Elastic Dislocation Modelling of Fractures in the Carboniferous Limestone: East Midlands, UK*

Peter Boult[1], Brett Freeman[2], and Graham Yielding[2]

Search and Discovery Article #10225 (2010)
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*Adapted from oral presentation at AAPG Convention, Denver, Colorado, June 7-10, 2009. Please refer to closely related poster by Peter Boult, Brett Freeman, and Graham Yielding, 2009, Fractured Carboniferous Limestone Sealed by a Volcanic Ash - A New Play in the East Midlands UK, Search and Discovery article #10212

[1]Low New Biggin Oil Ltd, London, United Kingdom (Boultbis@westnet.com.au)
[2]Badley Geoscience, Spilsby, United Kingdom

Abstract

The Strelley-1 well encountered a minimum 27 m of hydrocarbon column in fractured Dinantian Limestone in the East Midlands, UK. Fault population statistics and a first-pass elastic dislocation forward model of the limestone reservoir in the Strelley up-dip structure has been created. These indicate that the optimum trajectory of a planned appraisal/ development well to intersect tensional fracture should penetrate the reservoir near the top of the structure and then track sub-horizontally down the flank of the structure in a southeasterly direction towards the discovery well.

Seismic interpretation of 2D lines along sometimes very winding English country roads was aided by using a sophisticated seismic interpretation package that displays seismic panels in true perspective from any view point. The seismic image is often poor, but the use of fault statistics and mapping of wall-rock shear and longitudinal strains helped constrain the 3D structural model. The top reservoir horizon in this 3D model was then forward modelled for displacement on fault surfaces within the up-dip Strelley structure. Using elastic dislocation theory, prediction of fracture type and orientation were then modelled by assuming that fracturing within the limestone was predominantly caused by Variscan rifting/extension. This model predicts that high palaeo-shear stresses and resulting shear plane failure are limited to within 400 m of the footwalls of the main bounding faults of the structure. Minor faults nearby to the well have very little influence over fracture type and orientations. Low paleo-shear stresses and associated tensile fractures occur in an orthogonal orientation to a projected sub-horizontal trajectory of a well, planned over a 2 km interval, between the crest of the structure and the original well intersection of the reservoir.

A further 50 km of 2D seismic over the structure is planned for 2009 and a well in 2010.

References

Swann, G. and Munns, J., 2003, The hydrocarbon prospectivity of Britain's onshore basins, DTI.

Wright, T.J., 2002, Remote monitoring of the earthquake cycle using satellite radar interferometry: Phil. Trans. R. Soc. Land, v. A/360, p. 2873-2888.

Elastic dislocation modelling of fractures in the Carboniferous Limestone: East Midlands, UK.

Pete. Boult (LNBO, UK, Ginkgo ENPGNG OZ)
Brett Freeman, Graham Yielding (Badleys, UK)

Linked to Poster - Fractured Carboniferous Limestone Sealed by a Volcanic Ash! A New Play in the East Midlands UK - *Theme V: Fault Segmentation and Linkage - Impacts on Exploration and Development, June 8, 2009 from 1:15 PM to 5:00 PM*

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Conclusions

- Elastic dislocation forward modelling of strain and stress associated with accumulated slip on large faults provides an insight into the prediction of fractures in the Dinantian Limestone UK – compliments stochastic modelling

- The Strelley structure in the East Midlands
  - Is sealed by ductile volcanic ash
  - Has an estimated 180 m of closure
  - Has a highly fractured limestone reservoir
  - Is capable of producing at 2000+ barrels per day – *from a vertical well*

- Drilling a horizontal well, which encounters open fractures and maximum permeability in the Dinantian Limestone, requires the prediction of
  - Palaeo-fractures (TT FaultED)
  - Open fractures (TT StressTester)

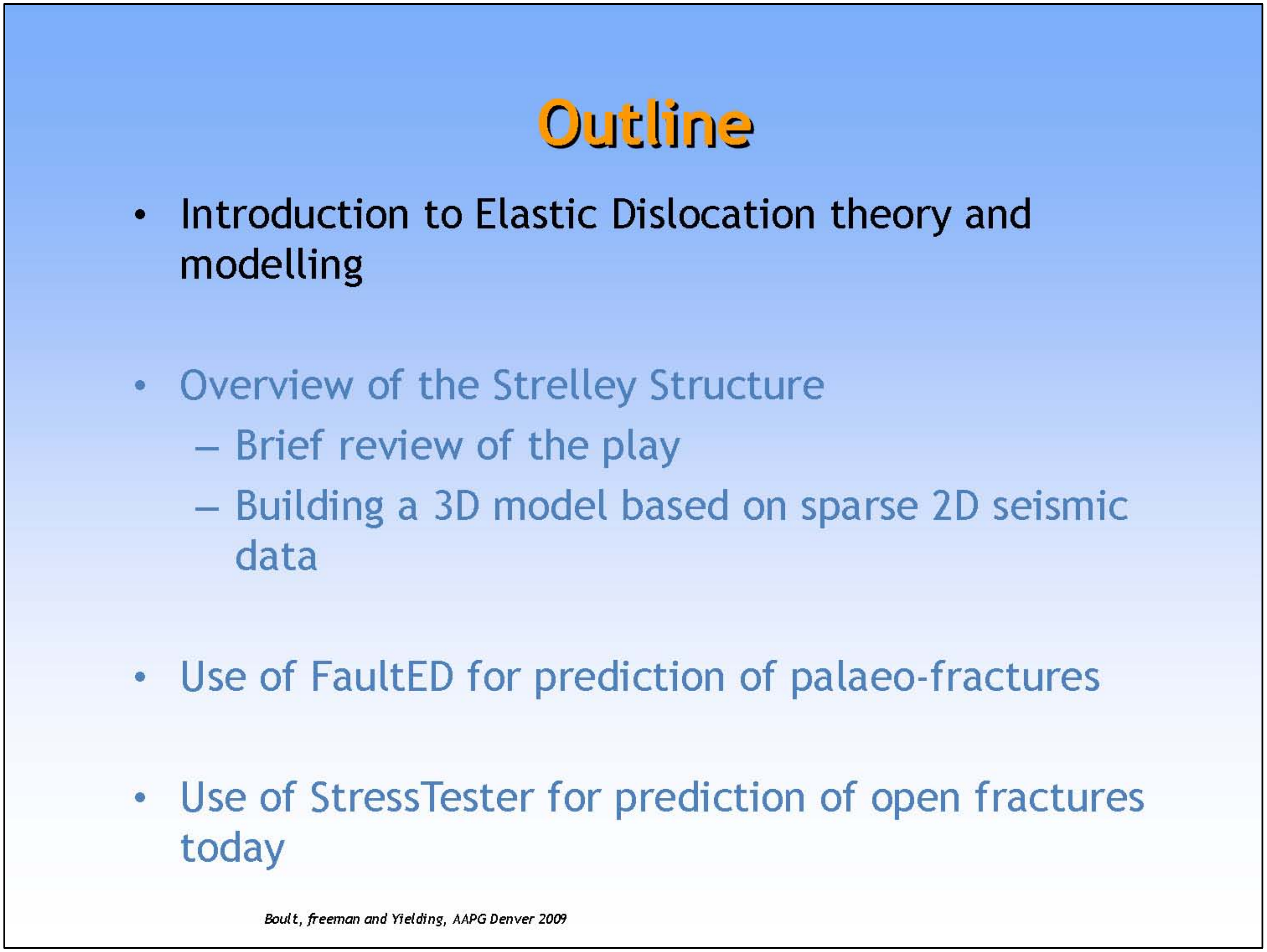
Outline

- Introduction to Elastic Dislocation theory and modelling

- Overview of the Strelley Structure
  – Brief review of the play
  – Building a 3D model based on sparse 2D seismic data

- Use of FaultED for prediction of palaeo-fractures

- Use of StressTester for prediction of open fractures today



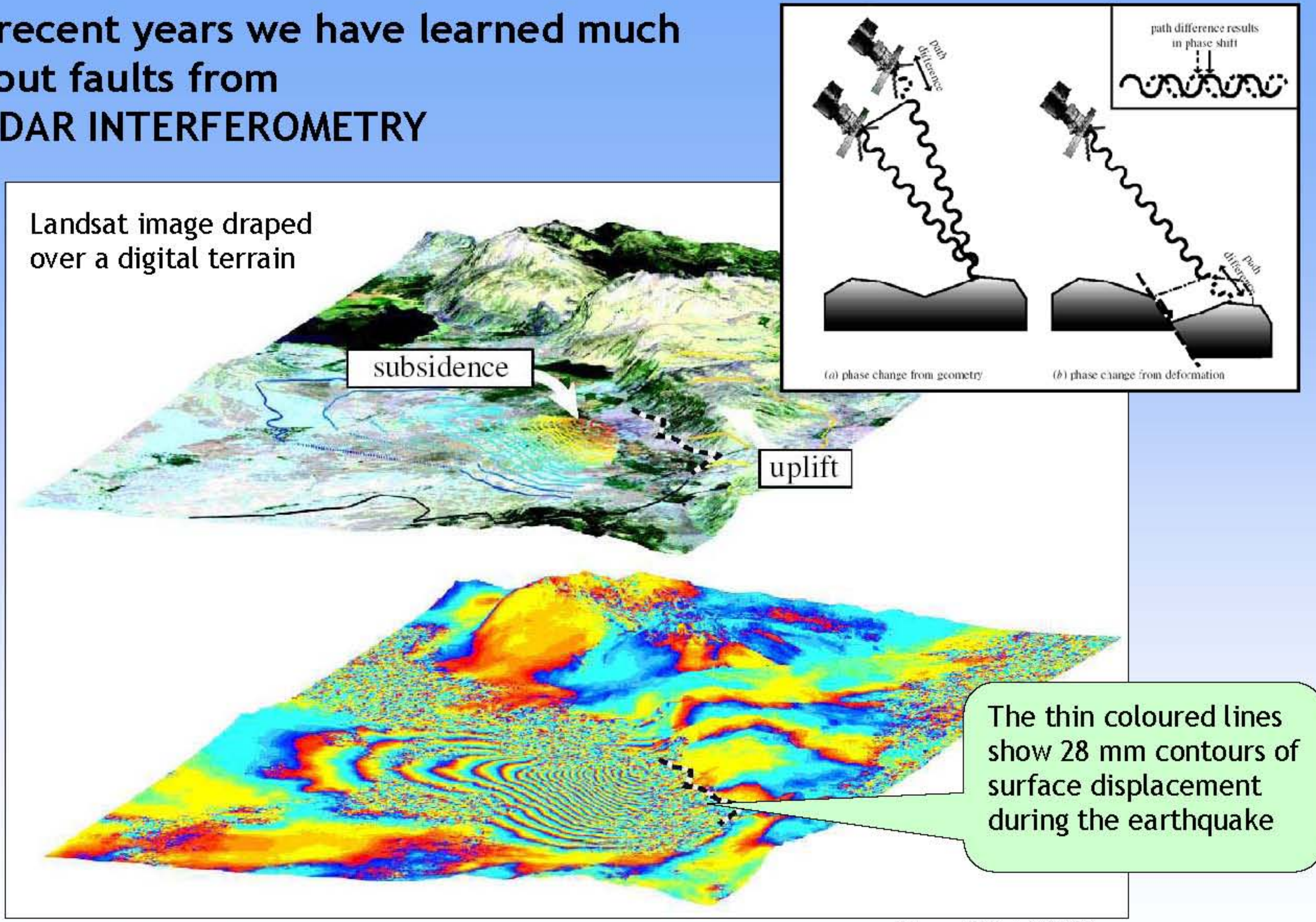
Notes by presenter:

