Apports des modèles analogiques pour l’interprétation structurale de la sismique

William Sassi

Workflow for this talk

- **Introduction**
  - **Context**
  - **Main goals**
- **2D structural modelling in FTB**
  - **From Thrustpack to Ceres Integrated studies**
- **3D and 4D analogue sand-silicone experiments**
  - **Folding and fault development**
  - **From surface to volumetric restoration**
- **Conclusion**
  - **Perspectives on fundamental and applied R&D for structural geologists**

Unfolding? a surface or a layer!


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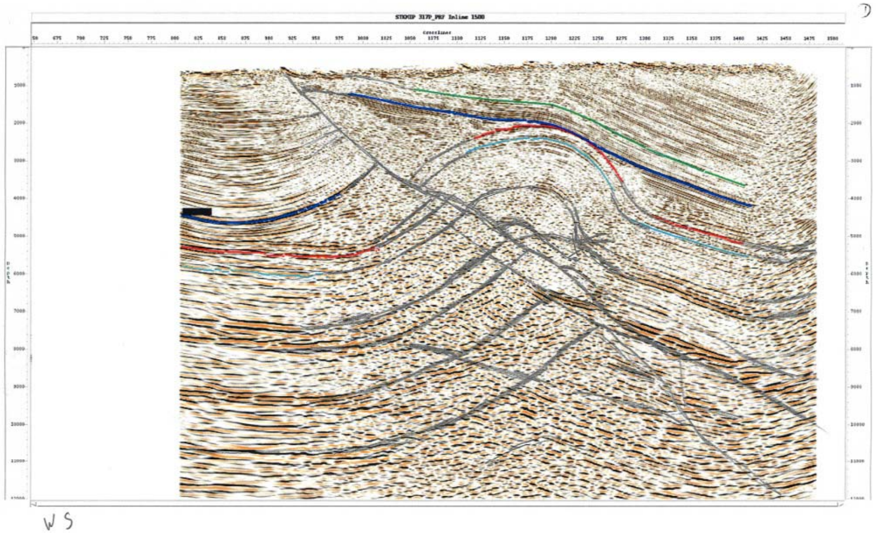

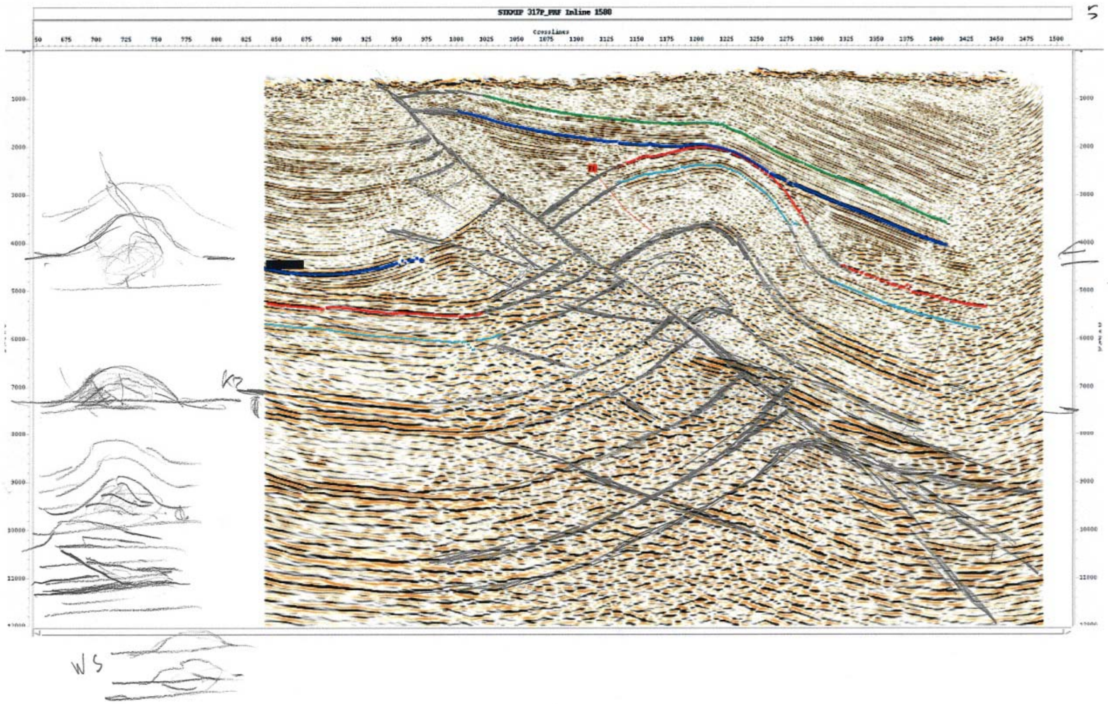

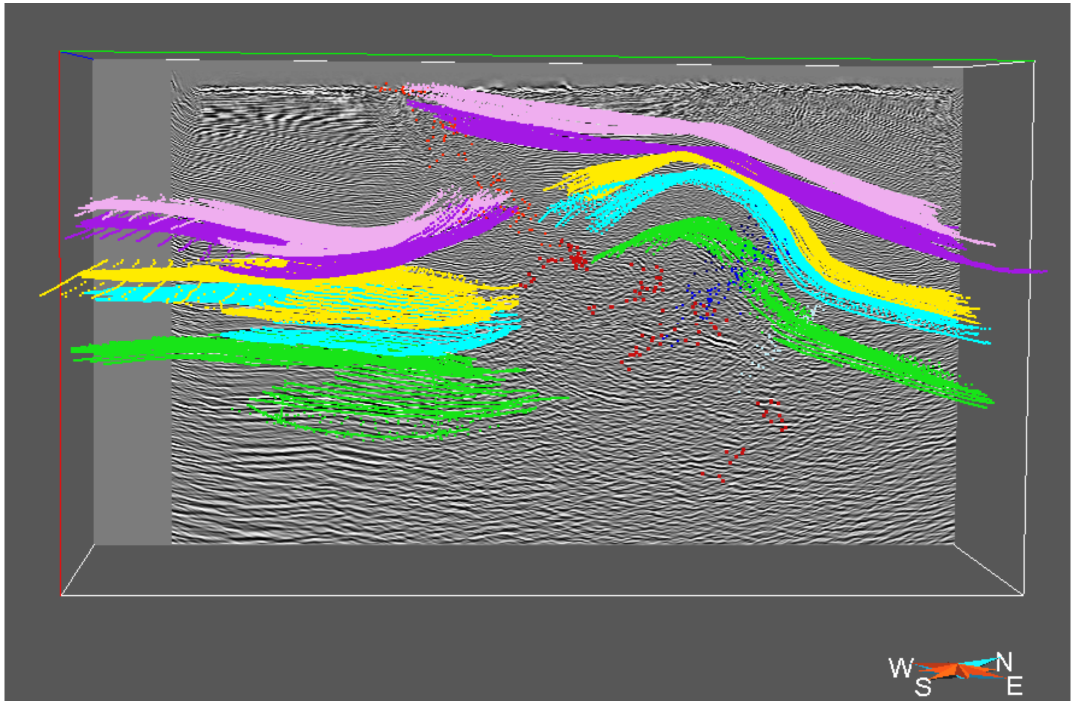
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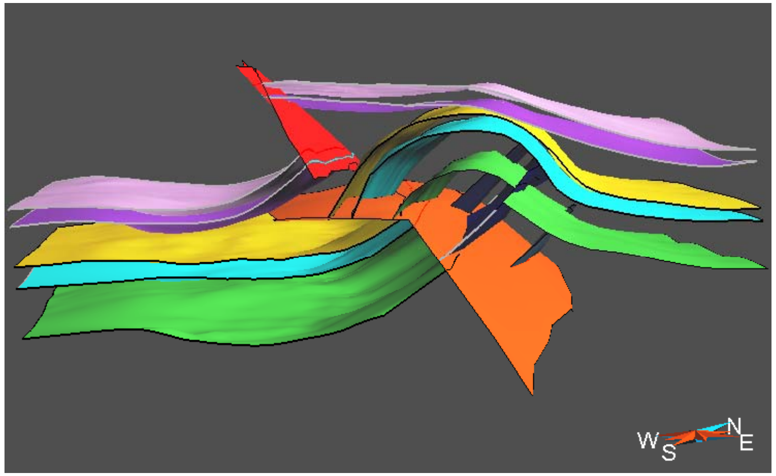
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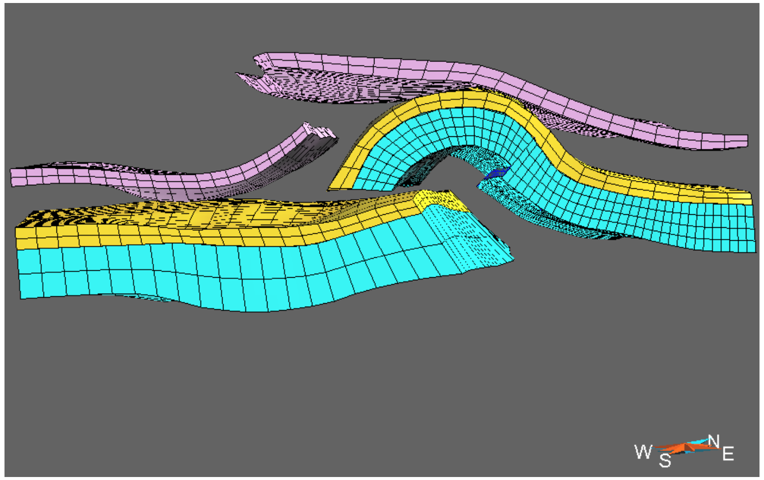
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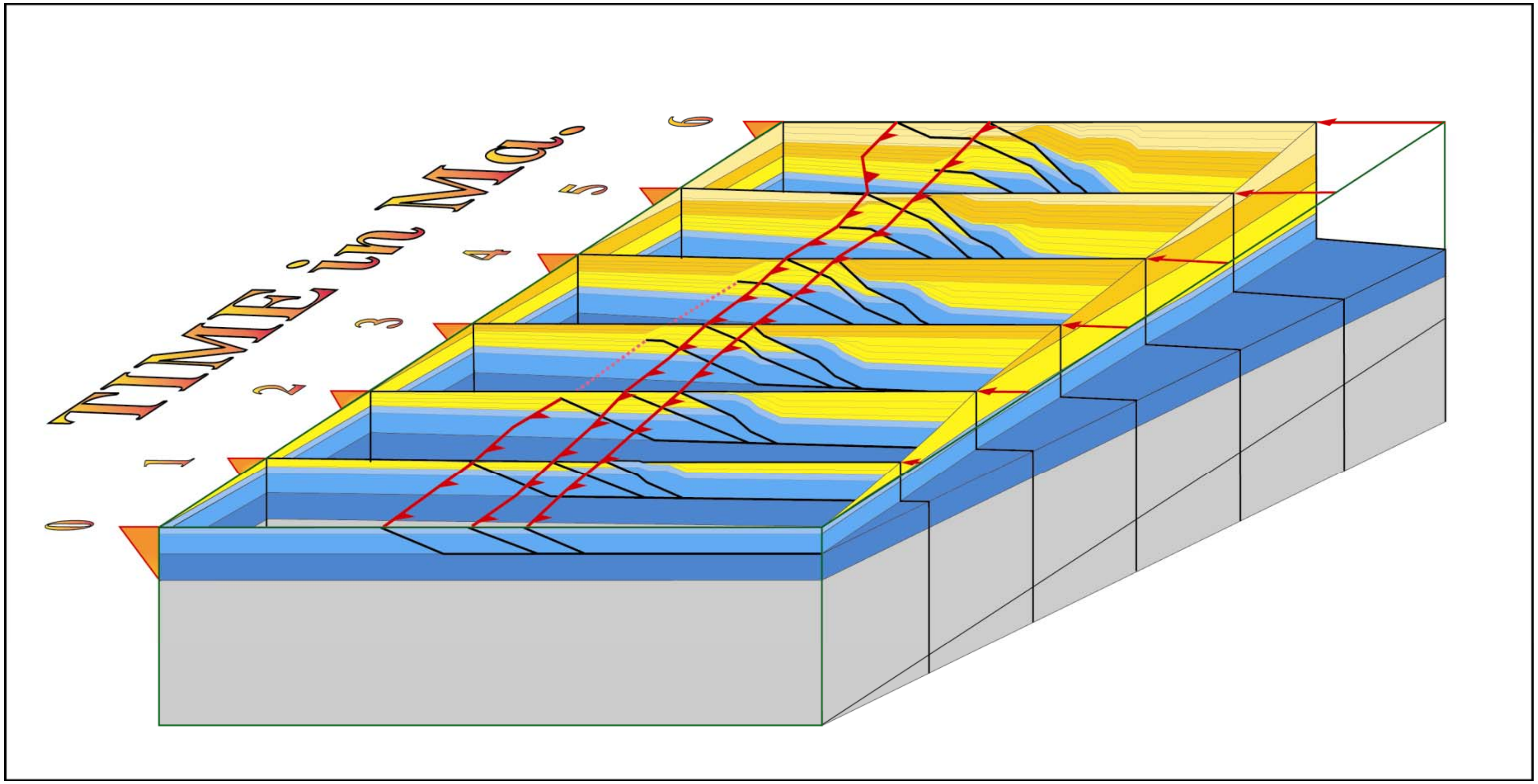
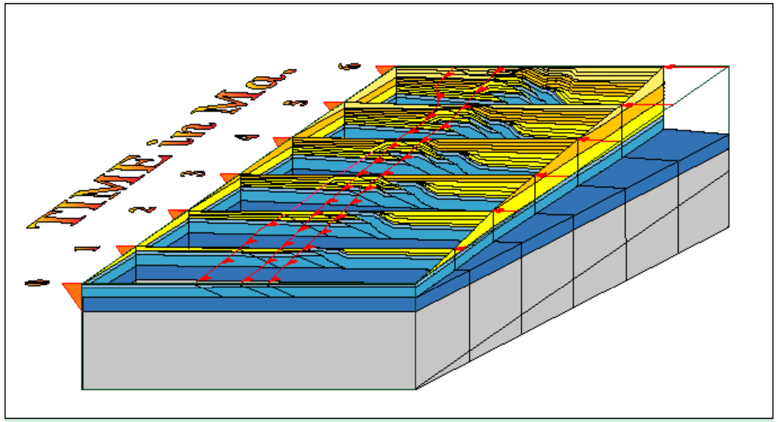
Structural modeling along 2D cross sections

From Thrustpack to Ceres studies

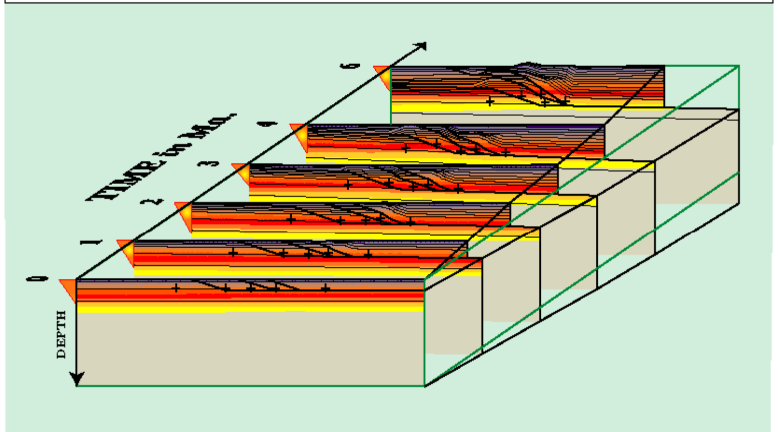


Methodology

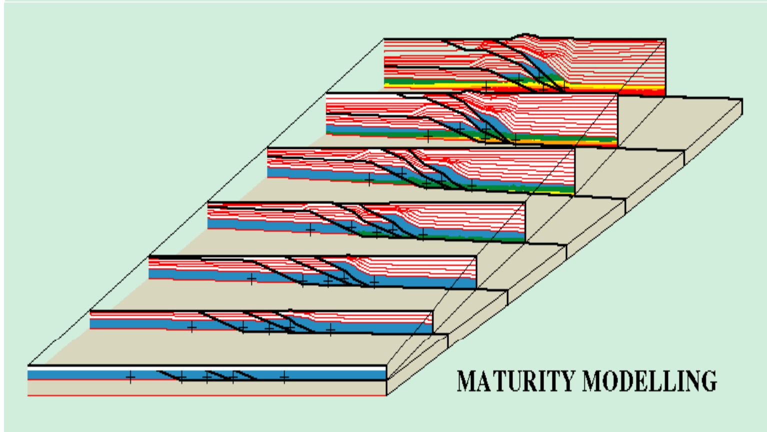
GEOMETRY --->



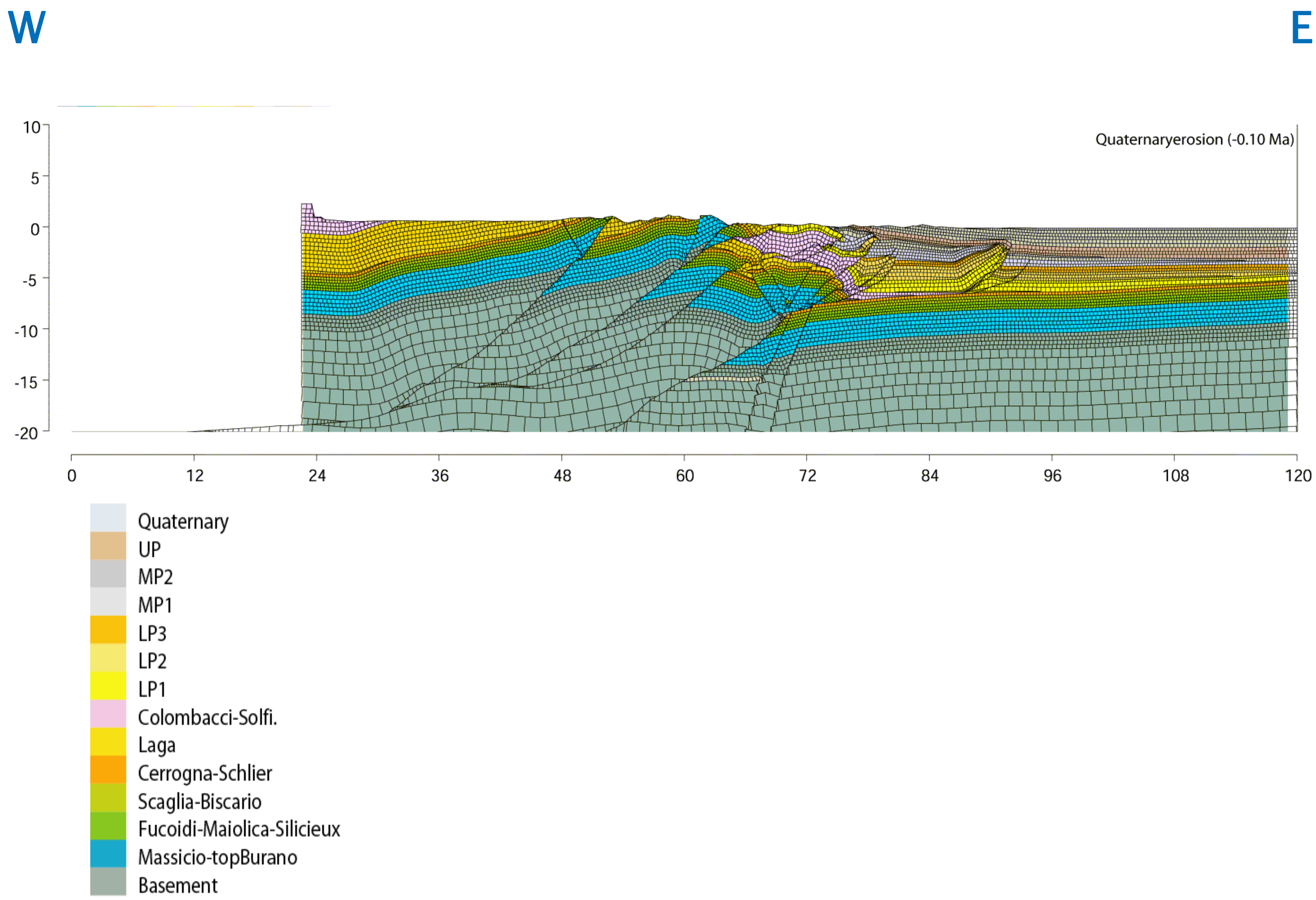
TEMPERATURE --->



MATURITY --->



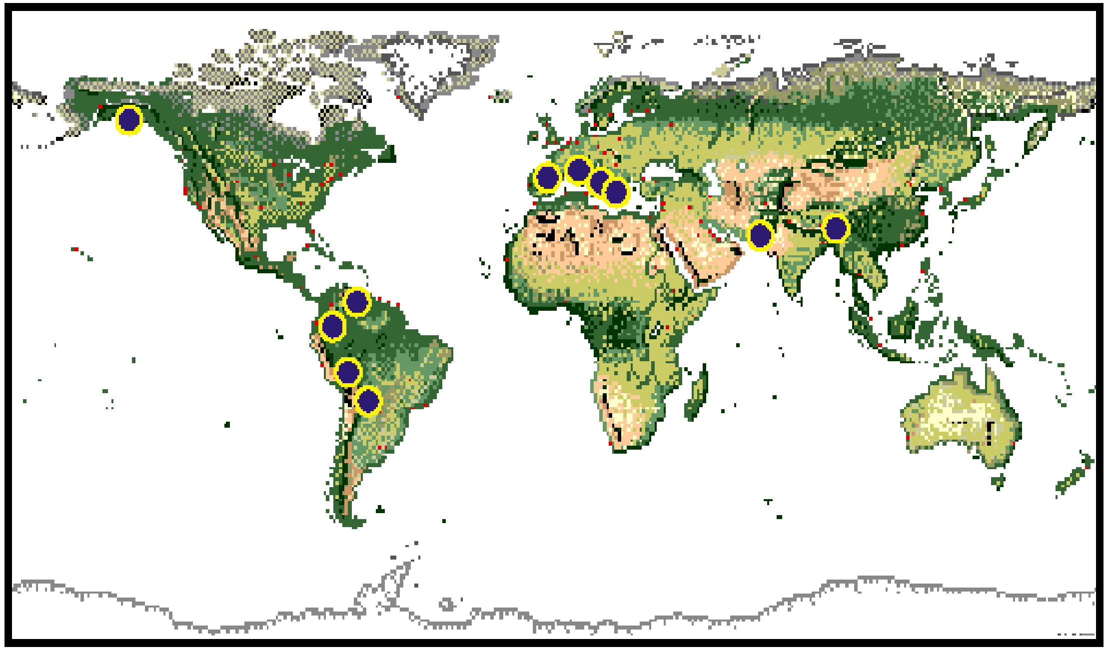
THRUSTPACK MODELLING



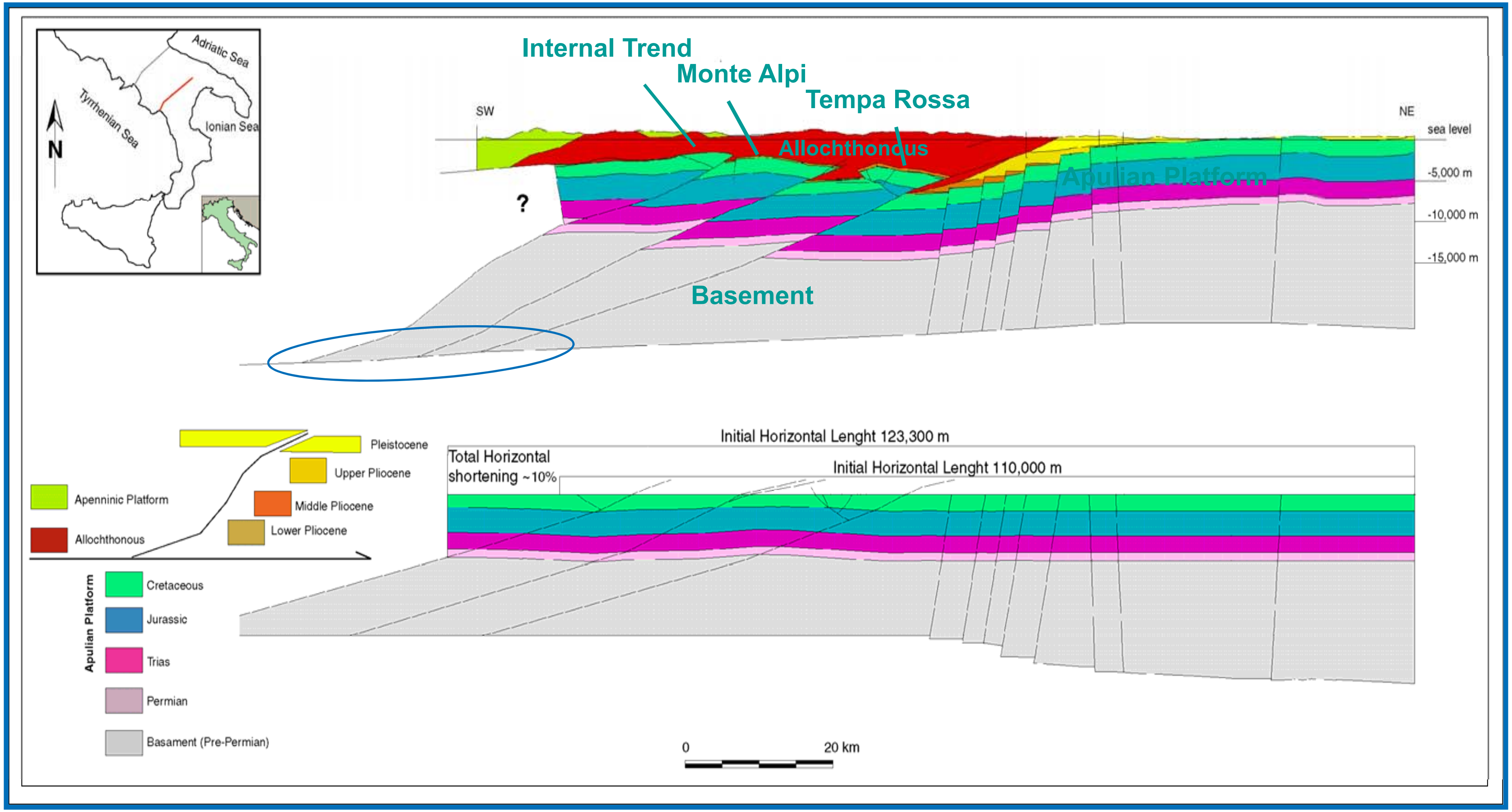
Methodology improved through many modelling studies in thrust belts since 1995

Applications in many tectonic contexts

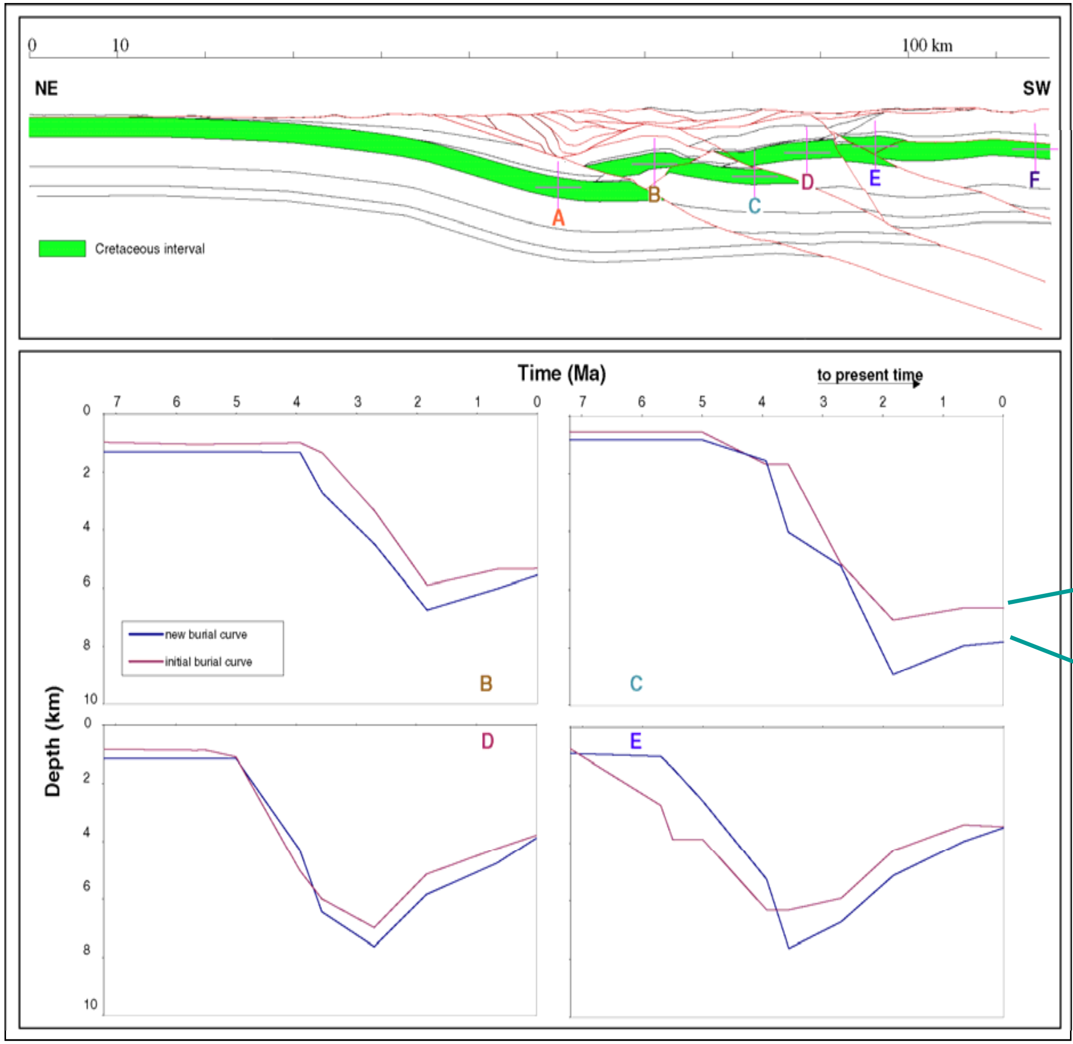
- Western Alps
- Himalayas, Pakistan
- Venezuela, South Am.
- Bolivia, South Am.
- Albania
- Alaska, North Am.
- Southern Apennines
- Canadian Rockies



