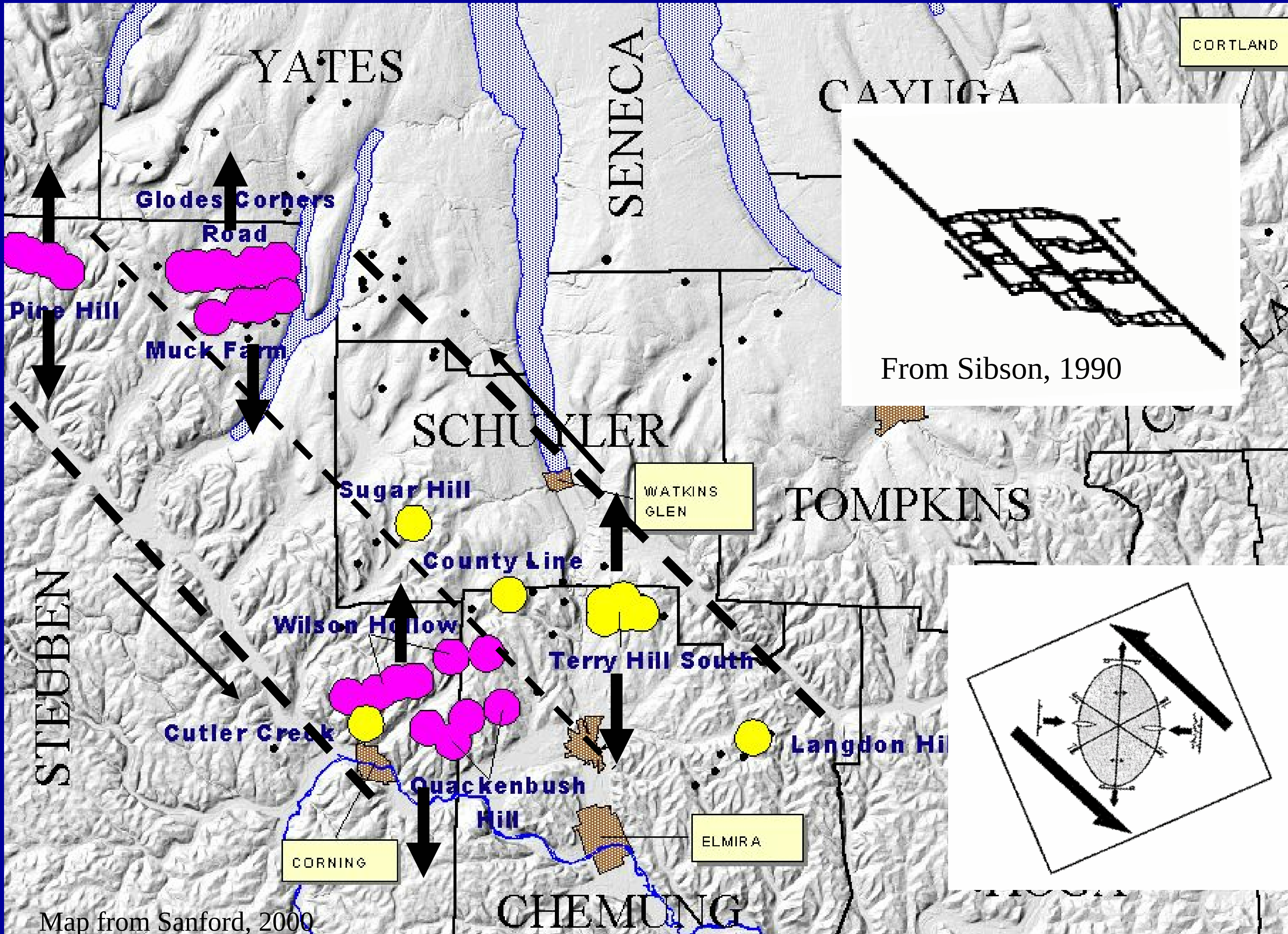


Pattern is fractal – vug in core very similar to pattern in field

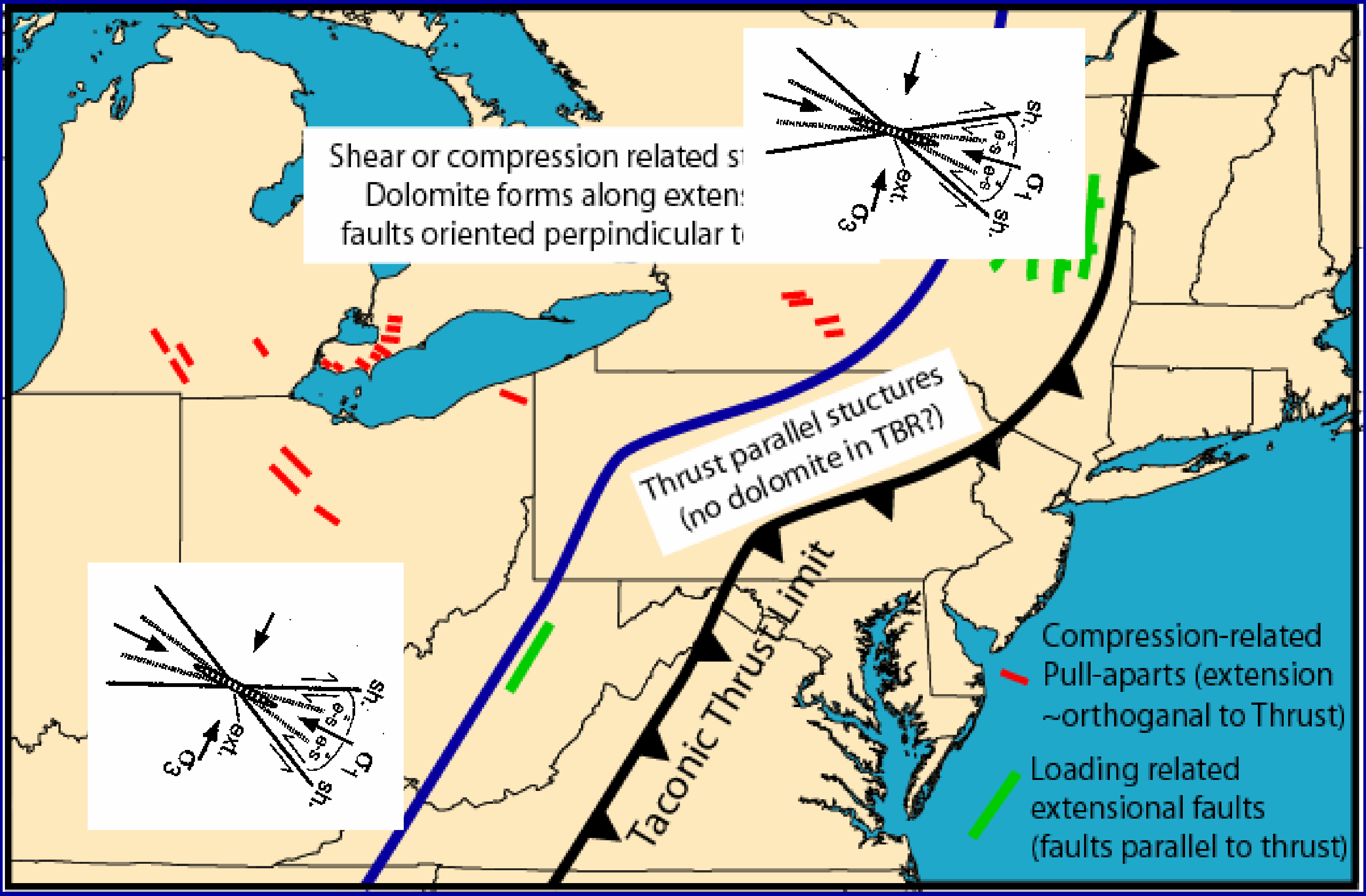
Volume Reduction During Dolomitization

- The dolomite molecule ($CaMg(CO_3)_2$) is 11% smaller than two calcite ($CaCO_3$)molecules
- If there is a one-for one replacement of one dolomite for every two calcite molecules there should be an 11% volume reduction (Weyl, 1960)
- If this even occurs, it’s minor: if 20 meters of strata were dolomitized, this would only produce a ~2 meter sag – this would not be detectable on seismic

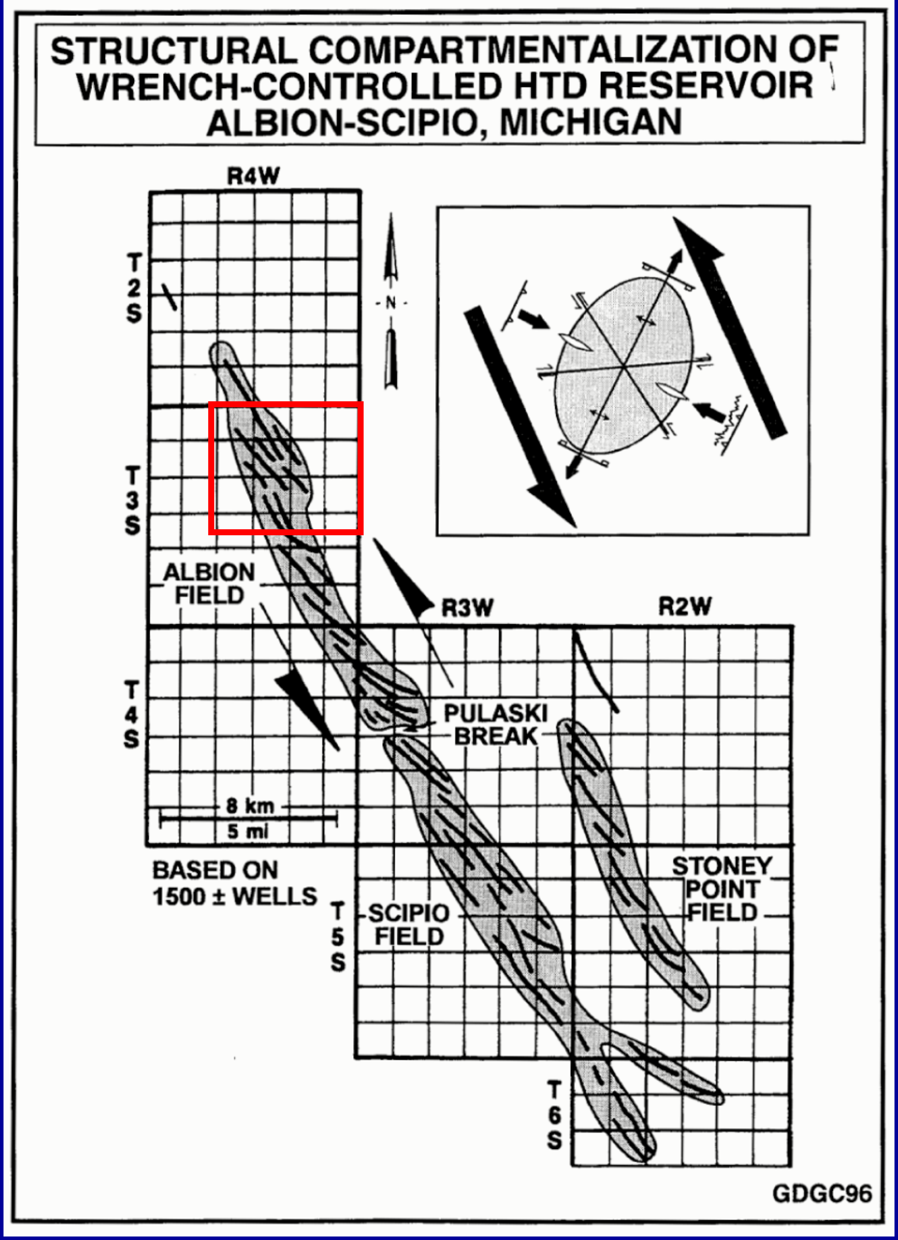
- Most sags probably produced by transtensional faulting with an element of dissolution



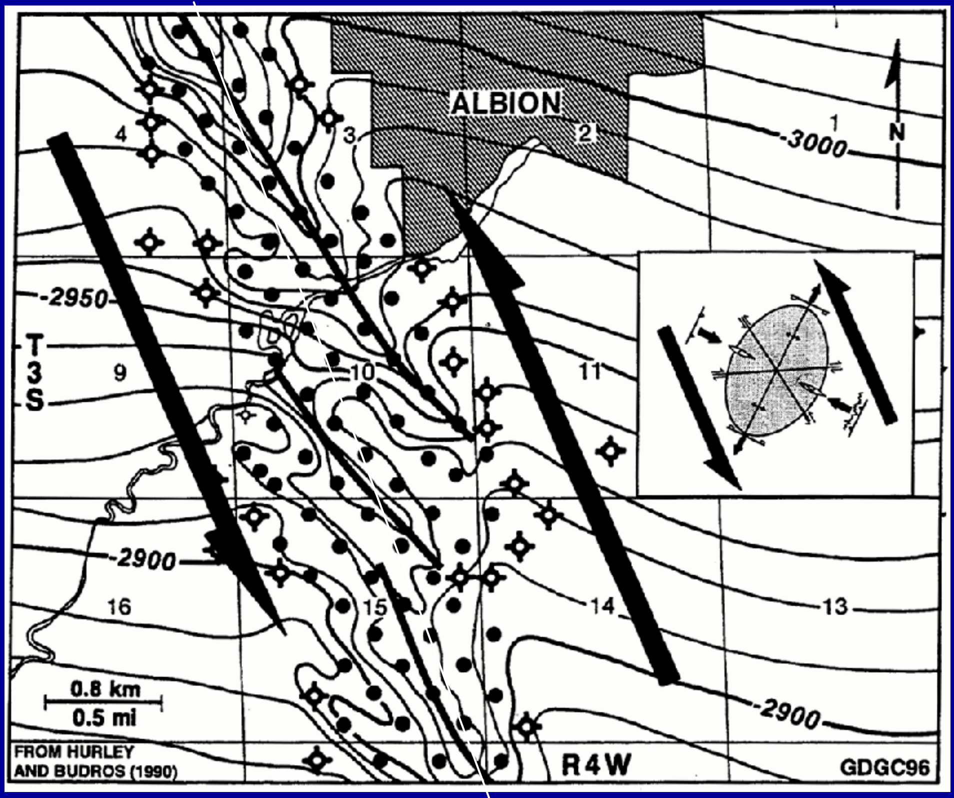
Idea #1 pull-aparts between larger scale strike-slip faults

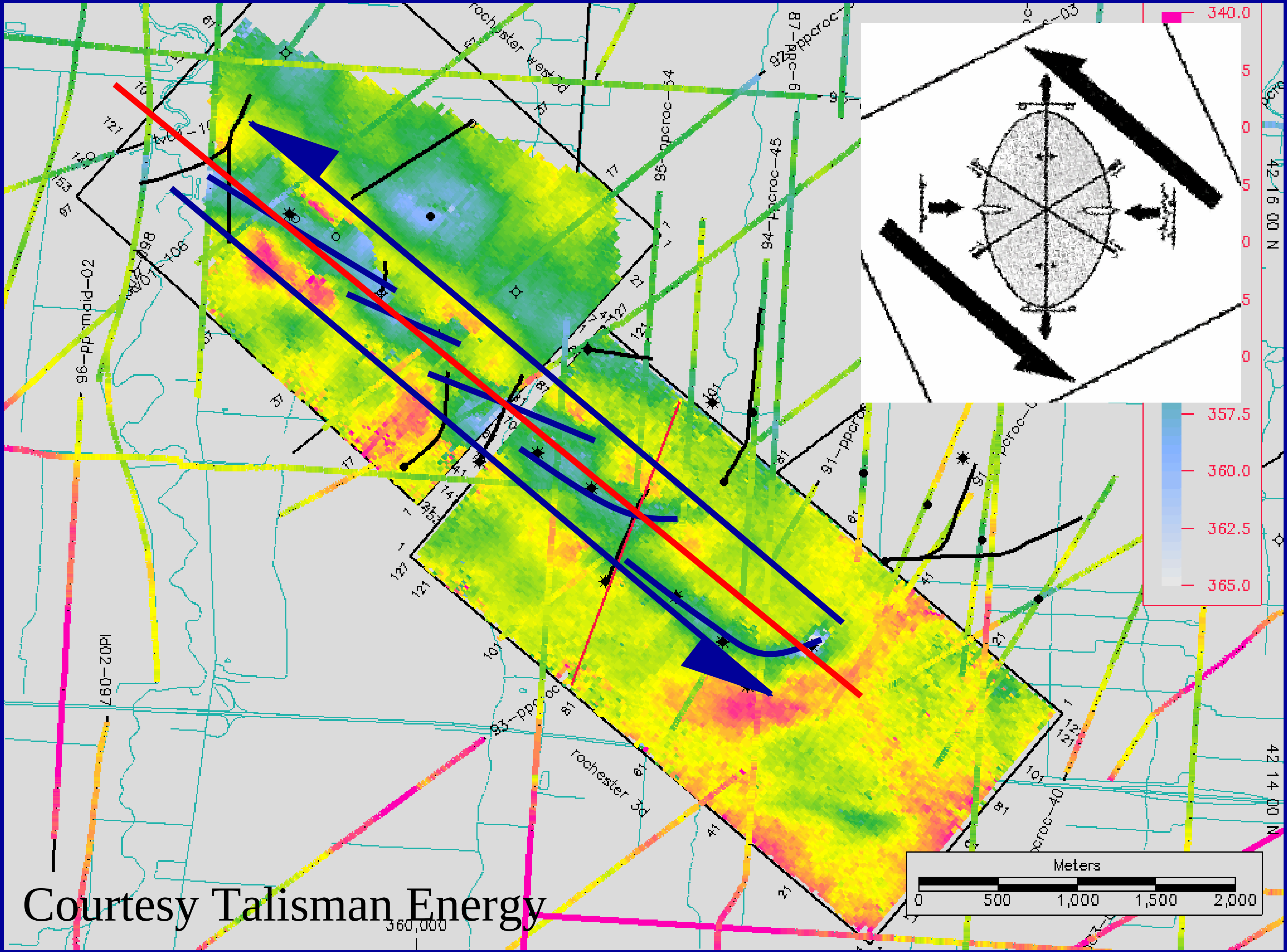


Idea #2, most fields overlie strike-slip or transtensional faults, some left-lateral, some right lateral



