Insights into the Regional Evolution of the Outer Fold-and-Thrust Belt, Niger Delta, from Combining New Techniques in 3-D Sequential Geomechanical Restoration with Decompaction*

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Abstract

We propose to use new techniques in 3D restoration to fully restore a complex model of compressional structures including a detachment fold, a forethrust fault-bend fold, and a structural wedge in series located in the outer fold-and-thrust belt, deepwater Niger Delta. The structural growth history is recorded by growth stratigraphy and erosional surfaces that record the kinematics of deformation. Beyond the problem of the mesh generation that such a system raises, the vertical variations in mechanical properties, the flexural-slip folding, and the non-cylindrical nature of the structures make the 3D restoration of this system challenging.

We address these challenges by employing a new 3D geomechanical restoration method with an implicit meshing method that facilitates the mesh generation of models including thin layers, unconformities, and/or pinch-out. In addition, we use a transversely isotropic material property in the geomechanical restoration that has been shown to be a reasonable approach for modeling flexural-slip folding without explicitly including slip surfaces in the 3D model. Moreover, accounting for decompaction during sequential restoration improves the assessment of the basin history. An exponential porosity-depth relationship is used to compute the decompaction in 3D after each restoration step.

We combine these new techniques to restore our model sequentially, using transverse materials and an appropriate set of boundary conditions, and apply decompaction after each restoration step. The results are compared to kinematic restorations

of regional transects. In the case of inconsistencies between the kinematic and mechanical techniques, such as extremely different regional shortening or fault slip amounts, additional displacement constraints are set to better constrain the 3D geomechanical restoration. The outcomes of the restoration, such as strain distribution and 3D gradients of fault slip, allow us to enhance our understanding of the regional evolution of the Niger Delta toe and demonstrate the capabilities of geomechanical restorations in addressing complex, 3D deformations with sediment compaction.

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AAPG meeting 2012, April 25th

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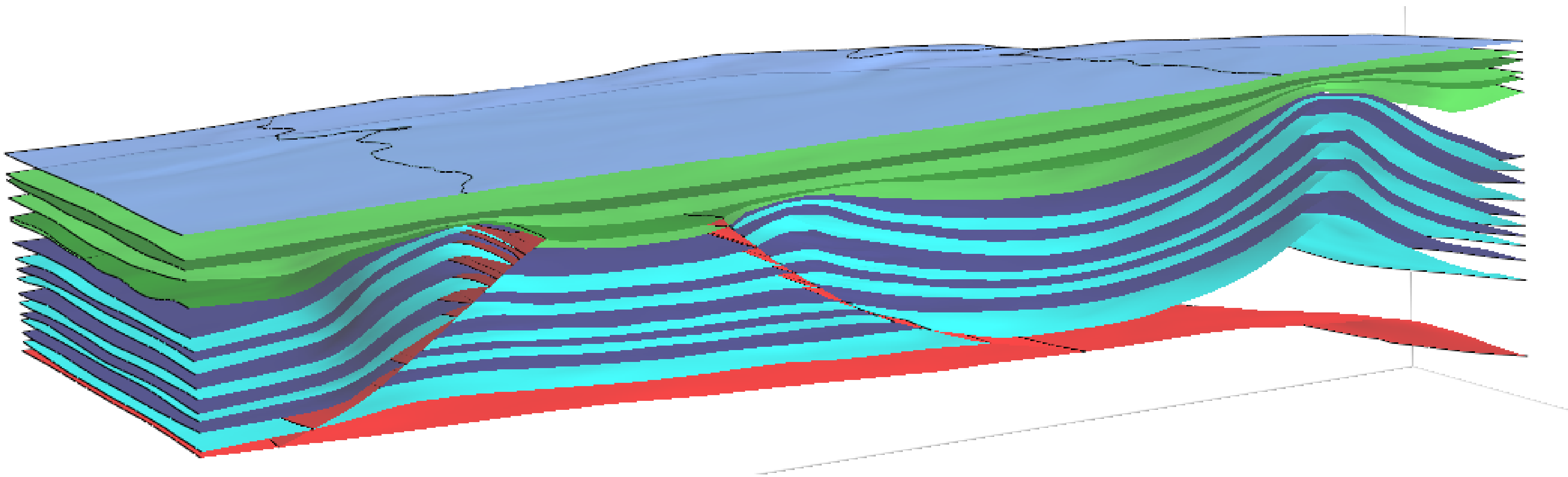
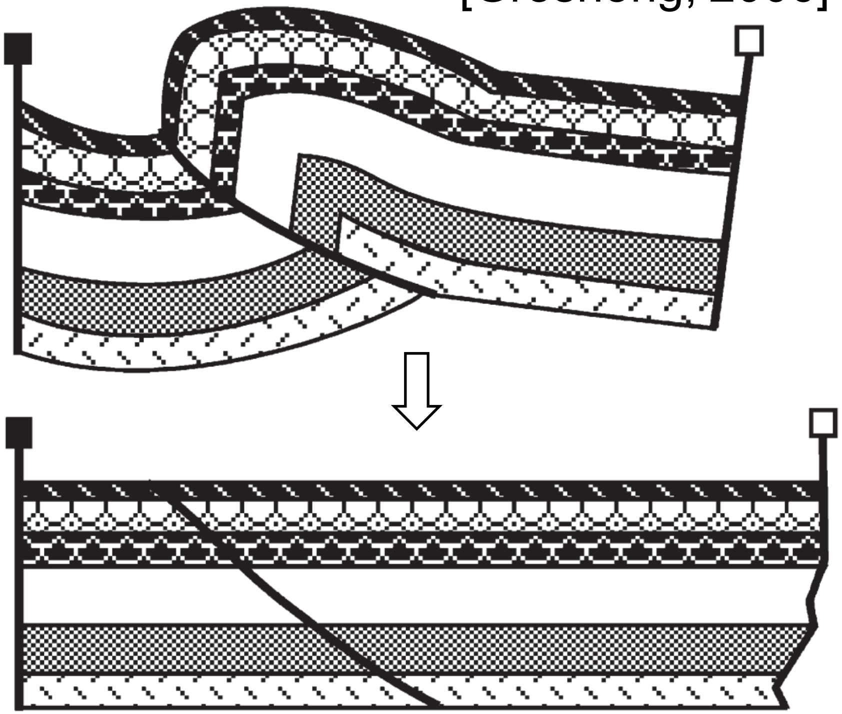


Structural geology and restorations

- Kinematic models of structures allow a better understanding of the deformation
- Structural restoration provides a mean to (in)validate structural interpretations and recover geometric evolution and timing of deformation

[Groshong, 2006]



Kinematic restorations

- **Preservation of a geometric criteria (angle, length, area, volume)**
- **On cross-sections**

    - Plane strain assumption

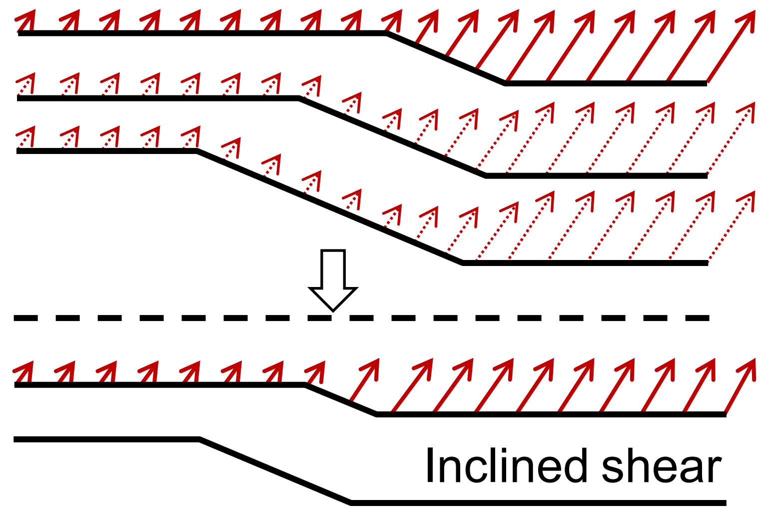
[Chamberlin, 1910; Dahlstrom, 1969; Groshong, 2006]

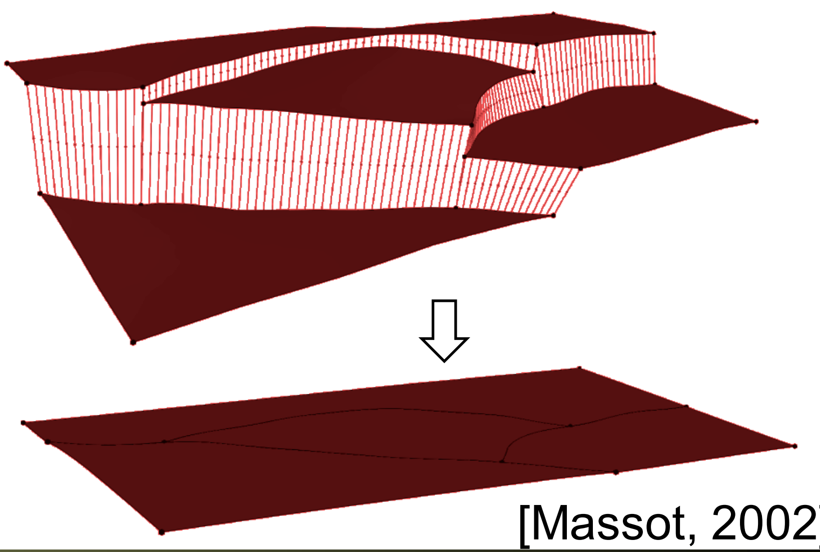
- **Map and volume restoration**

    -Fault constraints

[Gratier et al., 1991; Gratier and Guillier, 1993; Rouby, 1994; Thibaut, 1994; Samson, 1996; Leger *et al.*, 1997; Samson, 1996; Rouby et al., 2000; Griffiths, 2002; Mallet, 2002; Massot, 2002]

[Mallet, 2002; Massot, 2002; Muron, 2005]





[Massot, 2002]

Input styles of deformation

No internal deformation

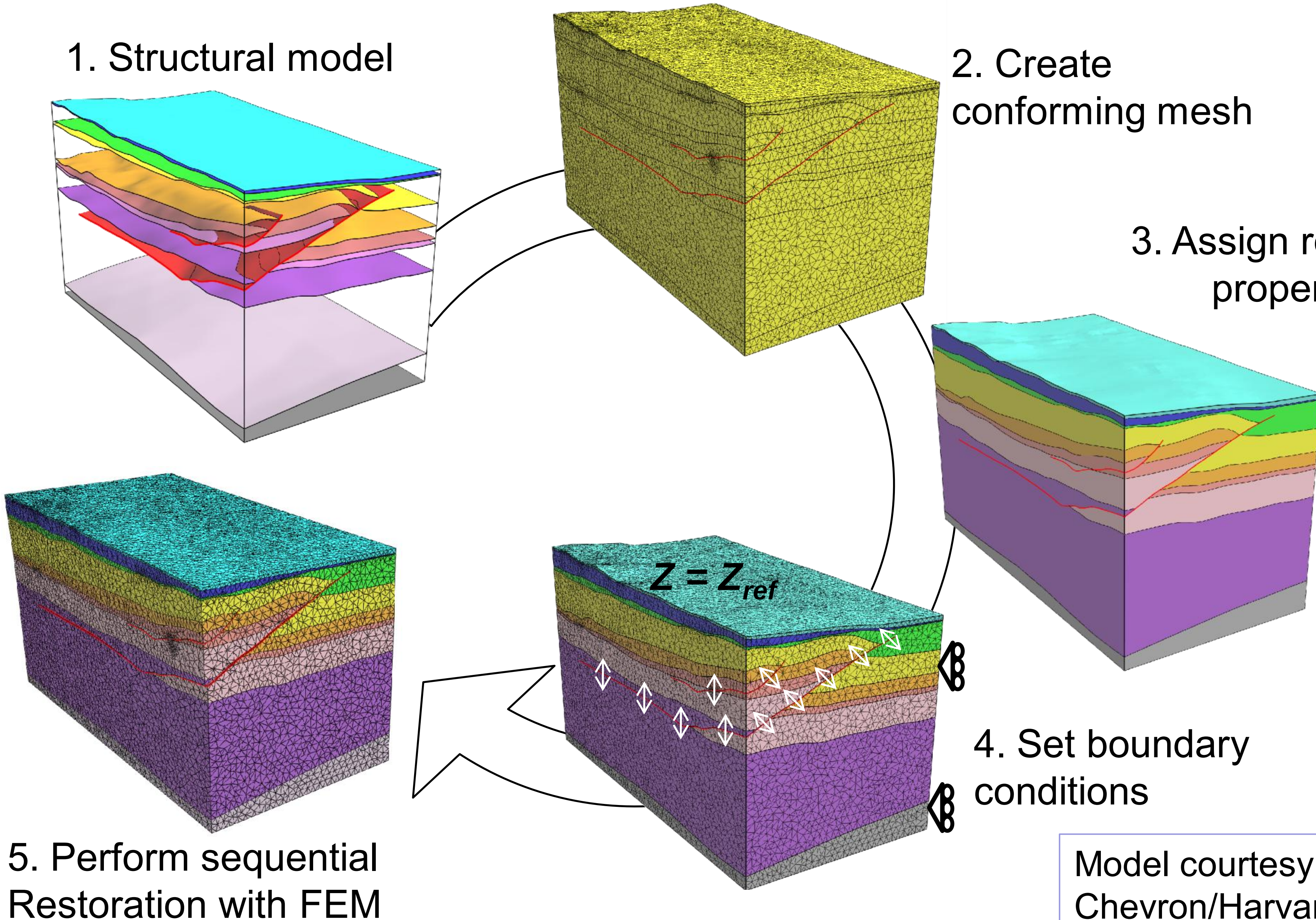
Geomechanical restoration

- Rock properties control macroscopic structures, deformation styles, fault propagation, …
- Accounting for these properties during restoration is important

➡ ***Geomechanics***
[De Santi et al., 2003; Muron, 2005; Moretti et al., 2006; Maerten et al., 2006; Guzofski, 2009; Durand-Riard et al., 2010]

Elastic behavior
Strain energy minimization

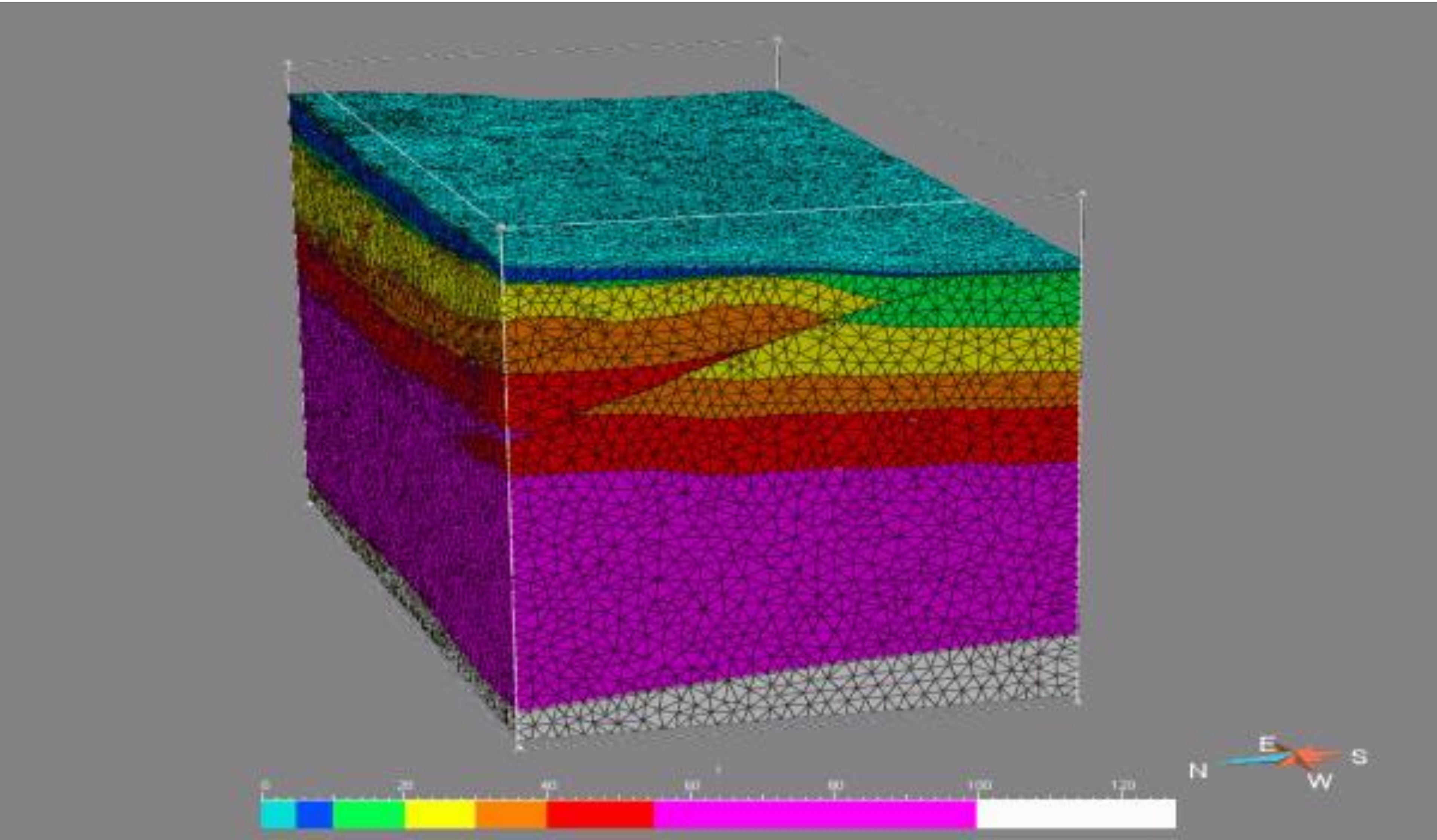
Geomechanical restoration workflow



Model courtesy of Chevron/Harvard

3D sequential geomechanical restoration

[Muron, 2005]



