Structural Analysis for Fracture Optimization*

Catalina Luneburg[1], Bob Ratliff[1], and Alex Page[1]

[1]Geology, Landmark Software, Halliburton, Highlands Ranch, Colorado (Catalina.Luneburg@halliburton.com)

Abstract

In this article we present an innovative multi-disciplinary workflow based on a structural modeling technique, 'Complex Geometry fields,' that enables a geologist to generate attribute predictors for fracture densities, such as detailed bedding geometry, curvature, dip, and strain across an asset or basin. We explain and demonstrate how this technique can be used to benefit the operators of unconventional assets in the following way: the attribute predictors can be used to 'map out' an estimate of the fracture density distributions in three dimensions in a study area, which, in turn, can be used to optimally orient laterals well sections. The orientation of the laterals well sections with respect to the best estimate of the natural fracture orientation trends is thought to be of critical importance when designing completions and induced hydraulic fracture operations that ultimately control the flow of hydrocarbons into the well bore and thence to surface facilities. The computations to generate these geometry fields and predictors are based on the geometry of interpreted surfaces using established kinematic models, such as vertical/oblique shear and flexural slip that account for compressional or extensional tectonic regimes and also the geomechanical lithological competency of the target formations. A good understanding of the structural components of the basin architecture is critical not just for hydrocarbon maturity but also in terms of understanding the behavior or natural and induced fracturing and faulting. After the structural geology attributes have been computed, this information is then combined with and calibrated to other useful information, such as 3D azimuthal seismic attributes or petrophysical and geomechanical observations derived from well locations to give the highest degree of accuracy with respect to predicting the gross distribution of the regional stress state and, therefore, understanding the associated development of fracture densities. The applications of creating a multi-disciplinary 3D numerical model of the subsurface that is enriched with this regional structural geology component are

wide-reaching, but they really benefits completion and hydraulic fracturing design as well as full field well planning strategies and the associated logistics because a high fidelity prediction of the subsurface has been generated across an entire asset.

Selected References

Fox, J.E., G.L. Dolton, and J.L. Clayton, 1991, Powder River Basin, *in* H.J. Gluskoter, D.D. Rice, and R.B. Taylor, editors, Economic Geology, U.S.: Geological Society of America, The Geology of North America, P-2, p. 373-390.

Stearns, D.W., 1967, Certain aspects of fracture in naturally deformed rocks, *in* R.E. Rieker, editor, NSF Advanced Science Seminar in Rock Mechanics: Bedford, Air Force Cambridge Research Laboratories, p. 97-118.

Stearns, D.W., 1971, Mechanisms of drape folding in the Wyoming Province, *in* A.R. Renfro, L.W. Madison, G.A. Jarre, and W.A. Bradley, editors, Symposium on Wyoming tectonics and their economic significance: Twenty-Third Annual Field Conference Guidebook, Wyoming Geological Association, p. 125-143.

Stearns, D.W., 1978, Faulting and forced folding in the Rocky Mountains foreland, *in* V. Matthews, III,, editor, Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 1-37.

Twiss, R.J., and E.M. Moores, 1992, Structural Geology: W.H. Freeman & Company, New York, 532p.

Natural fractures significantly influence the hydraulic behavior of fractured reservoirs – production is enhanced in areas of high fracture density

Important to quantitatively characterize and model the geometry of natural fracture systems using direct or indirect (proxies) methods

Predicting fracture geometry and density is critical for reservoir development and production fore-casting, and optimizing well trajectories and drilling

Fractures critical in rocks with very low primary porosity by providing secondary porosity and permeability
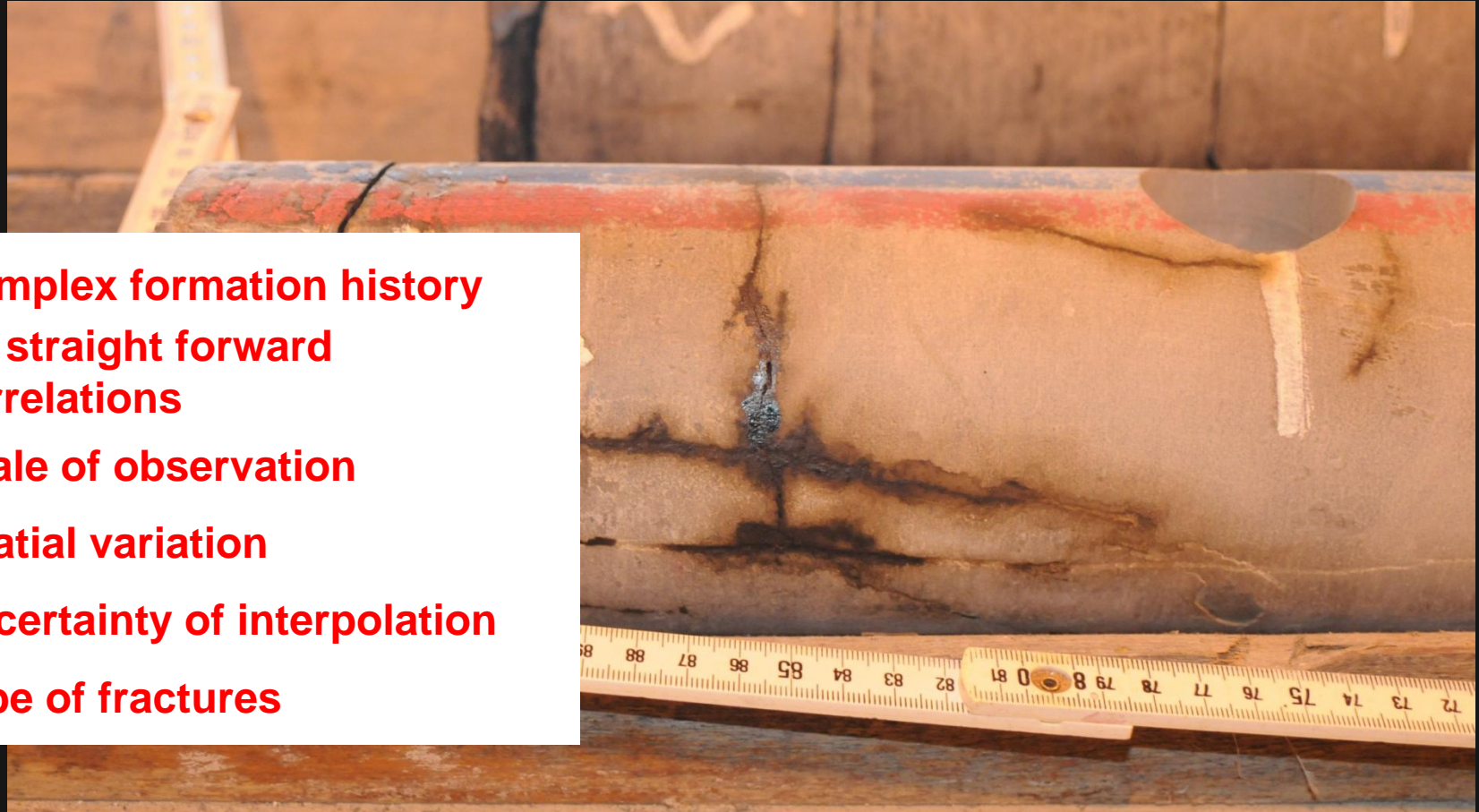
- **Complex formation history**
- **No straight forward correlations**
- **Scale of observation**
- **Spatial variation**
- **Uncertainty of interpolation**
- **Type of fractures**

Well bore with oil seeps along fractures

Teapot Dome, WY

- Southwestern margin of Powder River Basin WY, Laramide age foreland basin

- Unconventional fractured reservoir

- Naval Petroleum Reserve (1915) and RMOTC (1977) - recently sold
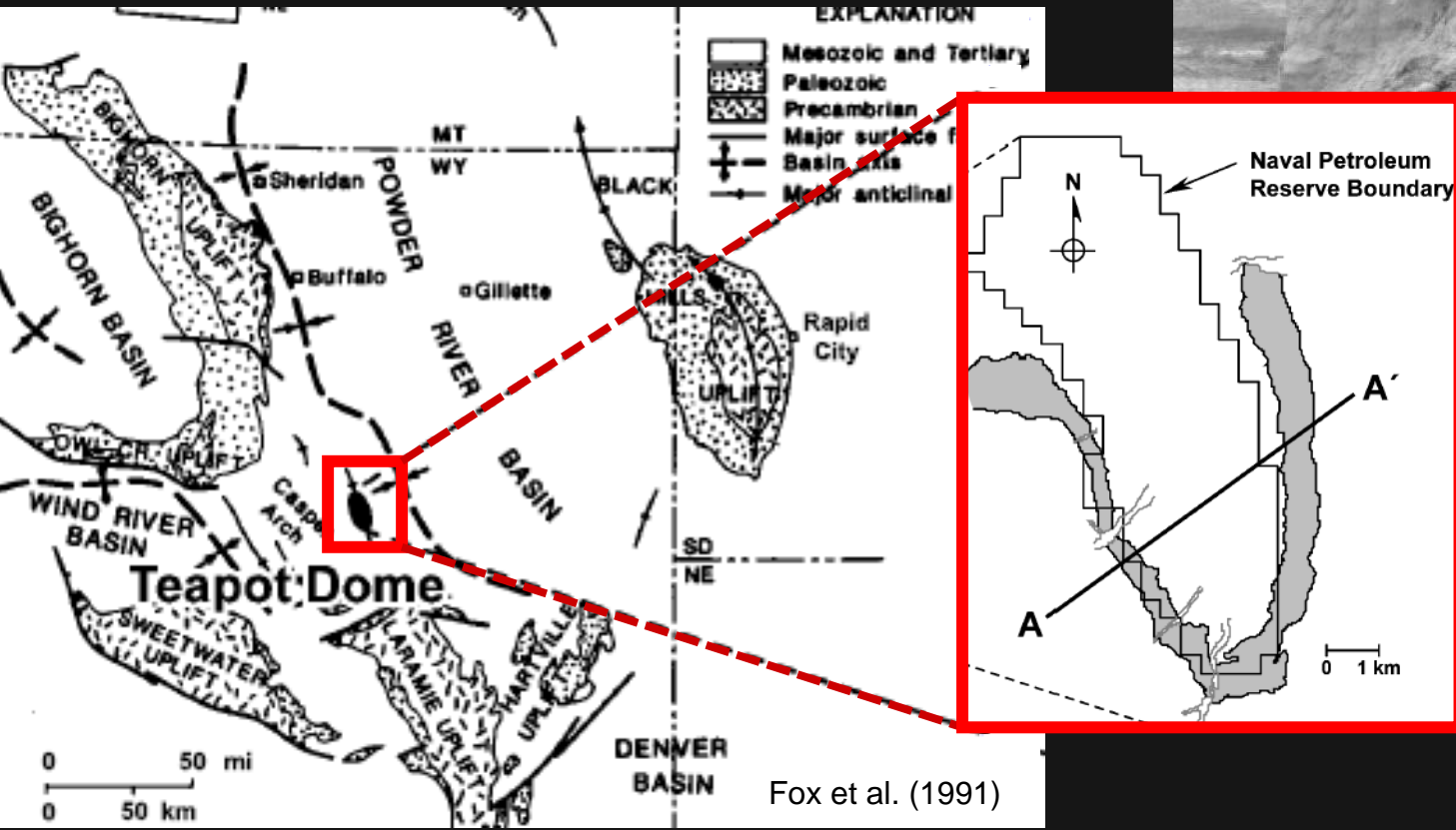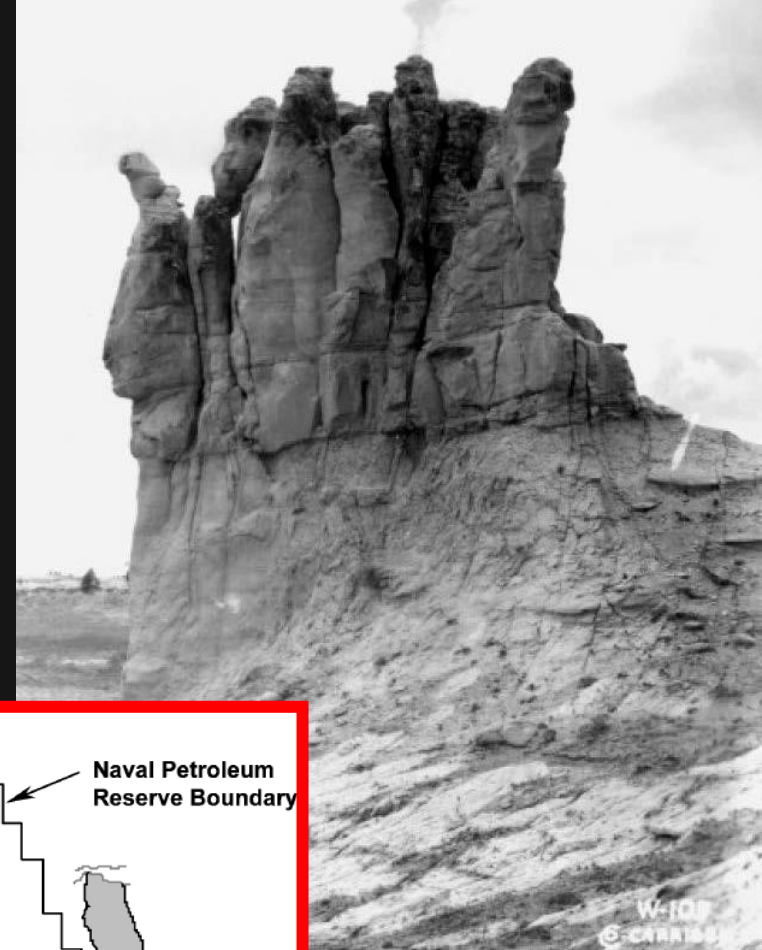
Fox et al. (1991)

Teapot Dome, WY

- Basement-cored, doubly plunging W-SW verging anticline

- E-NE dipping basement –involved blind thrust

- Four-way closure HC trap

Best Fit Plane (Rectangle)
  Dip: 3.1
  Dip Azimuth: 145.73
Best Fit Fold Axis (Triangle)
  Trend: 154.65
  Plunge: 3.06

Sample Size N: 857
Normalized Eigenvalues S1, S2, S3: 0.973, 0.025, 0.002
Shape Parameter K: 1.47
  (girdle K<1; cluster K>1)
Strength Parameter C: 6.14
  (weak C<3; strong C>3)
Uniformity Statistic Su: 3942.1
  (deviation from uniformity: 95% Su>11.07; 99% Su>15.09)
[Refer to Help for more details.]

Eigenvector Trend   Plunge Eigenvalue
1 (Rectangle) 325.73 86.9   0.973
2 (Circle)   64.62   0.48   0.025
3 (Triangle) 154.65 3.06   0.002

Equal Area, Lower Hemisphere Stereonet

Section A

Section B

Section C

Section E

Section D

Teapot Dome, WY

- Basement-cored, doubly plunging W-SW verging anticline

- E-NE dipping basement –involved blind thrust

- Four-way closure HC trap

Wells mainly in the fold hinge/crest!

Best Fit Plane (Rectangle)
  Dip: 3.1
  Dip Azimuth: 145.73
Best Fit Fold Axis (Triangle)
  Trend: 154.65
  Plunge: 3.06

Sample Size N: 857
Normalized Eigenvalues S1, S2, S3: 0.973, 0.025, 0.002
Shape Parameter K: 1.47
  (girdle K<1; cluster K>1)
Strength Parameter C: 6.14
  (weak C<3; strong C>3)
Uniformity Statistic Su: 3942.1
  (deviation from uniformity: 95% Su>11.07; 99% Su>15.09)
[Refer to Help for more details.]

Eigenvector Trend Plunge Eigenvalue
1 (Rectangle) 325.73 86.9   0.973
2 (Circle)   64.62   0.48   0.025
3 (Triangle) 154.65 3.06   0.002

Equal Area, Lower Hemisphere Stereonet
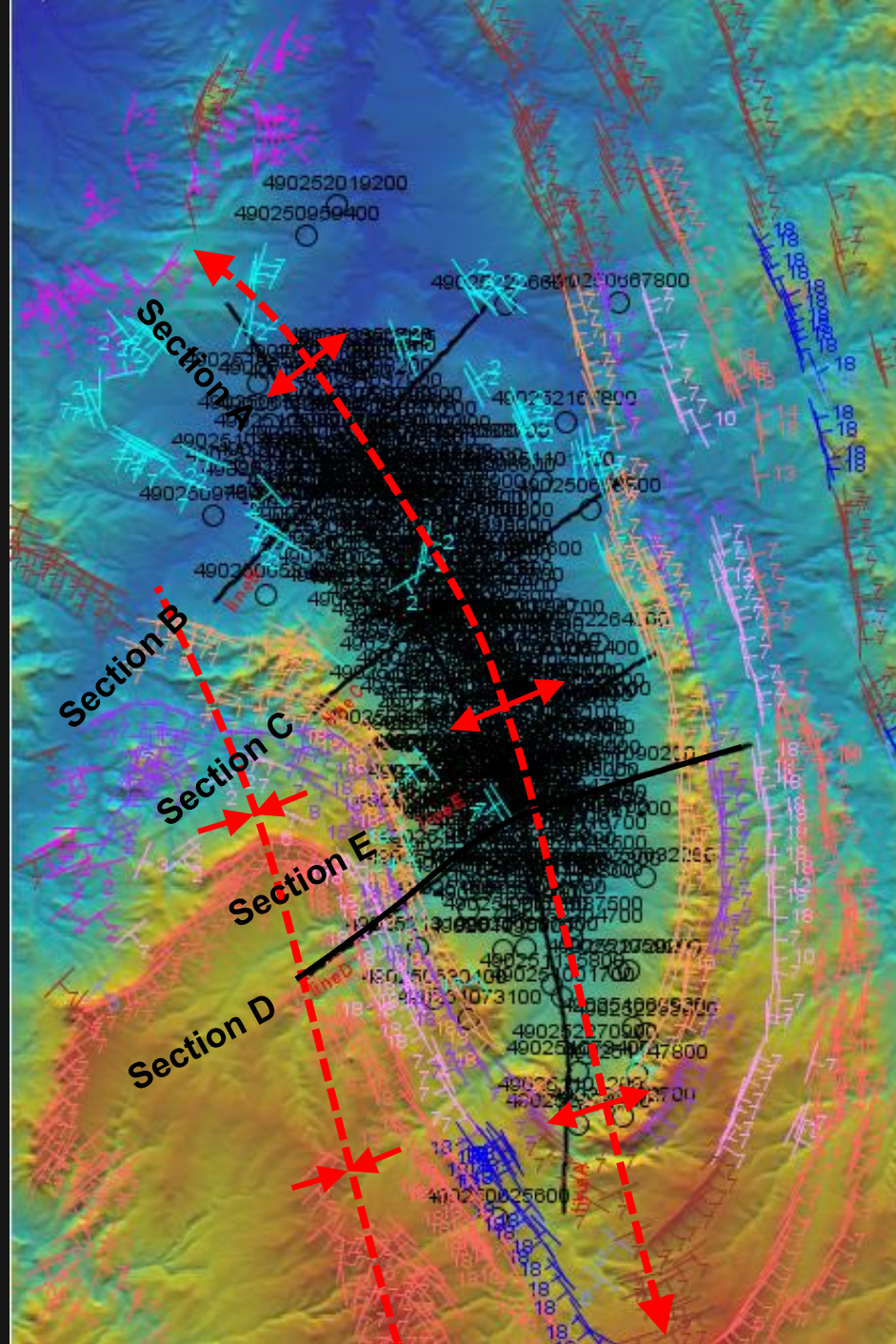
Teapot Dome Geologic Column
Natrona County, Wyoming
T 38 & 39 N R 78 W