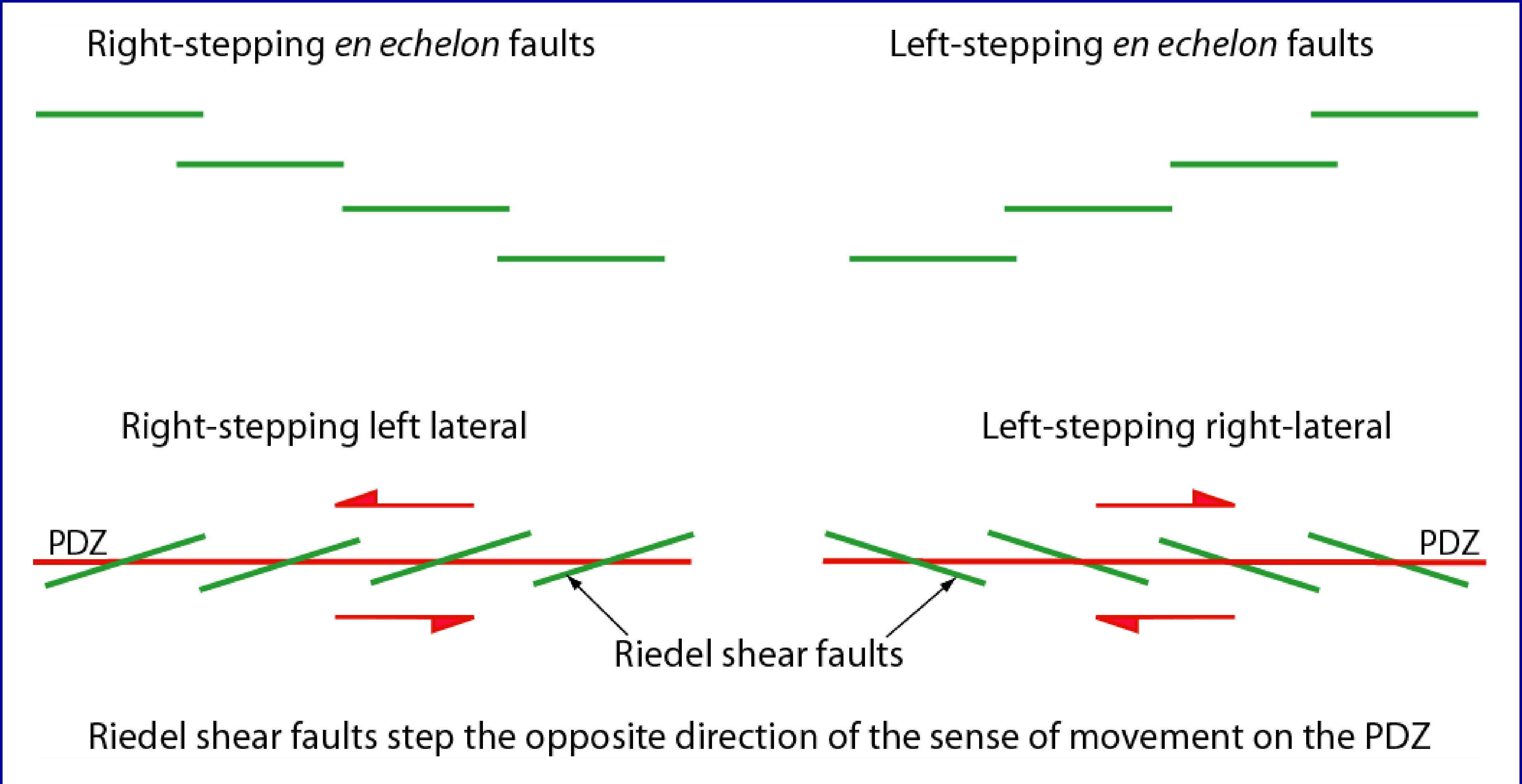
• Hurley and Budros, 1990 did detailed mapping of synclines and found en echelon pattern that they interpreted to have been formed by Reidel Shears



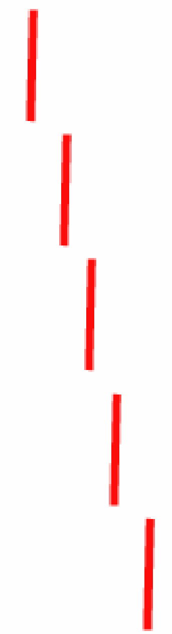


Smith Interpretation, March 2005: *en echelon* Reidel Shears overlying straight left-lateral strike slip fault – this is not entirely right

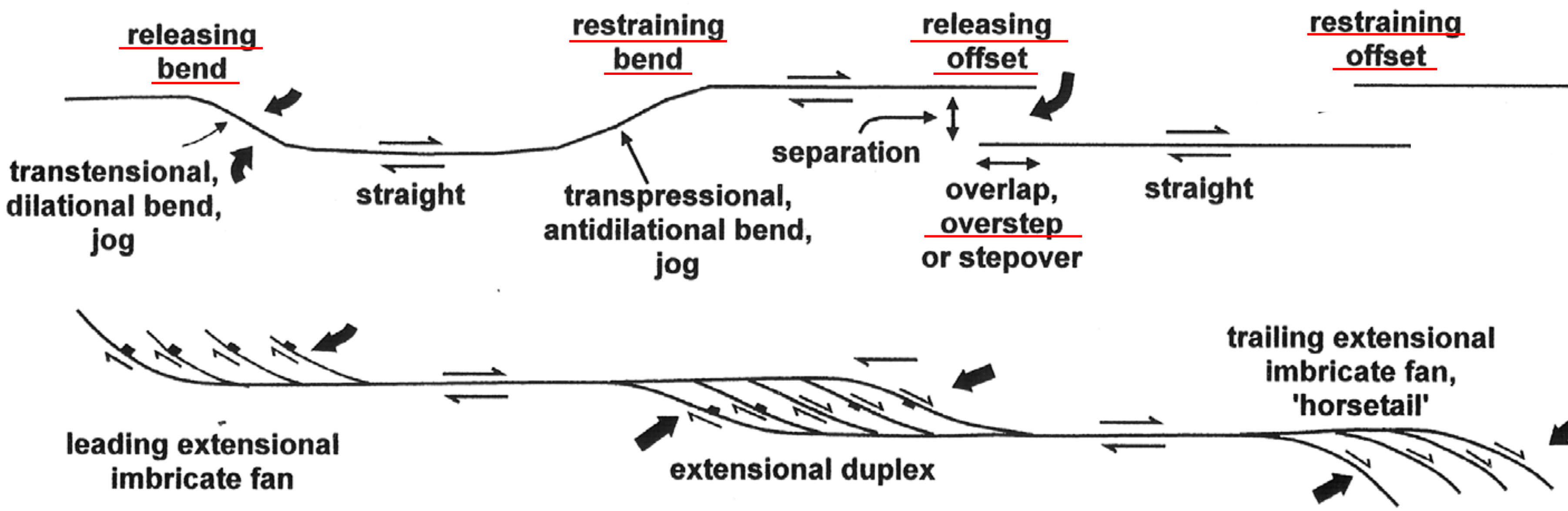
Simple Structures of Strike-Slip Faults



PDZ (principal displacement zone or the trend of the master strike slip faults)

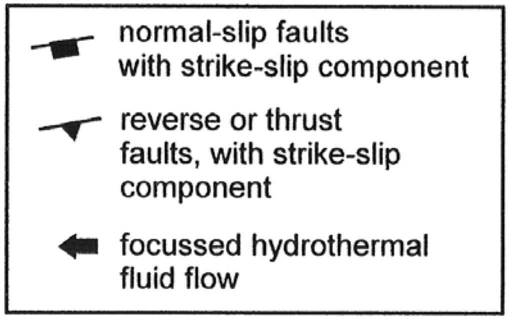


LEFT STEPPING



Pull-apart basins form at releasing oversteps or bends

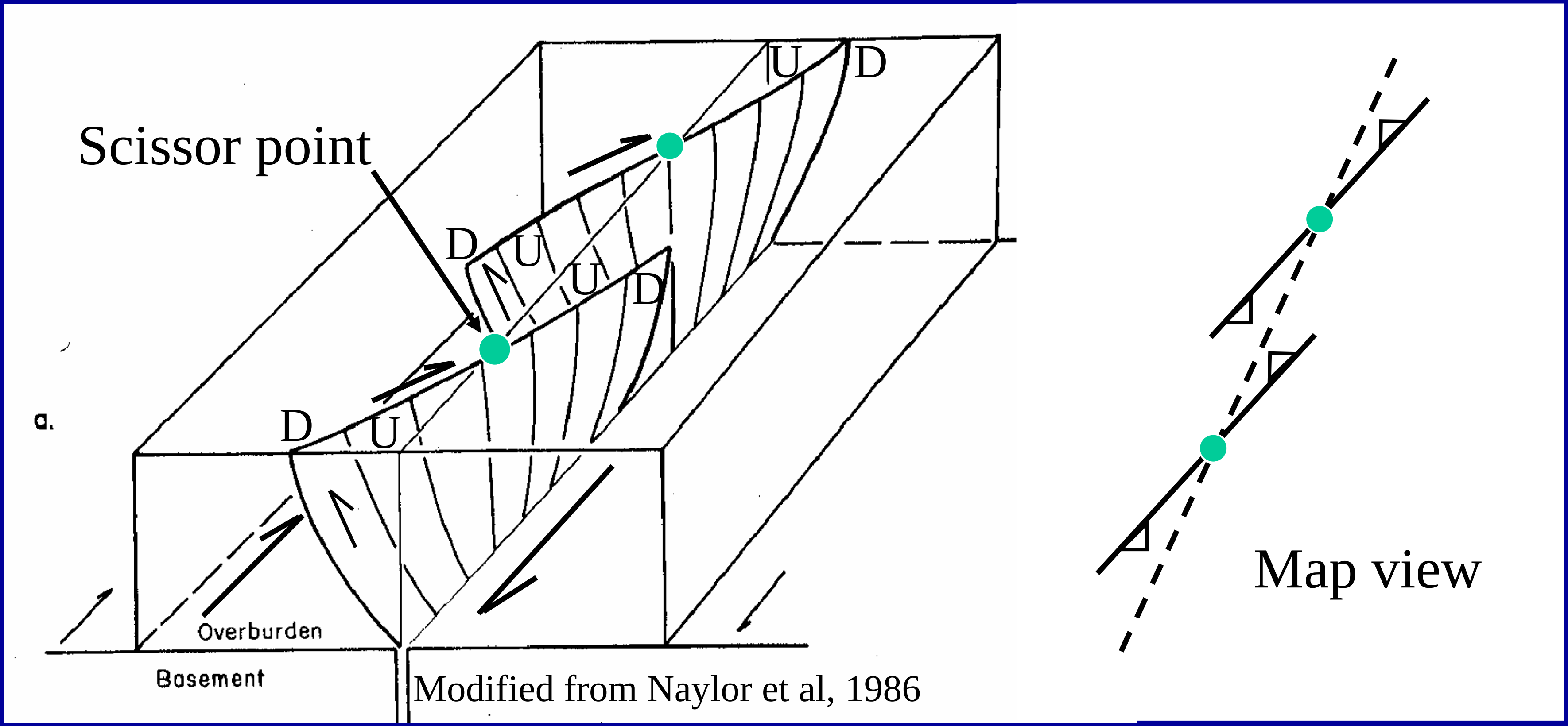
Horestails form at fault tips



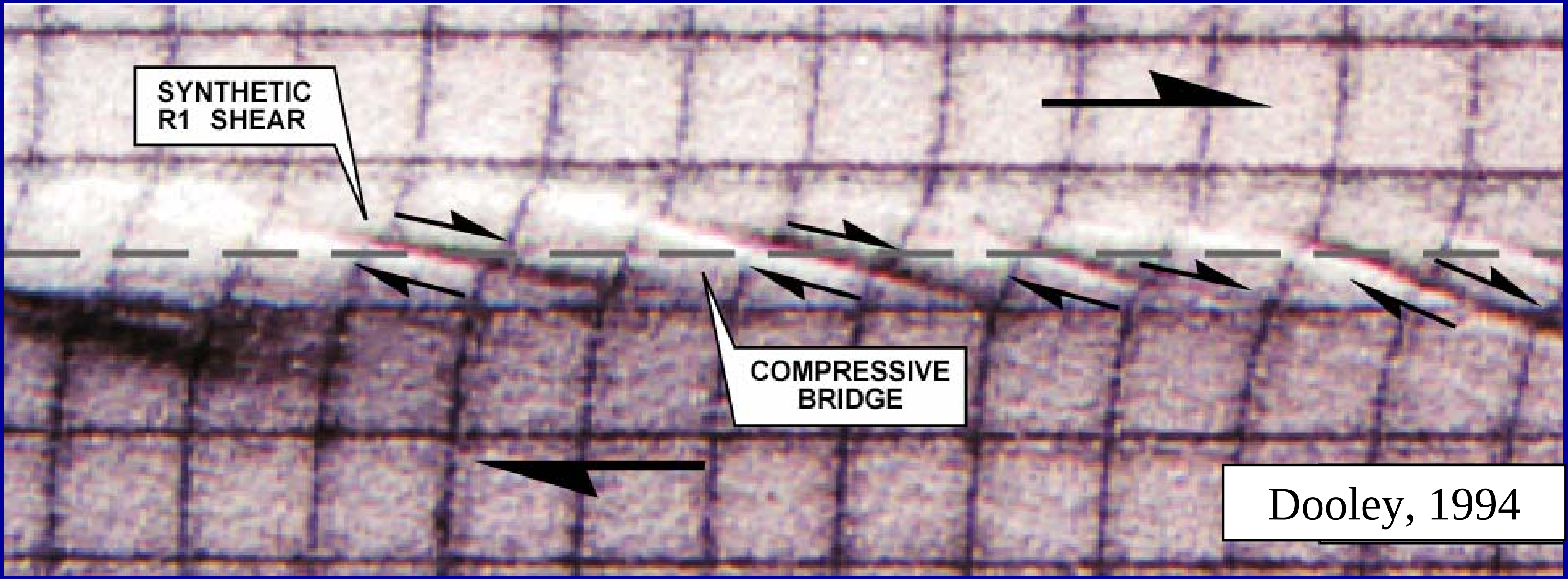
Some common terms for wrench faults – note that hydrothermal fluid flow is focused in transtensional features (modified from Woodcock and Fisher, 1988 by Davies, 2001)

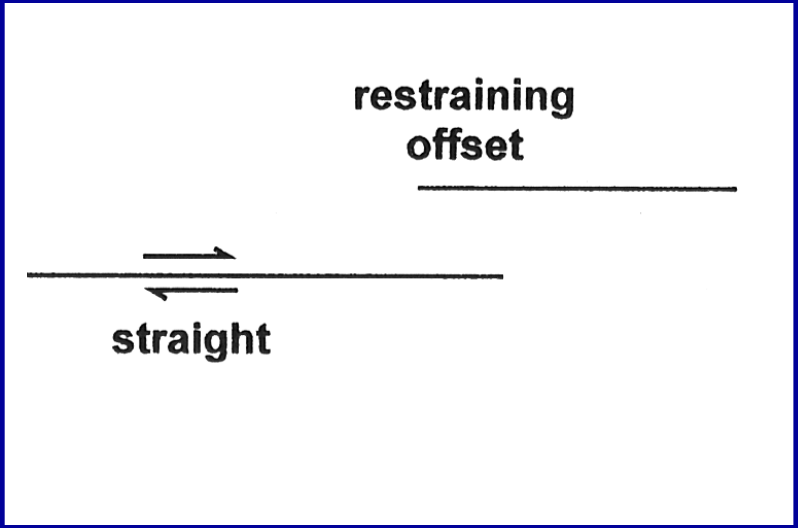
Riedel shears - *en echelon* synthetic fault segments that form at ~17° to the principal displacement zone, and characteristically step in the opposite direction to the imposed strike-slip motion.

Each shear is a scissor fault: the dip and sense of movement reverse at its scissor point (where it crosses the plane of the master fault).