The Tempa Rossa section through the Southern Apennines Thrust Belt (After Sciamanna et al, 2004)



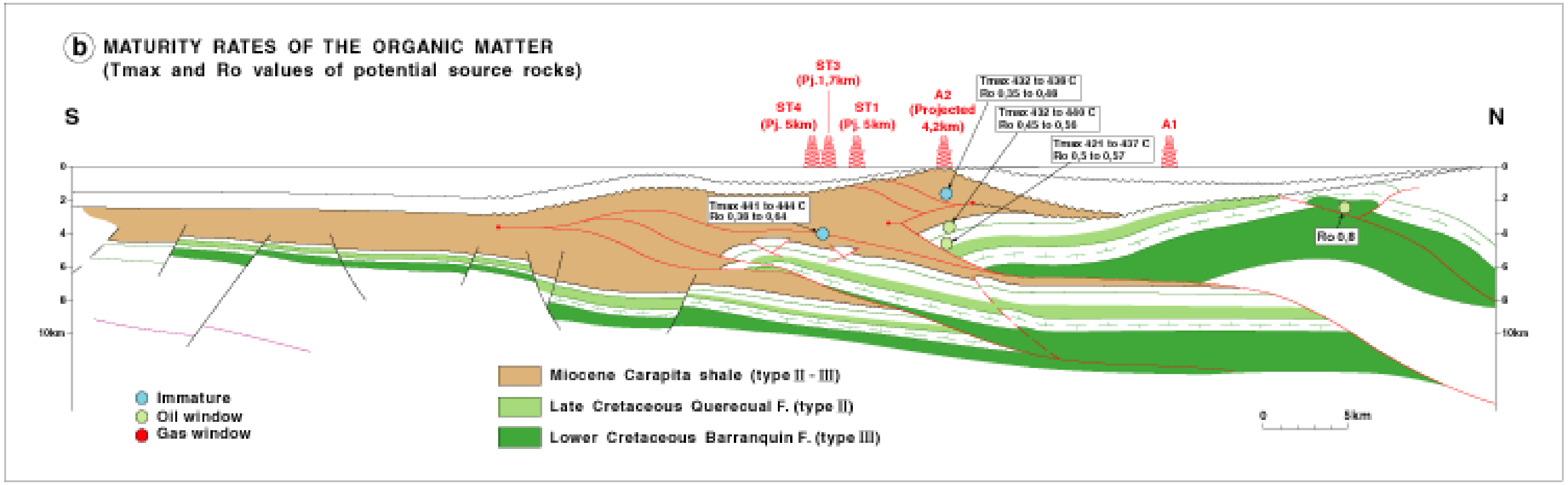
◆ Reducing uncertainties with Forward Modelling

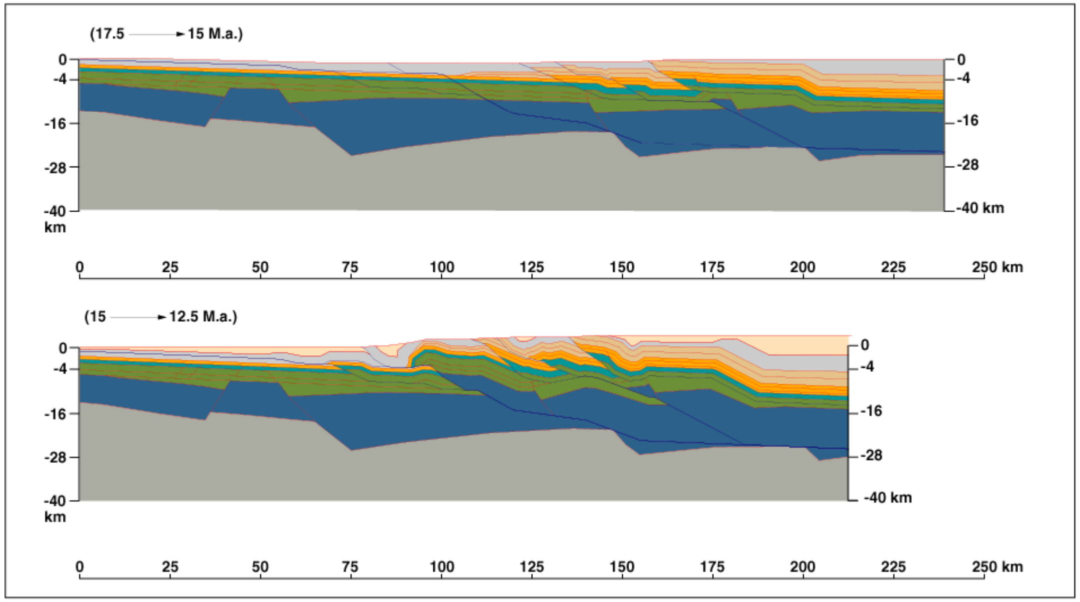


Preliminary Modelling

Final Modelling

1- Workflow for Petroleum and Reservoir modeling in FFTB
(Eastern Venezuela case study, Roure et col., 2000-2008)

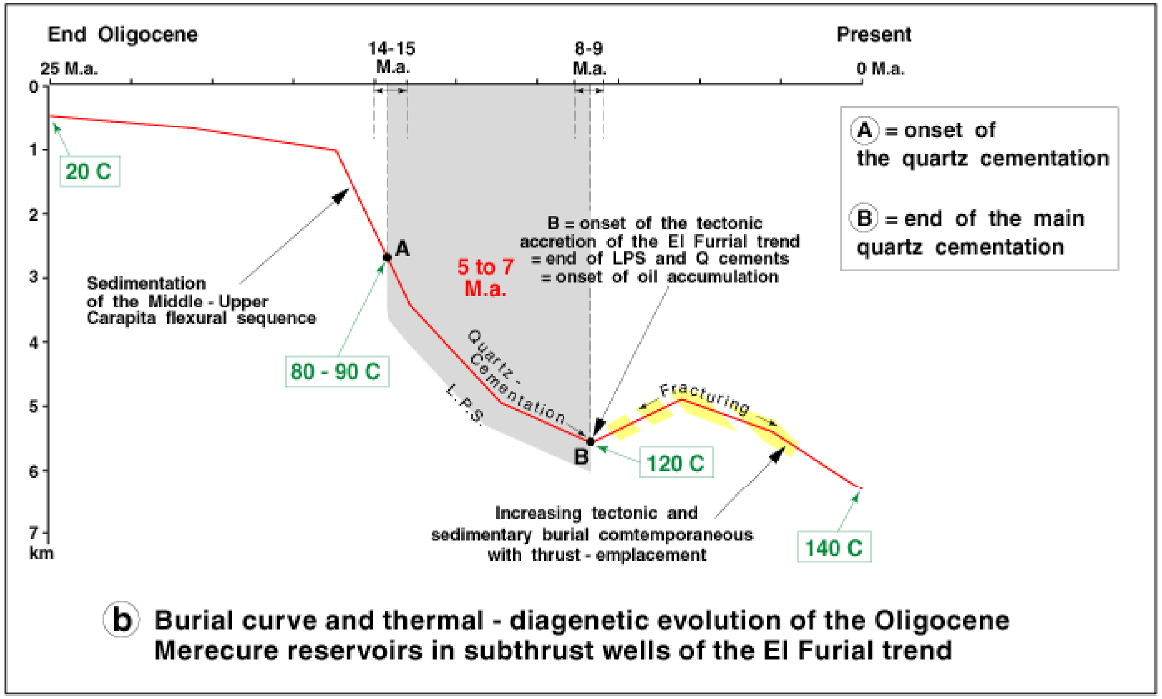




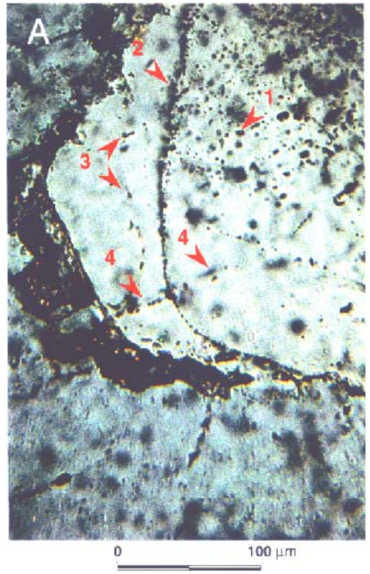
- 2D kinematic modelling is performed first

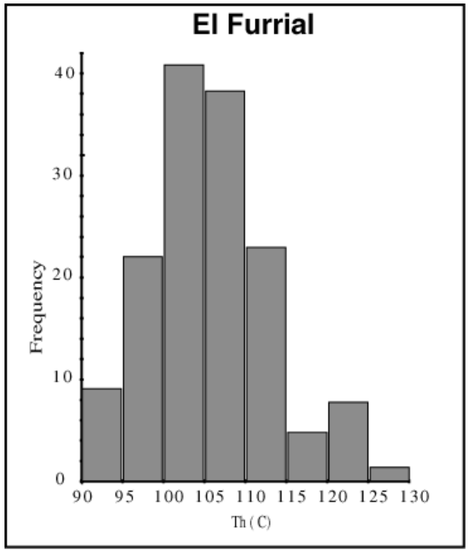
- Thermal modelling is then calibrated against BHT and maturity rank of organic matter (Tmax and Ro)

Q-cements can then be dated by plotting Th temperatures on burial curves by means of Thrutpack thermal modeling



b Burial curve and thermal - diagenetic evolution of the Oligocene Merecure reservoirs in subthrust wells of the El Furial trend

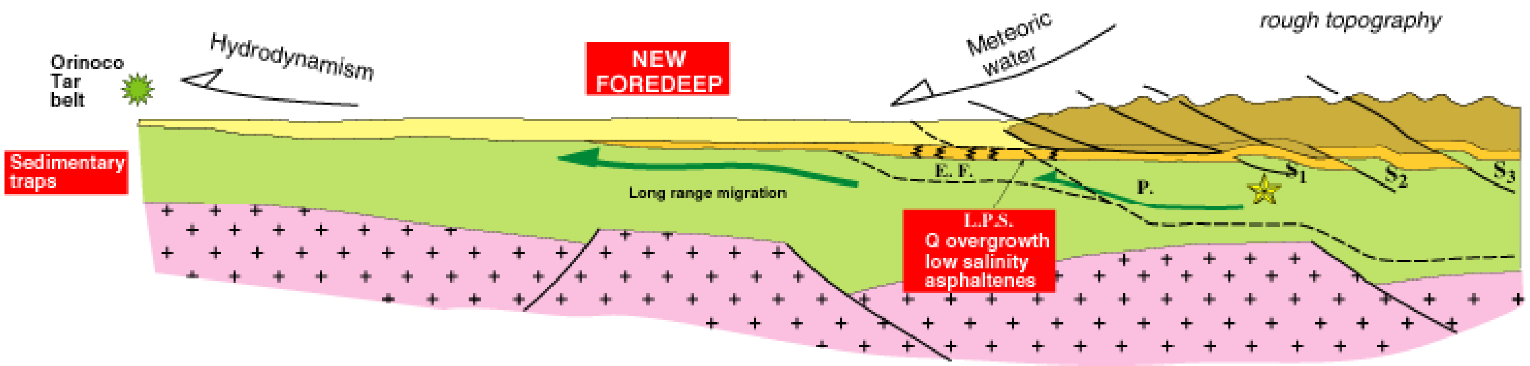




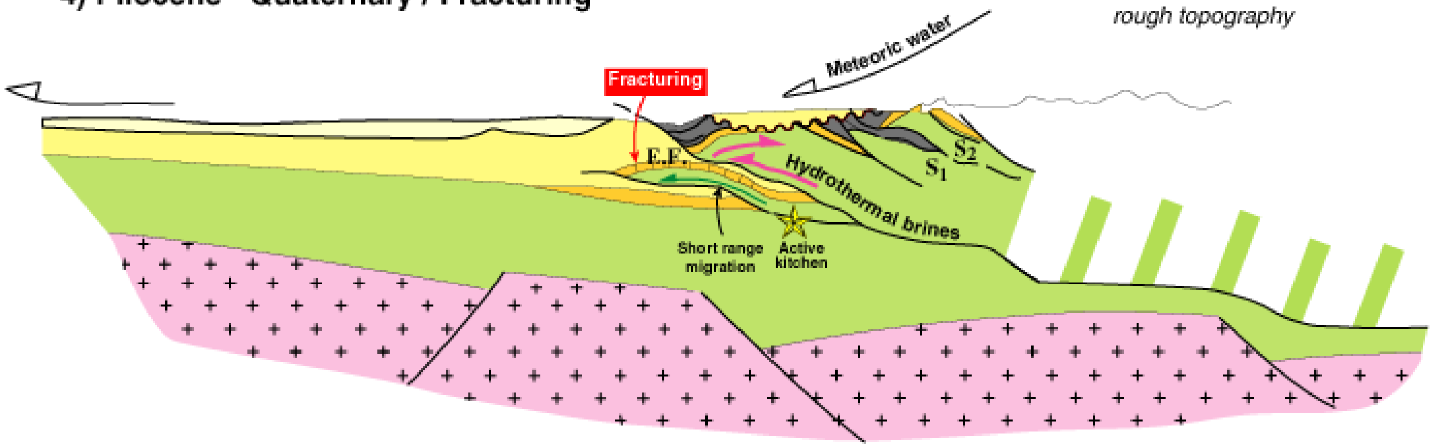
Q-cements always develop during a very narrow temperature and time interval...

BUT Overpressure may prevent the reservoir from further compaction...
and Diagenesis can also operate in an open system...

3) Middle-Late Miocene Hydrodynamism / Layer Parallel Shortening

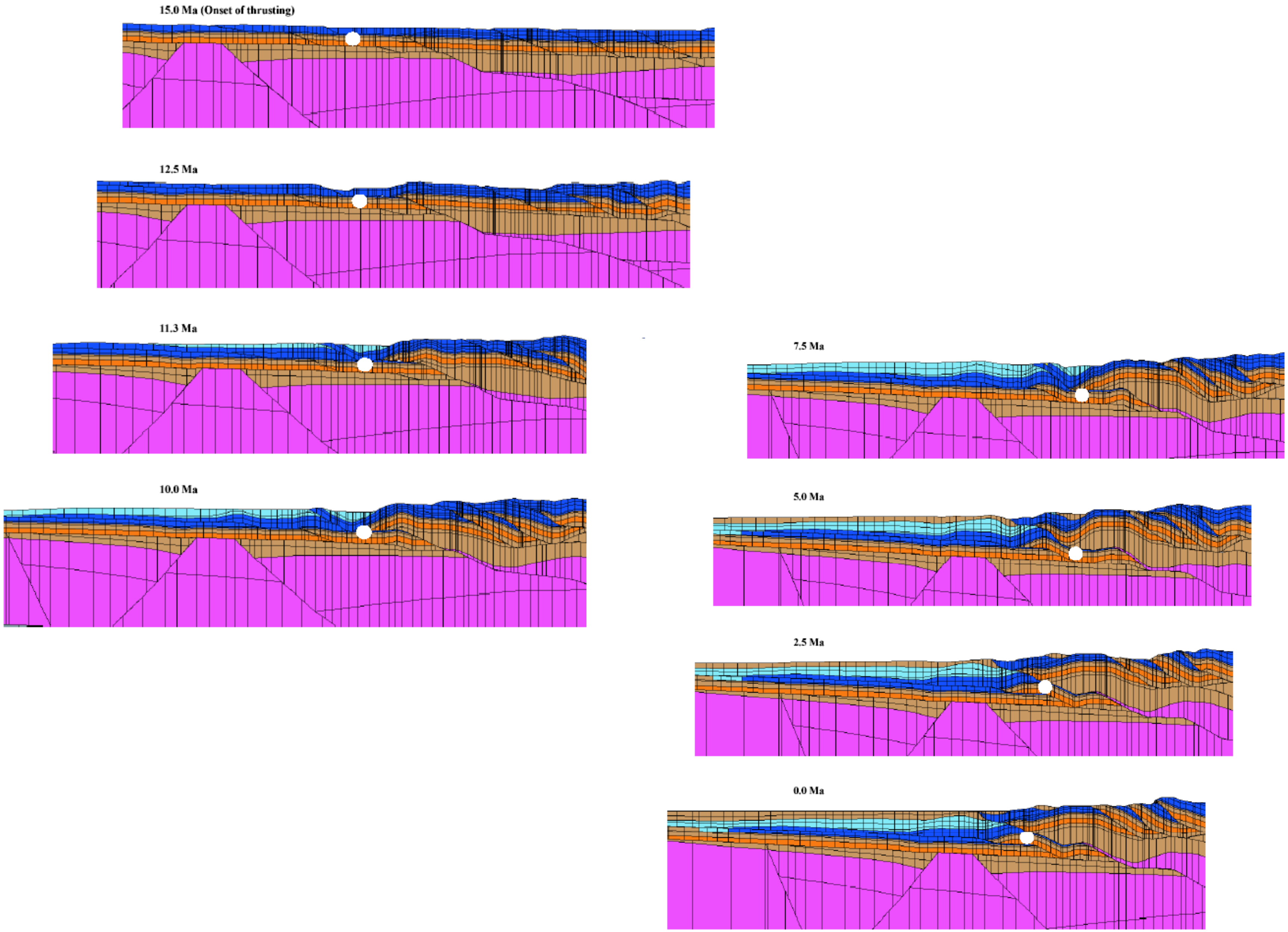


4) Pliocene - Quaternary / Fracturing

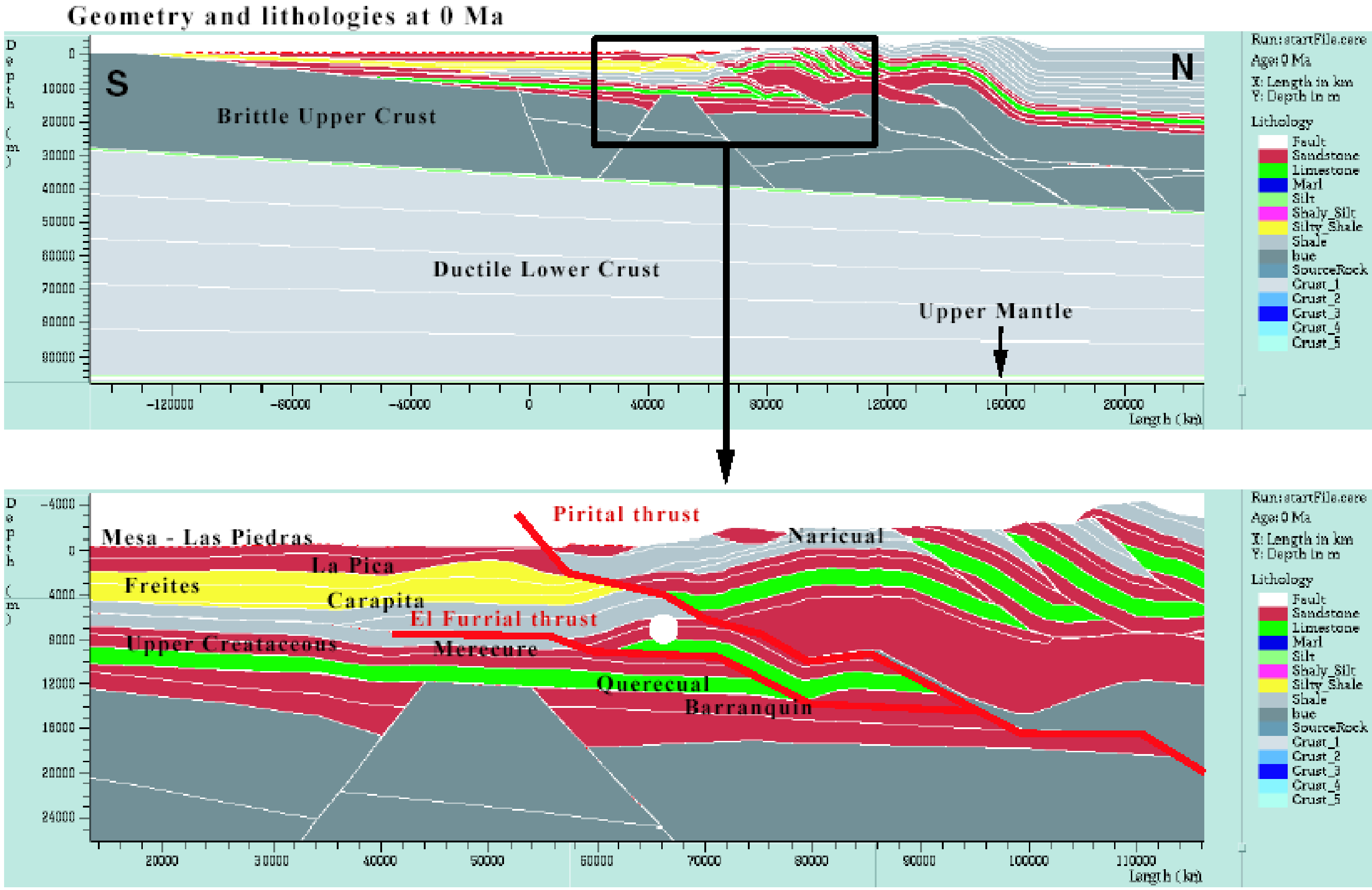


THEREFORE, fluid flow and pore fluid pressure modelling is required for reservoir prediction

Thrustpack templates are used as input data for Ceres 2D modelling



Although there is no formation water left,
δO18 values in Fluid inclusions from Q-overgrowths account for basinal, not meteoric fluids in the Naricual reservoir in Furrial.....



Main goals for structural interpretation

- **Ensure Structural Consistency**
  - Good Present Day Structure Geometry
  - Appraise all alternative scenarios of structural and sedimentological evolution

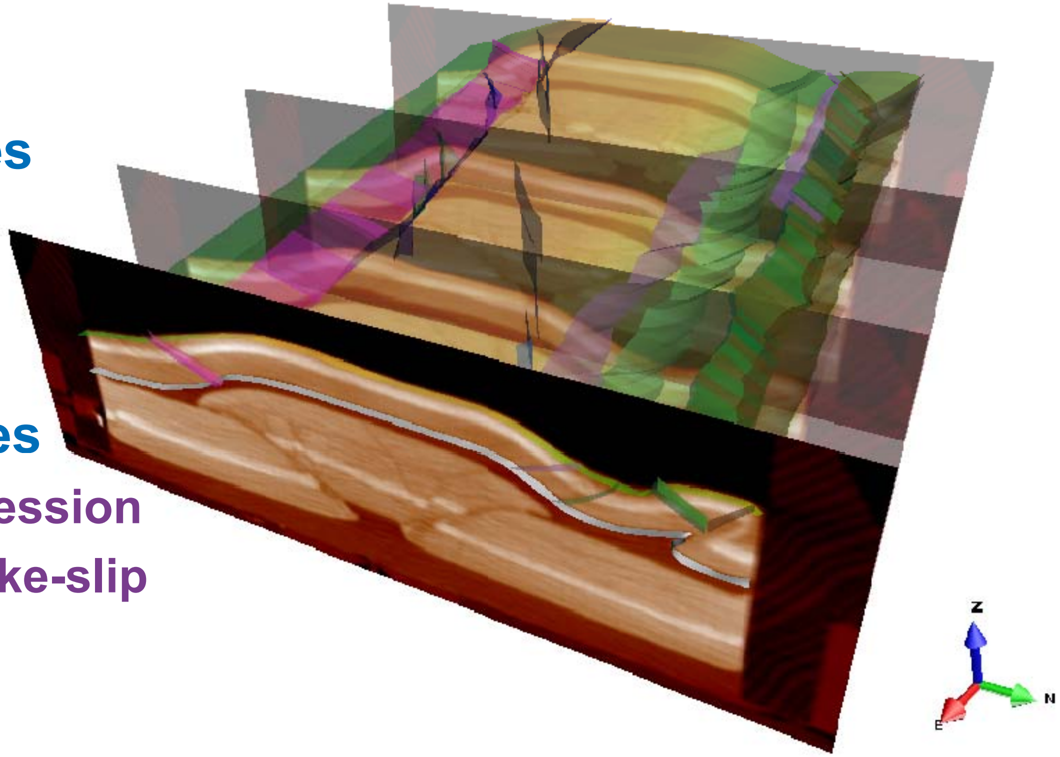
- **Produce a Forward Model**
  - Resetting original thickness & eroded volumes
  - Palinspastic maps
  - Geometry to Basin and Reservoir Models
  - Burial history curves

Restoration techniques and geomechanics

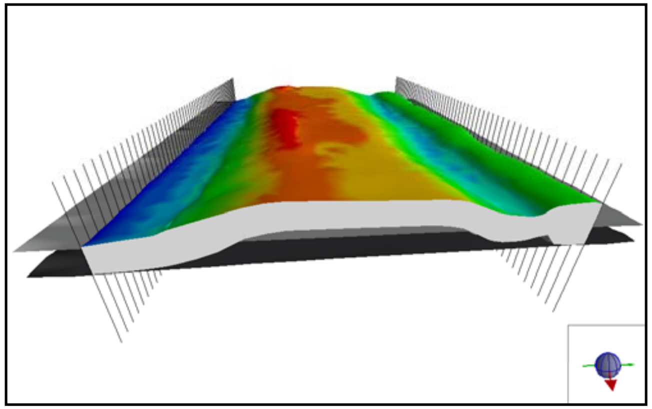
- **Simple-shear & flexural slip**
  - constant volume
  - fault-bend fold; detachment fault; tri-shear etc…
  - Back-stripping
- **Stress-Strain and rheology**
  - Requires to define temporal windows of major deformation processes
- **Fracturing processes**
  - Partly linked to burial and consolidation
  - Partly linked to tectonic and diagenesis
  - Partly acquired during loading and unloading events

ANALOGUE SAND-SILICONE MODELS

- **Single Tectonic Regimes**
  - **Extension**
  - **Strike Slip**
  - **Thrust**
- **Mixted Tectonic Regimes**
  - **Extension then compression**
  - **Compression then strike-slip**
  - **Transtension**
  - **Transpression**
- **Complex processes**
  - **Analogue to Salt diapirisms**
  - **Mechanical decoupling**
  - **Erosion/sedimentation**



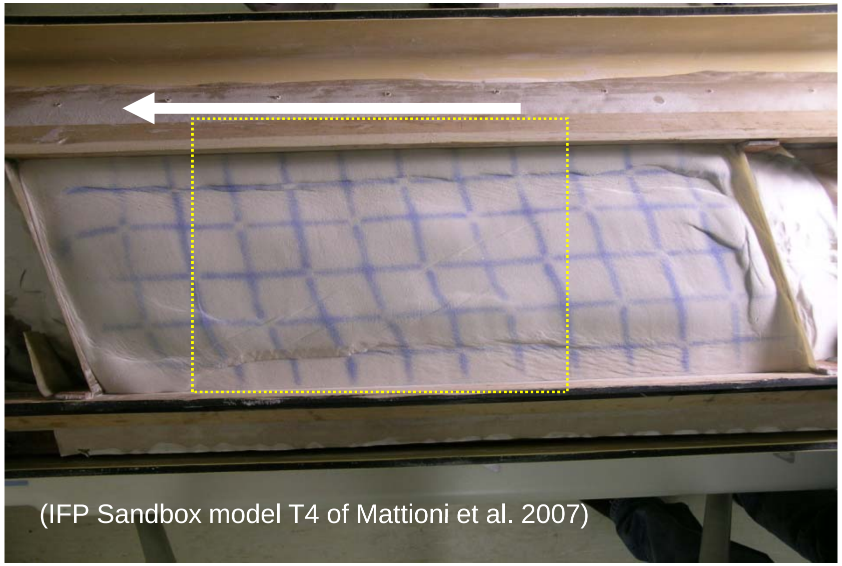
TWO OBJECTIVES



- Measure structural elements to better understand the mechanical evolution in Analogue Sandbox models
  - Investigate boundary conditions versus structural style
  - Investigate fault development, fault chronology and interactions
  - Fold and fault pattern versus loading and applied external strain