Rocky Mountain Oilfield Testing CENTER

Period	Formation		Lithology	Thickness	Depth (ft)	Productive
Quaternary	Alluvium			0-50		
	Fox Hills Sandstone			100		
	Lewis Shale			600		
	Mesaverde Group	Teapot Ss		50		
		"Pumpkin Buttes shale"		325		
		Parkman Ss		470		
				480		
				195	Outcropping units	
		Sussex Ss		30	195	
	Steele Shale			290		
		Shannon Ss		120	515	▪
Upper Cretaceous					635	
				1355		▪
	Niobrara Shale			450	1990	▪
	Carlisle Shale			240	2440	
	Frontier	1st Wall Creek		160	2680	
				245	2840	
		2nd Wall Creek		65	3085	▪
				175	3150	
		3rd Wall Creek		5	3325	
				265	3330	
	Mowry Shale			230	3595	
Lower Cretaceous	Muddy Sandstone			15	3825	▪
	Thermopolis Shale			135	3840	
	Dakota			85	3975	▪
	Lakota			10	4060	▪
	Morrison			270	4070	
Jurassic	Sundance	Upper		95	4340	
		Lower		150	4435	
		Crow Mountain		80	4585	
		Alcova LS		20	4665	
Triassic	Chugwater Group	Red Peak		520	4685	
Permian	Goose Egg			320	5205	
Pennsylvanian	Tensleep			320	5525	▪
	Amsden			160	5845	
Mississippian	Madison			300	6005	
Devonian through Cambrian	Undifferentiated			780	6305	
Pre-Cambrian	Granite				7085	

Over 22 MM barrels of oil since 1976

Several oil-producing formations
- Tensleep Ss
- 2nd Wall Creek Ss
- Shannon Ss
- Muddy Ss
- Dakota Ss

Cody Shale

Parkman

KMVU

Lewis

Fox Hills
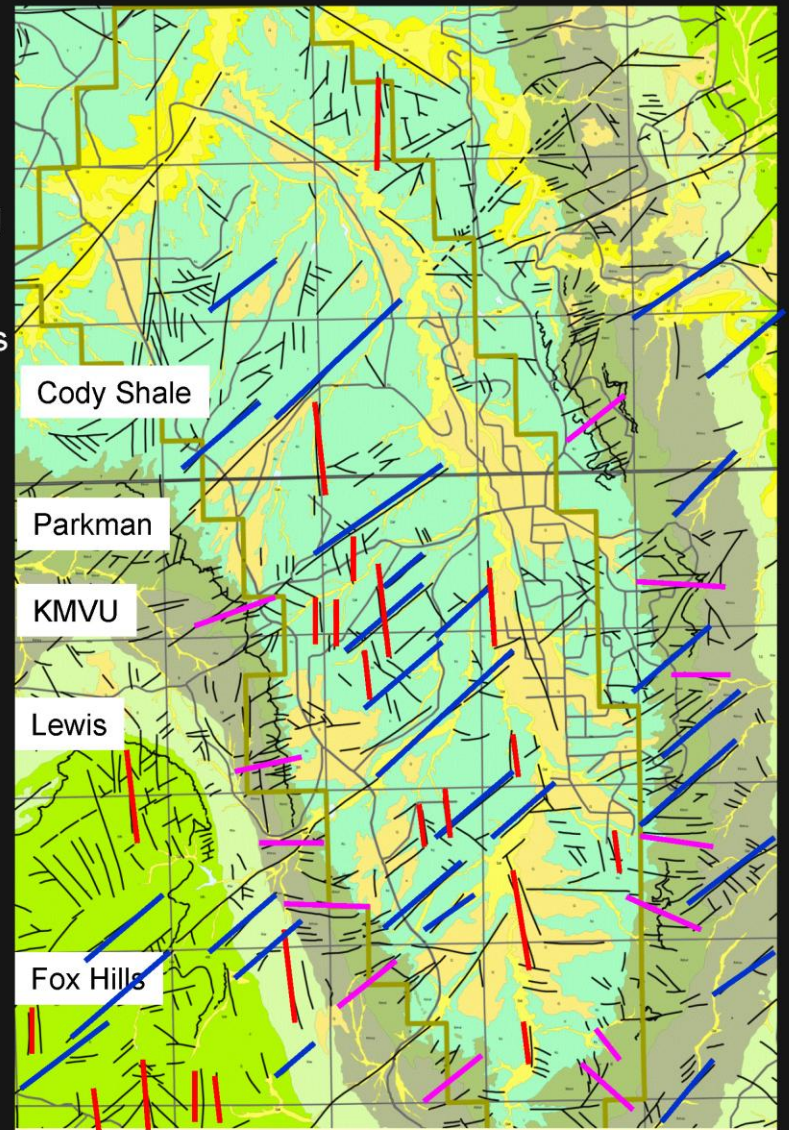
Presenter's notes: Geologic map with fractures.

Three prominent open fracture systems:

1. **hinge-oblique (NW)**
2. **hinge-parallel (NNE)**
3. **hinge-perpendicular (radial)**

Maximum permeability

- **mainly parallel to fold hinge**

- **locally also perpendicular to fold hinge where NE-striking cross faults**

- **Intersections of hinge-parallel and hinge-perpendicular faults and fractures increase interconnectivity and enhance permeability**
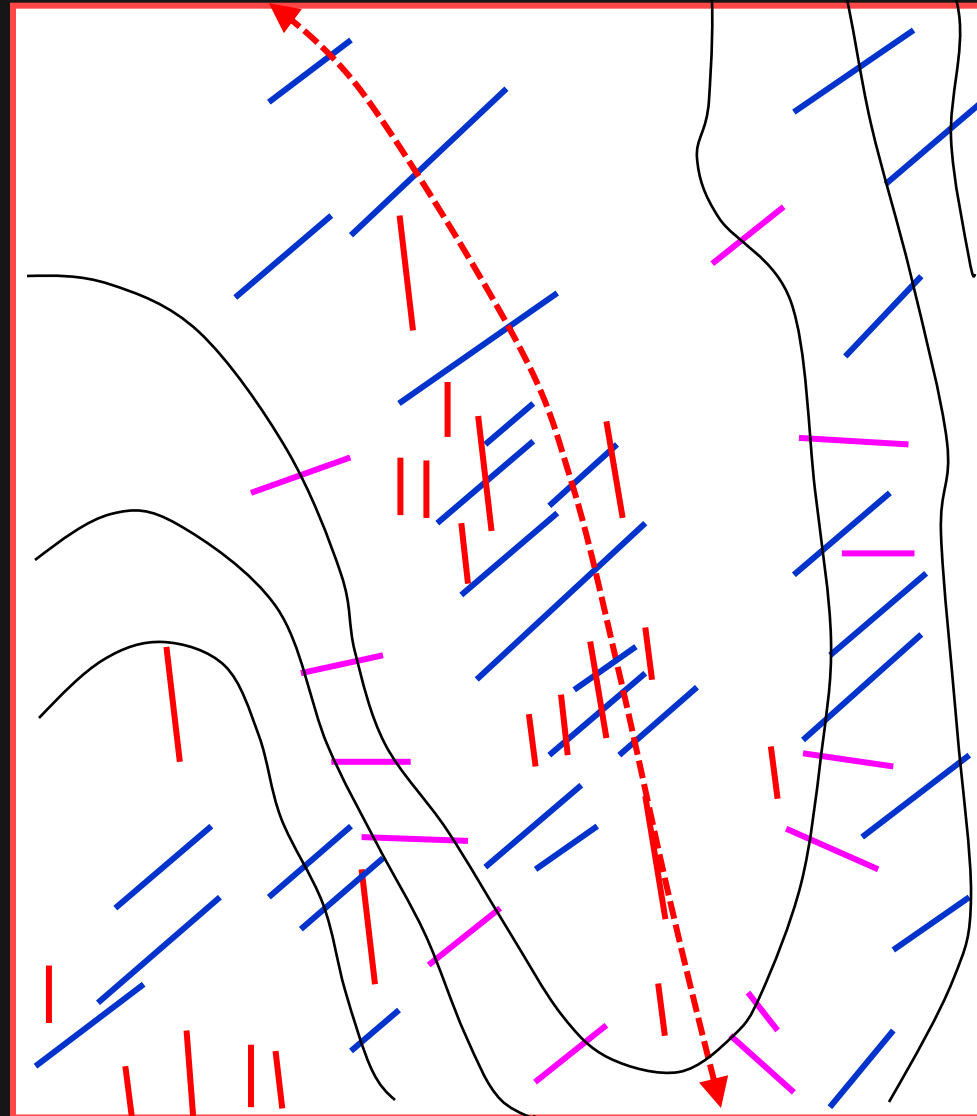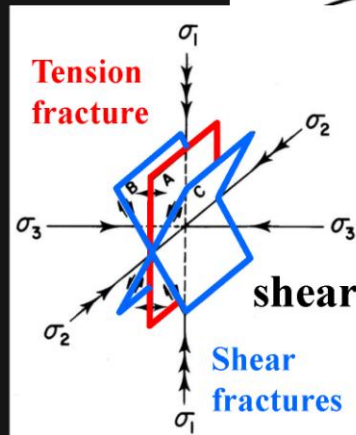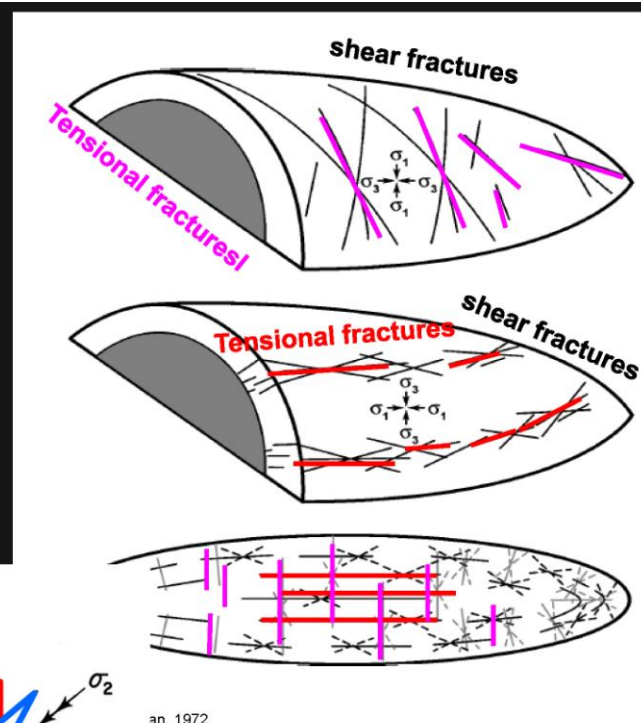
Presenter's notes: A genetic classification divides fractures into Type I and Type II (Stearns,1968). Type I fractures are composed of a tensional set oriented perpendicular to the fold axis with an associated conjugate shear set whose acute bisector coincides with the orientation of tensional fractures. Type II fractures are composed of an extensional set oriented parallel to the fold axis with an associated conjugate shear set whose acute bisector coincides with the orientation of extensional fractures. Consequently, open fractures are classified as tensional, extensional, or shear sets with orientation perpendicular, parallel, or oblique to the structural axis.

Fold 1B-types and their fracture patterns

- The orientation and localization of the reservoir fracture population depends on the dominant folding mechanism.

- Fractures concentrate at certain domains of the fold morphology.

Twiss & Moores 1992
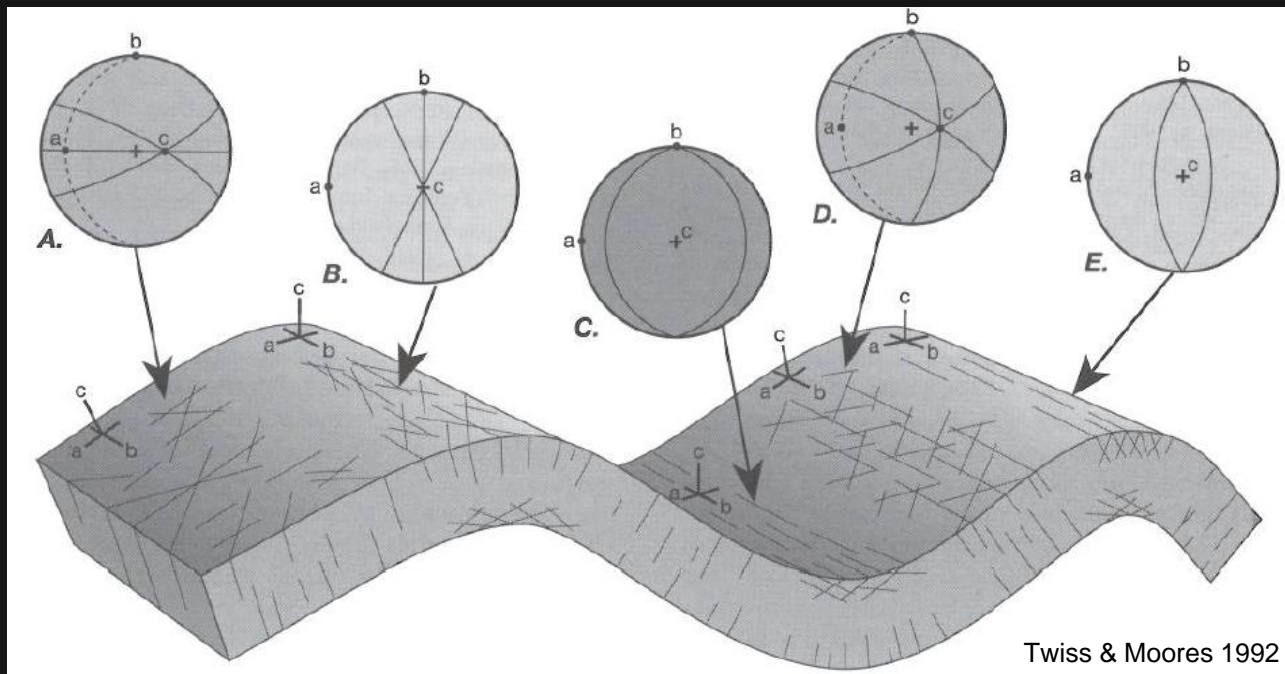
Typical fracture patterns due to folding (concentric-parallel folds)

Fold 1B-types and their fracture patterns

Flexural Flow   Flexural Slip   Composite
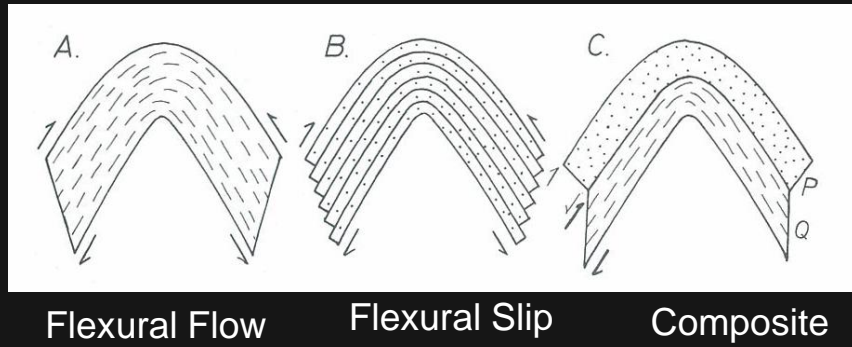
Flexural flow + parallel folds
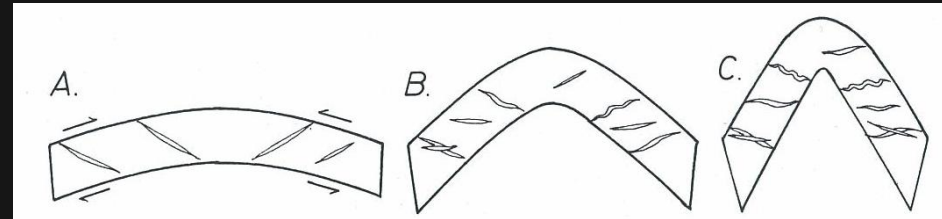
Progressive development of shear fractures in flexural slip folds