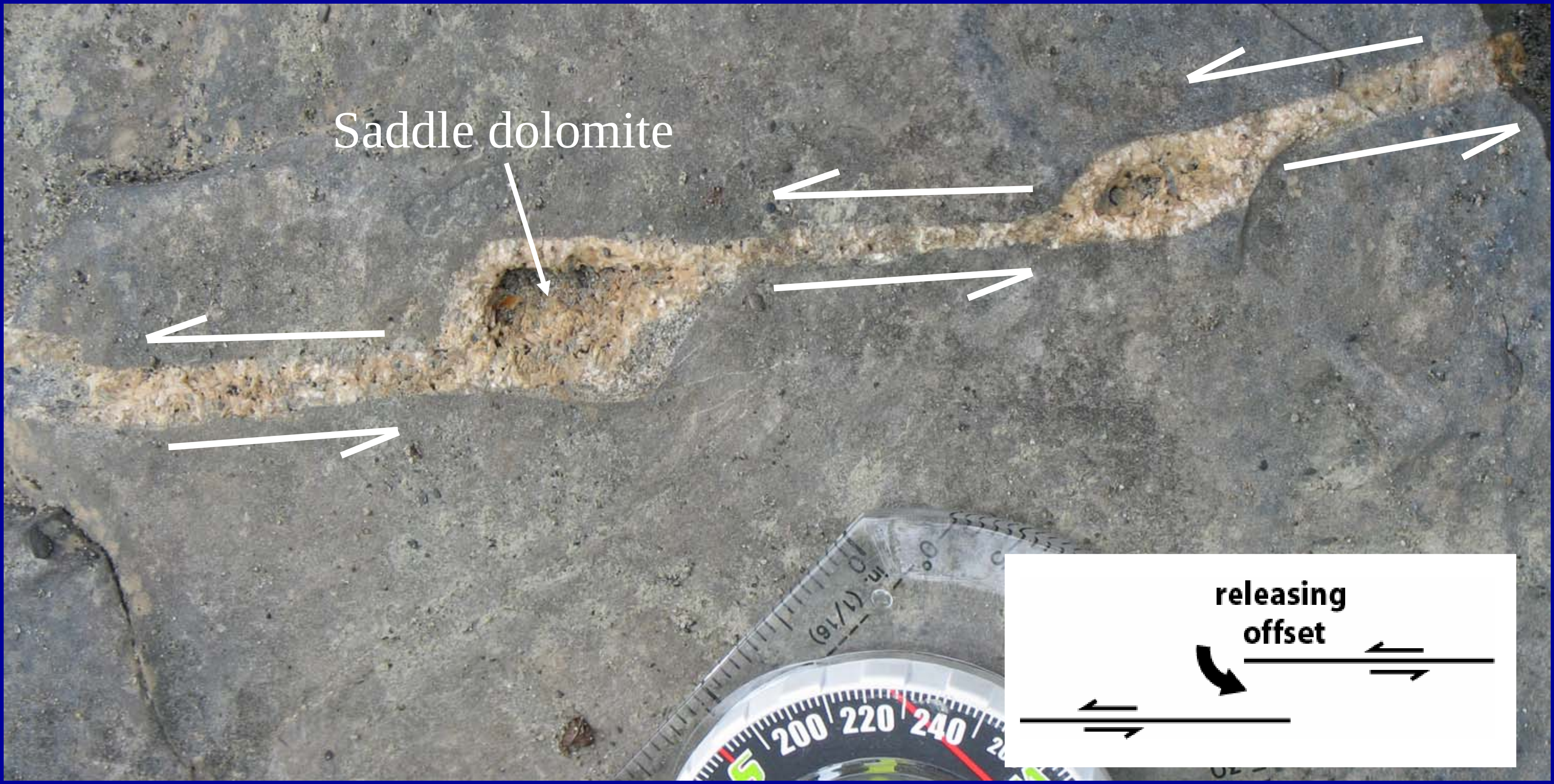
Modified from Naylor et al, 1986



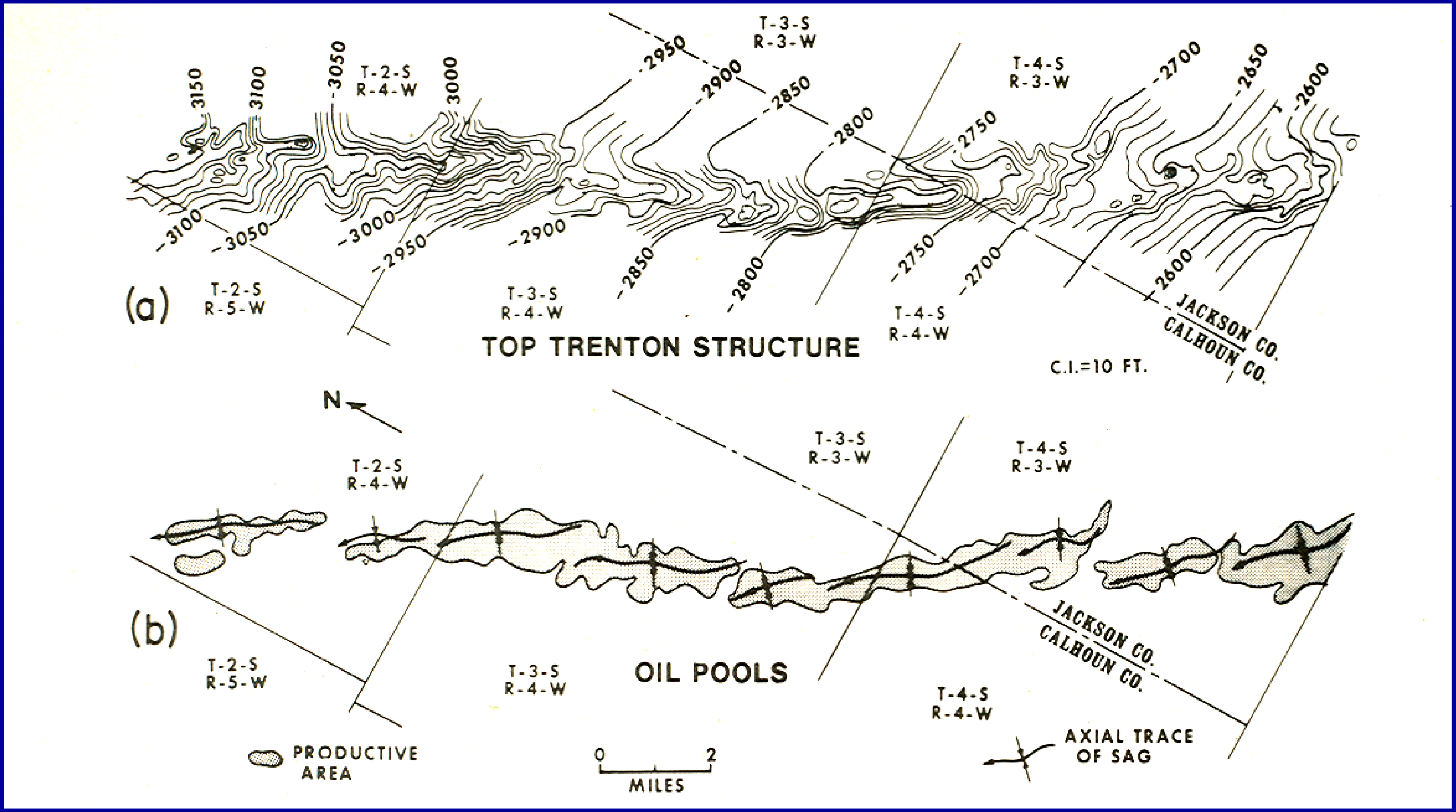


Zones between Riedel shear faults are restraining offsets where “pop-ups” or compressive bridges form

This is not a scenario that would produce a sag or be conducive to hydrothermal fluid flow

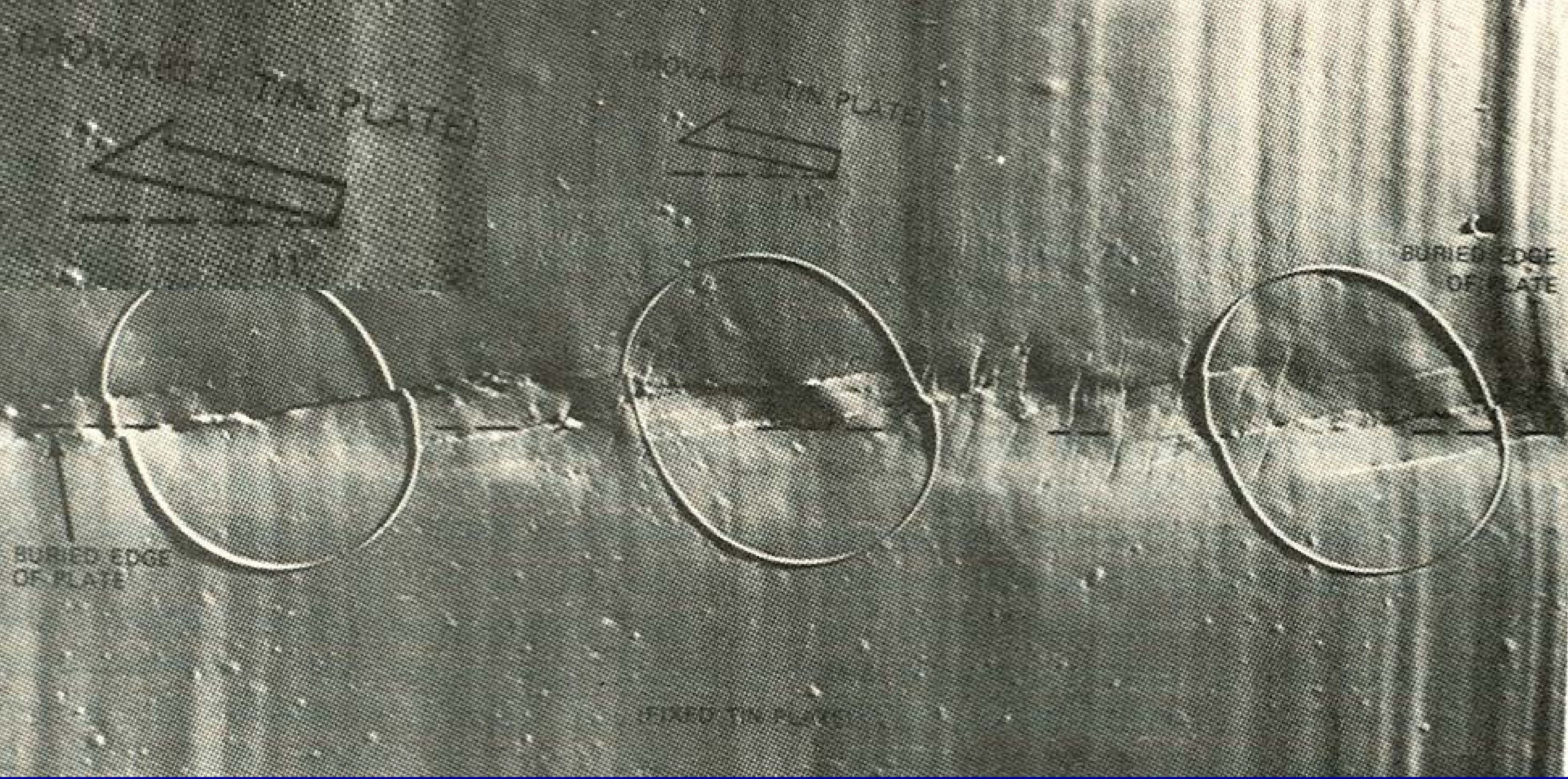


En echelon faults with "pull-aparts" in the overstep – left-stepping, left-lateral – the opposite of Riedel Shears – hydrothermal fluid flow, mineralization (saddle dolomite) and porosity development is focused in these transtensional features



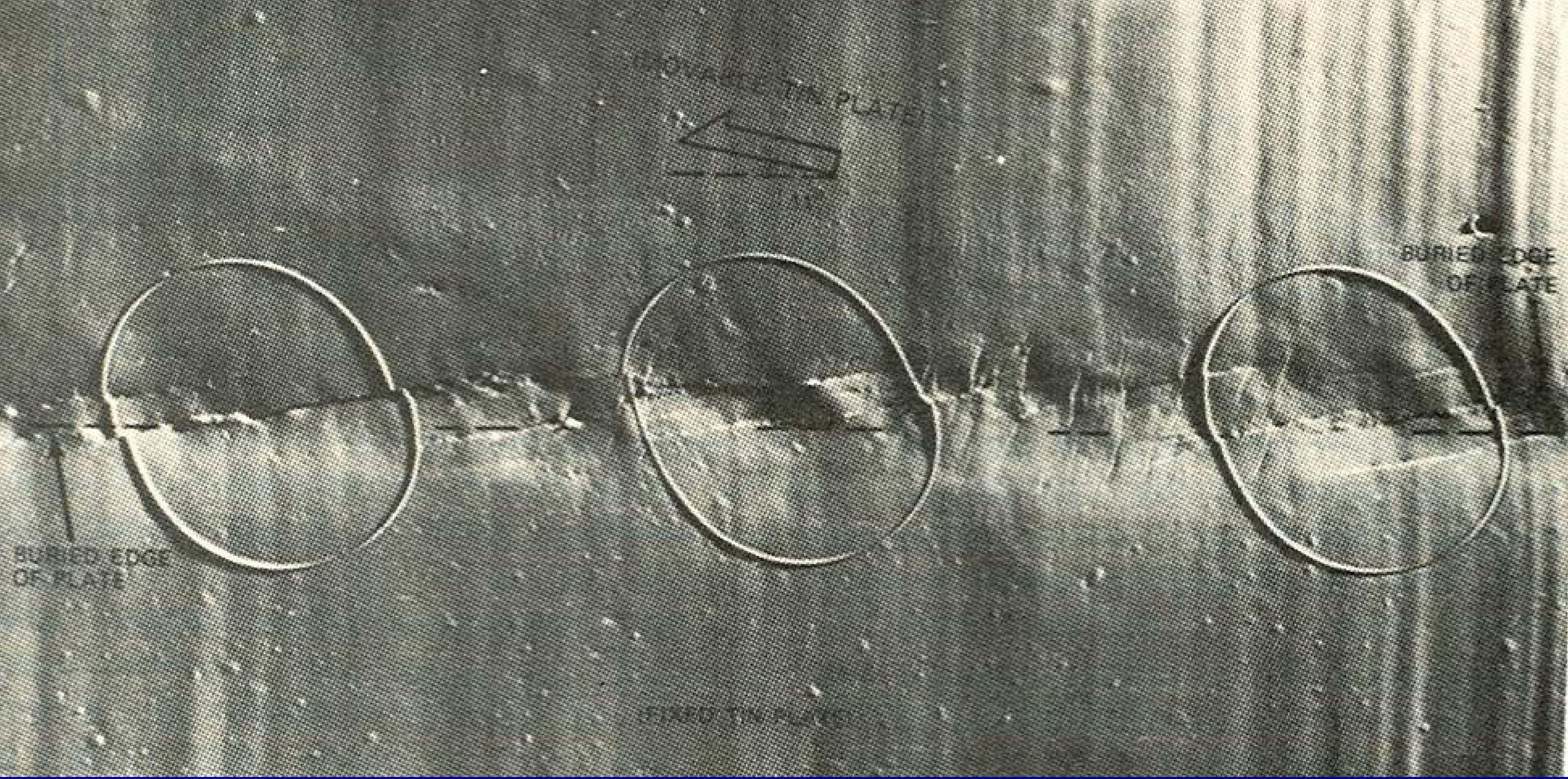
Harding, 1974 – Mapped *en echelon* sags in "Scipio-Albion" Field, noted that they trended at less than 17º to trend of underlying fault

Note that they are right-stepping, fault interpreted to be left-lateral



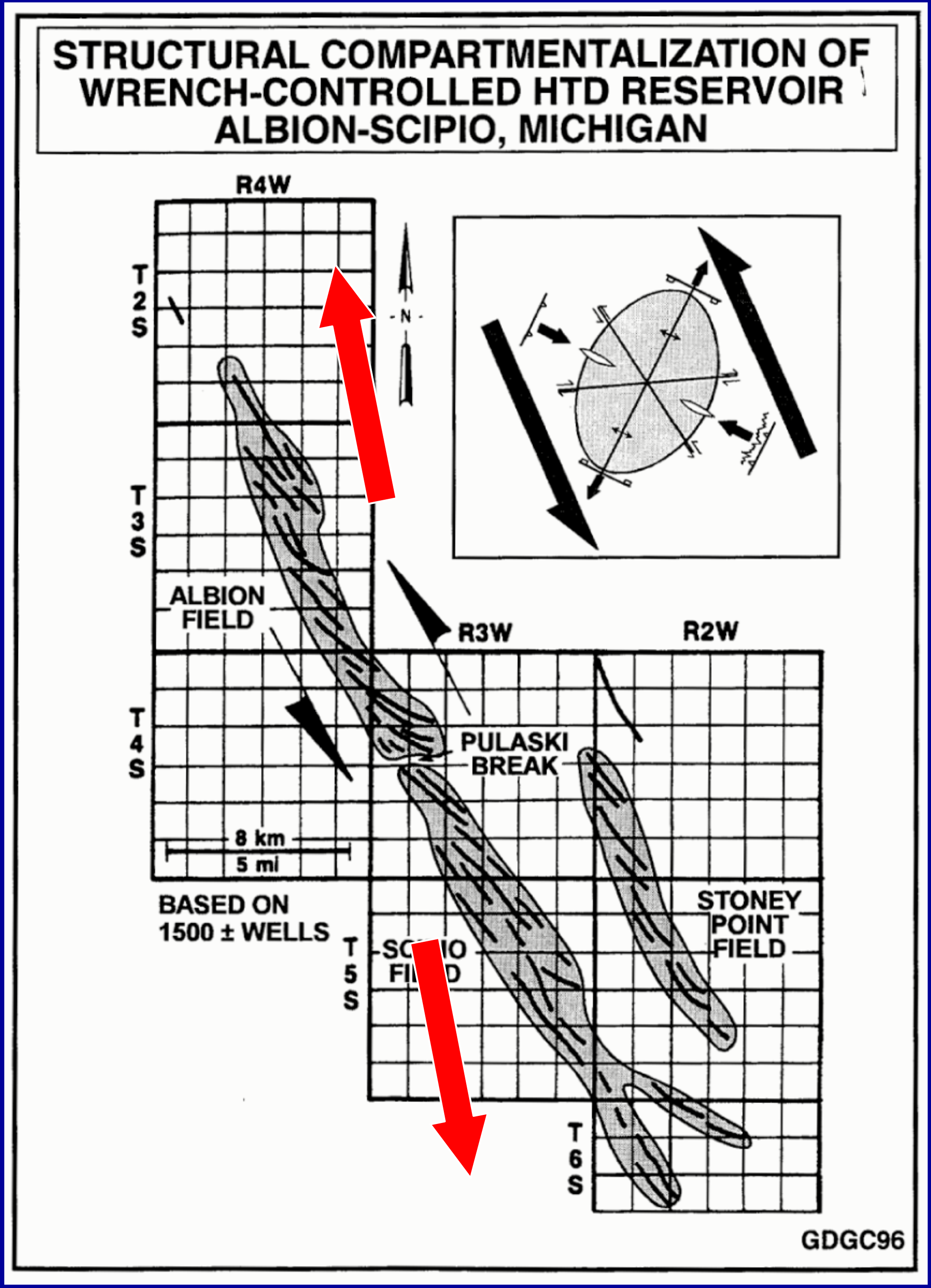
Harding, 1974 – In order to produce the sags found at Albion Scipio, Harding added a component of extension to the fault movement or “oblique divergent slip” at 11º to trend of fault

“Oblique divergent component would have emphasized the extensional effects of the mild deformation and would have tended to open the synthetic fractures, facilitating dolomitization”



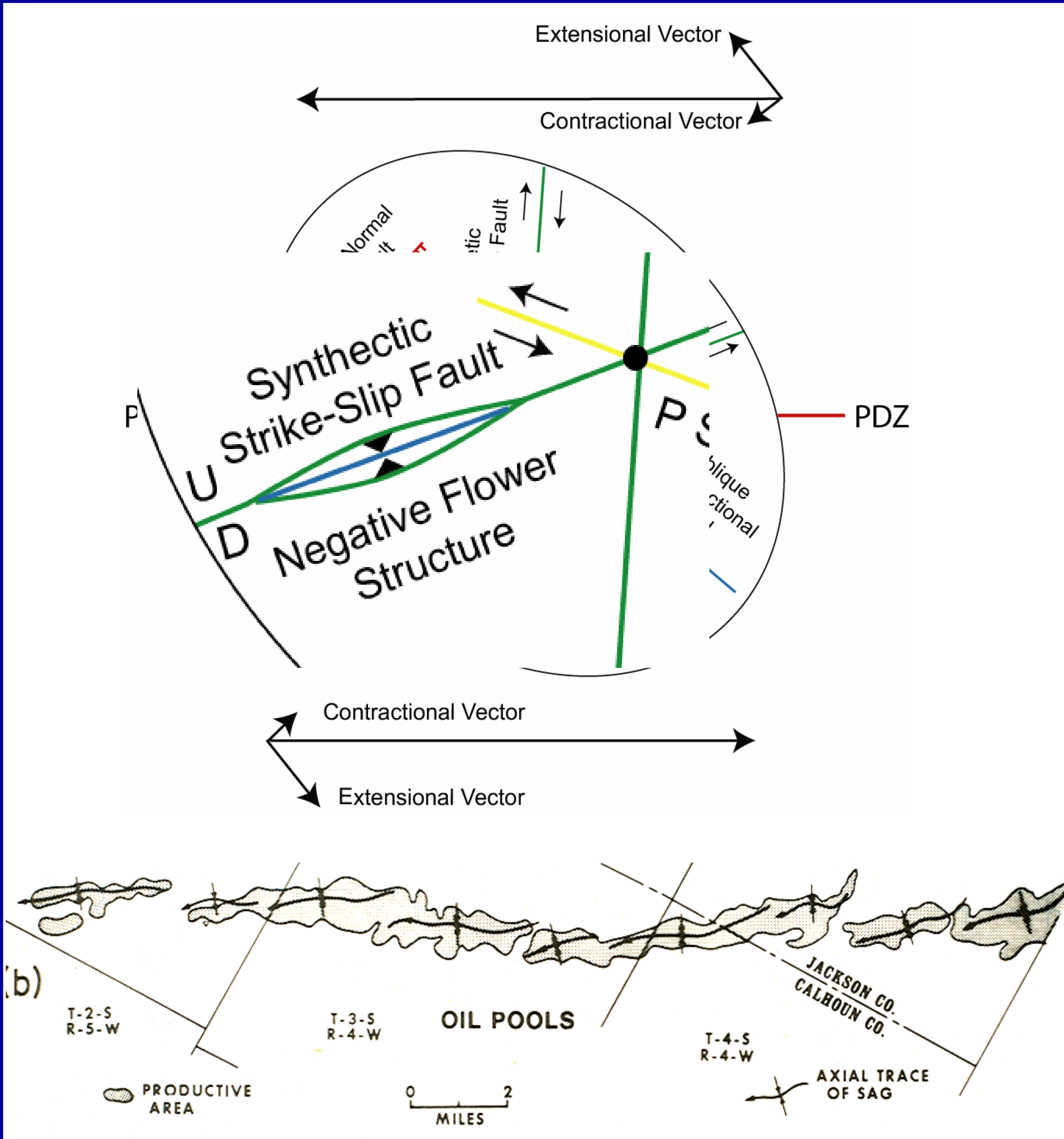
This type of faulting would occur when there was a pre-existing basement fault that was reactivated in an oblique divergent sense