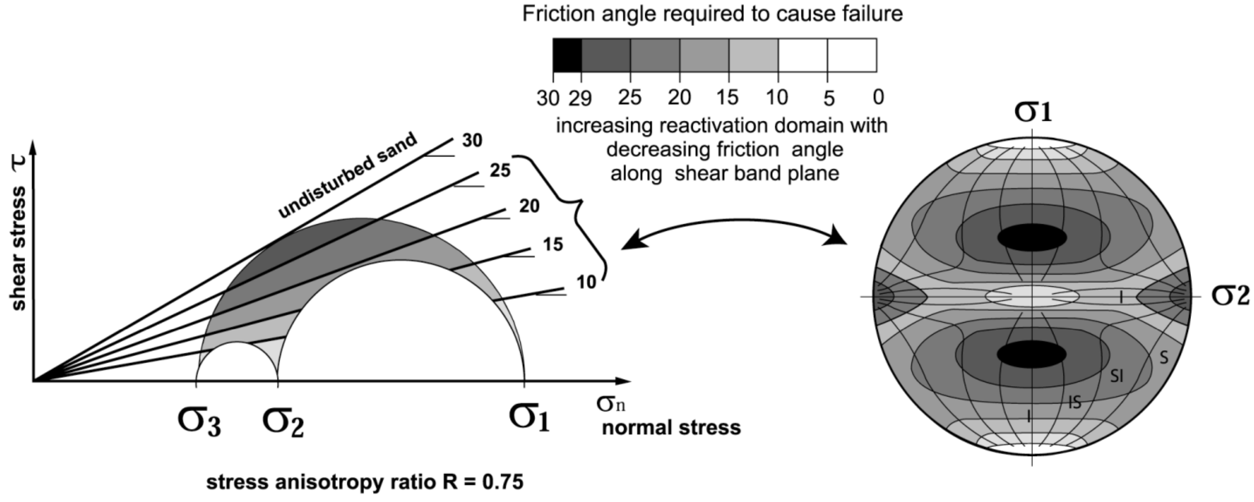
- Propose Restoration standards
  - Update Workflows for efficient sequential calculations
  - Define New Algorithms for volume restoration
  - Acceptable and Non-Acceptable Errors

SAND= Granular Material

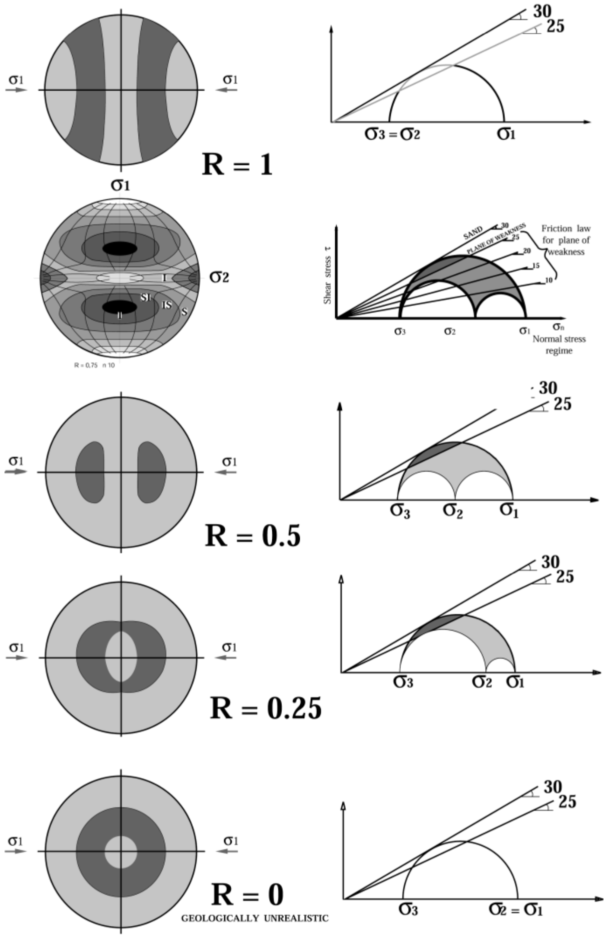

(IFP Sandbox model T4 of Mattioni et al. 2007)

- Brittle behaviour
  - good analogue in fault geometry and kinematics and reactivation
  - Dilation is strong
  - **Sand friction coefficient // most rocks**
- **Mode II discontinuities** (no mode I)

Sand and Corundum are Mohr-Coulomb materials



Material and scaling: sand=brittle silicone=ductile

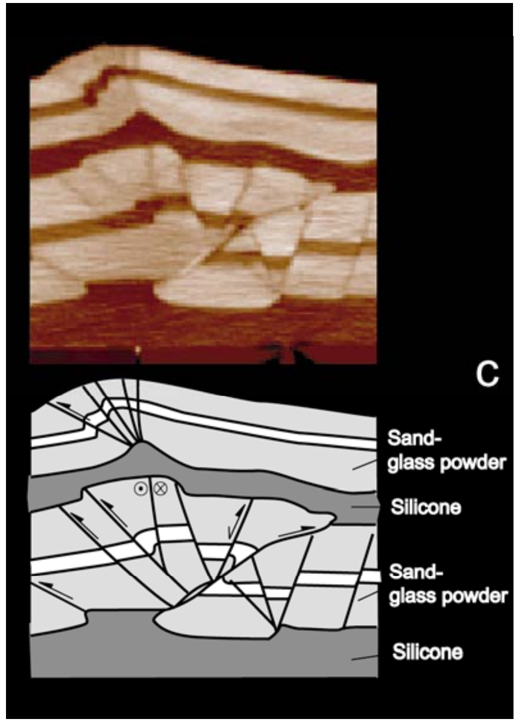


Mohr - Coulomb Analysis

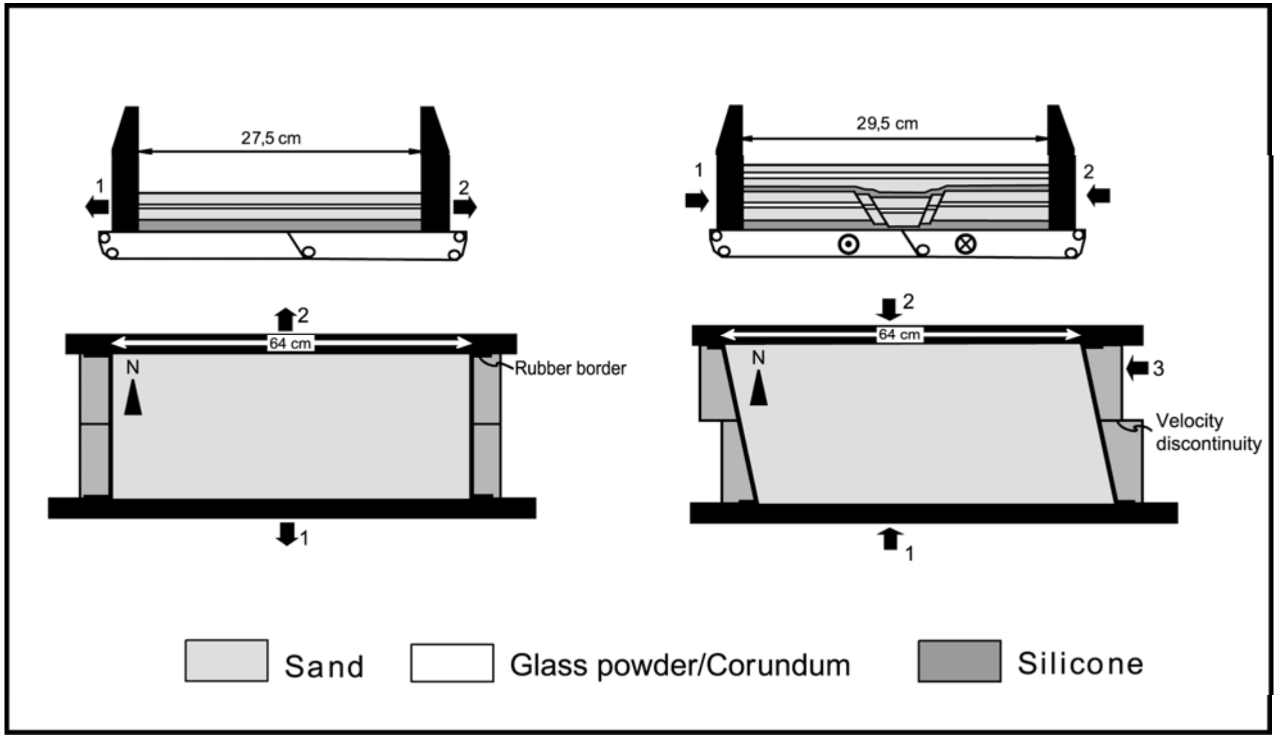
New faults

versus

fault reactivation

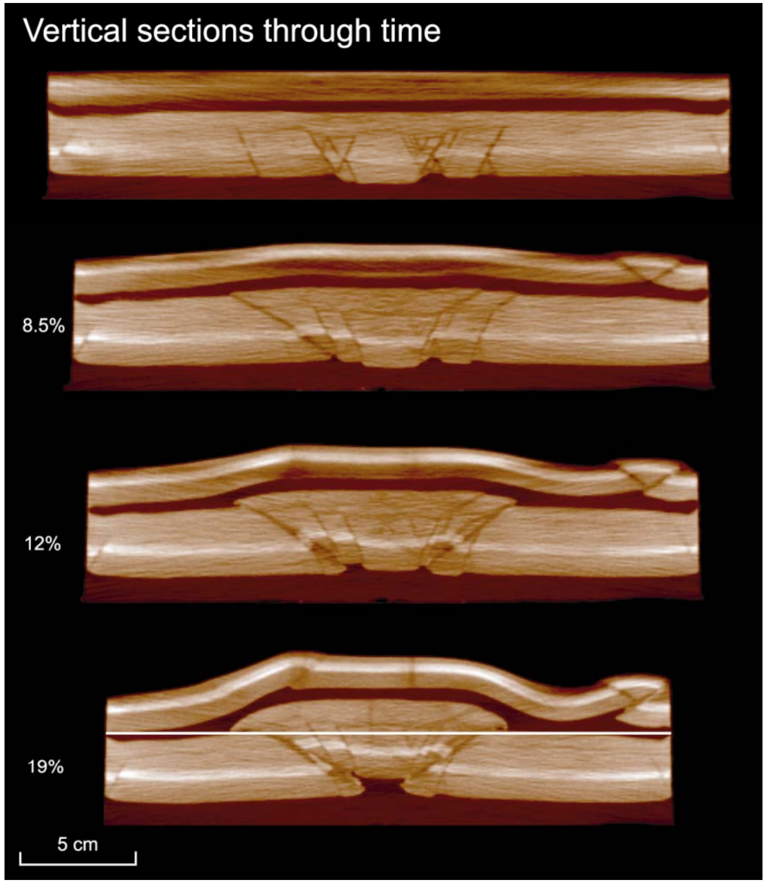


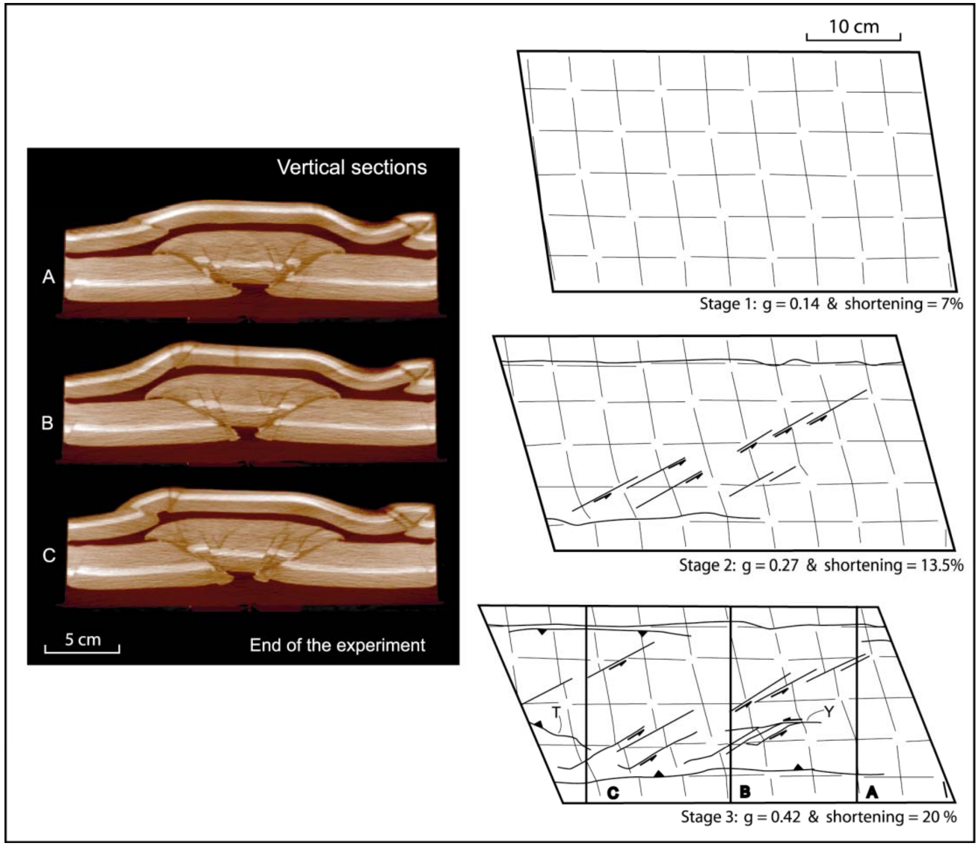
Experiment T4: Extension + Transpression (Vss=3cm/h)



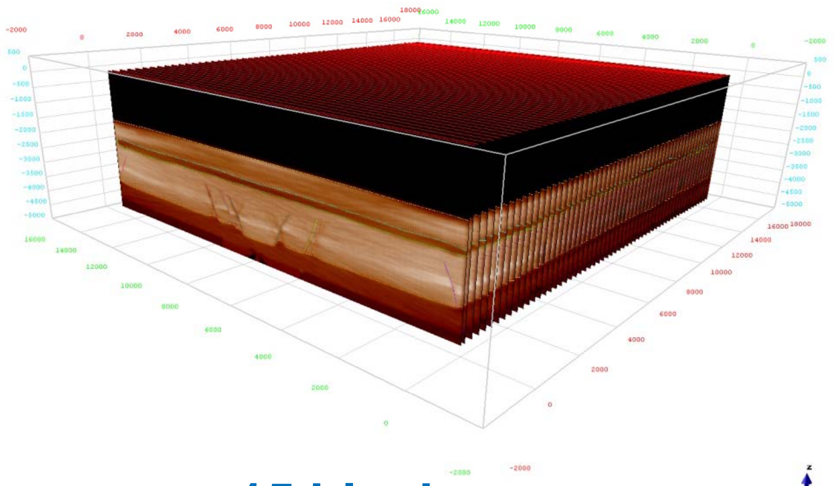
(After Mattioni *et al.* 2007)

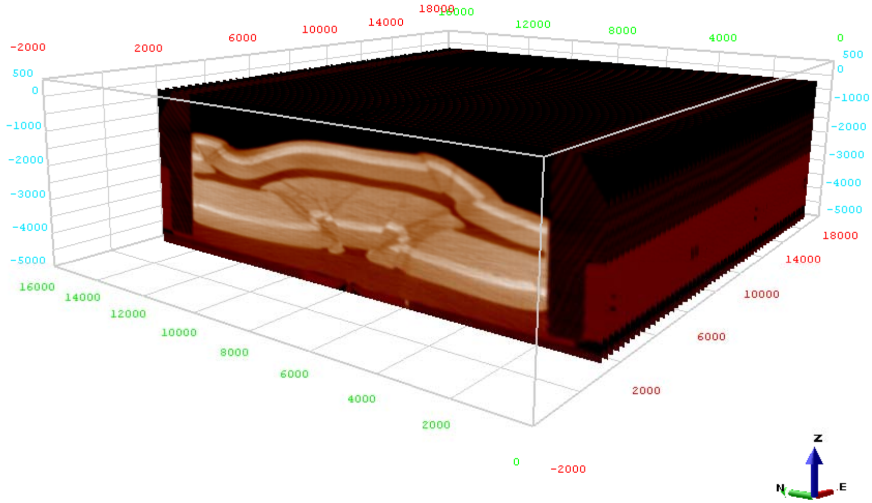
Experiment T4: Extension + Transpression (Vss=3cm/h)





Data sets

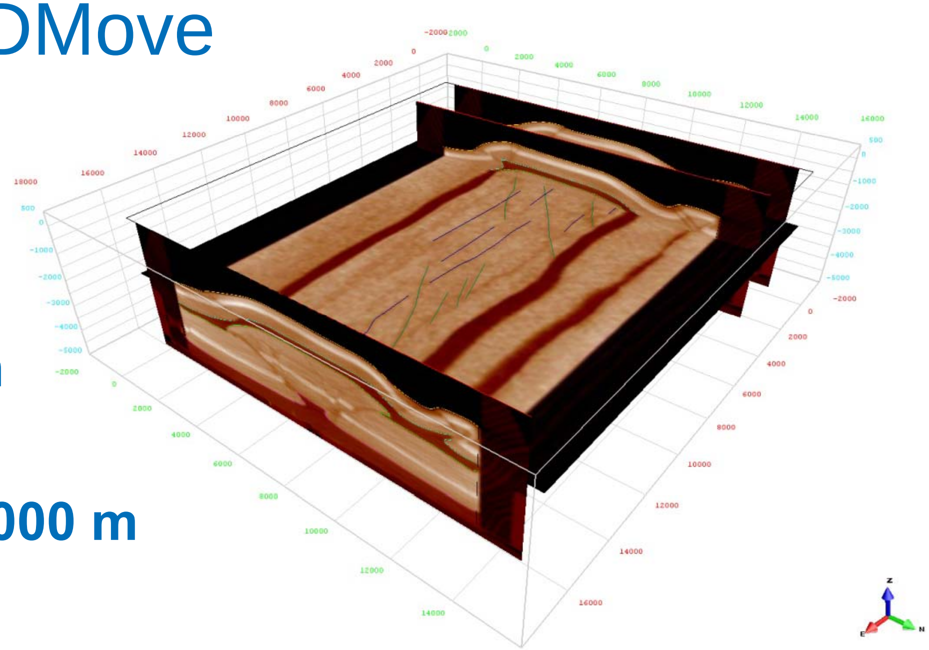




- **15 blocks**
- **01 - 02 → extension phase**
- **02 - 03 → sedimentation**
- **03 - 15 -> transpression**

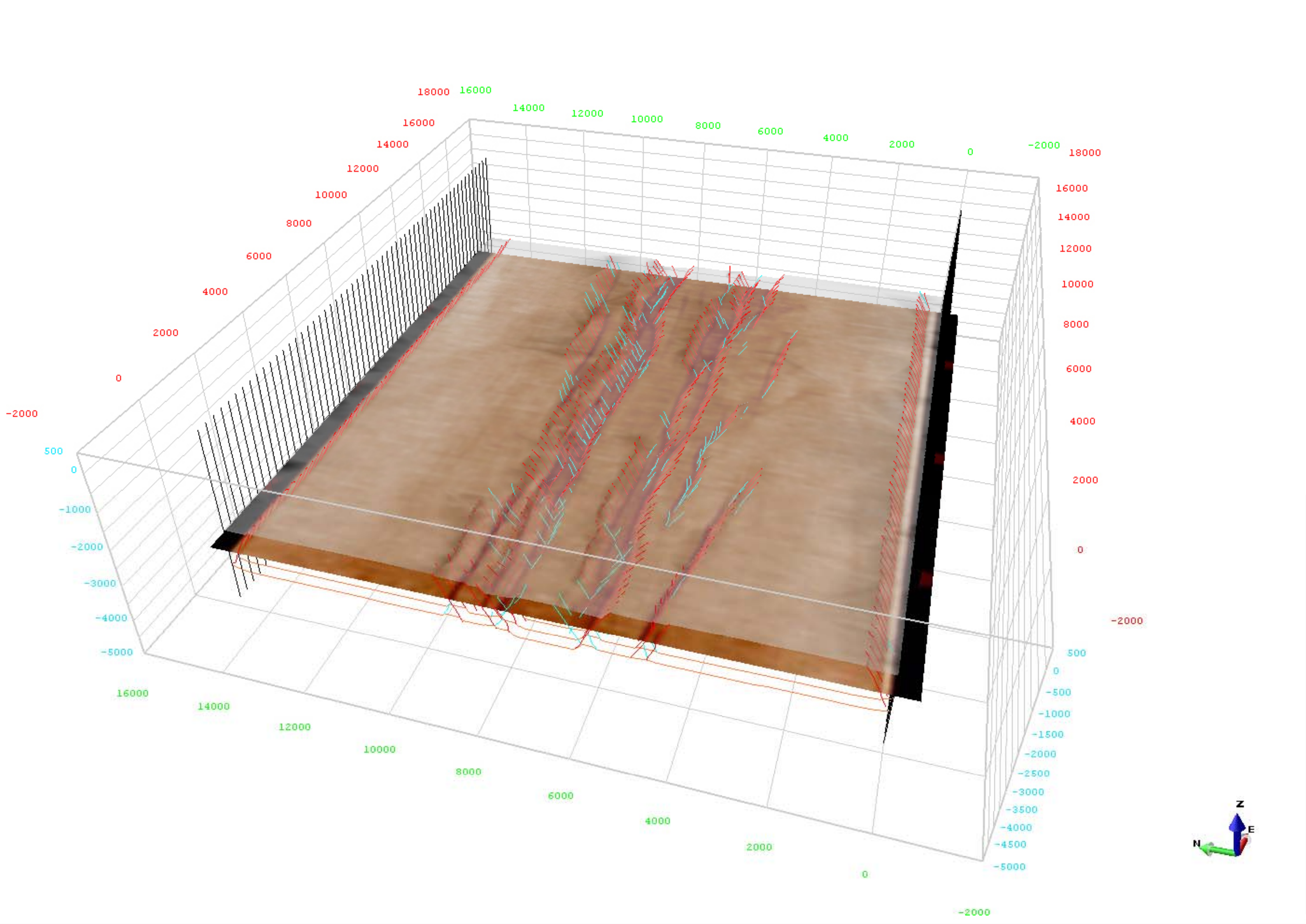
- **All blocks digitised D02 + D03-D15**

Building a 3D Model in 3DMove



- **Resolution in pixel: 1px = 40m**
- **Height of overbuden: 6cm= 3 000 m**
- **Dimension of the box**
  - **70*30*10 cm3 scaled to 35*15*5 km3**

A Block diagram was built with 57 parallel cross sections given by pixels images from CT X-ray scanner