The effects of fractures on fluid flow are only now beginning to be properly included into cellular reservoir models and reservoir simulators. However, evaluating the impact of faults and fractures on fluid flow is hampered by the difficulty of adequately defining the entire fault and fracture network e.g. their spatial distribution, orientation and type or mode of fracturing.

The application of fractal-based methods, enables the extraction of fault and fracture population information from seismic and well data, but does not easily define the spatial aspects of faults and fractures throughout the reservoir. The slip distributions on faults that are likely to have exerted a significant control are not considered in fractal based methods and rock mechanics is ignored in the need to generate a fully populated sub-seismic fault model.

Recent advances in the application of Elastic Dislocation (ED) theory to the modelling of faulted geological structures have led to the development of a novel method for the prediction and mapping of fracture permeability thus delineating areas of enhanced reservoir productivity. ED theory, widely used by seismologists and geologists to predict surface deformation following earthquakes (Okada 1992, Stein et al. 1988), has been extended recently to analyse sets of faults mapped on seismic reflection profiles in order to predict sub-seismic faults (Maerten et al., 2001; Bourne & Willemse, 2001; Bourne et al. 2001).

In recent years we have learned much about faults from RADAR INTERFEROMETRY



Dinar fault - SW Turkey.

From Wright 2002

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Notes by presenter: The 1995 earthquake ruptured a 10 km section of the Dinar fault, marked by the black and white line.

What have we learned

1/. Many active faults slip by repeated earthquakes.

2/. Deformation during the slip event can be accurately modelled by elastic dislocation theory.

3/. The accumulated deformation over many seismic cycles represents multiple ‘elastic’ slip events, plus inter-seismic relaxation processes.

4/. Most subsidiary faulting/fracturing is probably generated during the slip event rather than during the inter-seismic relaxation.

What is the significance of these lessons

Modelling the strain and stress changes associated with accumulated slip on large faults **may** provide a first-order prediction of the distribution and style of minor faults and fractures that are too small to map in the sub-surface.

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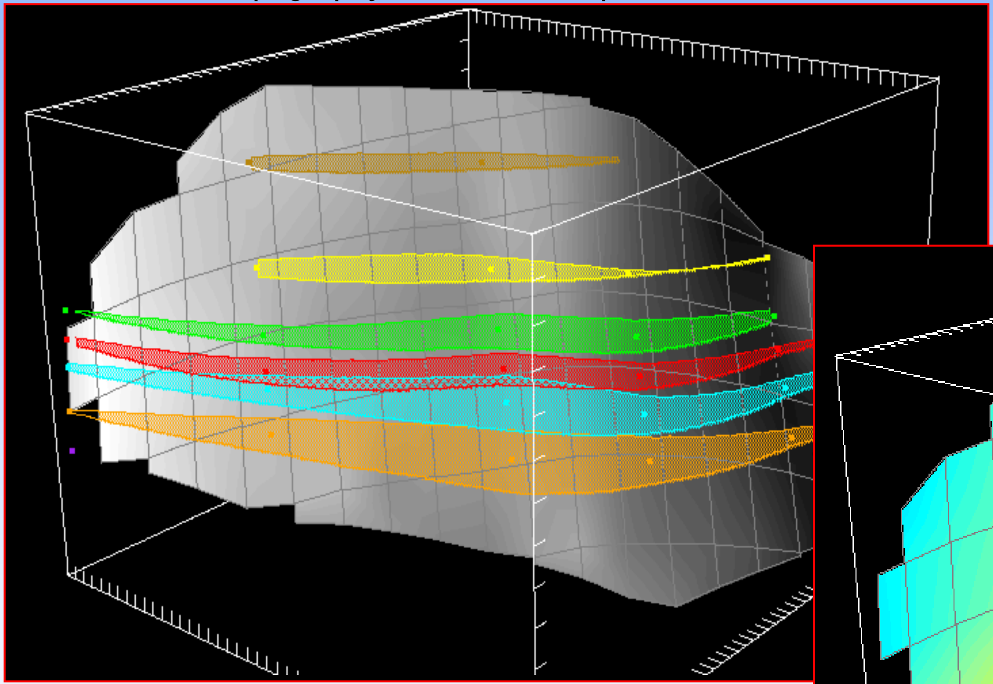
Notes by presenter: This would have major benefit in the characterisation of fractured hydrocarbon reservoirs.

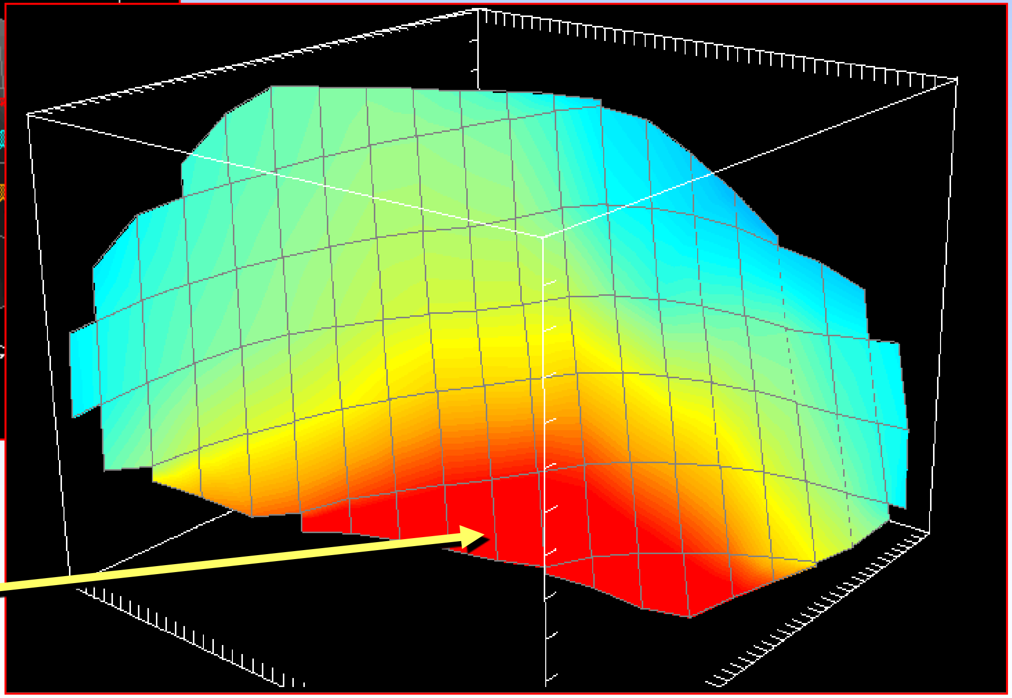
Introduction to Elastic Dislocation methodology

Fault surface topography and horizon separations



Horizon polygons enable accumulated slip to mapped onto a fault surface

Contoured throw on a fault surface - *fault continues below the deepest interpreted horizon*



