3-D Geometry and Kinematic Evolution of Deep-Water Toe Thrust Anticlines*

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Abstract

Deep-water toe thrust anticlines have been interpreted using traditional models derived from observations in orogenic thrust belts and accretionary prisms, such as fault-propagation folds, detachment folds, and both simple- and pure-shear fault bend folds. However, high quality 3D seismic data show that the deep-water anticlines typically display extreme variations in along-strike fold morphology which are not accounted for by any individual one of the above models; multiple conflicting kinematic models would have to be applied to explain different parts of a single structure.

We present a kinematic model of a singular detachment fold within the Niger Delta outer fold and thrust belt. The fold asymmetry and fault vergence change 180 degrees at several locations along the fold, even though the shortening increases monotonically from two minima at the fold terminations, to a single maximum at the fold crest, and no lateral transfer structures are present. Evolution of this fold has been studied using a combination of depth-converted seismic data, well data, and structural modeling, including structural restorations, isopach mapping, and area balancing. The results show that the fold originated as a buckle fold and was subsequently cut by several basinward and landward dipping thrusts that penetrated the fold at different depth levels. The kinematic analysis shows that fold grew by limb steepening through progressive limb rotation and magnification of a single crest, around a fixed fold axis. Shortening rates vary from 20 m/Ma (0.2 mm/year) at the low amplitude ends of the fold, to 200 m/Ma (2 mm/year) at the crest.

References

Corredor, Freddy, John H. Shaw, and Frank Bilotti, 2005, Structural styles in the deep-water fold and thrust belts of the Niger Delta: AAPG Bulletin, v. 89, p. 753-780.

Kostenko, Olga V., Steve J. Naruk, Willem Hack, Manuel Poupon, Hans-Jurg Meyer, Miguel Mora-Glukstad, Charles Anowai, and Margaret Mordi, 2008, Structural evaluation of column-height controls at a toe-thrust discovery, deep-water Niger Delta: AAPG Bulletin, v. 92, p. 1615-1638.

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Shell International E&P

American Association of Petroleum Geologists
Theme XIII: Seismic Structural Interpretation
Case Histories for Hydrocarbon Exploration & Exploitation
2009

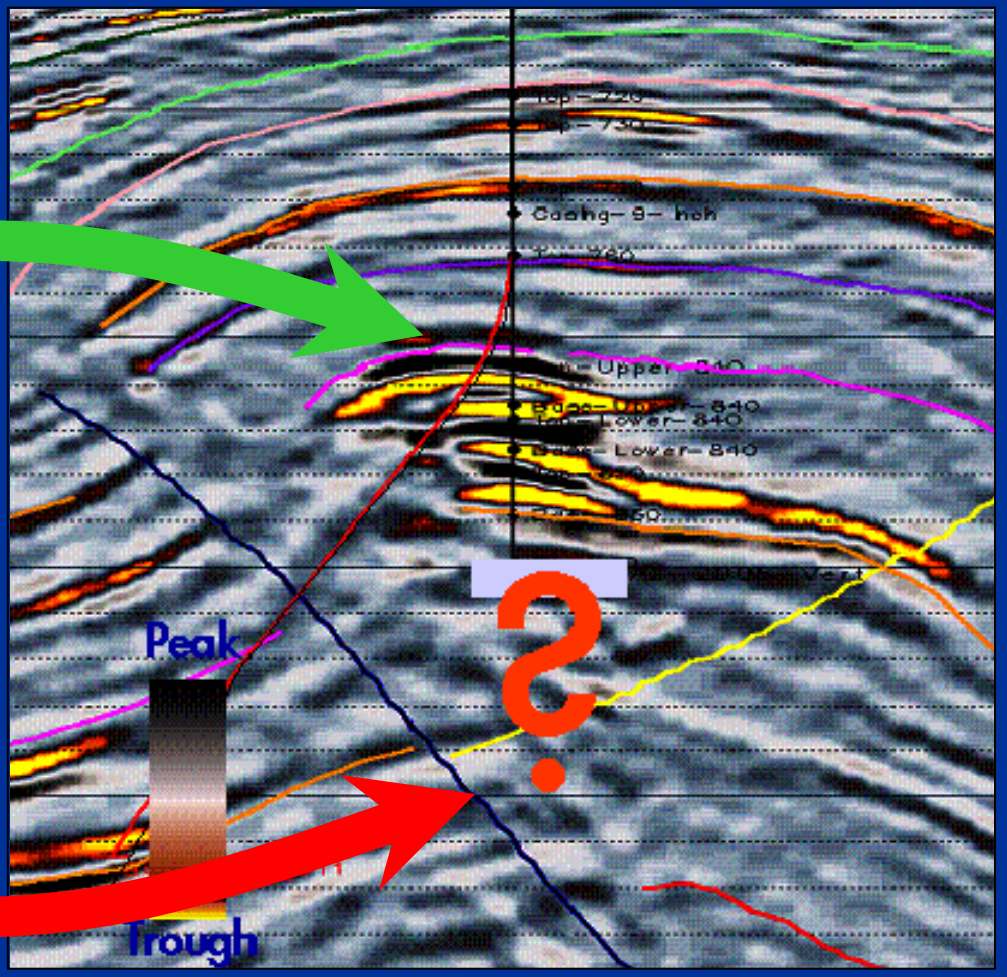
Objectives:

- Exploration success in the offshore foldbelts depends on understanding their architecture
- Deep water gravity-driven foldbelt structures are fundamentally different from onshore orogenic foldbelts
- Architecture of seismic wipe-out zones is critical to determining the trap elements
- Multiple serial reconstructions significantly reduce structural uncertainties in wipe-out zones

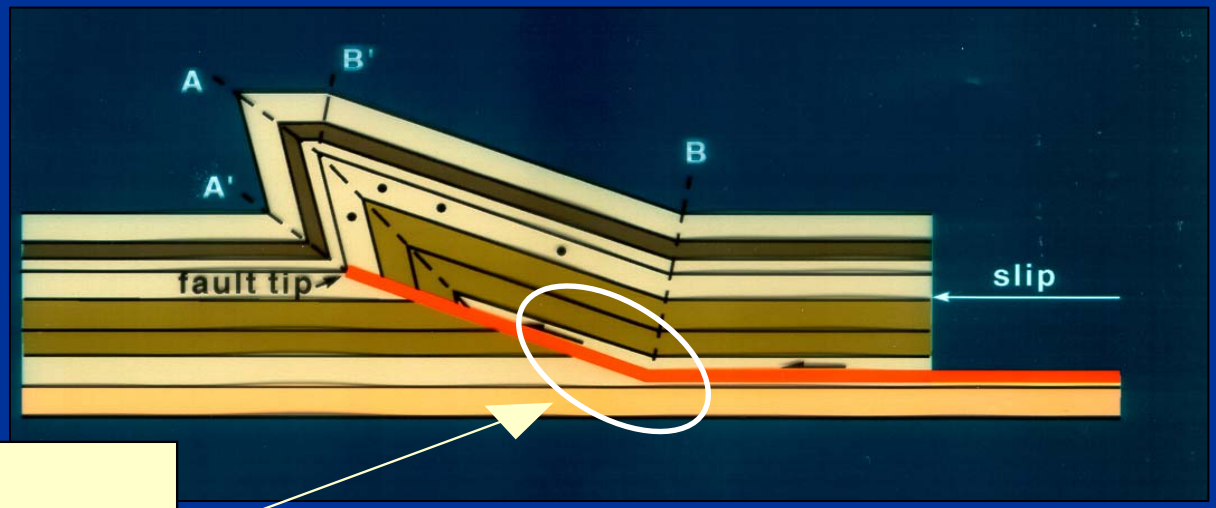
Typical Toethrust Discovery

Upper levels are amplitude supported

What's the deeper, un-imaged non-amplitude-supported potential?

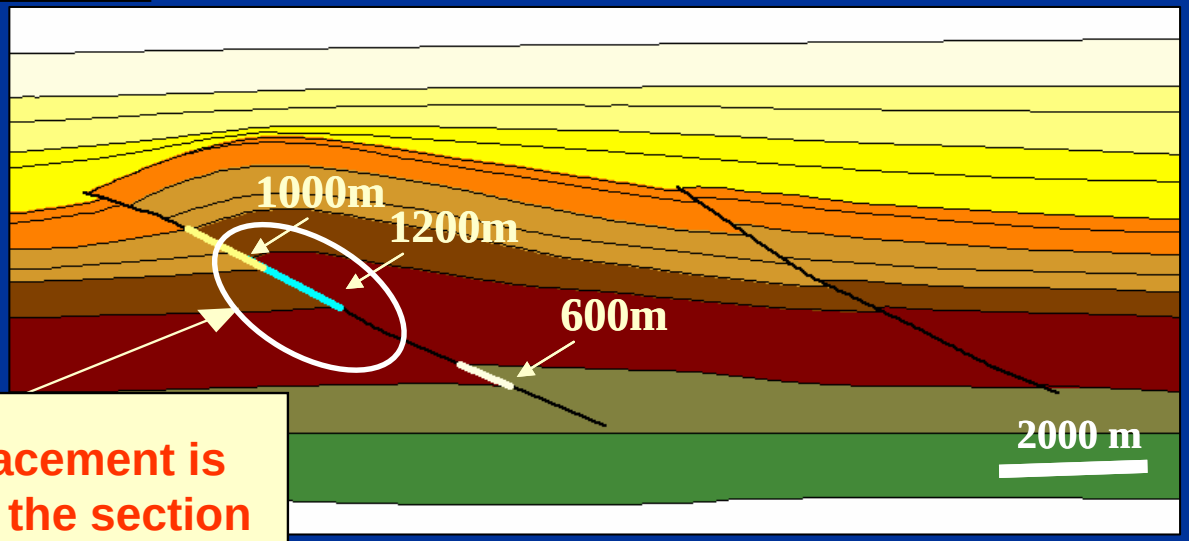


Onshore classical thrust-fold models and interpretation rules - don't apply in the offshore structures



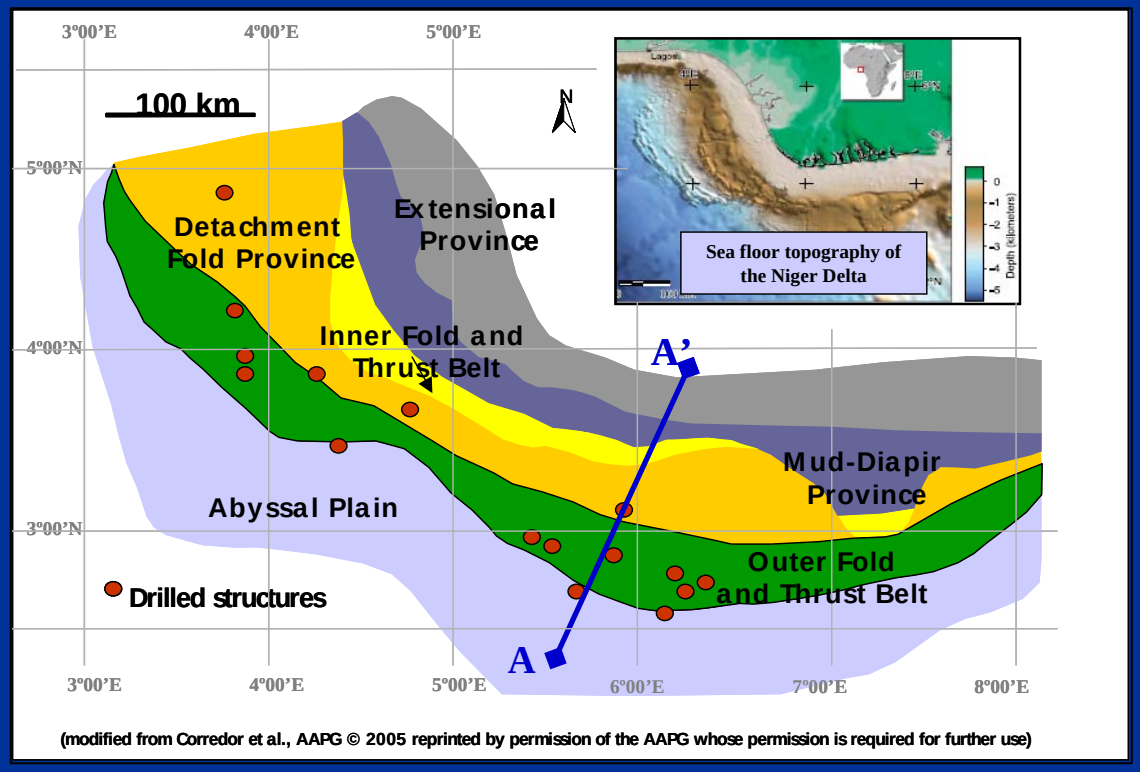
Onshore orogenic foldbelt

Maximum displacement is near the detachment



Offshore gravity-driven foldbelt

Maximum displacement is in the middle of the section



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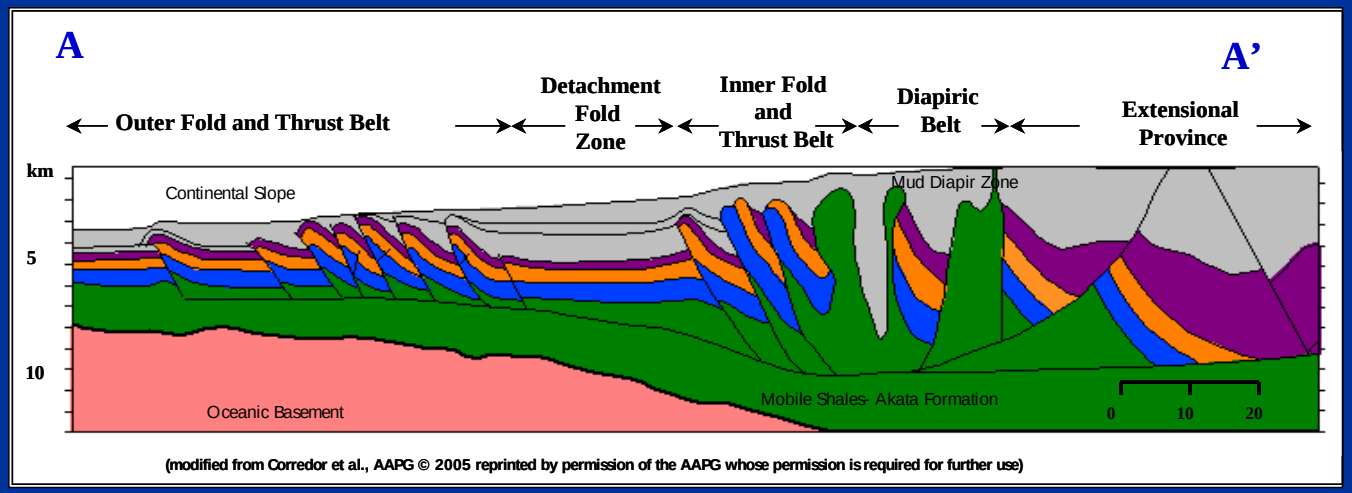
Niger Delta regional map showing deep water prospects