Tangential Longitudinal Strain
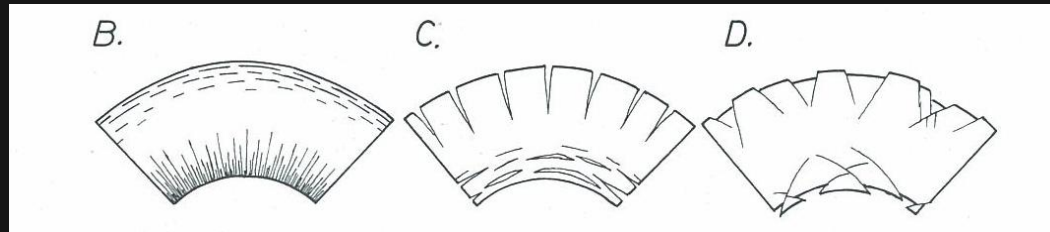
Kink Fold
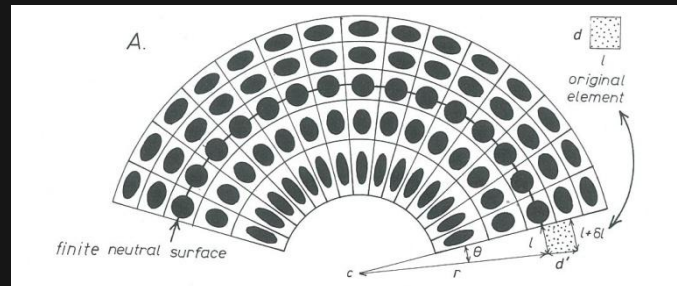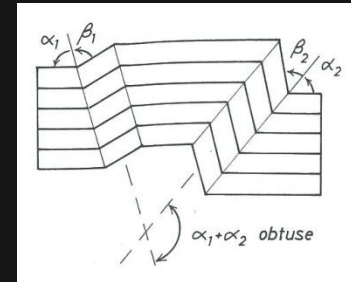
Parallel (Bend) Folds
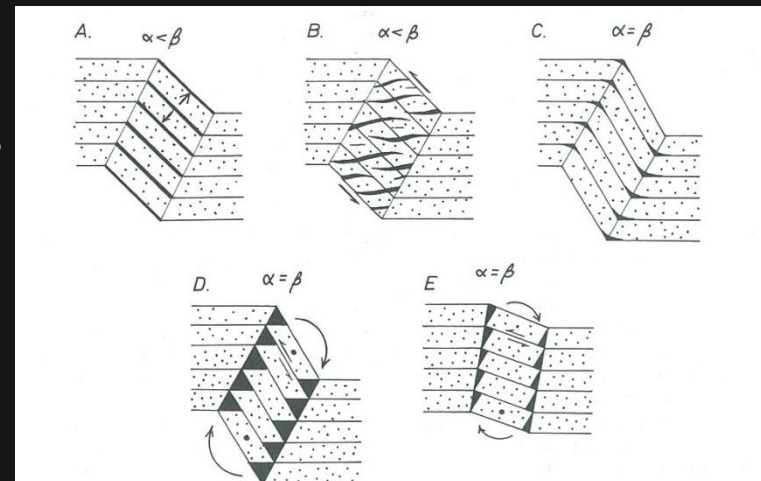
Teapot Dome 3D structure
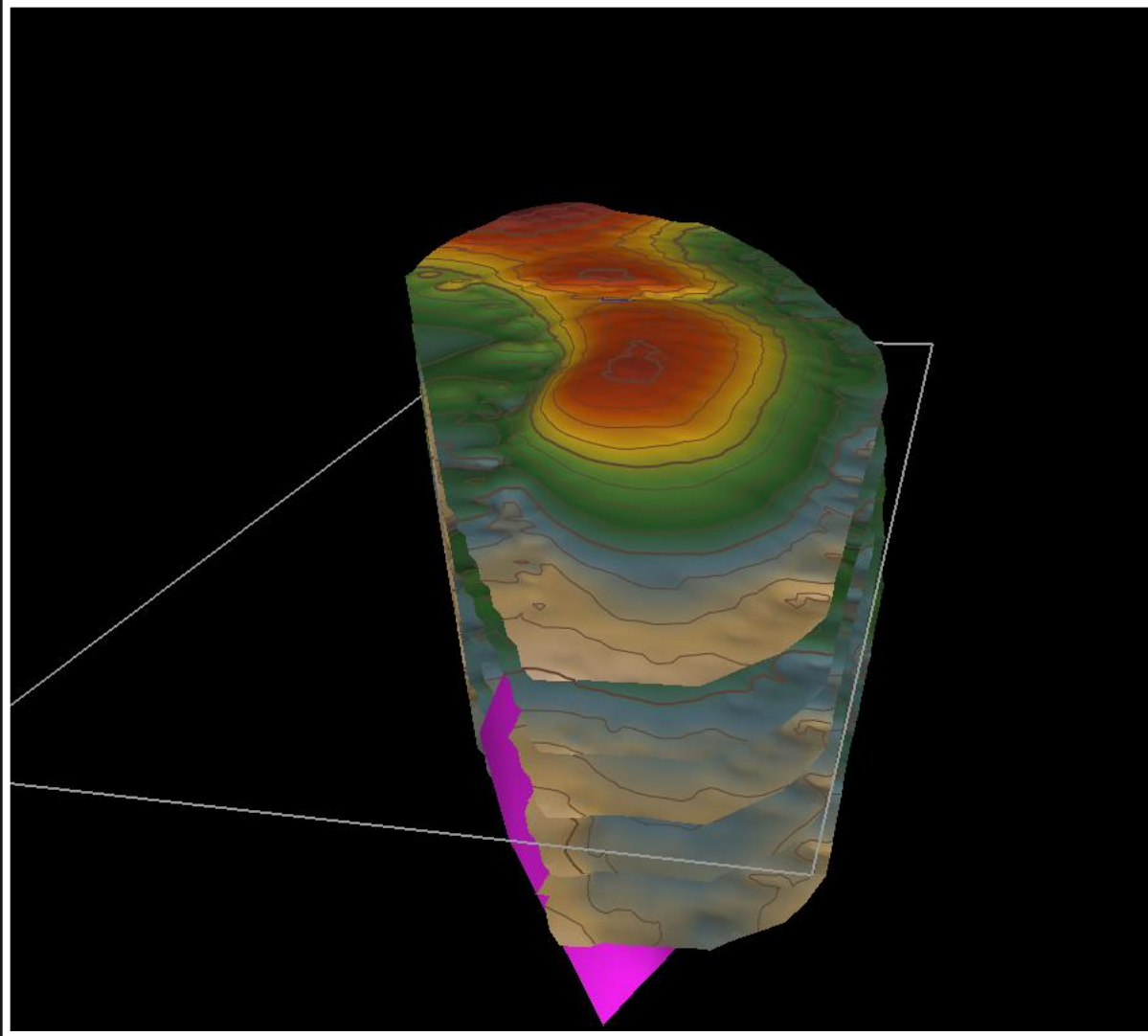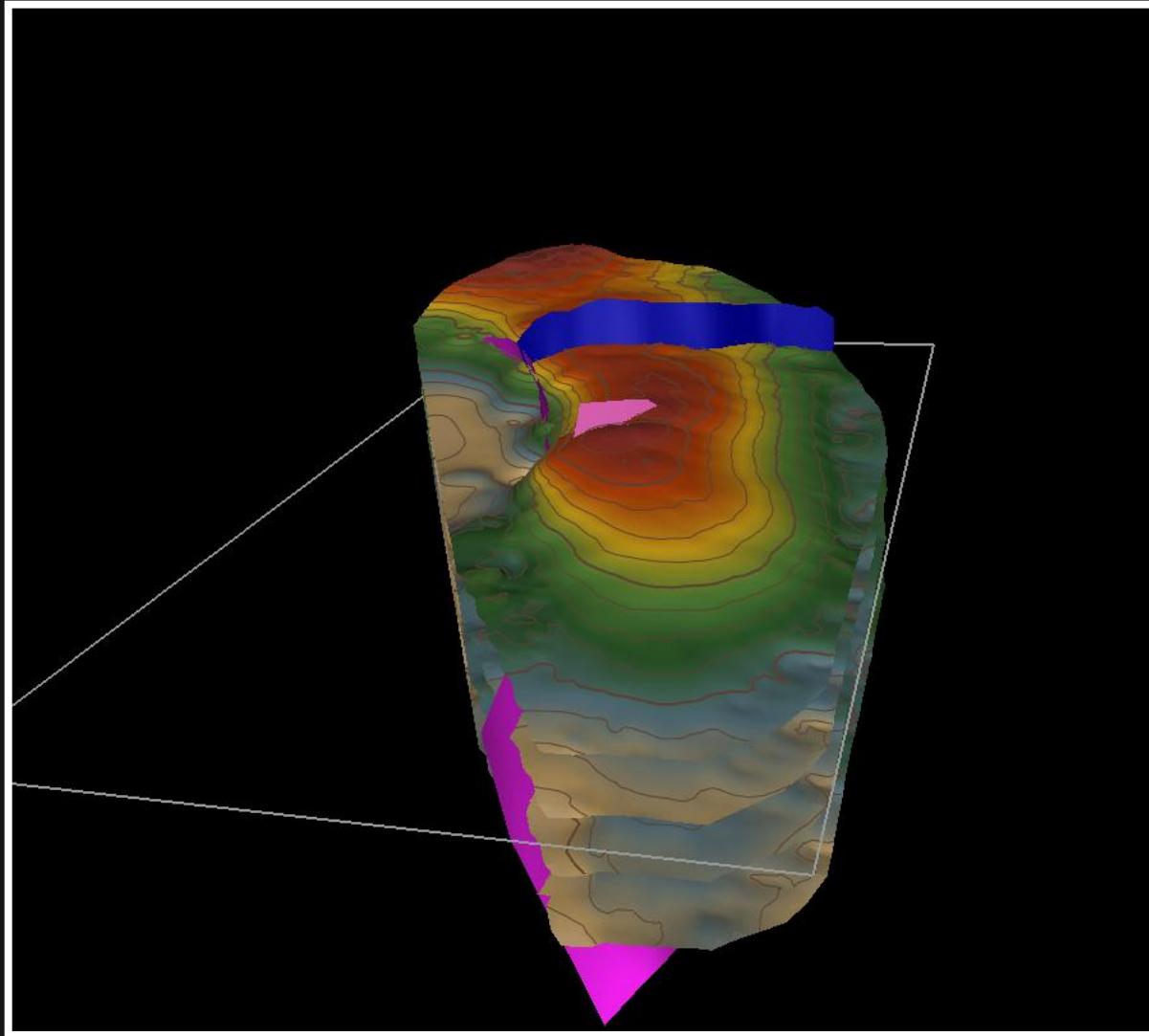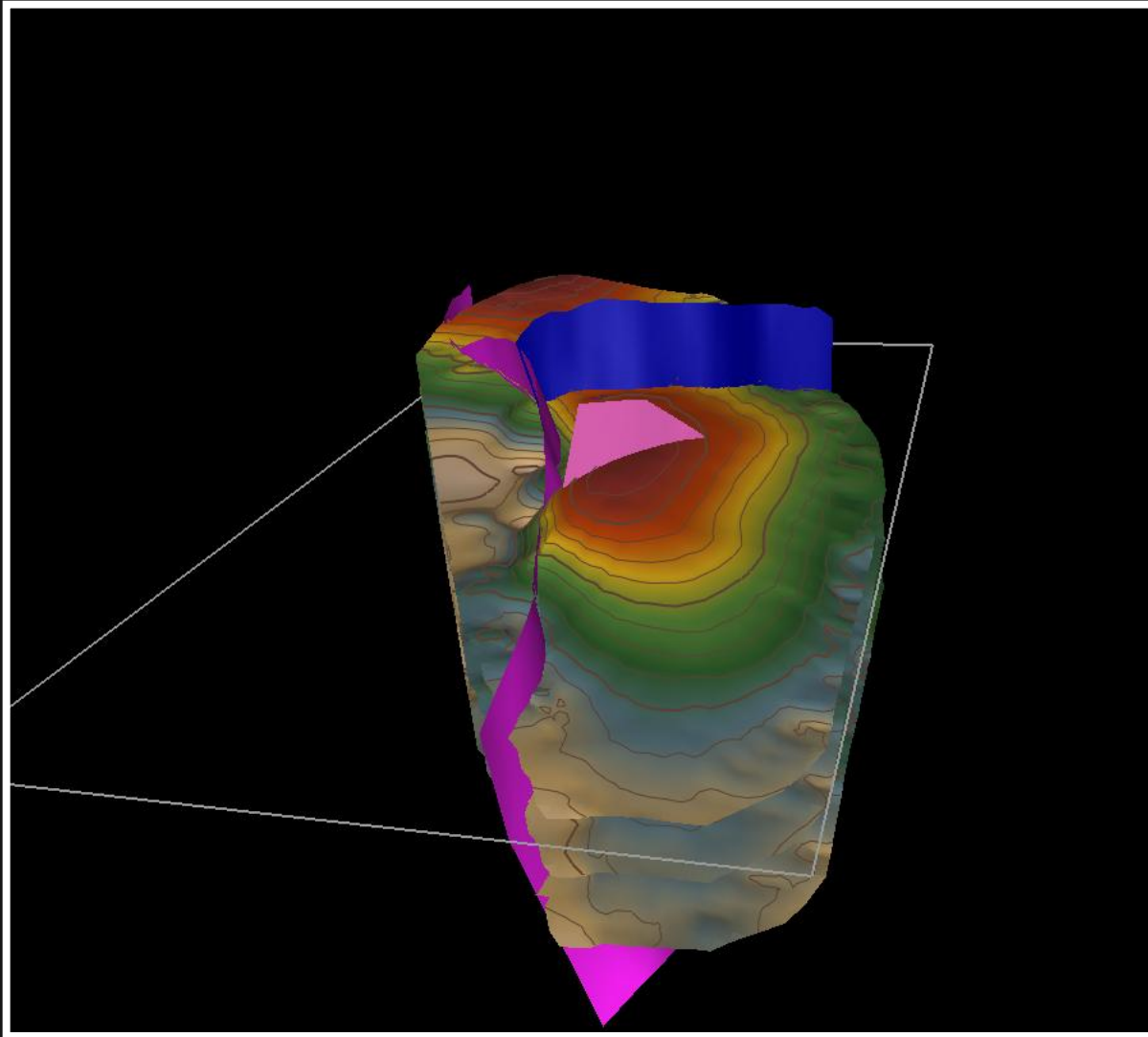
Teapot Dome 3D structure

Teapot Dome 3D structure

Teapot Dome 3D structure

Teapot Dome 3D structure

Teapot Dome 3D structure

Section D
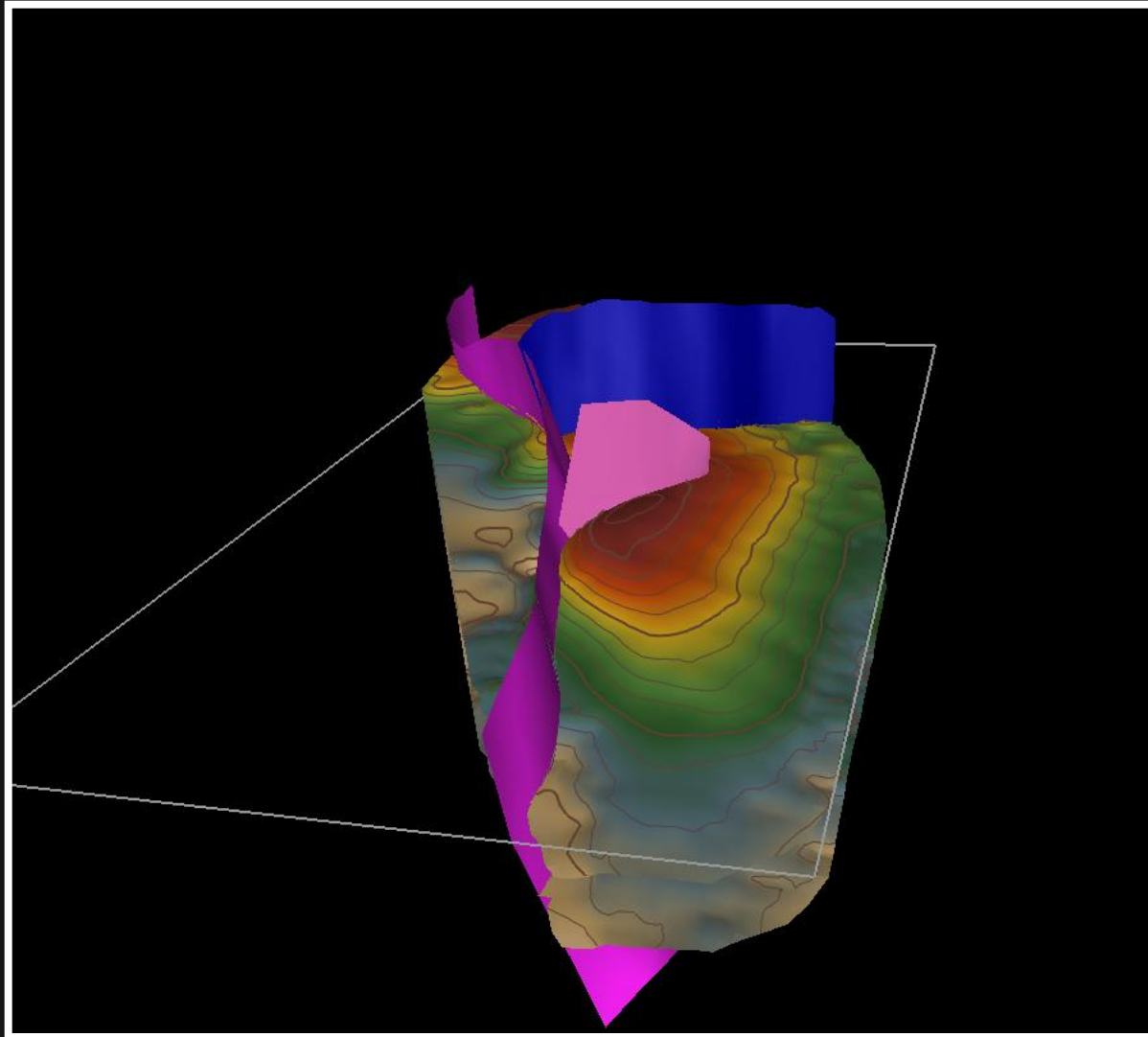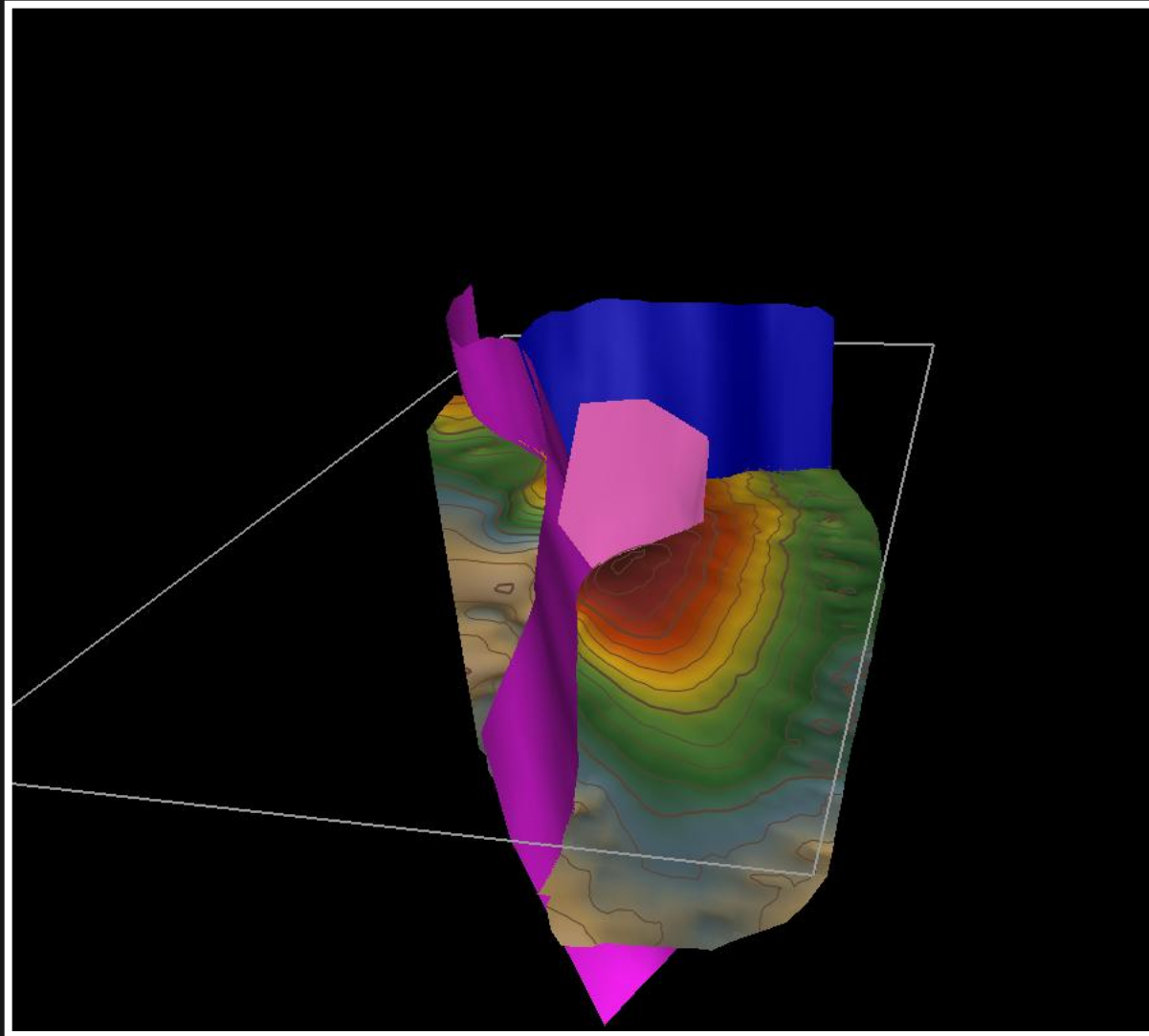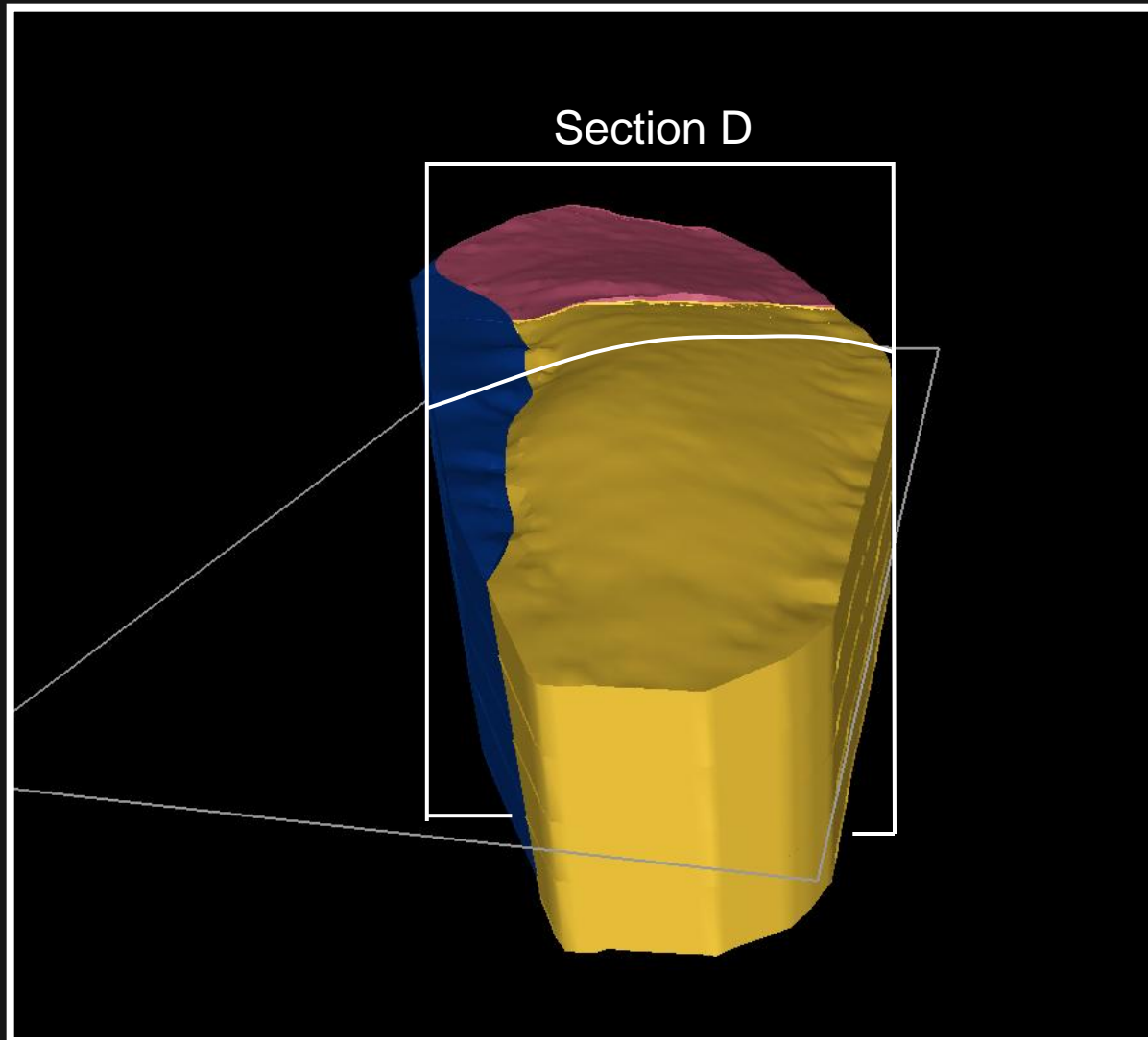
The role of the Teapot Dome fault