High displacement

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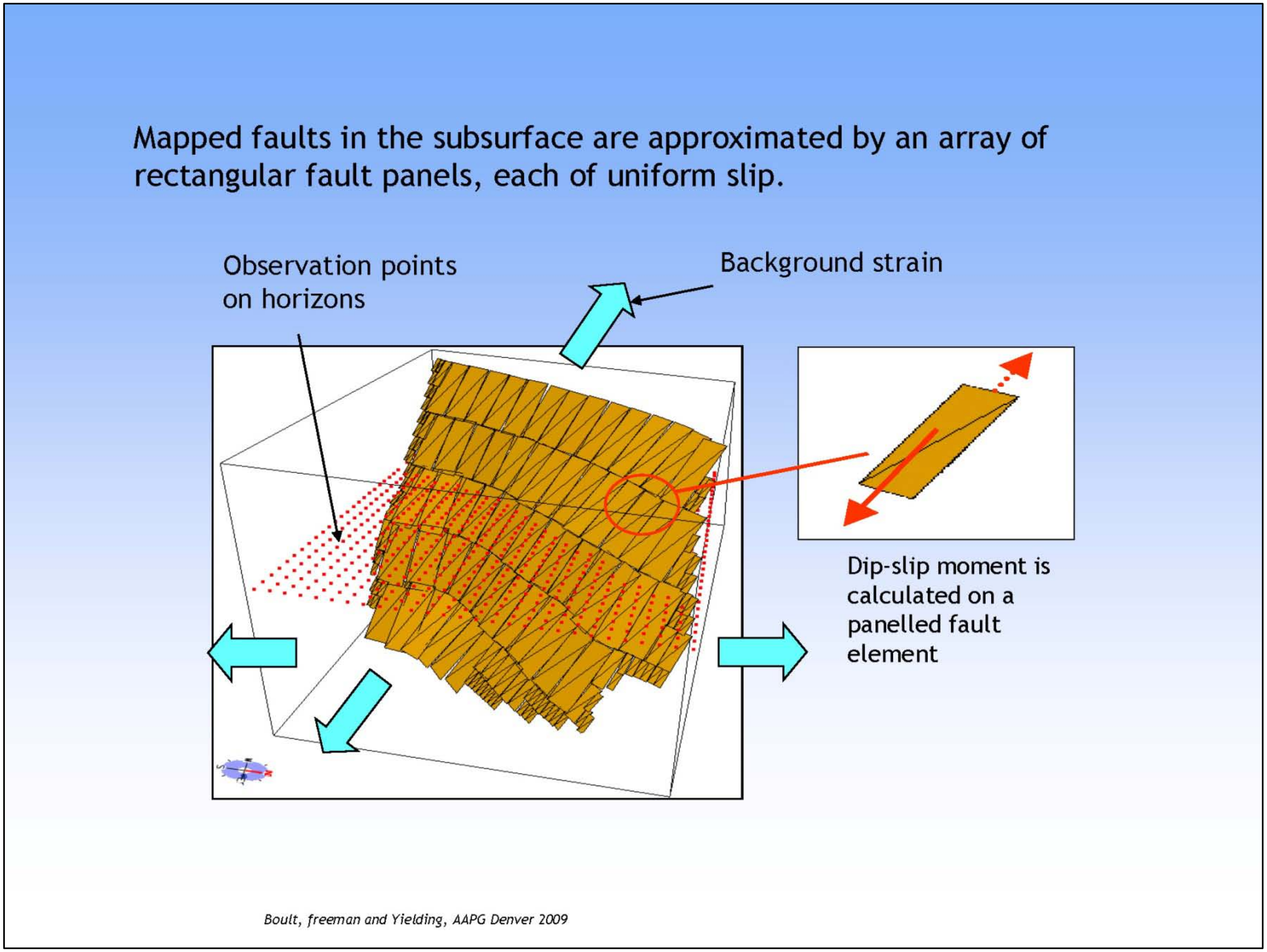

Notes by presenter: Each 'fault panel' is a rectangular dislocation plane with uniform slip, embedded in an elastic medium.
Using the equations of Okada (1992), the resulting displacement and strain tensor can be computed at any observation point in the medium by using the distance weight sum of contributions from each fault panel.

The corresponding stress tensor and failure mode (if any) at the observation point can then be computed using appropriate material properties.

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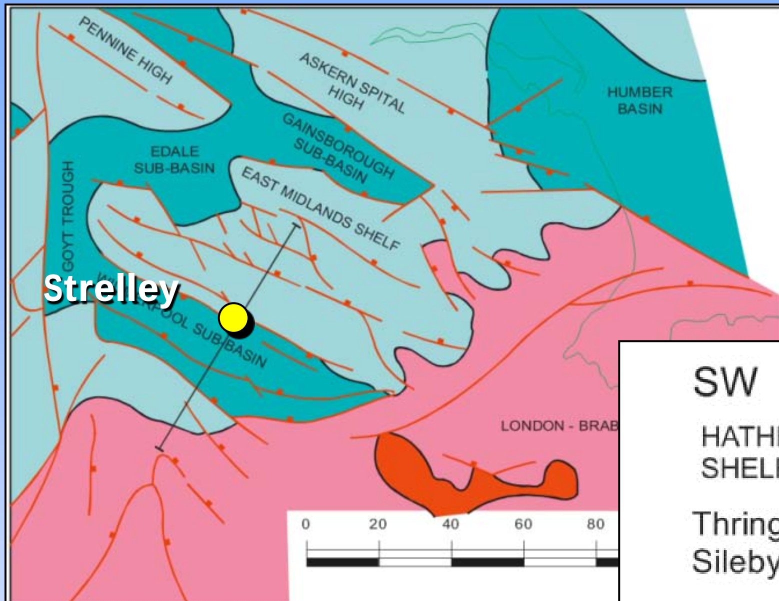
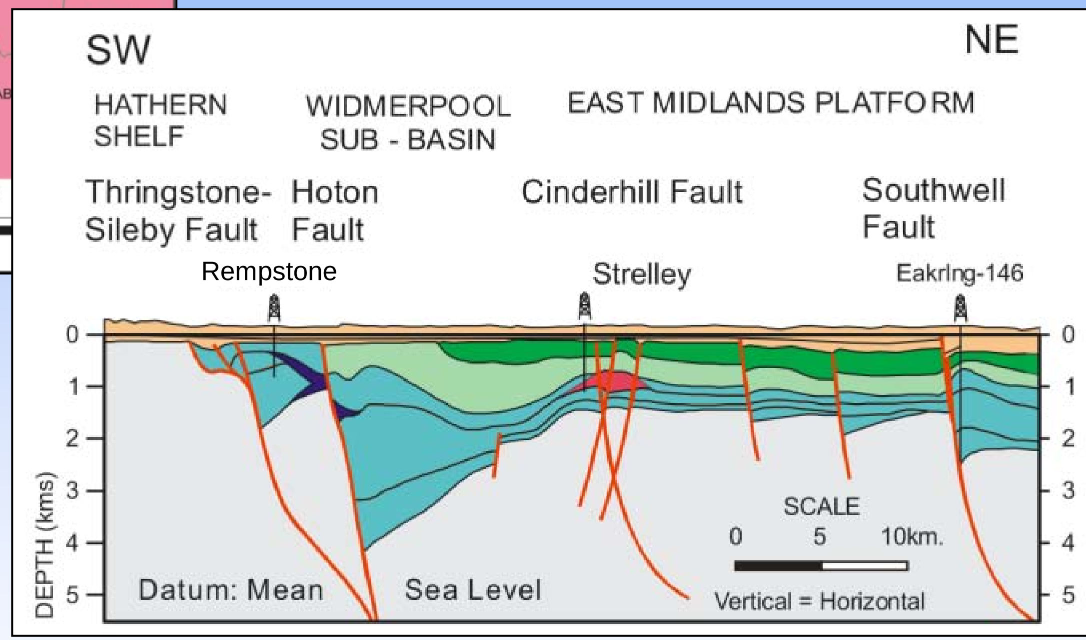
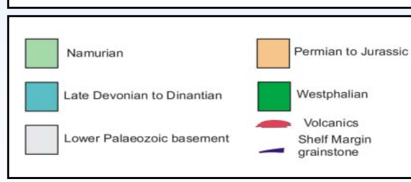
Structure

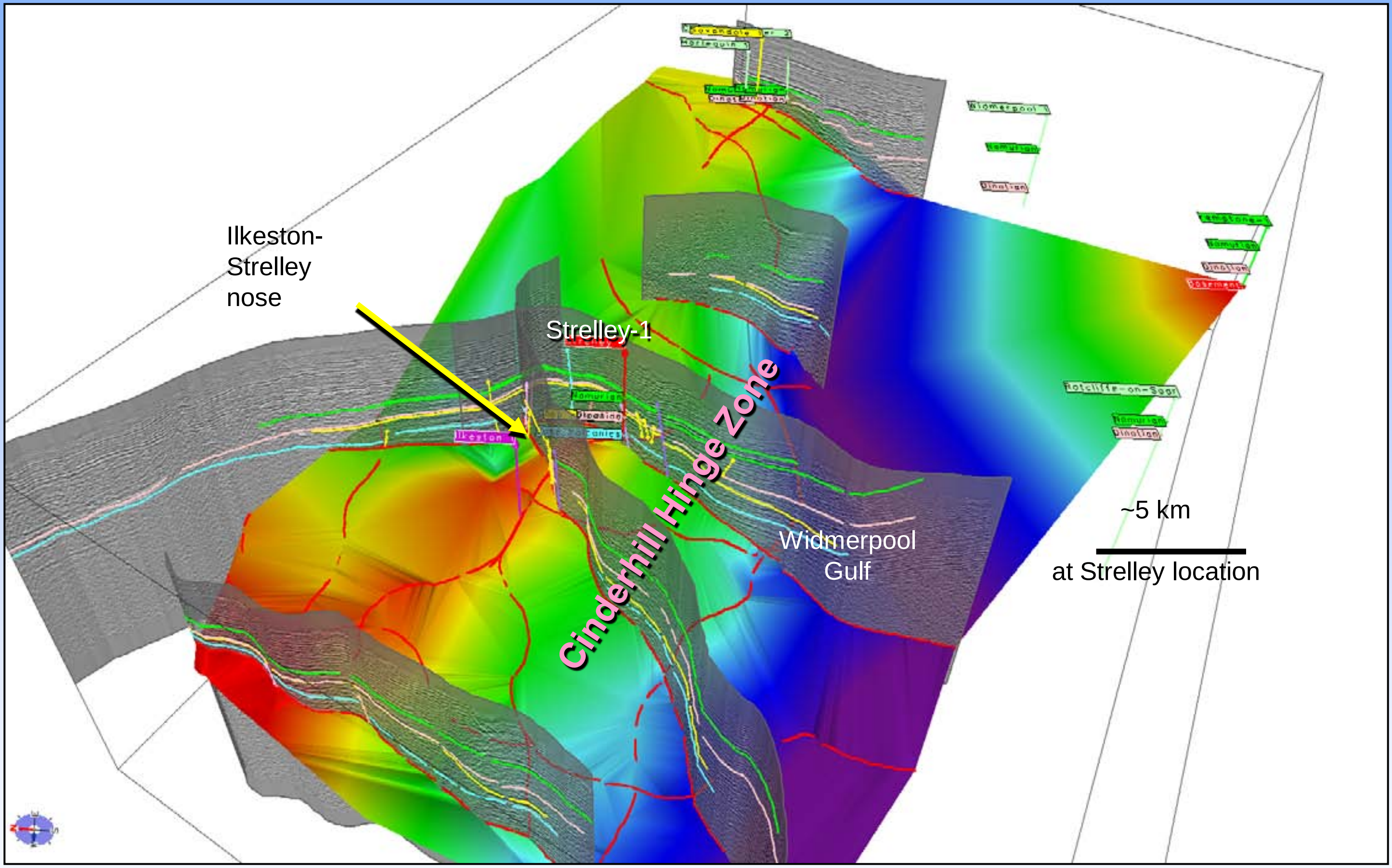


Carboniferous basins of eastern England and cross section (from Swann and Munns, 2003)





Structure



Top basement. Looking SE along the Widmerpool Gulf

Seismic coverage is sparse and more is needed to mature the prospect. Nevertheless, many faults occur on more than one line and modelled faults agree with nearby mine data.