Regional seismic profile across the Niger Delta shows:

- extensional province on the shelf
- contraction in the toethrust systems in the deep-water



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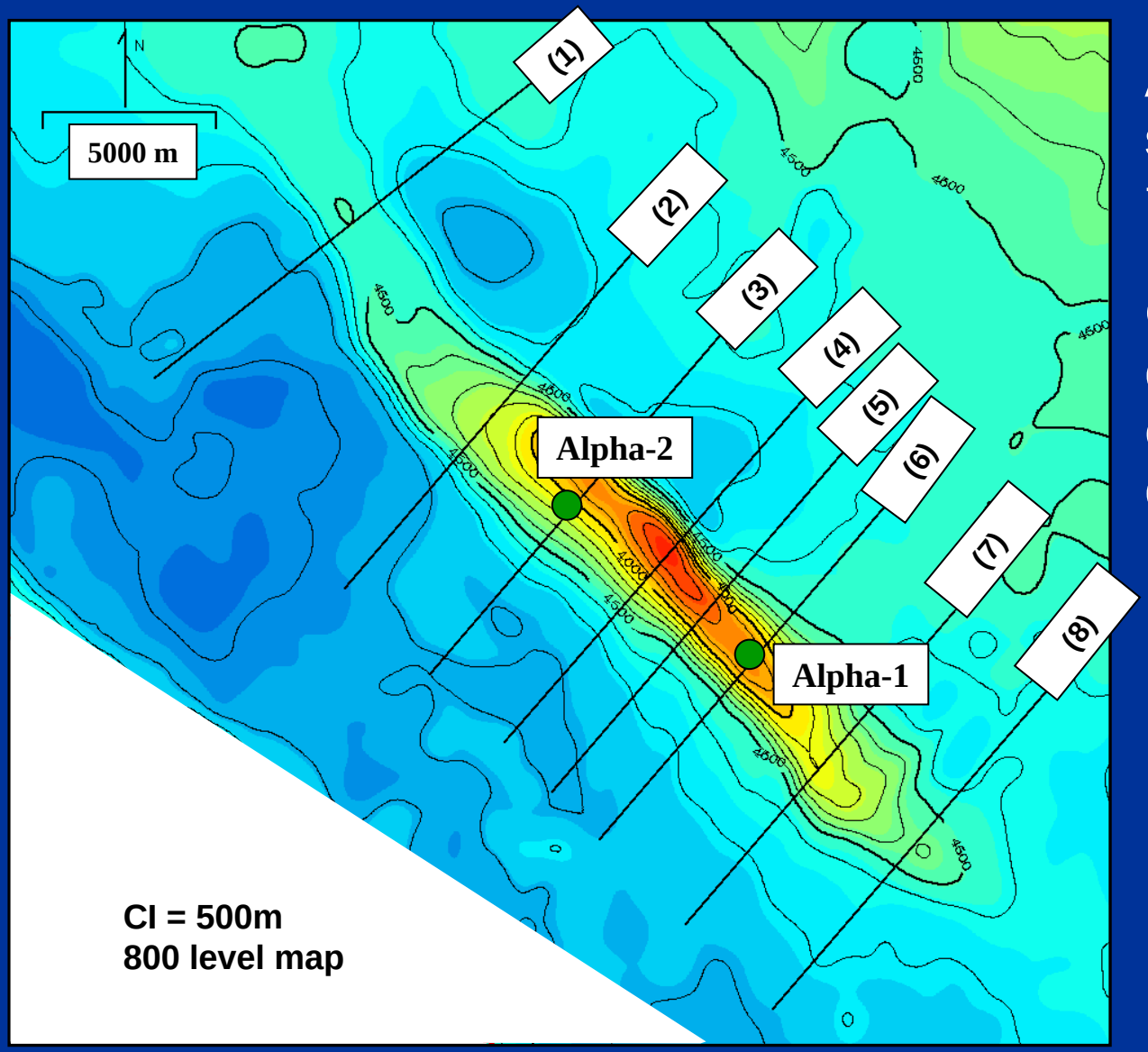
(Corredor et al, AAPG, 2005)

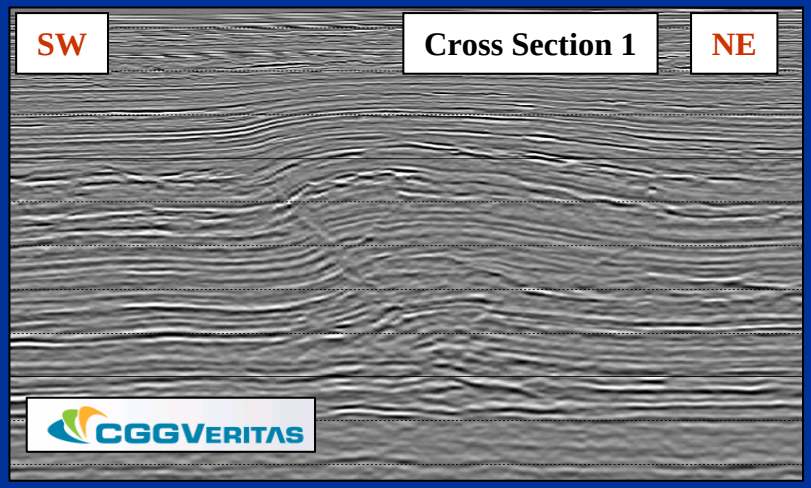


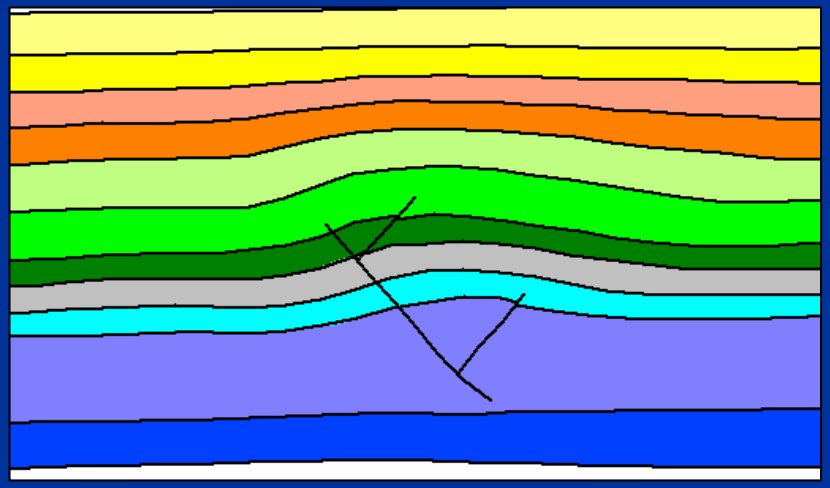
(Kostenko et al, AAPG, 2008)

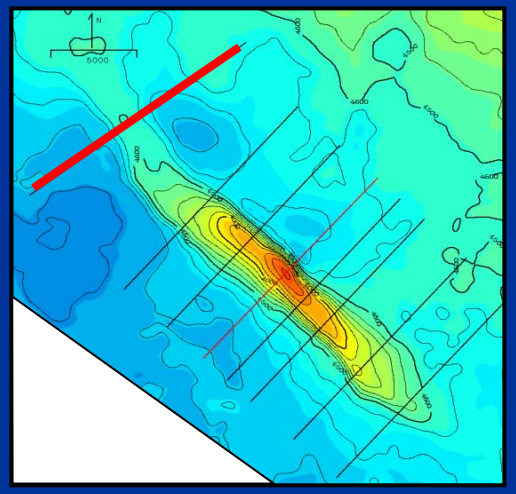
Alpha structure contour map showing well locations and the reversals in fold vergence

Changes in geometry require different, contradictory, classical 2D models at different locations!

Section 1- SW-verging low-amplitude faulted detachment fold



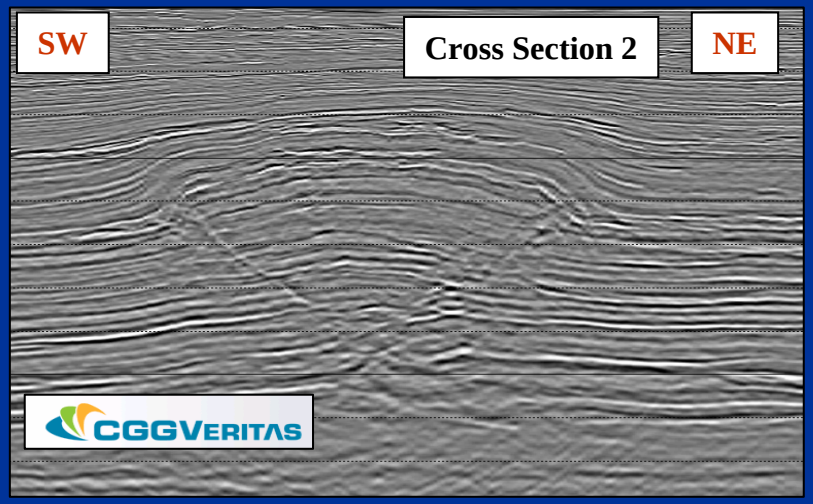


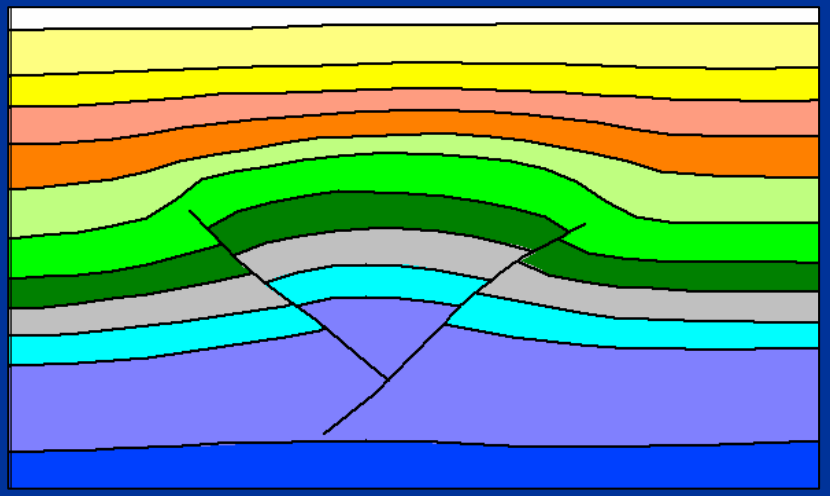


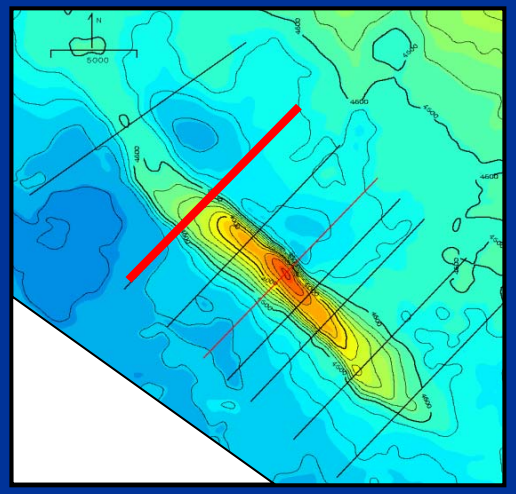
Horizon Legend:

Sea Floor	600	800	900
300	700	840	950
500	720	850	

Section 2 - Symmetrical faulted pop-up structure without preferred vergence



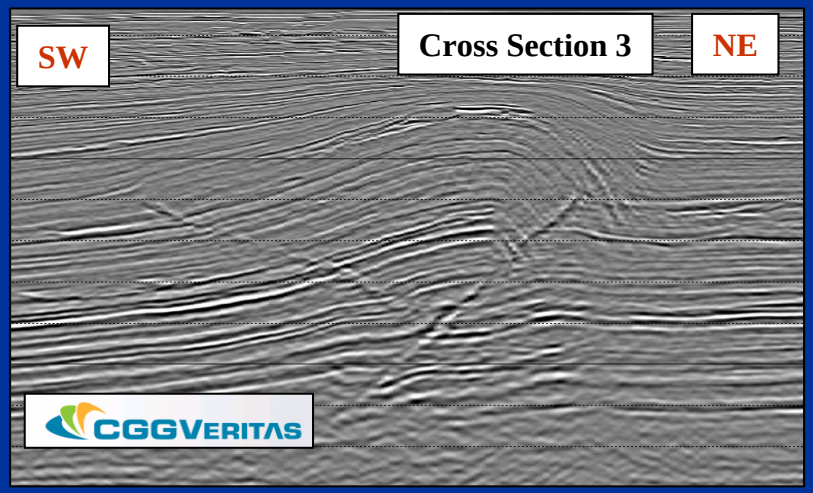


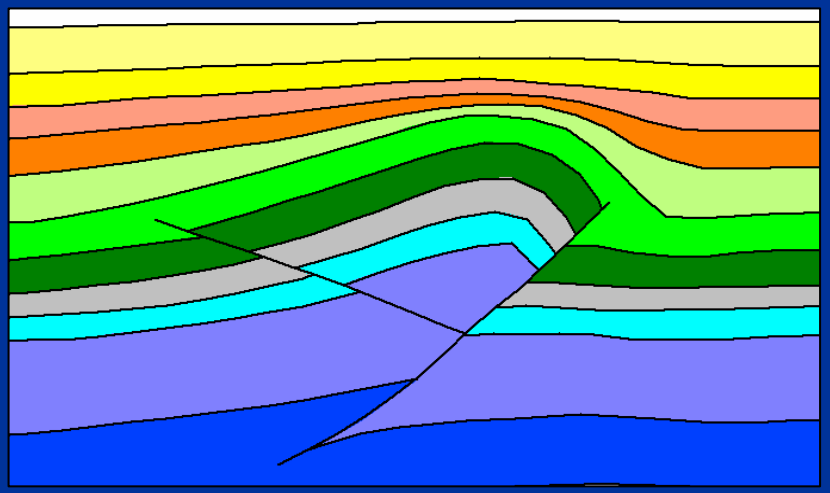


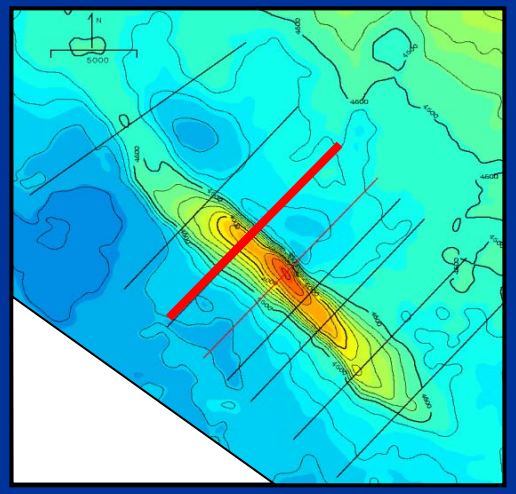
Horizon Legend:

Sea Floor	600	800	900
300	700	840	950
500	720	850	

Section 3 – NE-vergent faulted detachment fold (with backthrust)



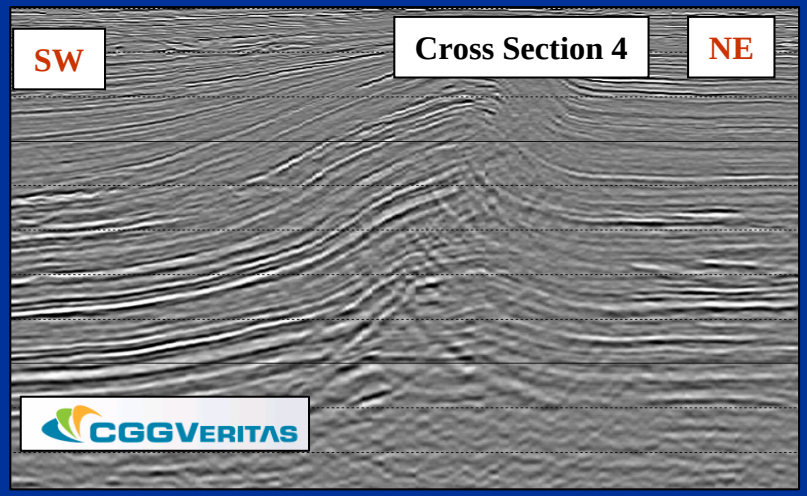


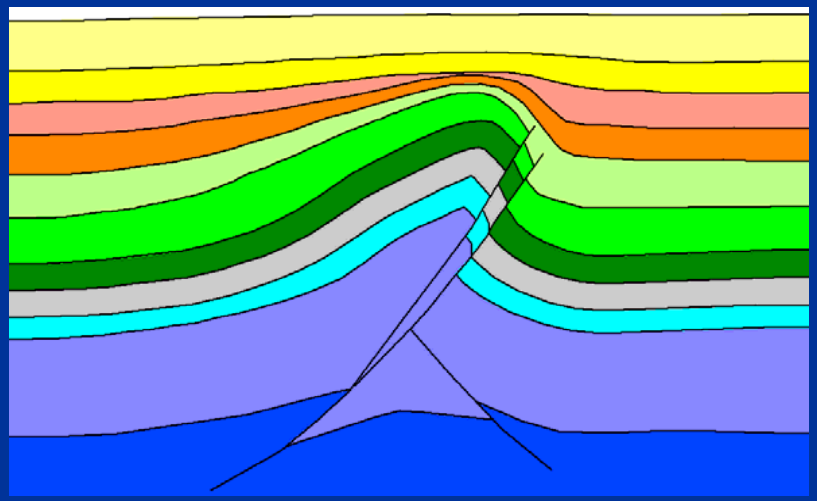


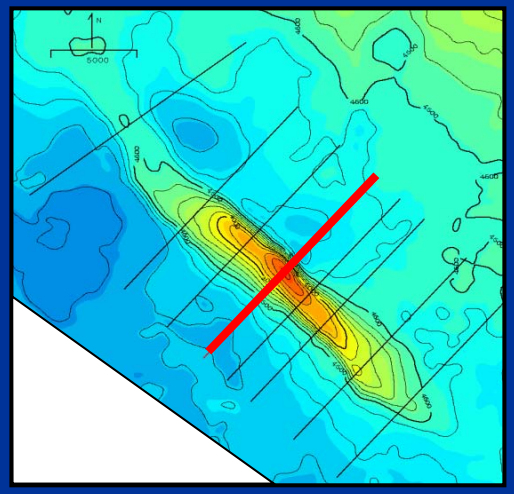
Horizon Legend:

Sea Floor	600	800	900
300	700	840	950
500	720	850	

Section 4 – NE-vergent faulted detachment fold (without backthrust)



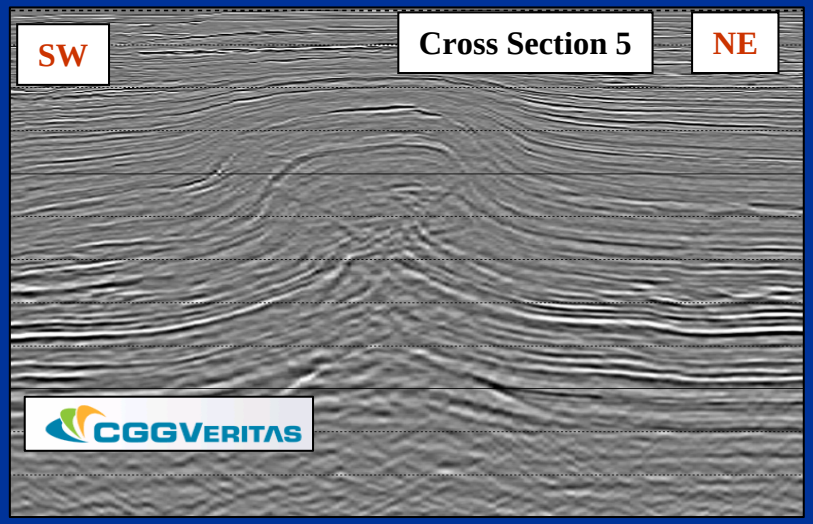


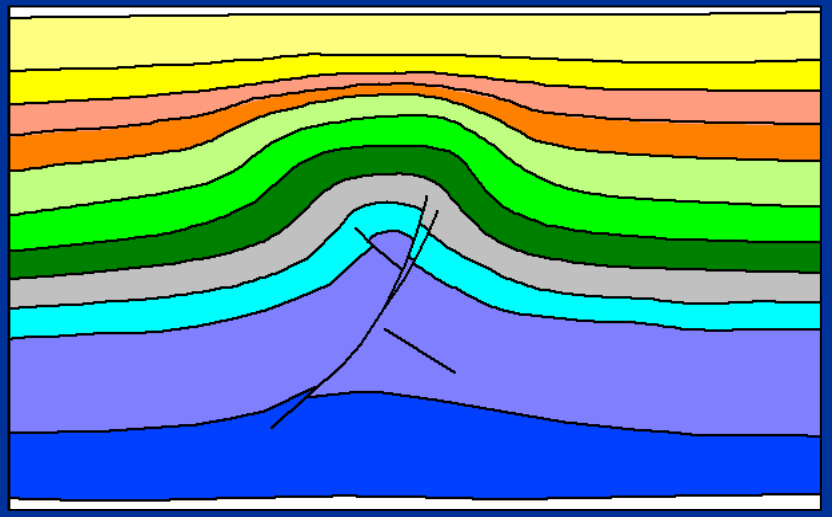


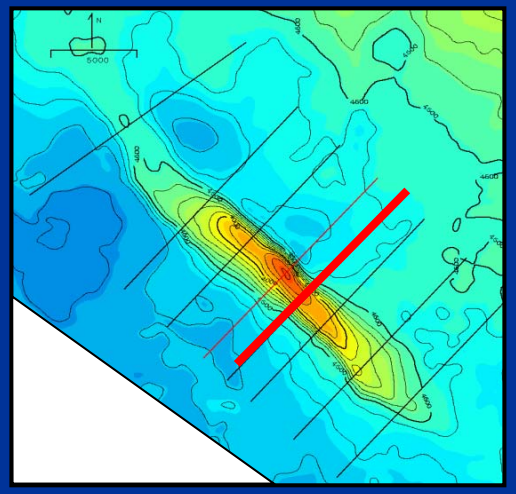
Horizon Legend:

Sea Floor	600	800	900
300	700	840	950
500	720	850	

Section 5 - Symmetrical box fold with slight vergence to NE



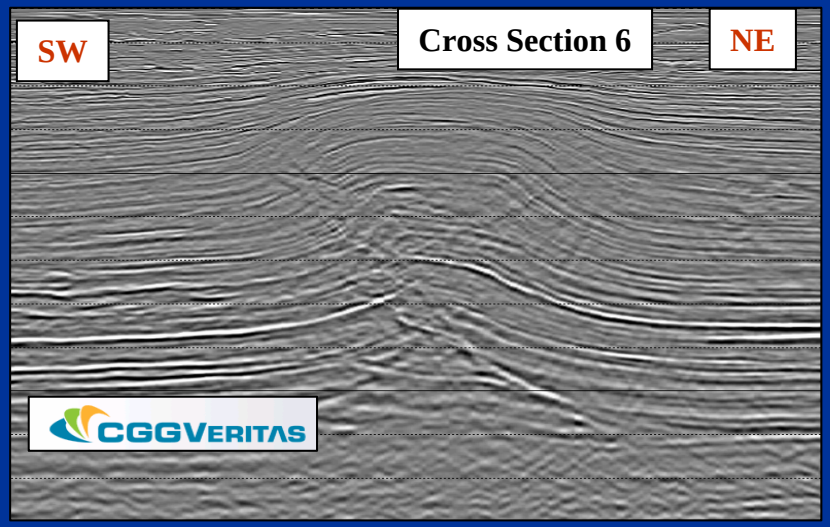


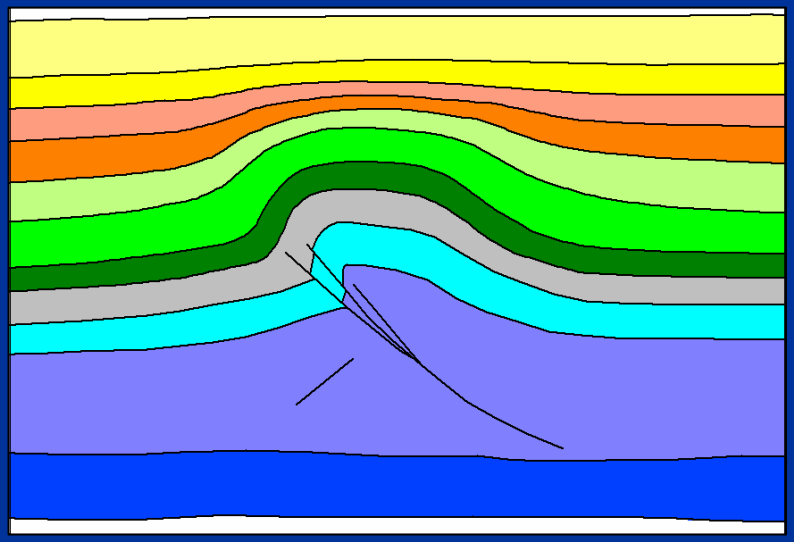


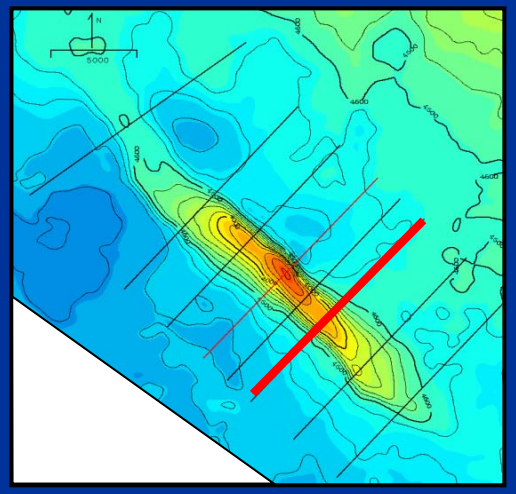
Horizon Legend:

Sea Floor	600	800	900
300	700	840	950
500	720	850	

Section 6 – SW-vergent faulted detachment fold



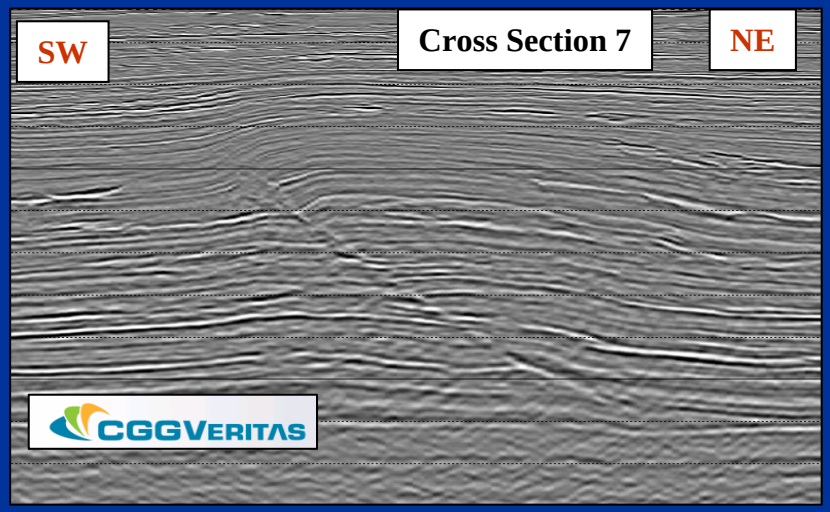


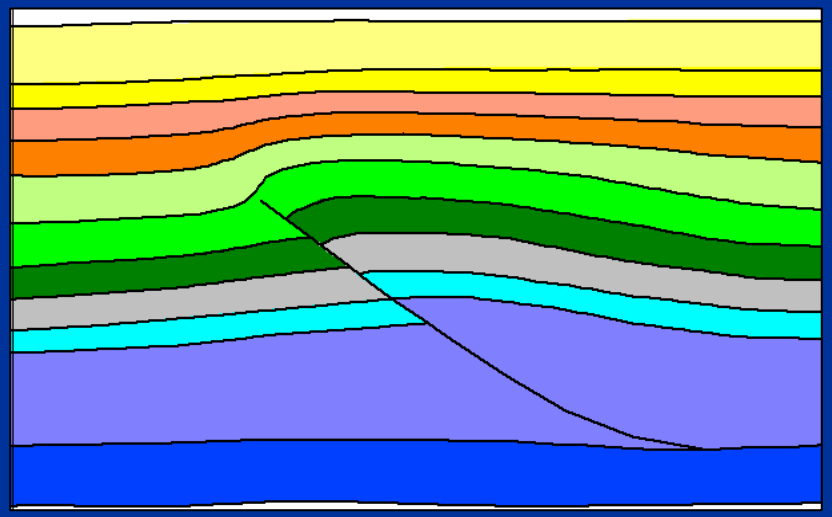


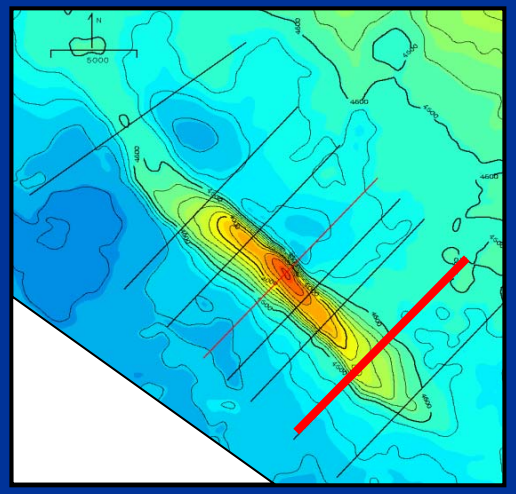
Horizon Legend:

Sea Floor	600	800	900
300	700	840	950
500	720	850	

Section 7- SW-vergent faulted detachment fold



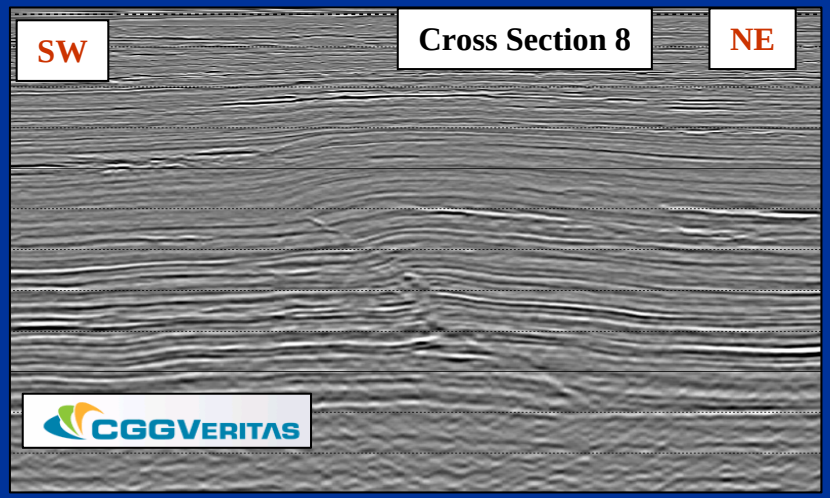


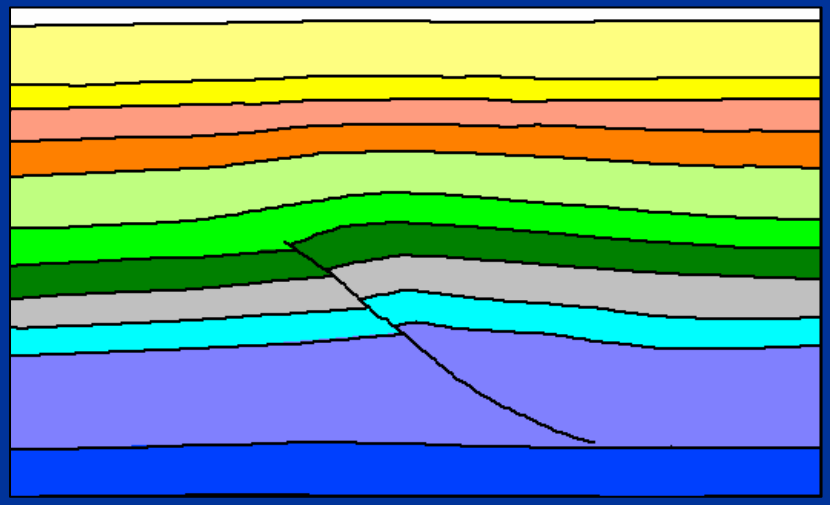


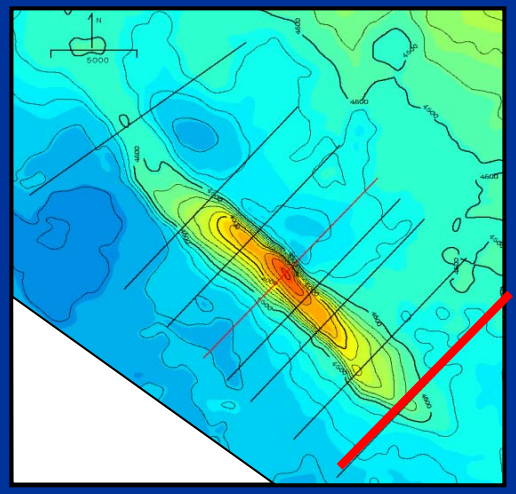
Horizon Legend:

Sea Floor	600	800	900
300	700	840	950
500	720	850	

Section 8 – SW-vergent faulted detachment fold







Horizon Legend:

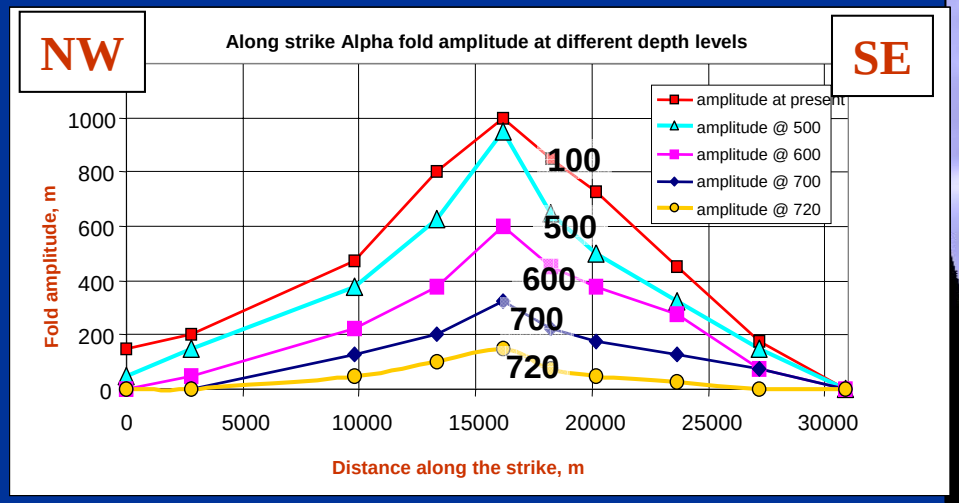
Sea Floor	600	800	900
300	700	840	950
500	720	850	

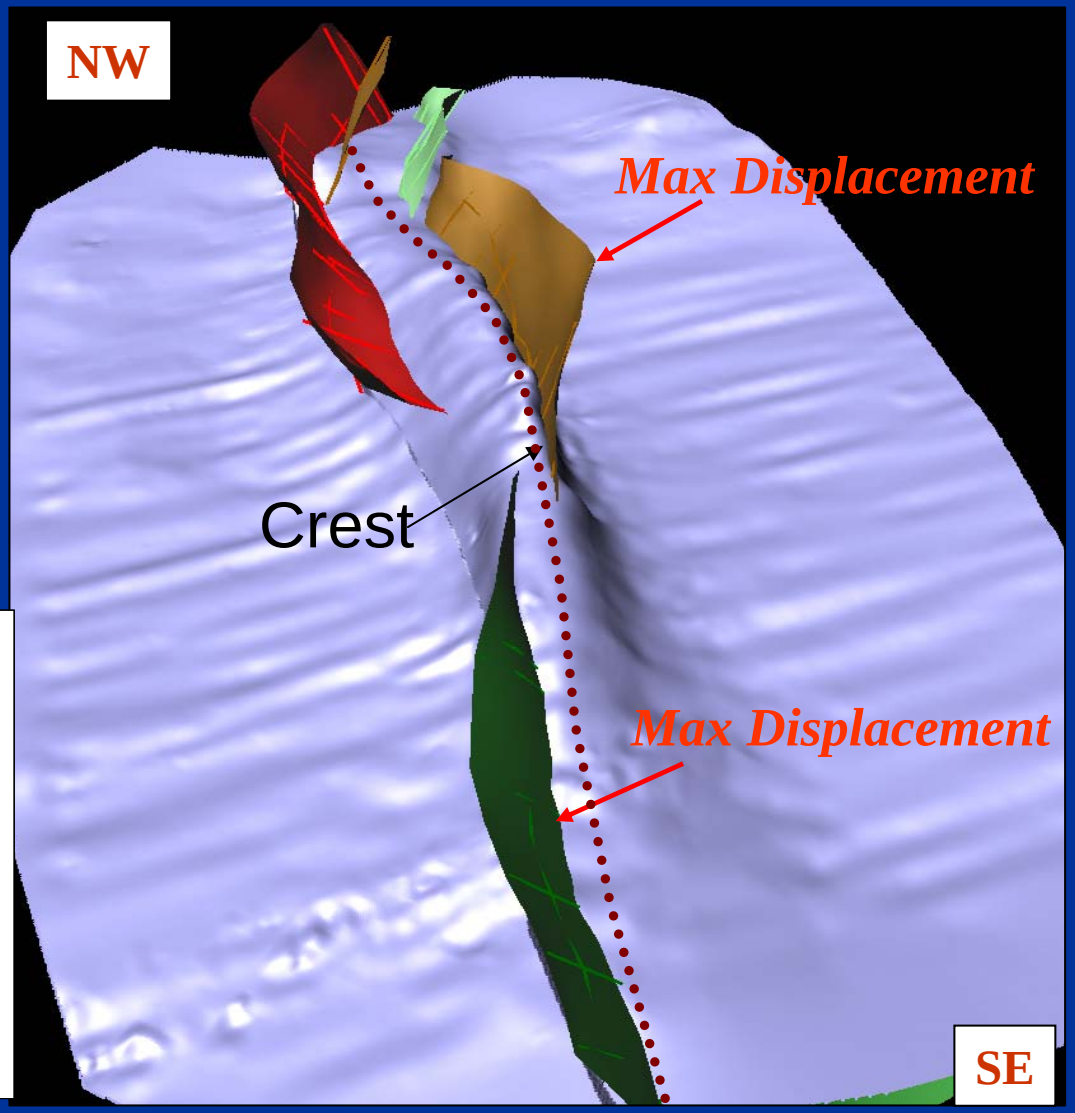
3D view of the Alpha structure showing change in fold vergence and thrust fault architecture along the strike

Maximum amplitude of fold is associated with minimum fault displacement.