Fault location and trajectory critical for:

- structural analysis and 2D/3D modeling
- strain distribution modeling
- volume estimates
- controls of deformation on
  fracture permeability

Fault interpretations:

- Extensional normal fault
- Basement-involved
  blind thrust fault with
  unconstrained trajectory
- Thrust fault
- Fold bend fold

Section D

WSW

ENE

Section D

WSW

ENE

topography

Legend (top to bottom):
- Fox Hills Ss
- Lewis Shale
- Kmvu Parkman
- Cody Shale - Steele
- Sussex Ss
- Shannon Ss
- Niobrara
- Carlisle
- F2WallCreek
- F2WC
- Dakota
- Redpeak
- Tensleep
- PC
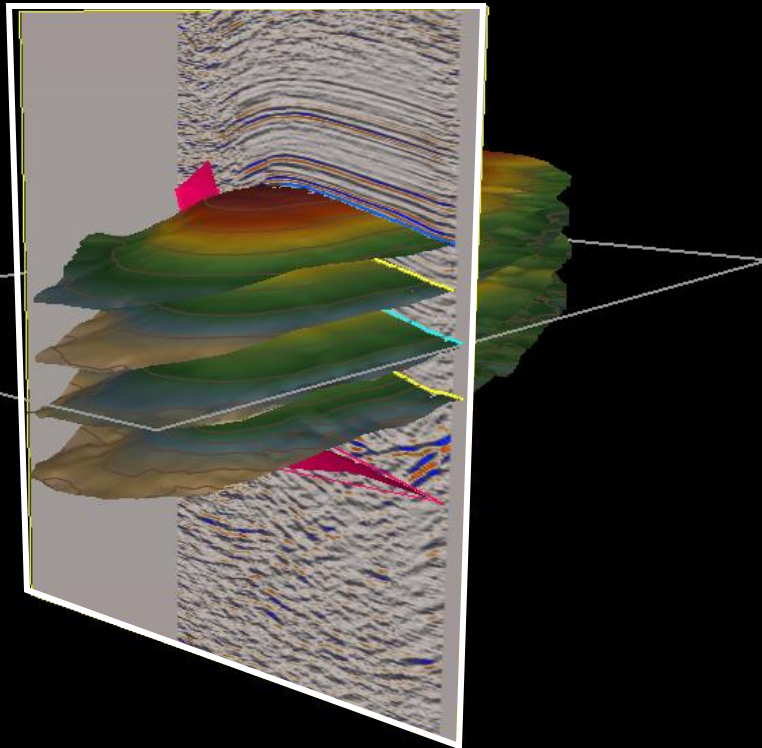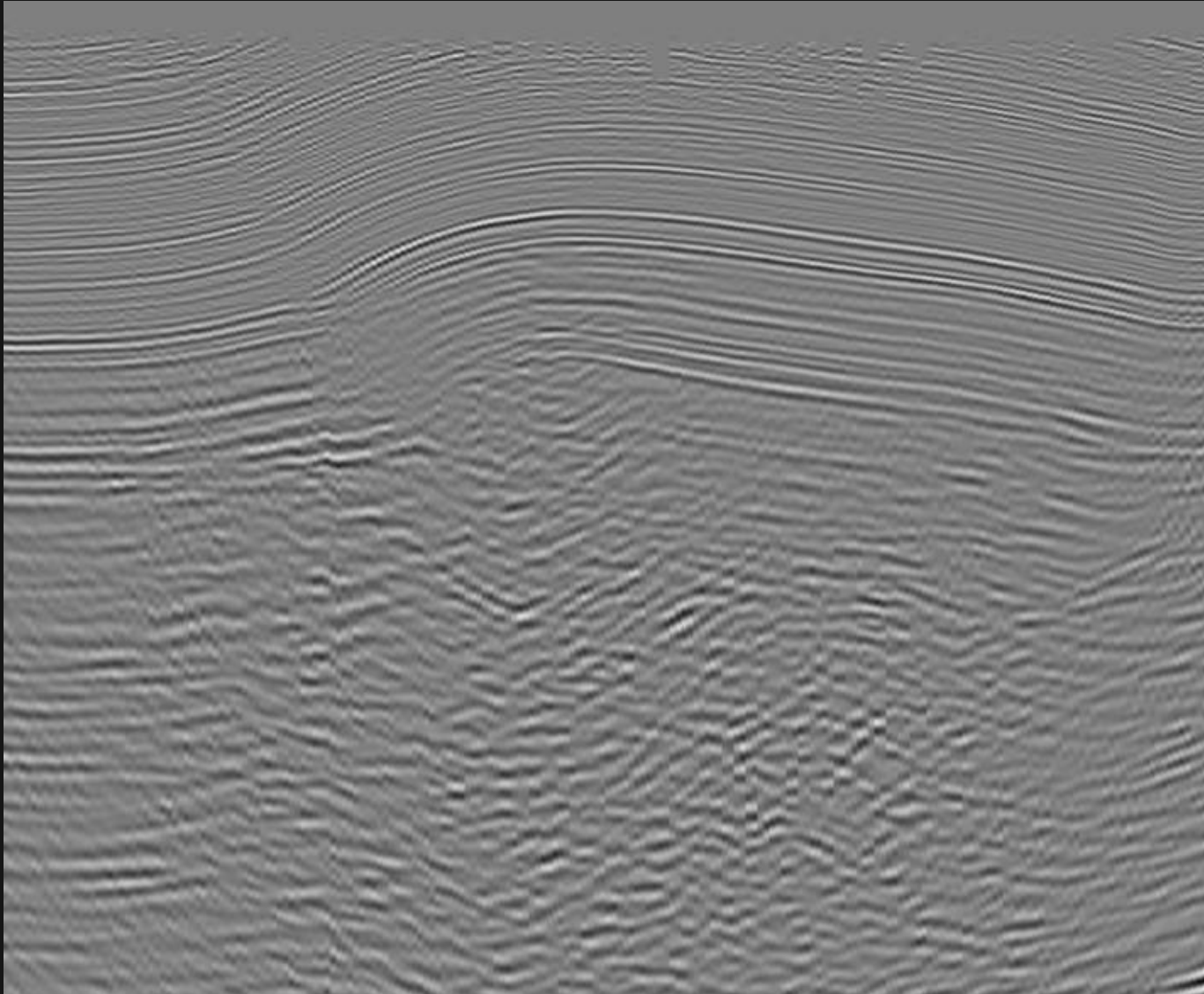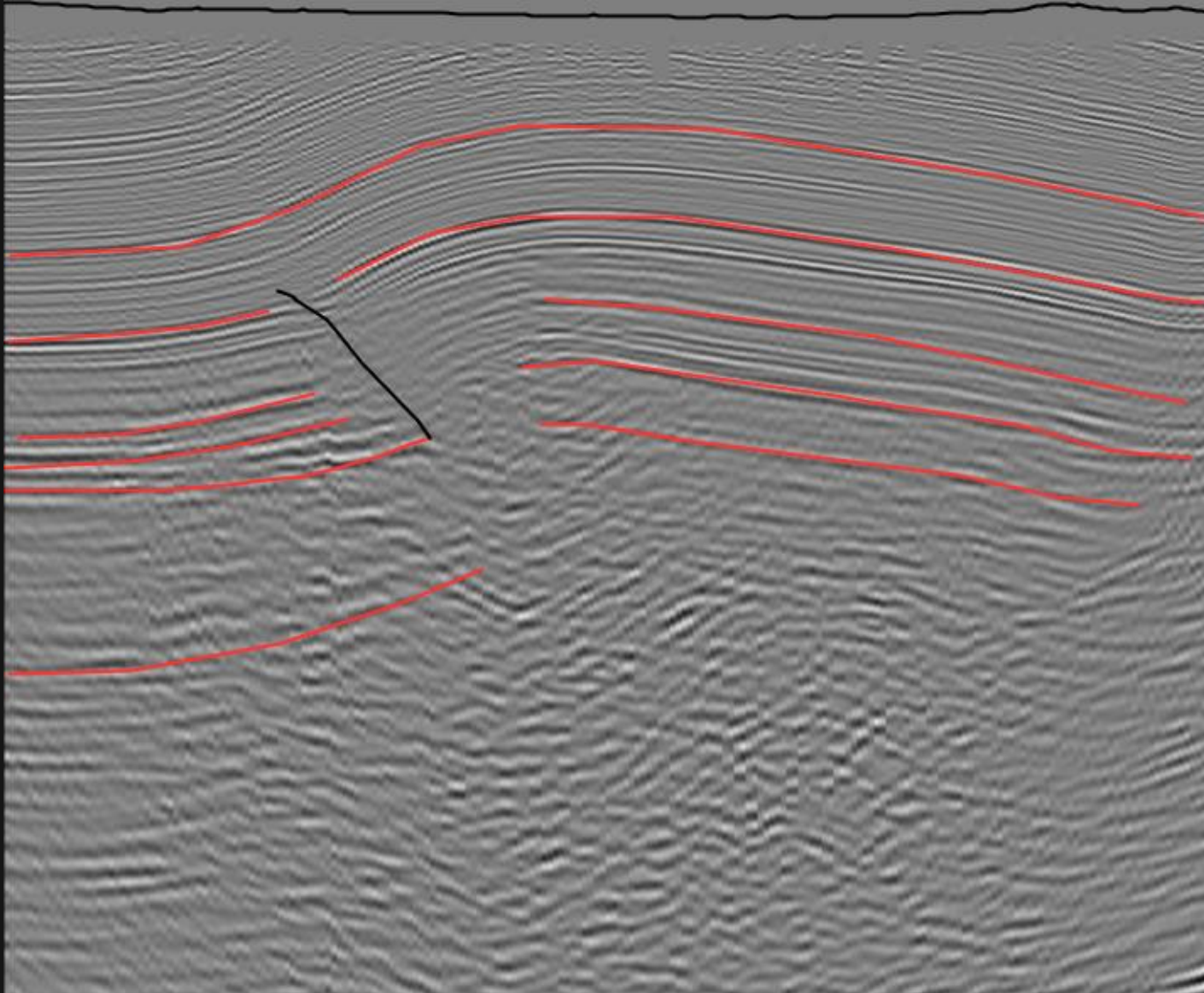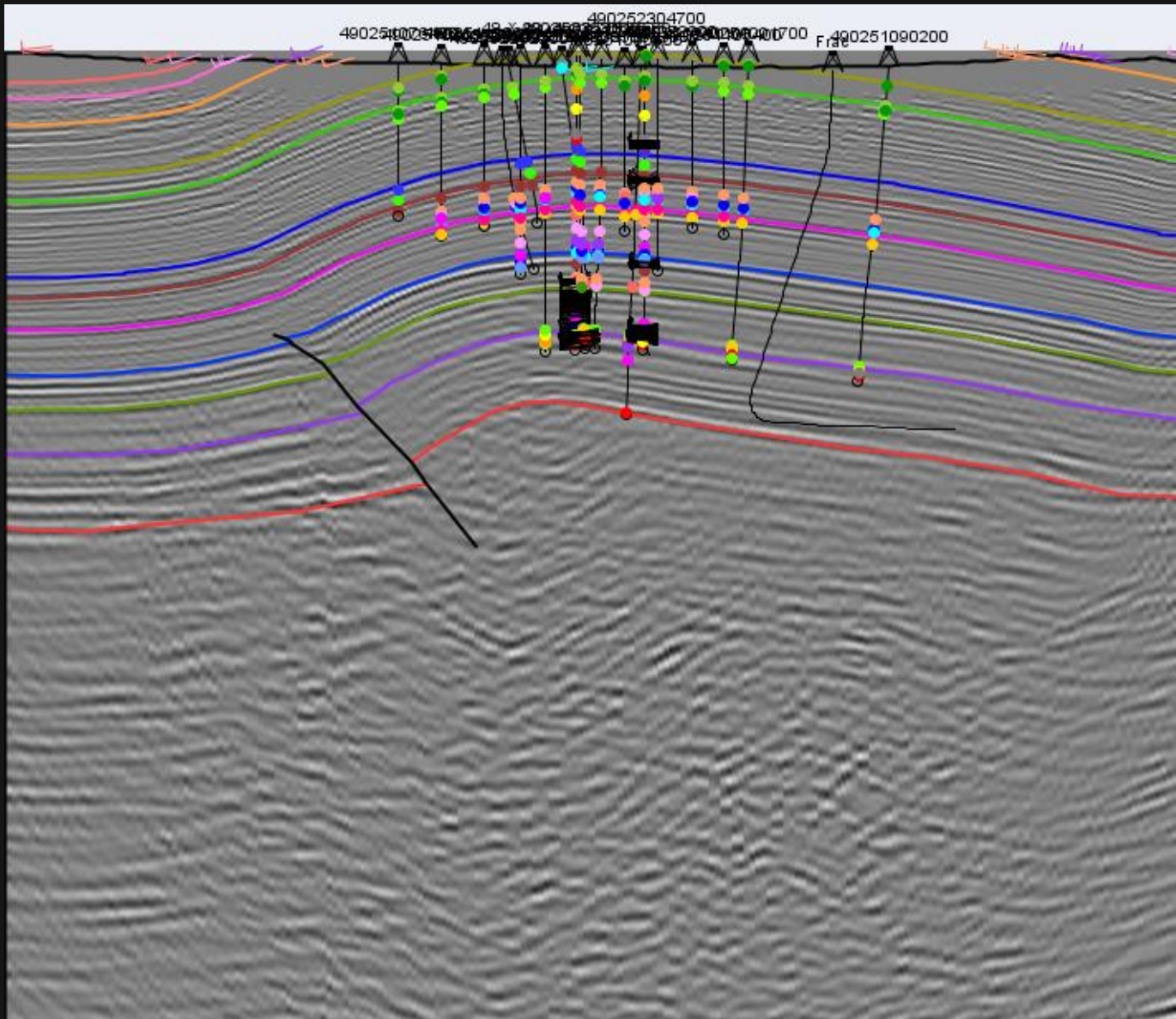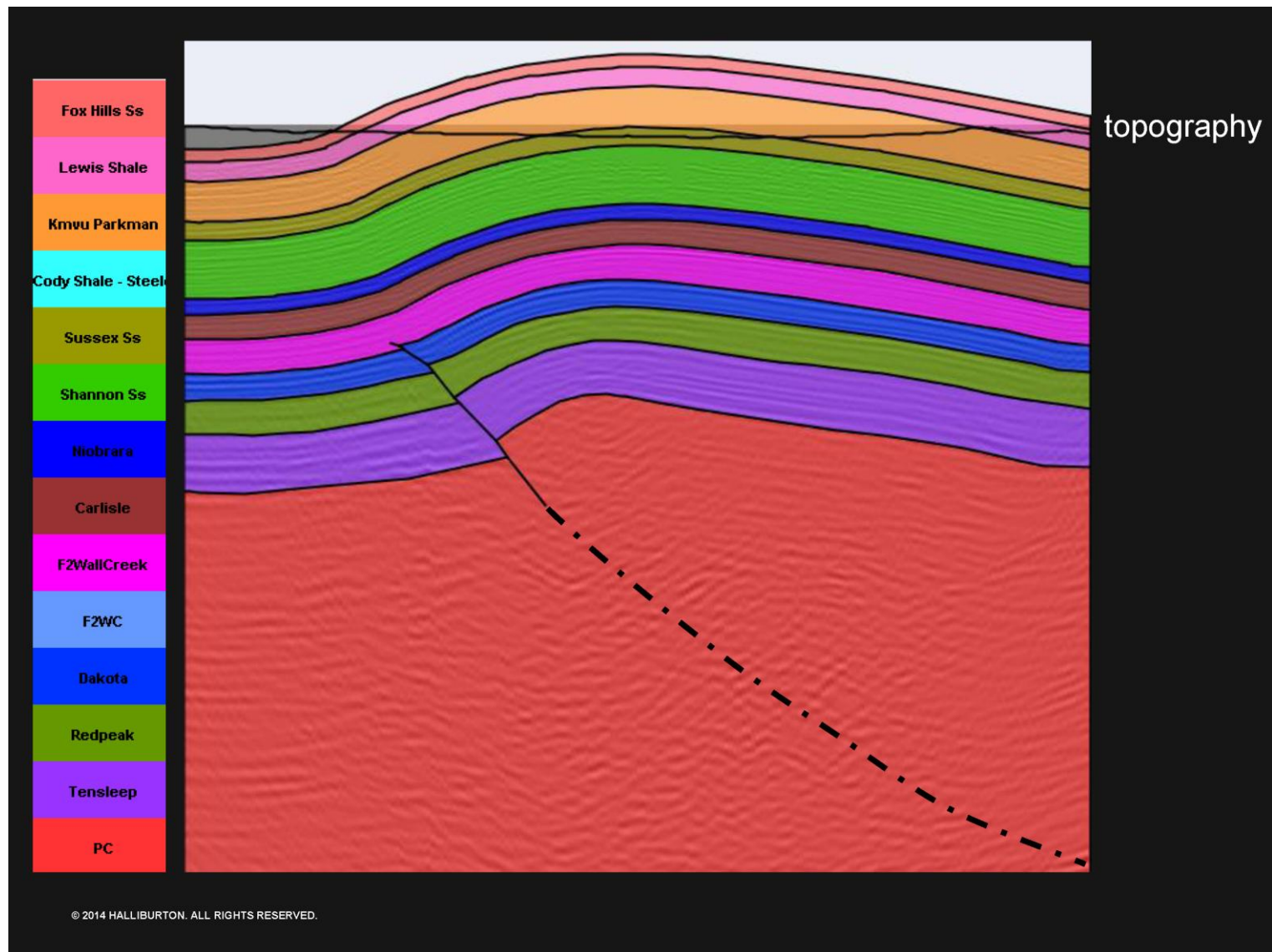
Presenter's notes: Original interpretation.