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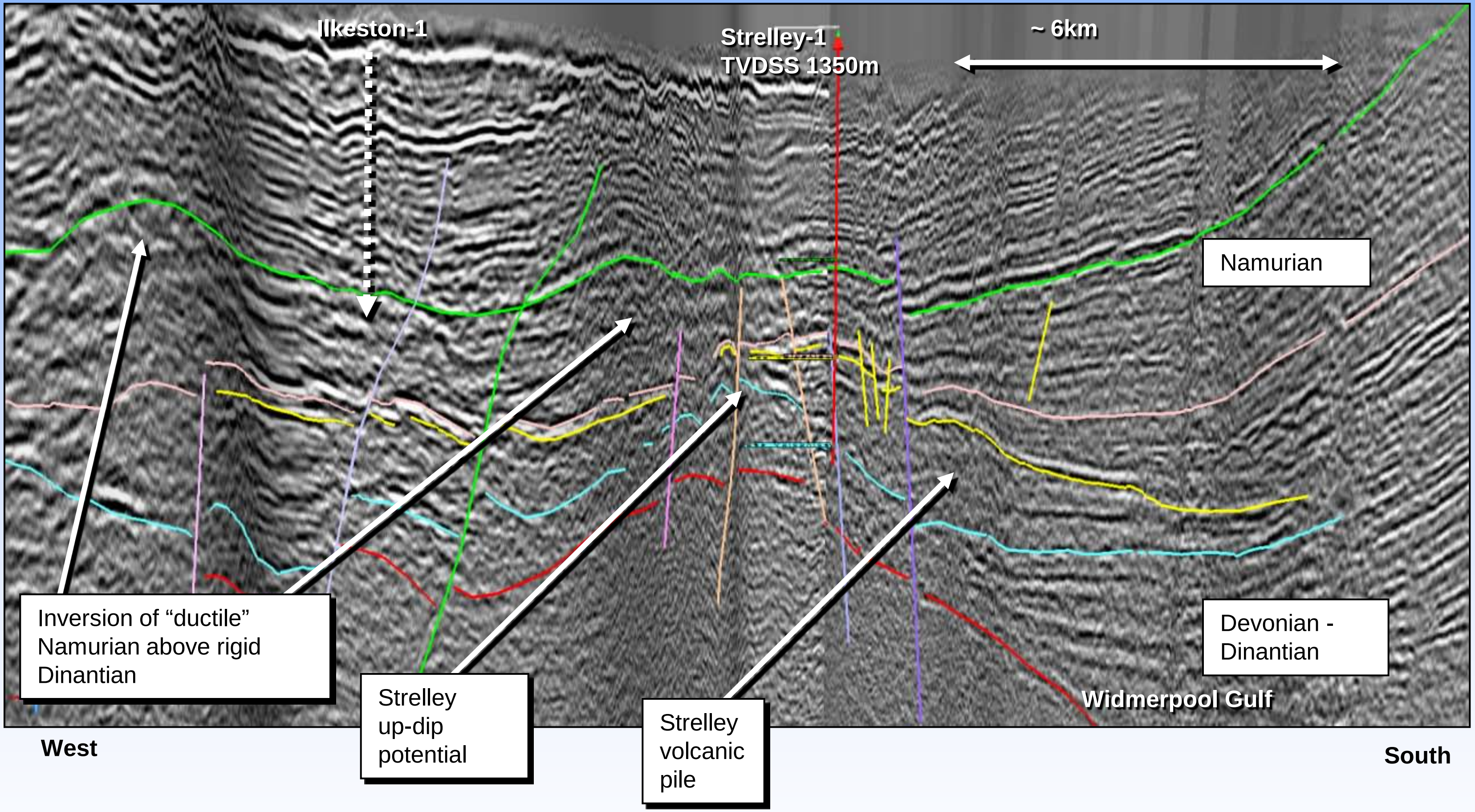
Structure

Cross- section



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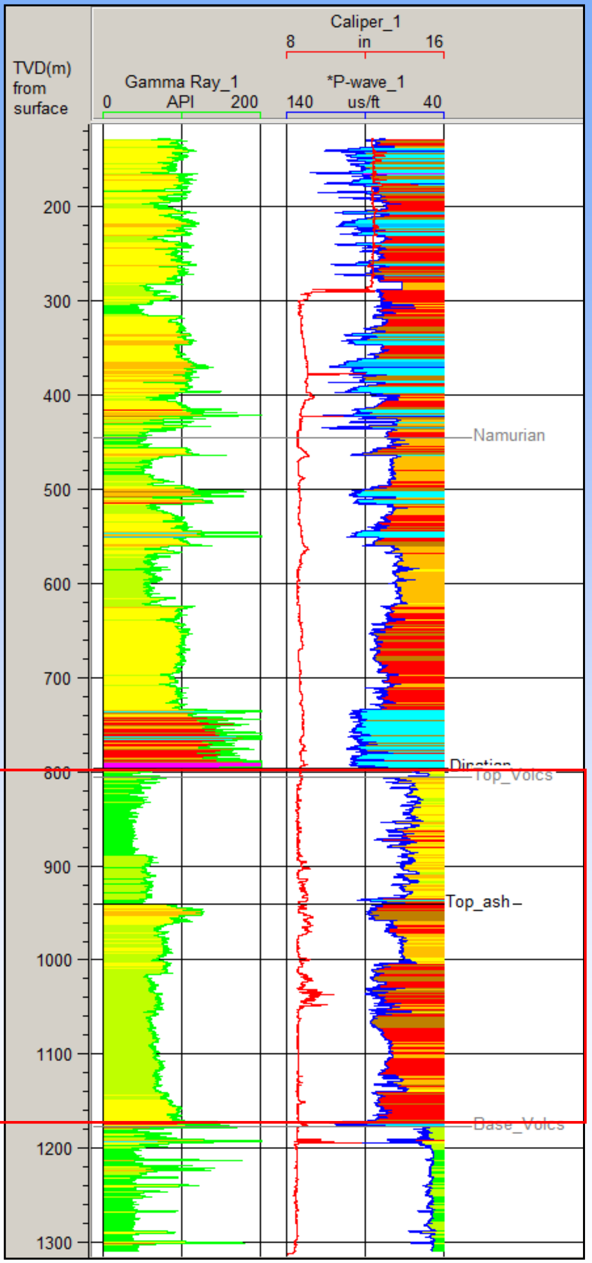
Strelley - 1



Seal

243 m of volcanic ash overlain by 135 m of lavas

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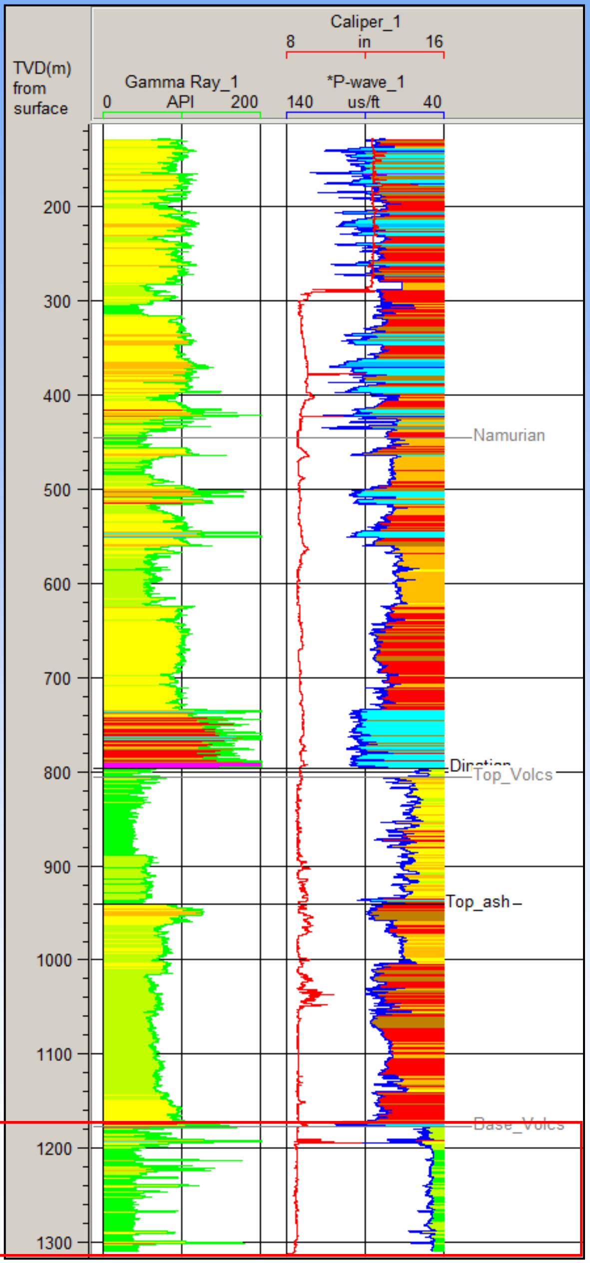
Strelley - 1