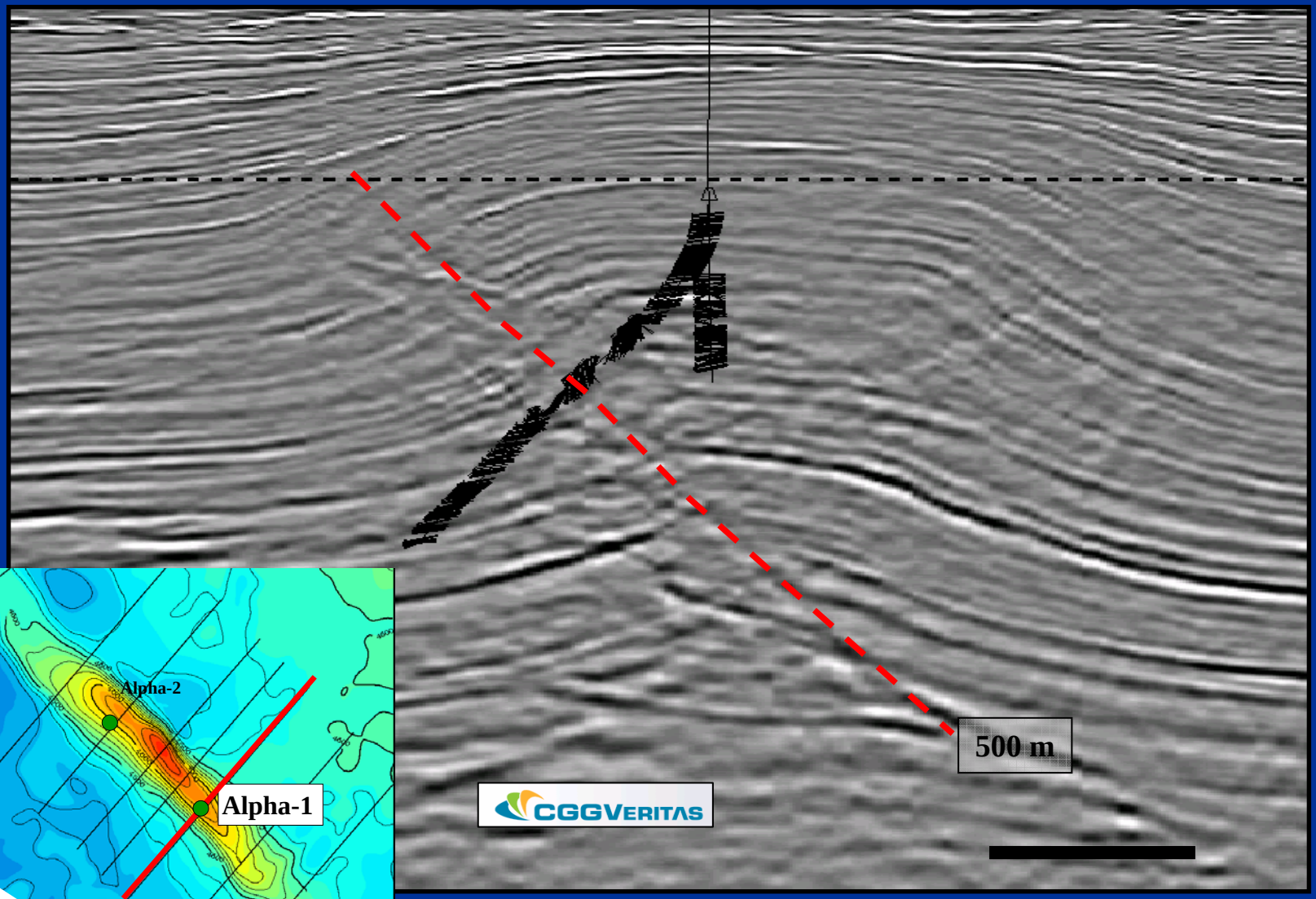
No lateral transfer (strike-slip) structures

Several faults – one fold!





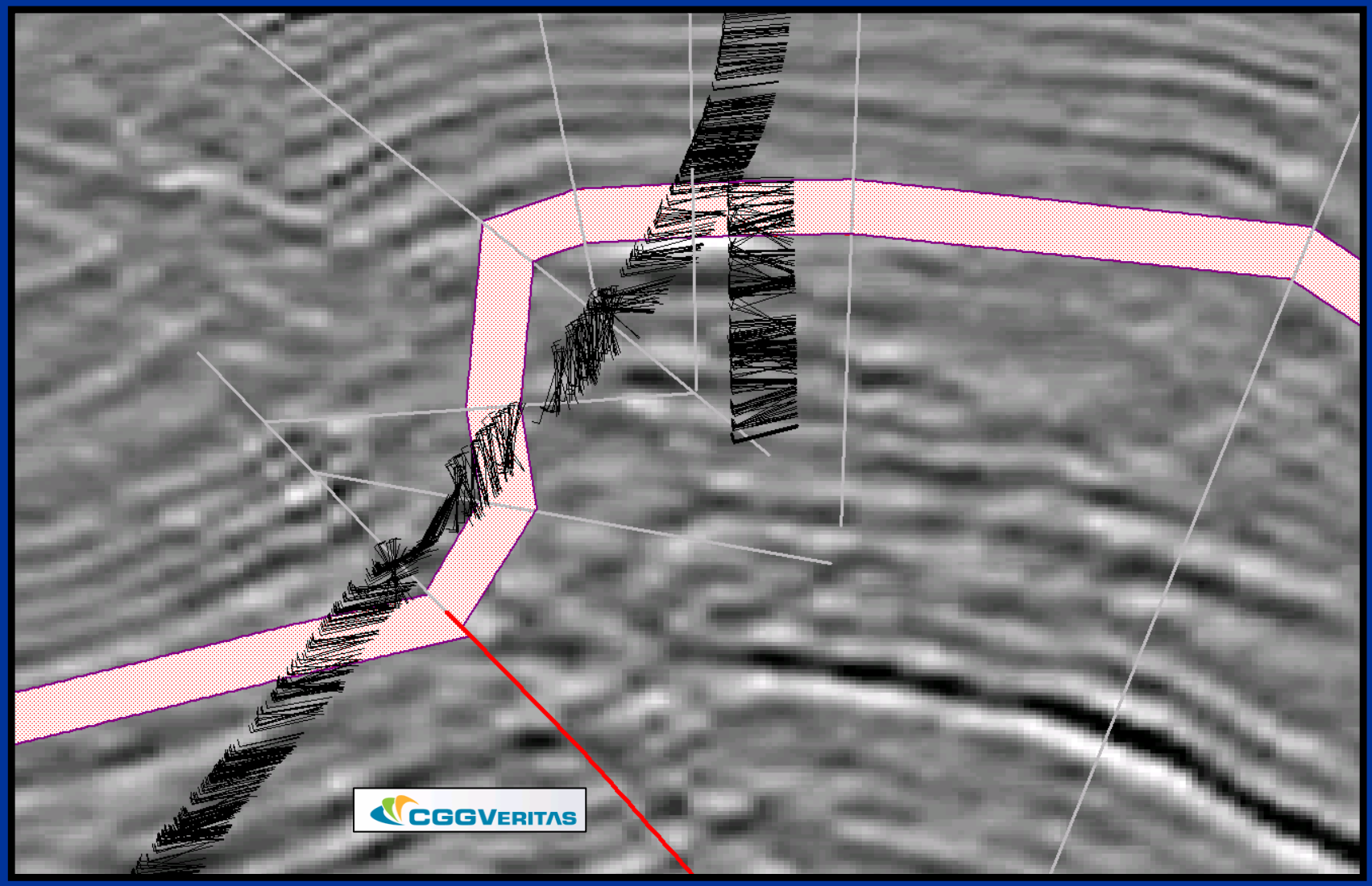
Alpha-1 Results
Wipe-out zone interpreted as fault



(Kostenko et al, AAPG, 2008)