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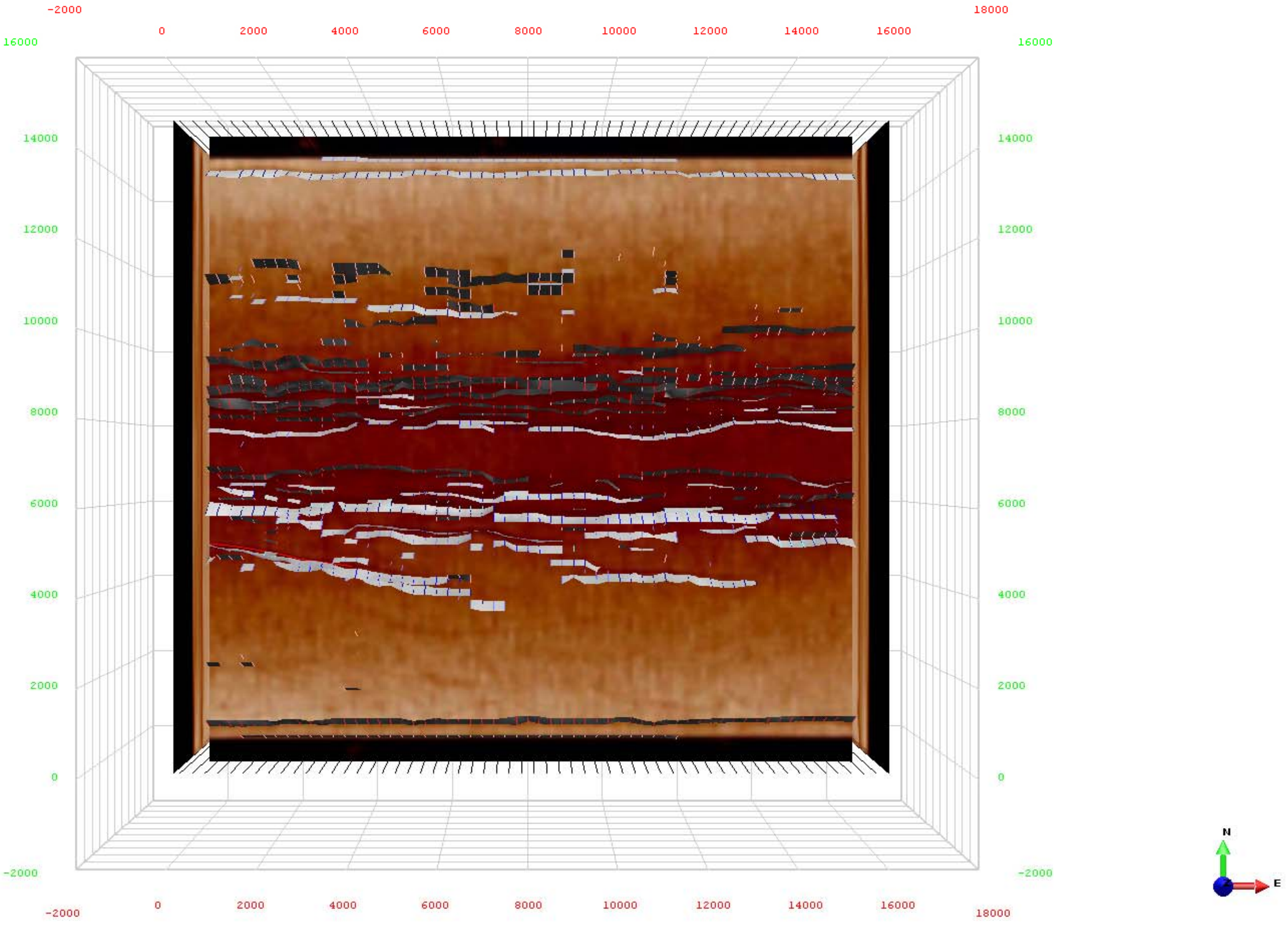
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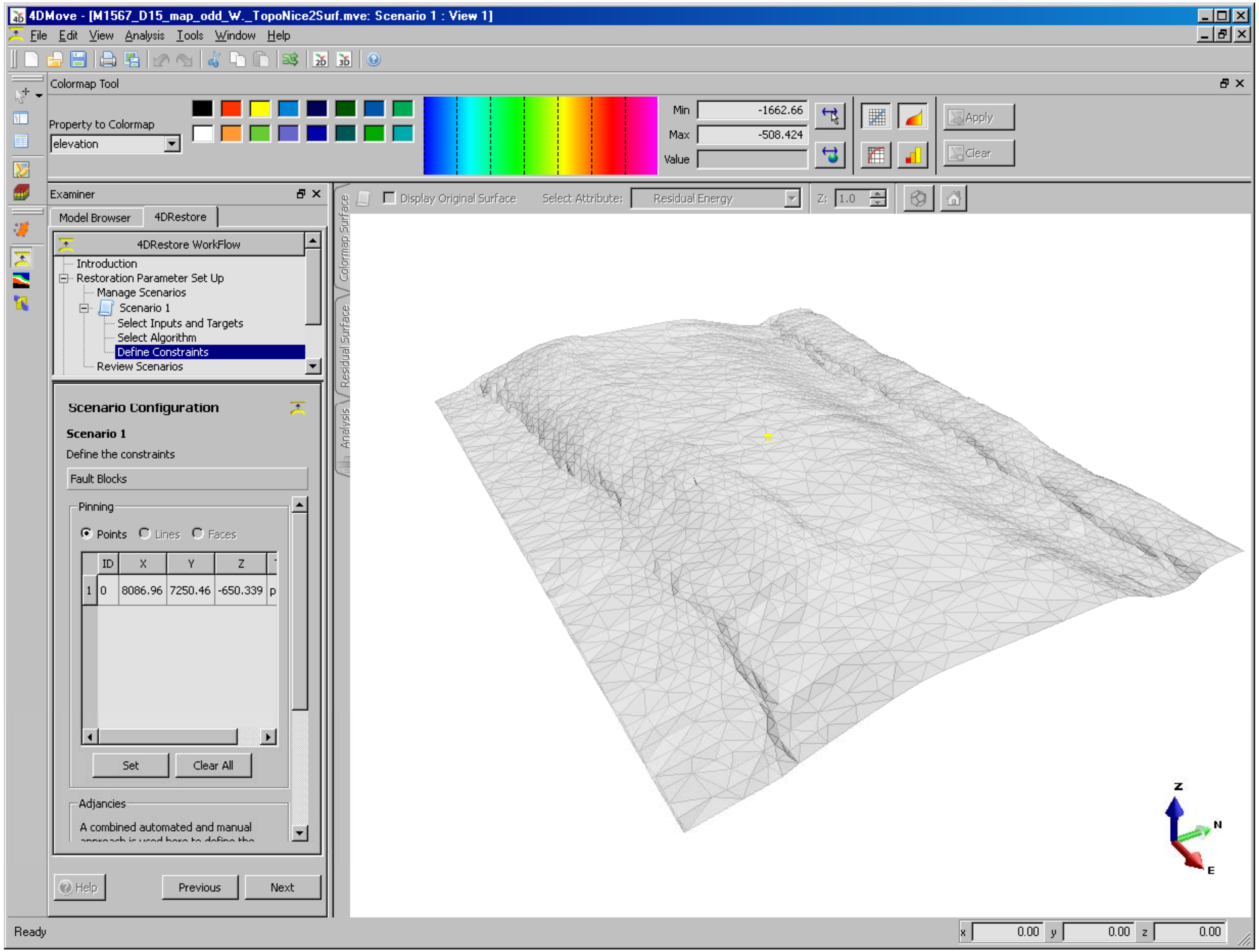
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4DRestore WorkFlow
Introduction
Restoration Parameter Set Up
Manage Scenarios
Scenario 1
Select Inputs and Targets
Select Algorithm
Define Constraints
Review Scenarios
Scenario Configuration
Scenario 1
Define the constraints
Fault Blocks
Pinning
Points
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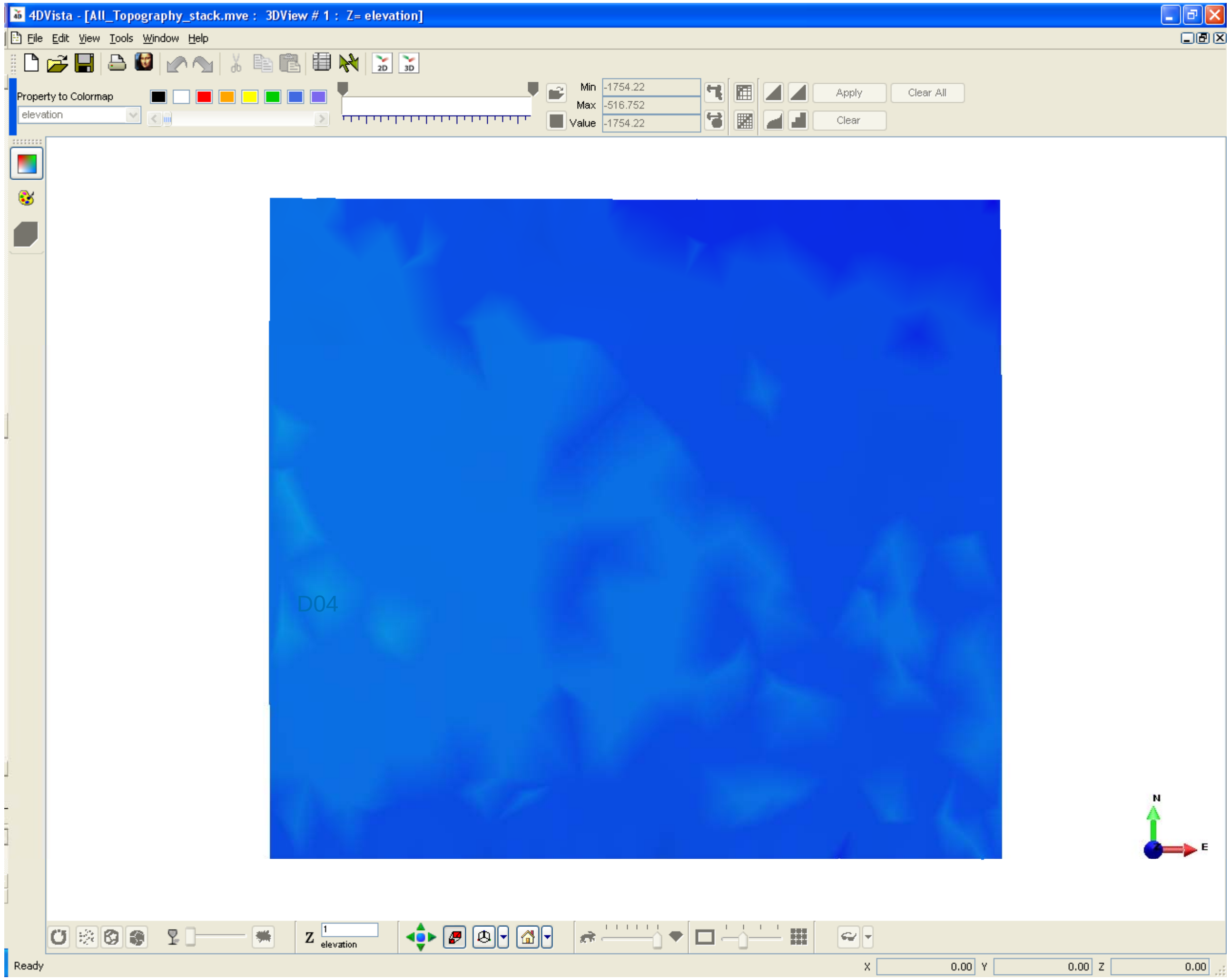
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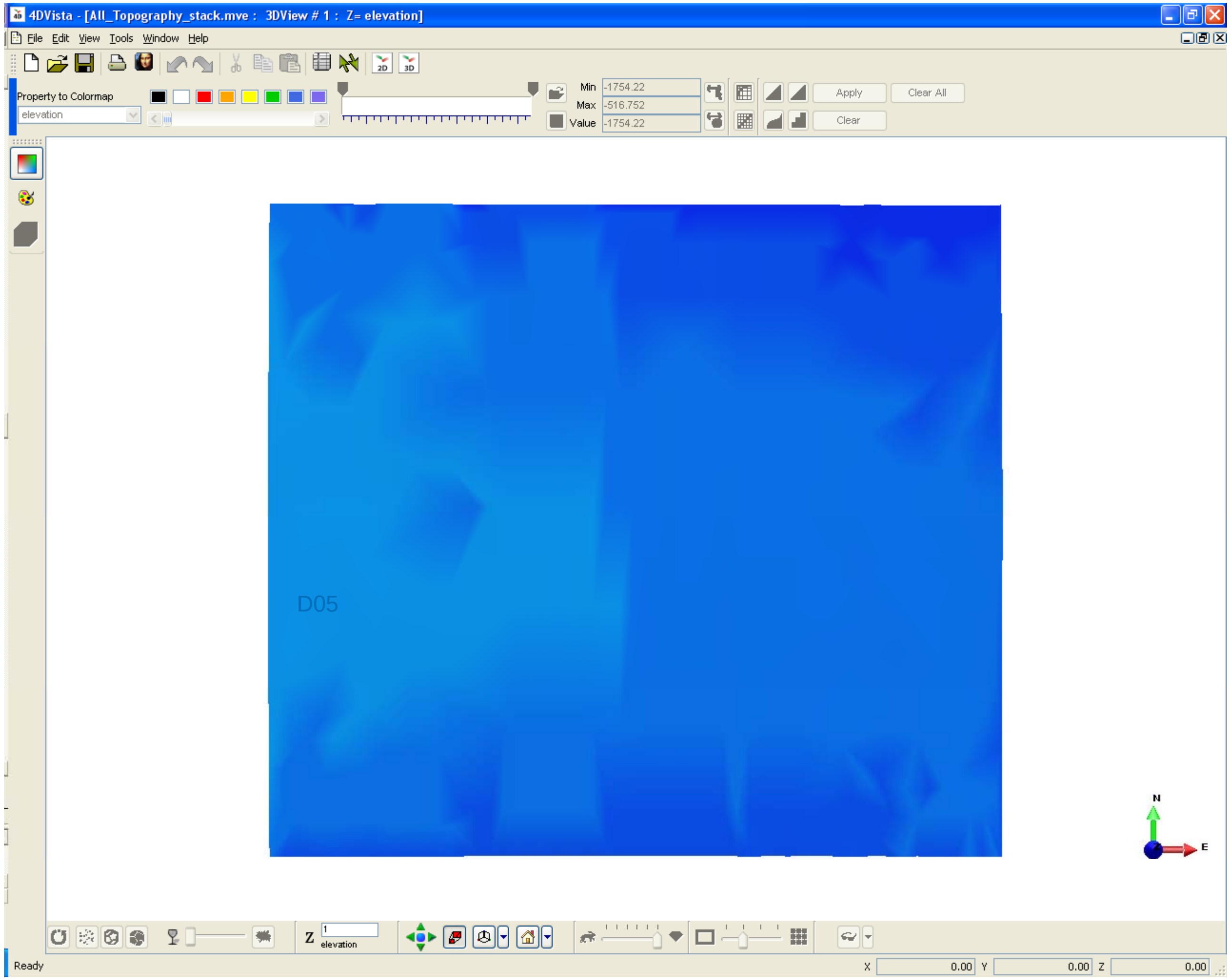
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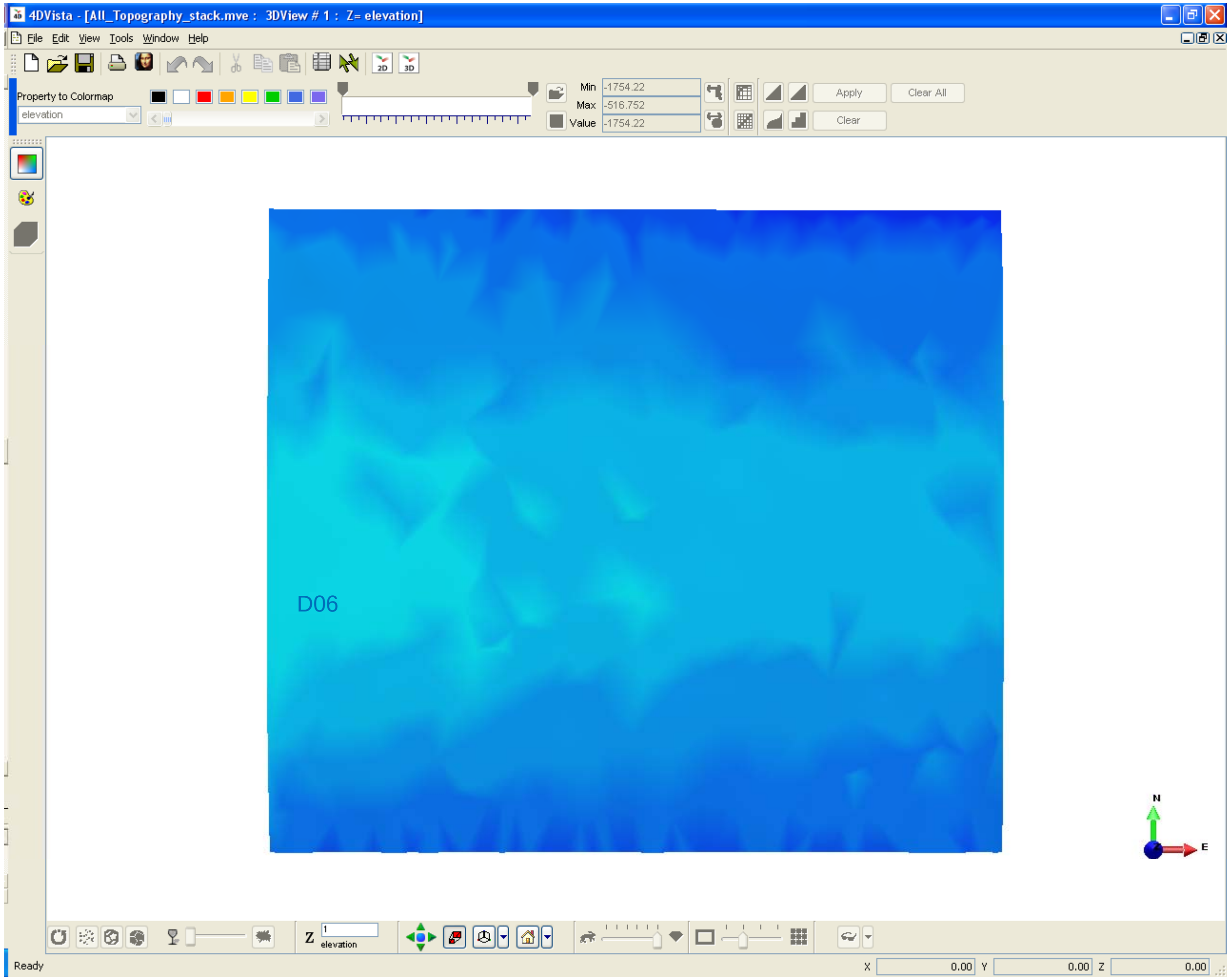
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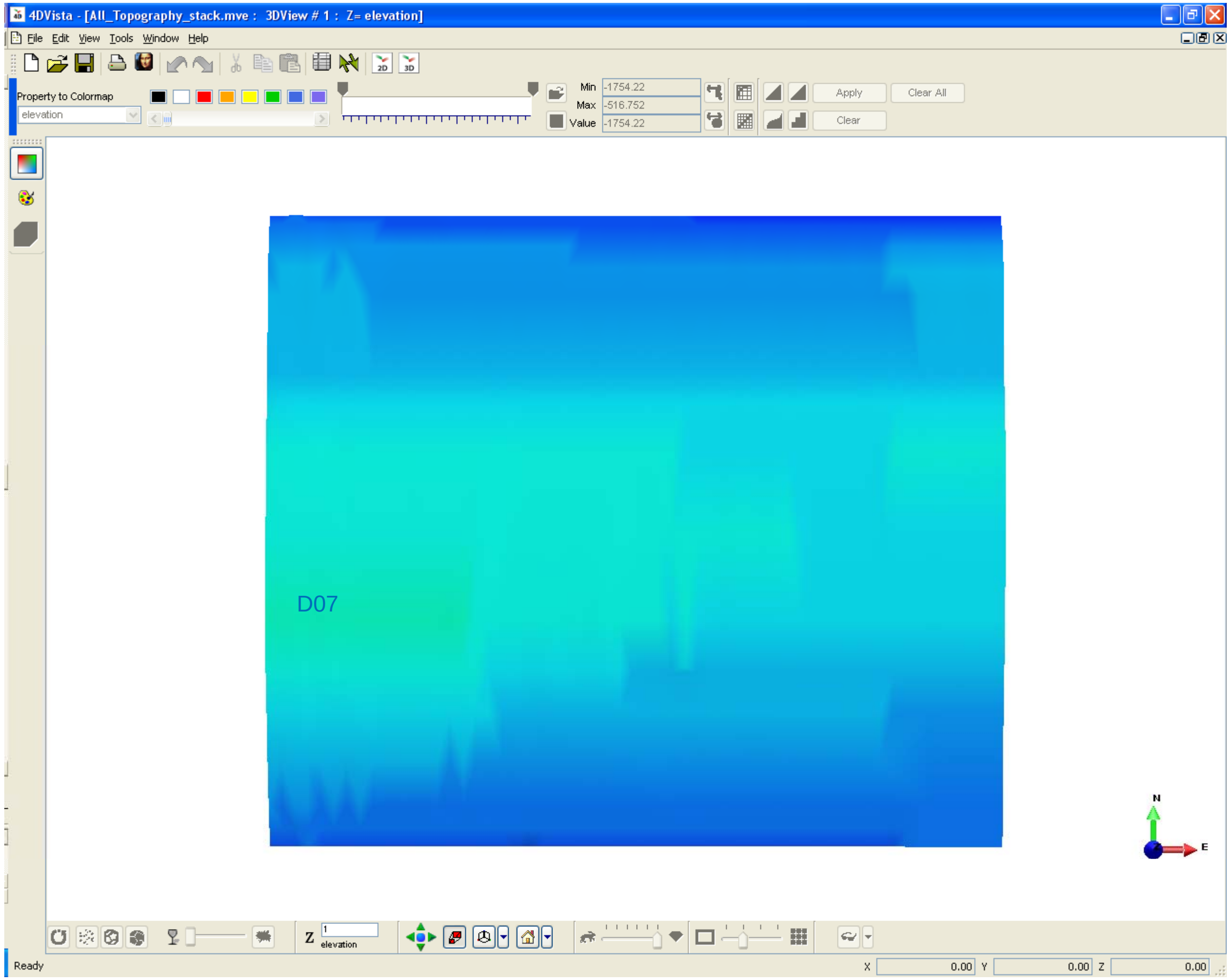
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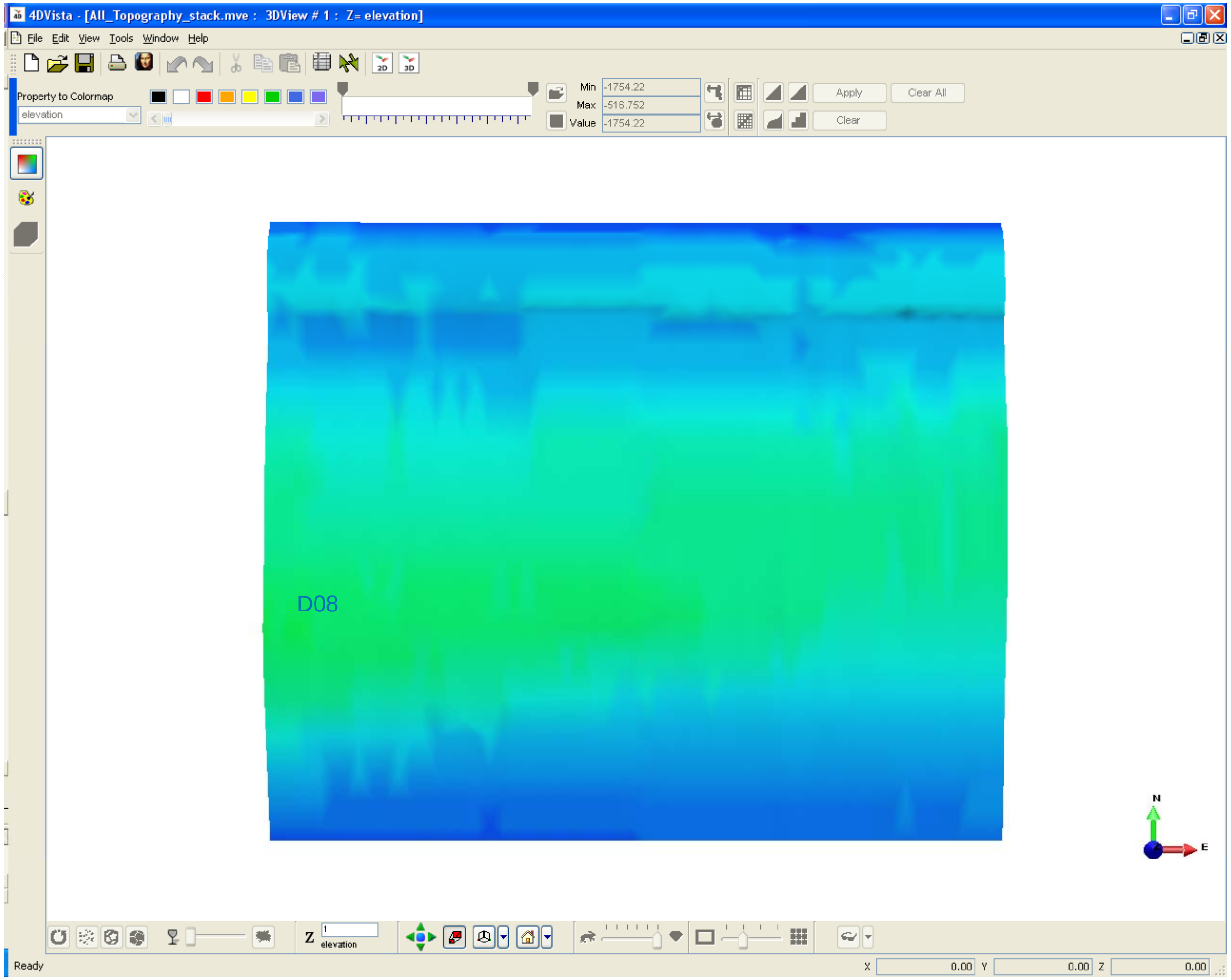
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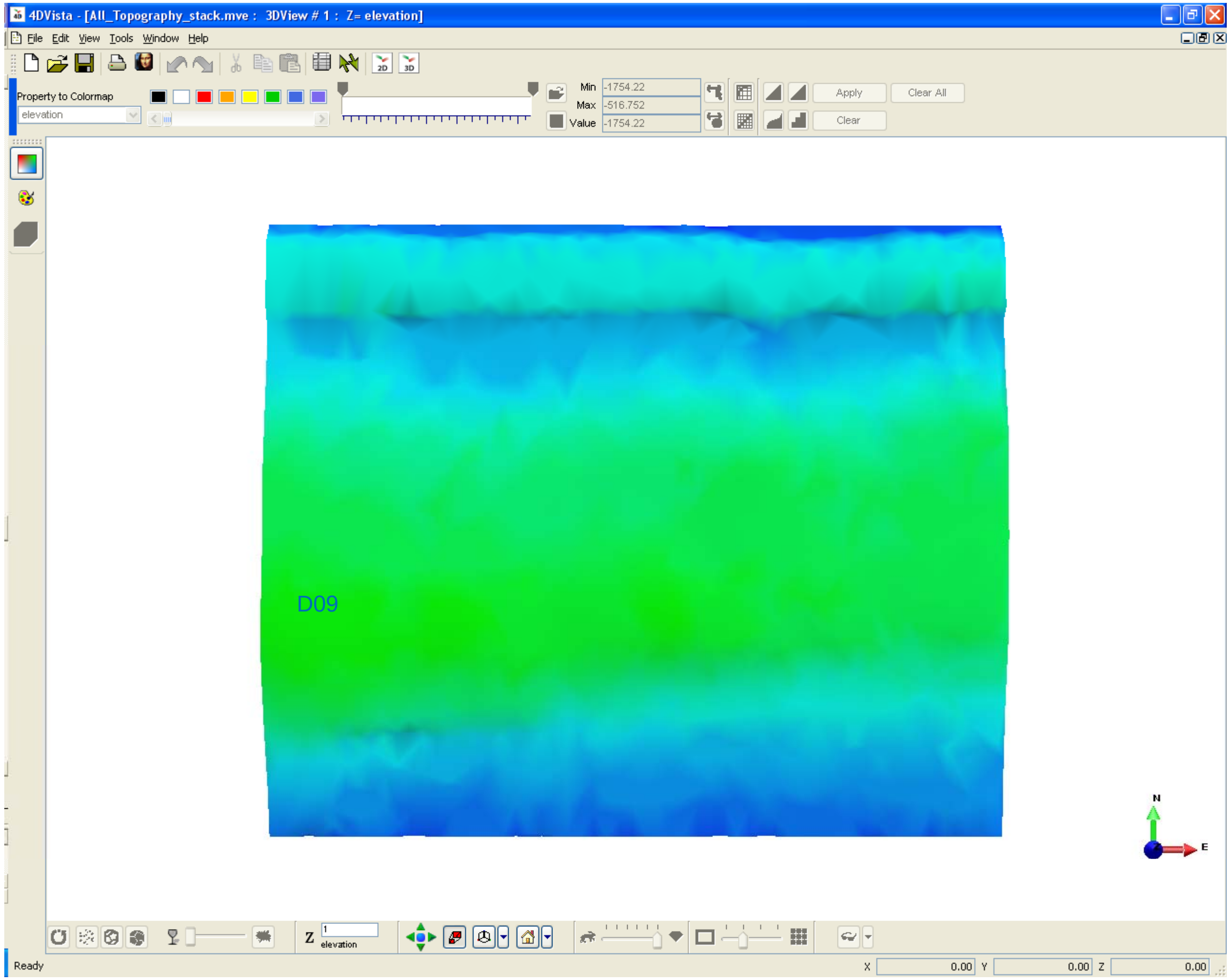
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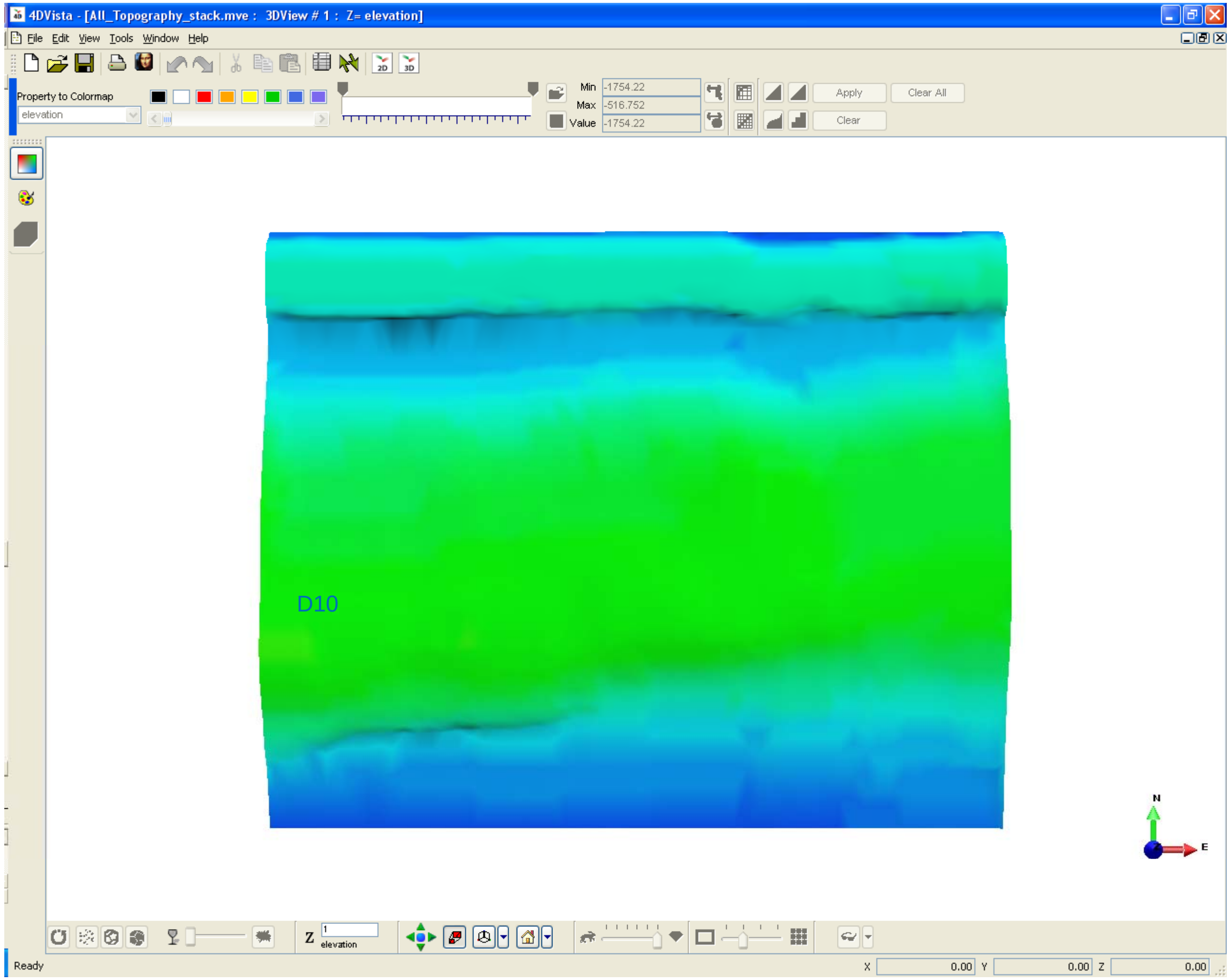
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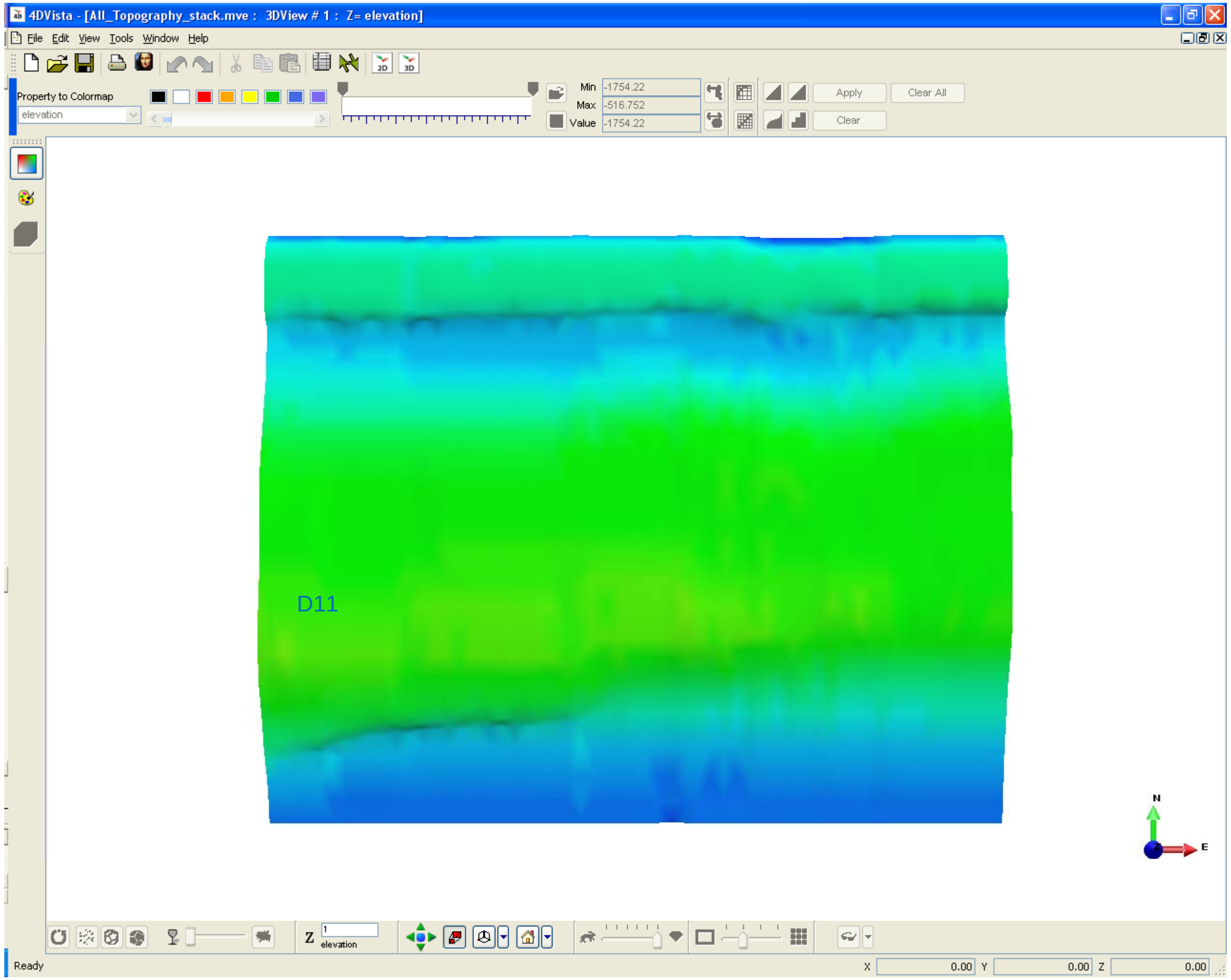
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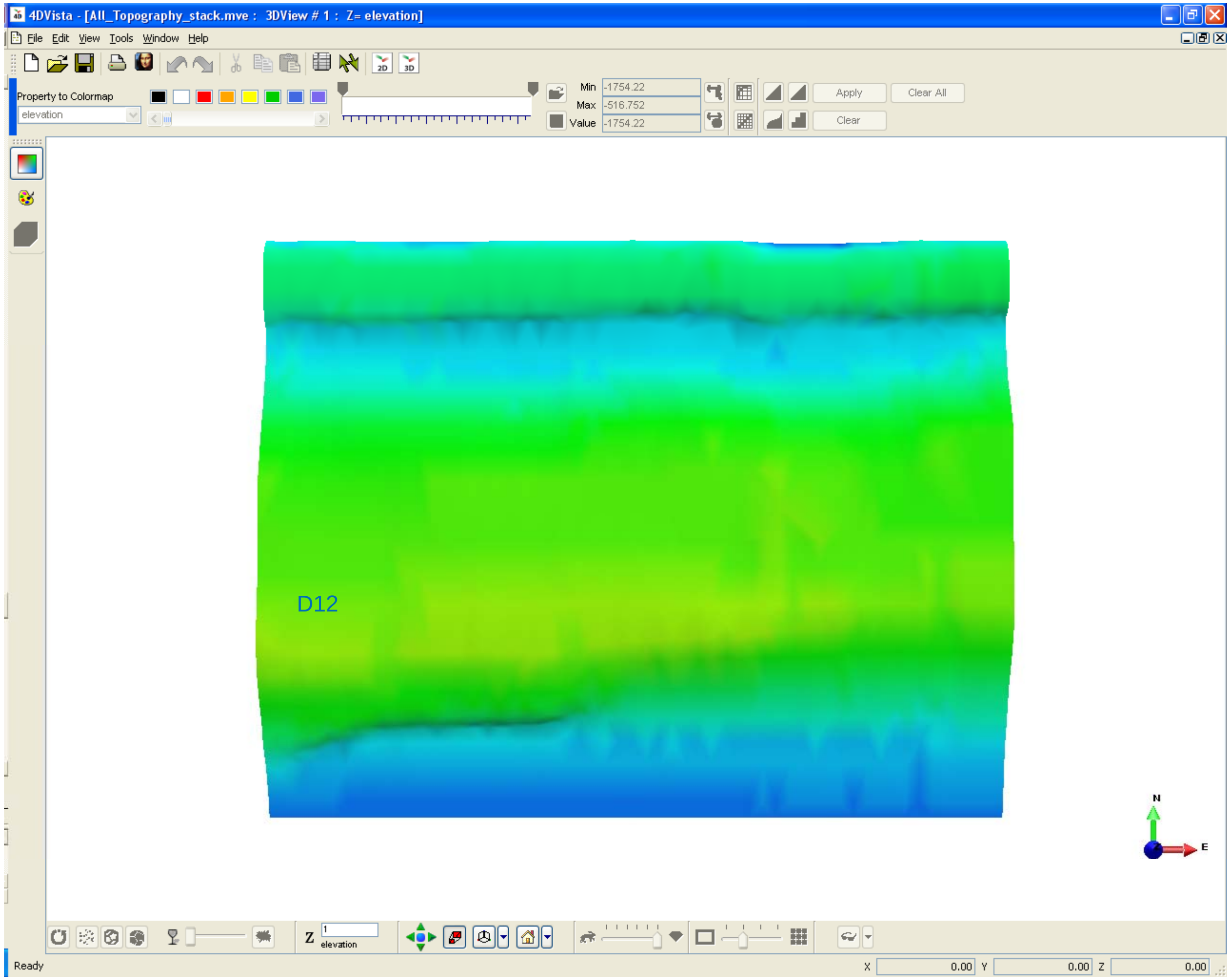
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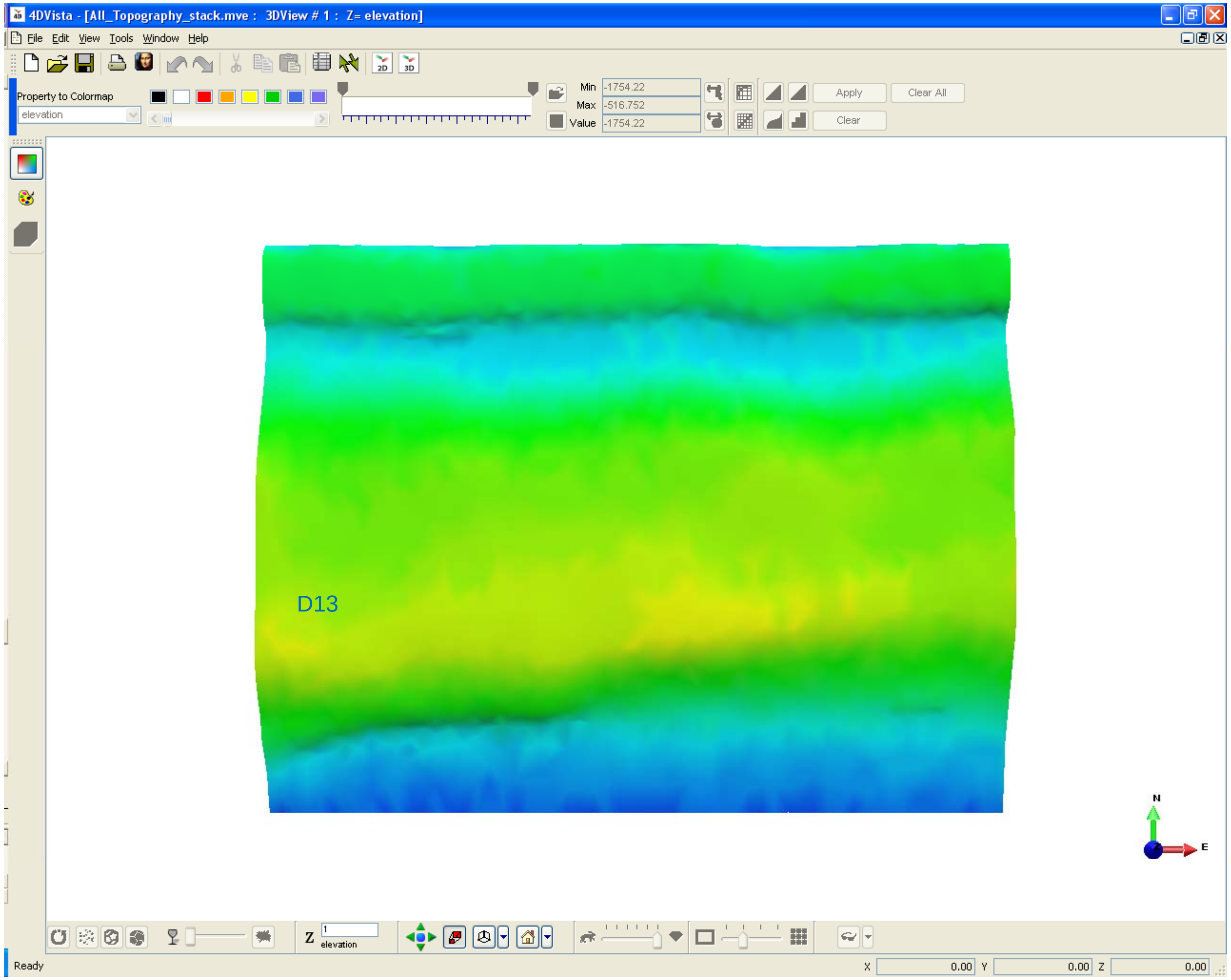
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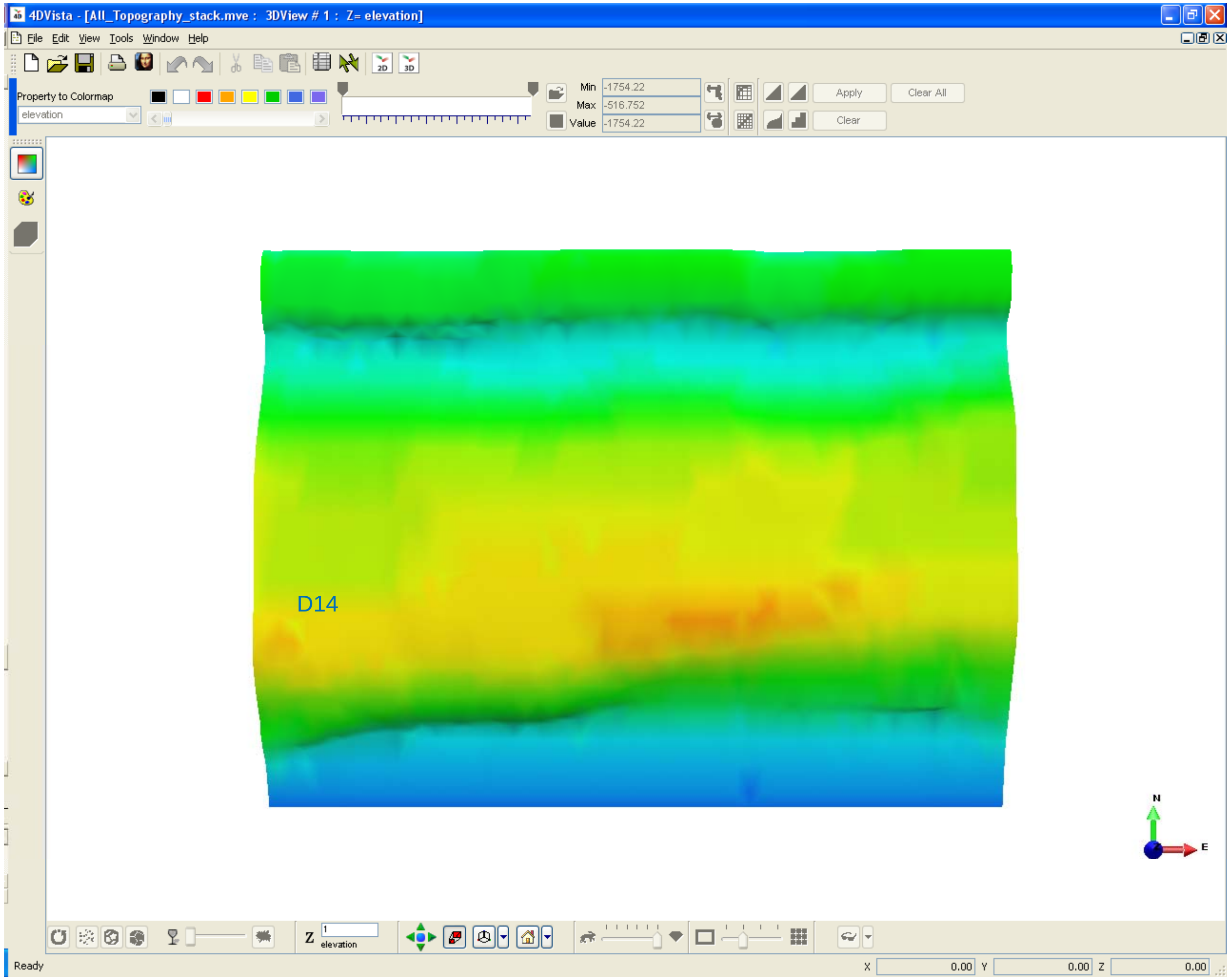
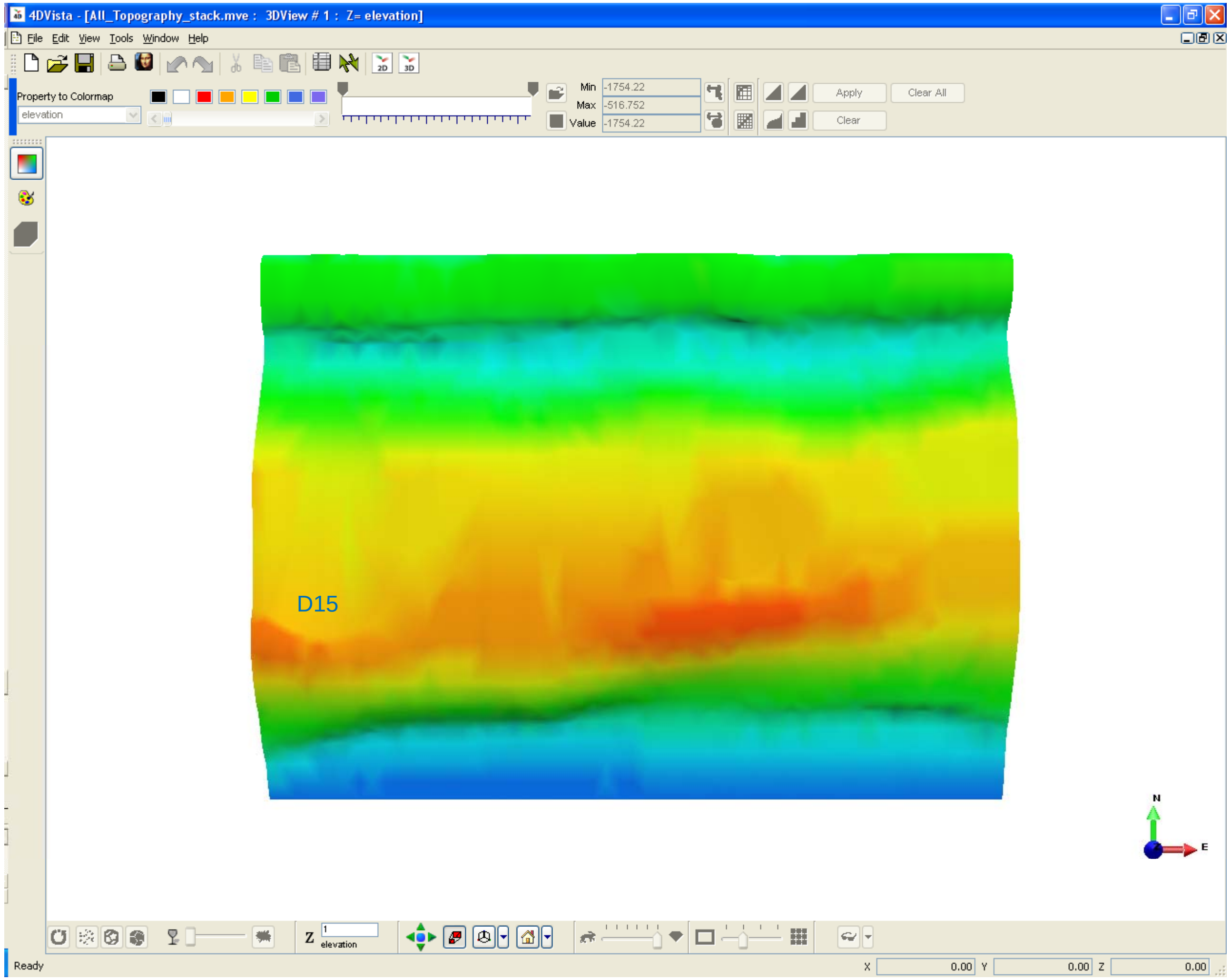
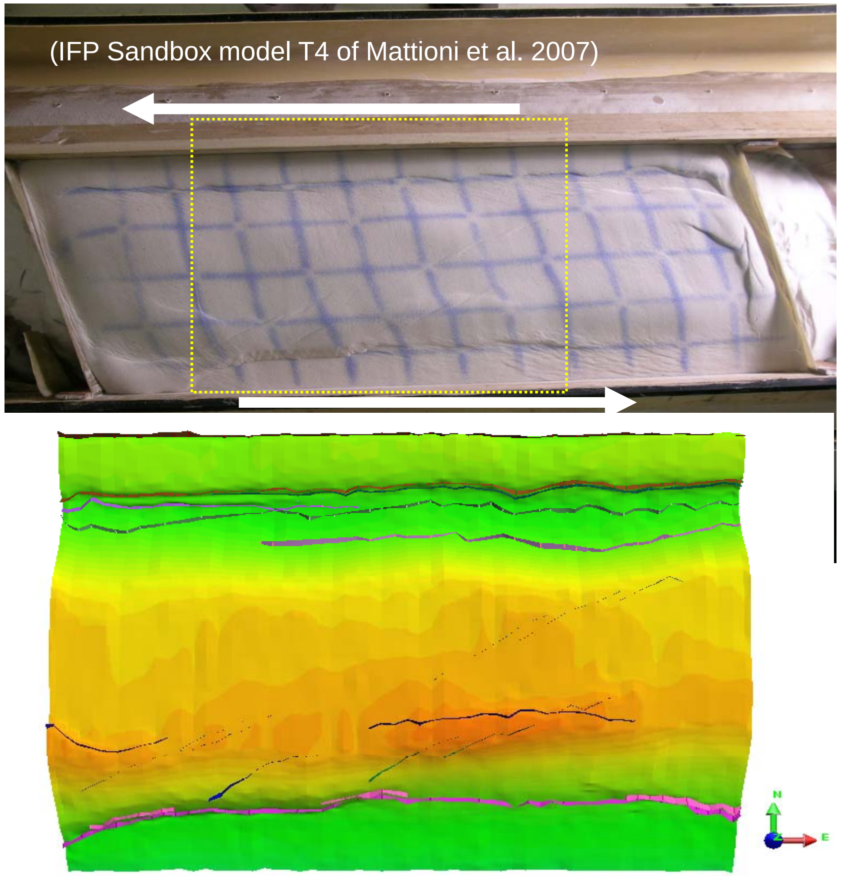
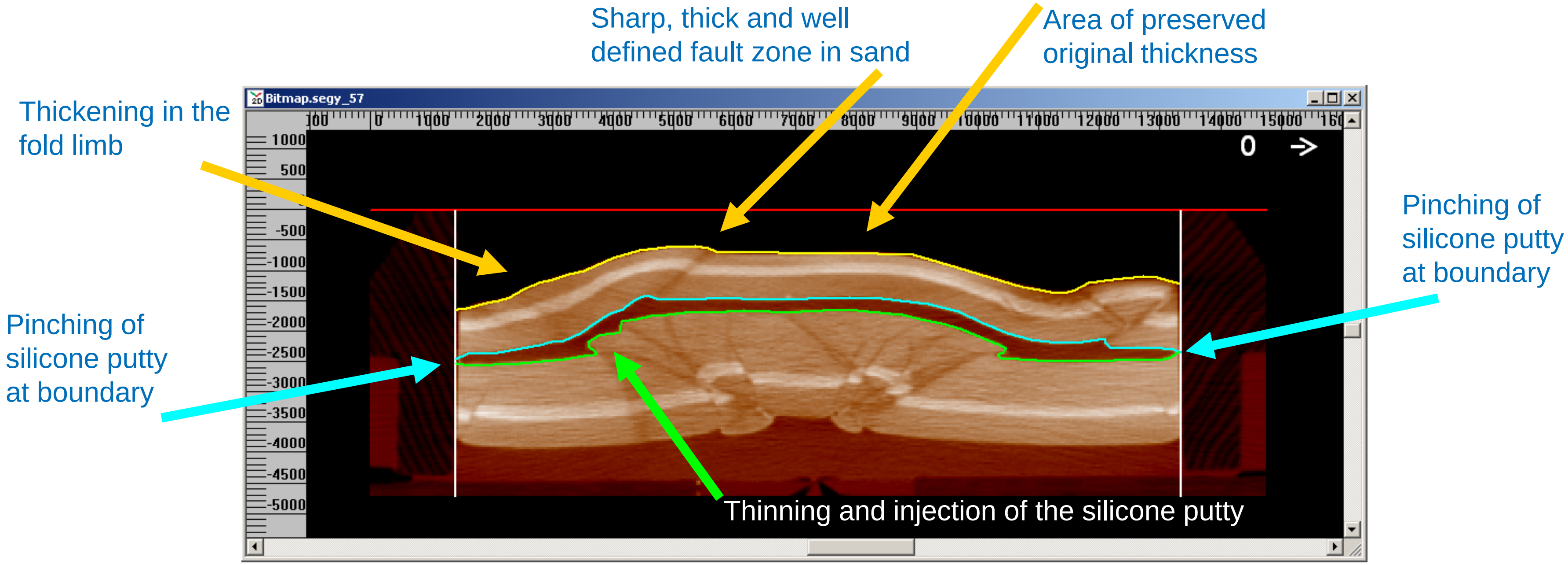