Riedels form at ~5-10º to fault trend



Based on Harding's work, the plate motion at Albion Scipio would have need to be rotated by ~11° toward N-S relative to the trend of the field

This would give the extensional vector as well as the left-lateral strike slip needed to produce the linked *en echelon* grabens

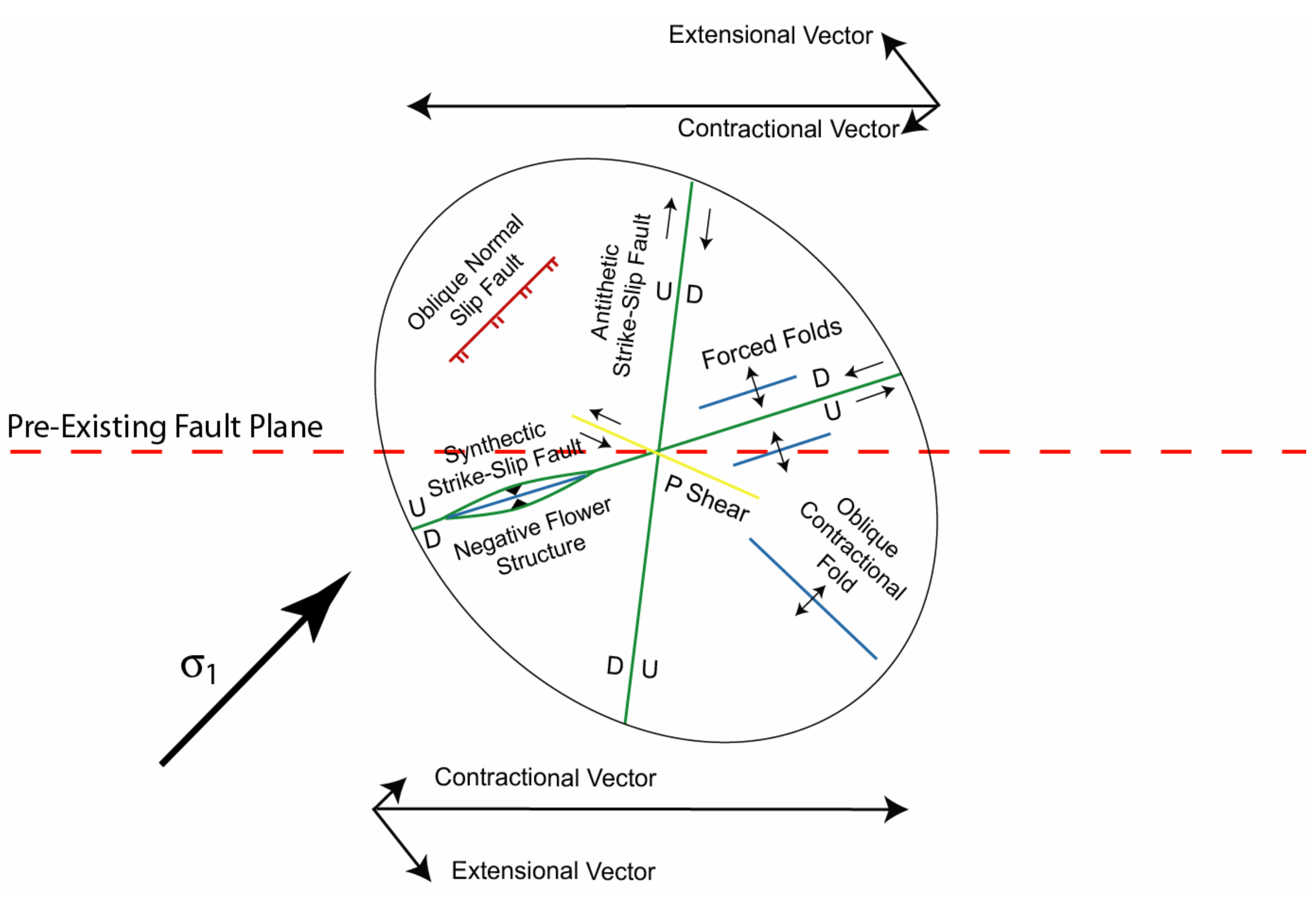


Harding (1985) later implied that each synthetic (Riedel) shear fault may produce its own negative flower structure

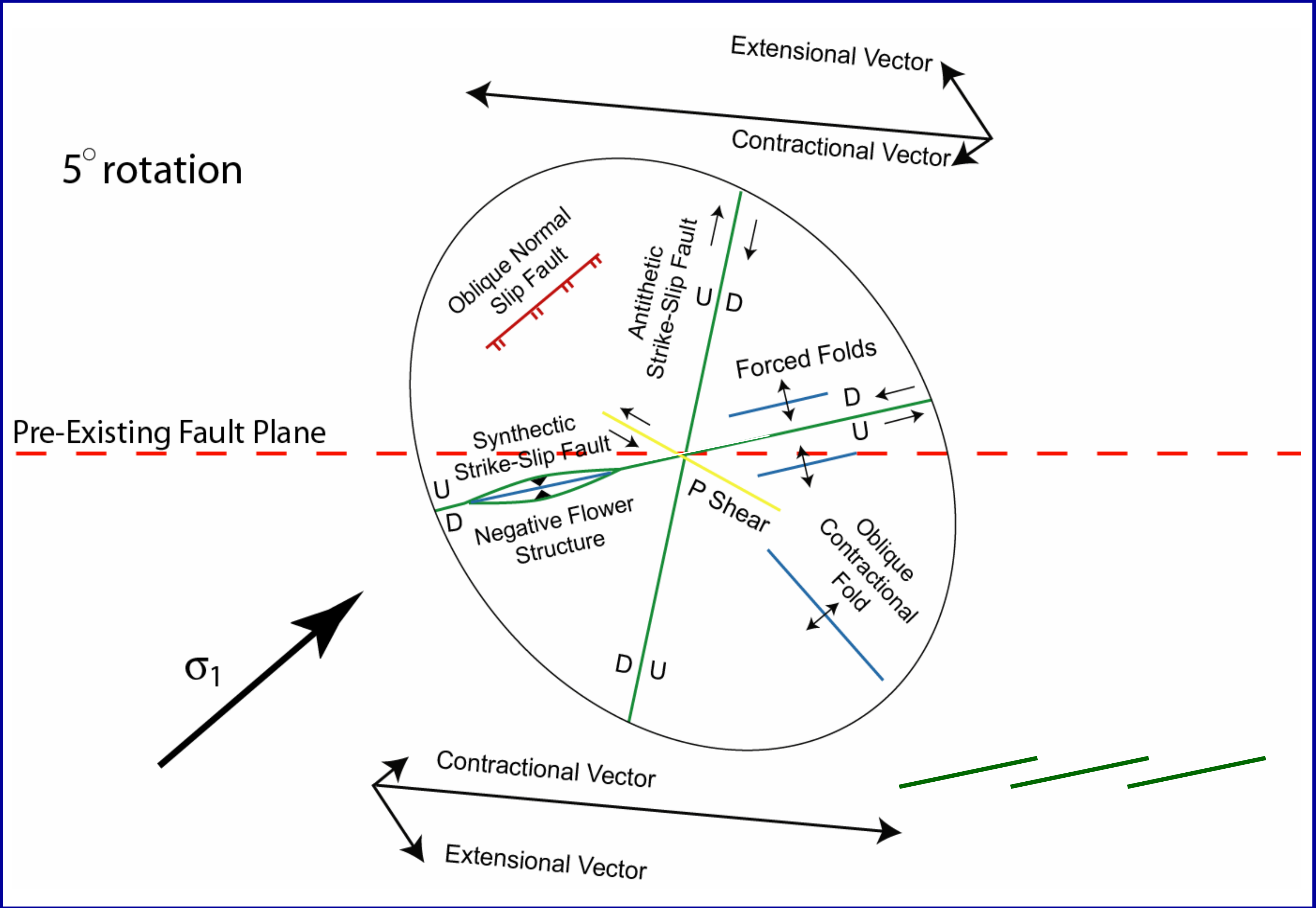
So the fields are composed not of a single negative flower structure but multiple *en echelon* negative flower structures – this is accentuated in an oblique divergent slip setting

Oblique Divergent Slip

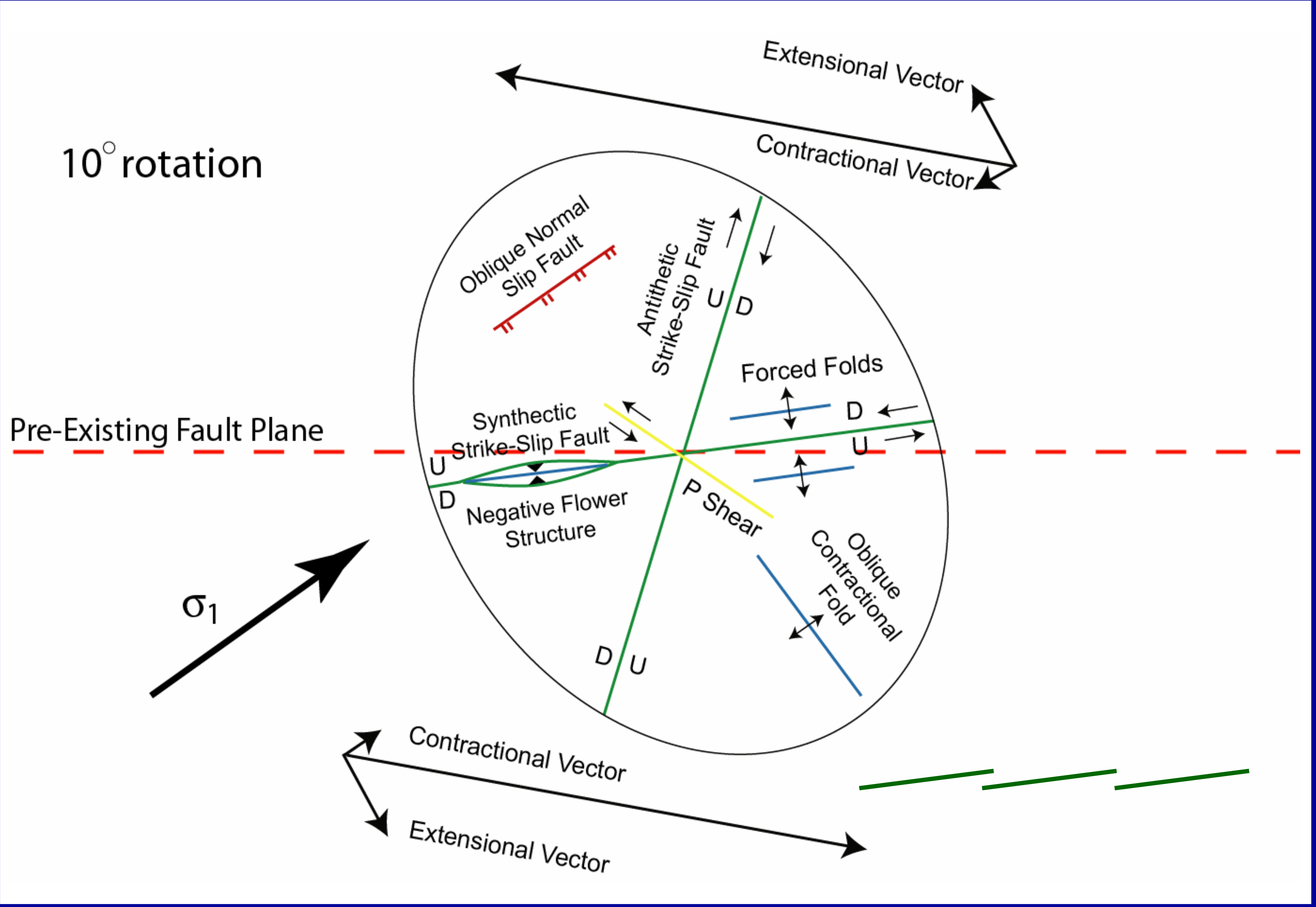
- In order to produce the sags found in the TBR reservoirs, there *must* be a component of extension as well as strike-slip
- This extension would also provide a conduit for upward flowing hydrothermal fluids
- The degree of rotation from pure strike-slip movement will control the angle of the synthetic (Riedel) shear faults, the subsidence patterns and porosity distribution within the sags
- The next few slides are ***hypothetical*** and will be tested with modeling



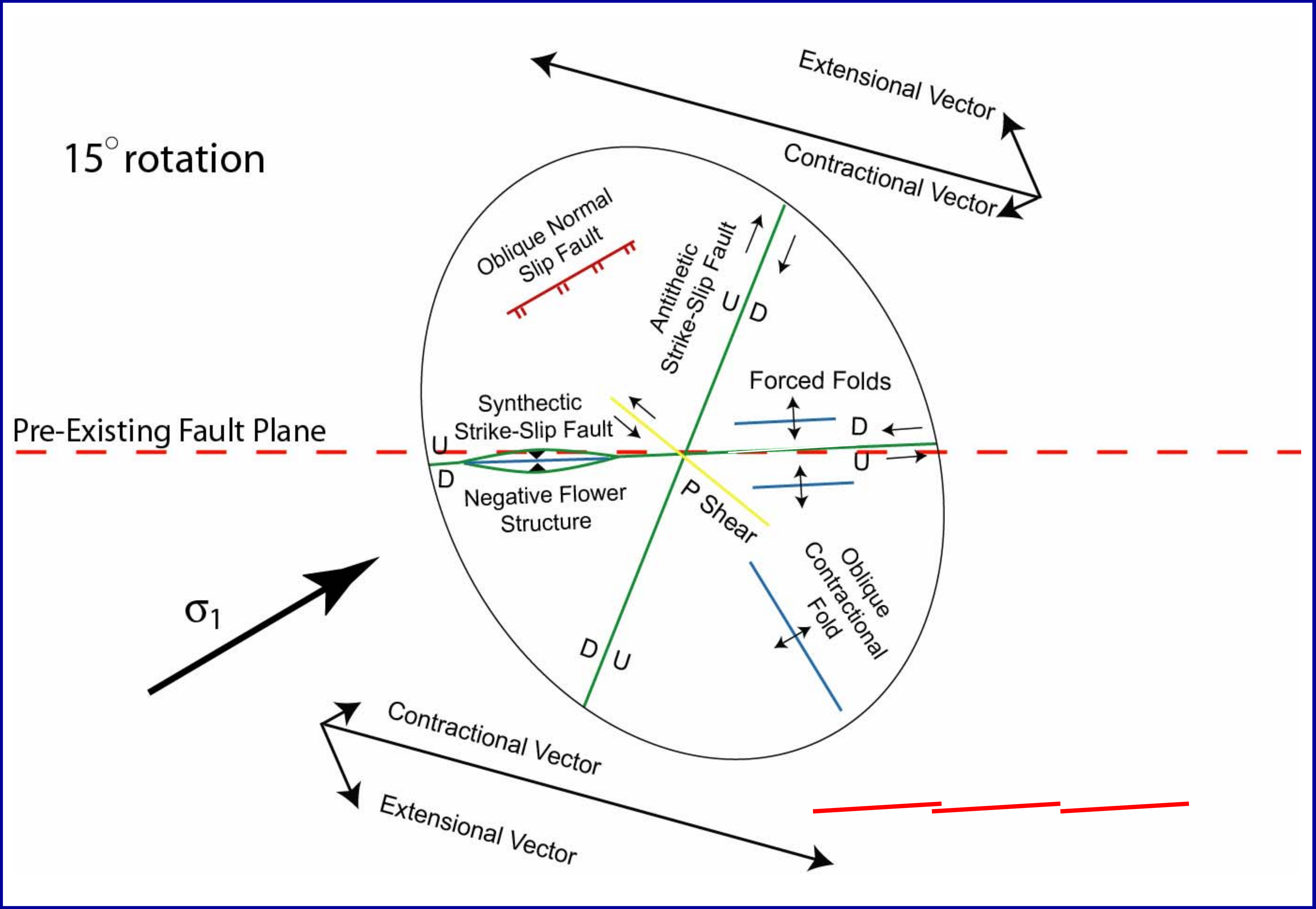
Strain ellipsoid from Harding et al., 1985