Reservoir

Highly fractured limestone
GR spikes = fractures filled with LCM

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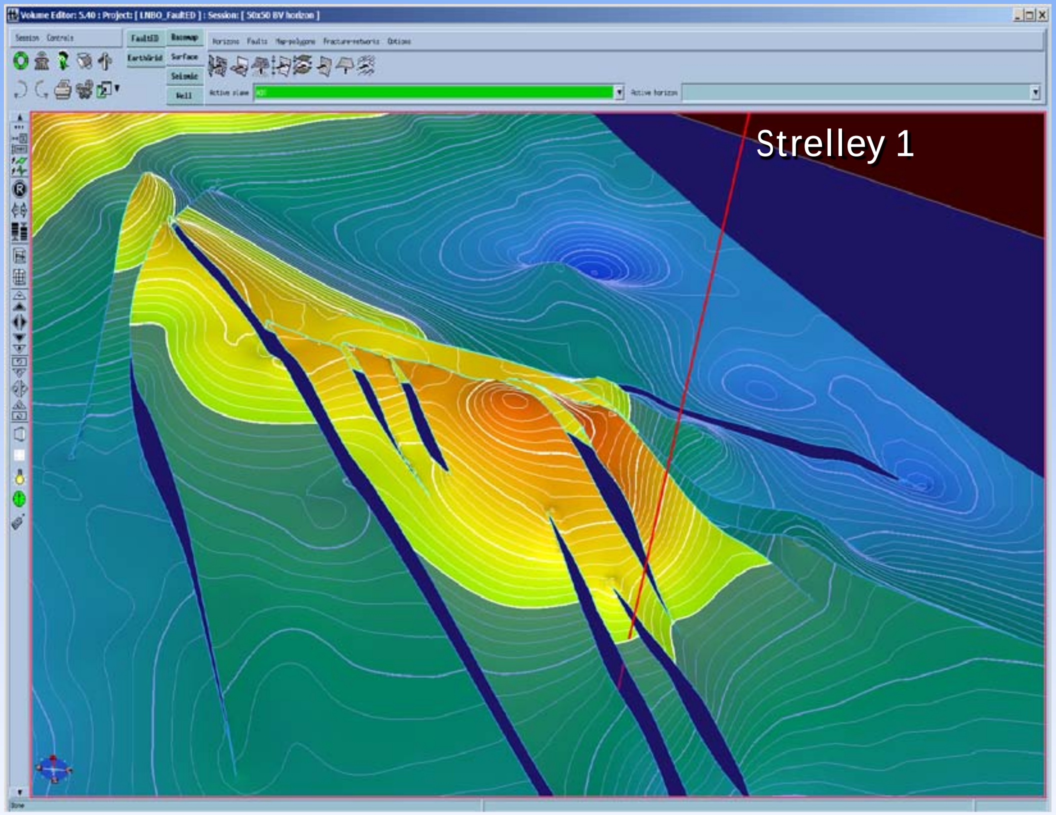
Charge

- Significant oil on cuttings over shakers
- Free oil in core fractures
- Water produced on test, but this was invalid because the well drilled on edge of structure

Top reservoir horizon (contour interval = 10 m) + closure if FWL at well.



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Reservoir

Very thick and capable of producing at 2000 BPD through fractures

Malham N Yorkshire, UK

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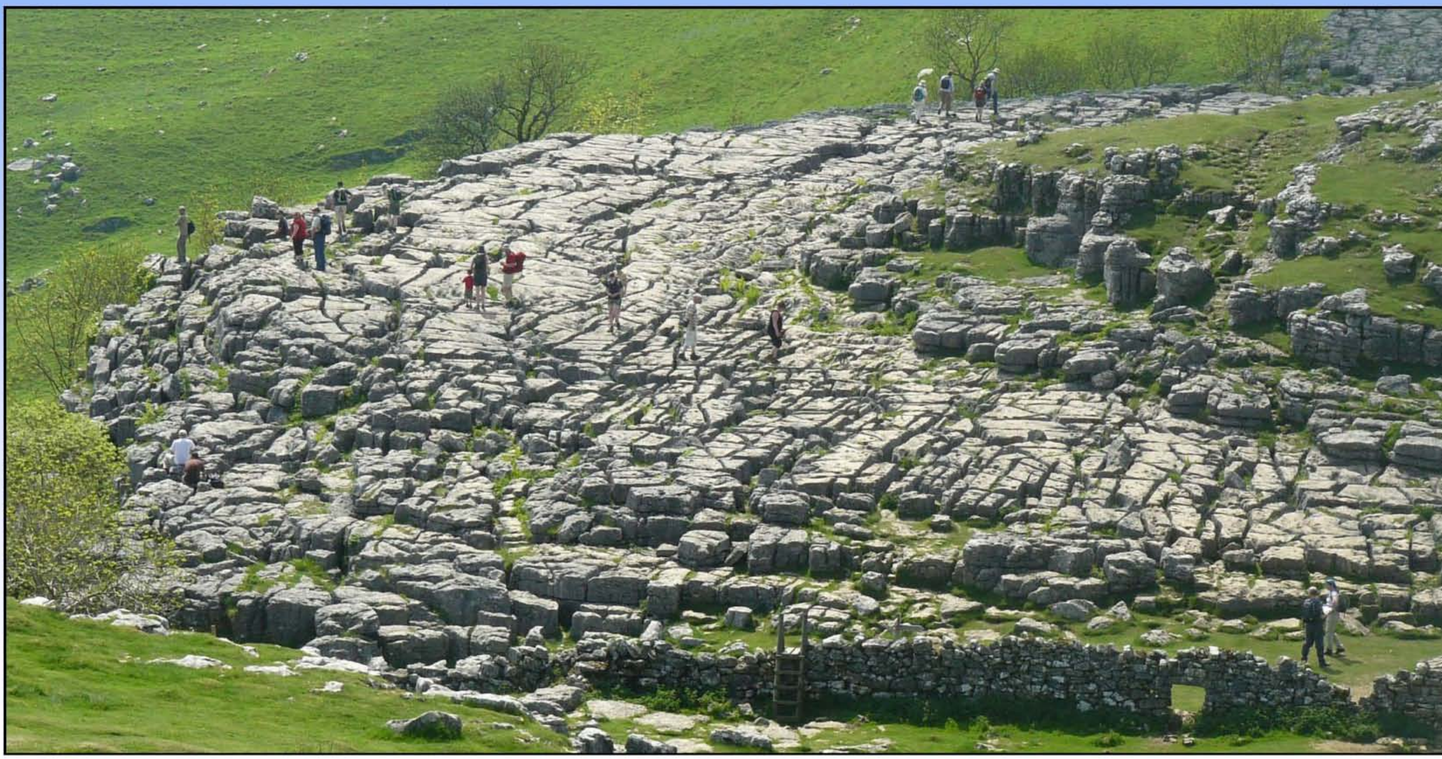
Reservoir

But what is the origin and location of fractures in the subsurface?



Malham N Yorkshire, UK

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Notes bt Presenter:

At present we are uncertain as to the origin of the fractures, but it is highly lvery that the very regular (over several kilometres around Malham at least) orthogonal set are a result of regional extension and the less regular oblique set the result of compression. Whether the extension that caused the orthogonal set was
1 N-S Dinantian extension and faulting, or
2 Late Westphalian / Stephanian NNE-SSW extension and faulting or
2 late Tertiary stress release associated with regional uplift,
is not known.

The latter case, which was not associated with major faulting, would result in a very regular orthogonal set of fractures across the Strelley structure and would be the "best case" scenario for planning a well. However, even though we see a very regular extensional fractures at Malham (and many other outcrop locations in the UK), we are unable to see the effect of faulting there on fractures because no major faults are exposed at surface. Thus we have also modelled the worst case scenarios, either 1 or 2 or both, using elastic dislocation modelling and the results are shown form here on.