Geomechanical restoration

Values:

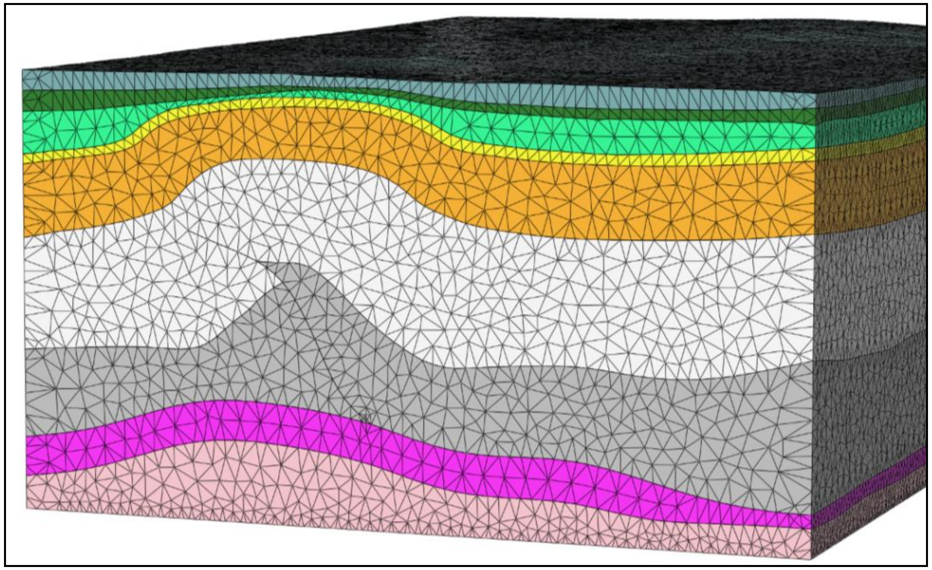
- More accurate representation of paleo-basin geometry: timing of hydrocarbon maturation, trap development, and structural relationships at the time of hydrocarbon charge.
- Strain history: top and fault seal capacity, reservoir porosity and fractures prediction

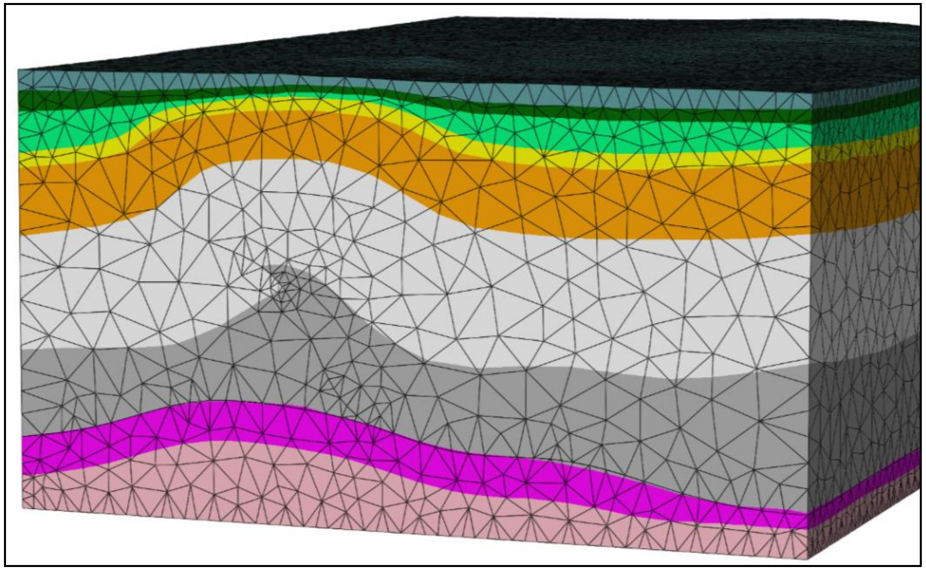
Applying it to a complex case study requires:

- Meshing complex structures, including unconformities, pinch-outs, small fault offsets
- Being able to decompact in 3D, accounting for basin deformation history (uplift, subsidence) or tectonic deformation between wells

New techniques in restoration

- Meshing issues
  - ✓ Implicit approach [Frank et al., 2007, Caumon et al., 2012, Durand-Riard et al., 2010]





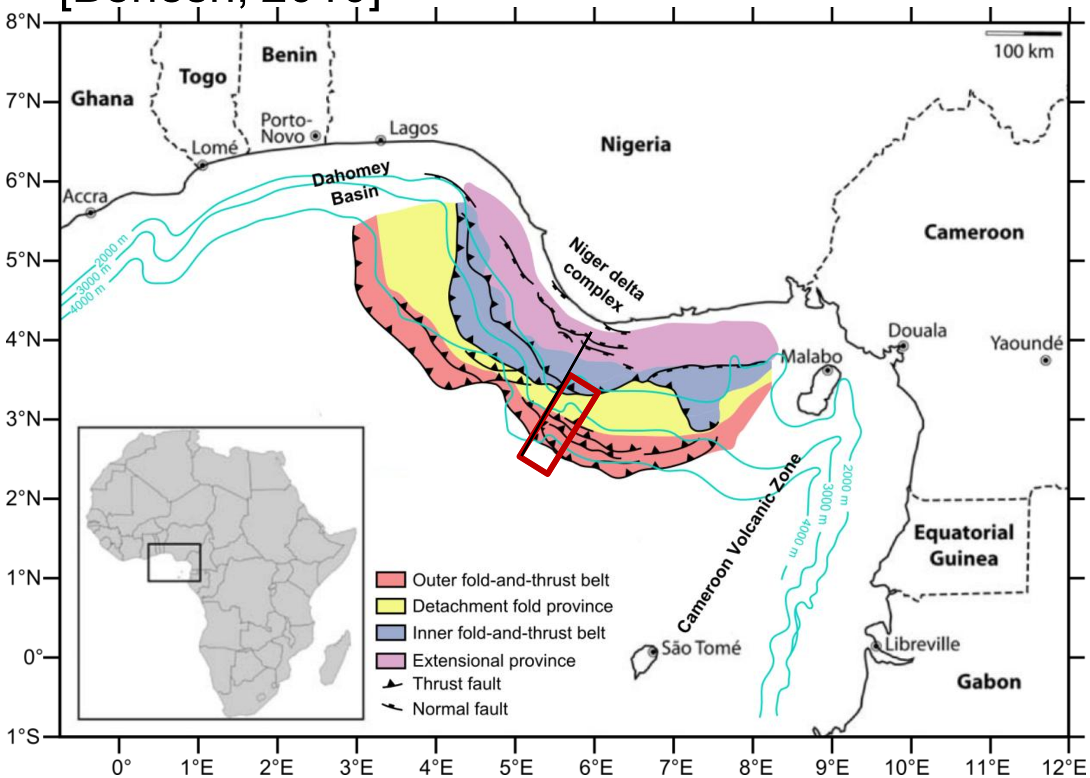
New techniques in restoration

- Meshing: Implicit approach
- Decompaction
  - ✓ Combine isostatic decompaction with 3D geomechanical restoration [Durand-Riard et al., 2011]

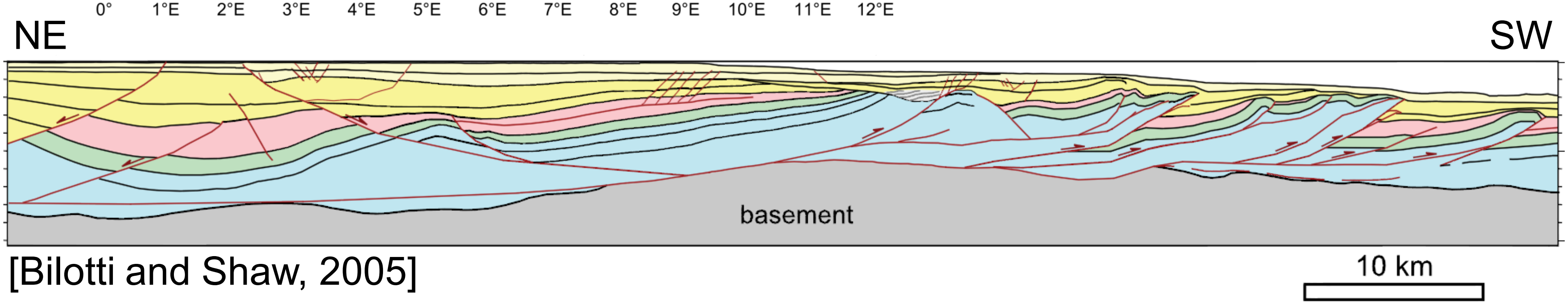
    The depth-porosity relationship $\Phi = \Phi_0 . e^{-cz}$ is solved numerically from top to bottom in the model after each step of restoration.

Regional settings

[Benesh, 2010]



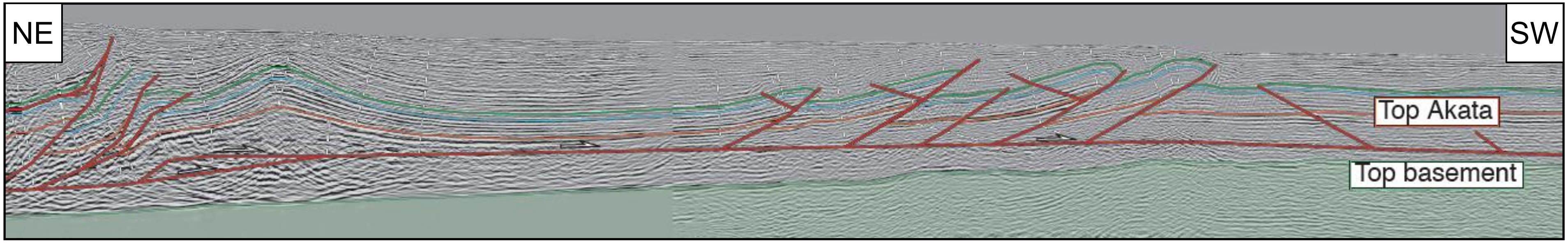
- Passive margin delta
- Gravity driven, linked extensional and contractional fault systems
- Prolific petroleum basin



[Bilotti and Shaw, 2005]

Area of interest

- Straddles the detachment province and the outer fold-and-thrust belt
- 2 main formations: Akata and Agbada

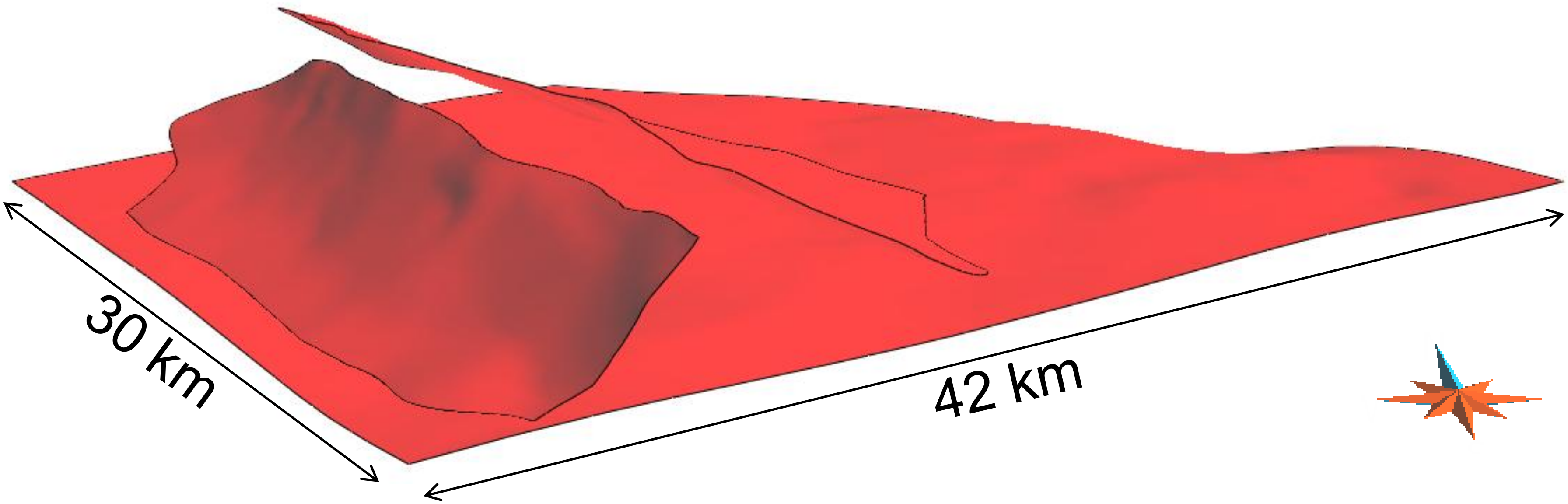


[Guzofski, 2007]