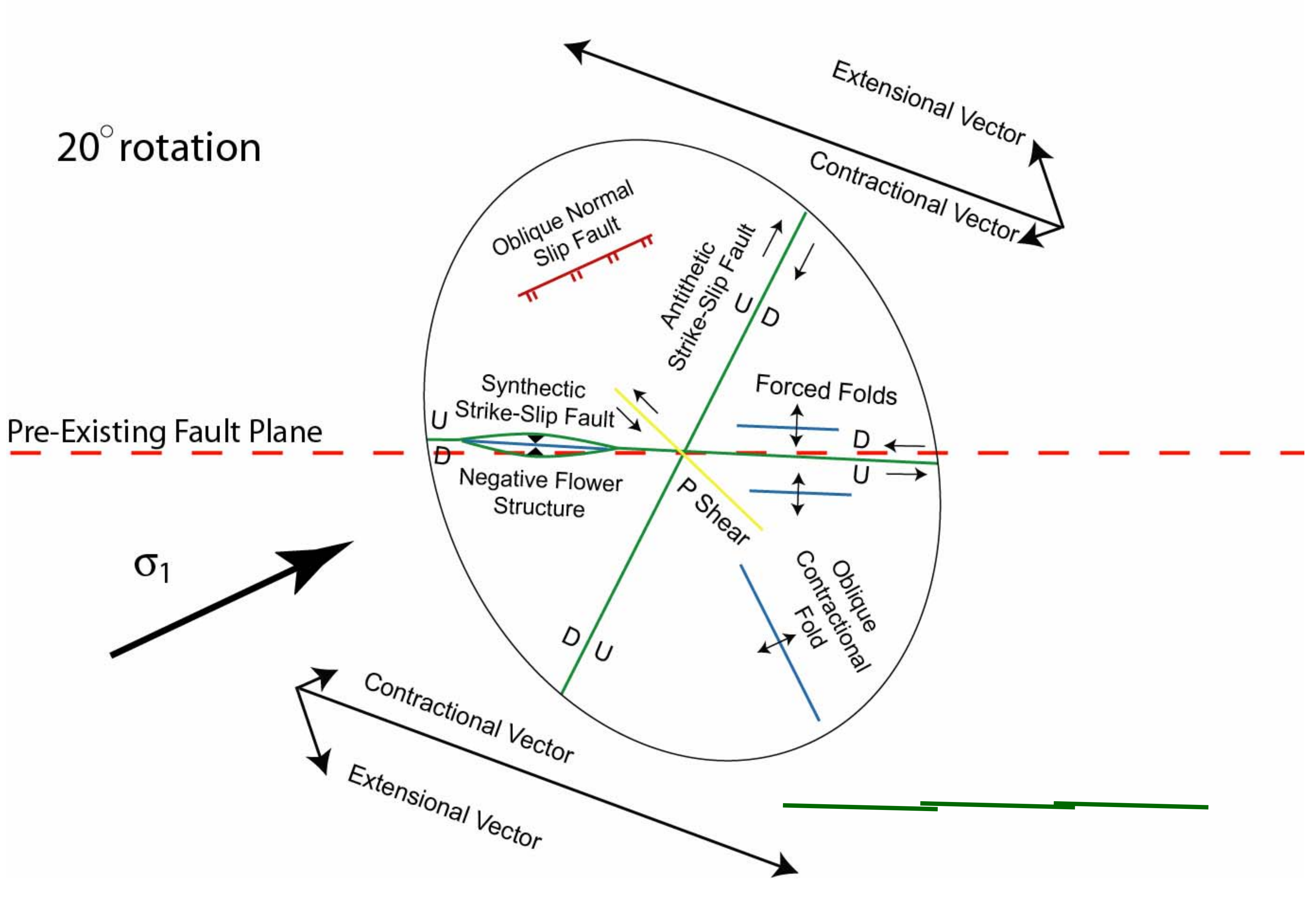
With rotation toward more divergent slip, angle of synthetics to PDZ decreases, extension on PDZ and synthetics increases



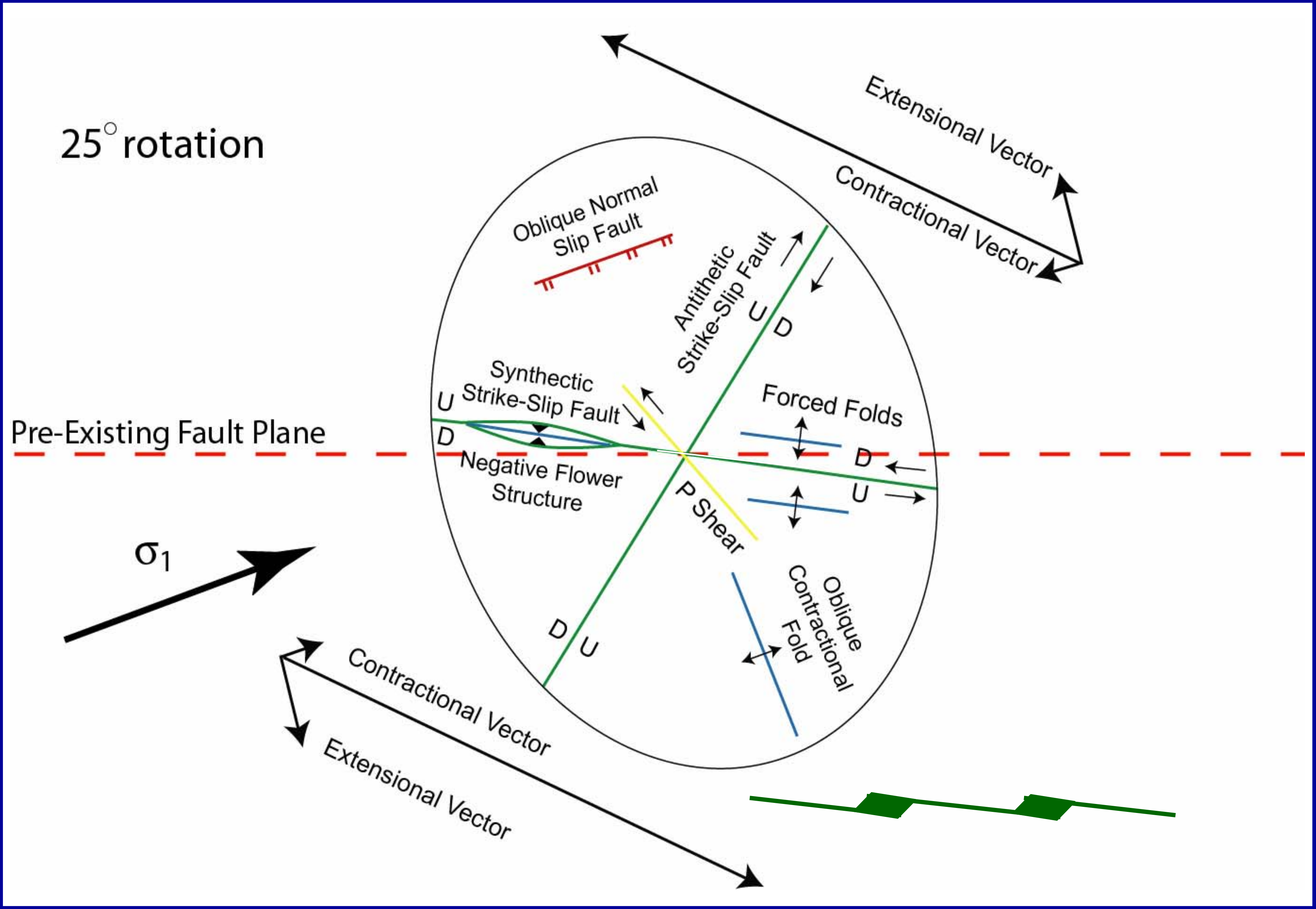
Still right-stepping left-lateral



Almost no step on en echelon synthetic faults as we approach 17º



Very minor left-stepping, left lateral



Left-stepping left lateral – pull aparts will form in stepovers

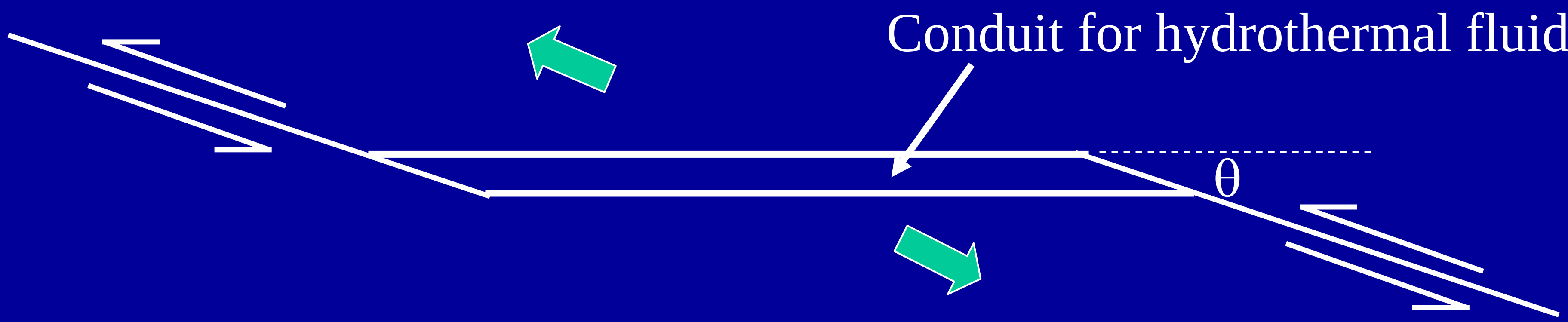
Sandbox Modeling

- We plan to take these hypothetical concepts and model them using clay or sand
- We will try a range of different scenarios of oblique divergent slip by moving the underlying plates at a range of angles to the fault plane
- We will try to match real examples from 3D seismic cubes and our quarry examples

Settings for Oblique Divergent Slip

- Dilational jog or stepover in larger strike slip fault system – this could occur in either a compressional or extensional tectonic setting
- Transfer faults associated with extensional faults
- Reactivation of pre-existing isolated fault that is not part of a larger fault system – this would probably require an overall extensional tectonic setting

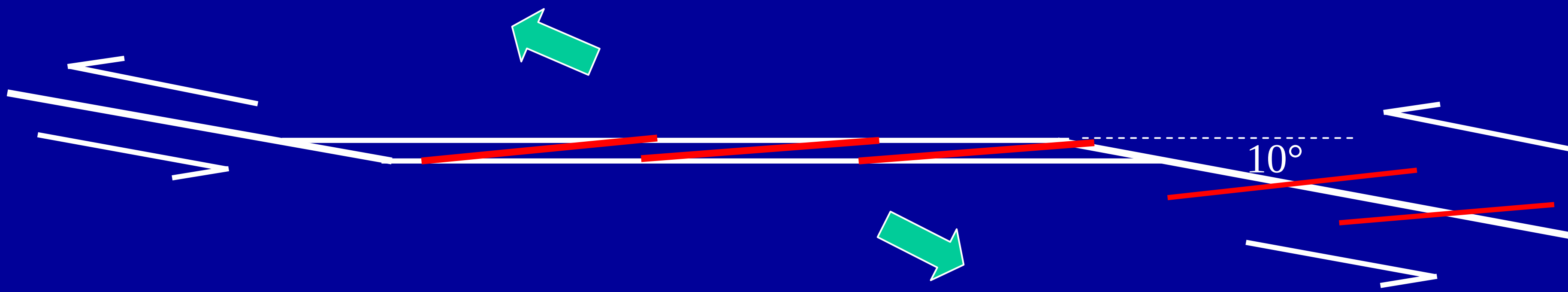
Dilational Jog



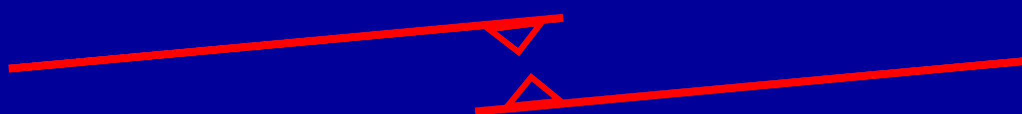
If θ <~17°, synthetic shear faults will step right, pop-ups will form in stepovers

If θ >~17°, synthetic shear faults will step left and pull aparts will form in stepovers

Dilational Jog



If θ <~17°, synthetic shear faults will step right, pop-ups or "compressive bridges" will form in stepovers



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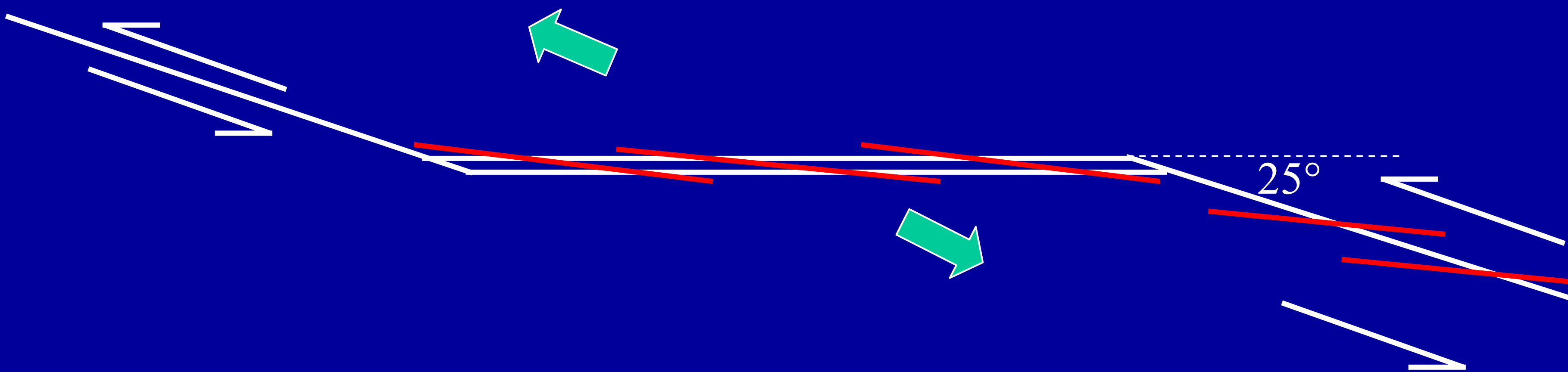
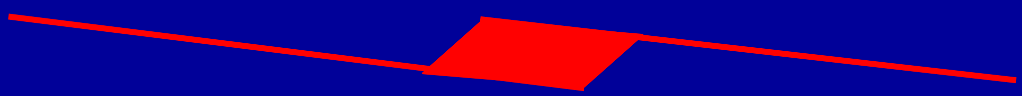
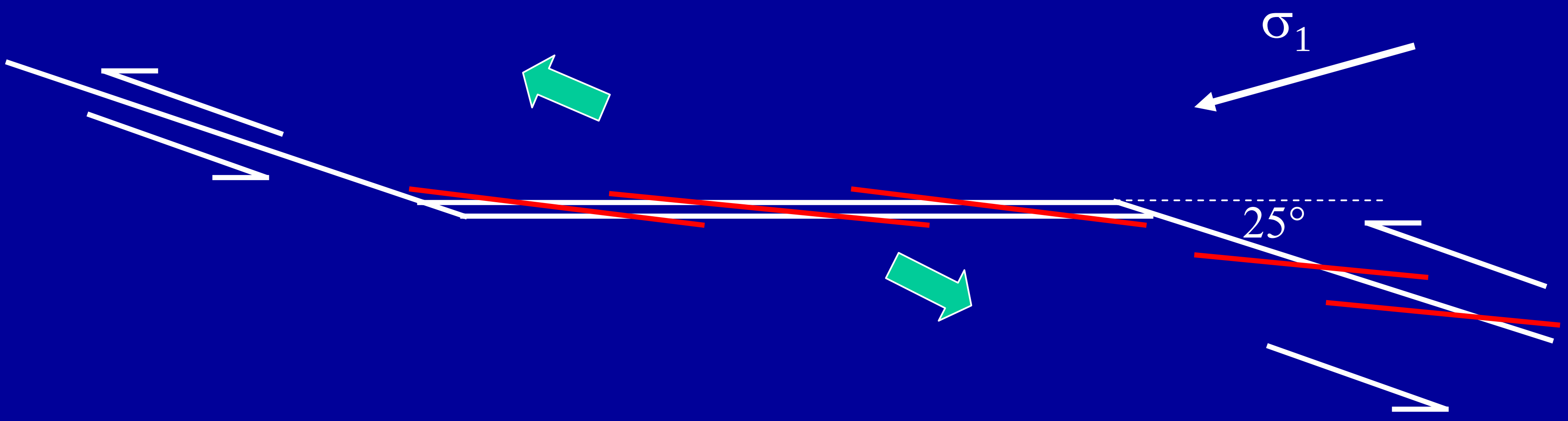


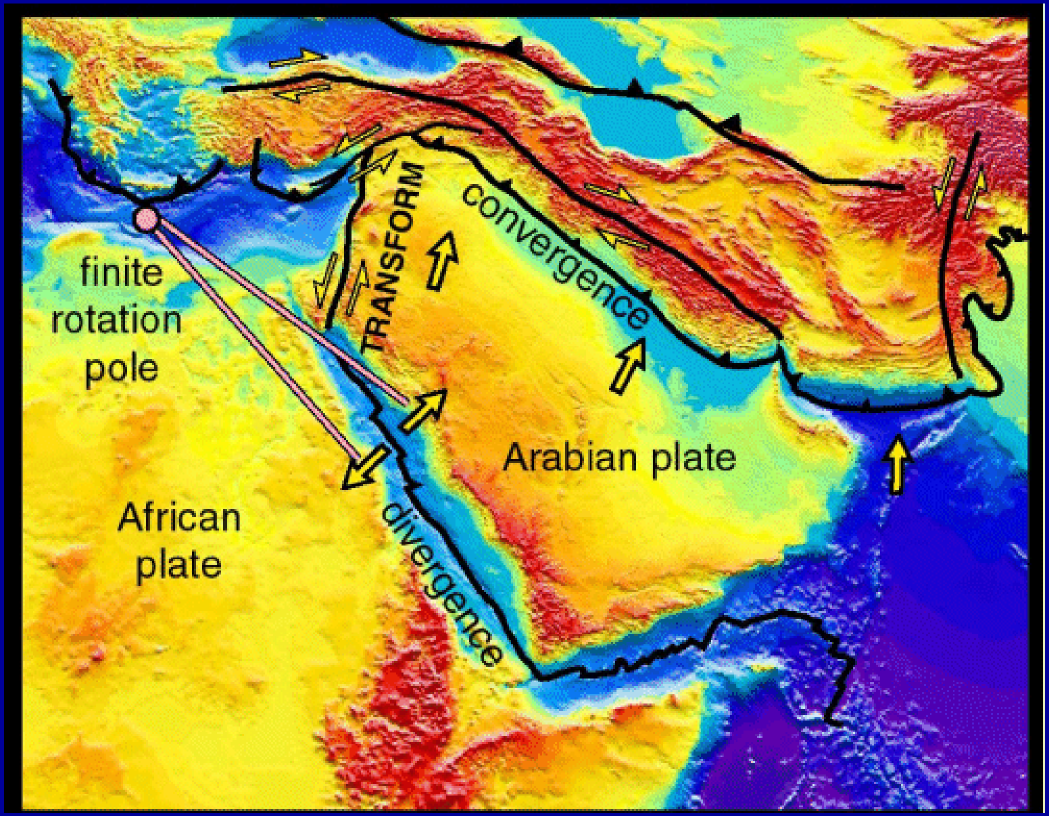
If θ >17°, synthetic shear faults will step left and pull aparts will form in stepovers