TRISHEAR

Fault prediction and forward modeling

predicted fault
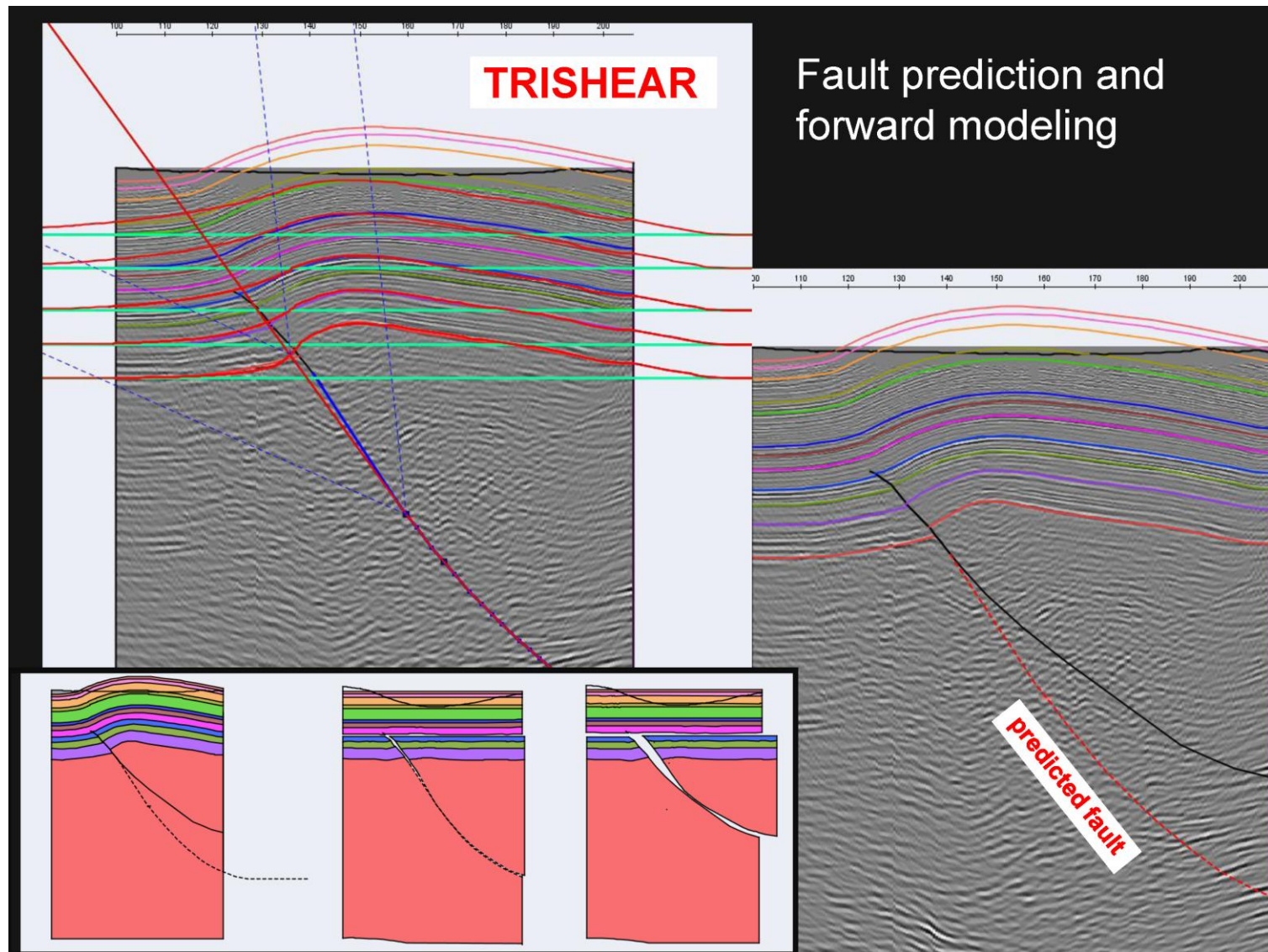
Presenter's notes: Predict fault trace based on hangingwall and footwall and cutoffs--steeper fault that probably soles out.

Forward modeling with trishear
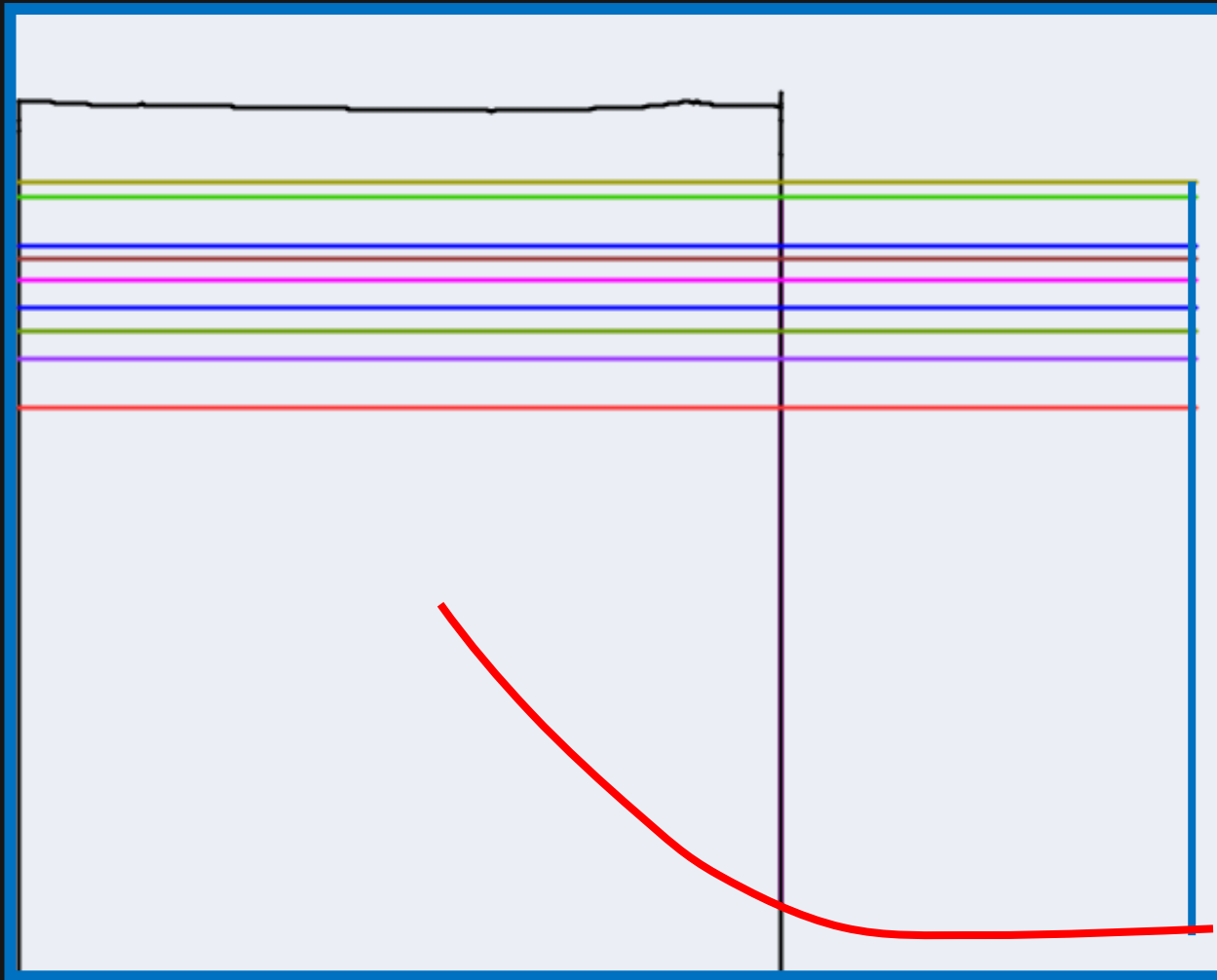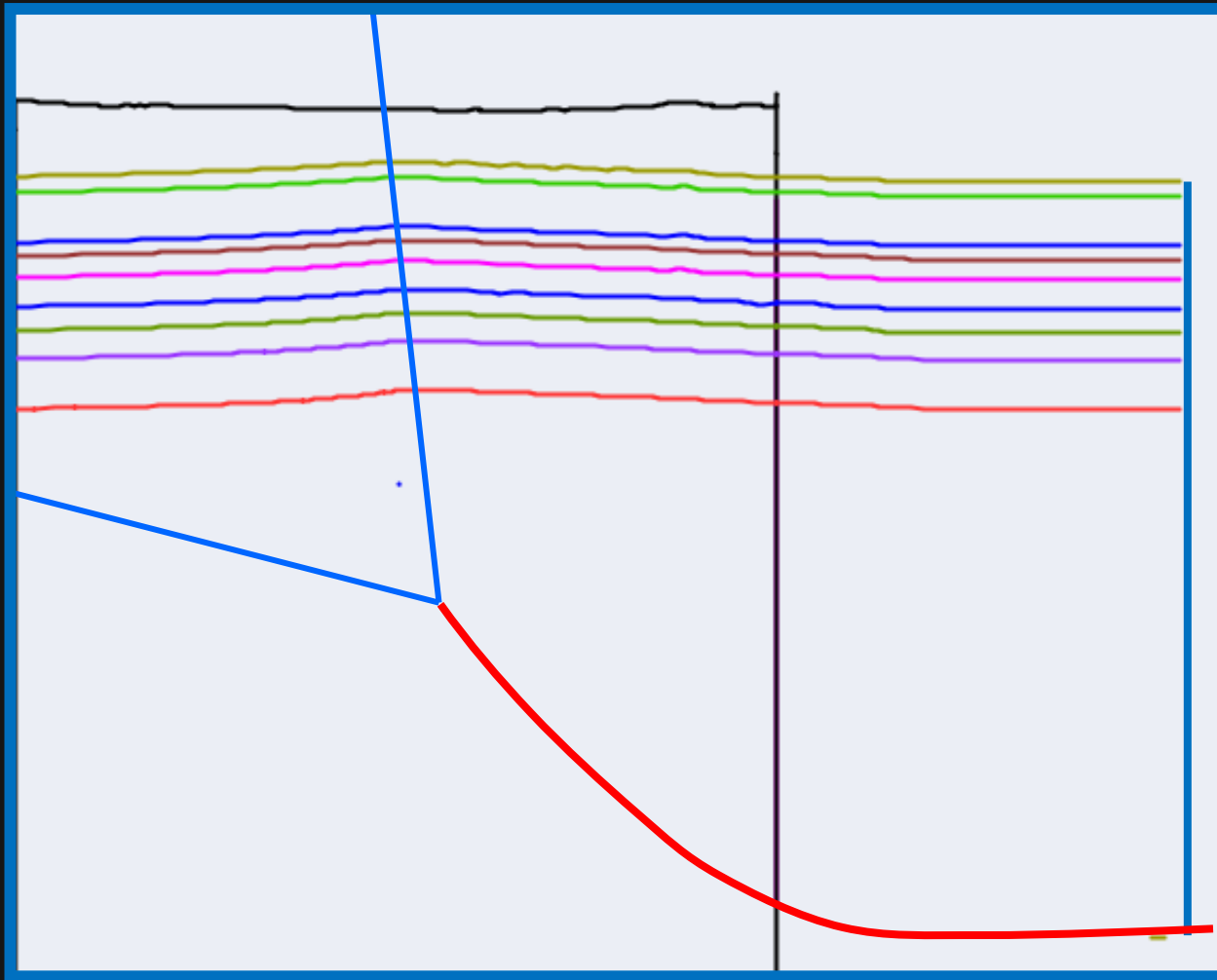
Forward modeling with trishear