- 3 main structures are included in a 1260km^2 model

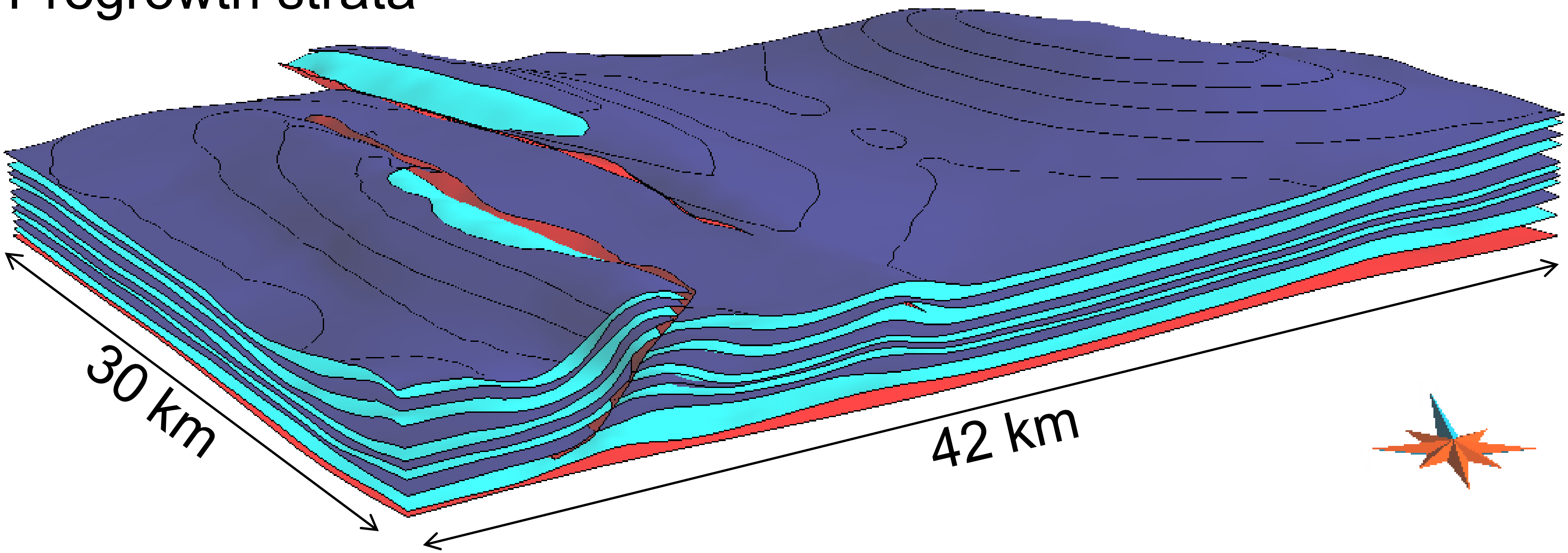
Case study

Faults

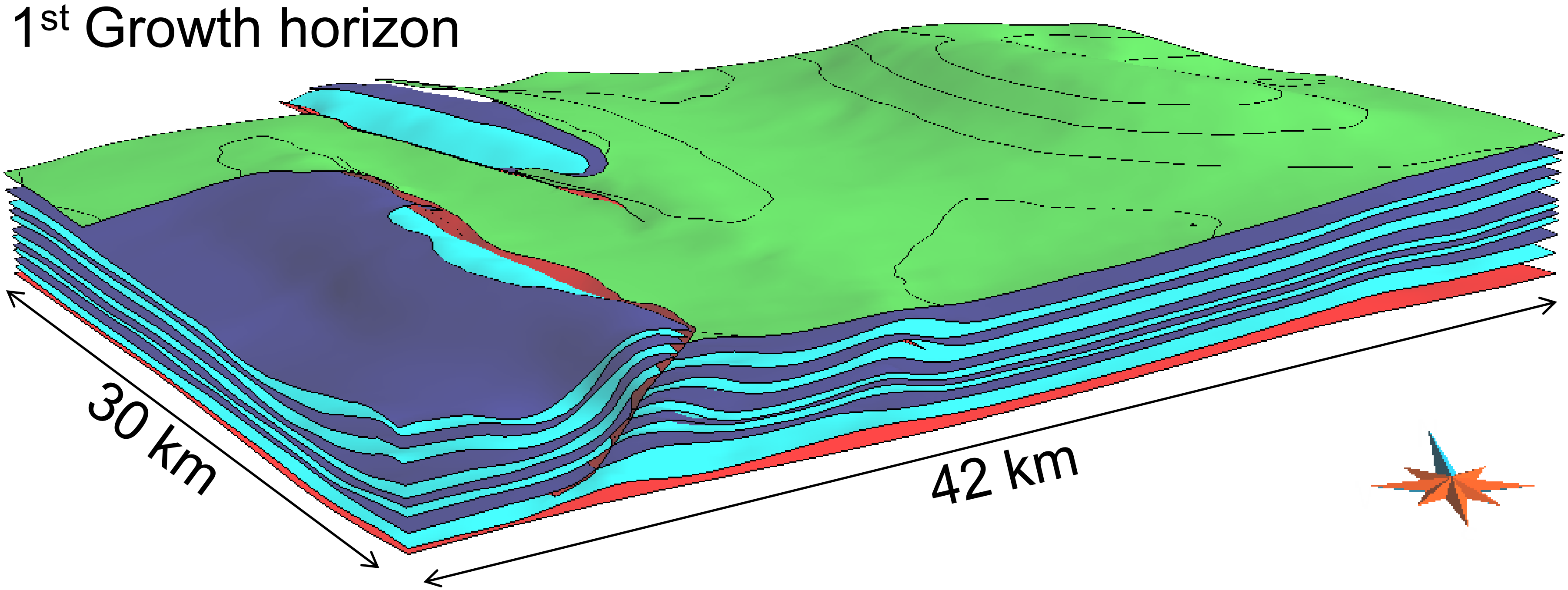


Case study

Pregrowth strata

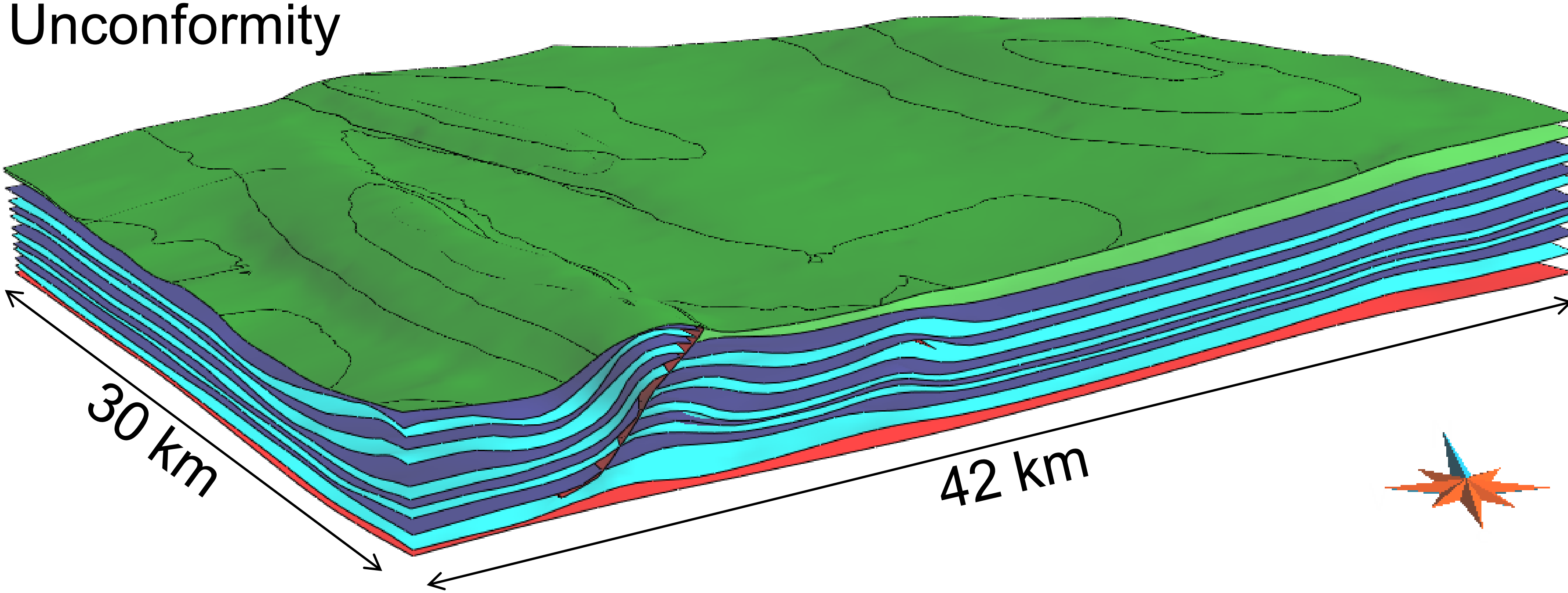


Case study

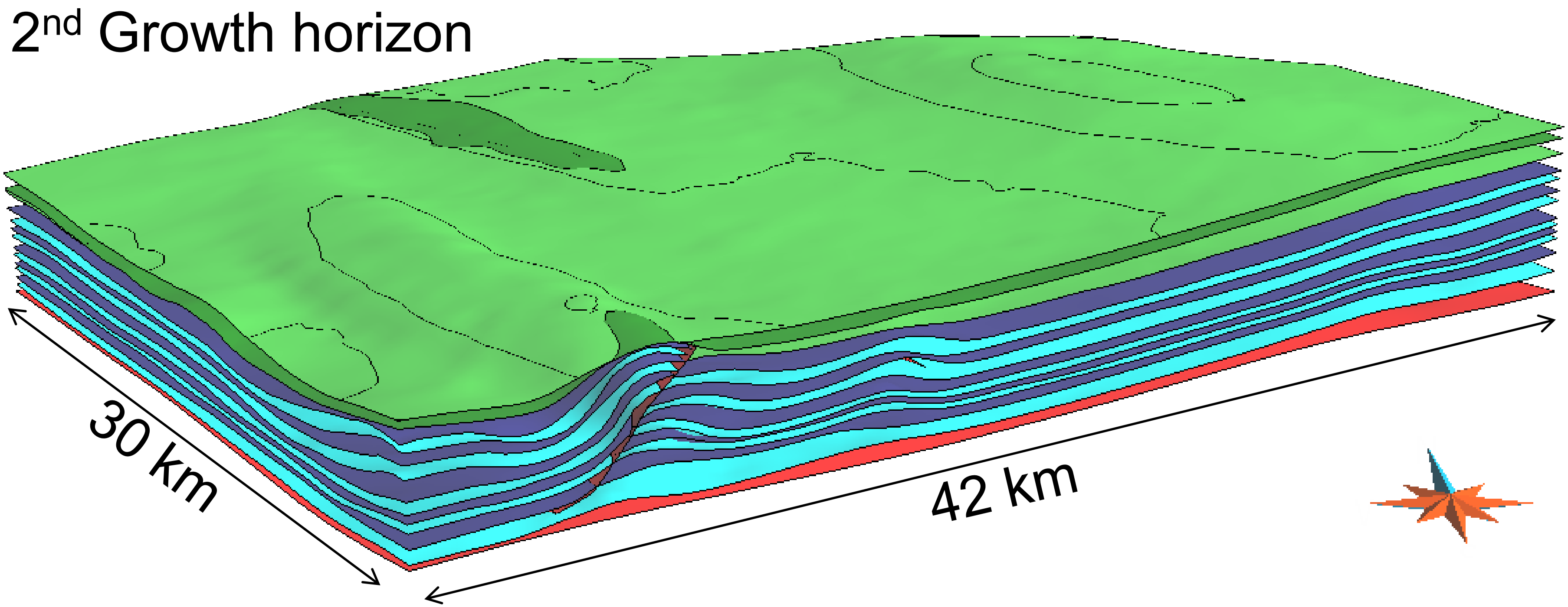


Case study

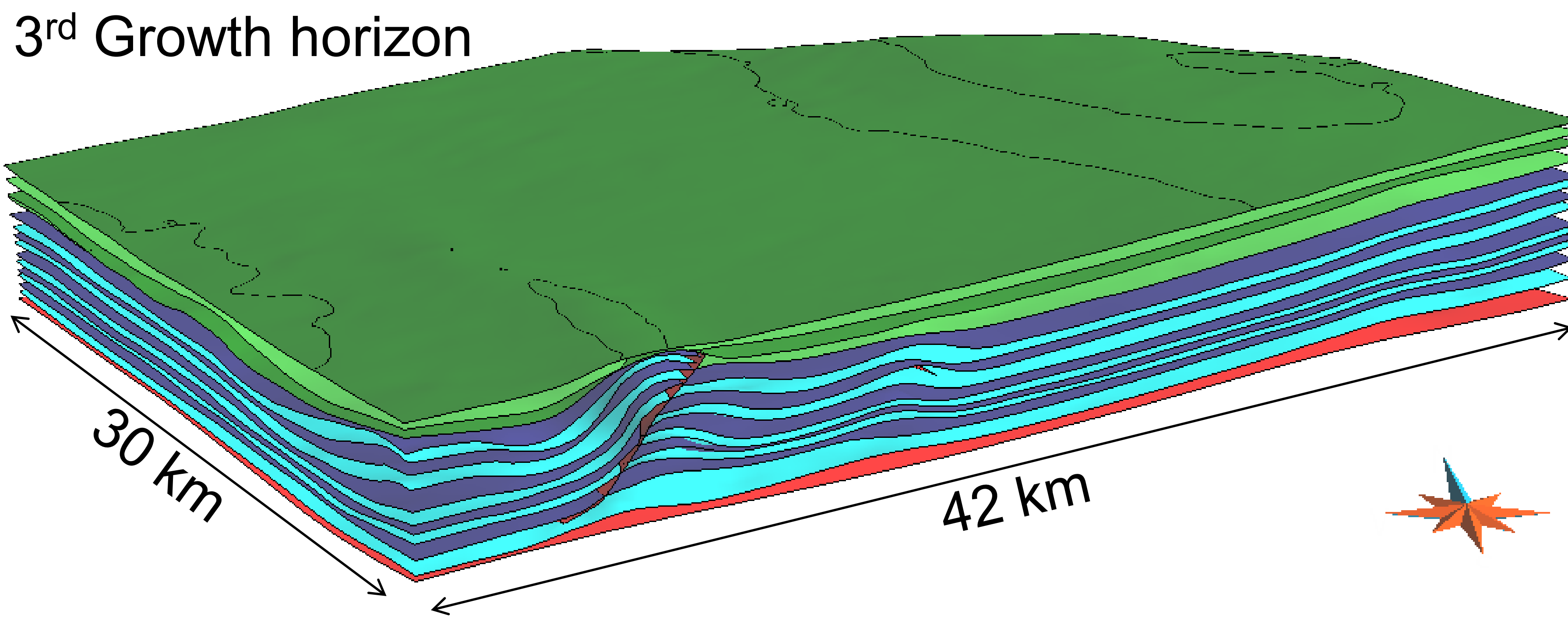
Unconformity



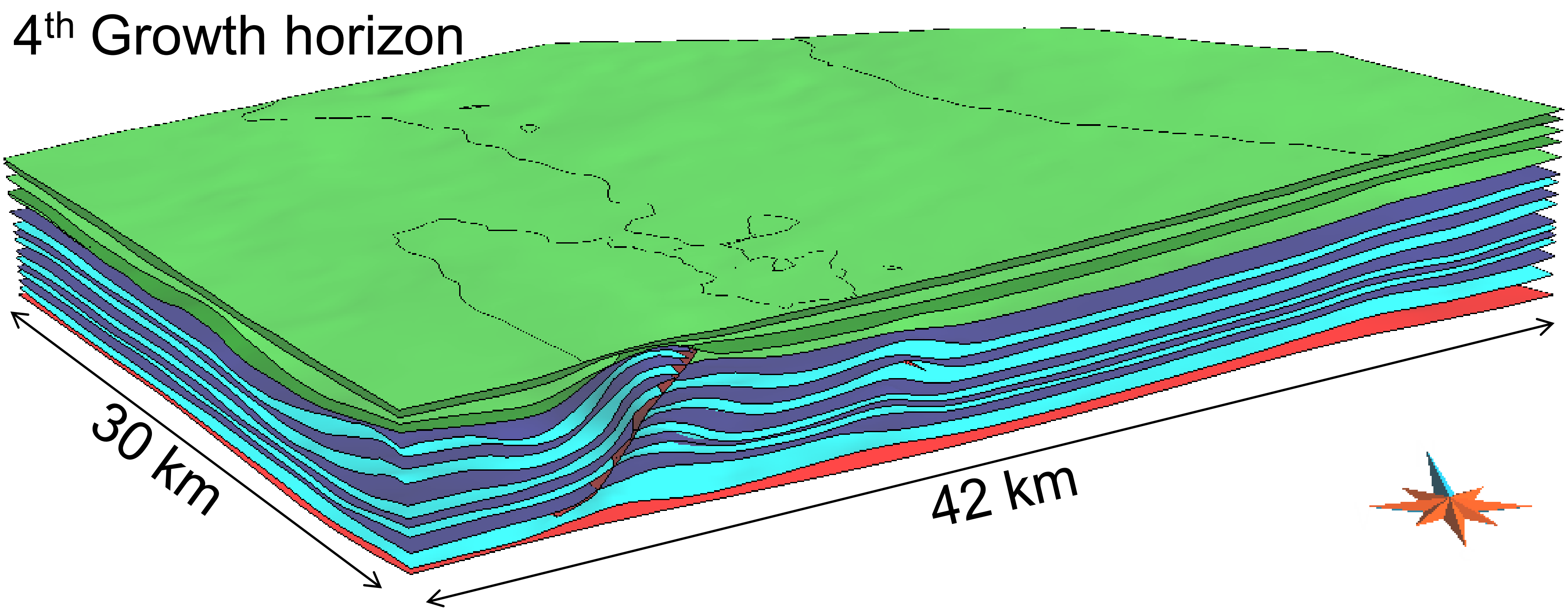
Case study



Case study



Case study



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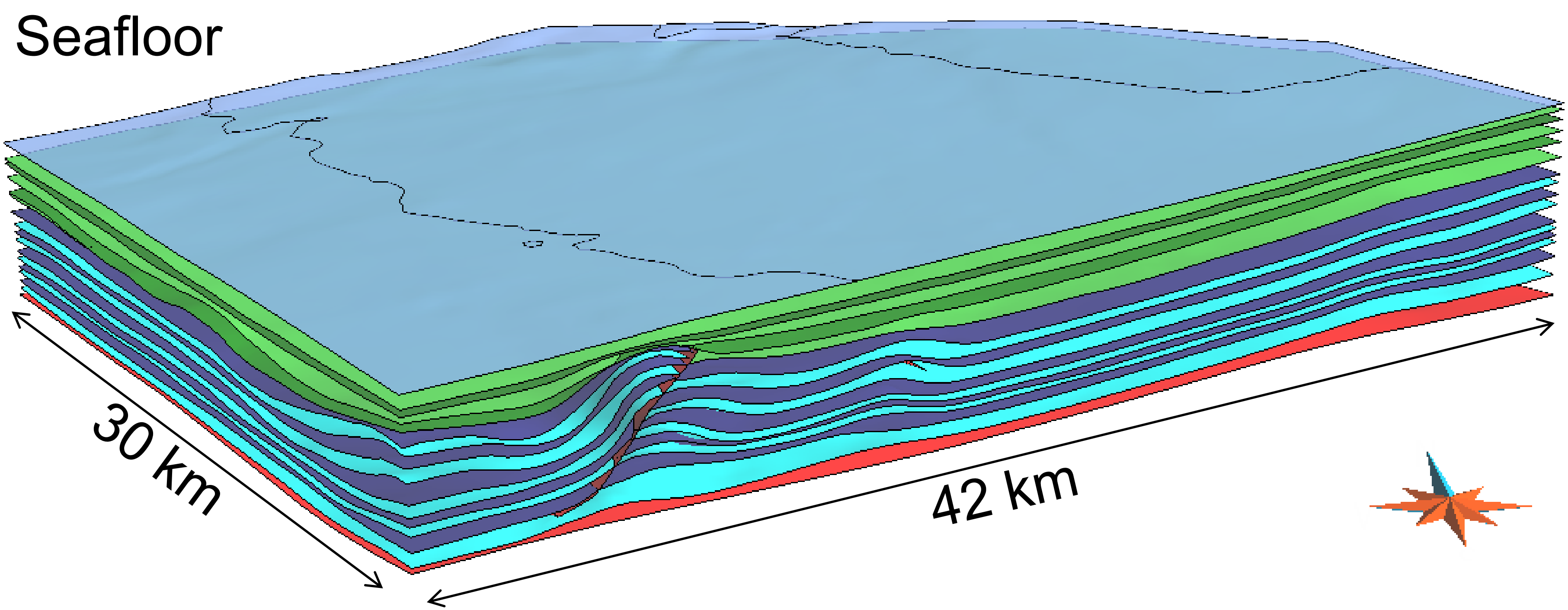