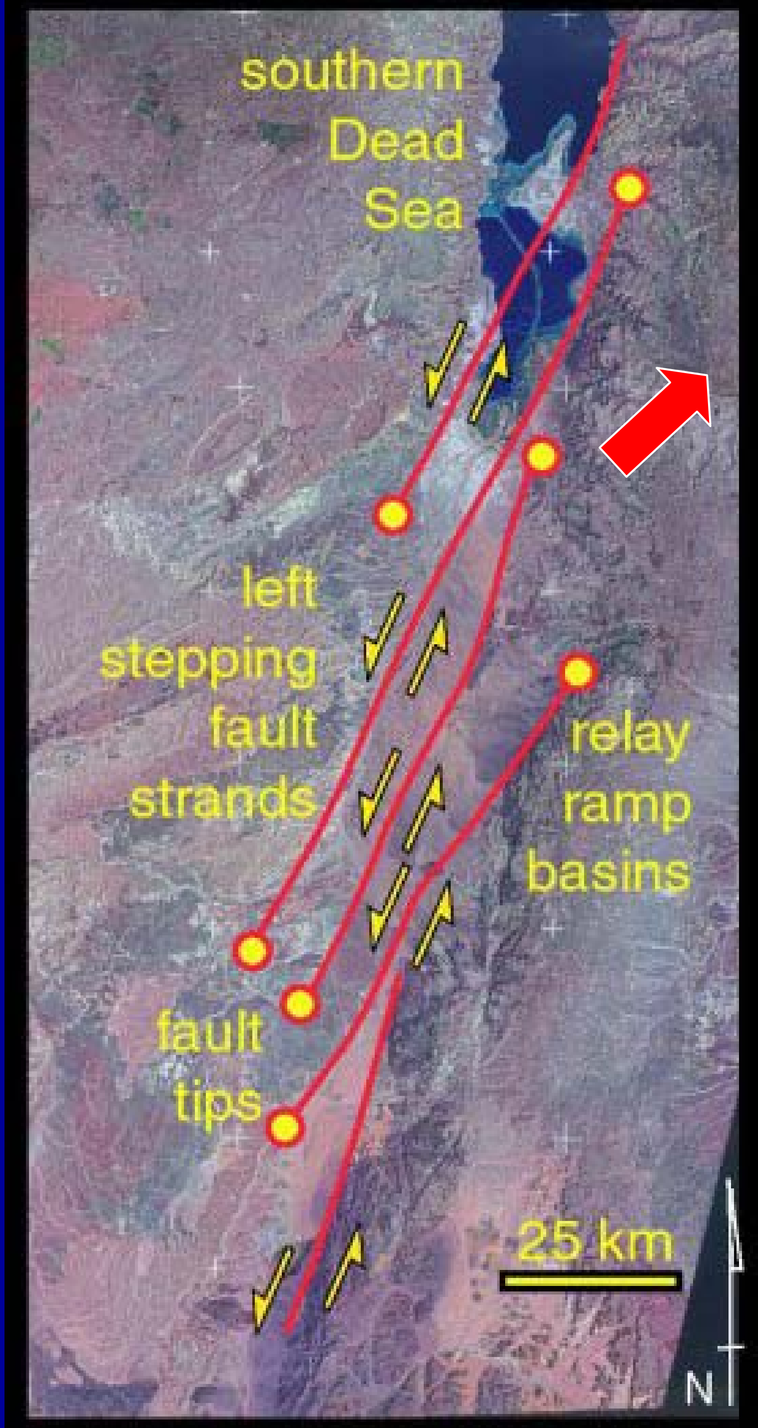


Dilational Jog



This type of faulting could occur due to compression at ~ 45° to the strike slip faults, or extension in the direction of the green arrows





Dead Sea Transform – Combination of extension and left-lateral strike slip leads to development of en echelon left-stepping left lateral scissor faults

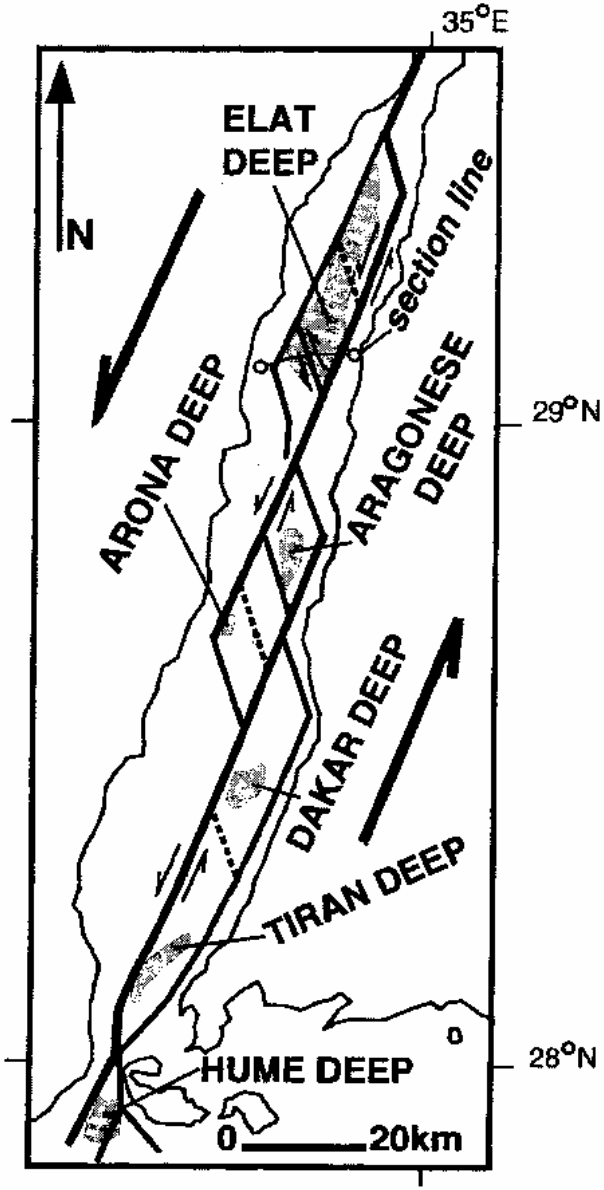
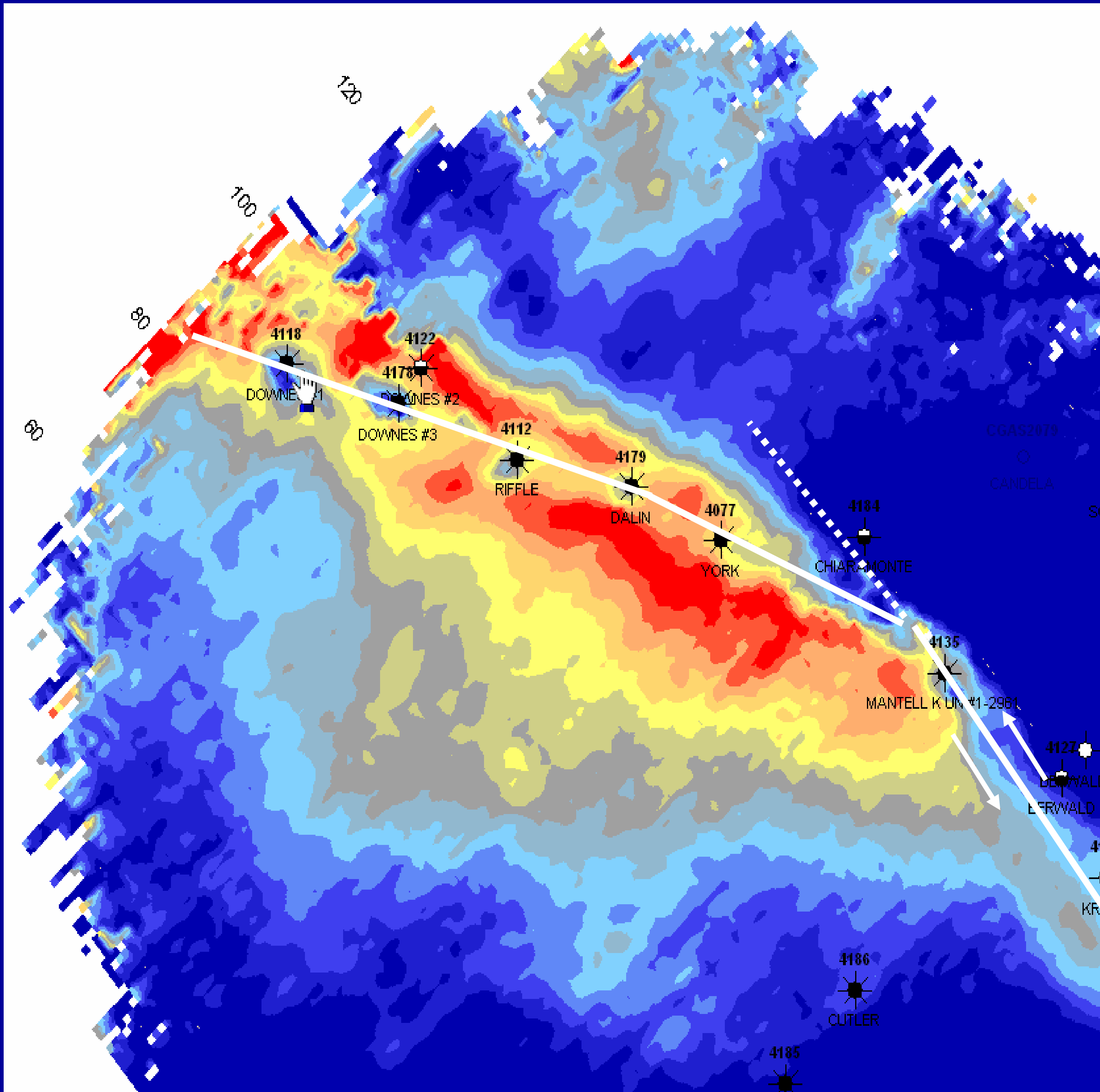


Fig. 12. Generalized structure map of the Gulf of Elat, southern Dead Sea Rift modified from Ben-Avraham and Zoback (1992). Shaded areas show bathymetric 'deeps.'

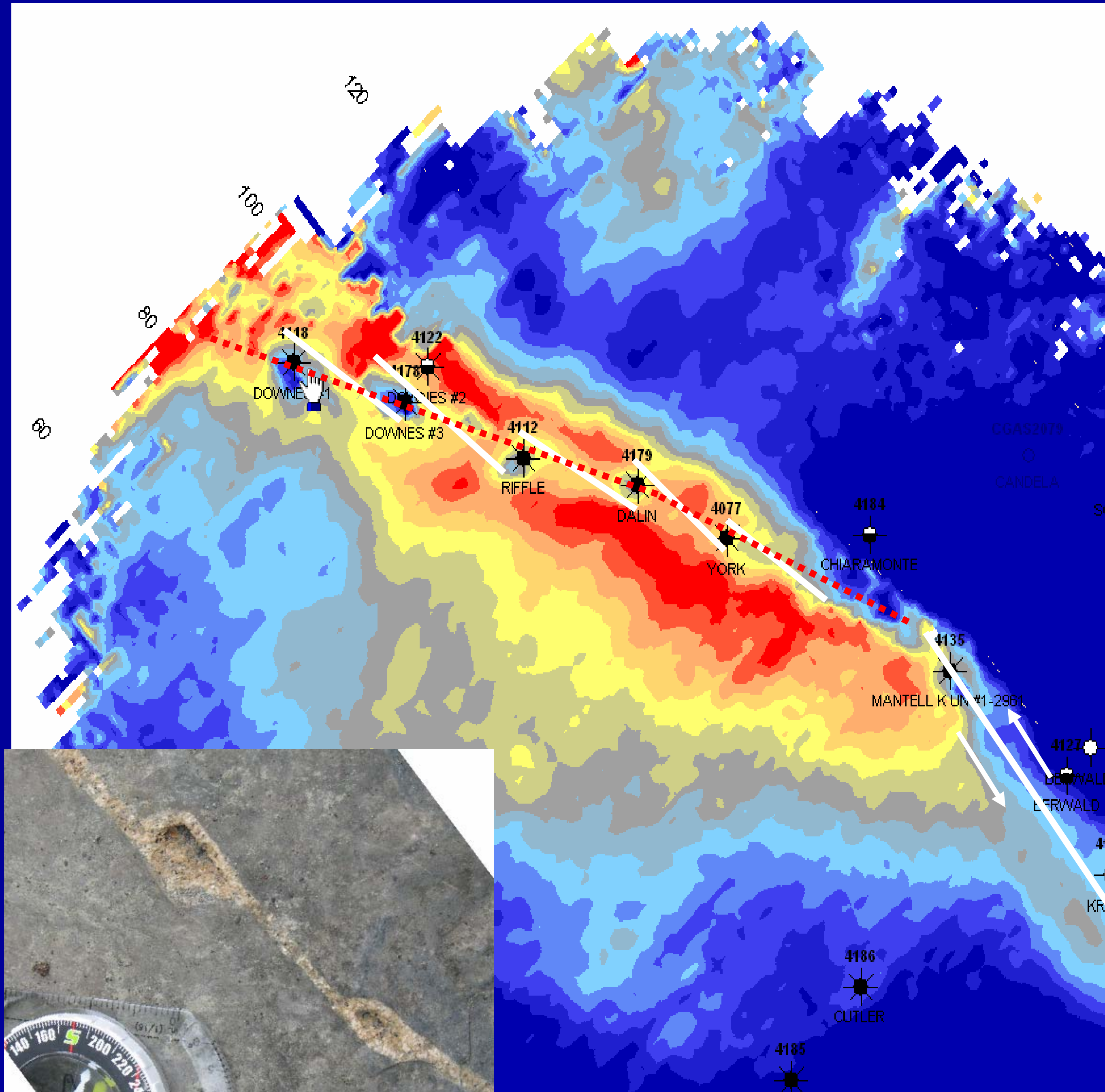
Because the faults step in the same direction that the fault moves, there are deep basins (holes) between the faults just as we have in some Trenton Black River Fields

There is also very common hydrothermal fluid flow and possible hydrothermal dolomitization in this basin (Friedman)



Perhaps York Field in NW Ohio formed at dilational jog on larger strike slip fault

The angle between the interpreted master strike slip fault and and the jog here is about 25 degrees



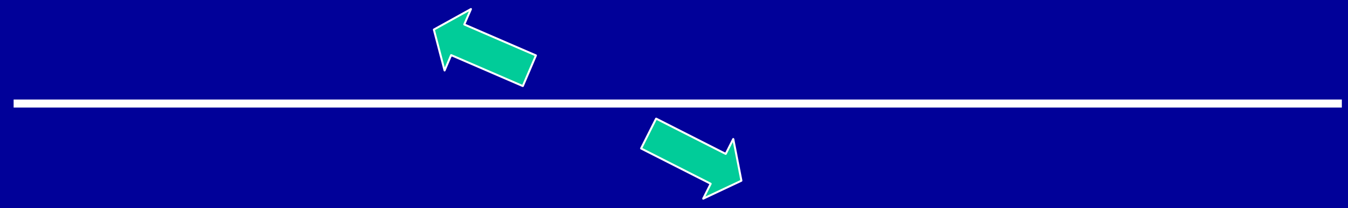
If that is the case, this field should have left-stepping Riedels associated with left-lateral fault movement and therefore should have “holes” where the Riedels overlap

The holes are better formed where the angle increases

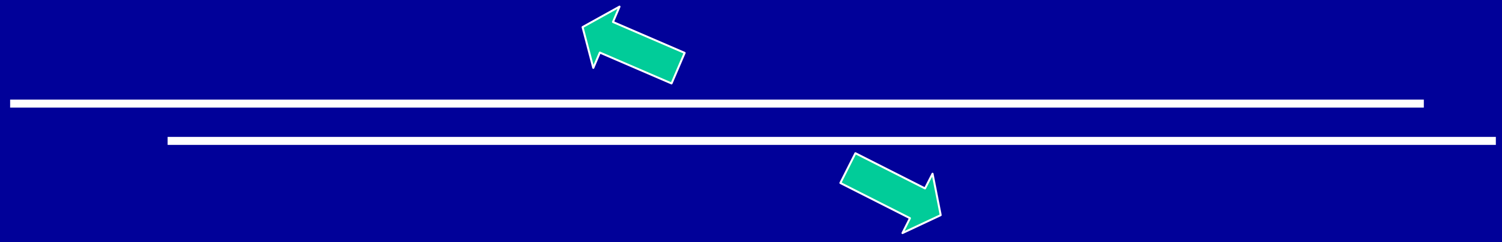
Oblique Divergent Slip on Pre-Existing Isolated Fault

A) Pre-existing basement fault

B) Oblique divergent stress applied

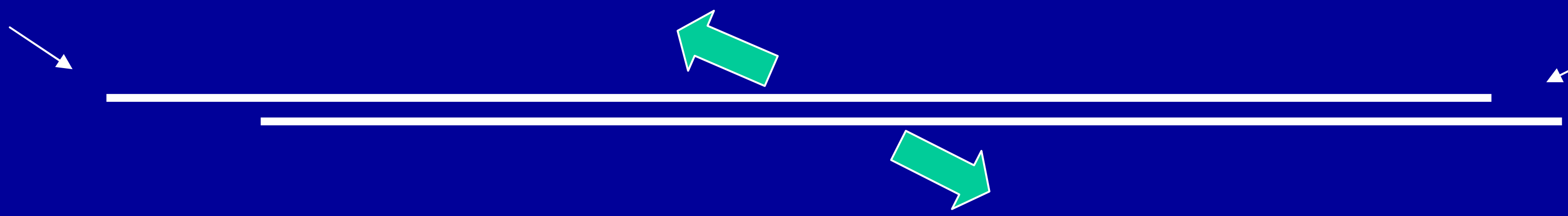


C) Transtensional pull apart

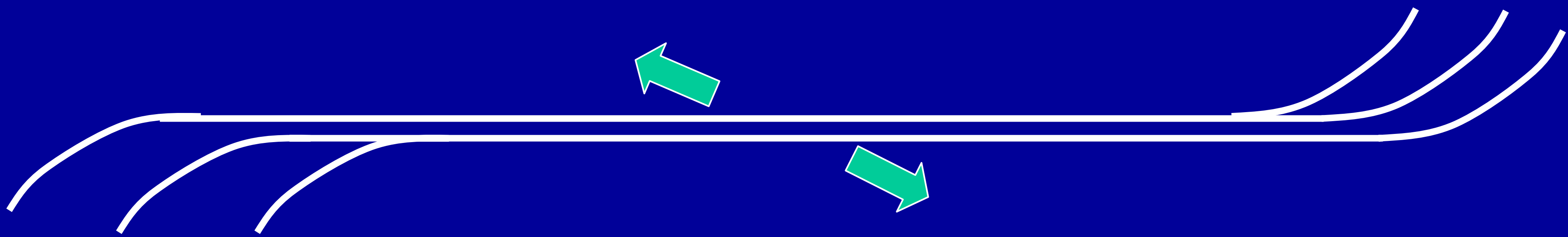


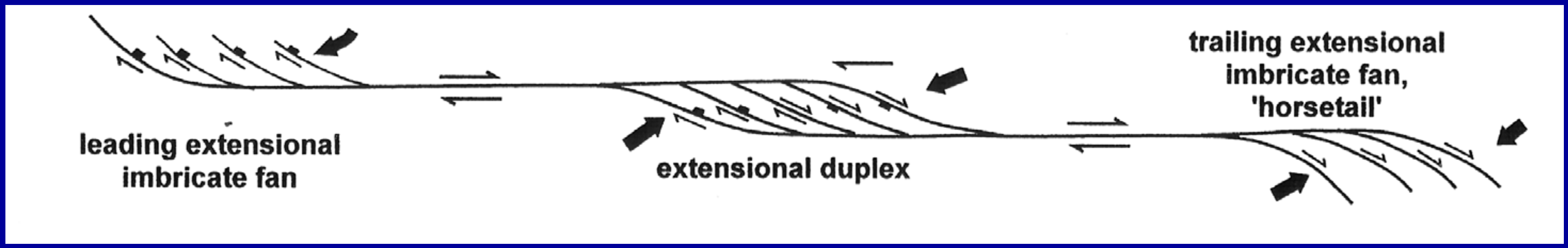
Oblique Divergent Slip on Pre-Existing Isolated Fault