Forward modeling with trishear
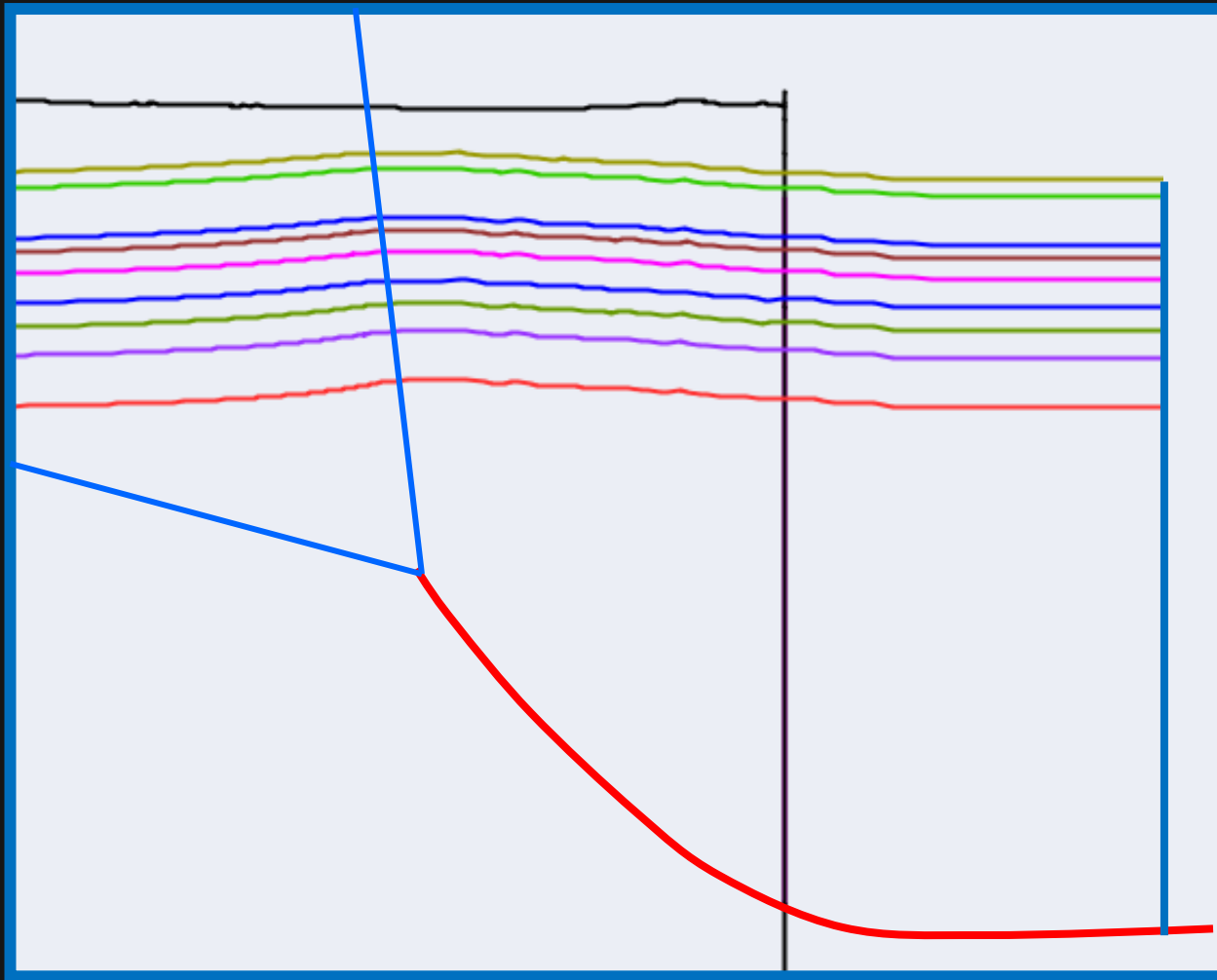
Forward modeling with trishear
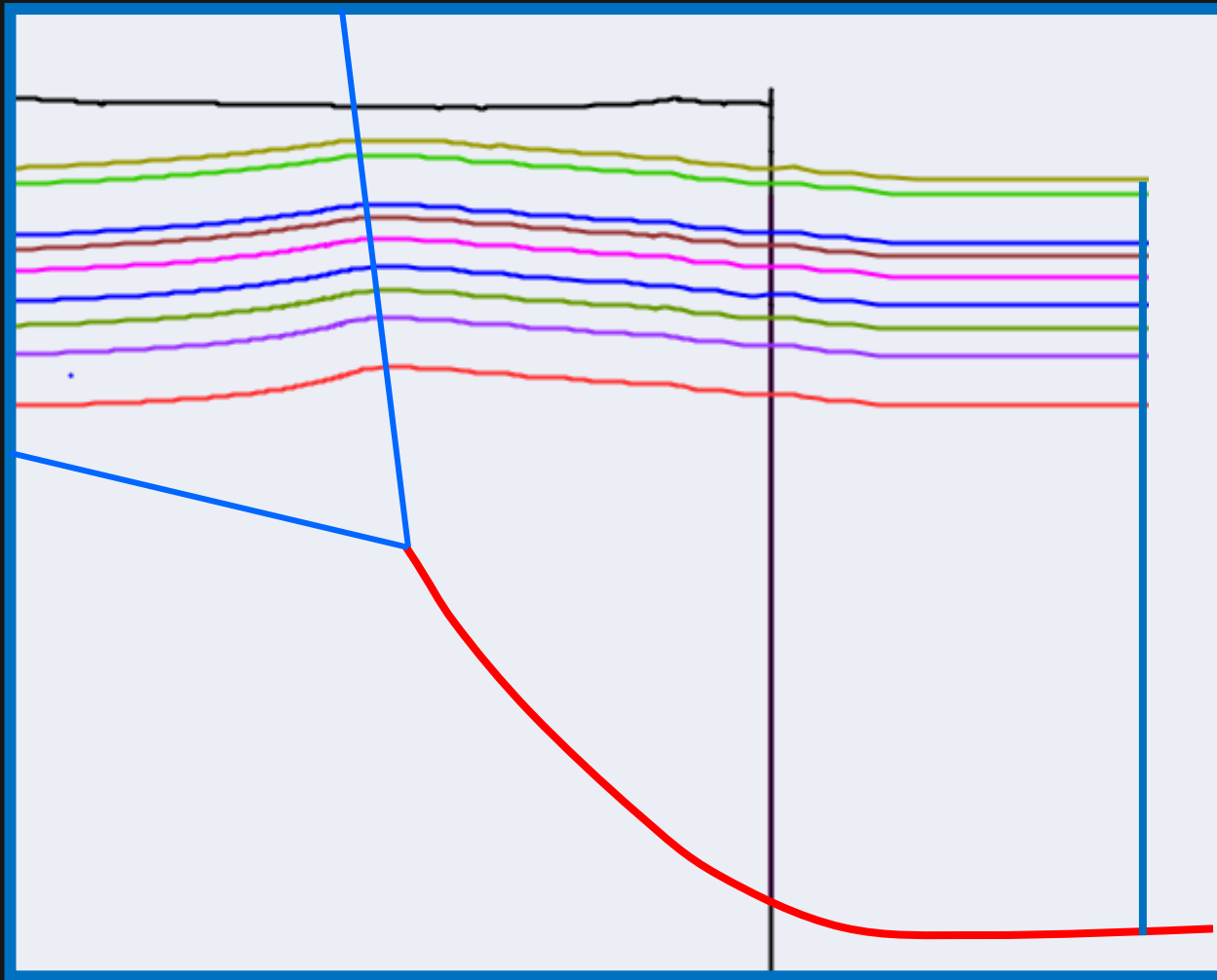
Forward modeling with trishear
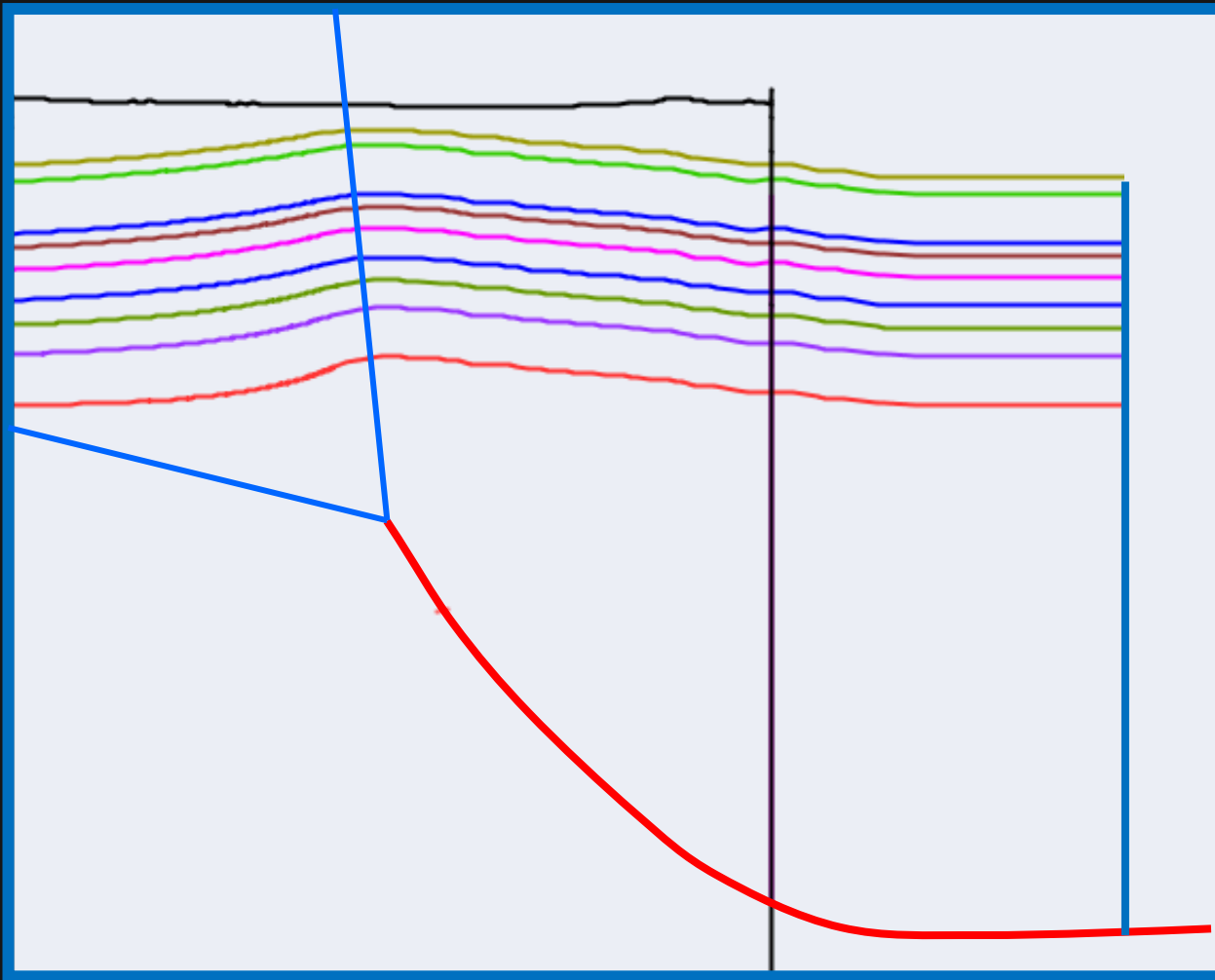
Forward modeling with trishear
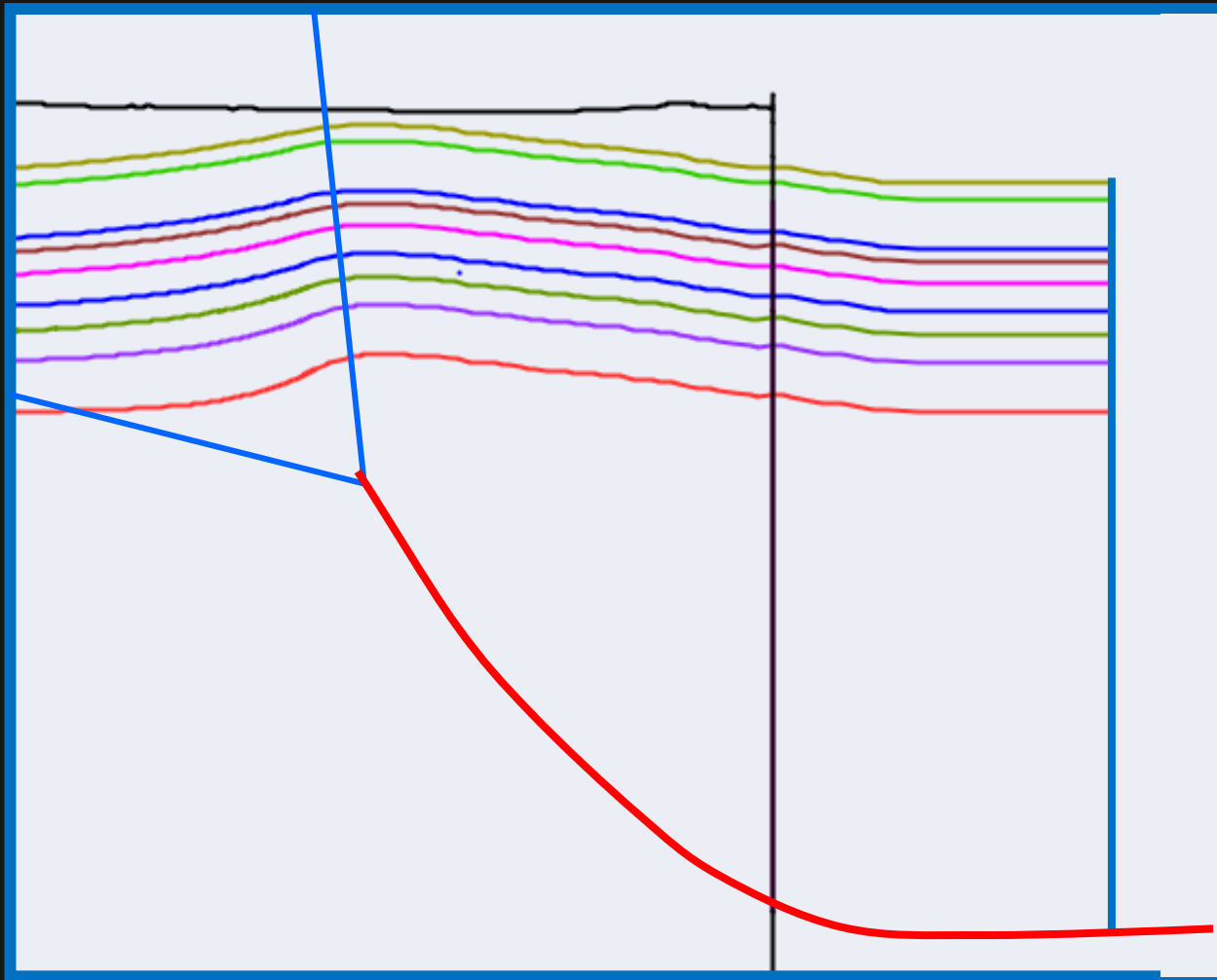
Forward modeling with trishear
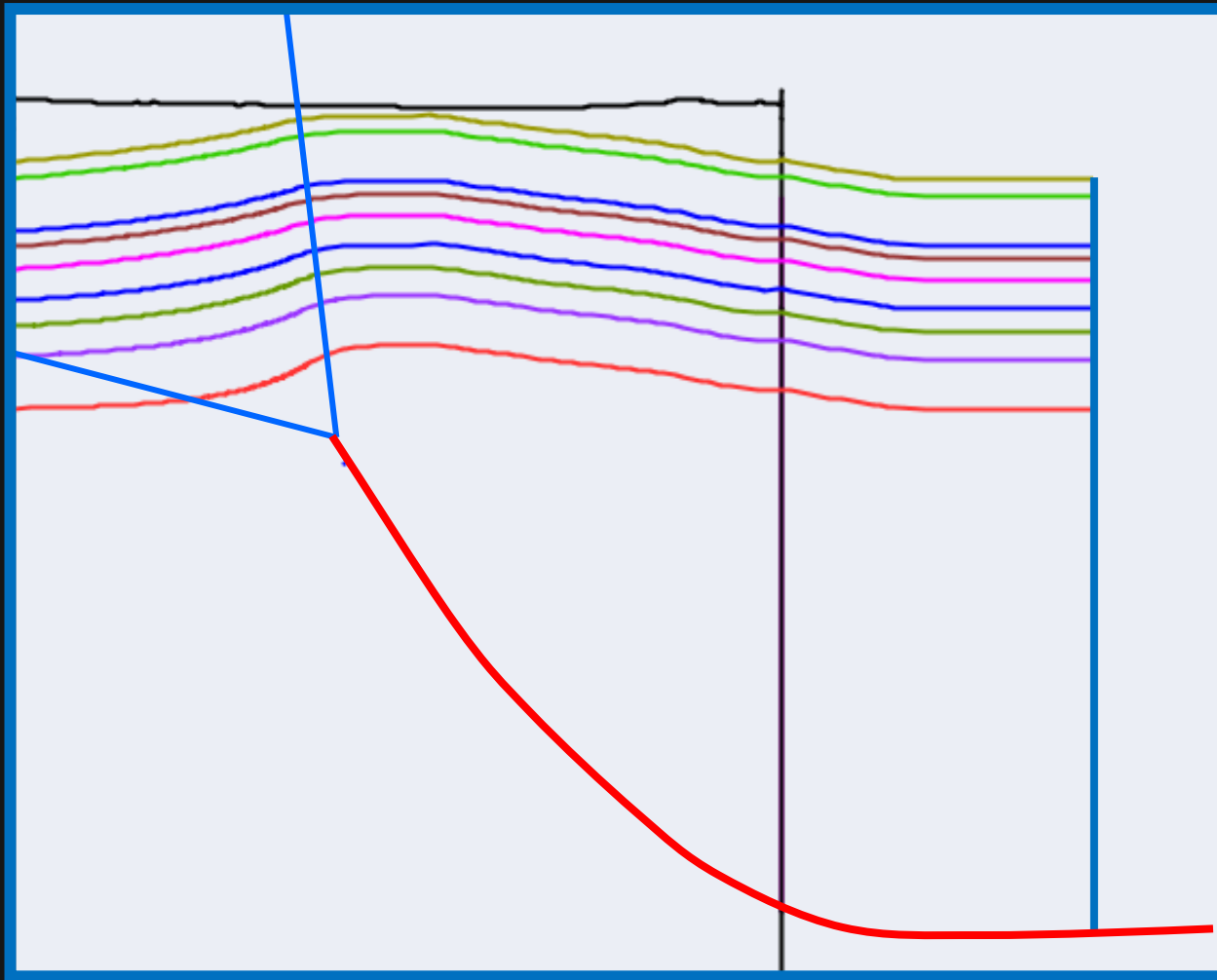
Forward modeling with trishear
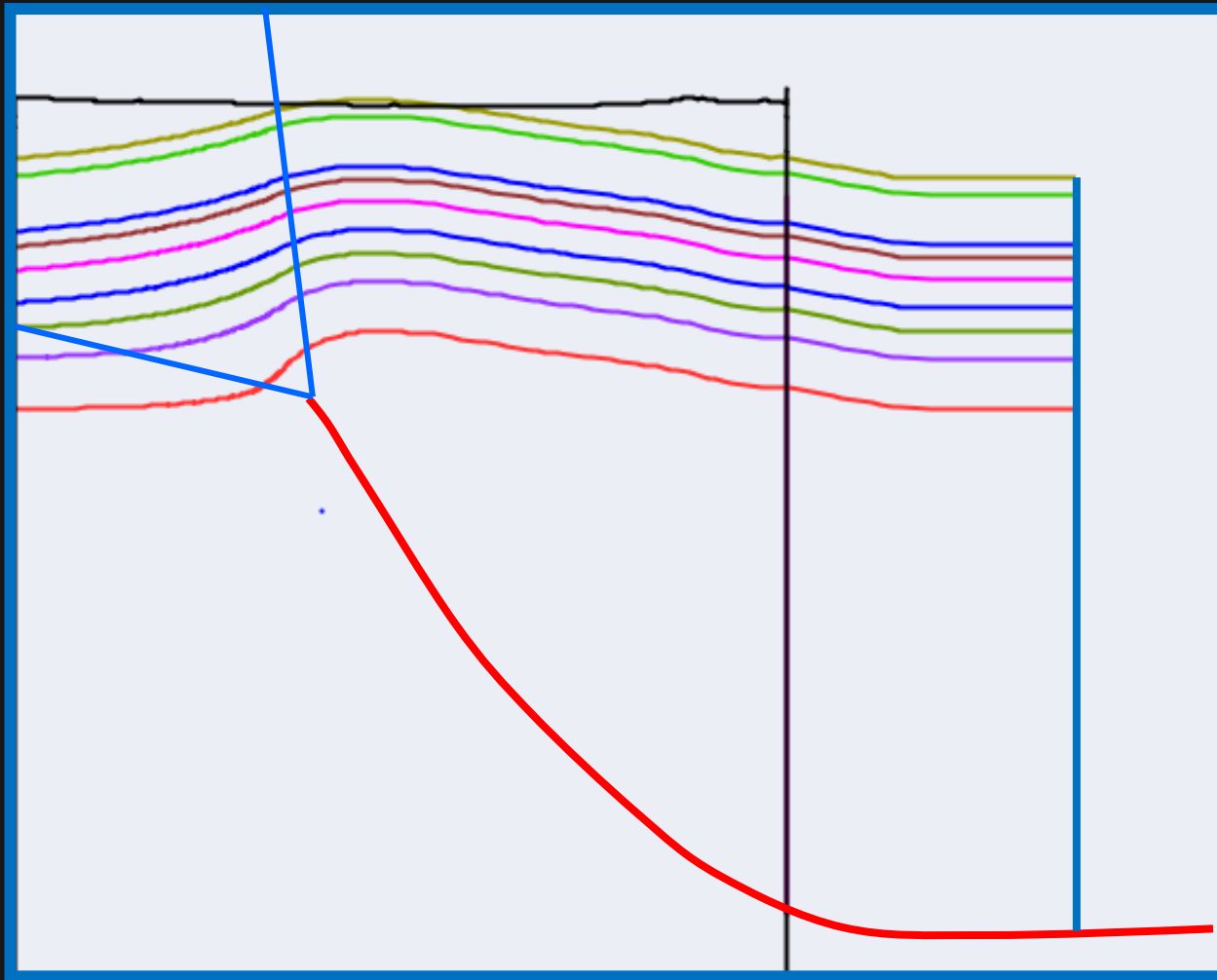
Strain as fracture proxy

Incremental strain = increments of distortion that affect a body during deformation from one stage to the next

Finite strain = summation of all of the incremental components representing the total distortion (strain) compared to its original shape.

Cumulative strain = summation of all of the incremental components from one step to the next – adding absolute values

HAVE TO KNOW DEFORMATION HISTORY!
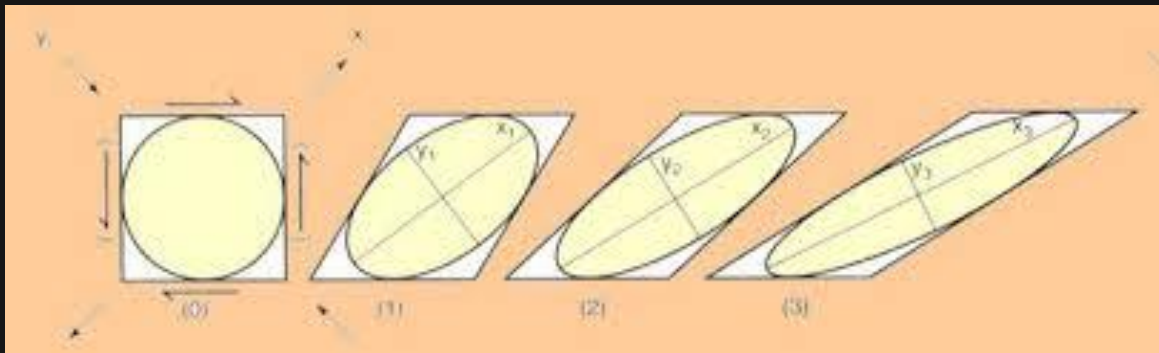
Stages of strain evolution
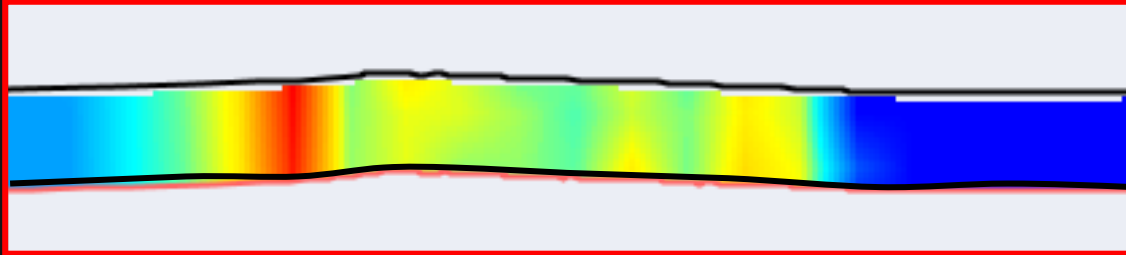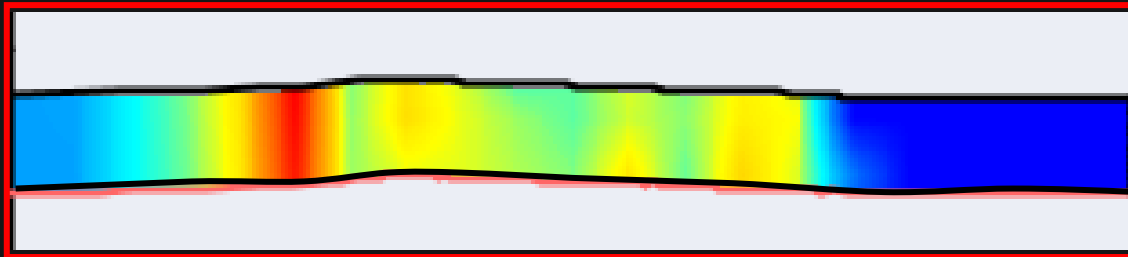
Incremental shear strain