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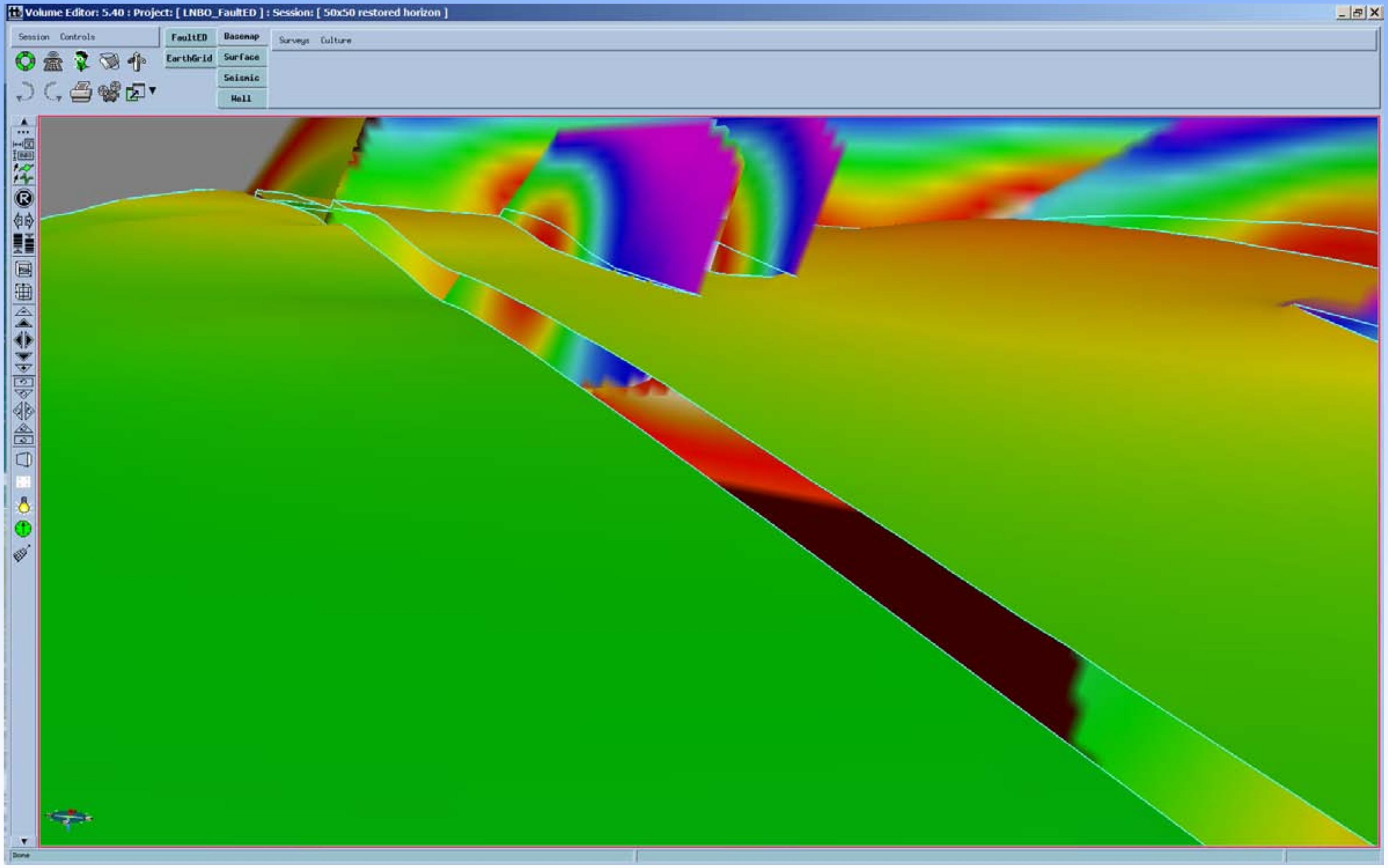
Top reservoir horizon with faults coloured according to displacement



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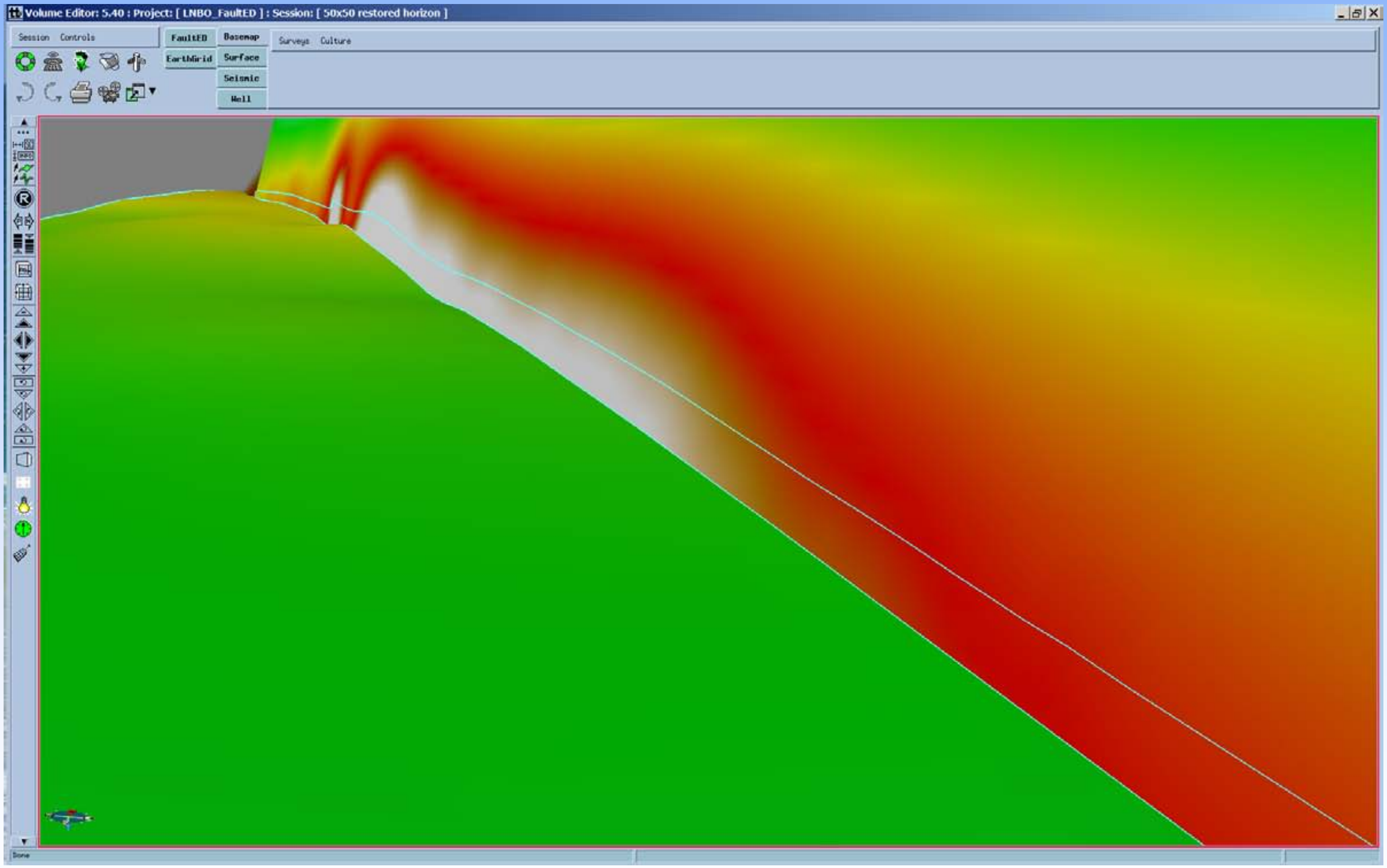

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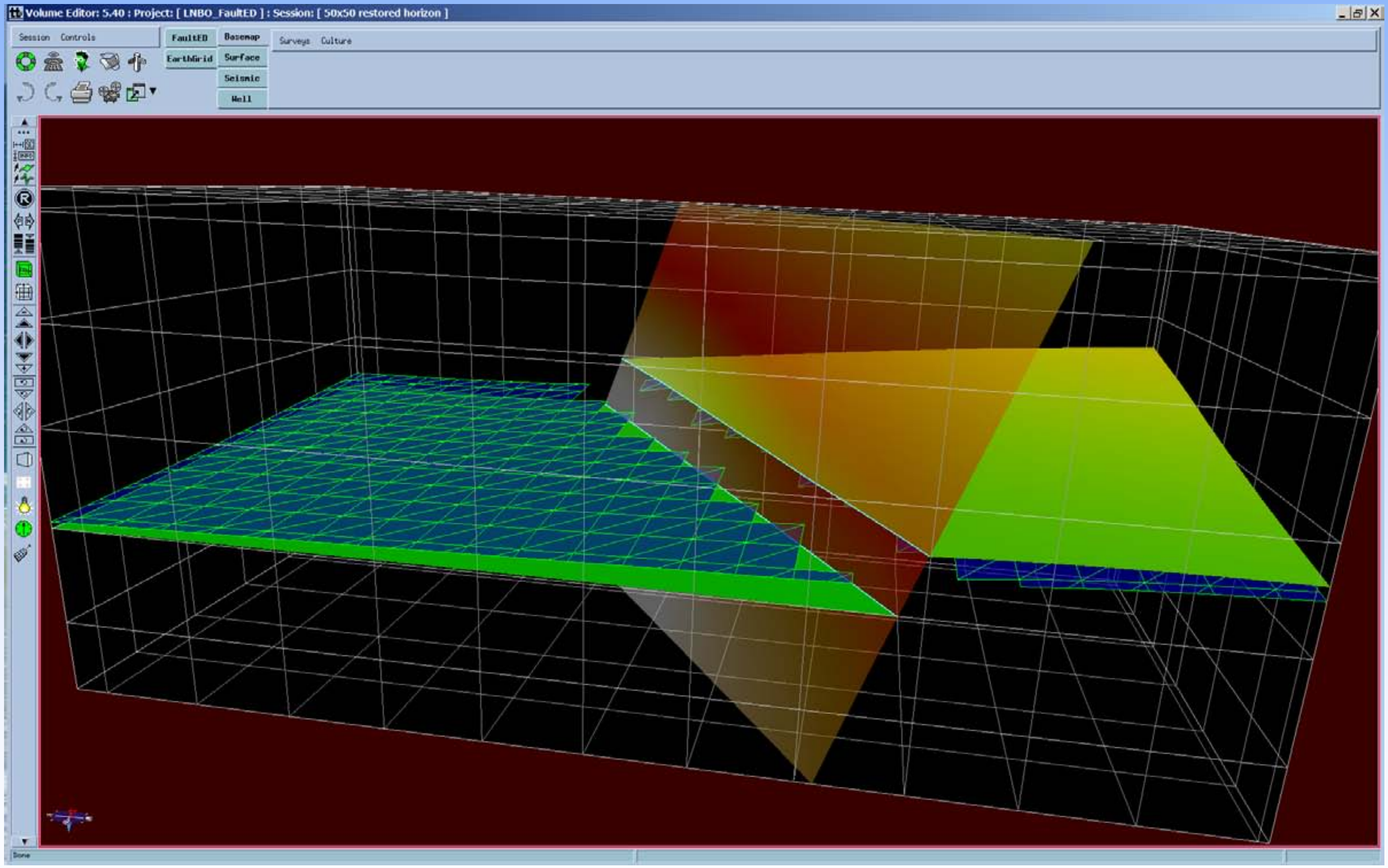
Original and restored (pre-faulted) horizons