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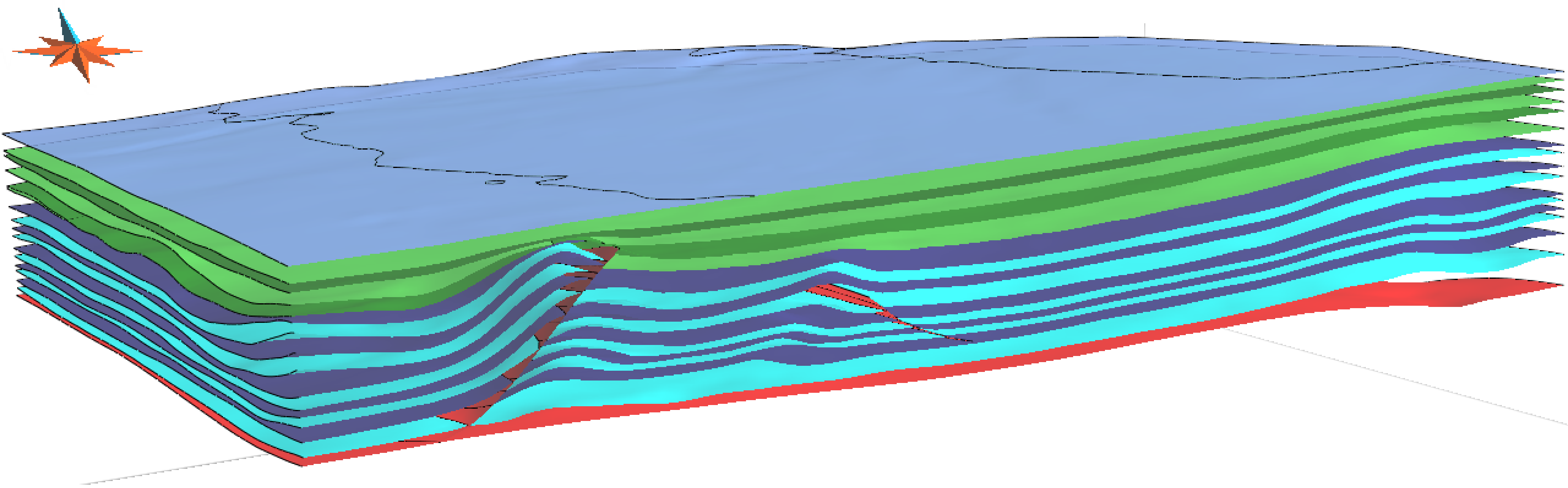
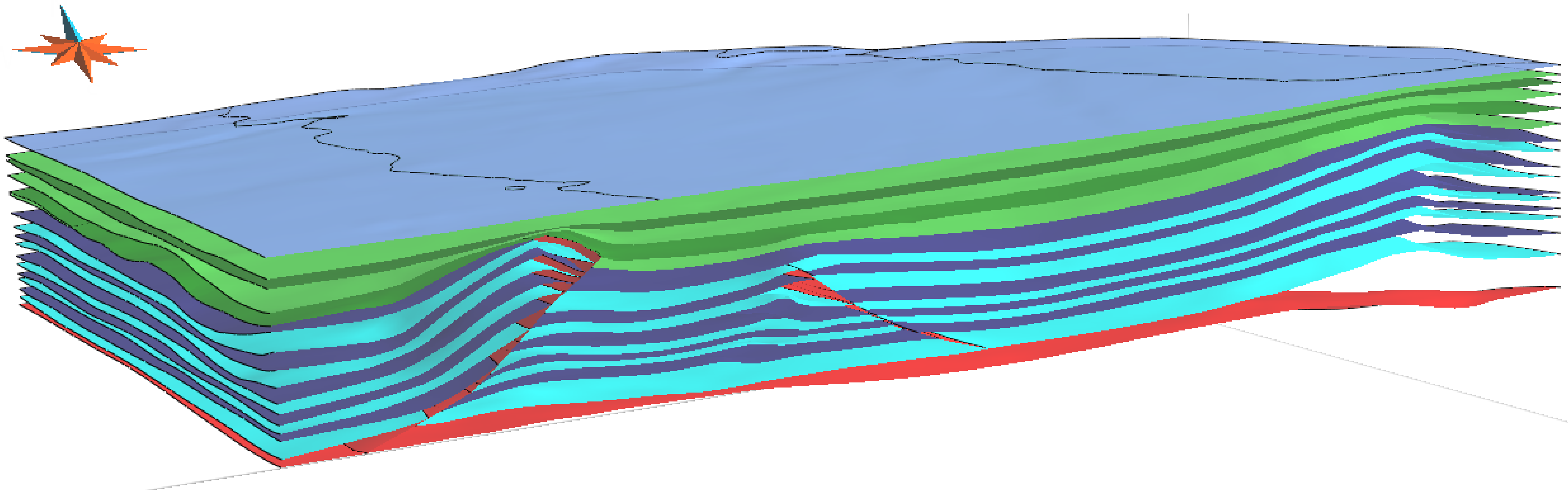


Case study



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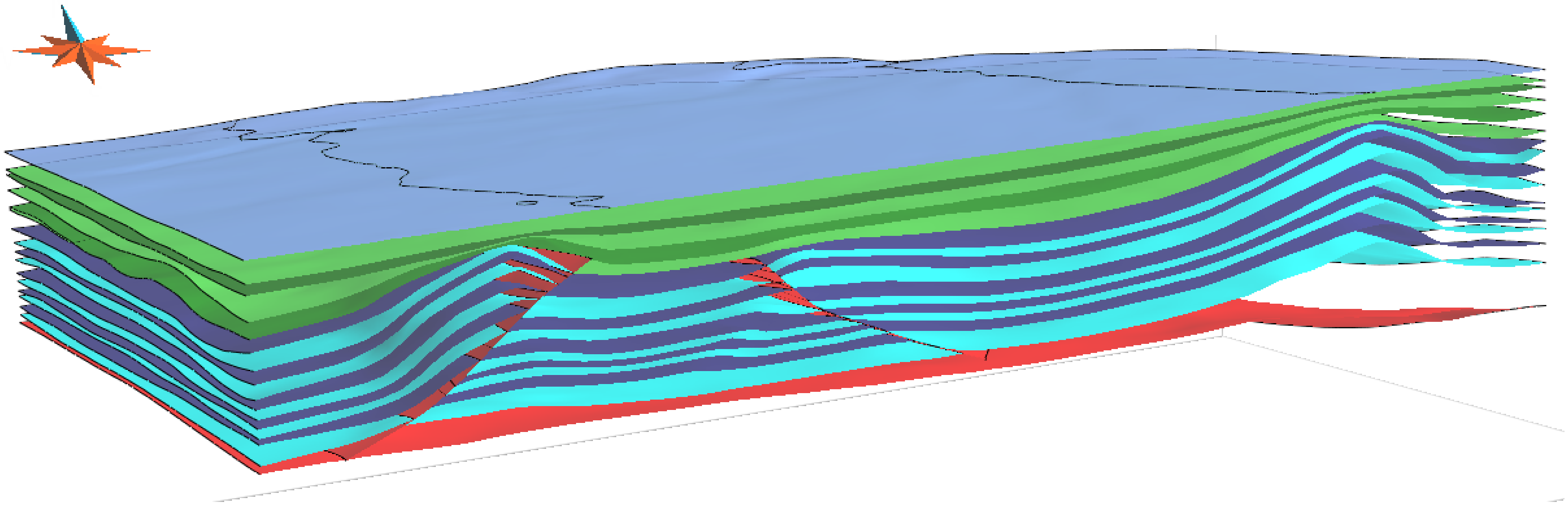

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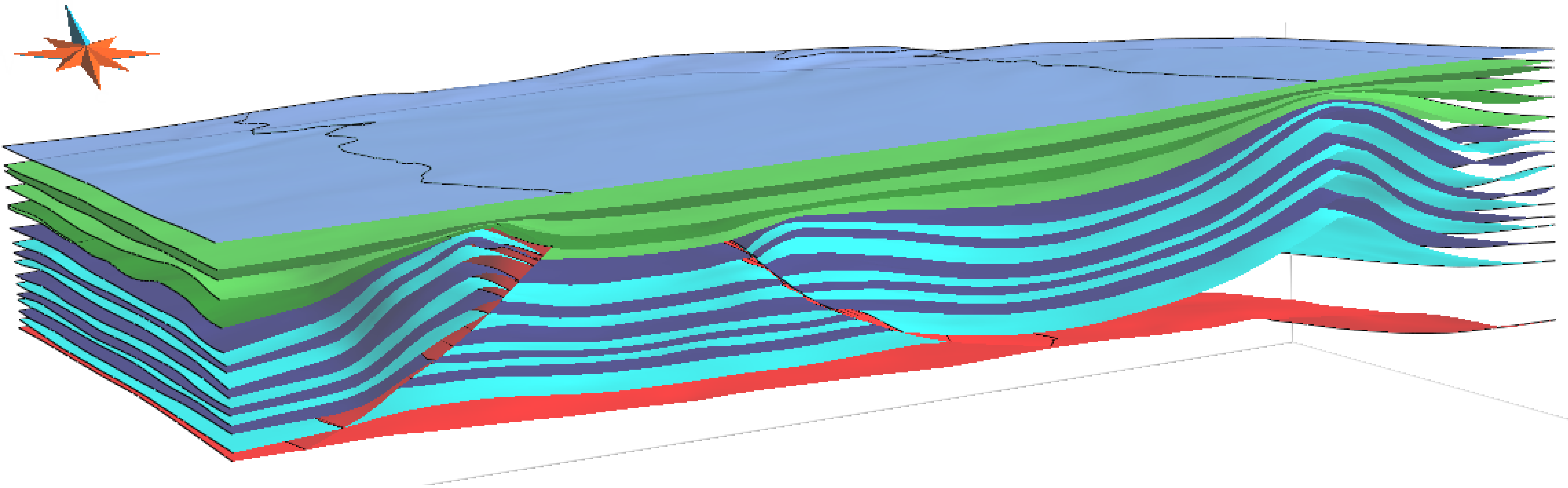

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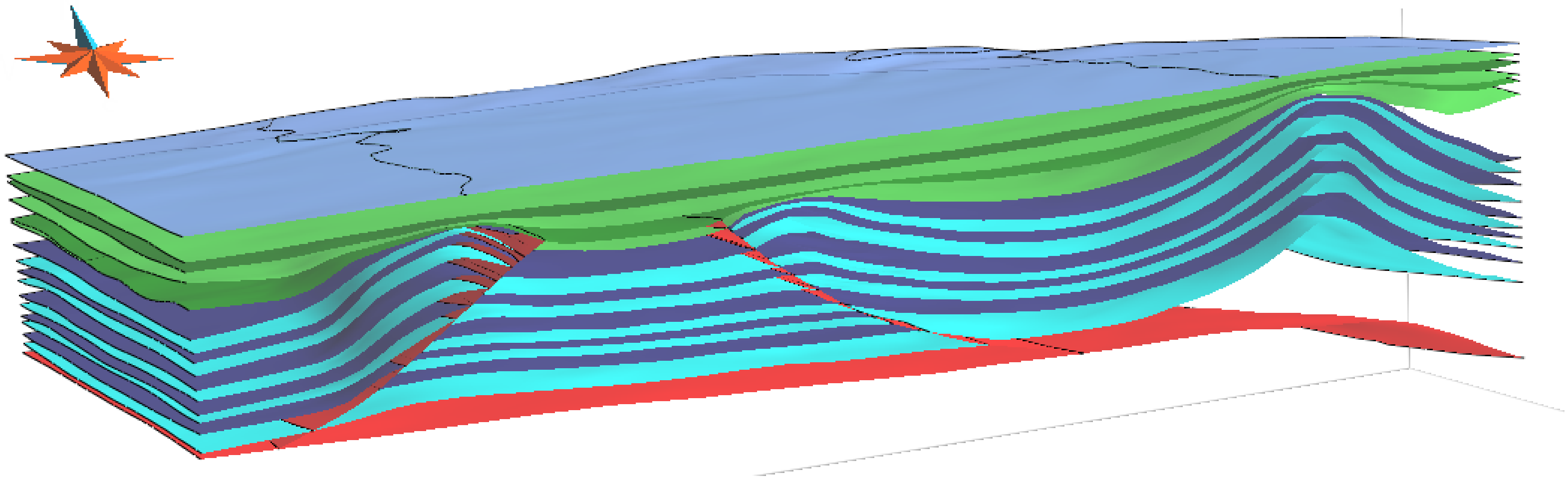
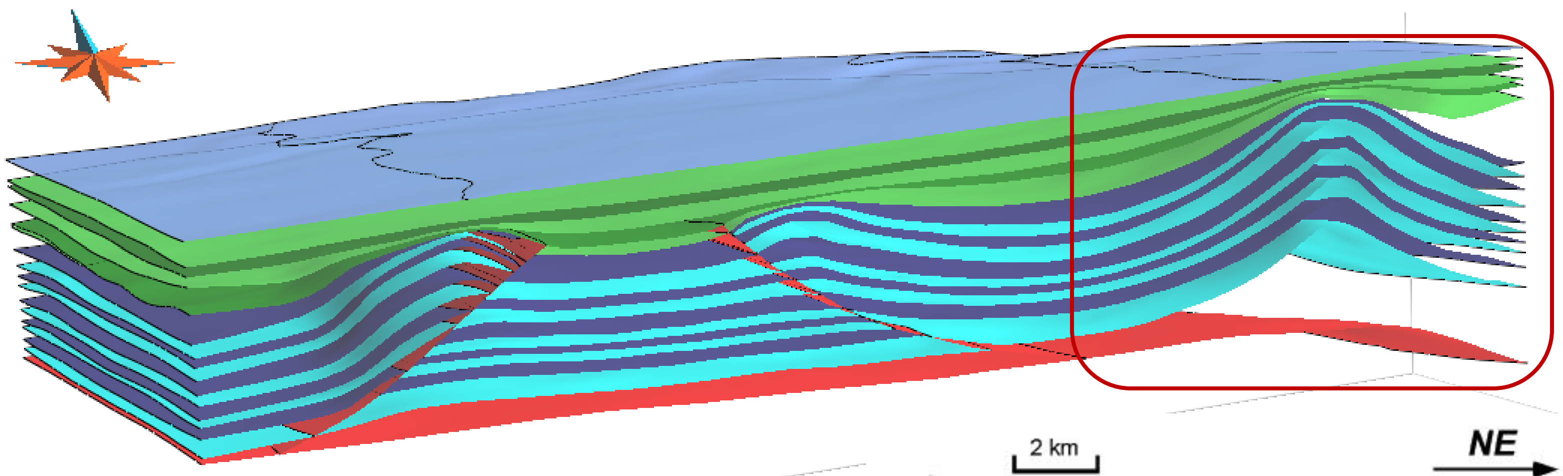
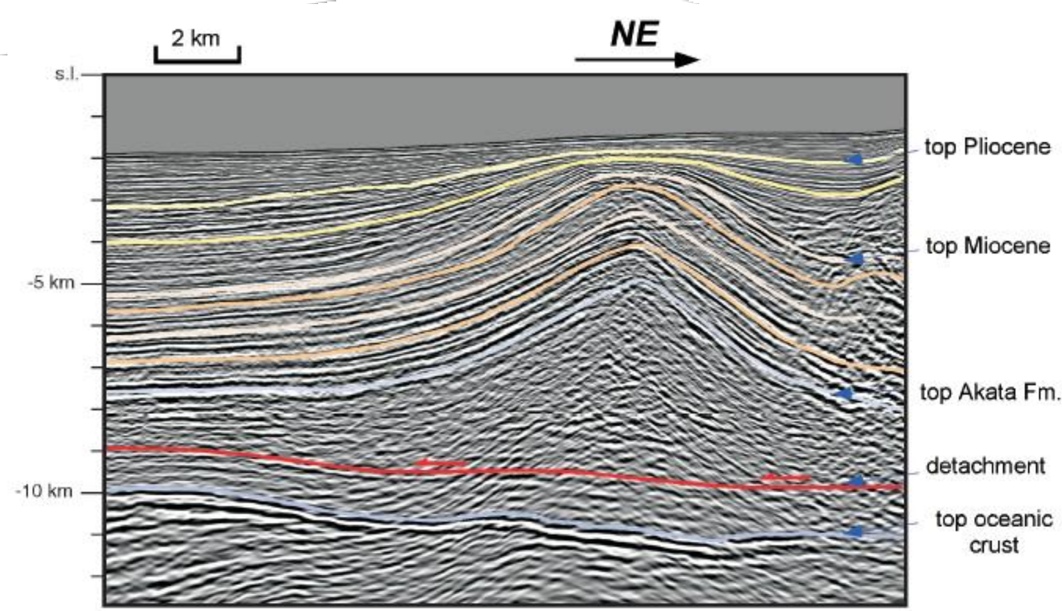