Finite shear strain

Cumulative shear strain
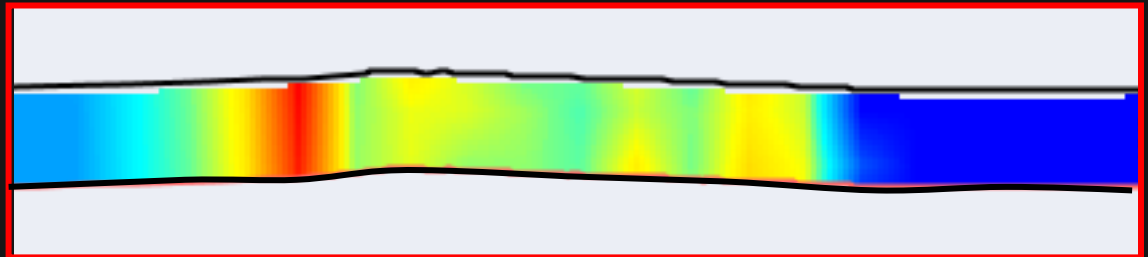
Stages of strain evolution

Incremental shear strain
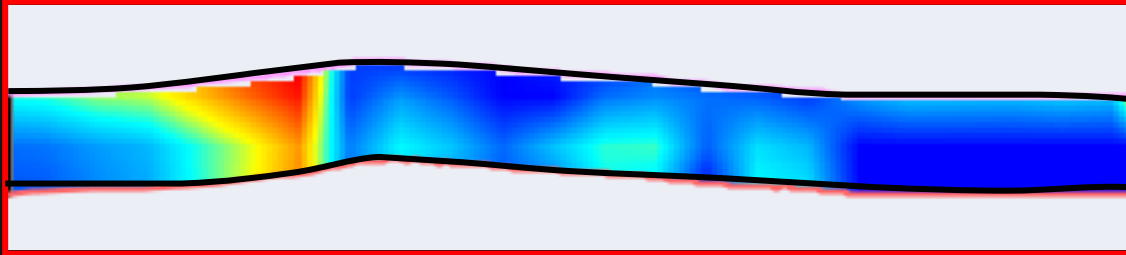
Finite shear strain
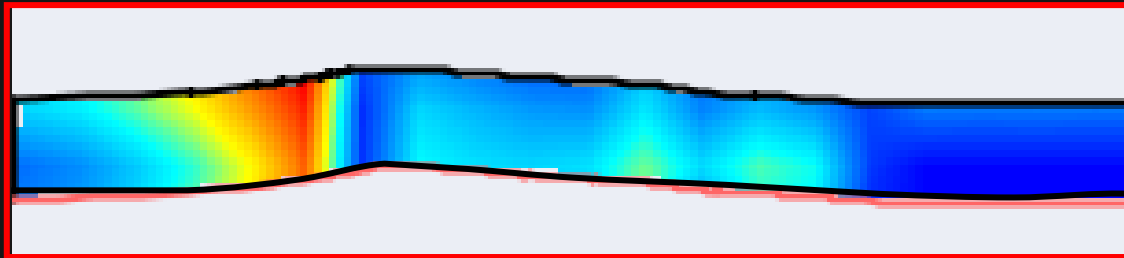
Cumulative shear strain
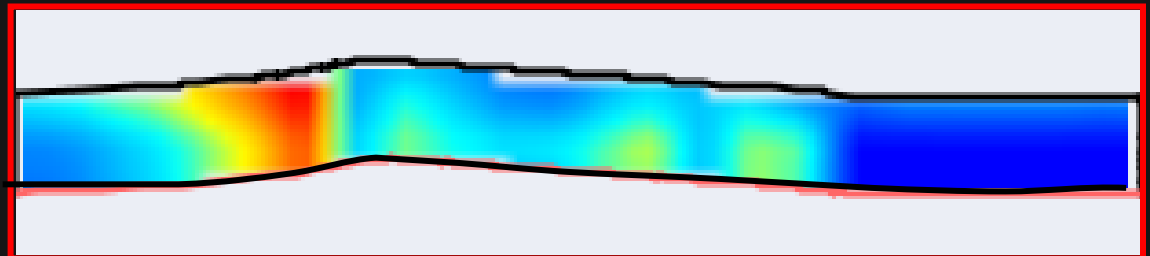
Stages of strain evolution

Incremental shear strain
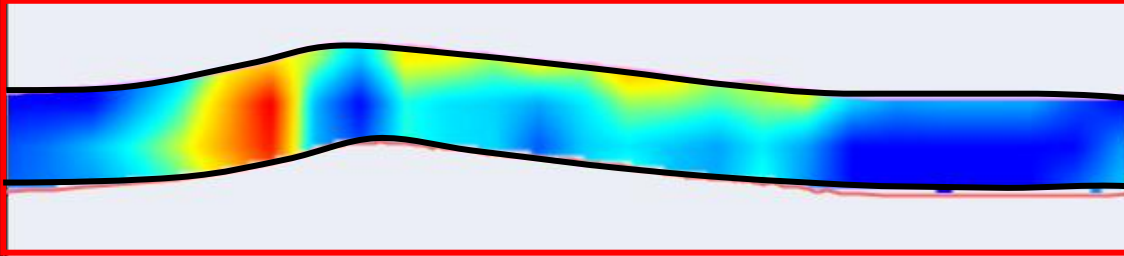
Finite shear strain
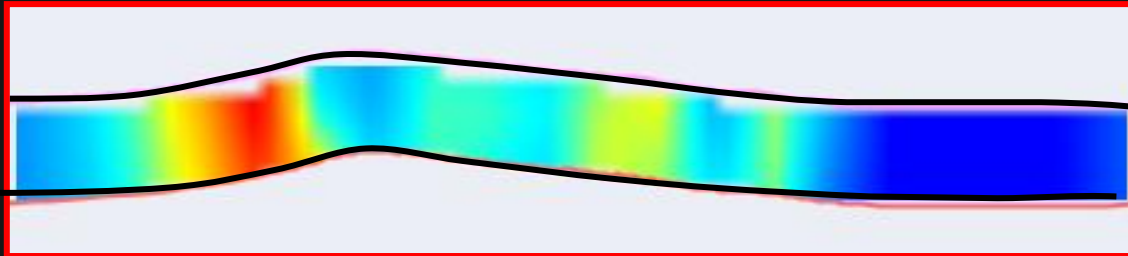
Cumulative shear strain
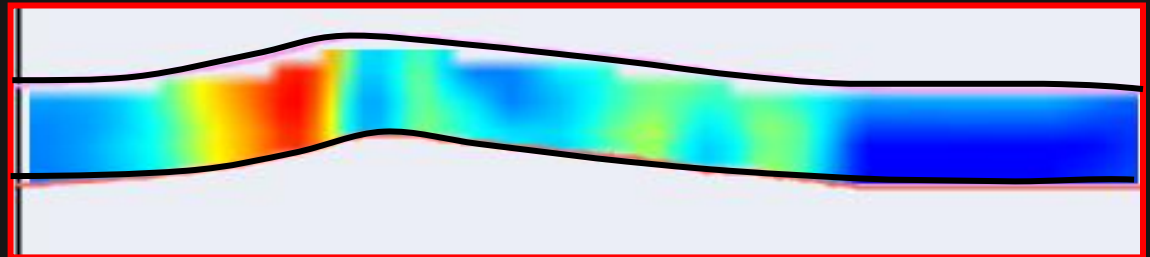
Stages of strain evolution

Incremental shear strain
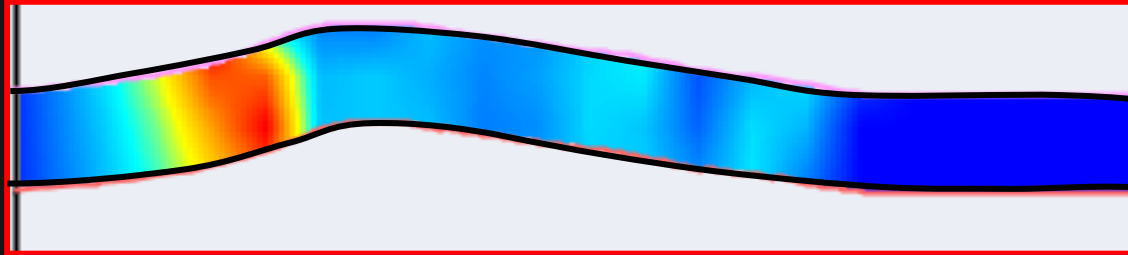
Finite shear strain
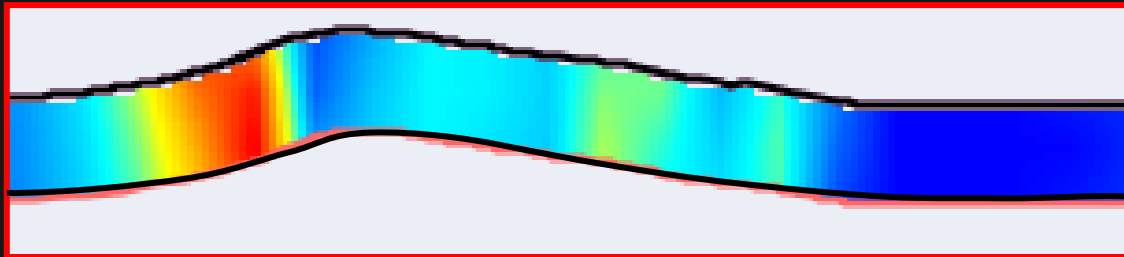
Cumulative shear strain
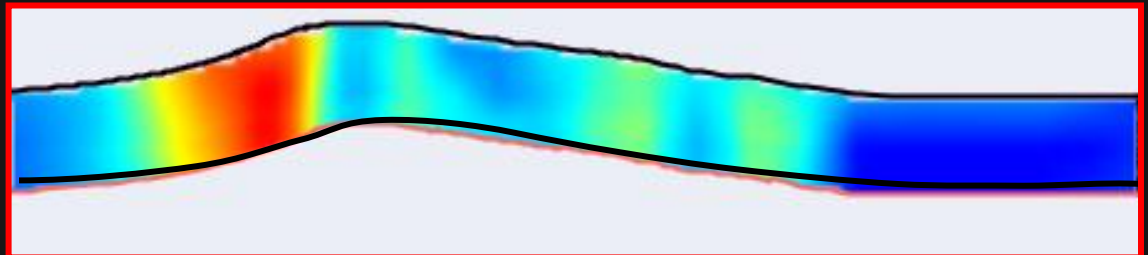
Curvature and dip as fracture proxy

Curvature

Dip

wavelength 20000 ft

wavelength 10000 ft

wavelength 5000 ft

3D curvature field

Geometry Fields

Dip

Incremental shear strain

Curvature

Finite shear strain

Bedding
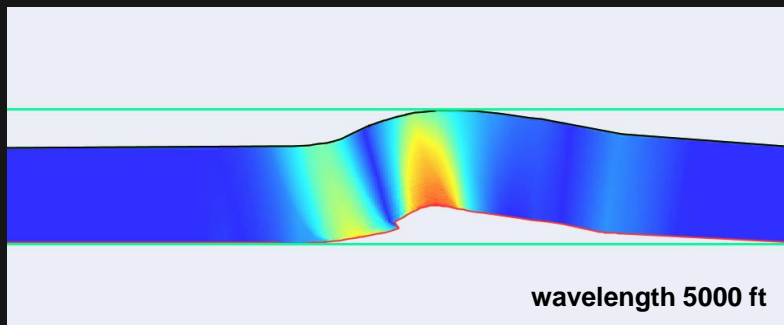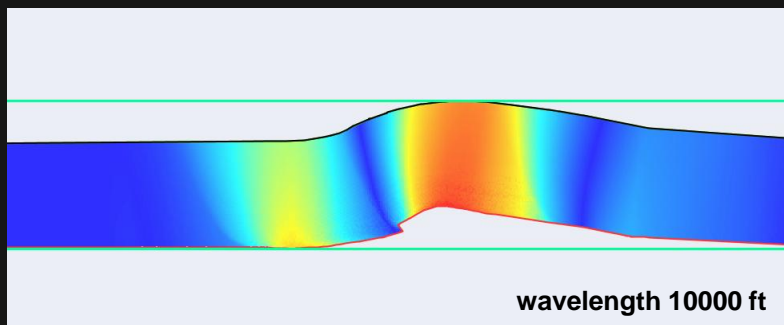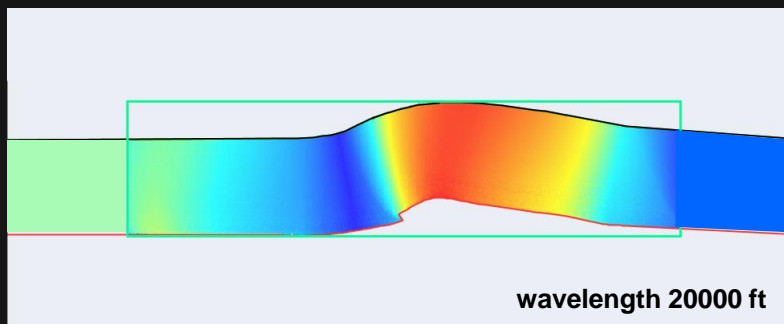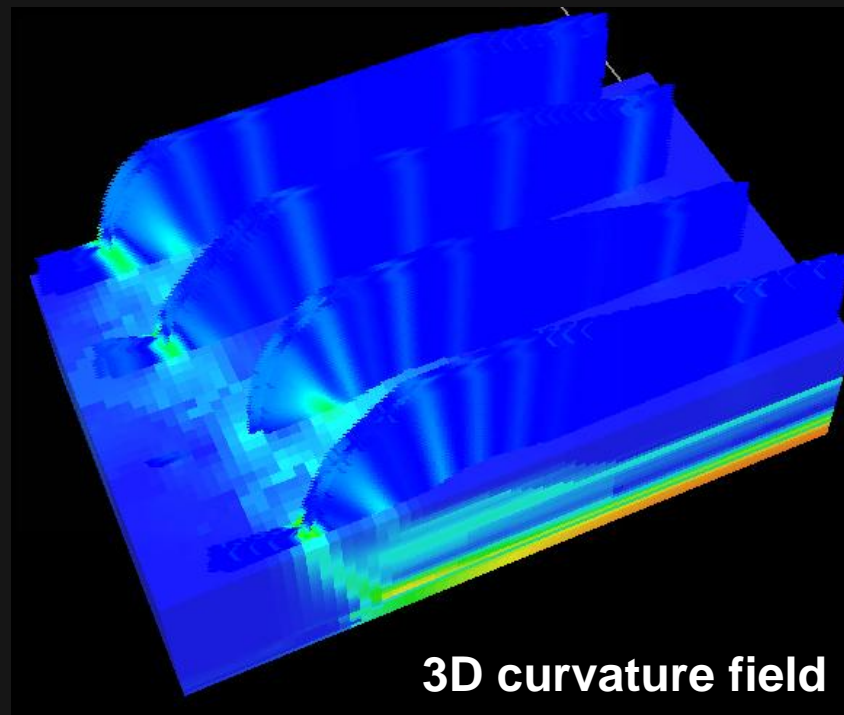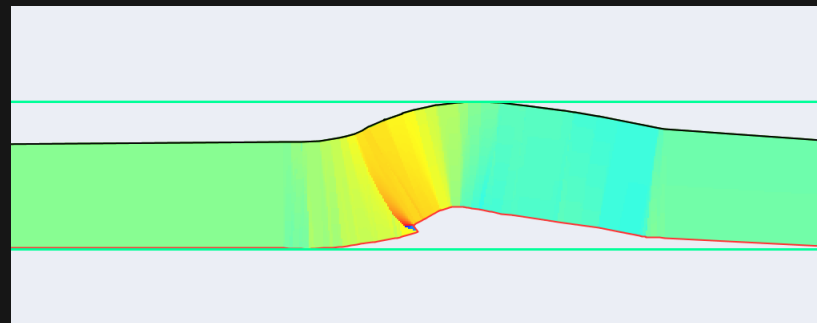
Cumulative shear strain
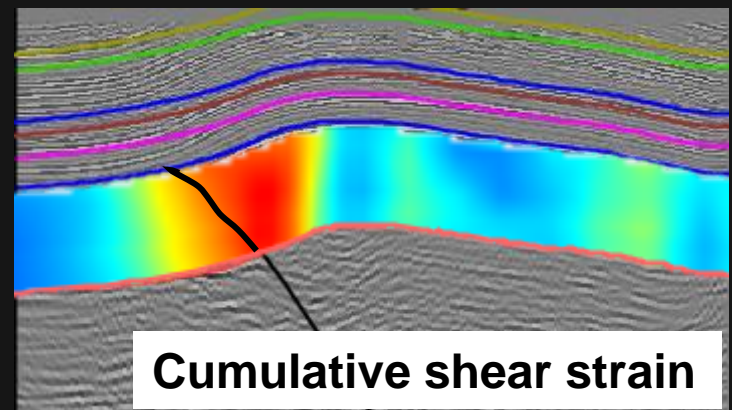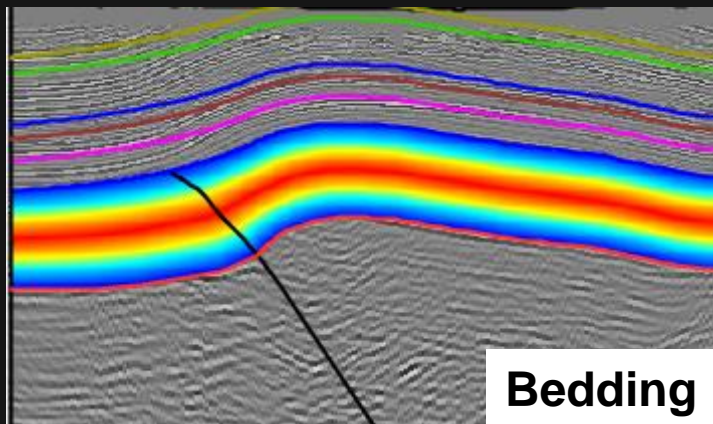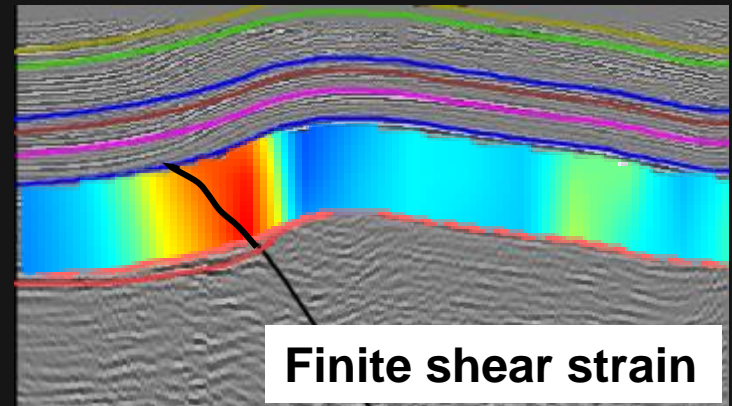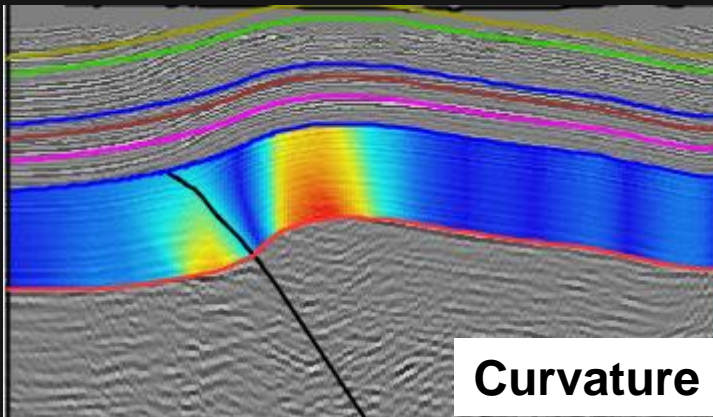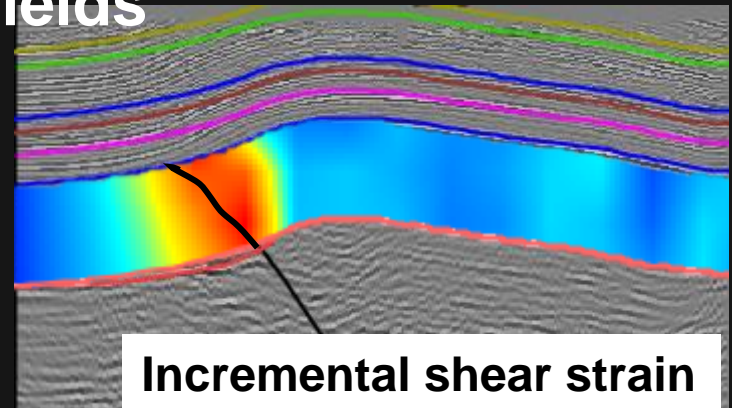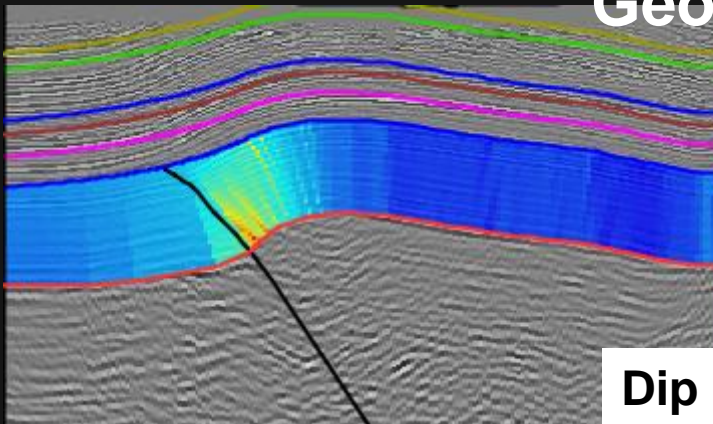
Evolution of strain and curvature