D) Movement must be accommodated at fault tips



E) Horsetails form at tips to accommodate fault movement





Oblique Divergent Slip on Pre-Existing Isolated Fault

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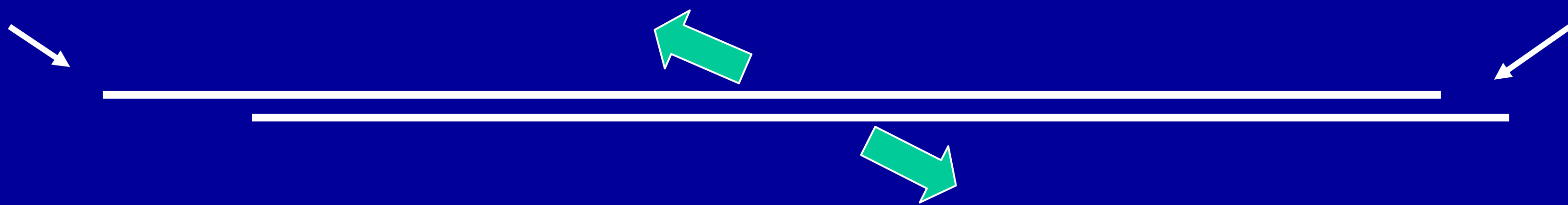

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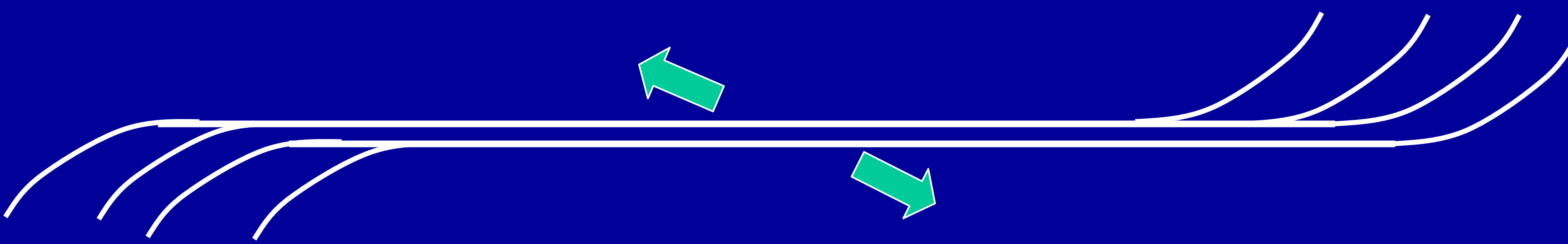
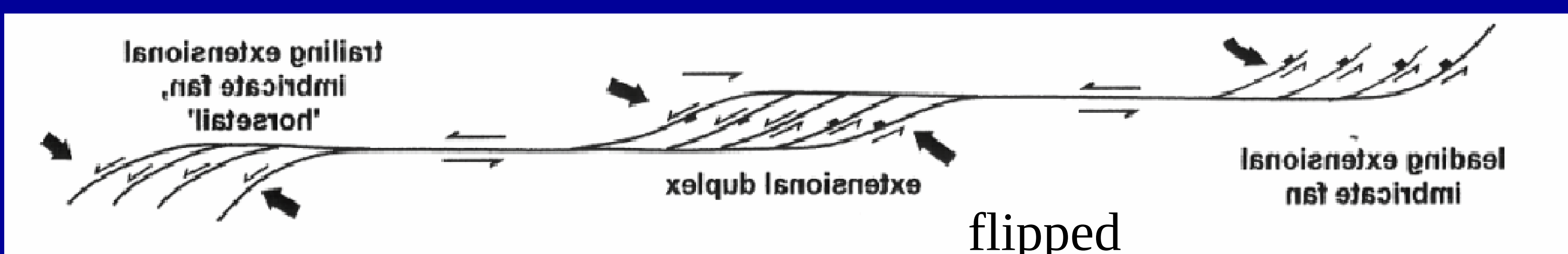
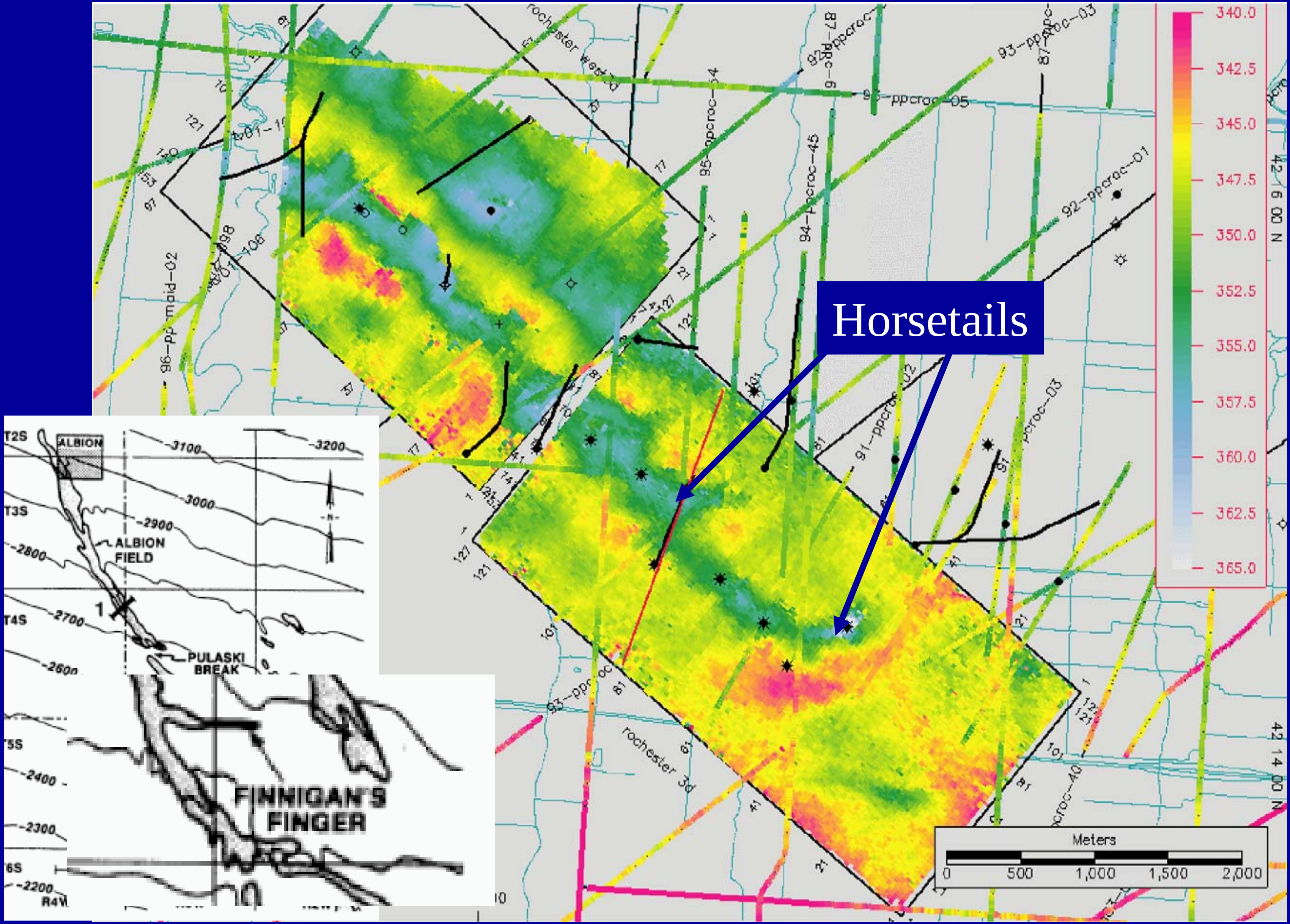
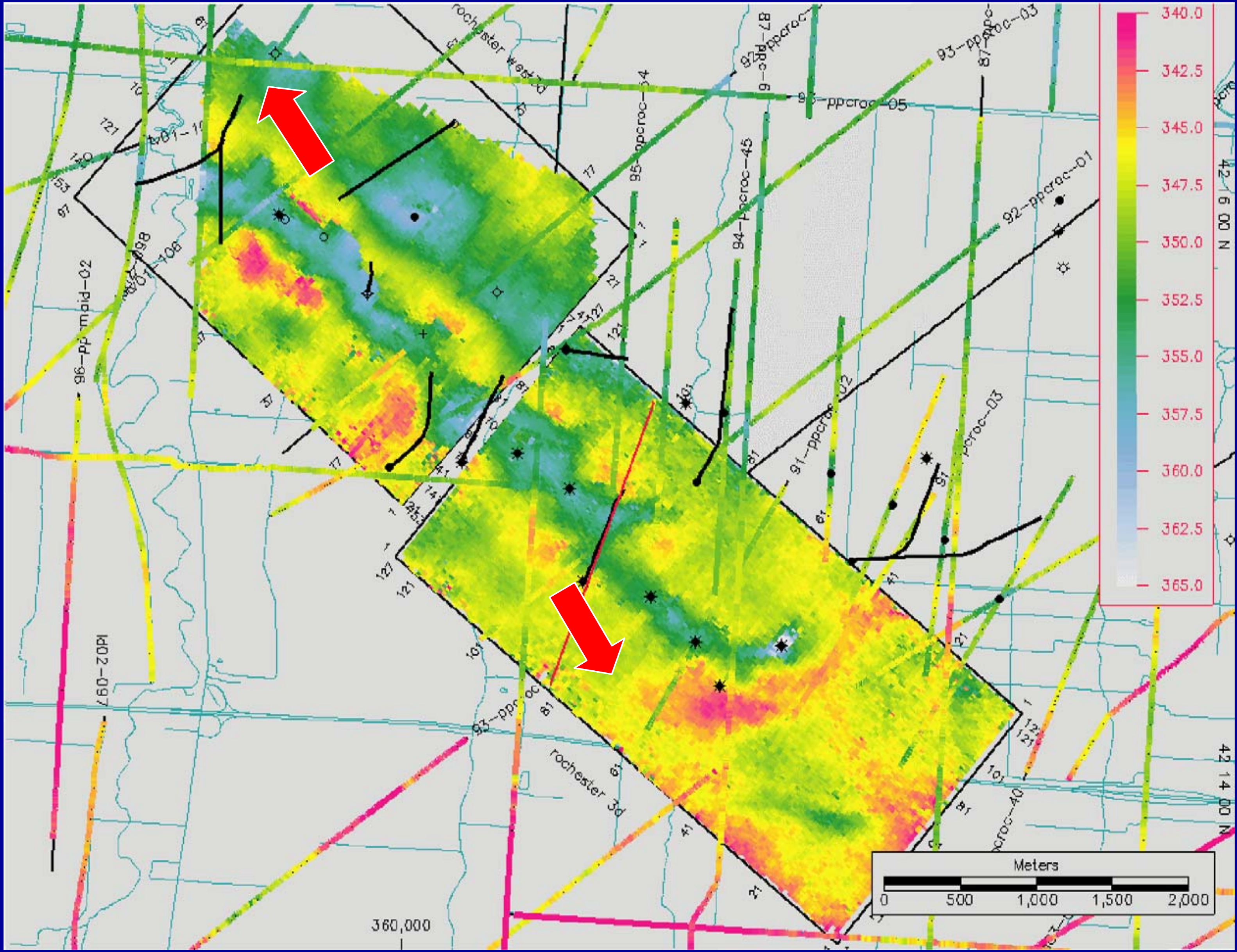


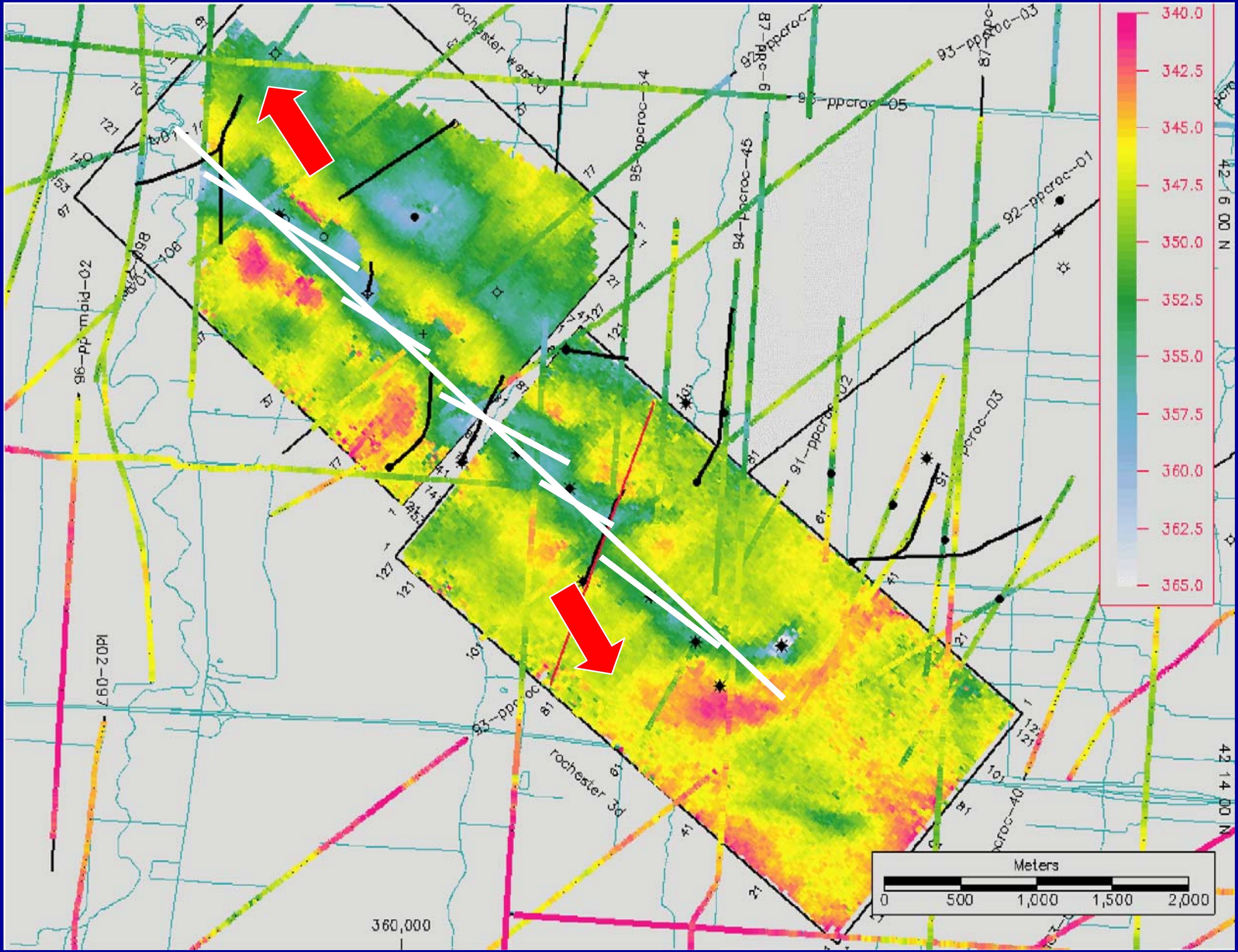




At least one end of the field has what looks like "horsetails" suggesting that it is at a fault tip – Albion Scipio has similar features



The ~continuous nature of the sag suggests that it formed from NNW-SSE Oblique divergent slip



As a result, Riedels should be oriented at something less than 17° to trend of graben –these look to be around 10°

How Divergent?