4DVista - [All_Topography_stack.mve : 3DView # 1 : Z= elevation]
File Edit View Tools Window Help
Property to Colormap
elevation
Min -1754.22
Max -516.752
Value -1754.22
Apply
Clear All
Clear
D14
N
E
Z
elevation
Ready
X 0.00 Y 0.00 Z 0.00

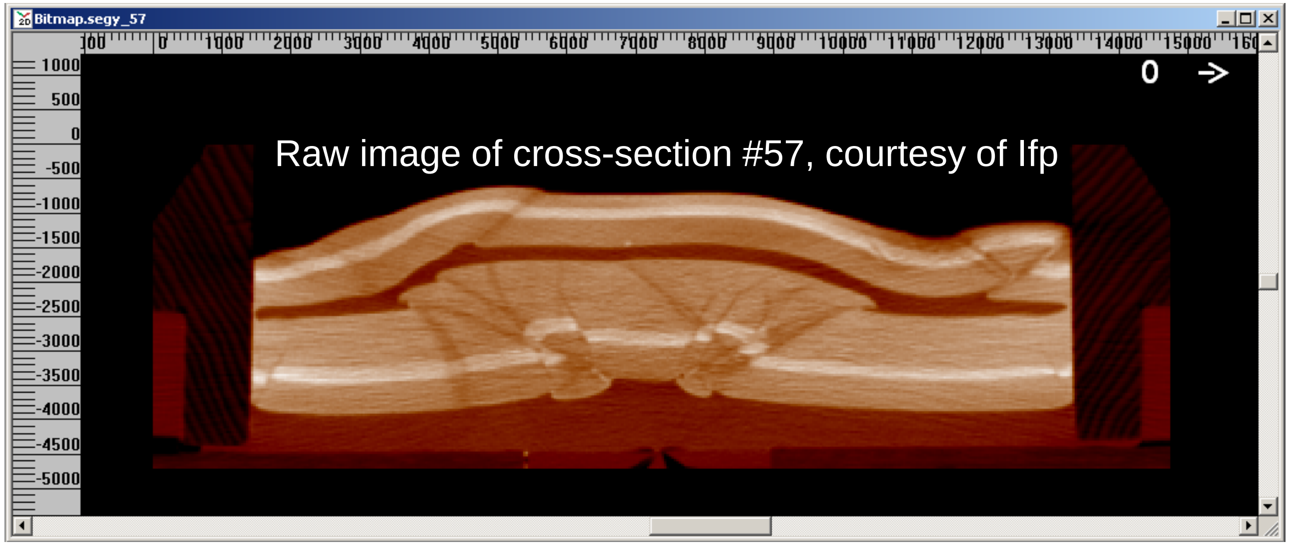

4DVista - [All_Topography_stack.mve : 3DView # 1 : Z= elevation]
File Edit View Tools Window Help
Property to Colormap
elevation
Min -1754.22
Max -516.752
Value -1754.22
Apply
Clear All
Clear
D15
N
E
Z
elevation
Ready
X 0.00 Y 0.00 Z 0.00

A sandbox experiment of force folding by graben inversion

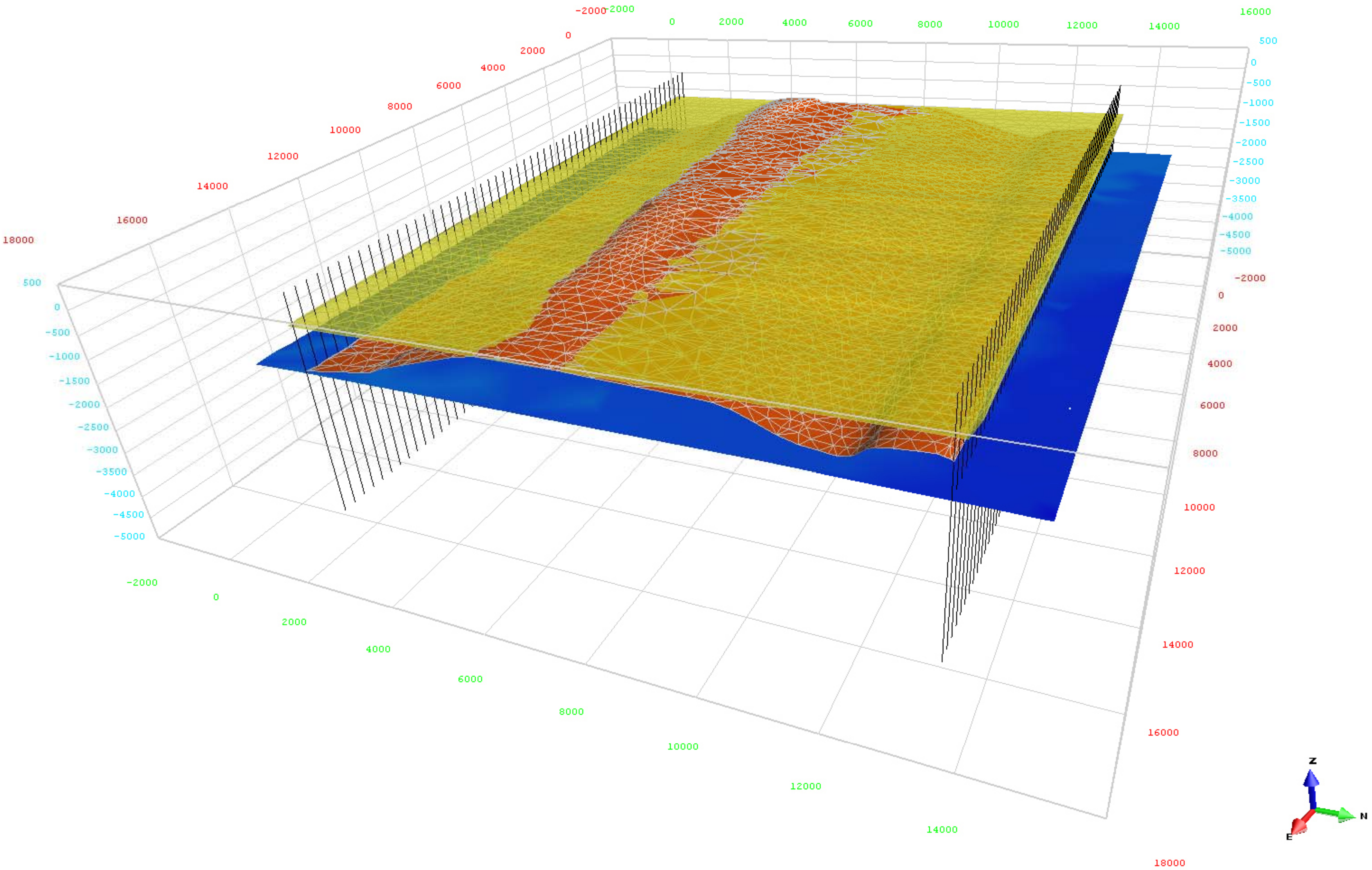


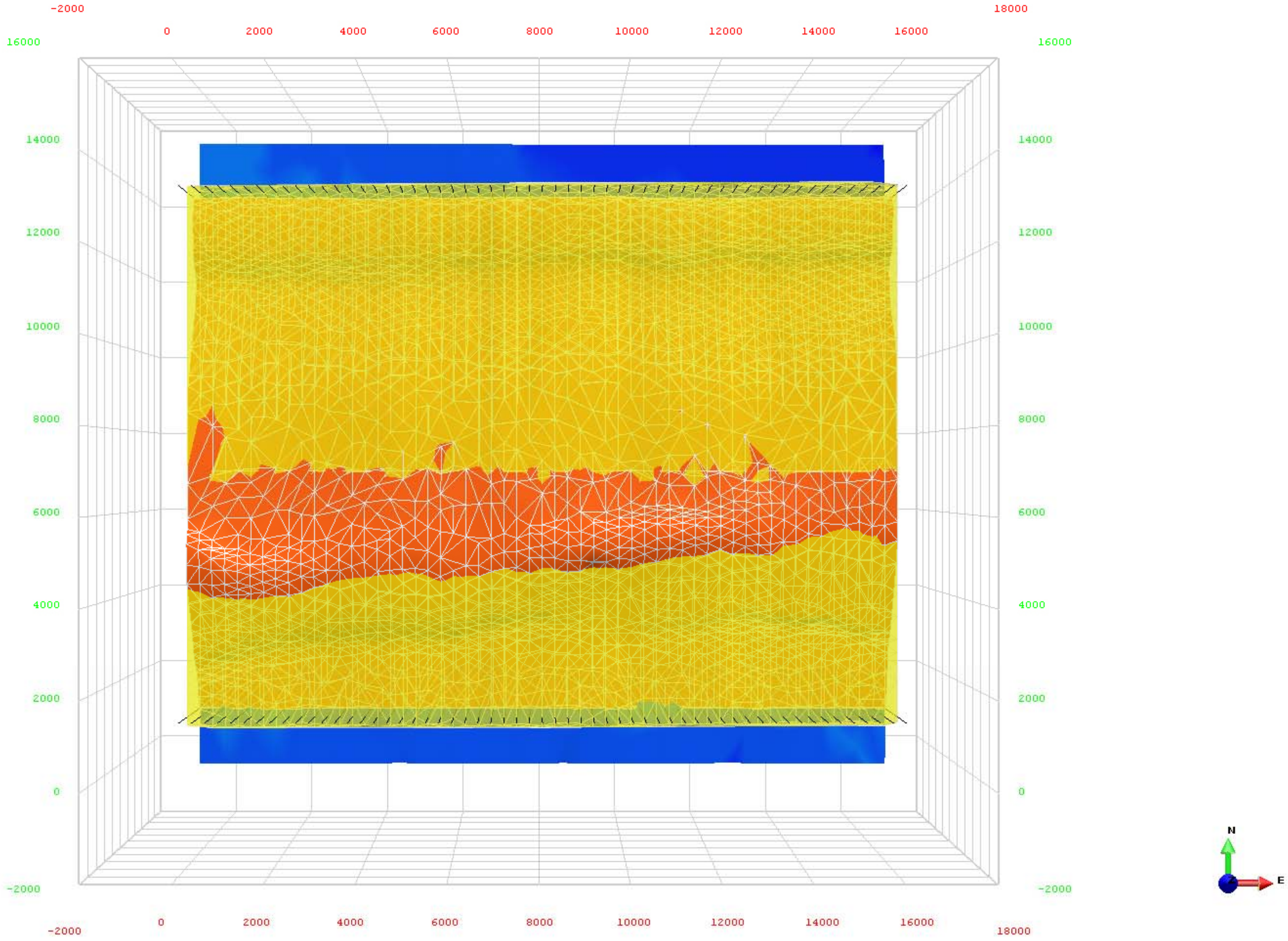


Sharp, thick and well defined fault zone in sand
Area of preserved original thickness
Thickening in the fold limb
Bitmap.segy_57
Pinching of silicone putty at boundary
Pinching of silicone putty at boundary
Thinning and injection of the silicone putty