Alpha-1 Results

Synthesis of tops and dipmeter data shows wipe-out zone is vertical fold limb



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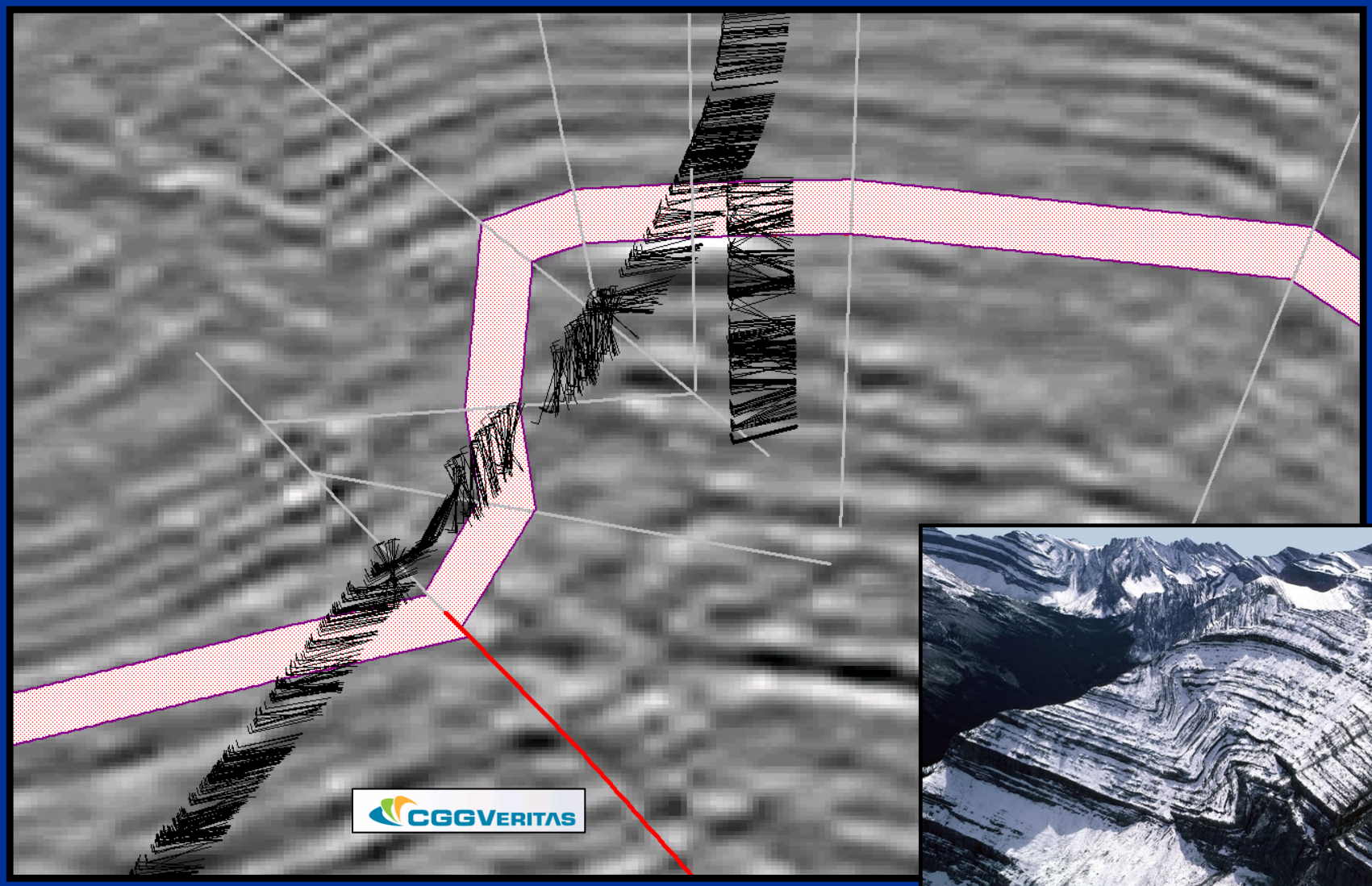
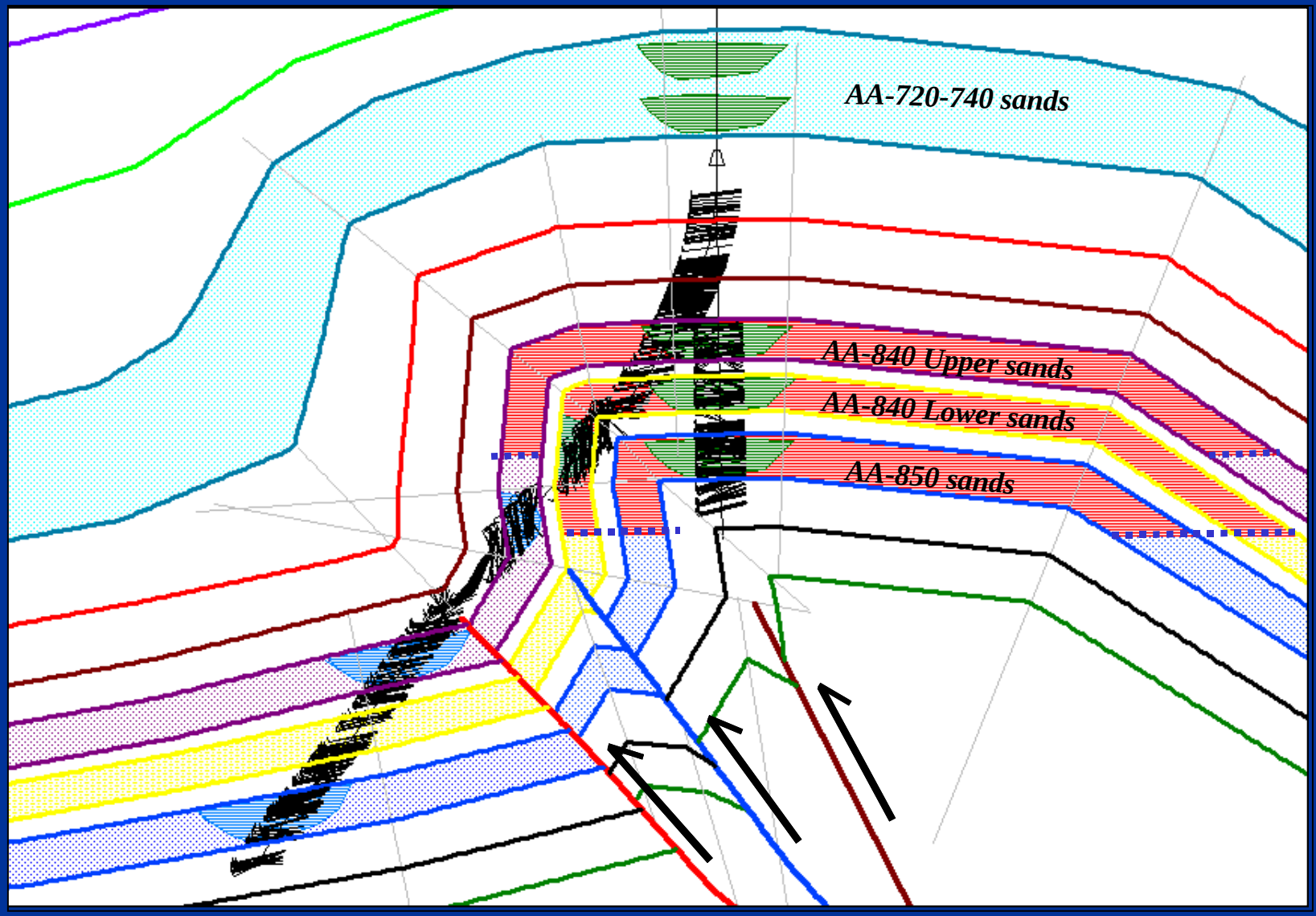
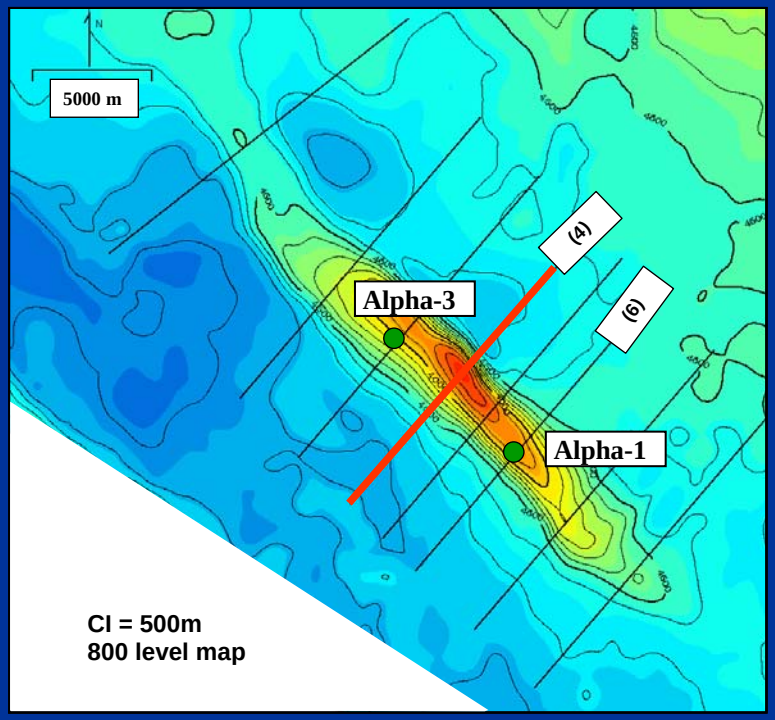
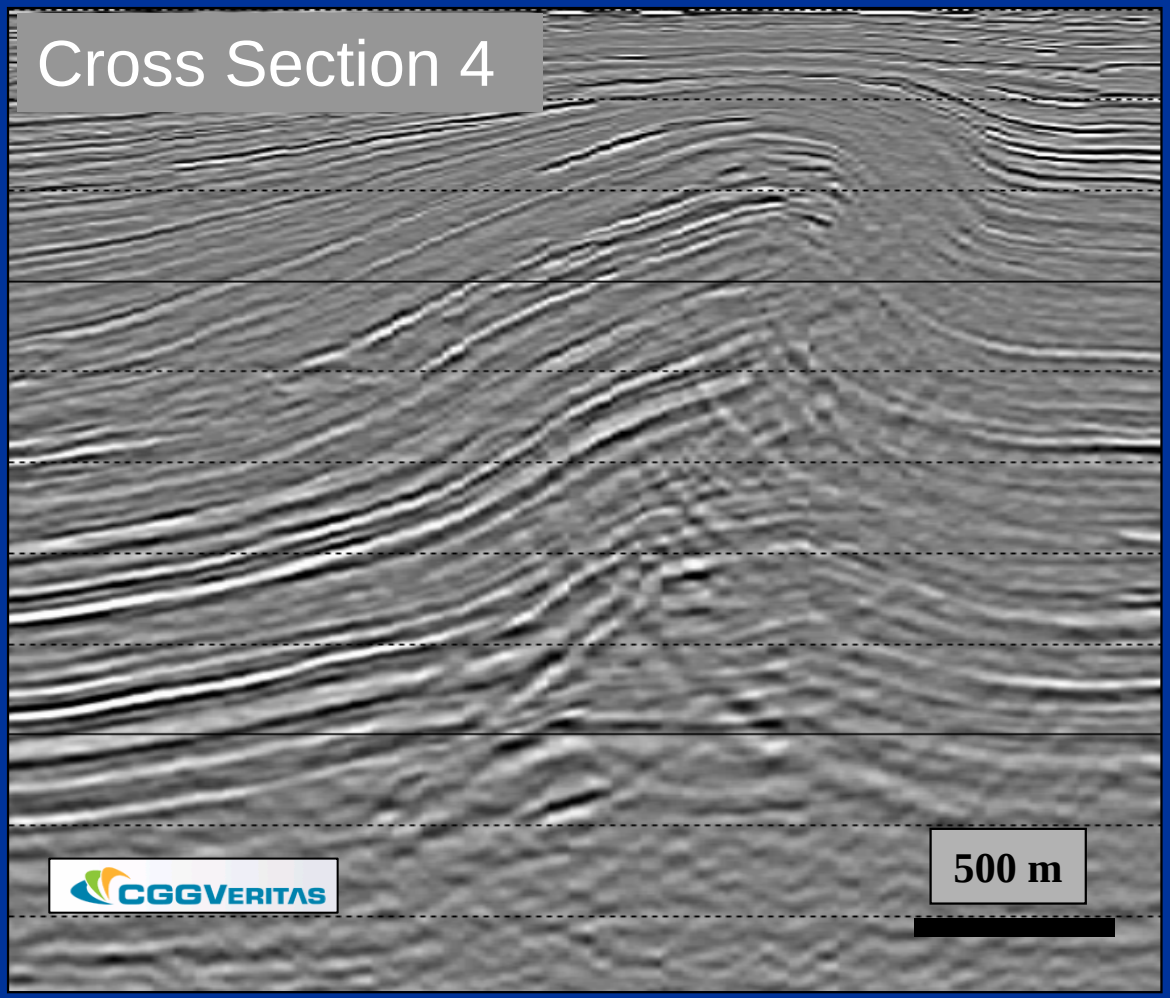


Completion of section requires faults in core to balance
Integration of MDT / OWC data shows OWC's higher than fault cutoffs



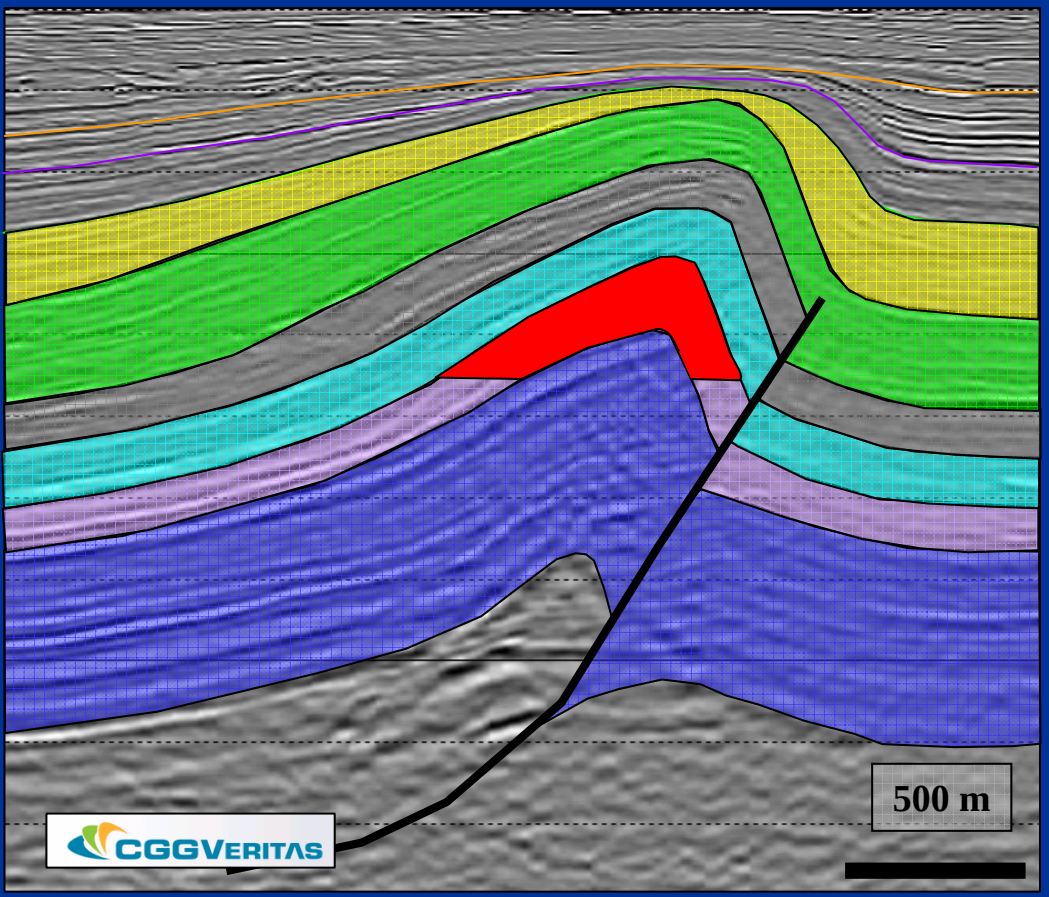
Cannot distinguish faults from vertical beds (No ST)
Cannot distinguish relative magnitudes of dip and fault dependent closure



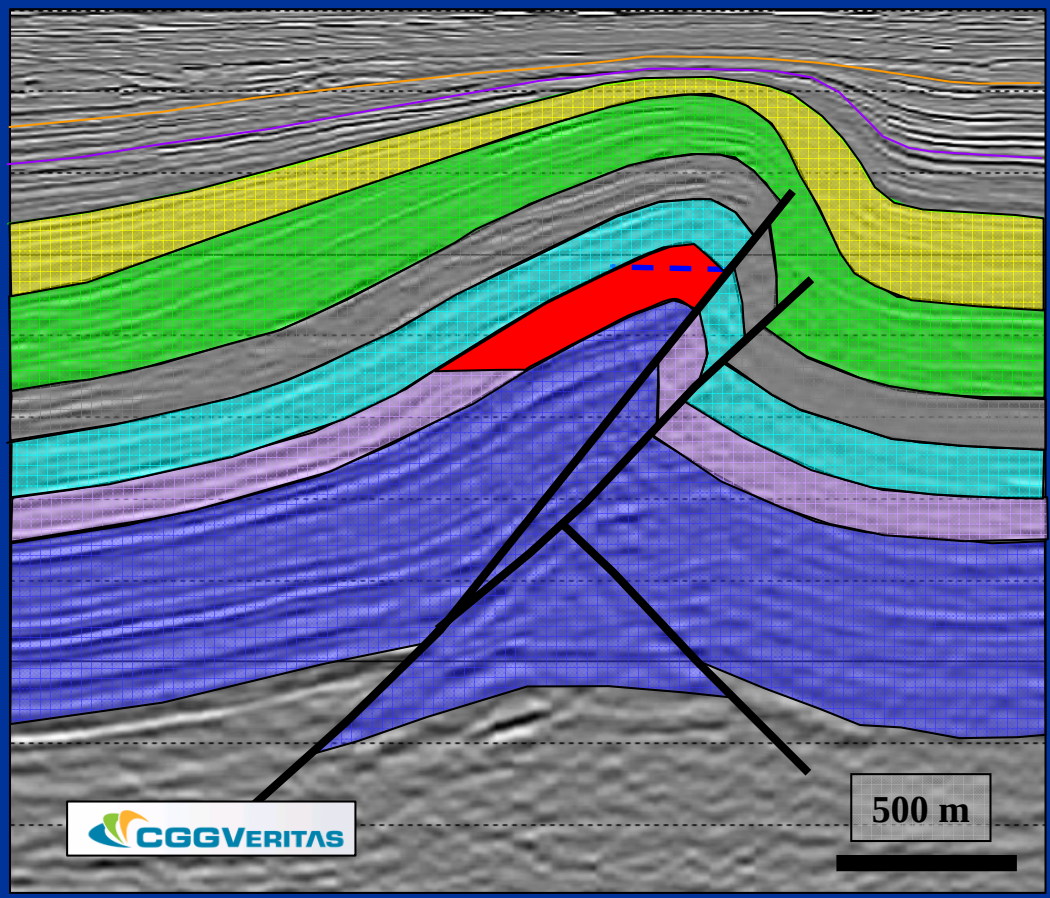


Cannot distinguish faults from vertical beds (No ST)
Cannot distinguish relative magnitudes of dip and fault dependent closure
Alternative possible structural interpretations

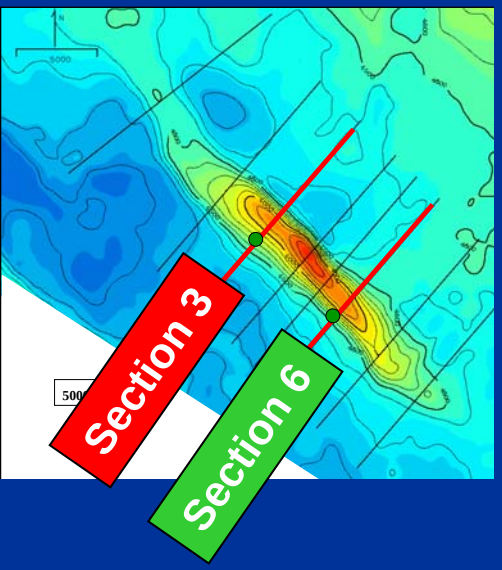
Structural Scenario 1
Dip closure only



Structural Scenario 2
Dip closure + fault closure



Reduce uncertainties by pseudo-3D restorations



1) Balance & restore serial sections.