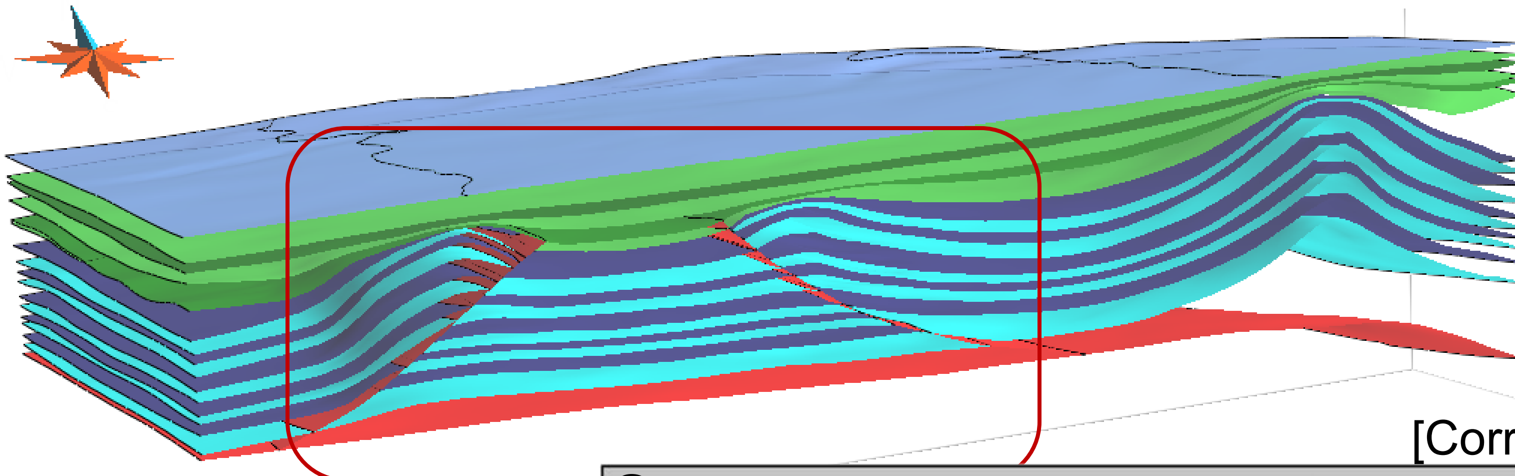
Case study



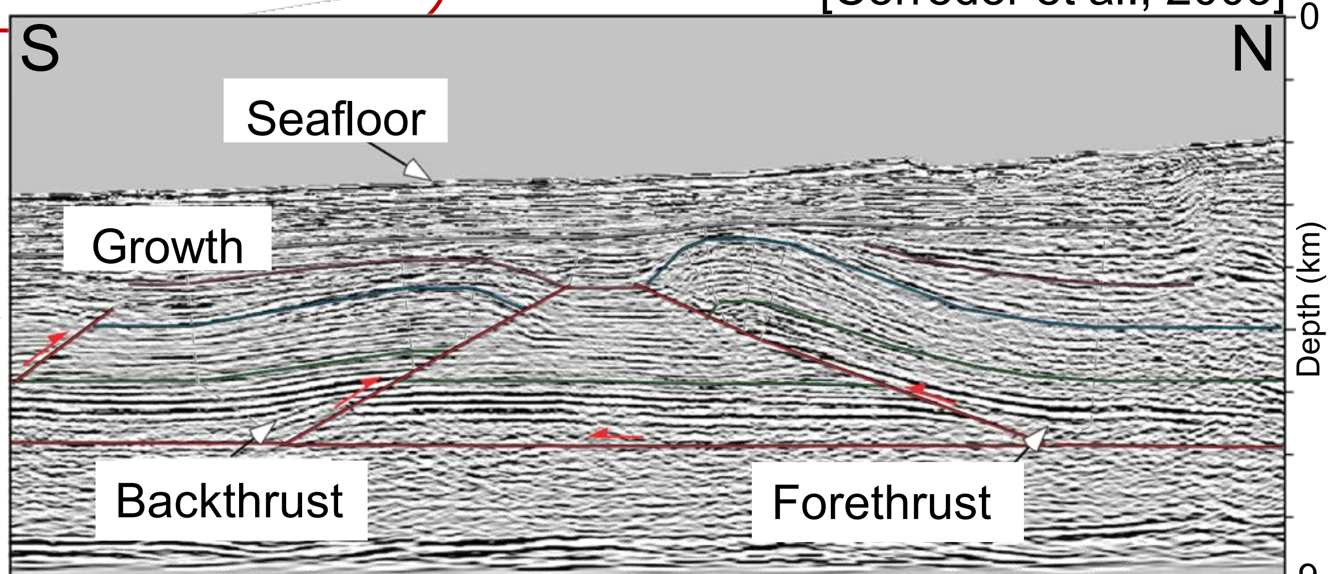
- •Anticlinal, core thickened, growth on top
- • Heterogeneous inclined-shear [Bilotti, 2005]
- • Detachment fold



Case study



[Corredor et al., 2005]

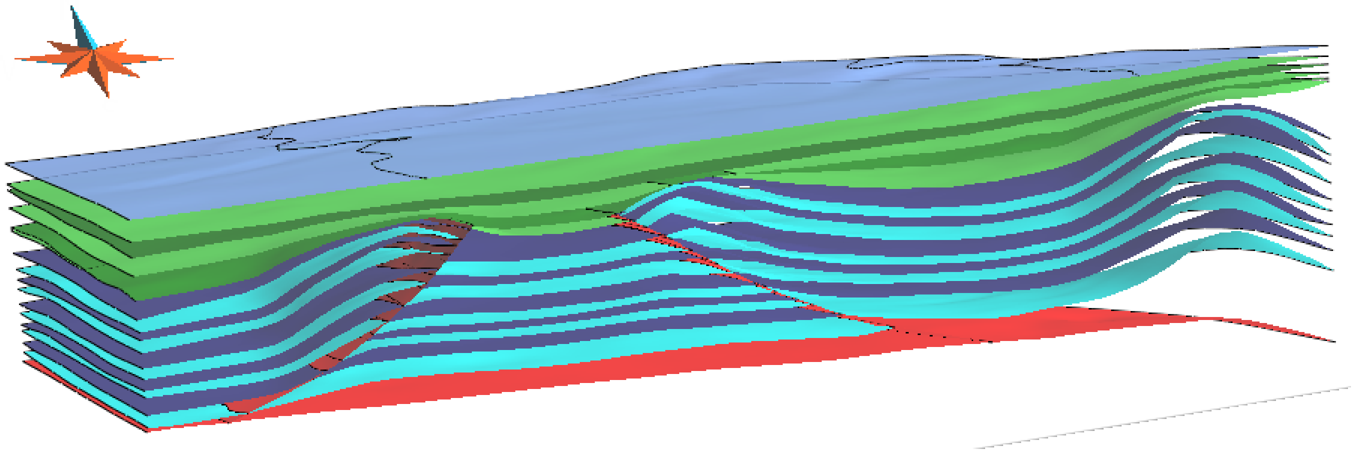


Dip of backlimbs less than the fault dip: strong shear component

Forethrust: simple shear fault bend fold

Backthrust: pure shear wedge

Case study



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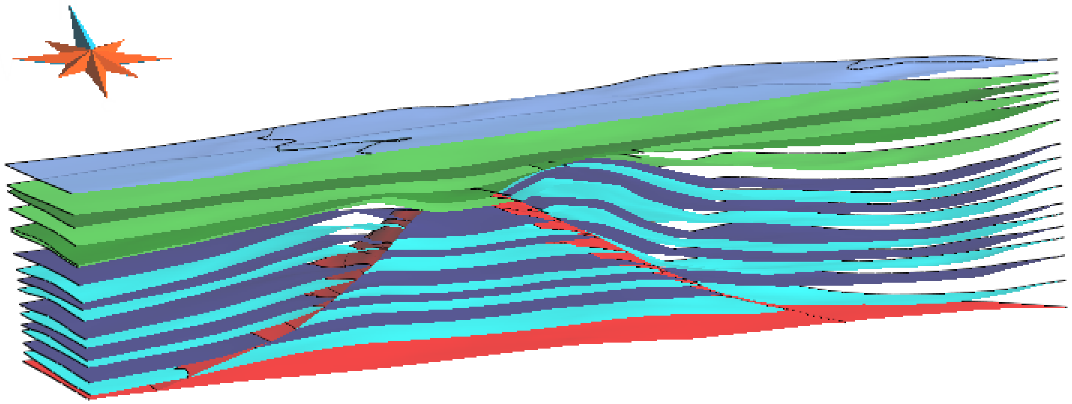
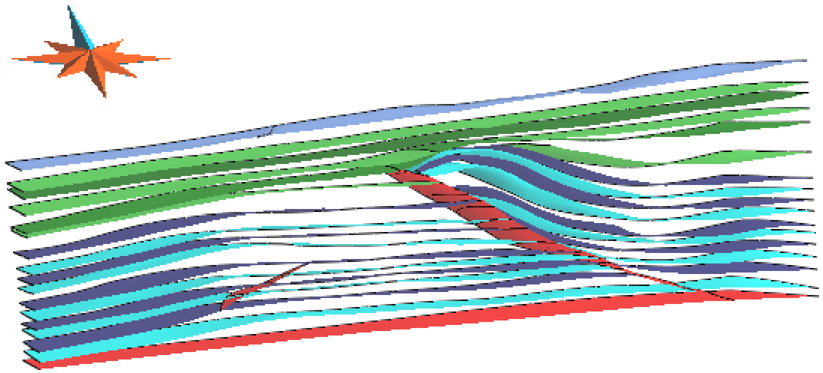


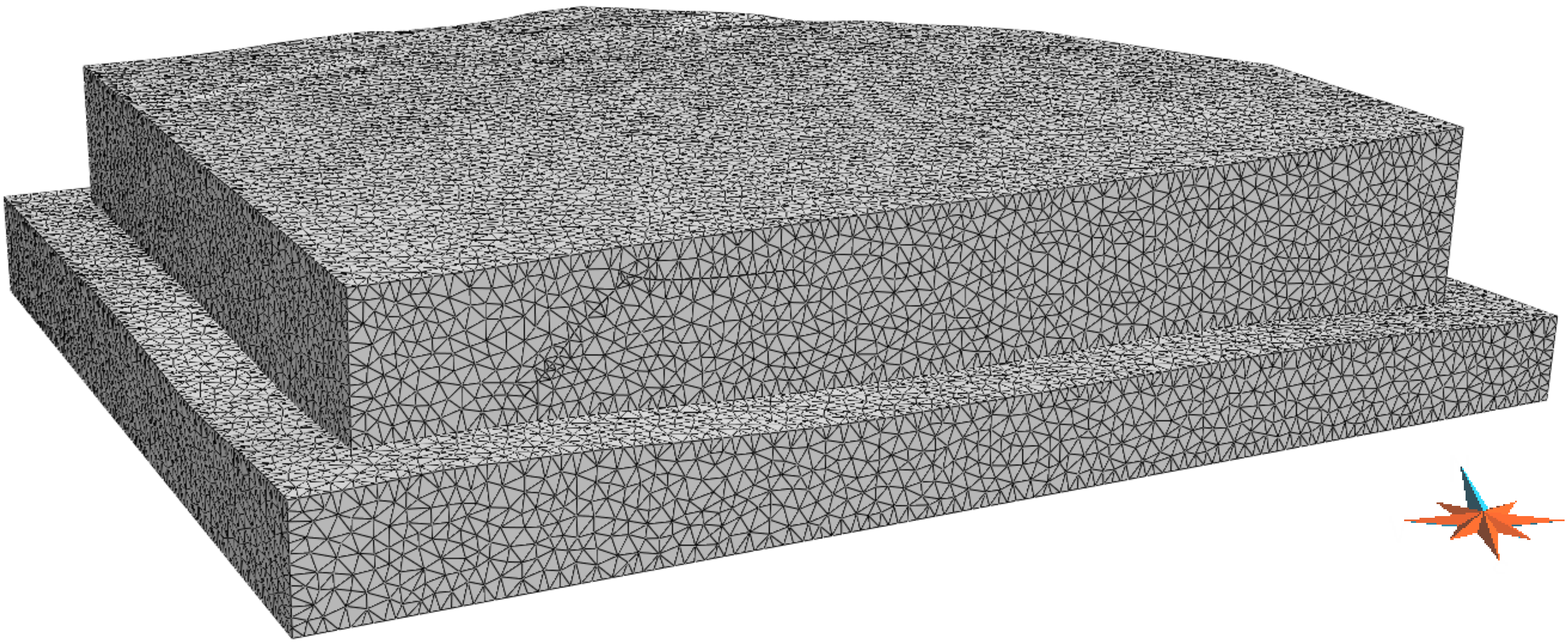
Case study



Motivations and challenges

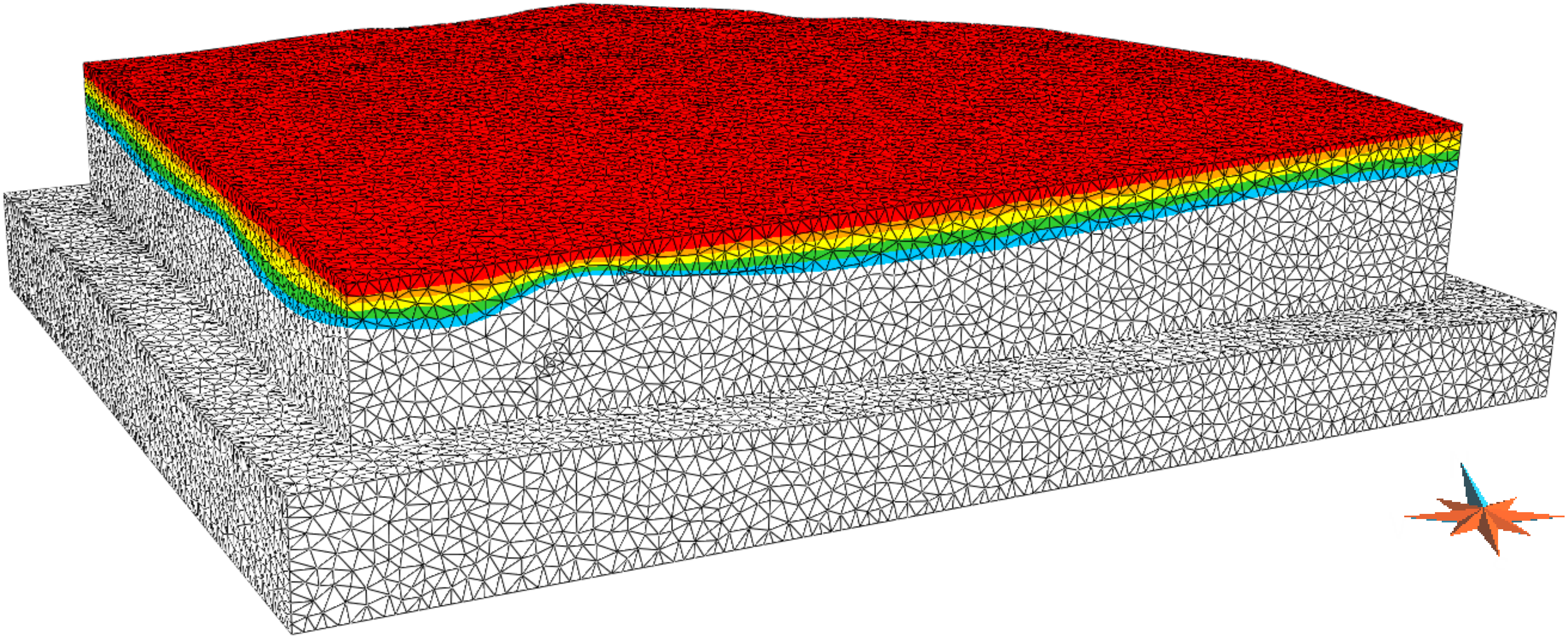
- Contractional structural features commonly found in fold-and-thrust belts
- Challenges:
  - Non-cylindrical structures
  - Different vergence directions
  - Meshing challenges due to the faults geometries and small offsets and thin / pinched-out layers

Restoration mesh



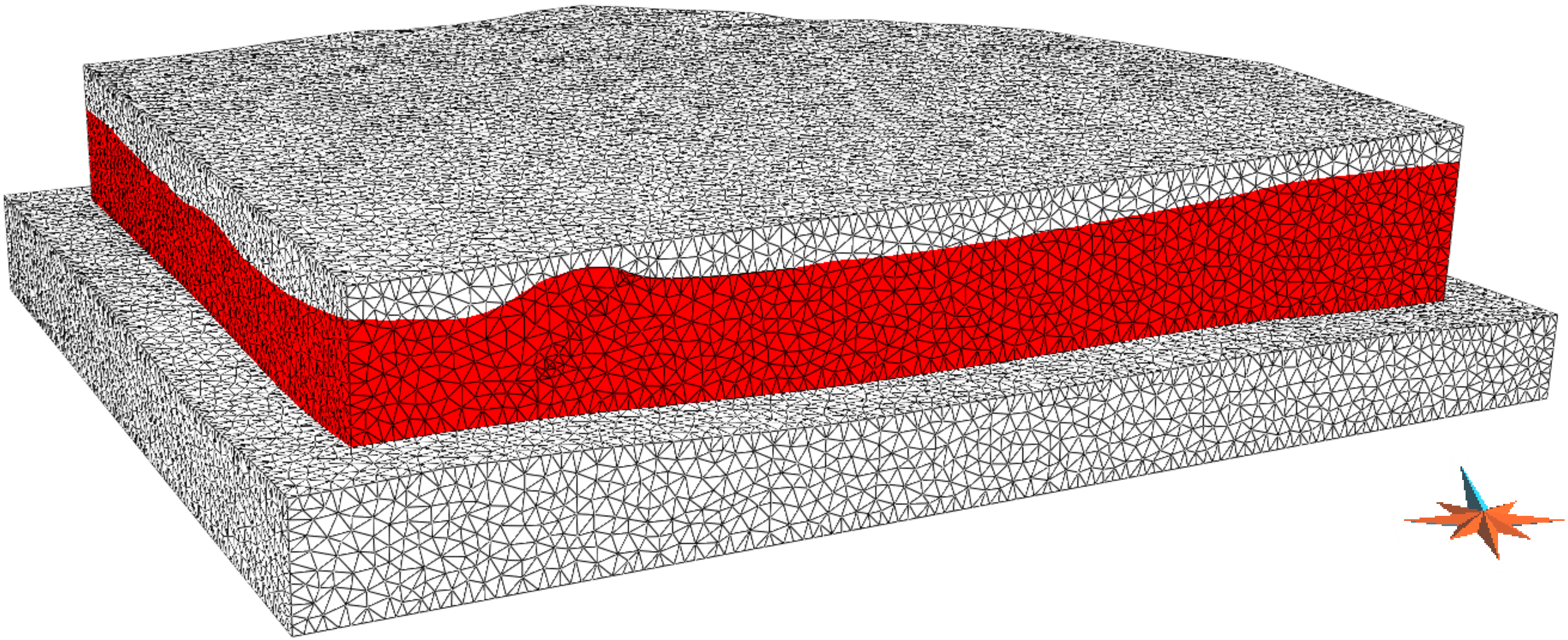
- Conformable only to the faults
- Base of the detachment larger to ensure sliding on the footwall