Bitmap.segy_57
Raw image of cross-section #57, courtesy of Ifp


-2000 0 2000 4000 6000 8000 10000 12000 14000 16000
500 0 -500 -1000 -1500 -2000 -2500 -3000 -3500 -4000 -4500 -5000
-2000 0 2000 4000 6000 8000 10000 12000 14000 16000 18000
Z
N
E


-2000
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
N
E

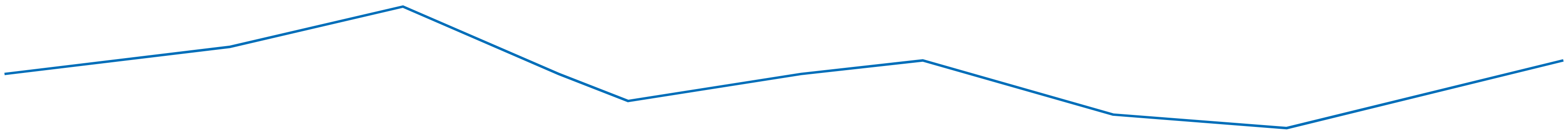
Working with surfaces

- Information recorded is poor just the total area, the dip and the curvature

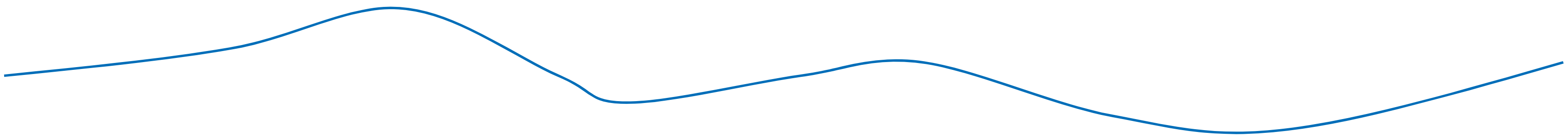
- Correlation between top and bottom surfaces of strata can help to characterise volumetric strain

- At the moment: double Z surfaces are not meshable and therefore restorable: a technique is needed to palliate this limitation

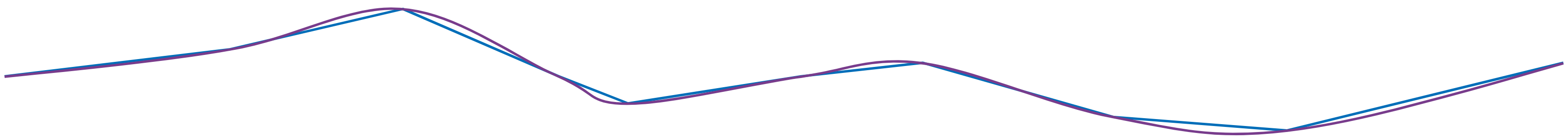
Line represented by straight segments

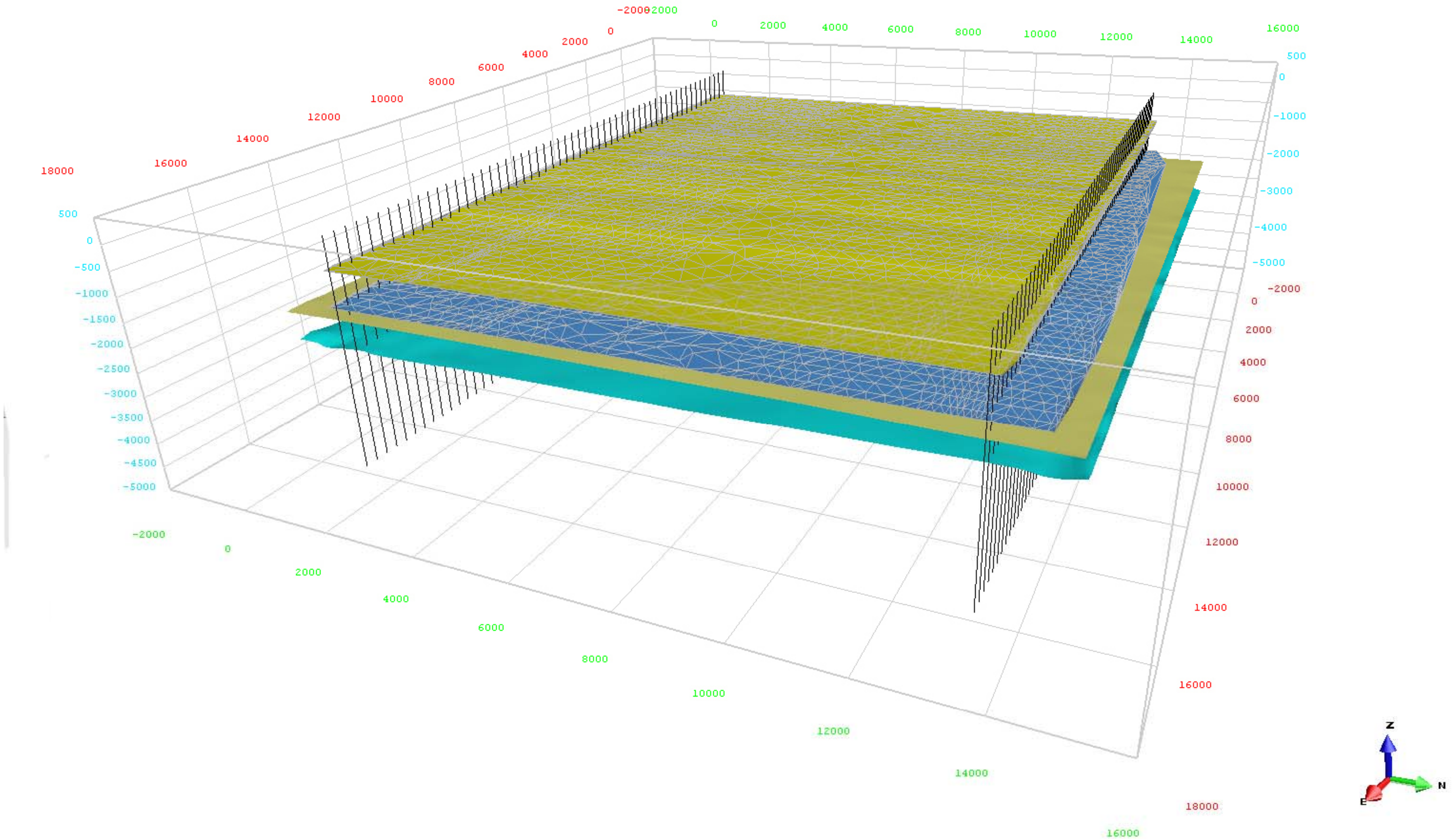


Line represented with spline interpolation



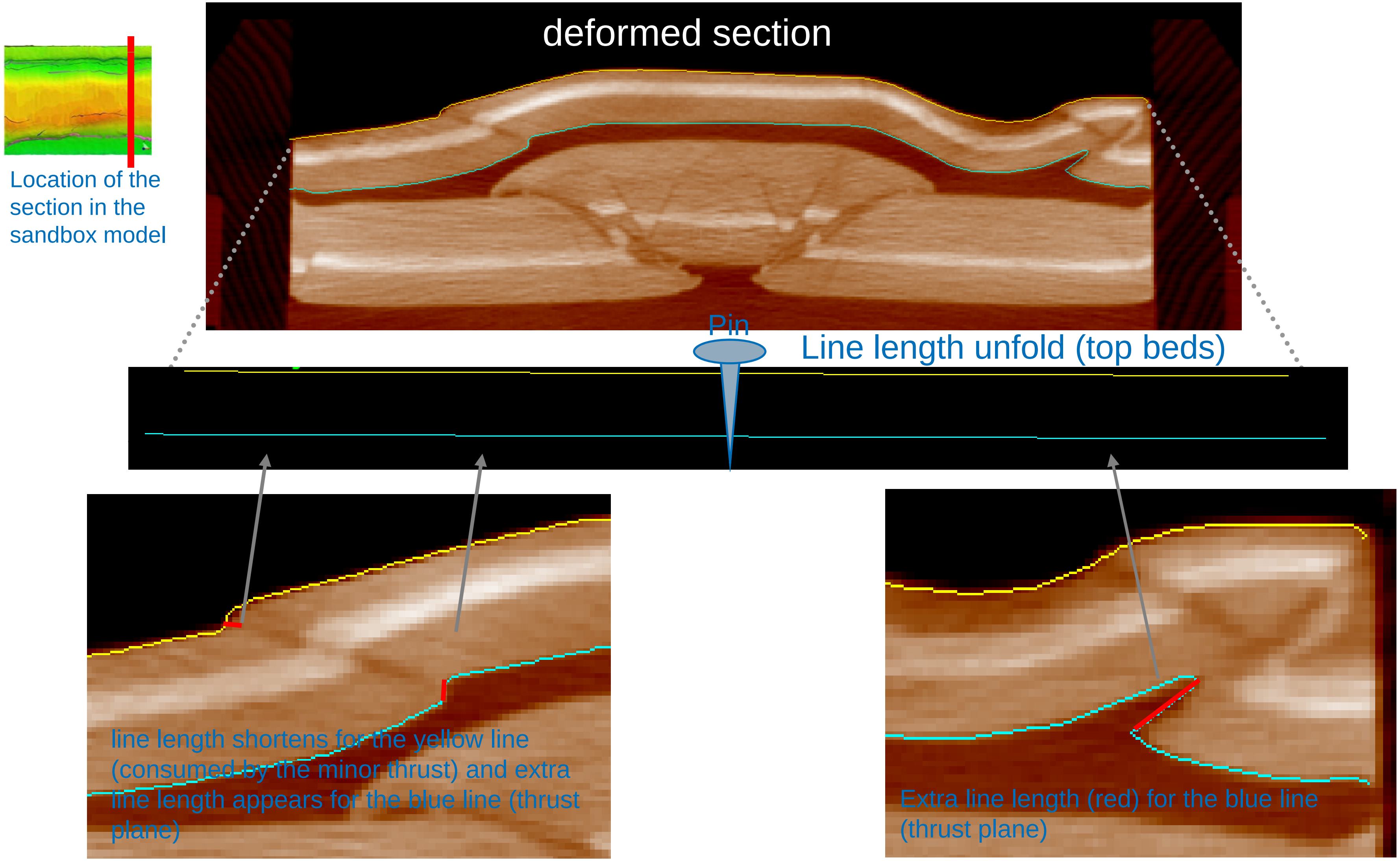
Difference between these two lines:

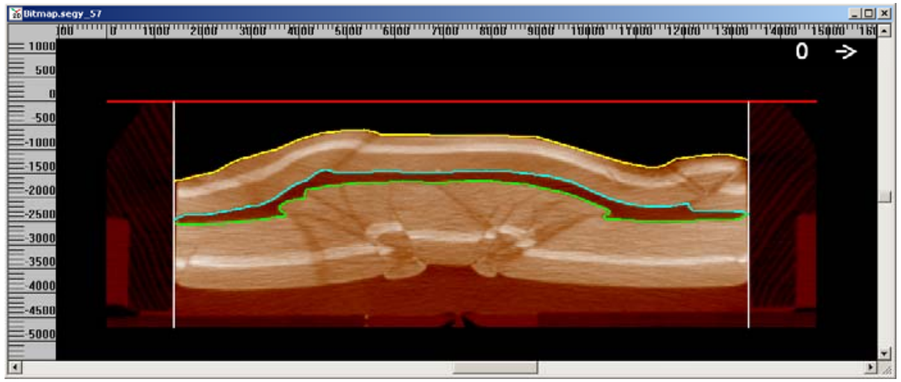




-2000
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
-2000
0
2000
4000
6000
8000
10000
12000
14000
16000
500
0
-1000
-2000
-3000
-4000
-5000
-2000
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
-2000
0
2000
4000
6000
8000
10000
12000
14000
16000
Z
N
E

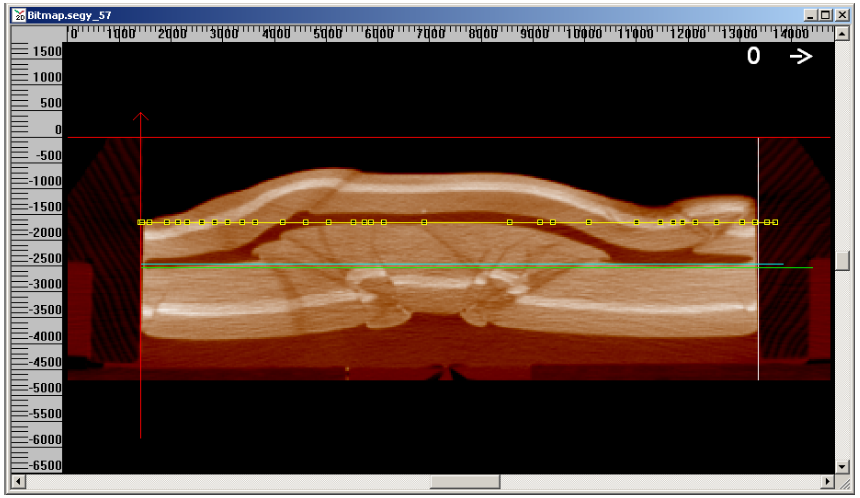
Line length unfold (top beds)

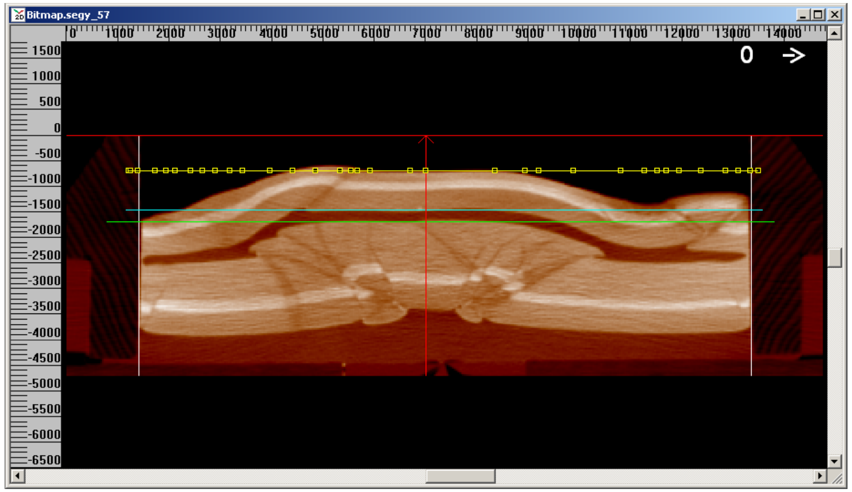


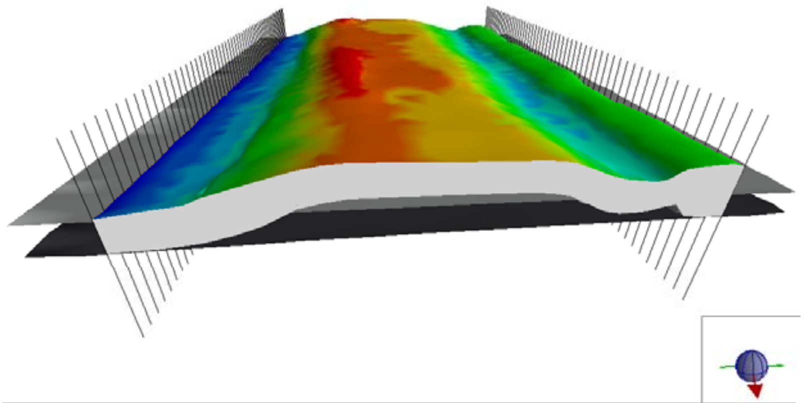


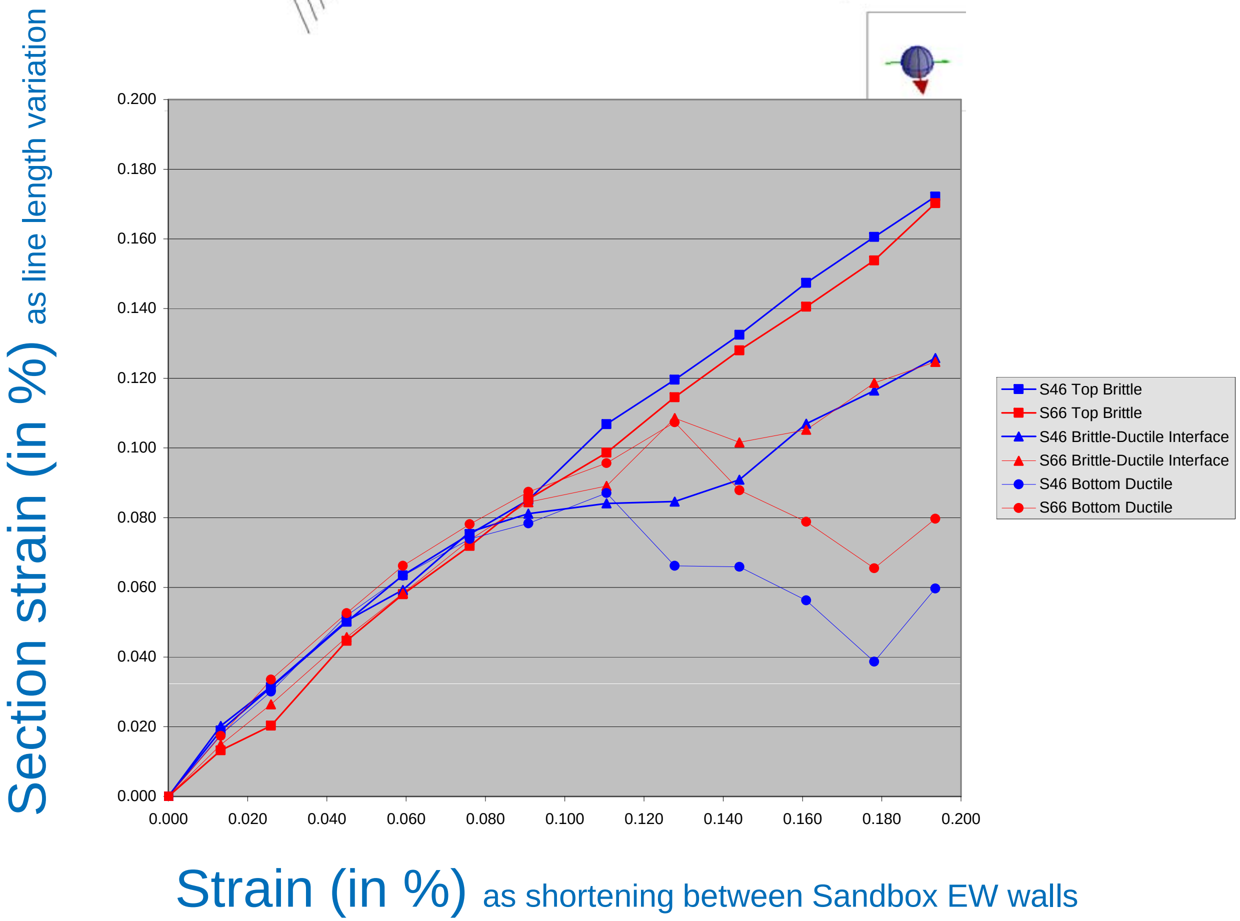
A. Pin line at southern edge

B. Pin line in the Middle of the box

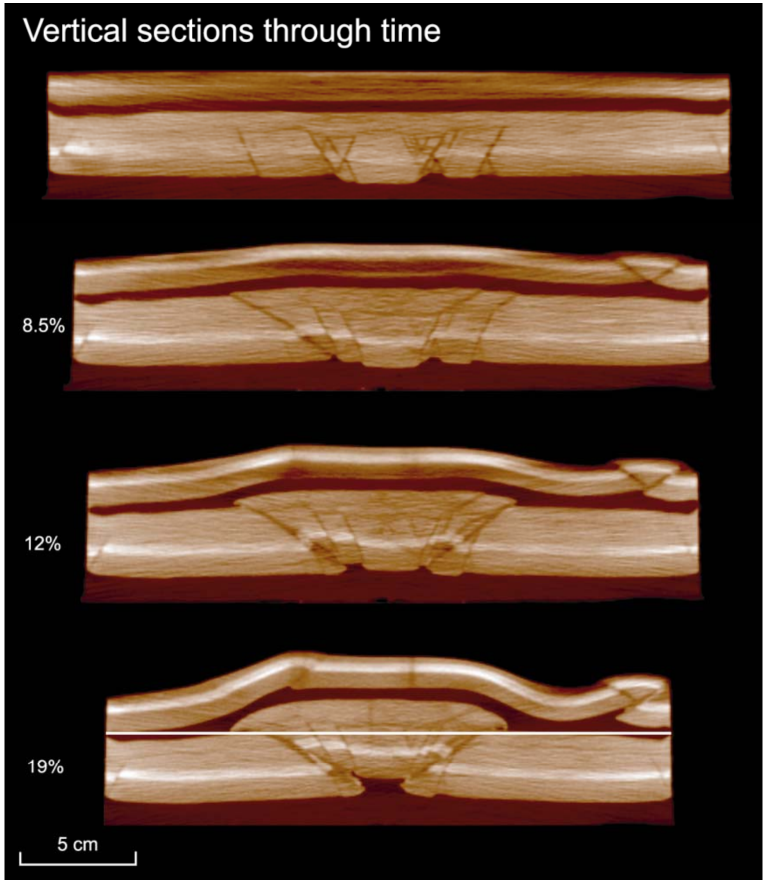


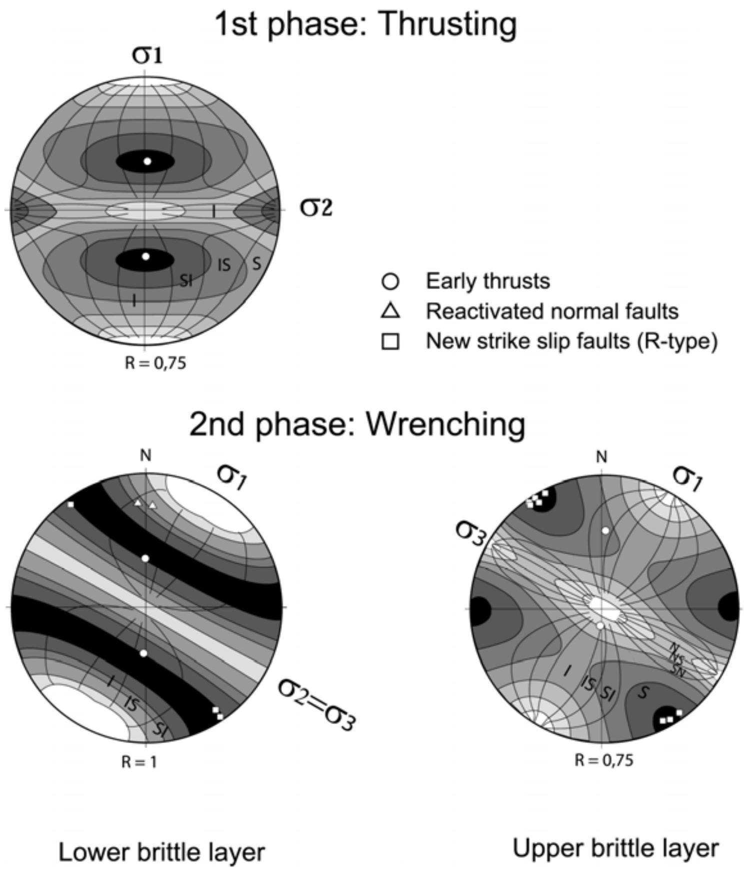


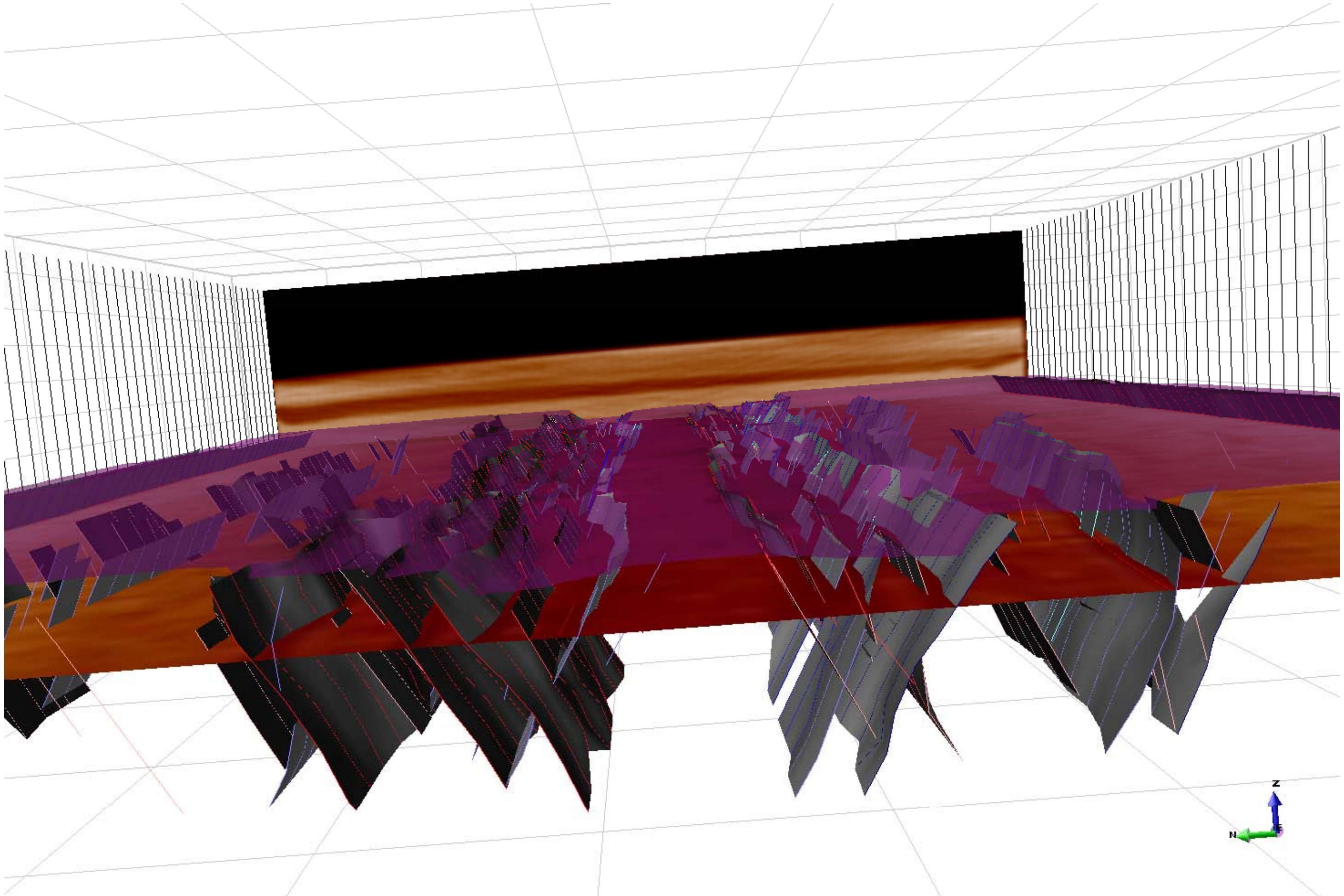



Section strain (in %) as line length variation
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
0.160
0.180
0.200
S46 Top Brittle
S66 Top Brittle
S46 Brittle-Ductile Interface
S66 Brittle-Ductile Interface
S46 Bottom Ductile
S66 Bottom Ductile
Strain (in %) as shortening between Sandbox EW walls