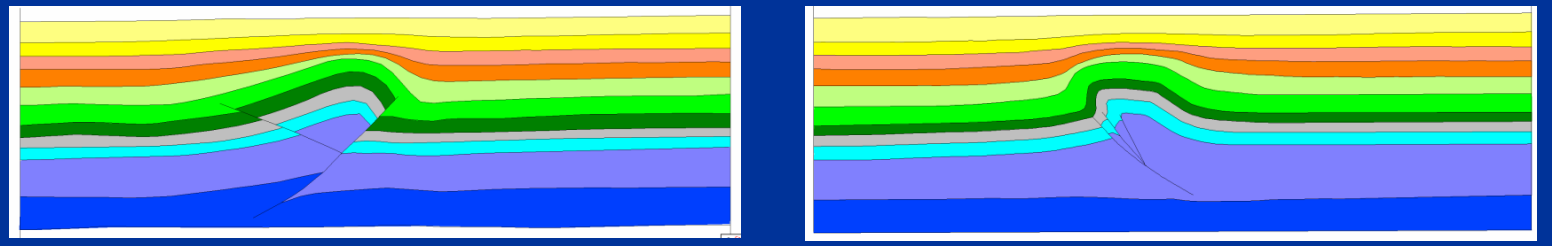
2) Ensure total shortening varies consistently between sections.

3) Ensure shortening rates vary consistently between sections

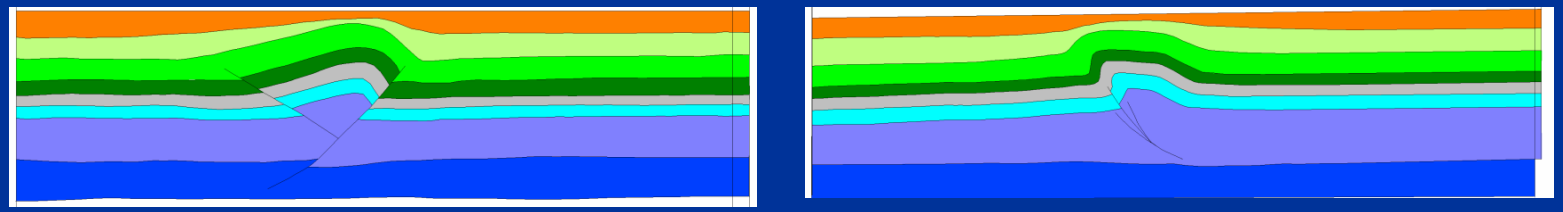
Section 3

Present day structure

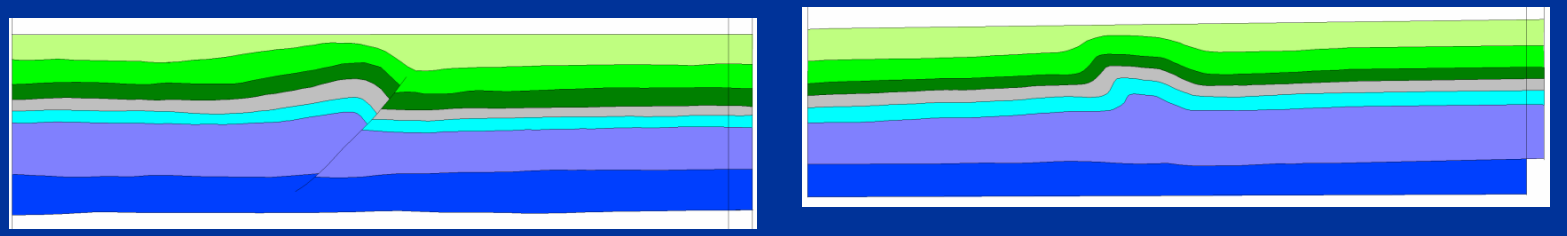
Section 6



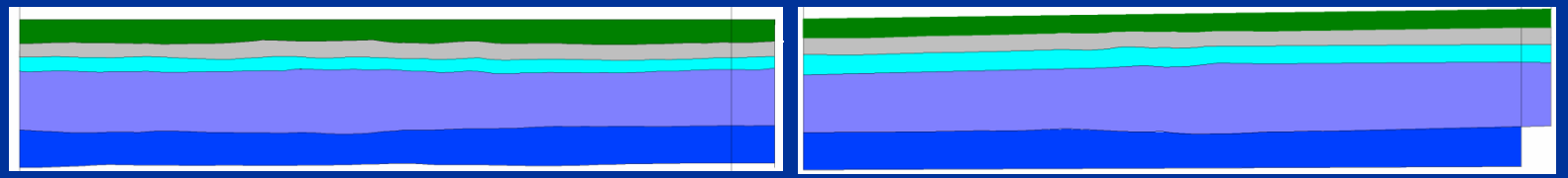
600 - Unfolded using flexural slip unfold and decompaction



700 - Unfolded using trishear, flexural slip unfold and decompaction



800 - Unfolded using trishear, flexural slip unfold and decompaction

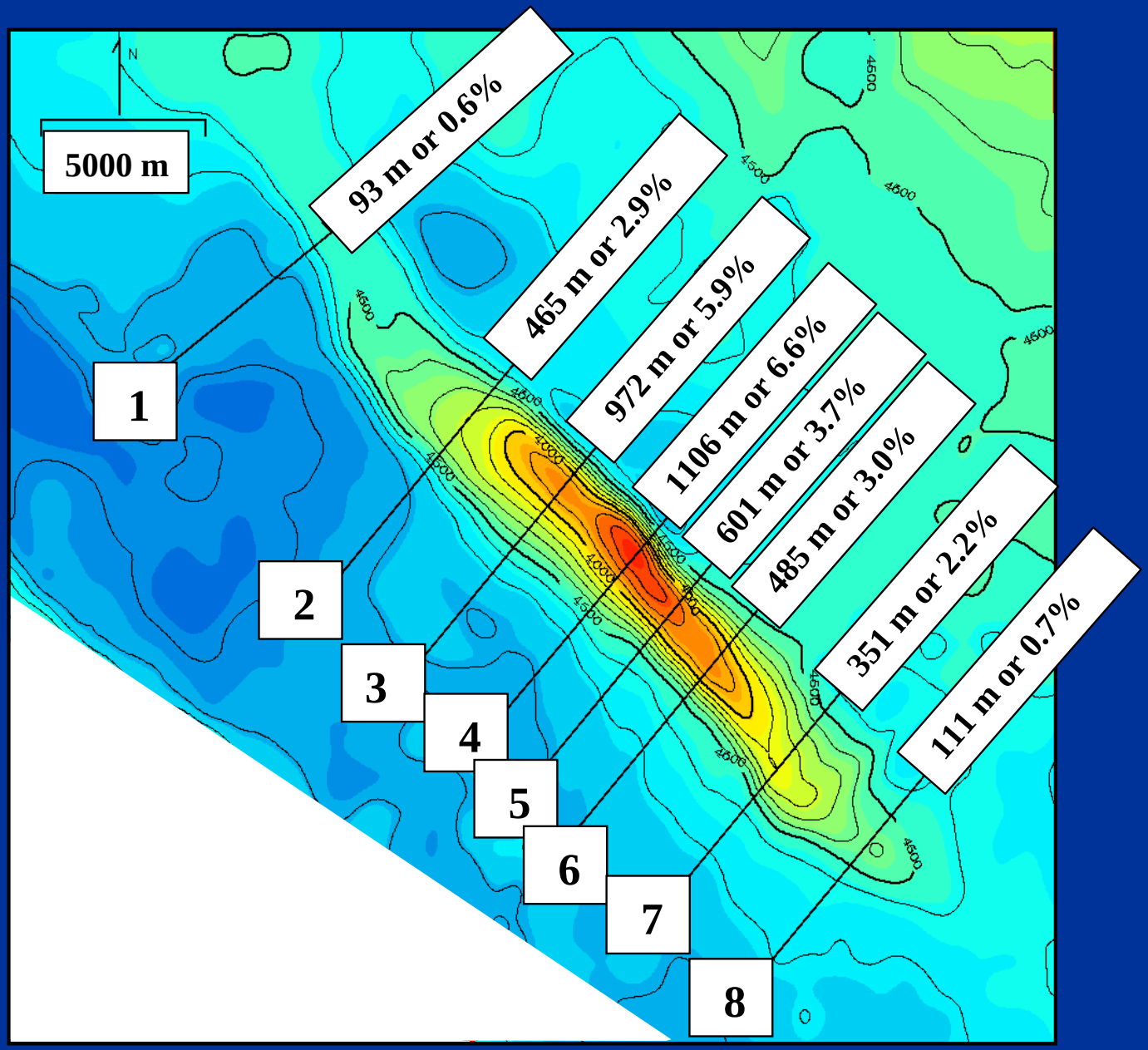


Reduce uncertainties by pseudo-3D restorations

1) Balance & restore serial sections.

2) Ensure total shortening varies consistently between sections.