100 m grid overlain



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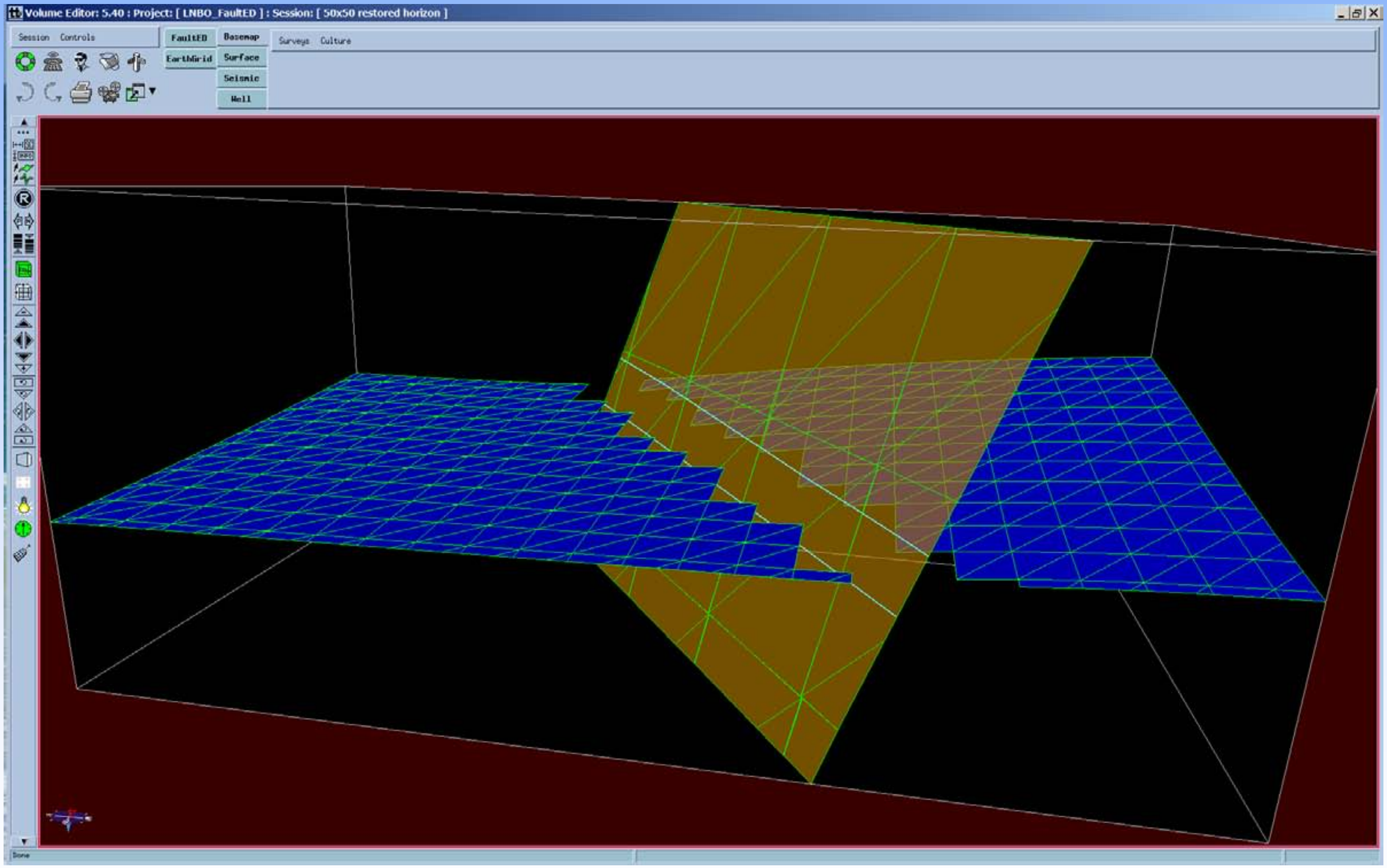
Restored horizon and panelled fault



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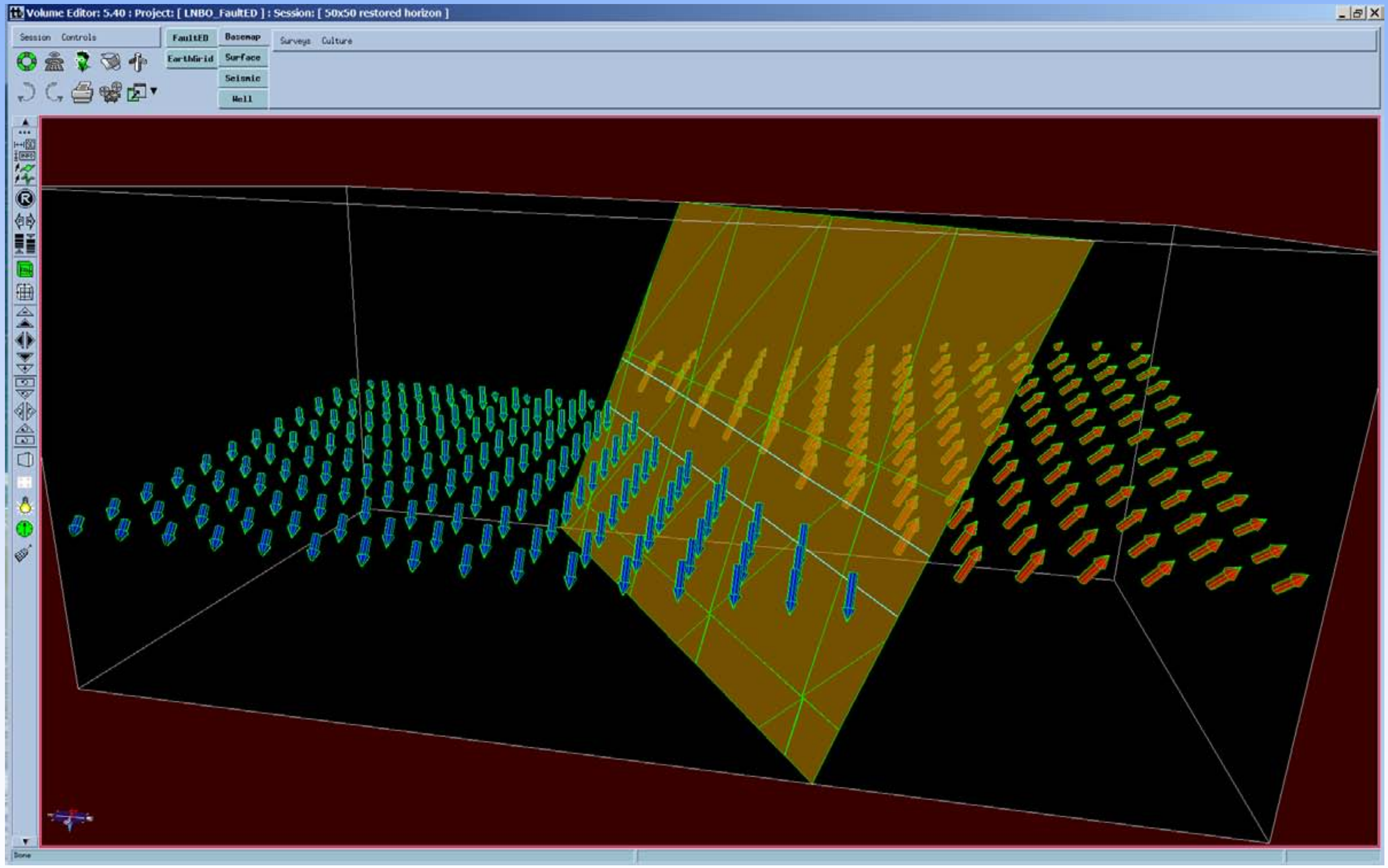
Relative subsidence and uplift during forward modelling