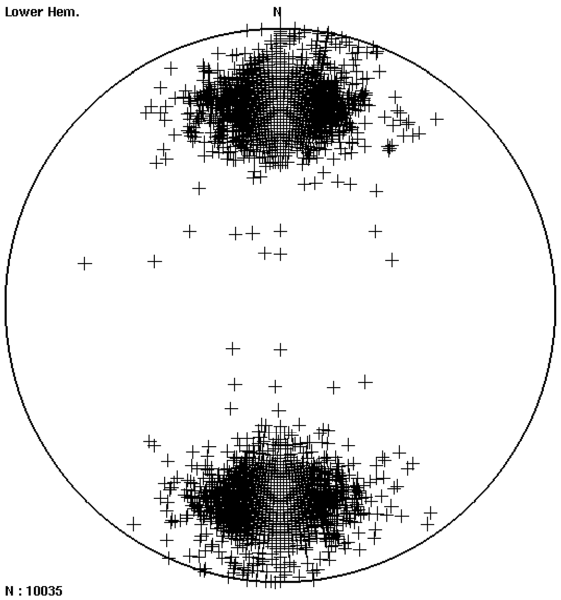
Experiment T4: Extension + Transpression (Vss=3cm/h)

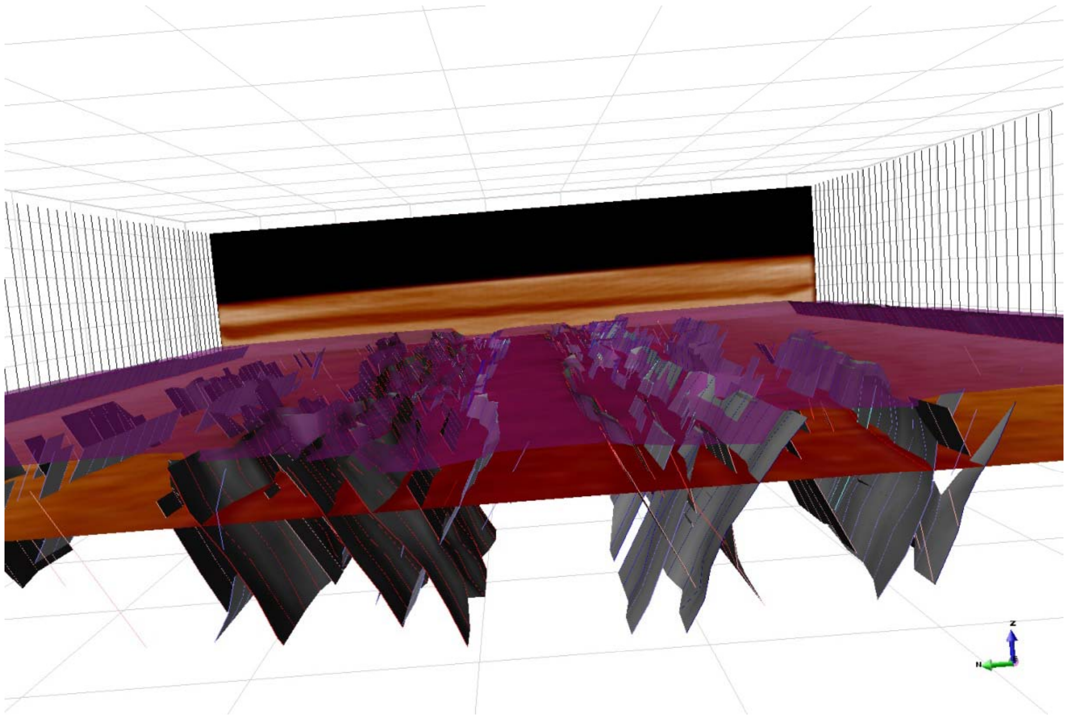





Z
N

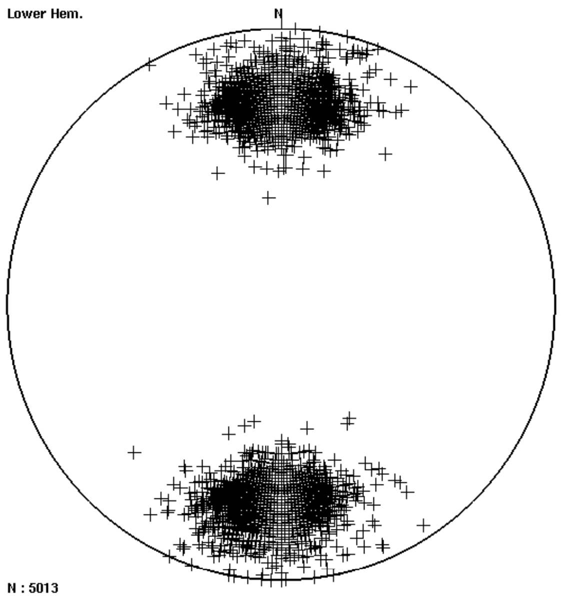
Step D2

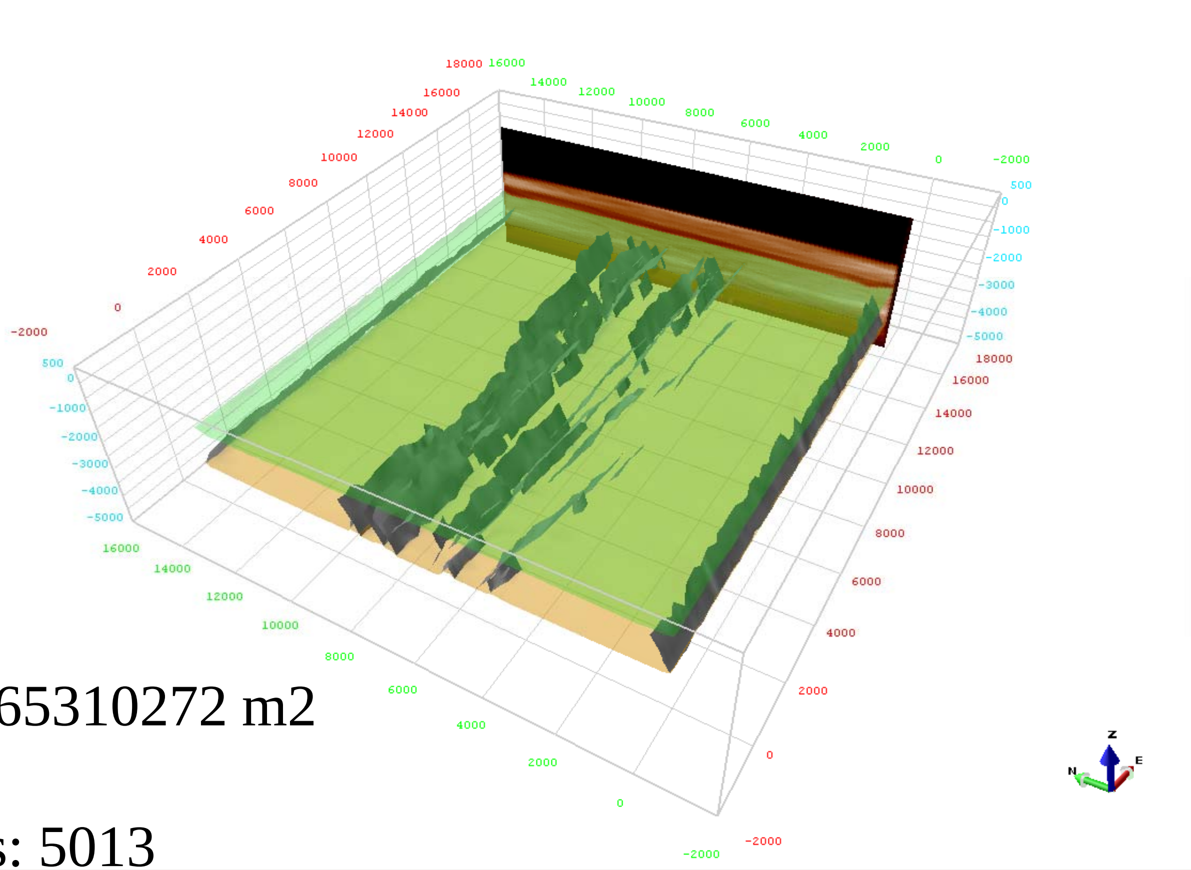




total fault surface area: 321178080 m2
number of faults: 227
number of mesh triangles: 10035

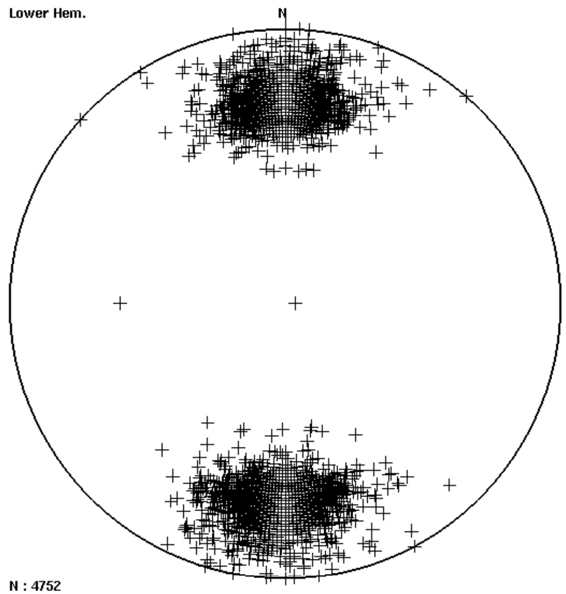
Step D4

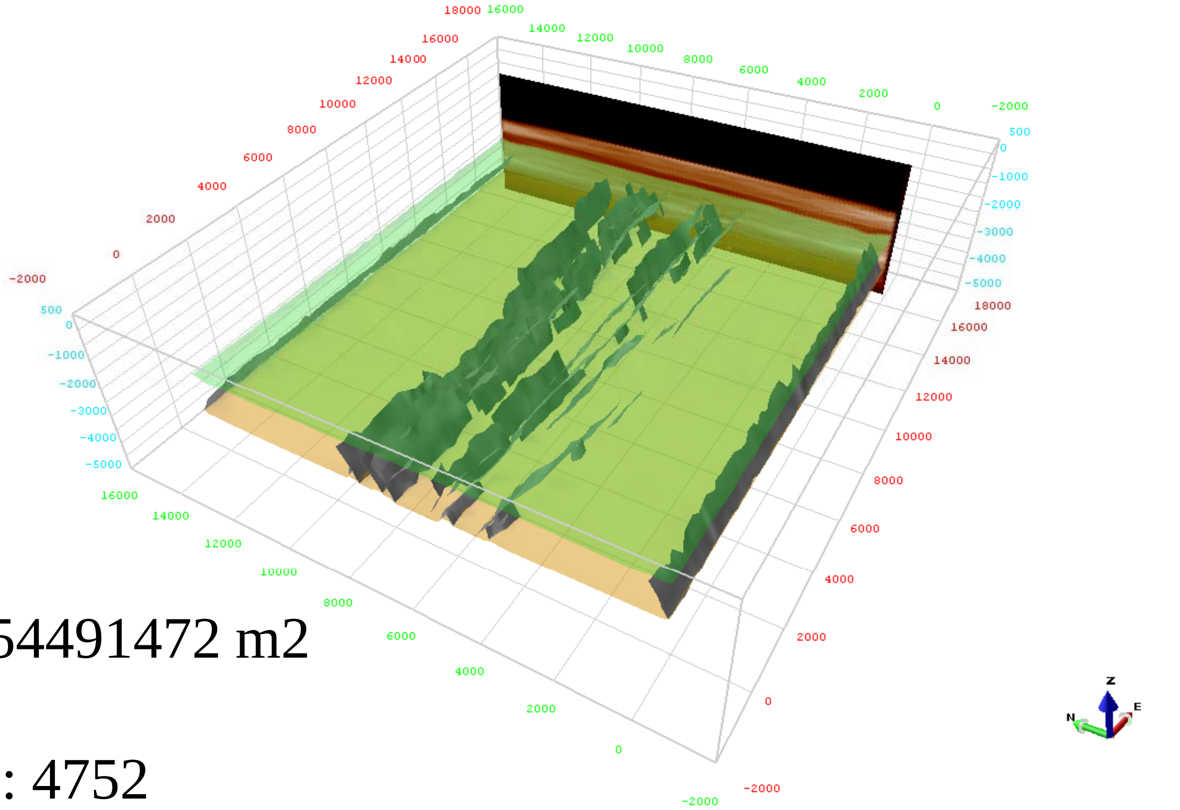




total fault surface area: 165310272 m2
number of faults: 106
number of mesh triangles: 5013

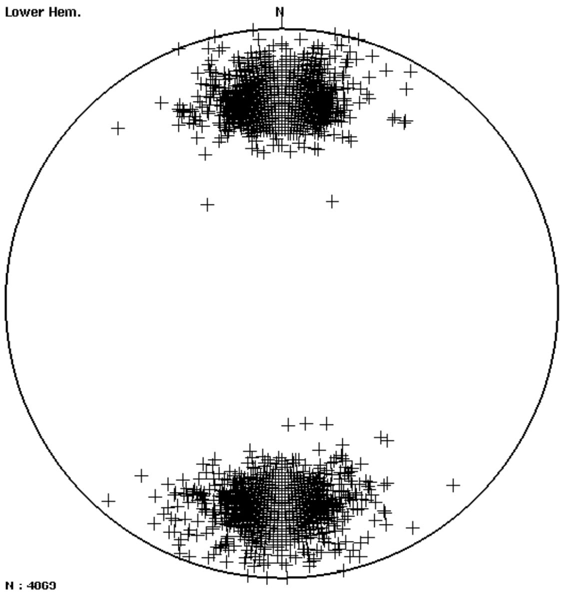
Step D5

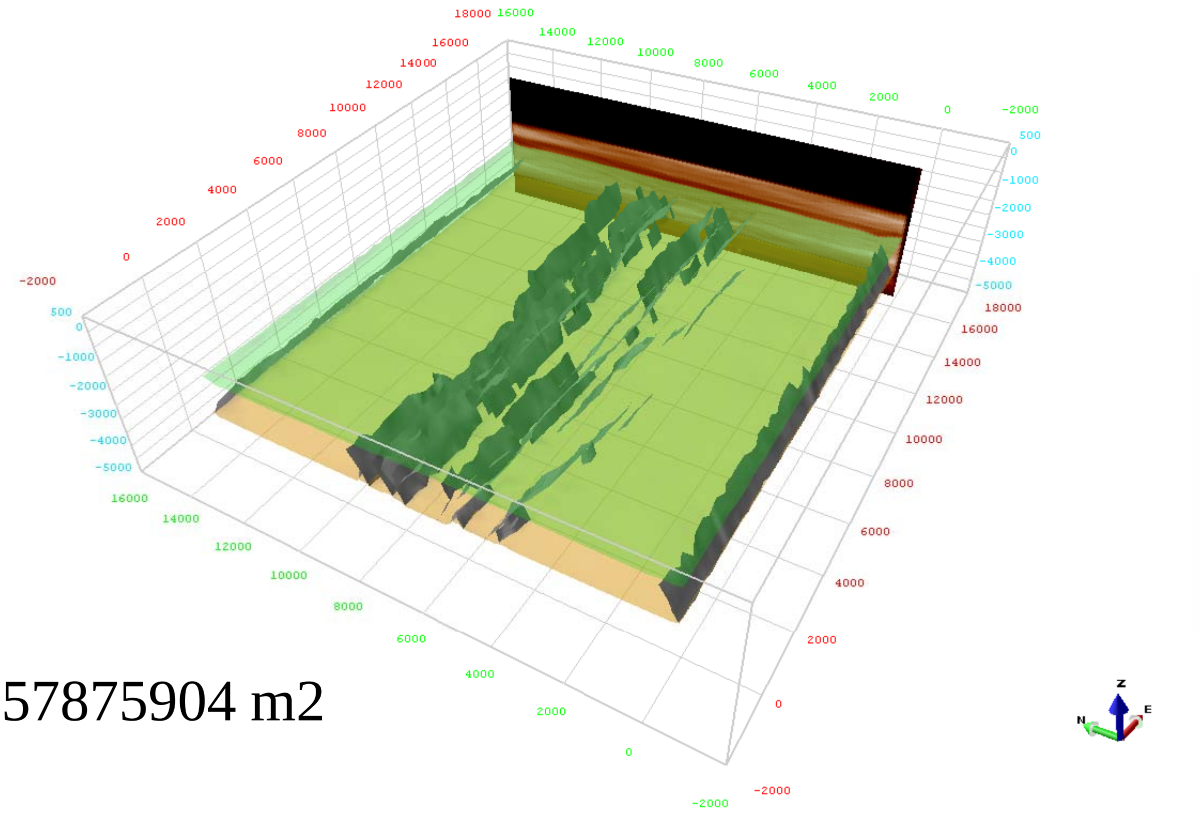




total fault surface area: 154491472 m2
number of faults: 88
number of mesh triangles: 4752

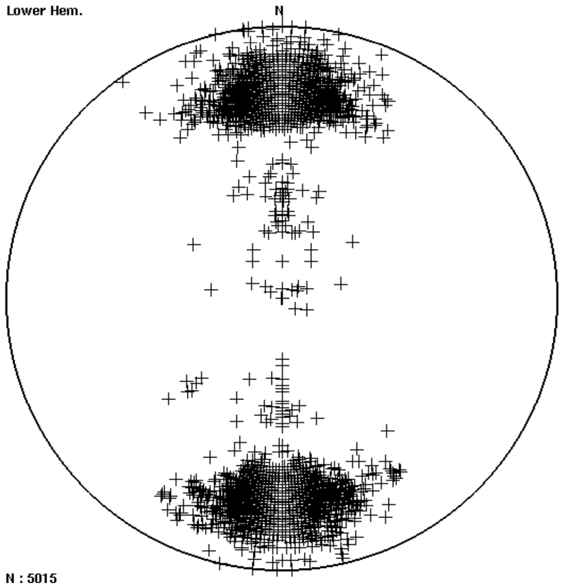
Step D6

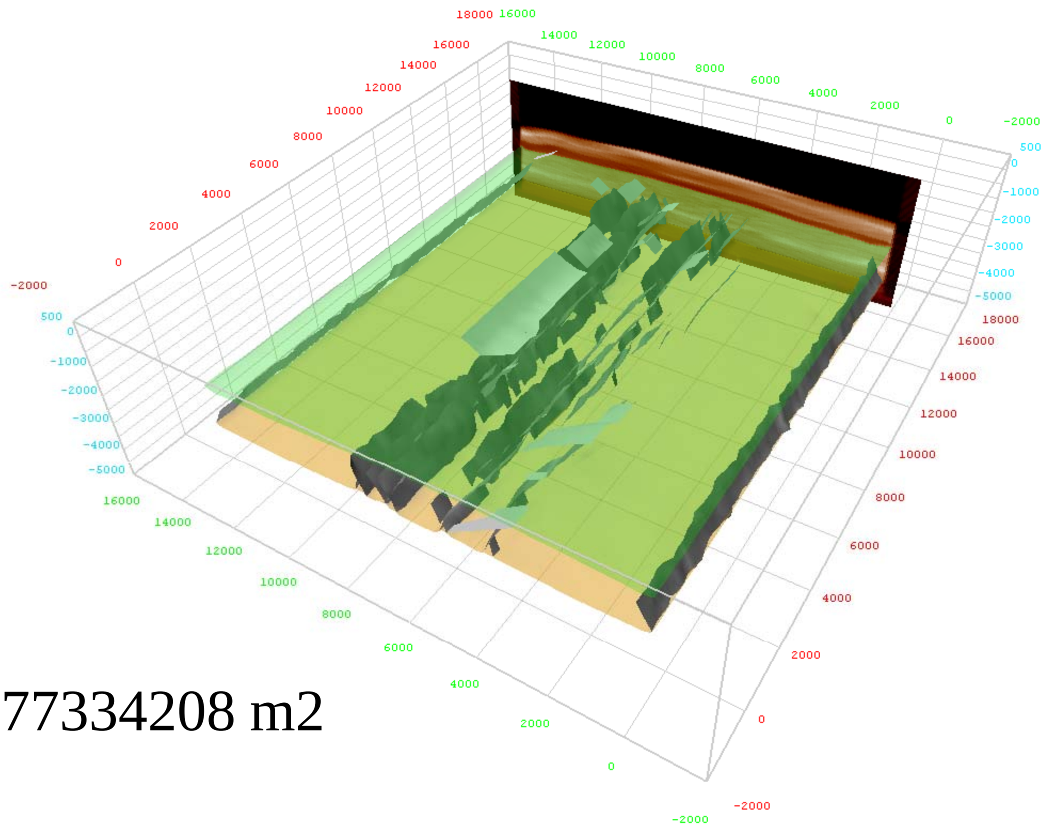




total fault surface area: 157875904 m2
number of faults: 88
number of mesh triangles: 4752

Step D7



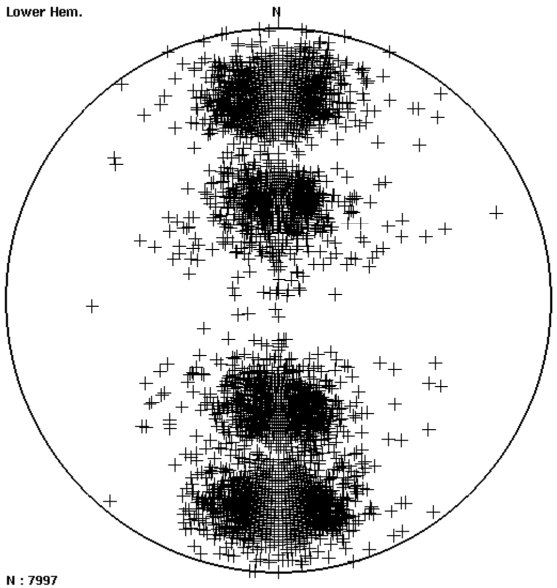


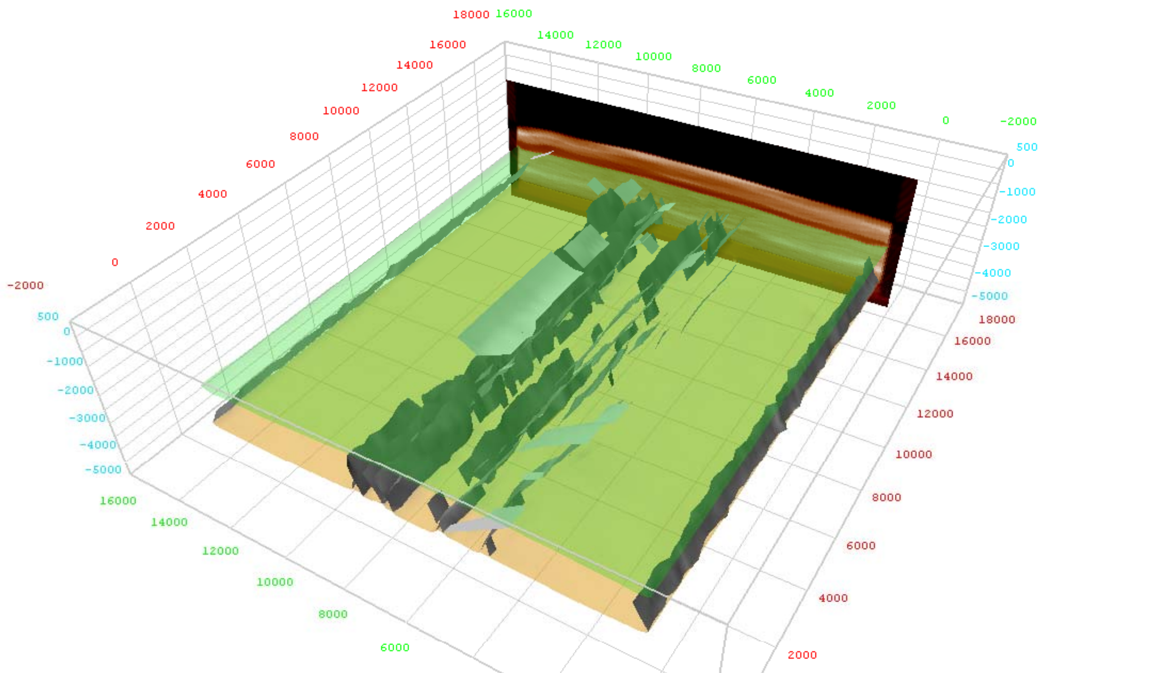
total fault surface area: 177334208 m2

number of faults: 97

number of mesh triangles: 5015

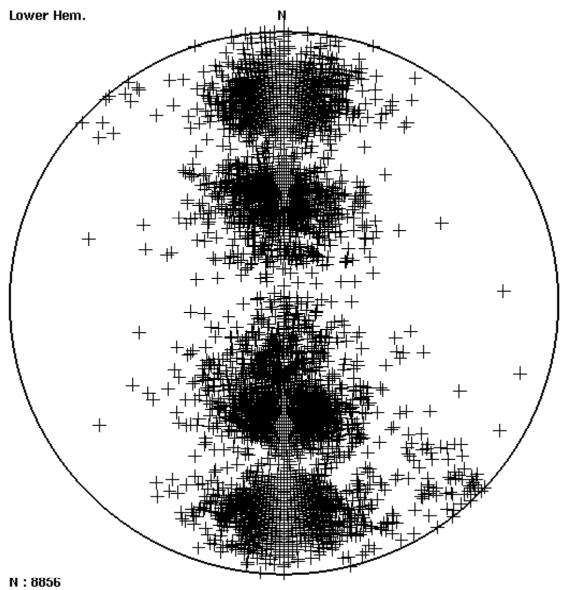
Step D8

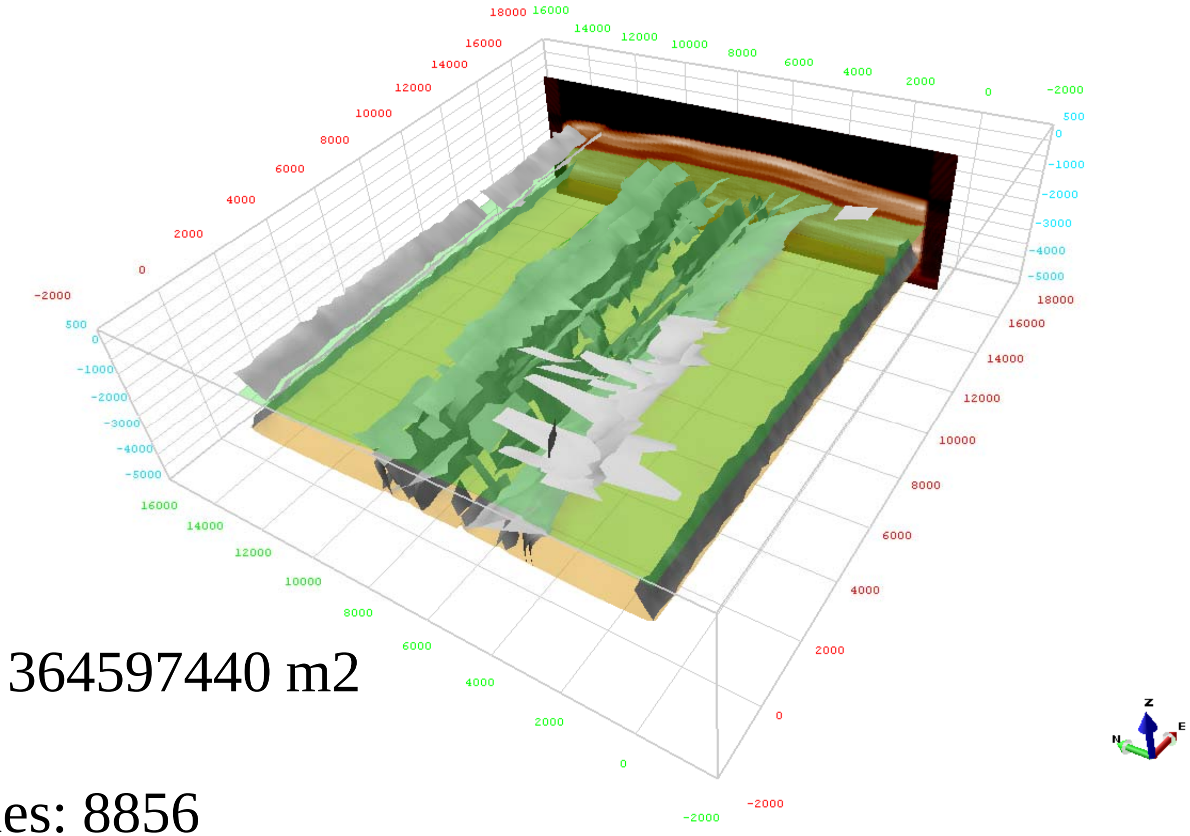




total fault surface area: 276836576 m2
number of faults: 102
number of mesh triangles: 7997