3) Ensure shortening rates vary consistently between sections



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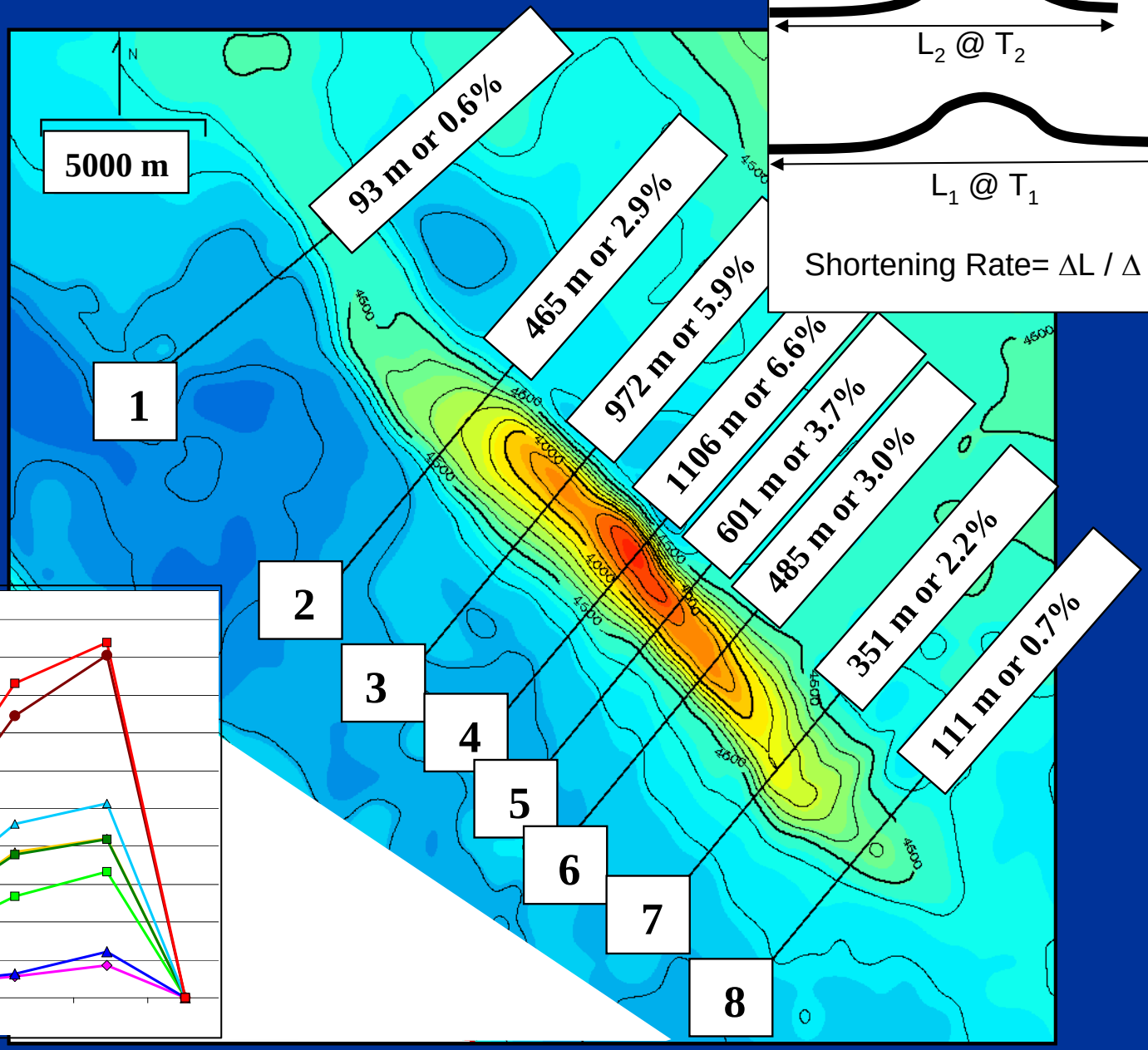
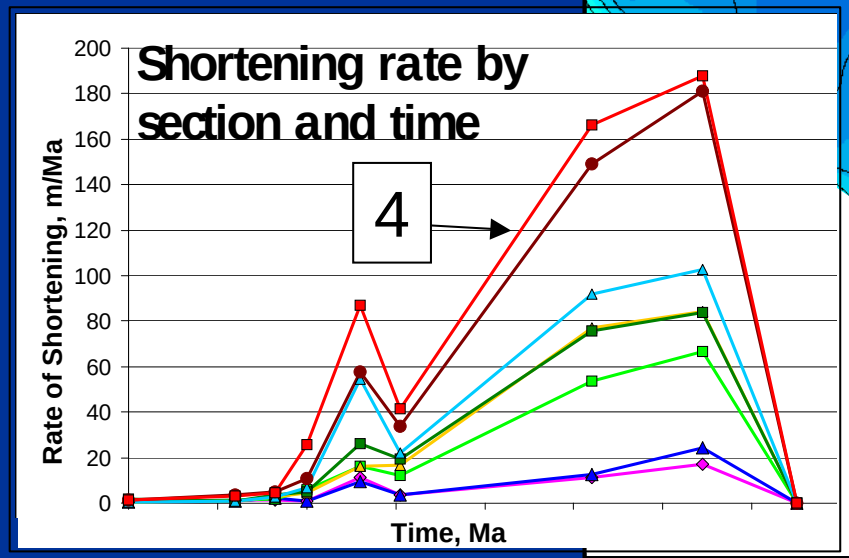
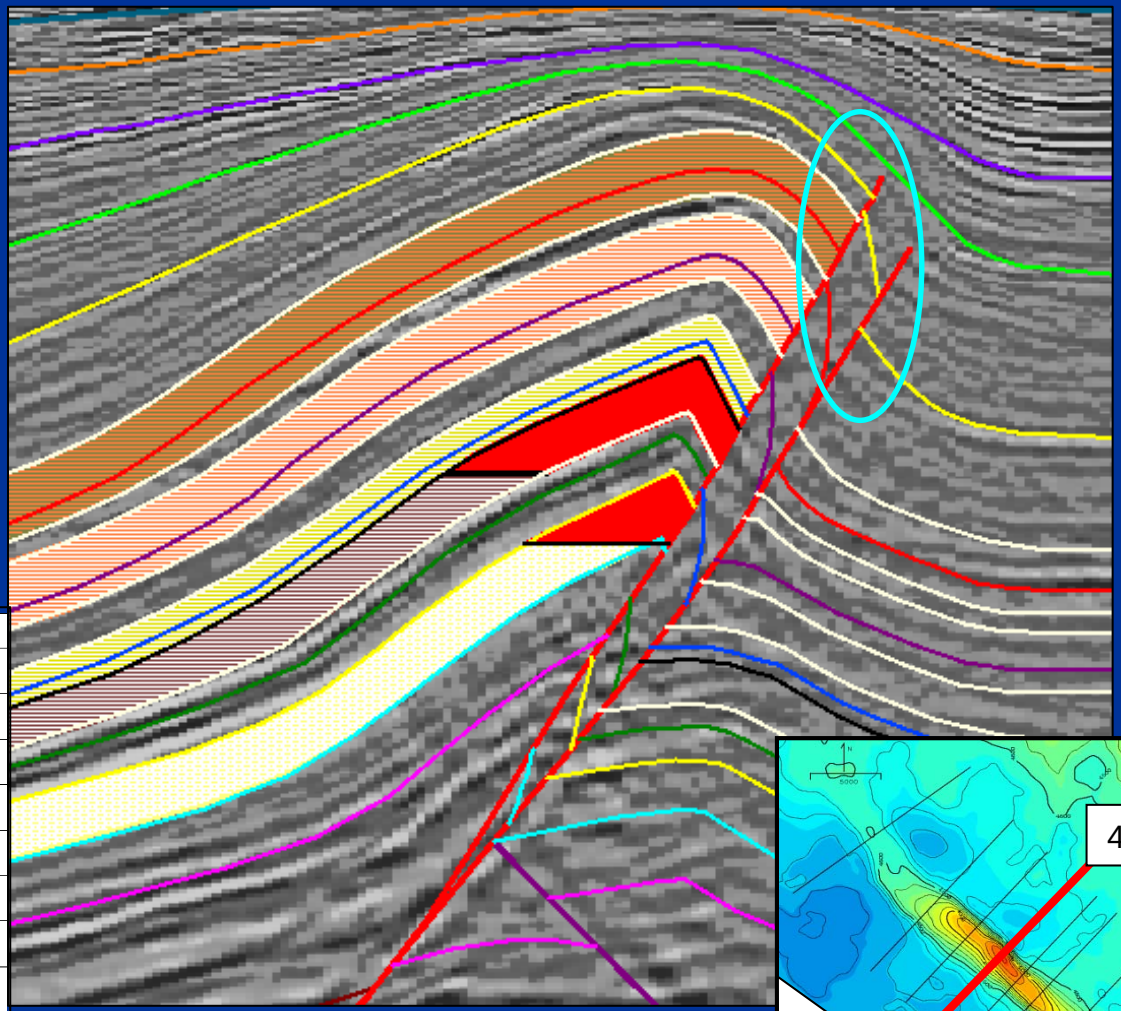


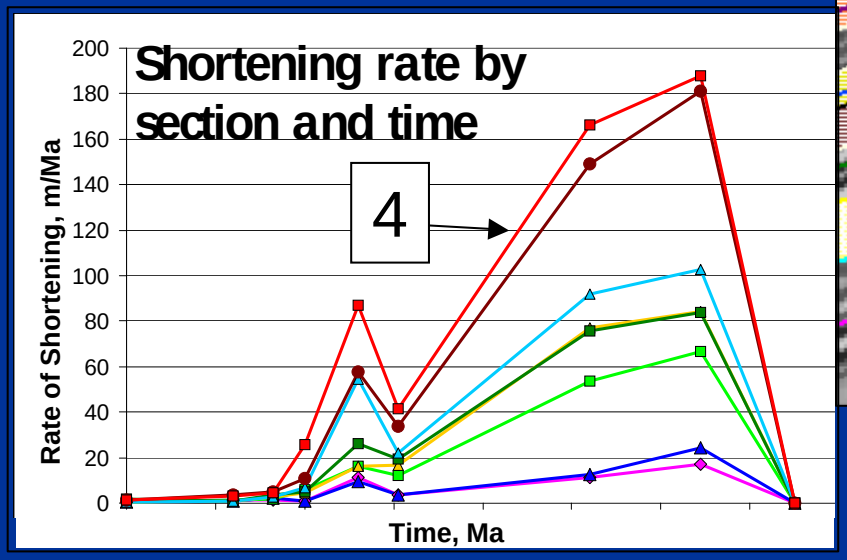


Result: Most likely model of Section 4

Balanced section based on consistent shortening magnitudes and rates across all sections, minimal thickness changes across faults

- 2 thrust faults in the forelimb
- 4-way closure
- fault dependent closure at 900 sand level
- alternative interpretations result in inconsistencies between sections

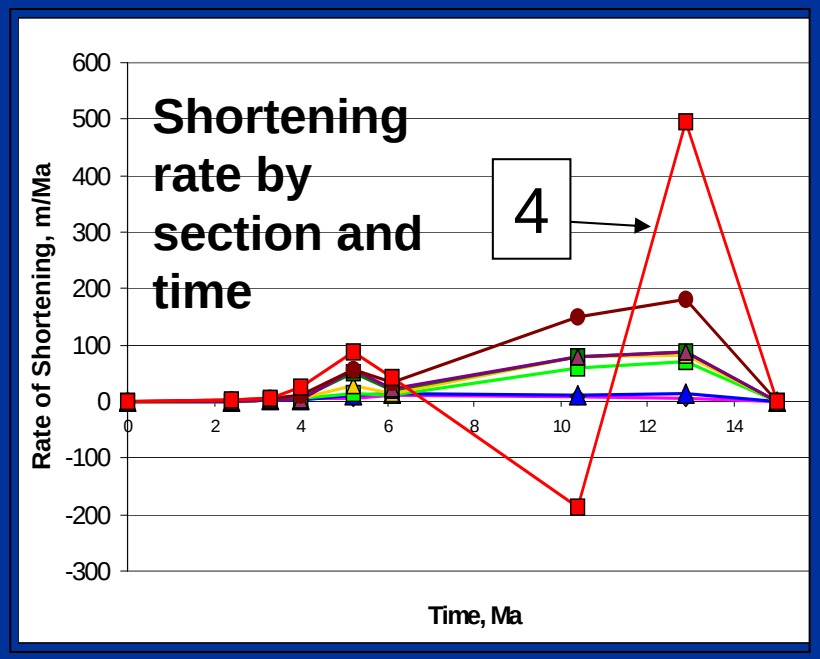


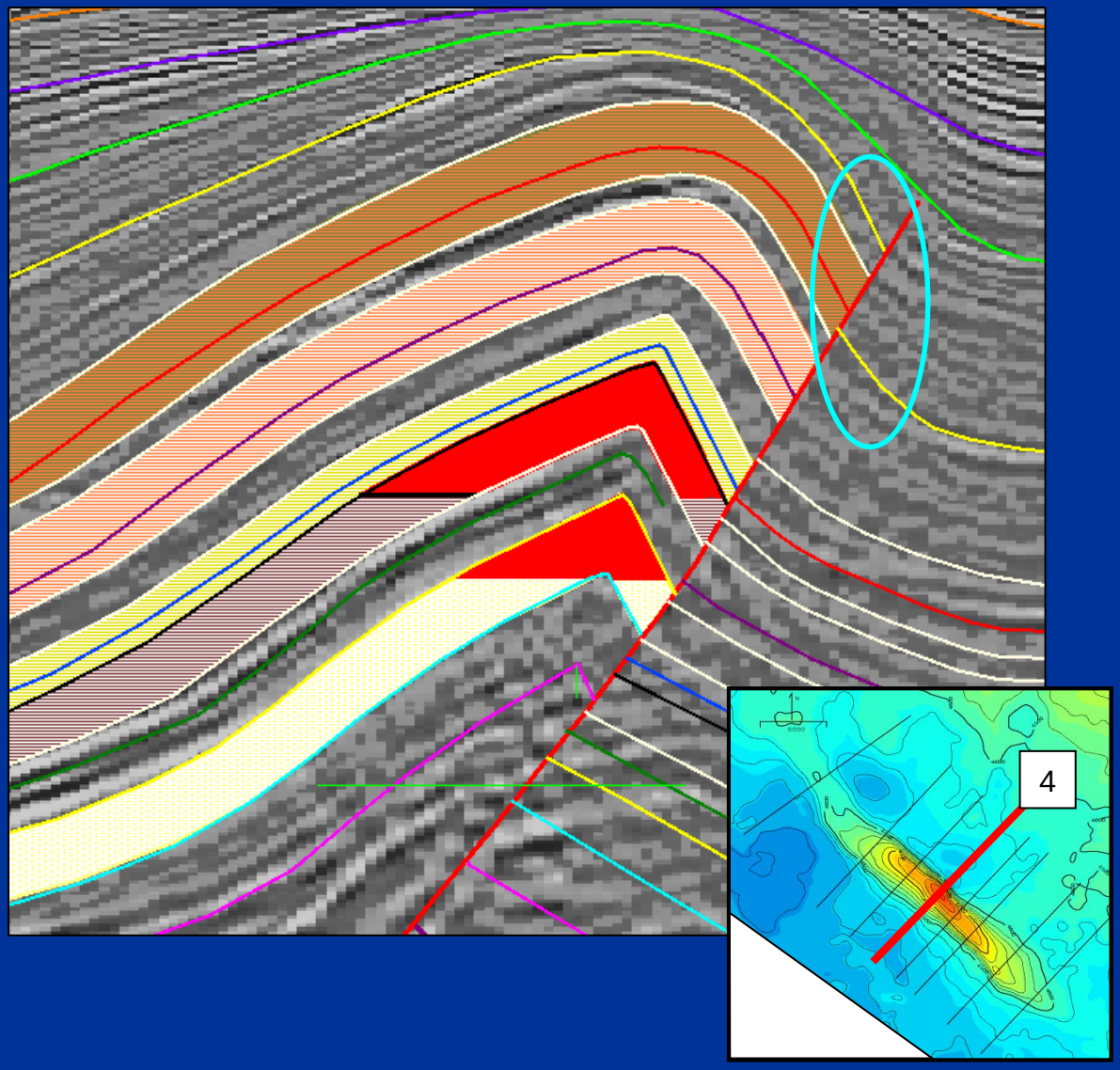


Example Alternative Model of Section 4

Balanced but not tied to the rest of the structure

- 1 thrust fault in the forelimb
- 4-way closure at 900 sand level
- Unrealistic representation of 720 growth strata level (in blue oval)
- Impossible shortening rate profile





Conclusions and implications:

- Exploration success in the offshore foldbelts depends on understanding their architecture.
- Serial palinspastic restorations greatly reduce the uncertainty in fault presence, location & displacement.
- Faults' potential locations and displacements are limited by requiring internal consistency of total shortening and shortening rates, from line to line.
- Thrust fault dependent columns represent upside potential in non-amplitude supported toethrust play.