Restoration mesh



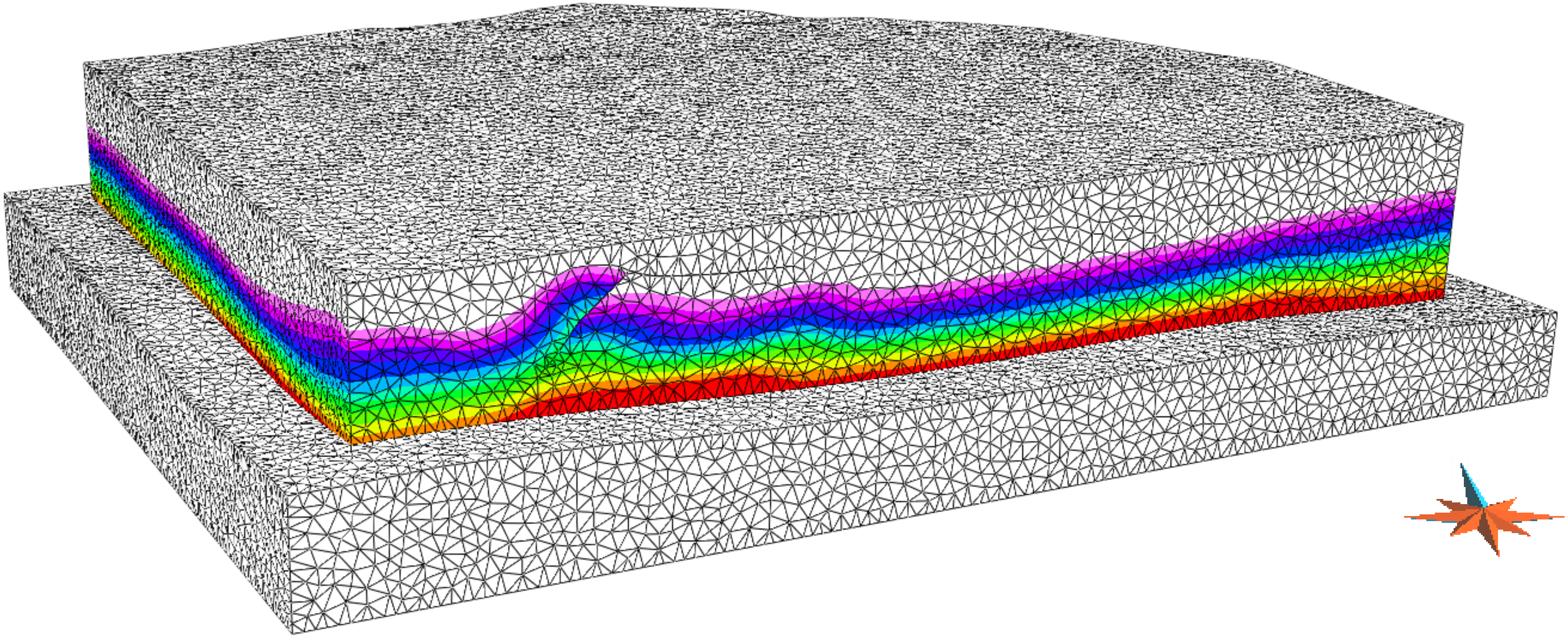
- One property to model the growth strata

Restoration mesh



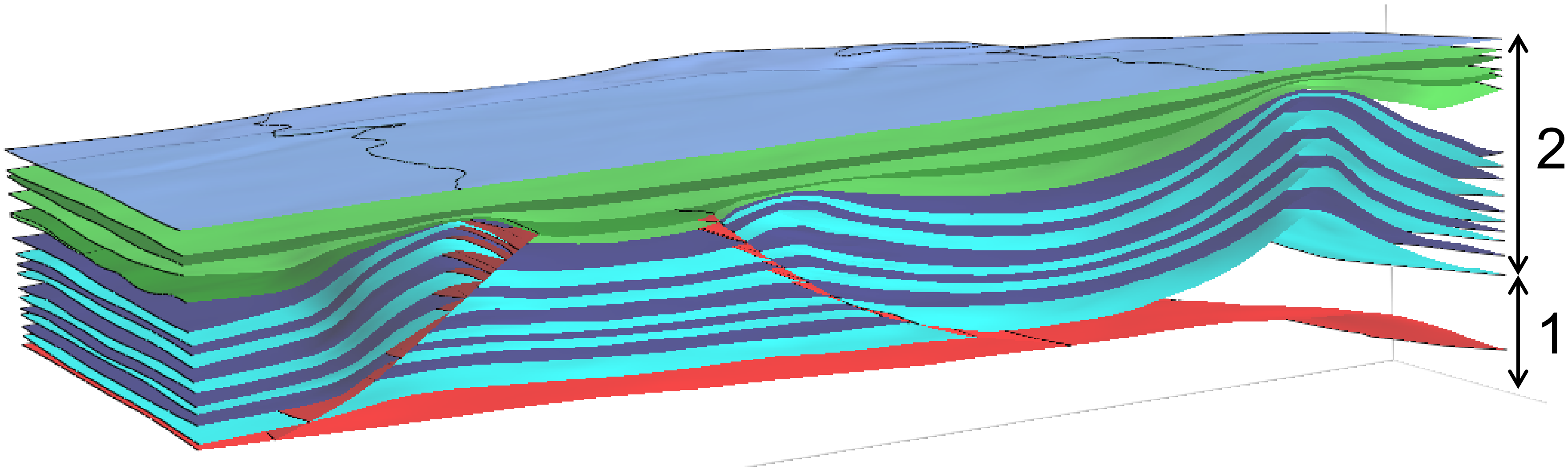
- One property to model the unconformity

Restoration mesh



- One property to model the pregrowth strata

Geomechanical properties



1. Akata Formation: Overpressured shales

   $E = 0.5$ GPa — $\Phi_0 = 0.63$

   $\nu = 0.41$ — $c = 0.00051$

2. Agbada Formation: Marine clastic sediments

   $E = 1.5$ GPa — $\Phi_0 = 0.65$

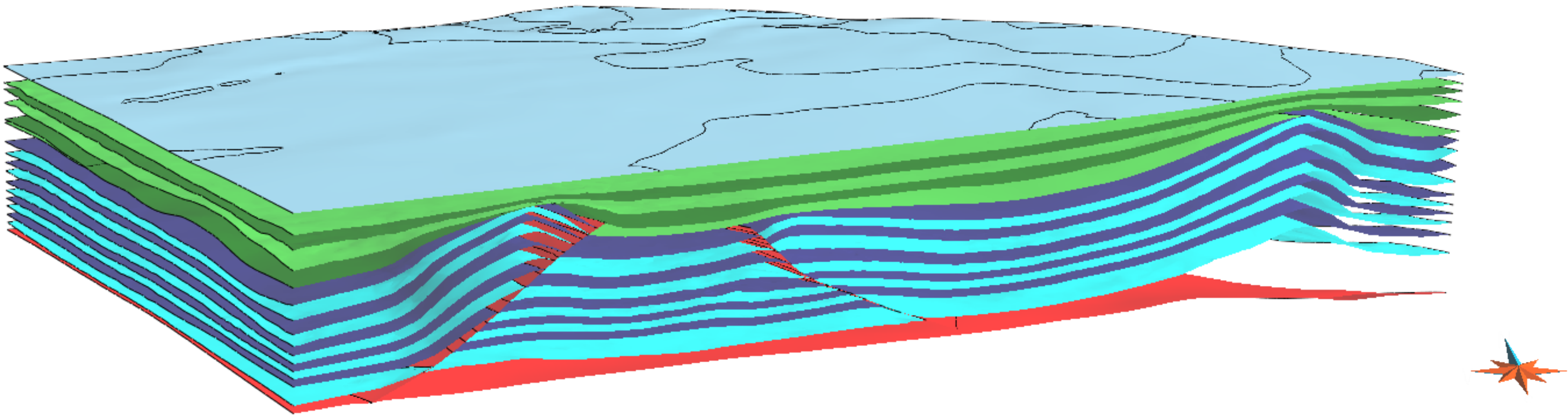
   $\nu = 0.37$ — $c = 0.0007$

Restoration parameters

- At each step of restoration, the top horizon is restored to its minimum elevation
- A fault contact condition ensures the sliding along the faults
- Only the hangingwall of the detachment moves