Incremental shear strain **Cumulative shear strain** **Curvature**
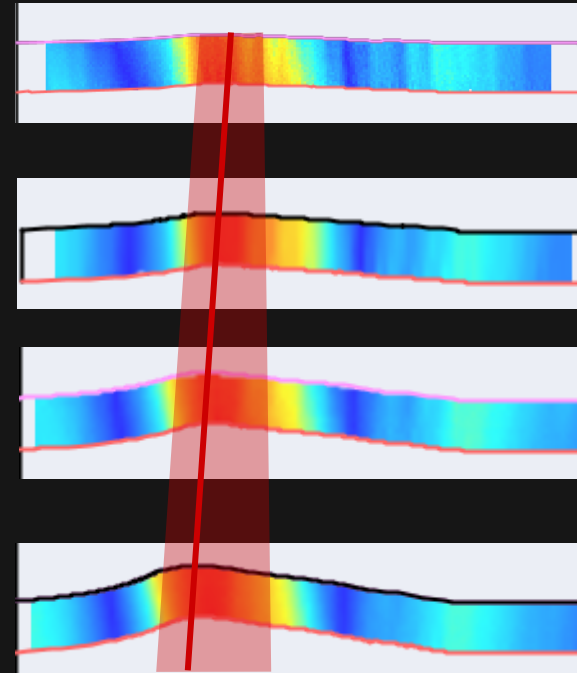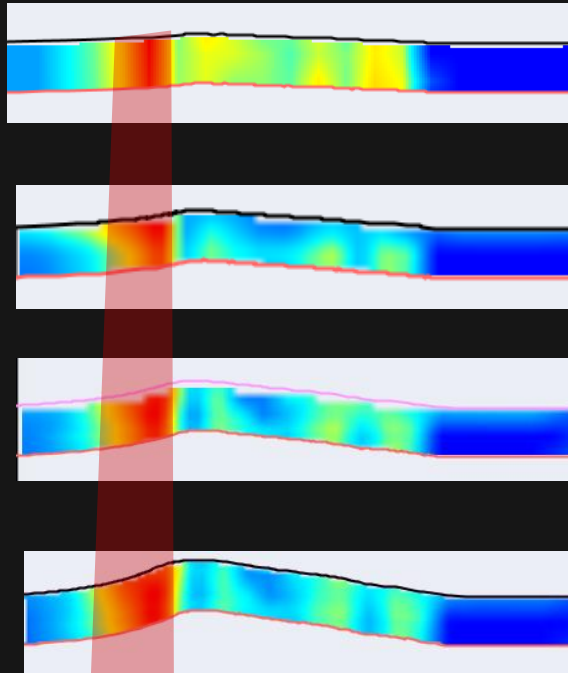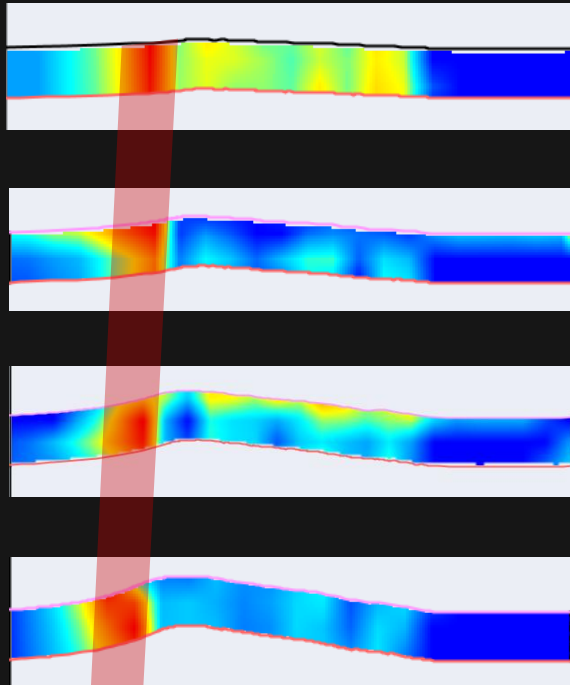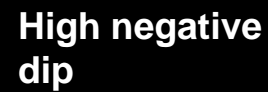

Zone of maximum incremental shear strain propagates

Zone of maximum cumulative shear strain propagates and widens

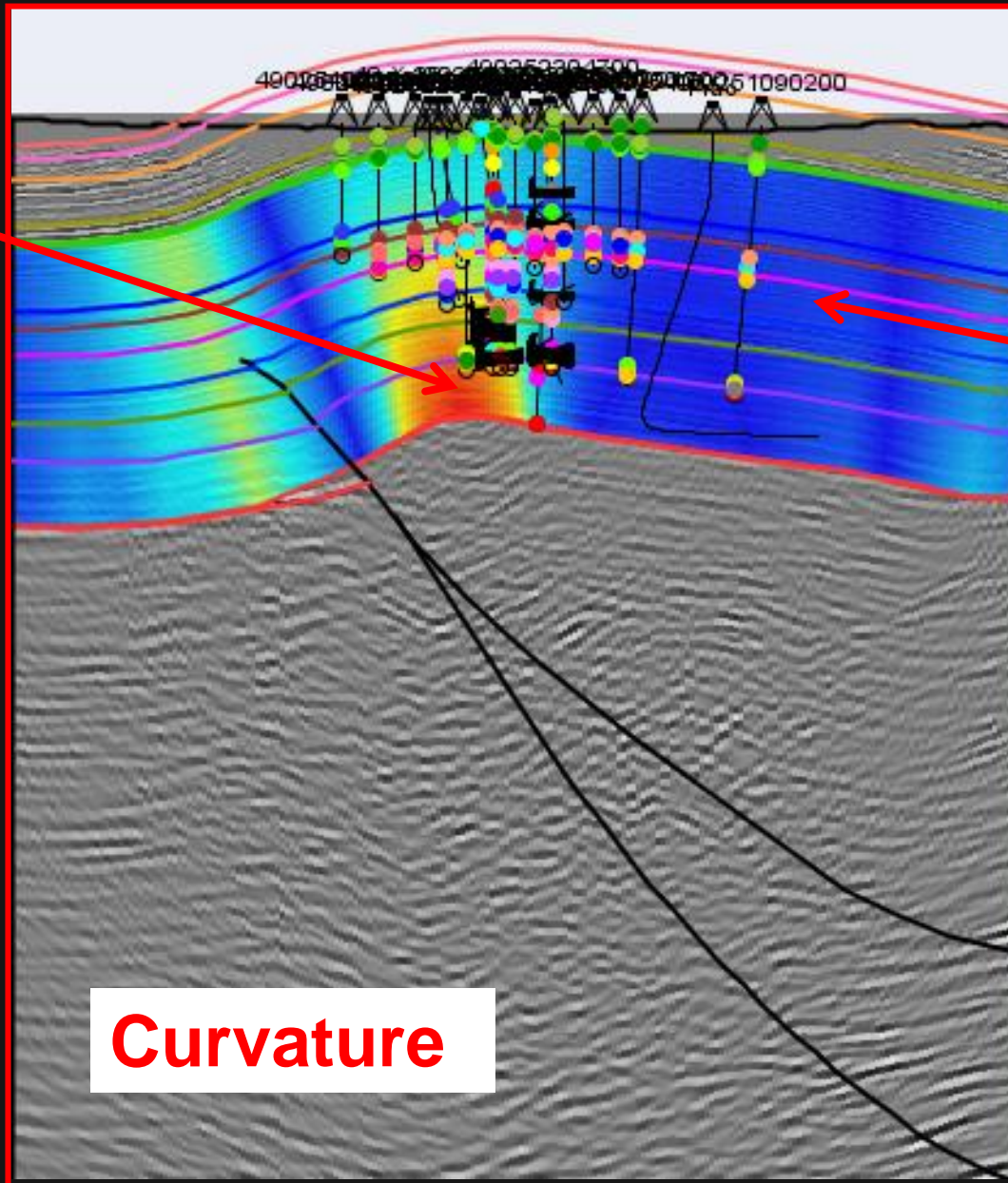Zone of max curvature propagates with hinge and widens

High curvature

High curvature

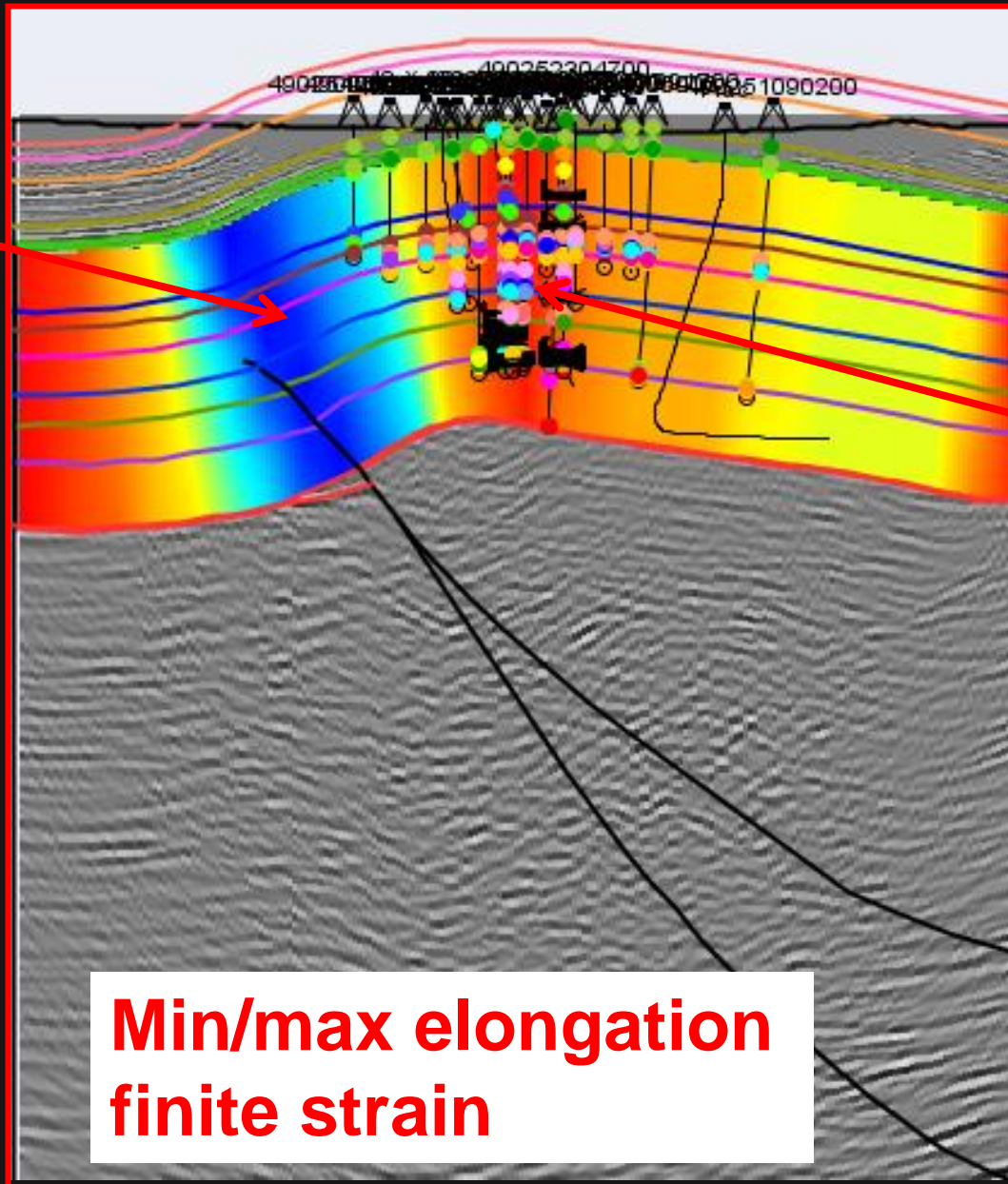Low curvature

Low min curvature

Curvature

Maximum elongation

High min elongation

Low min elongation

Minimum elongation

Min/max elongation finite strain

High shear strain

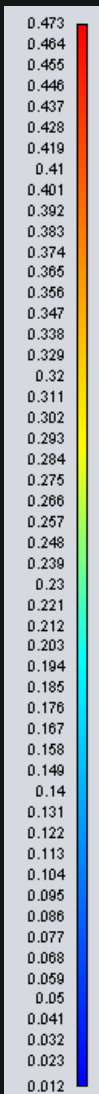High shear strain

Low shear strain

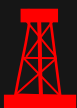Low shear strain

Cumulative shear strain
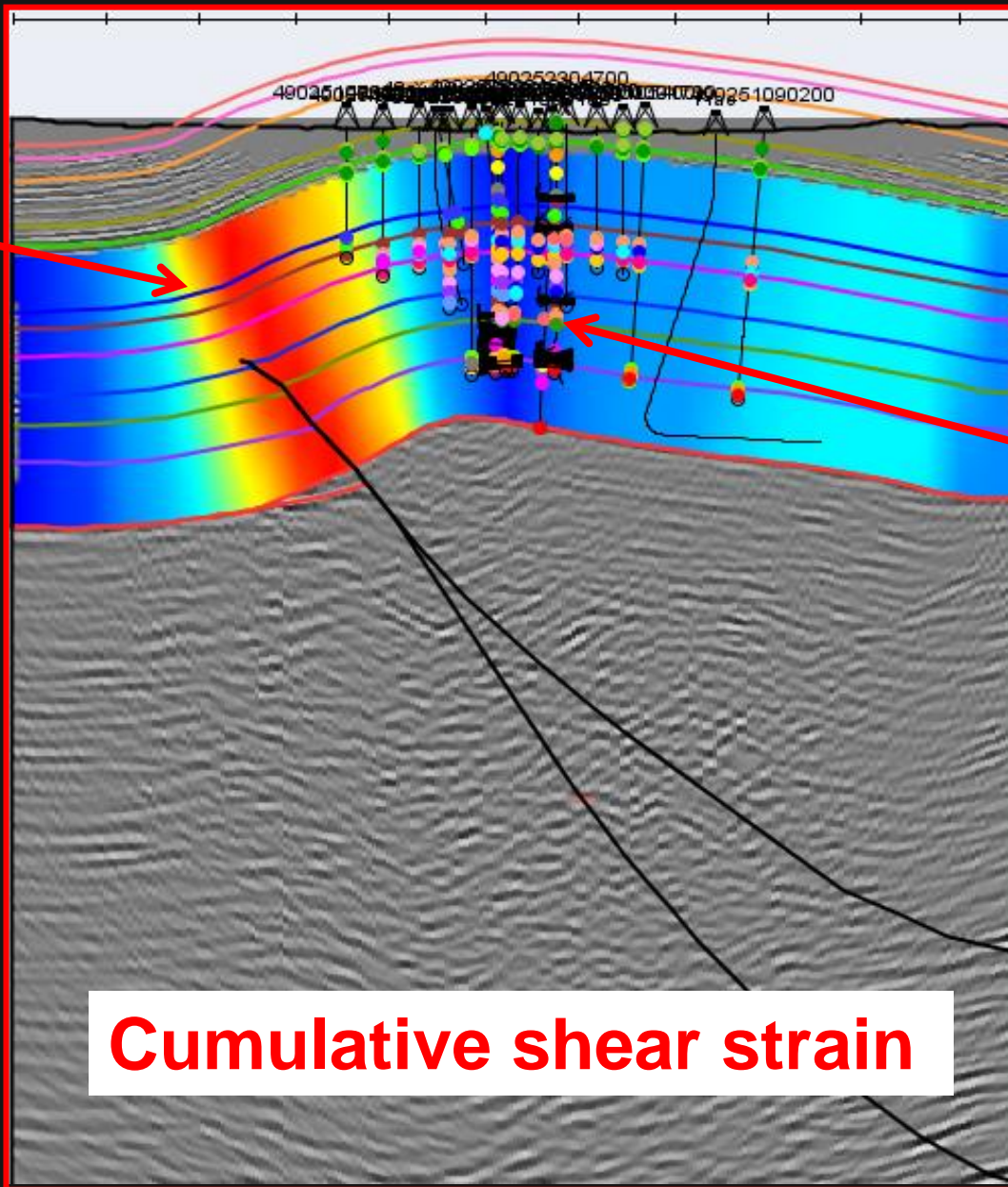
CONCLUSIONS

Strain can be used as a proxy for fracture intensity and distribution

Cumulative strain tracks the total rock damage and fracture accumulation

In tight fractured reservoirs fold limbs may be better conduits than fold hinges

Have to calibrate against structural model and folding mechanism

HALLIBURTON | Landmark