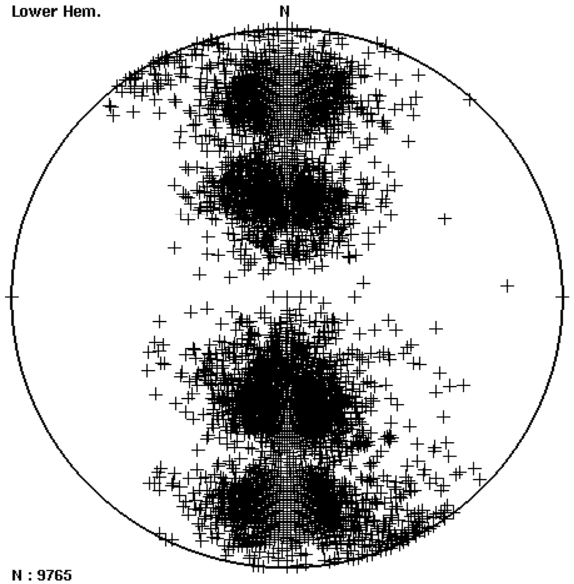
Step D9

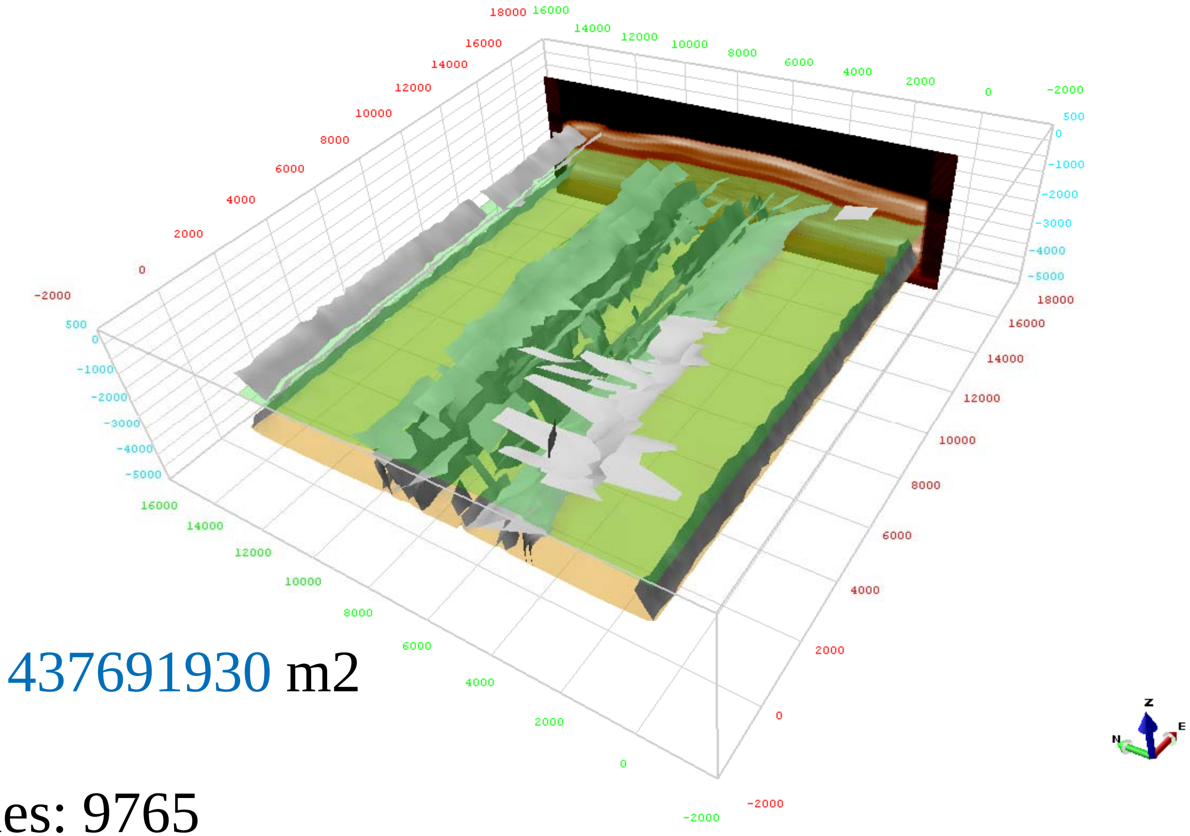




total fault surface area: 364597440 m2
number of faults: 130
number of mesh triangles: 8856

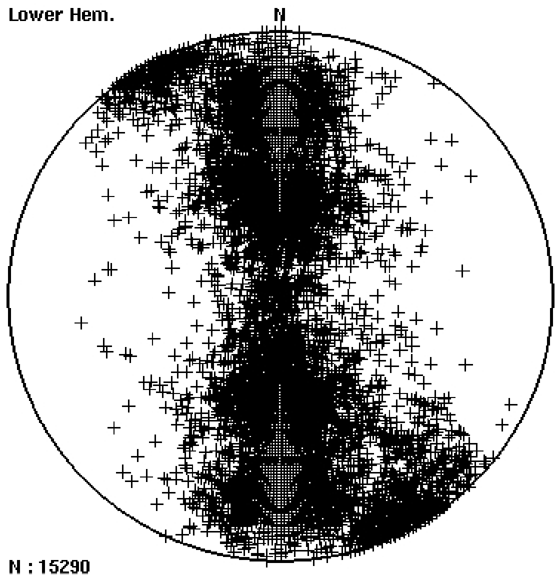
Step D10

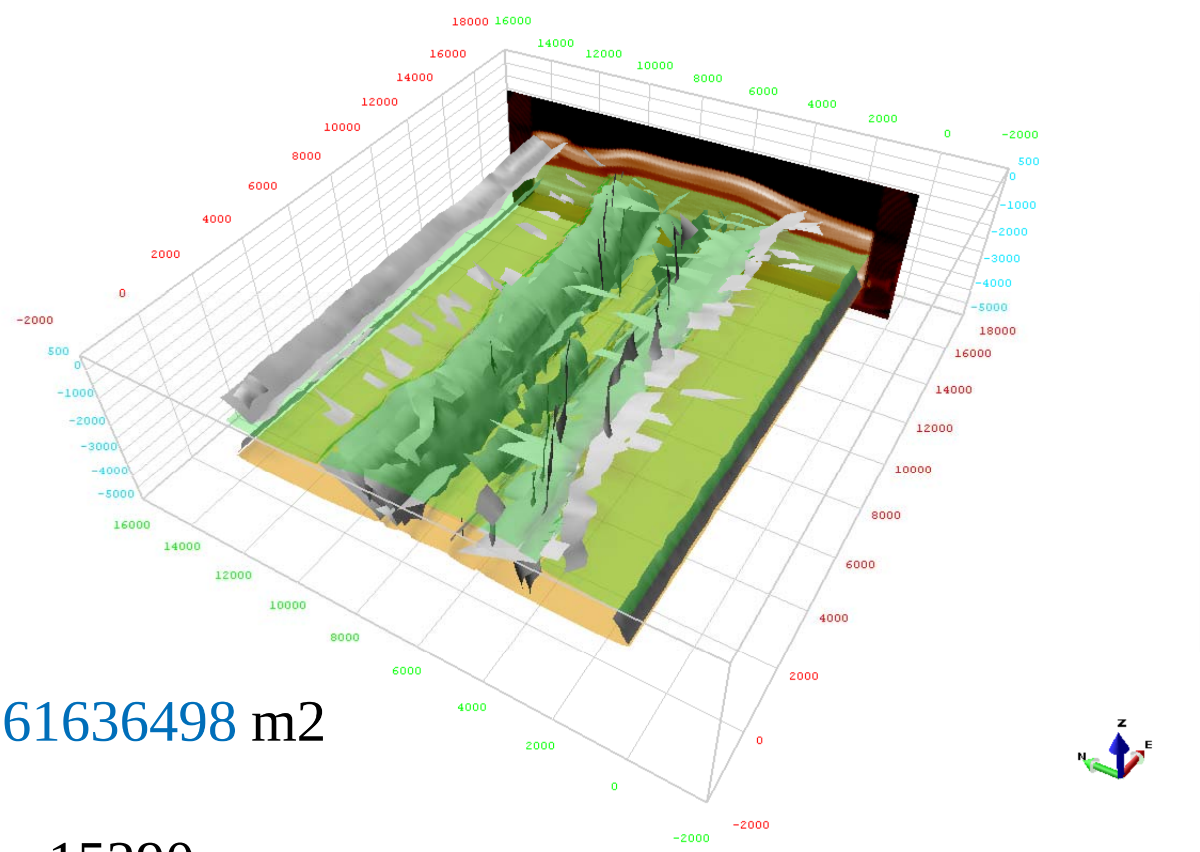




total fault surface area: 437691930 m2
number of faults: 143
number of mesh triangles: 9765

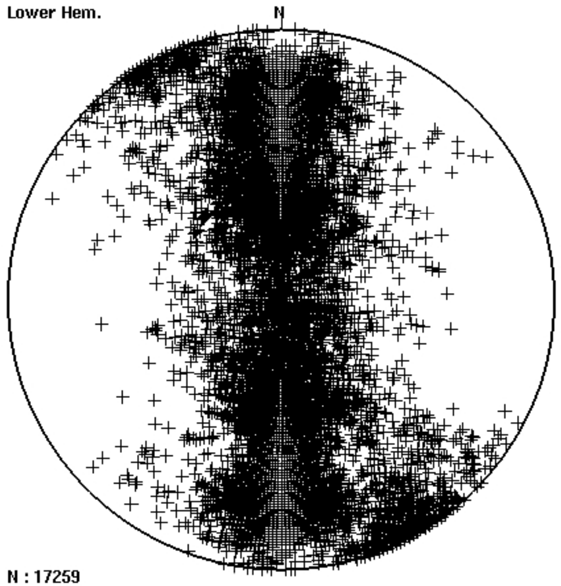
Step D11

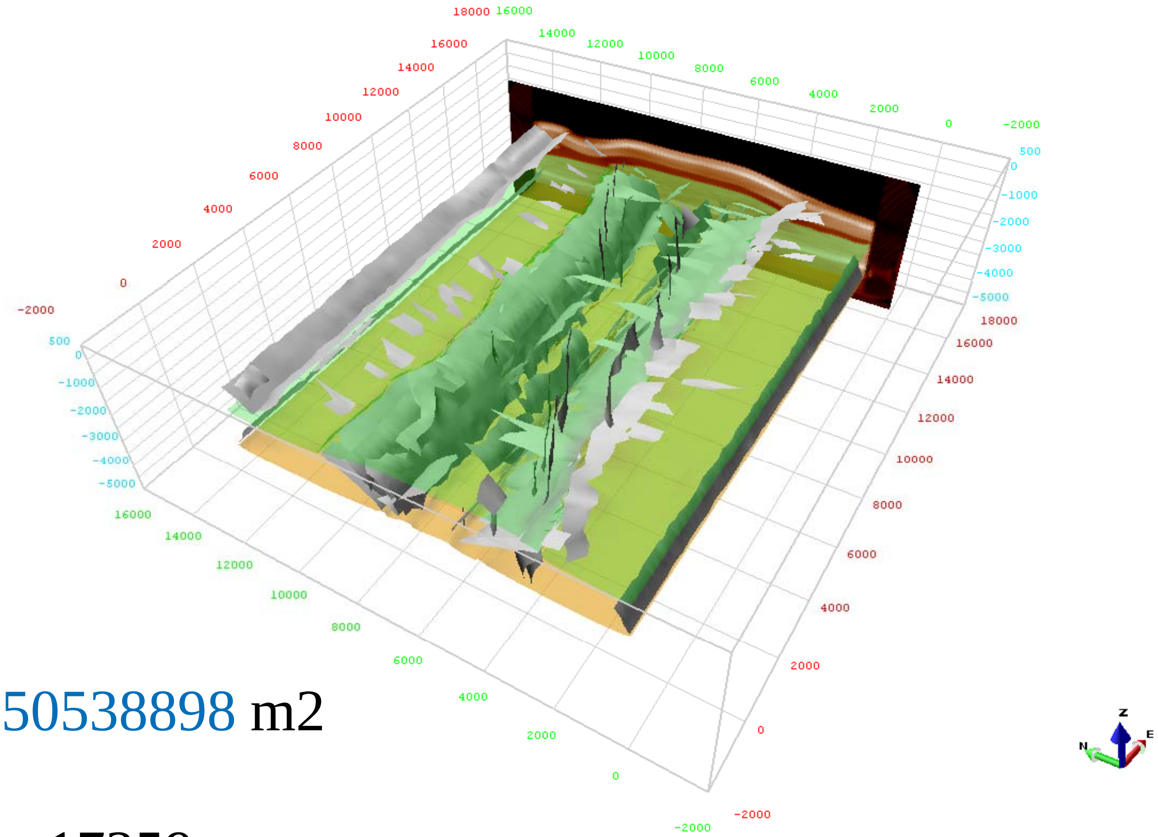




total fault surface area: 361636498 m2
number of faults: 143
number of mesh triangles: 15290

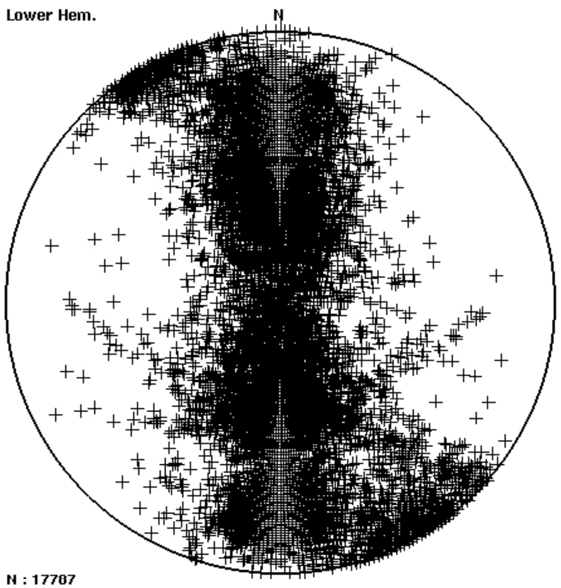
Step D12

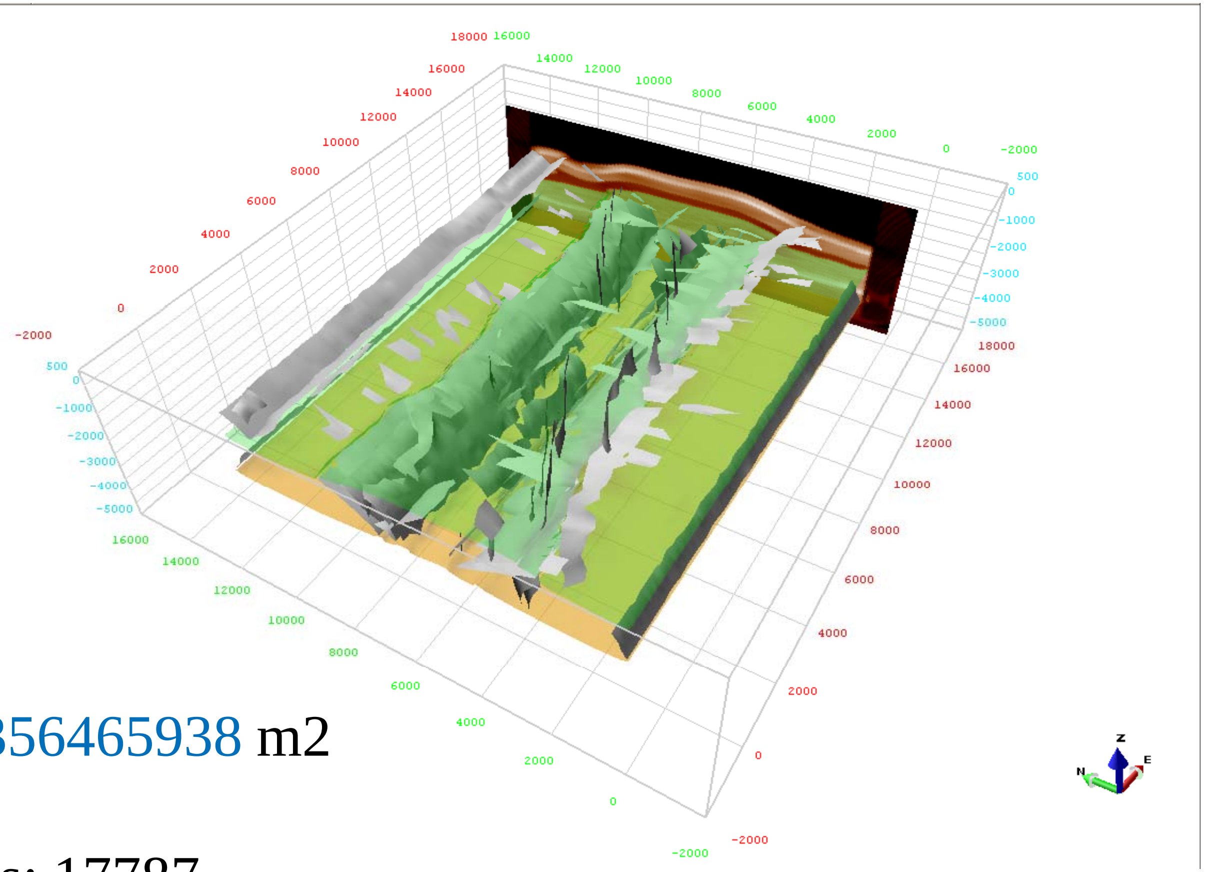




total fault surface area: 350538898 m2
number of faults: 151
number of mesh triangles: 17259

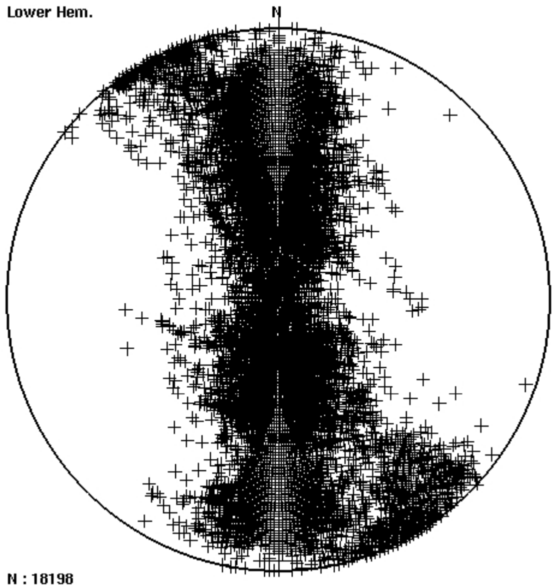
Step D13

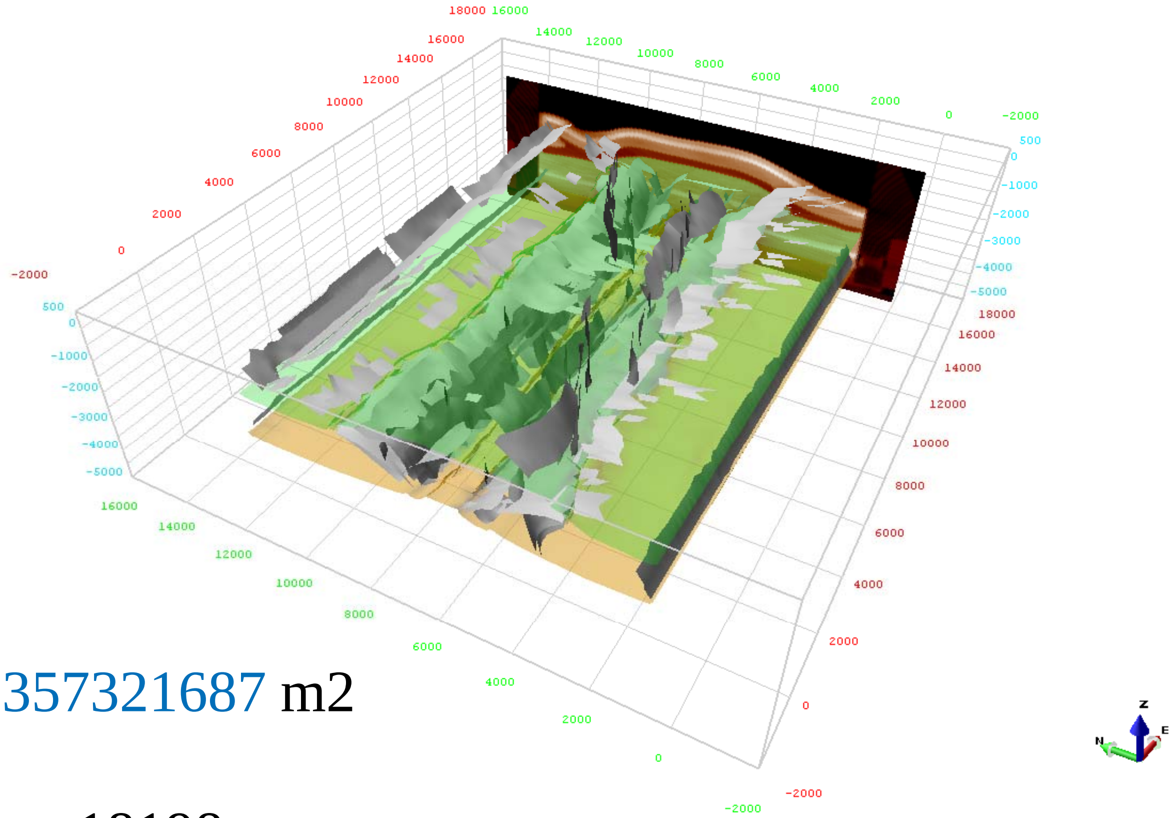




total fault surface area: 356465938 m2
number of faults: 162
number of mesh triangles: 17787

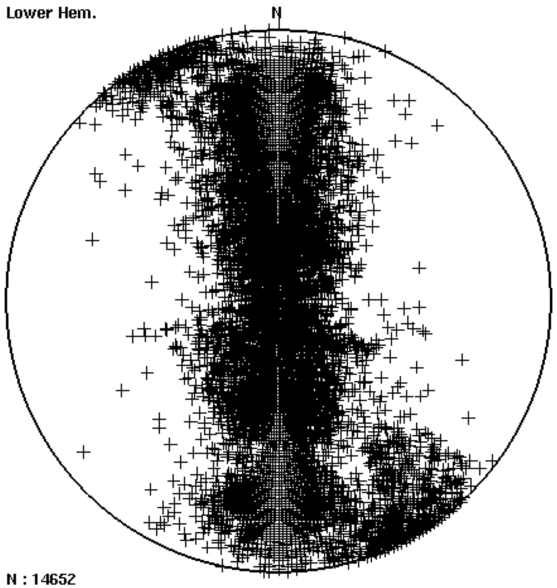
Step D14

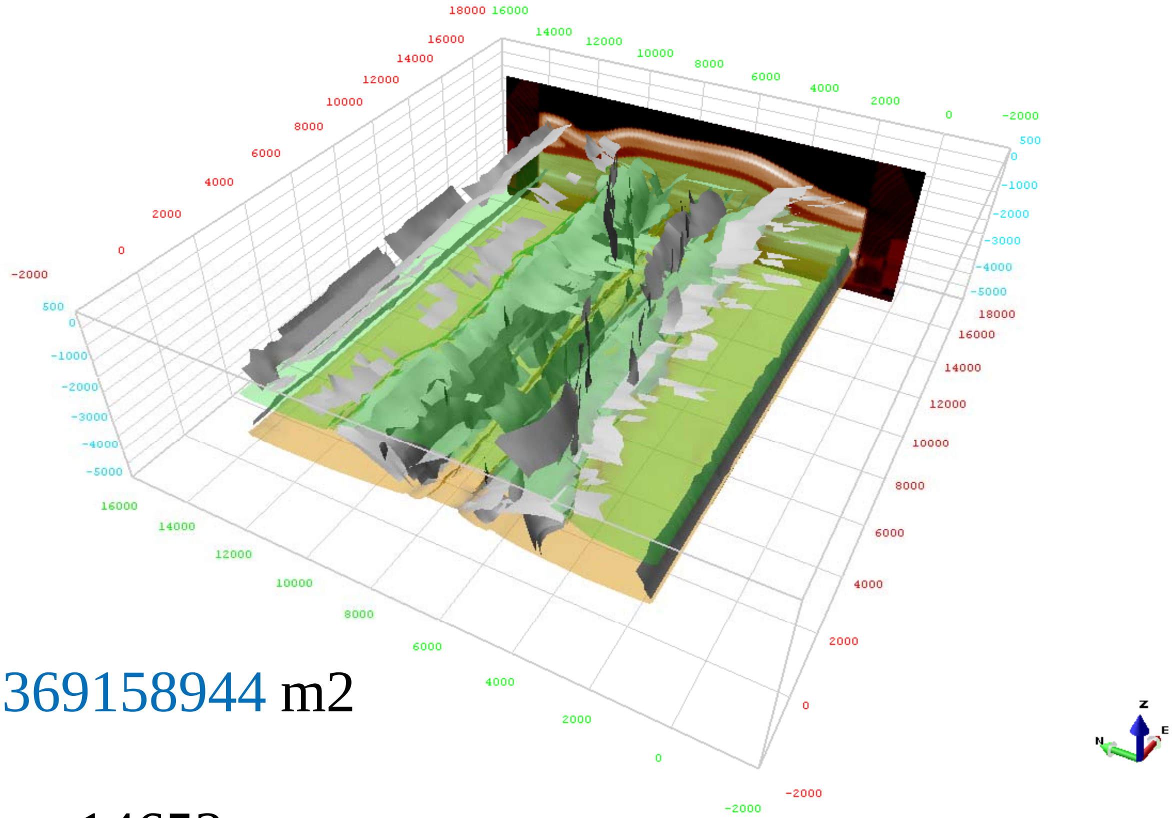




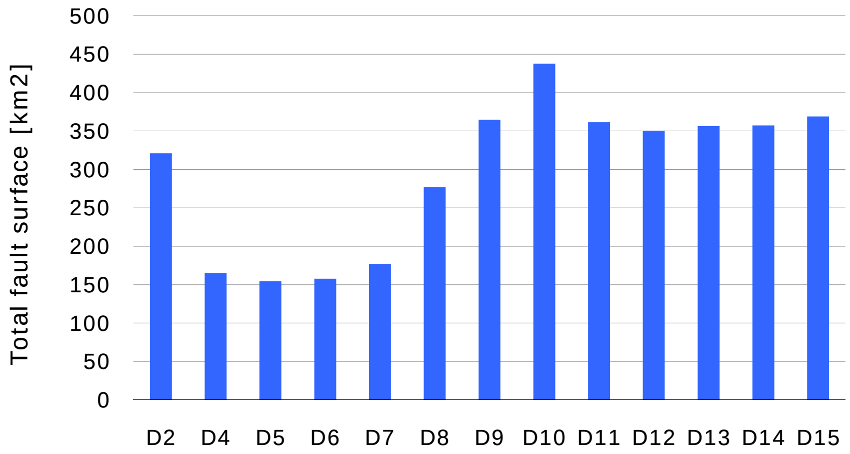
total fault surface area: 357321687 m2
number of faults: 210
number of mesh triangles: 18198

Step D15

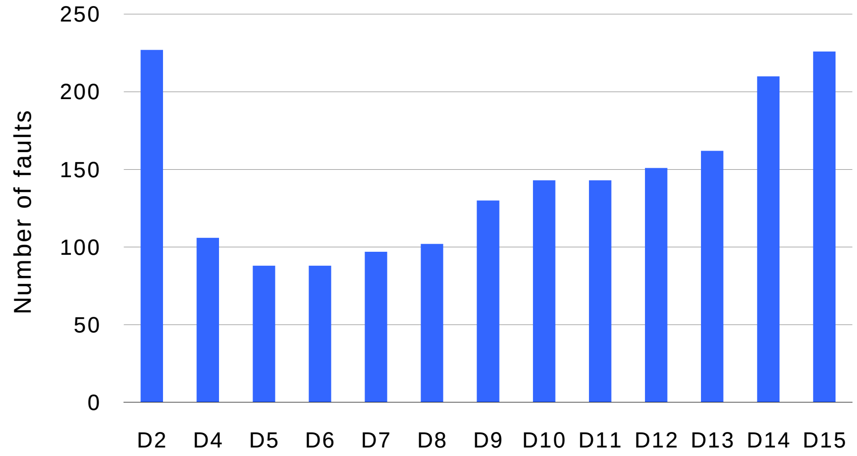




total fault surface area: 369158944 m2
number of faults: 226
number of mesh triangles: 14652



Area of faults [km2] in each time step



Number of faults in each time step

Conclusion

- 4Dsandbox experiments provide a tool for training purposes to highlight key concepts and deformation patterns of structural geology

- Digitization of 4Dsanbox examples brings an essential data base to quantify fault pattern and structural evolution

- The approach is a platform for the design and development of structural geology interpretation software

Main goals for structural interpretation

- **Ensure Structural Consistency**
  - Good Present Day Structure Geometry
  - Appraise all alternative scenarios of structural and sedimentological evolution
- **Produce a Forward Model**
  - Resetting original thickness & eroded volumes
  - Palinspastic maps
  - Geometry to Basin and Reservoir Models
  - Burial history curves

Perspectives

- **BM: Coupling of structural and stratigraphic modelling**
- **BM: integration of diagenesis & mineral kinetics**
- **Software dependent: simplify workflows**
- **Combine field work & physical and numerical experiments**