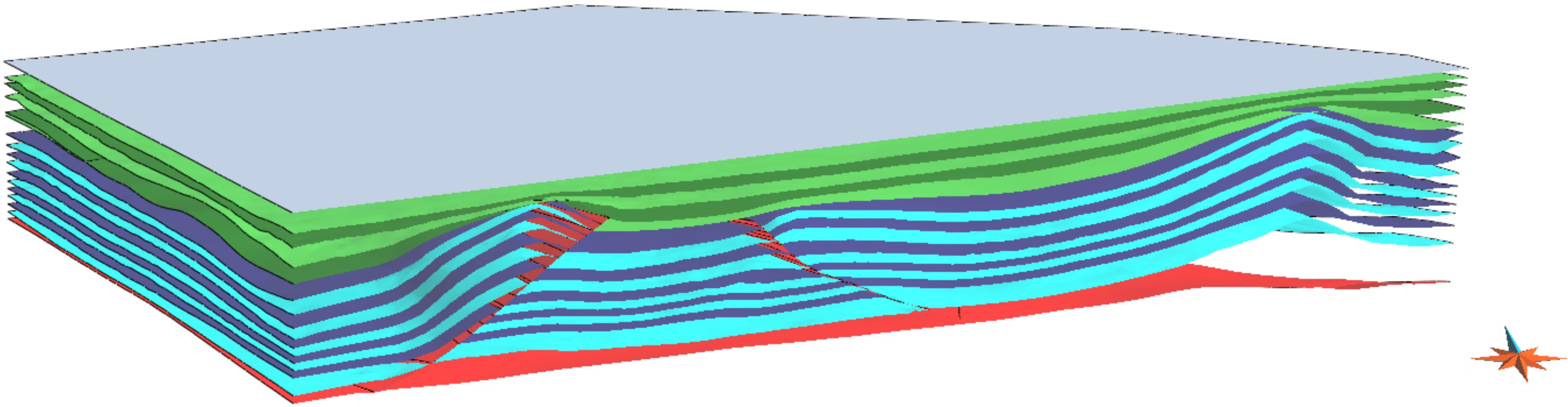
Results

Deformed model



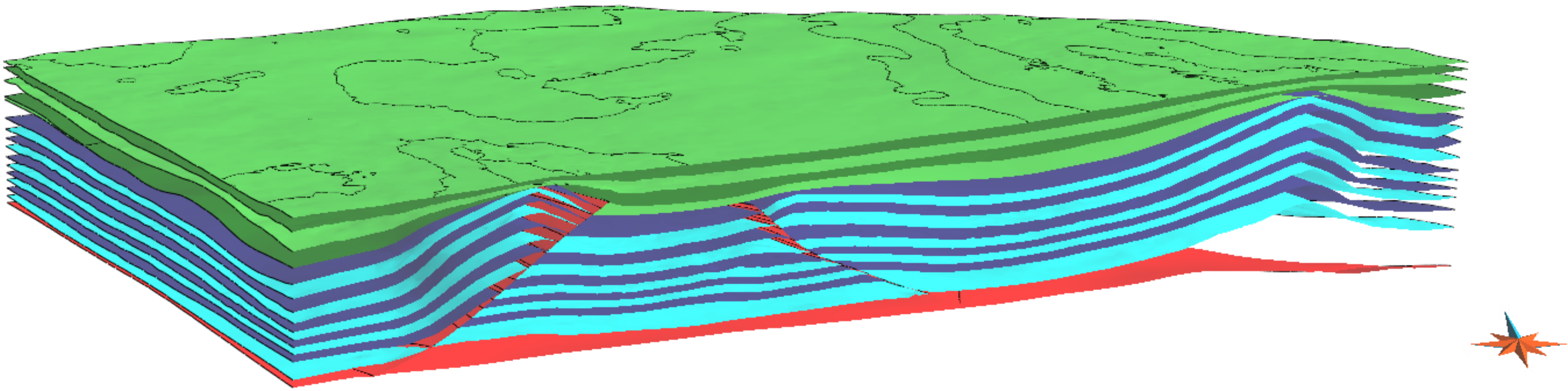
Results

Restored model



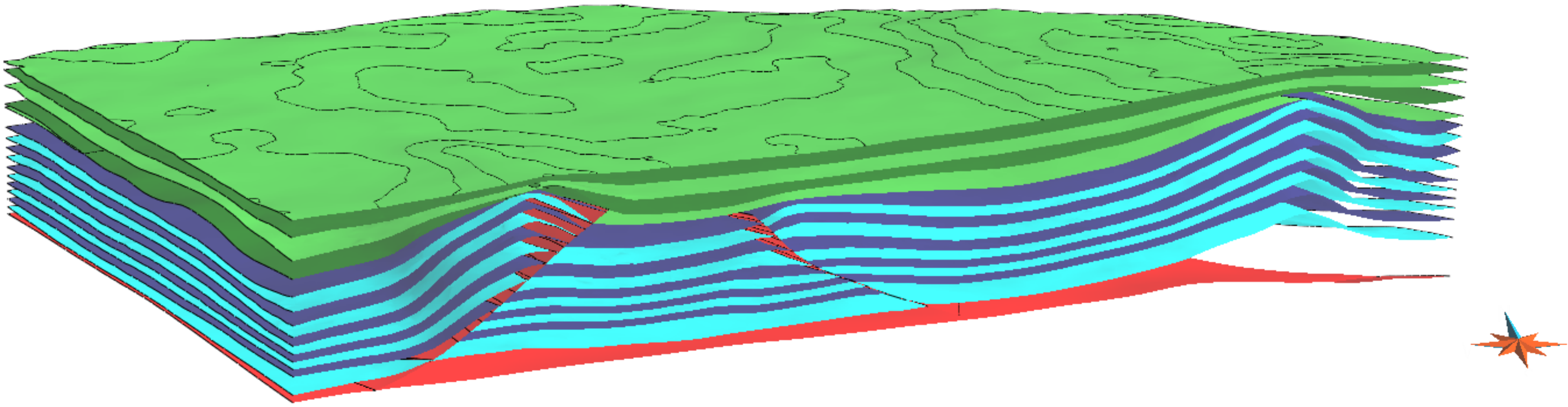
Results

Removal of the restored layer

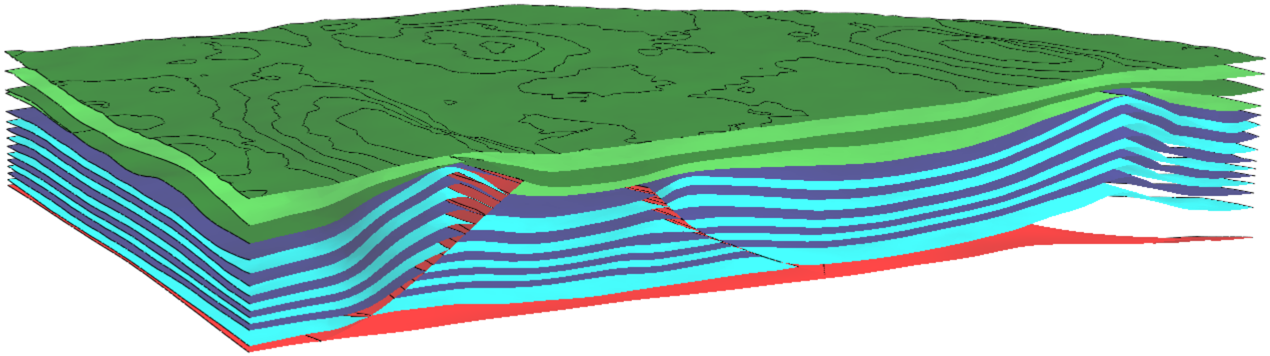


Results

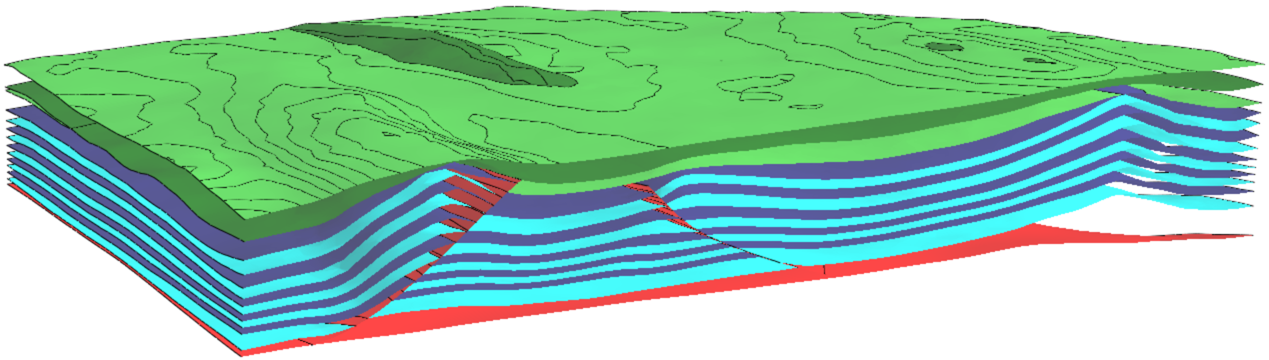
Decompaction



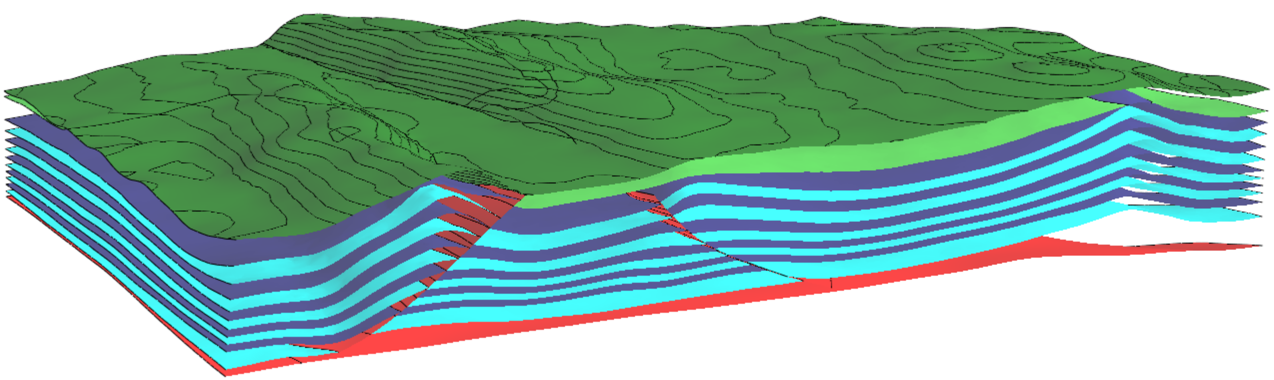
Steps 2-4



Restoration of the 4th growth horizon and decompaction

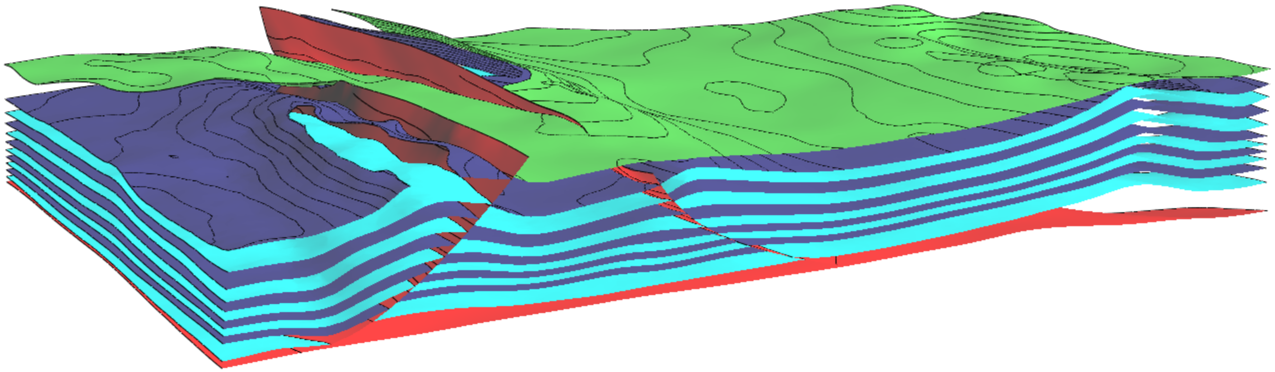


Restoration of the 3rd growth horizon and decompaction



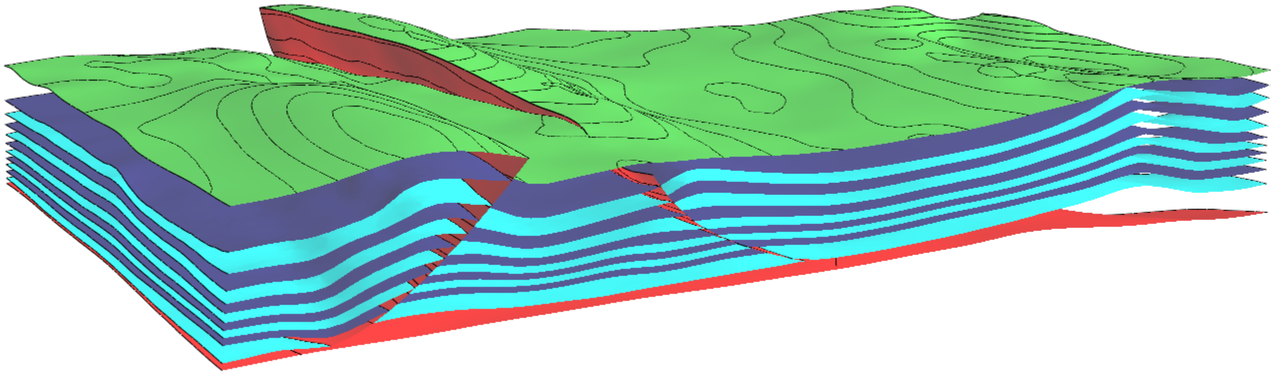
Restoration of the 2nd growth horizon and decompaction

Step 5

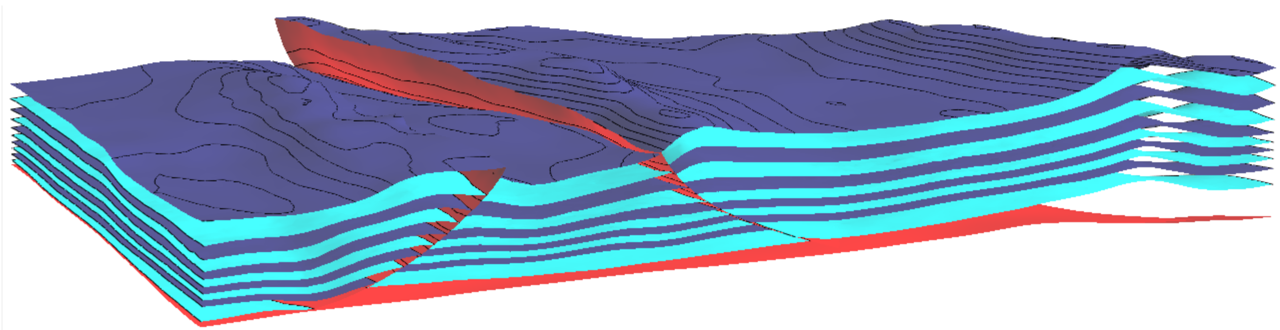


Restoration of the unconformity and decompaction

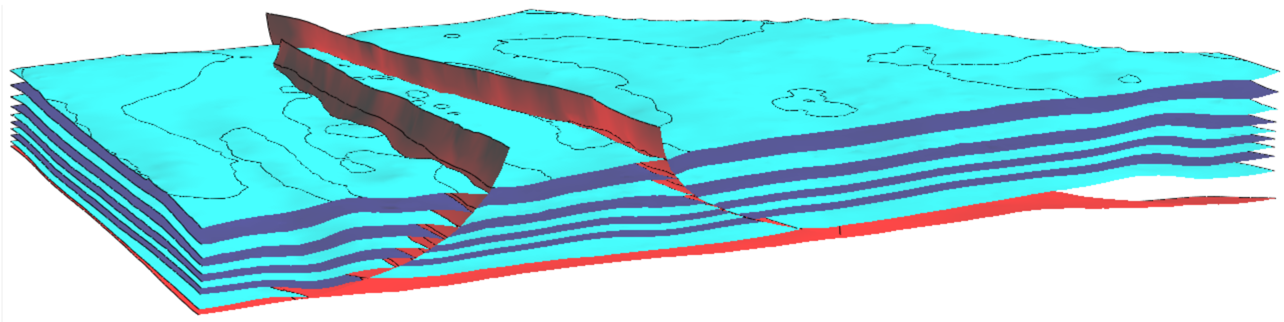
Use of the implicit approach to estimate the eroded volumes
→ Non eroded geometry of the horizons



Steps 6-7



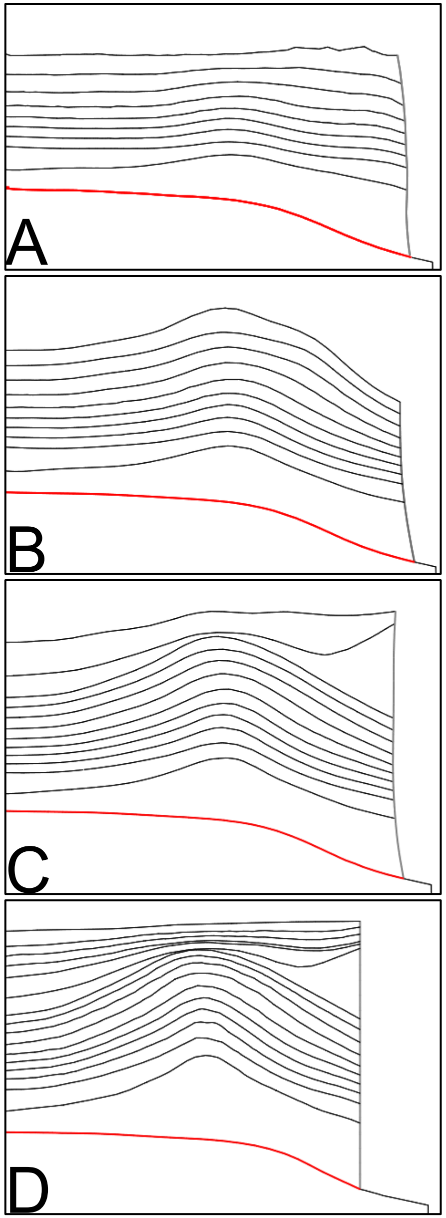
Restoration of the 1st growth horizon and decompaction

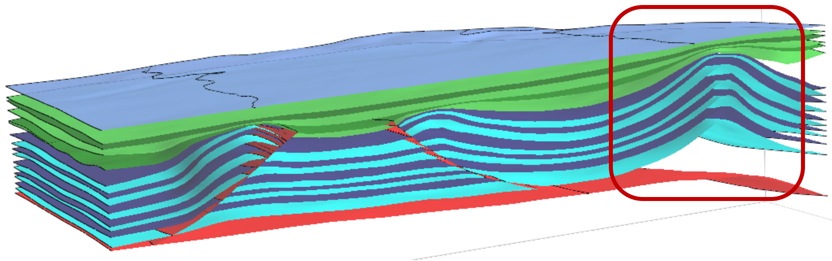


Restoration of the youngest pregrowth horizon and decompaction

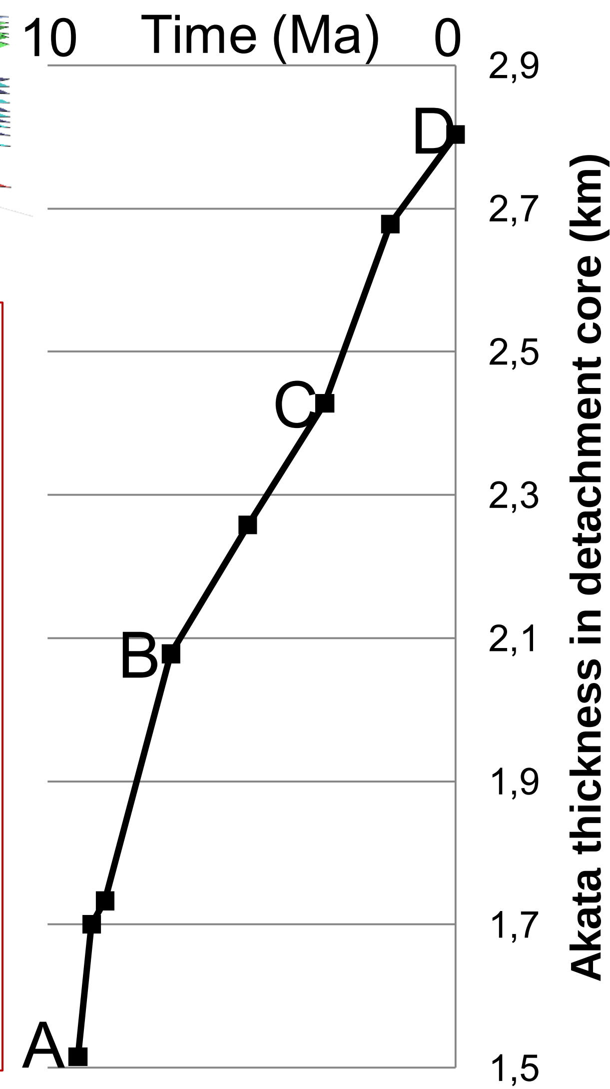
Slip residual < 10%

Detachment fold

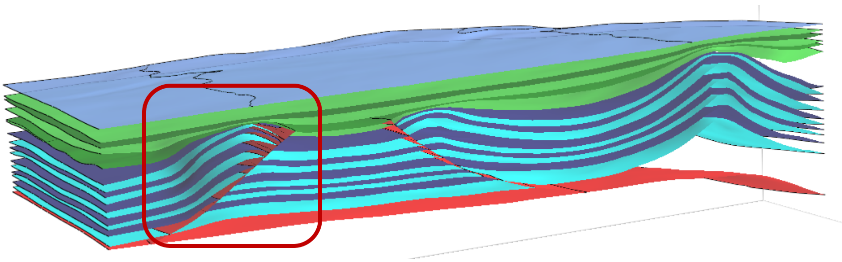




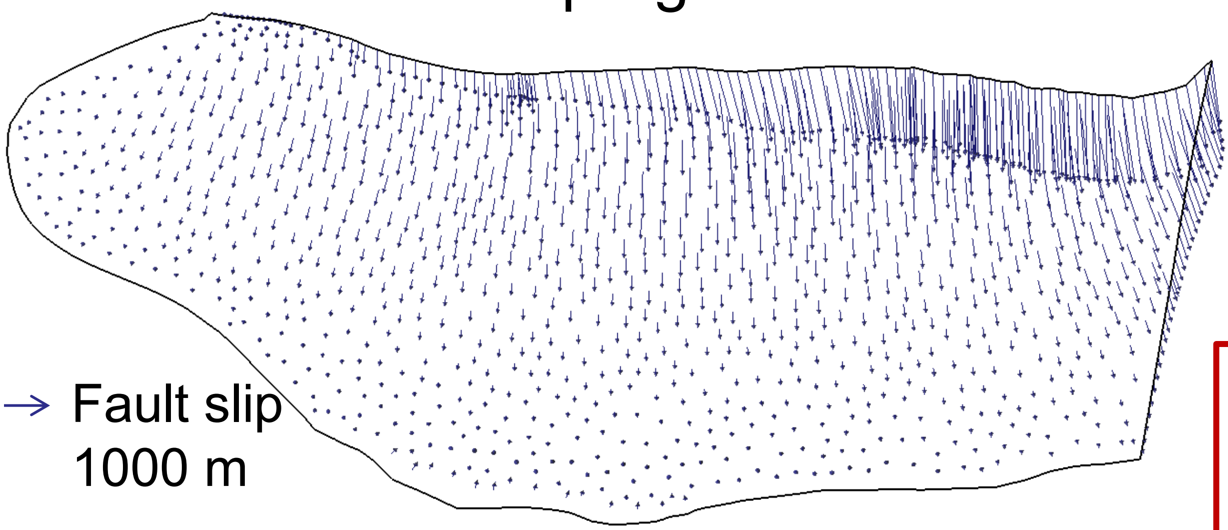
- Thickening of the detachment core through time
- Matches kinematic models of detachment folding
- Estimation of source rock volumes