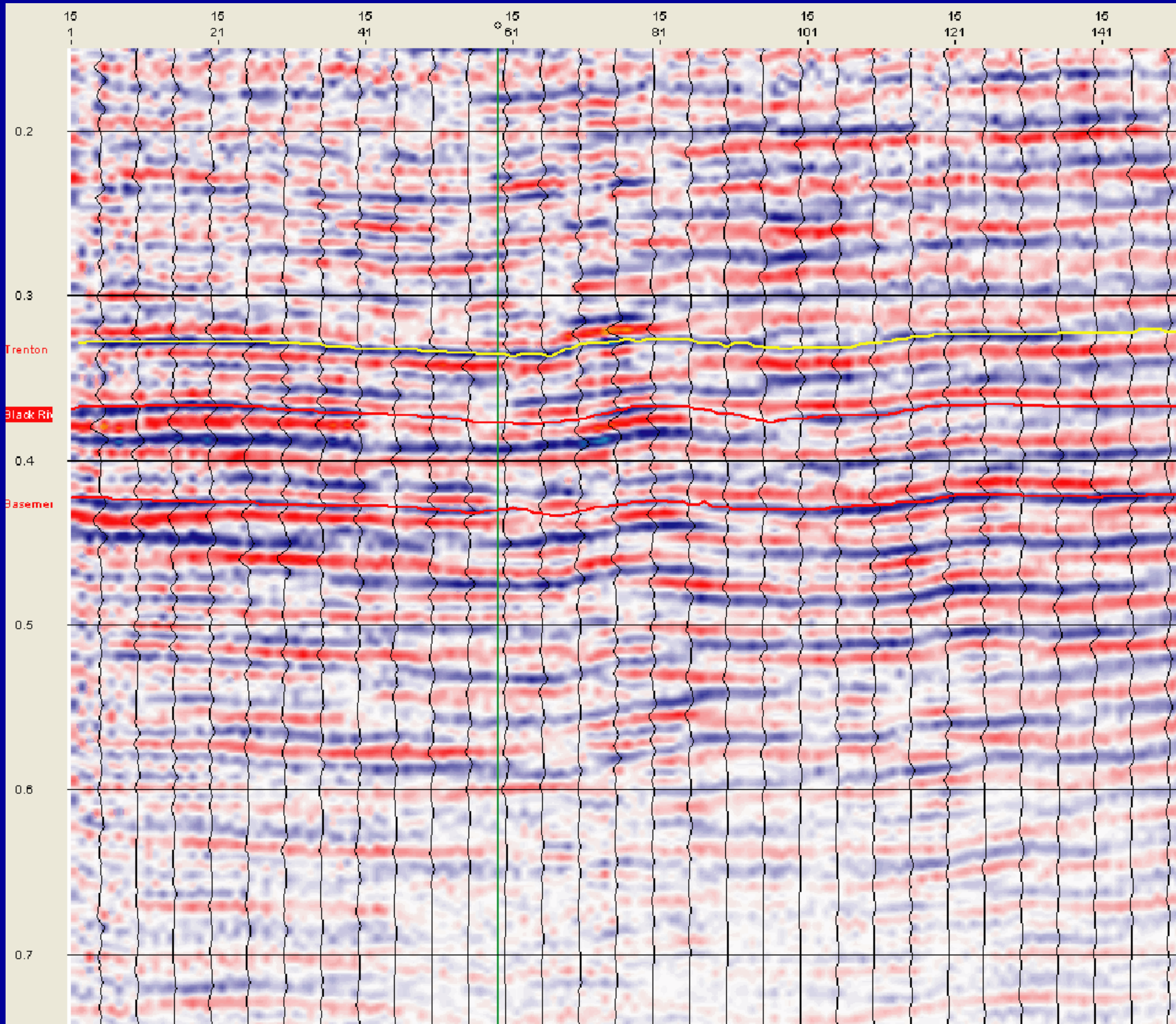
- The degree of divergence may be backed out by the angle of the en echelon faults to the overall trend
- If they are near ~17° and there are no “holes”, little divergence has taken place (could still be altered, but less so?)
- If they are at 0-17 but have no “holes” there has been some extension, but not past the point where the sense of step will change
- If there are “holes” the sense of step has changed and the direction of plate movement is probably at least 20 degrees off the trend of the fault

Implications for Production

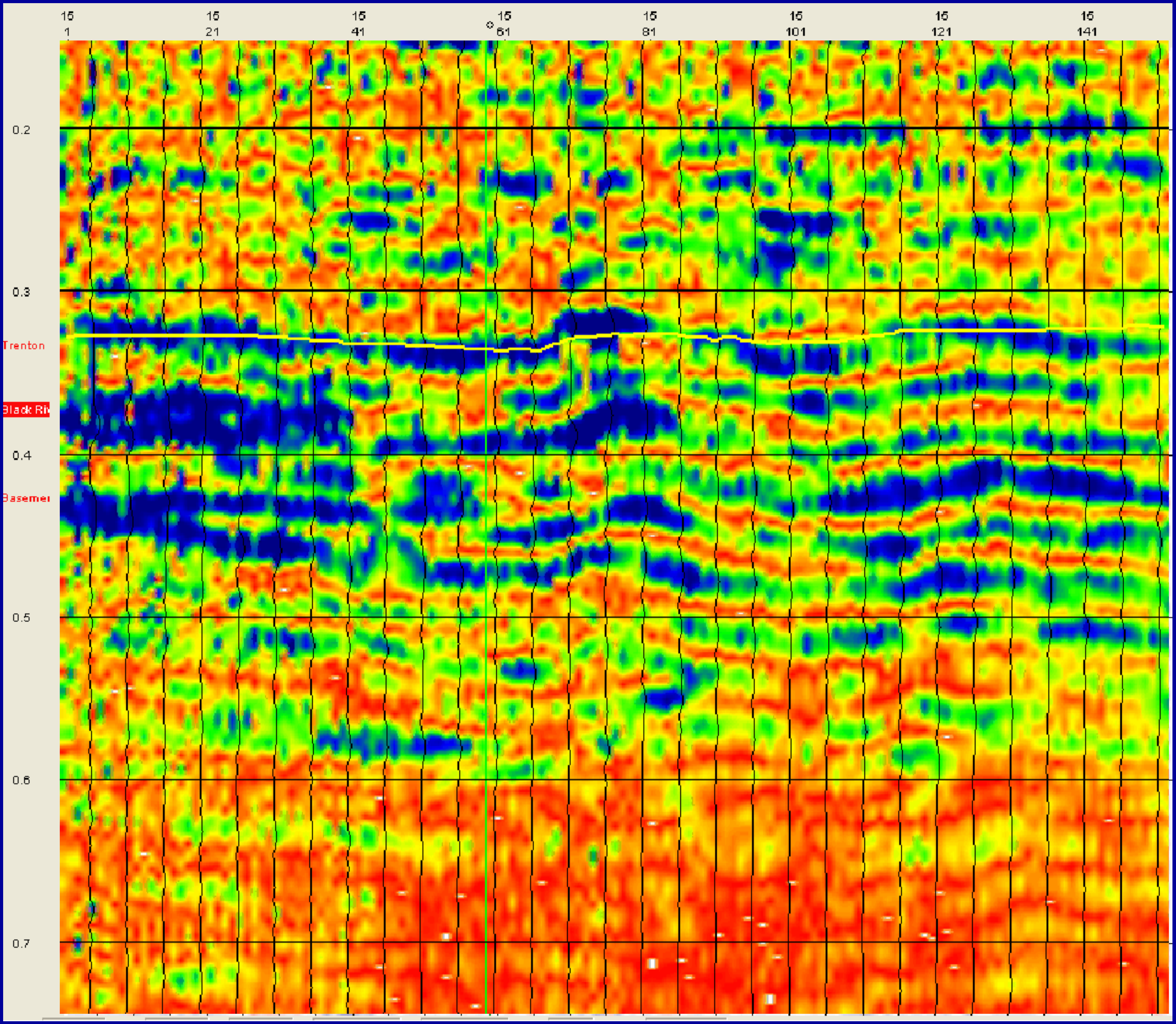
- A better understanding of the links between various faulting scenarios and production could help to high-grade prospects
- The amount of extension will likely control compartmentalization – the closer the Riedels are to the trend of the fault, the less compartmentalization may be likely to occur
- As the angle of movement changes, the appearance of the structures will change – but more than one type of structure could be dolomitized and productive

Variation is the Rule

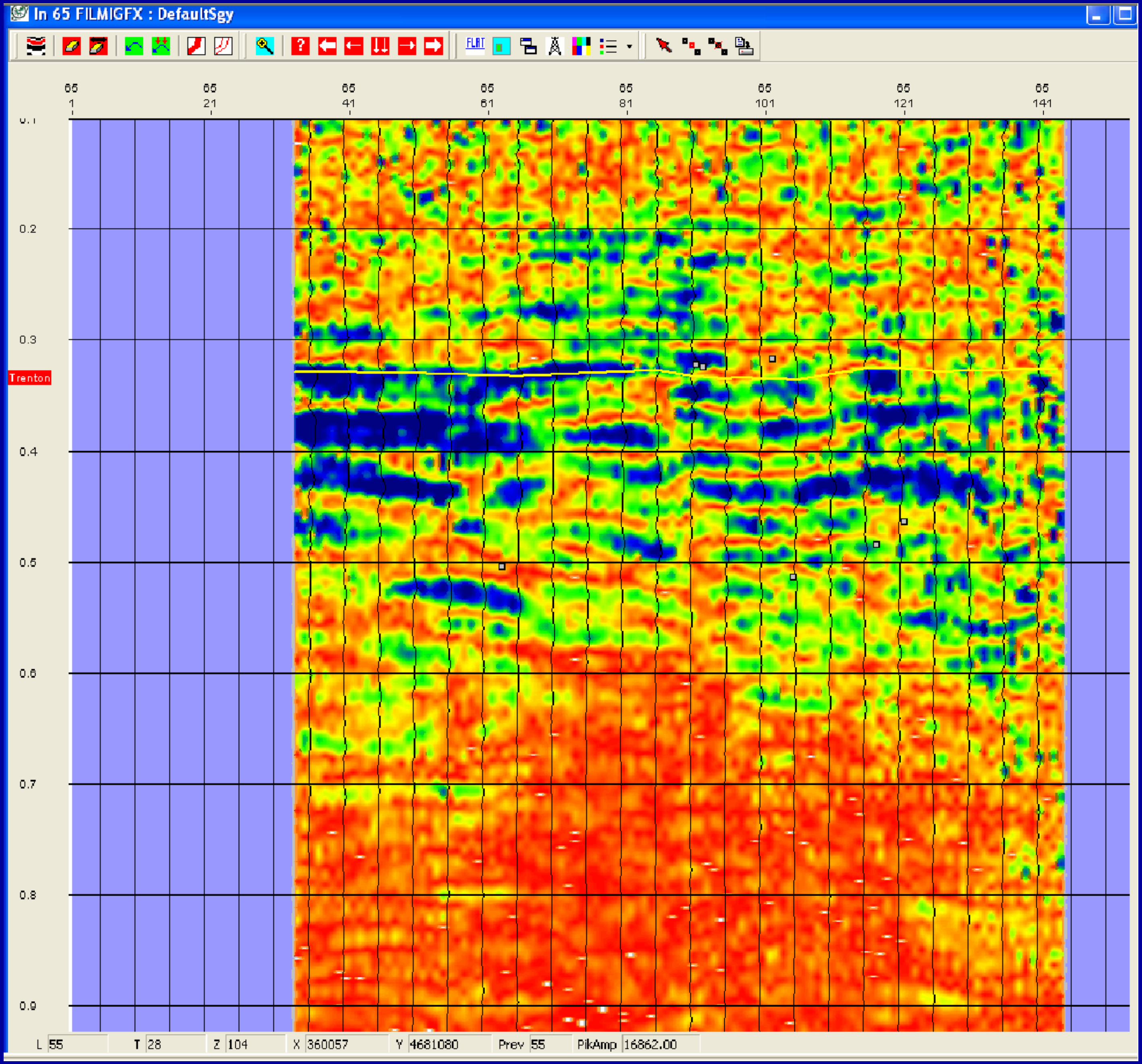
- There can be a lot of variation in the appearance of the sags
- Some sags are ~continuous, others are apparently isolated
- In addition to variations in the degree of extension, other controls include the thickness of the section above the basement, activation of more than one fault trend, the degree of faulting and more



Basement is involved in most or all of the faulting that affects Trenton



Instantaneous amplitude (envelope) makes subtle structures pop out



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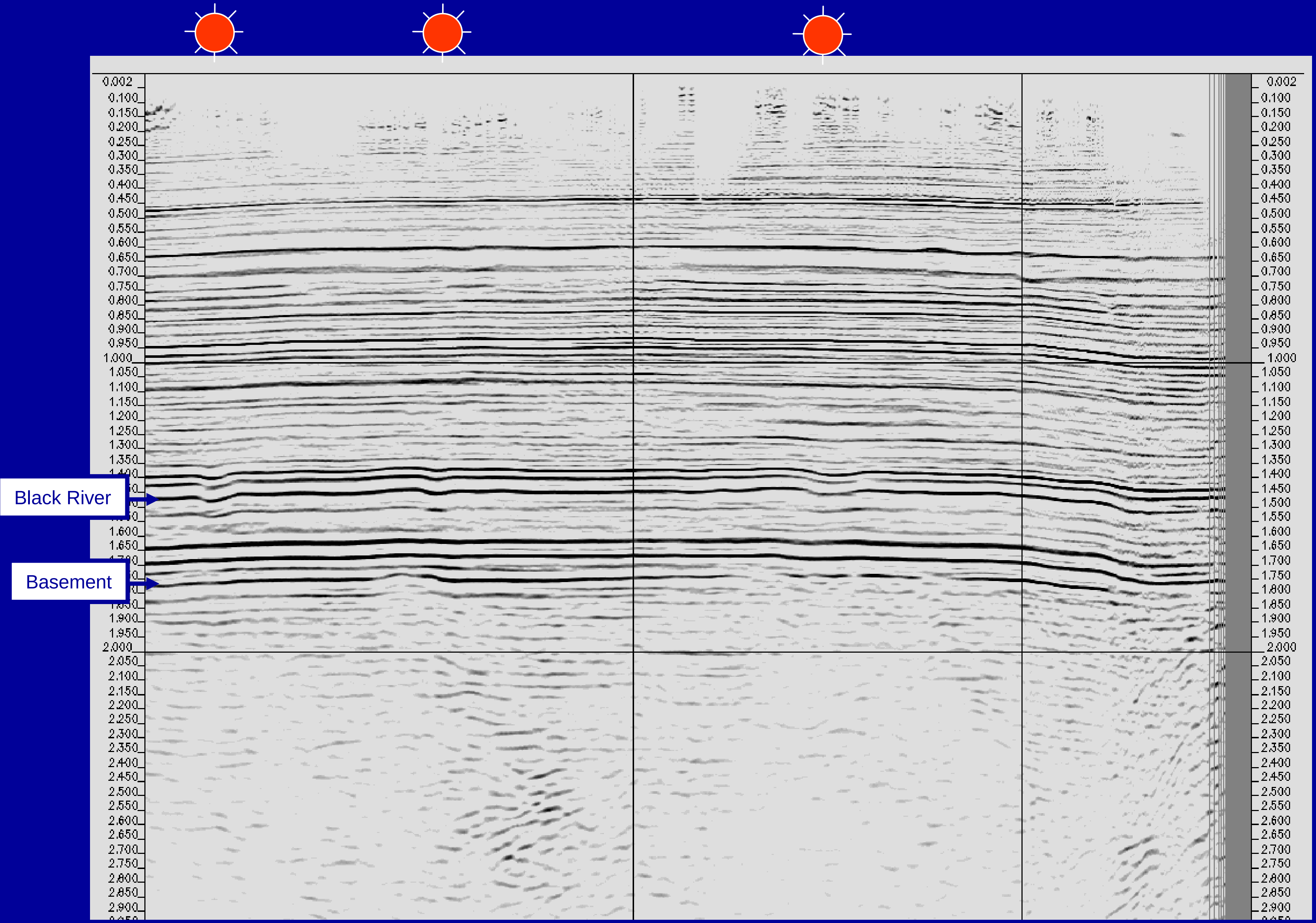
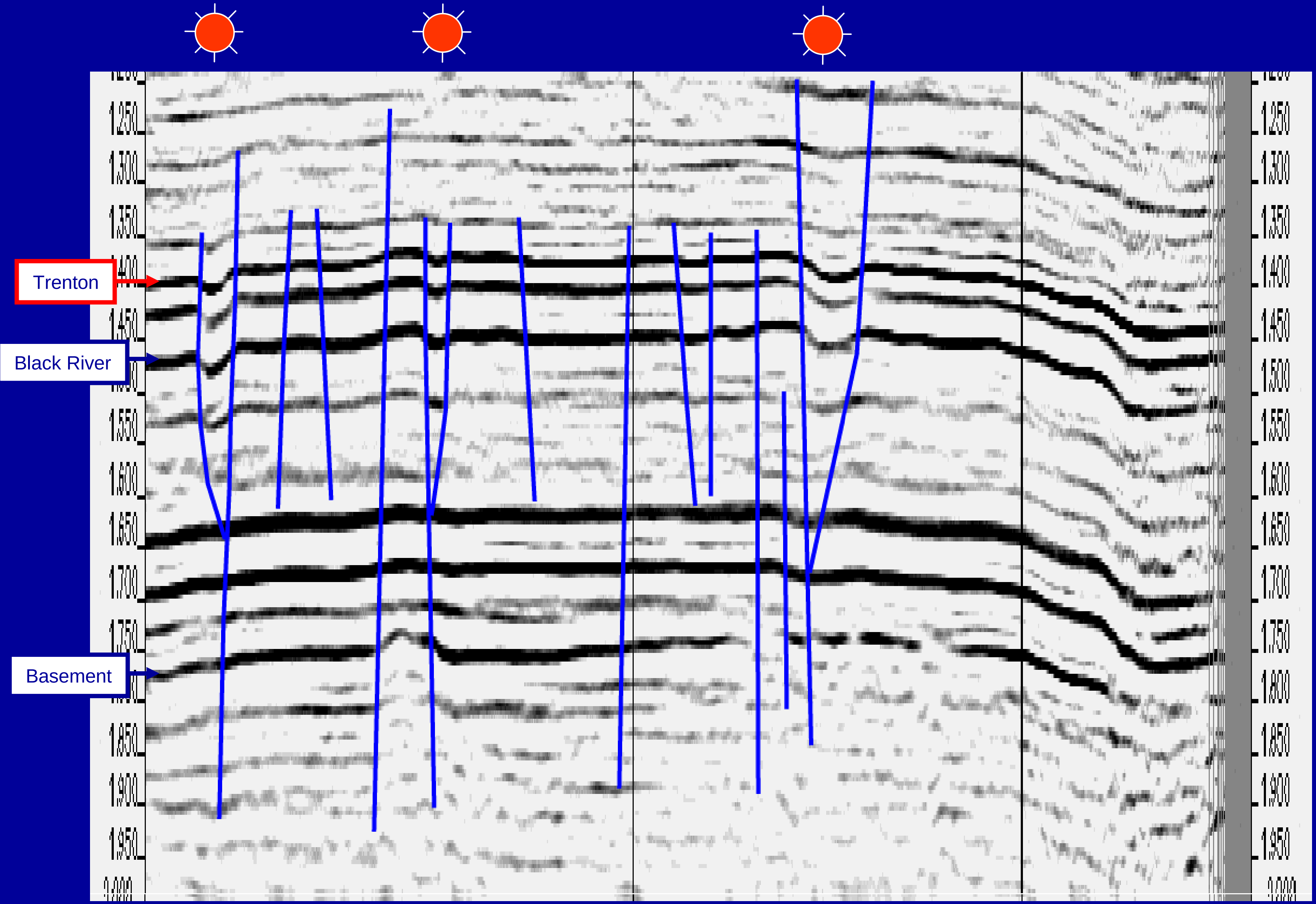


Seismic Line from heart of Black River producing area in NY with three producing wells, each in a separate sag – Beekmantown barely affected



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

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