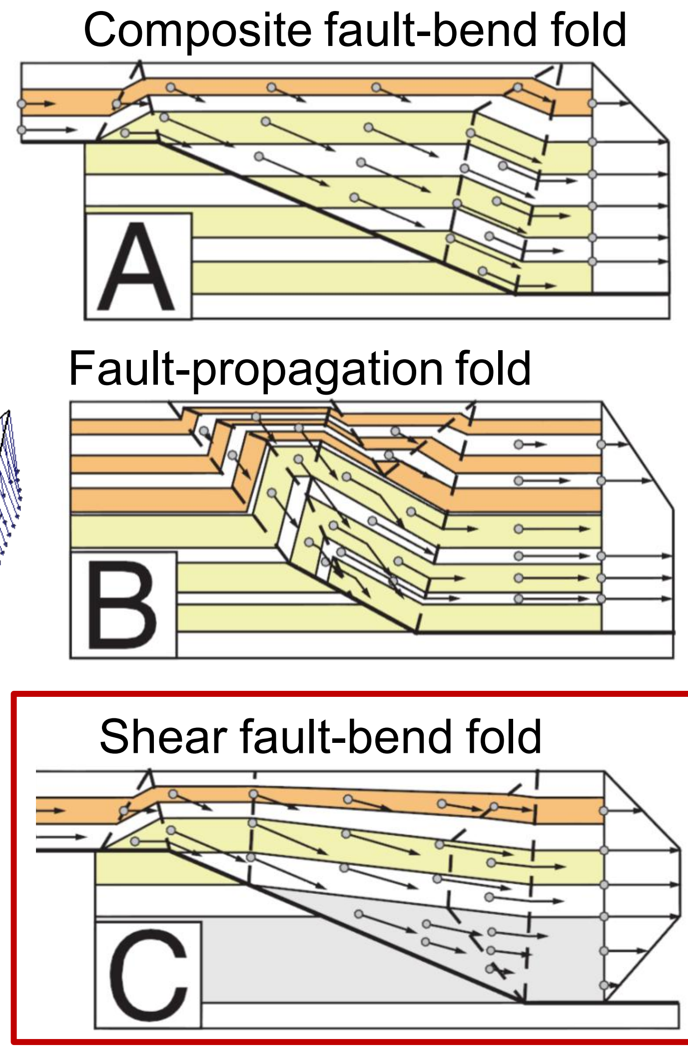
Slip on the forethrust



Restoration of the pregrowth

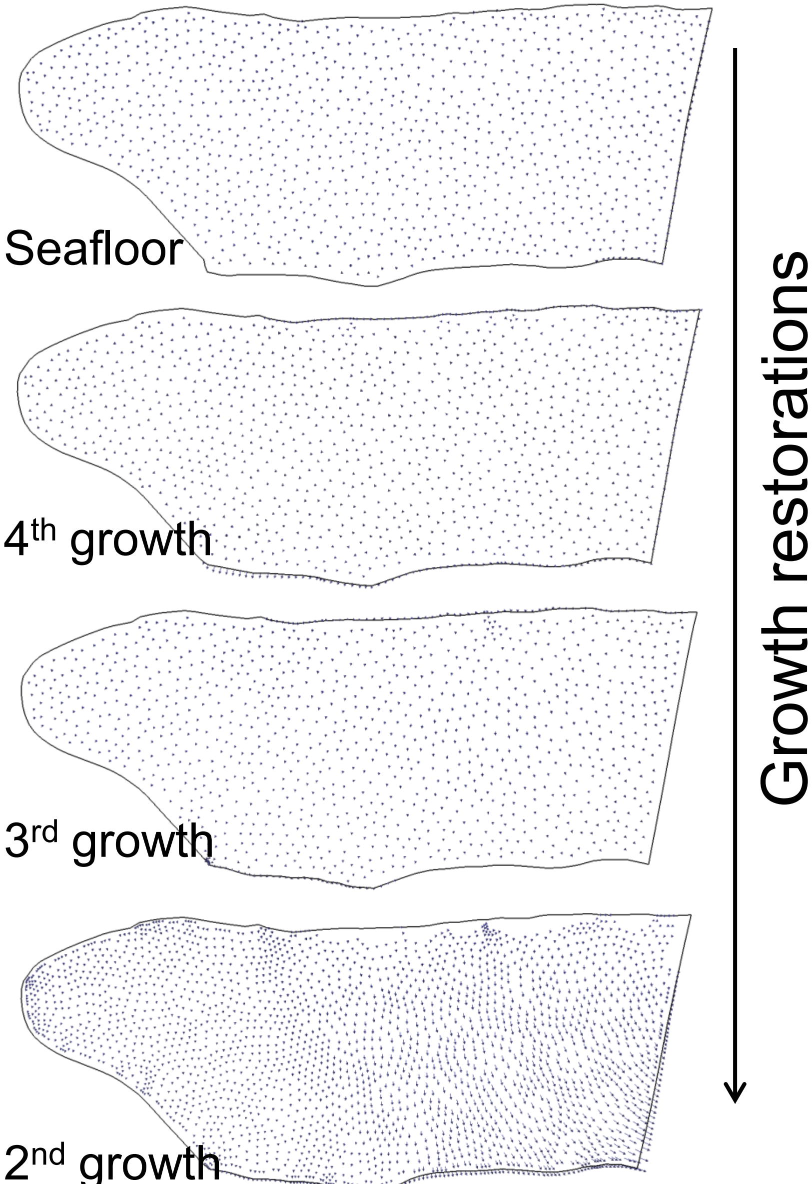


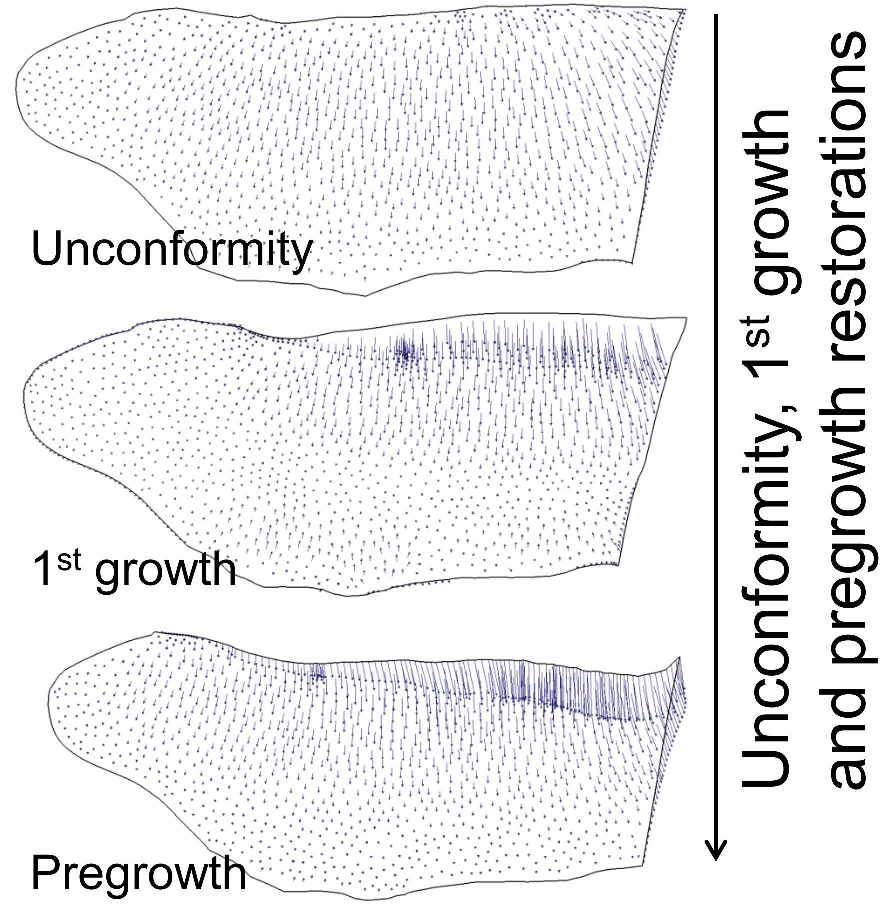
Slip profile on the forethrust matches the kinematics of a shear fault-bend fold



[Guzofski et al., 2009]

Forethrust slip evolution

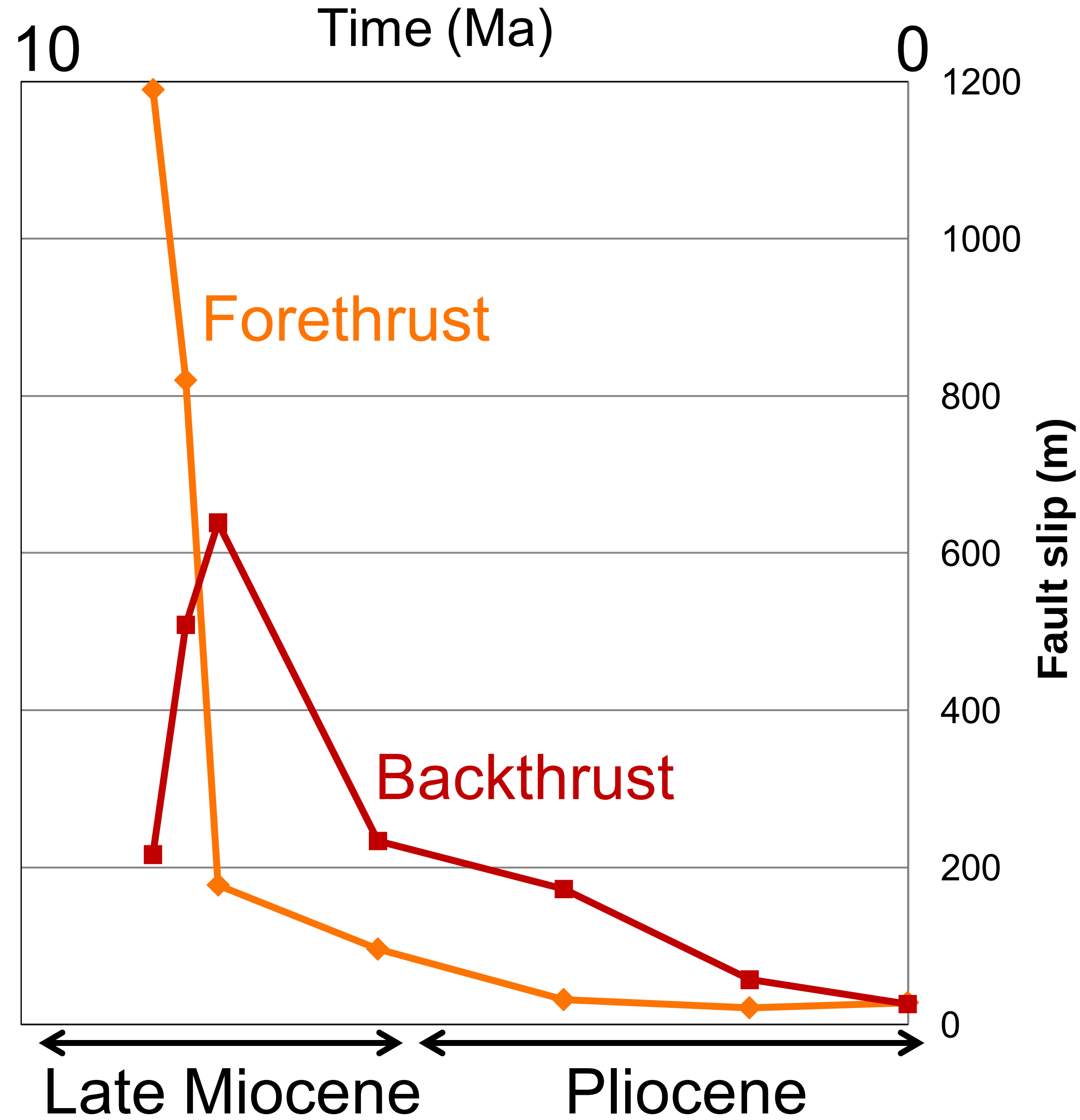




4D fault slip
Helps fault seal analysis

Faults slip

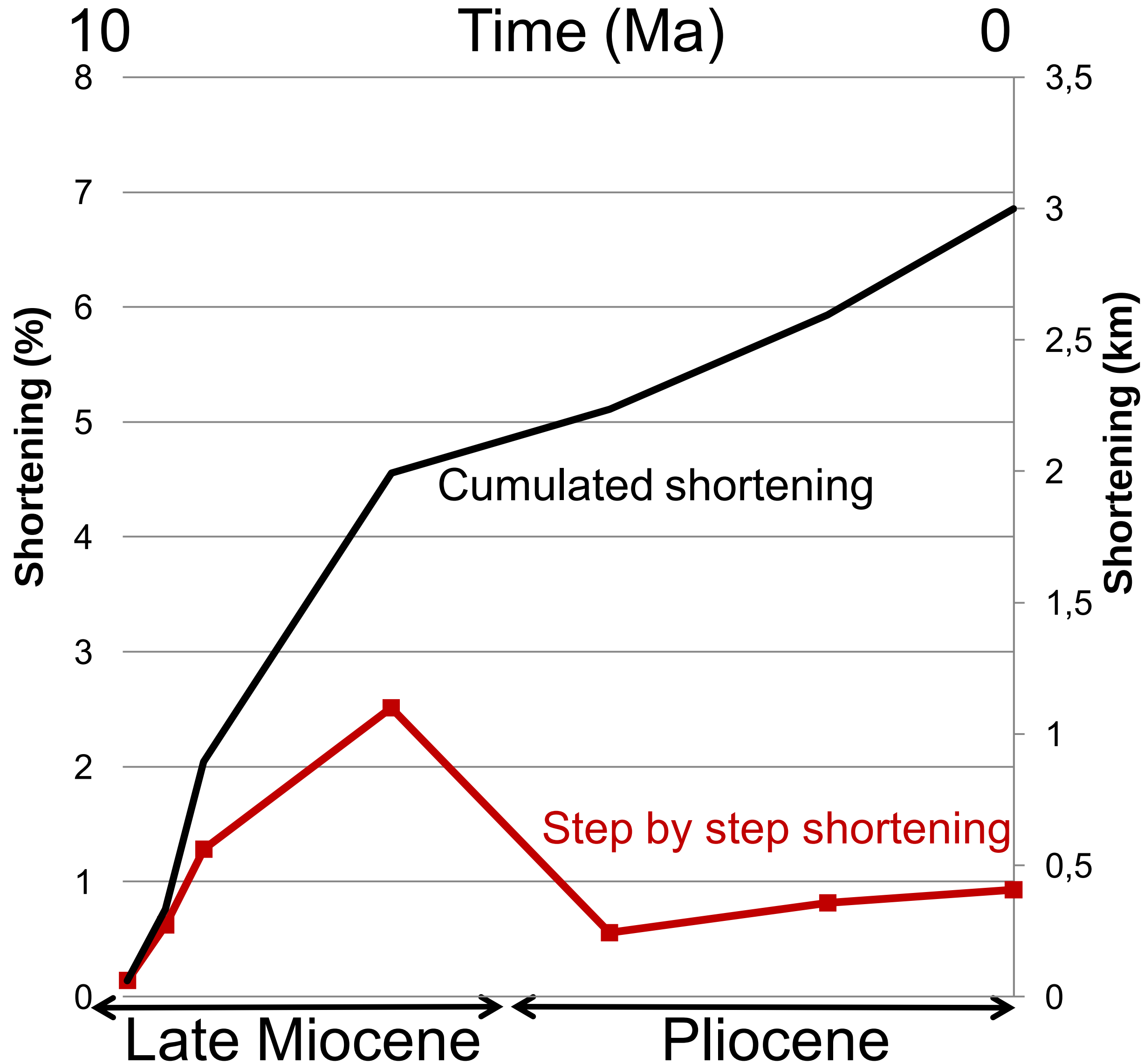
- Fault slip higher on the forethrust, and then on the backthrust.
- Timing of deformation, consistent with the deformation propagating basinwards.



Shortening

- Shortening rate varies through time
- Shortening rates small compared to kinematic restorations (14%)

→ Requires additional constraints on the lateral walls

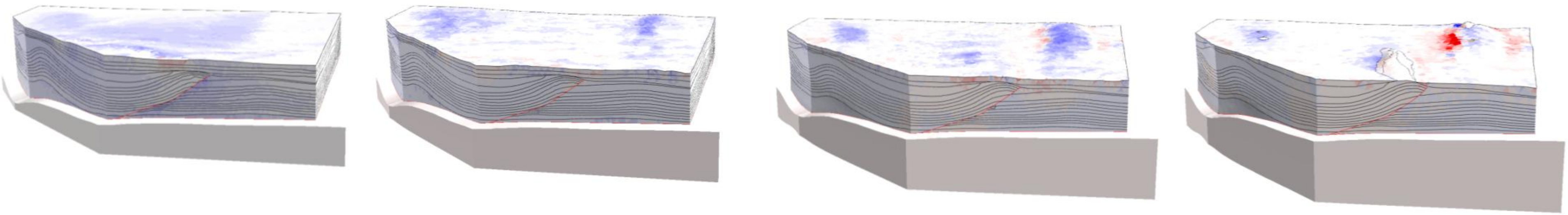


Conclusions

- Ability to restore and decompact a complex natural system
- Values in terms of structural geology:
  - Timing of deformation
  - Validation of kinematic interpretations
- Values in terms of petroleum geology
  - Evolution of a trap geometry Reservoir volume
  - Variations of thickness Fluid migration
  - Variations of slip Seal analysis

Perspectives

- Analysis of strain → Fractures prediction



- Include flexural slip: use of transversely isotropic materials [Durand-Riard et al., in press]
- Add geological constraints

Acknowledgements

Chris Guzofski (Chevron ETC)

Thanks for your attention