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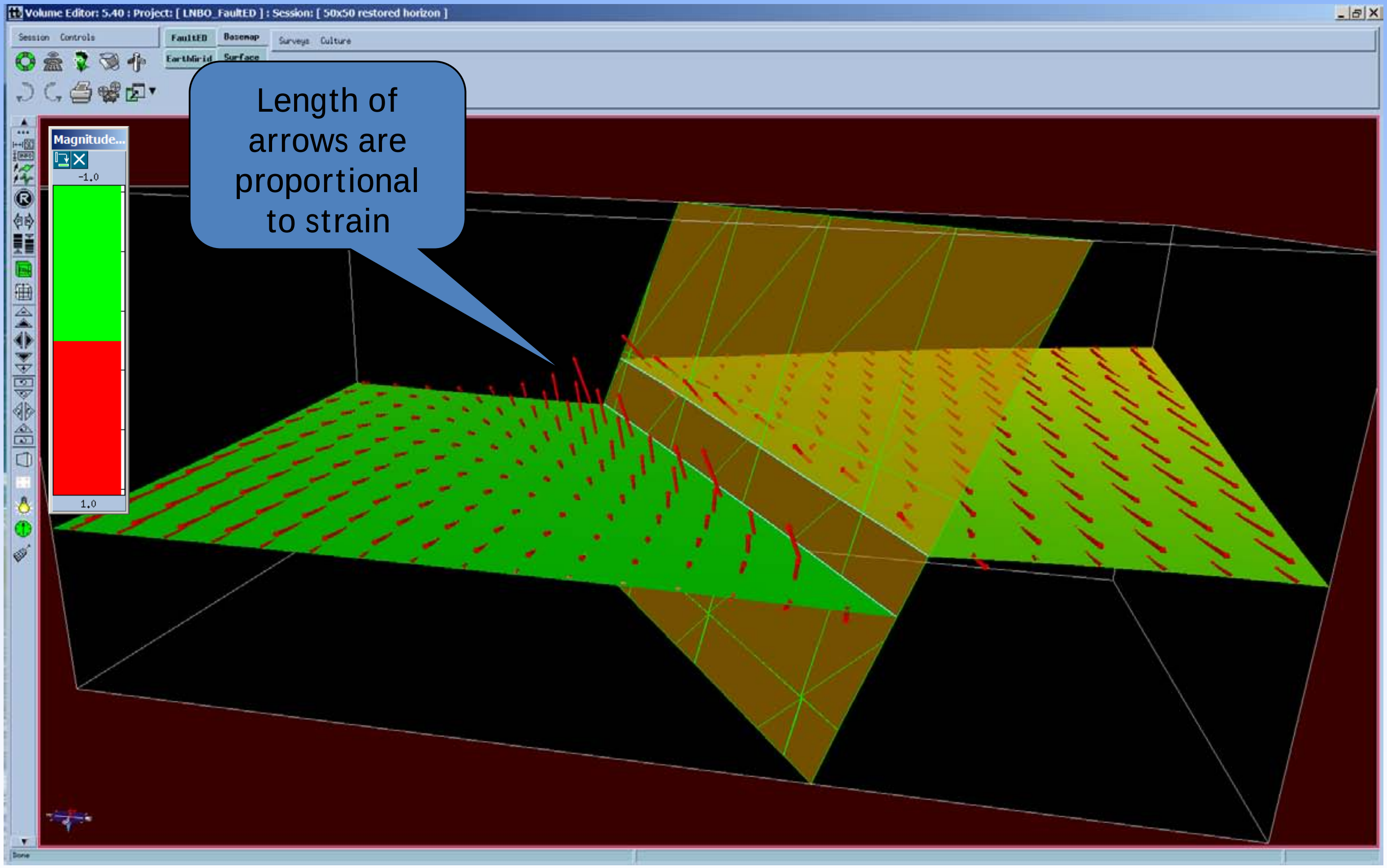
Deformed horizon + max principal strain (E1) red = extensional



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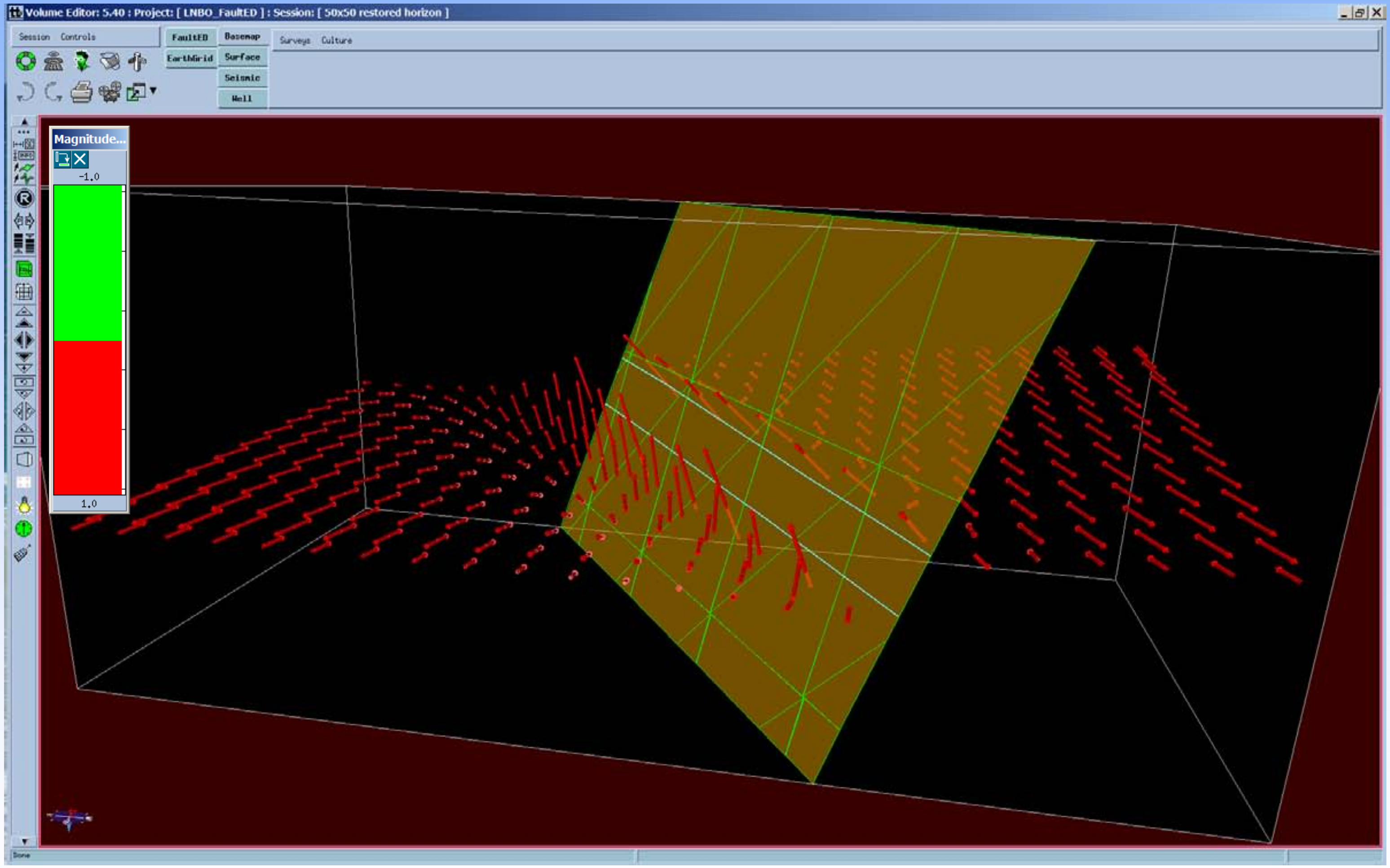
E1 only



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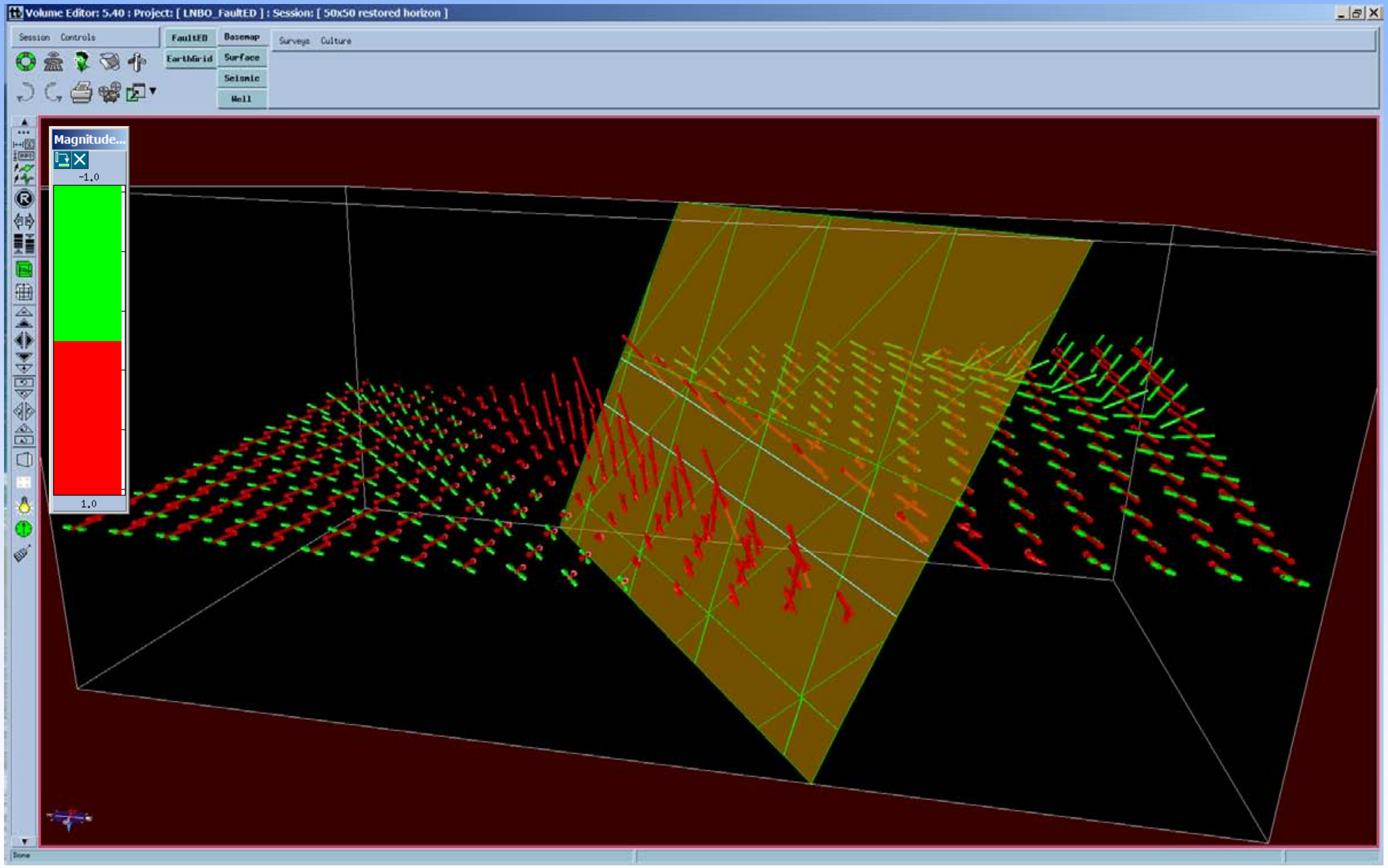
E1 + intermediate principal strain (E2)



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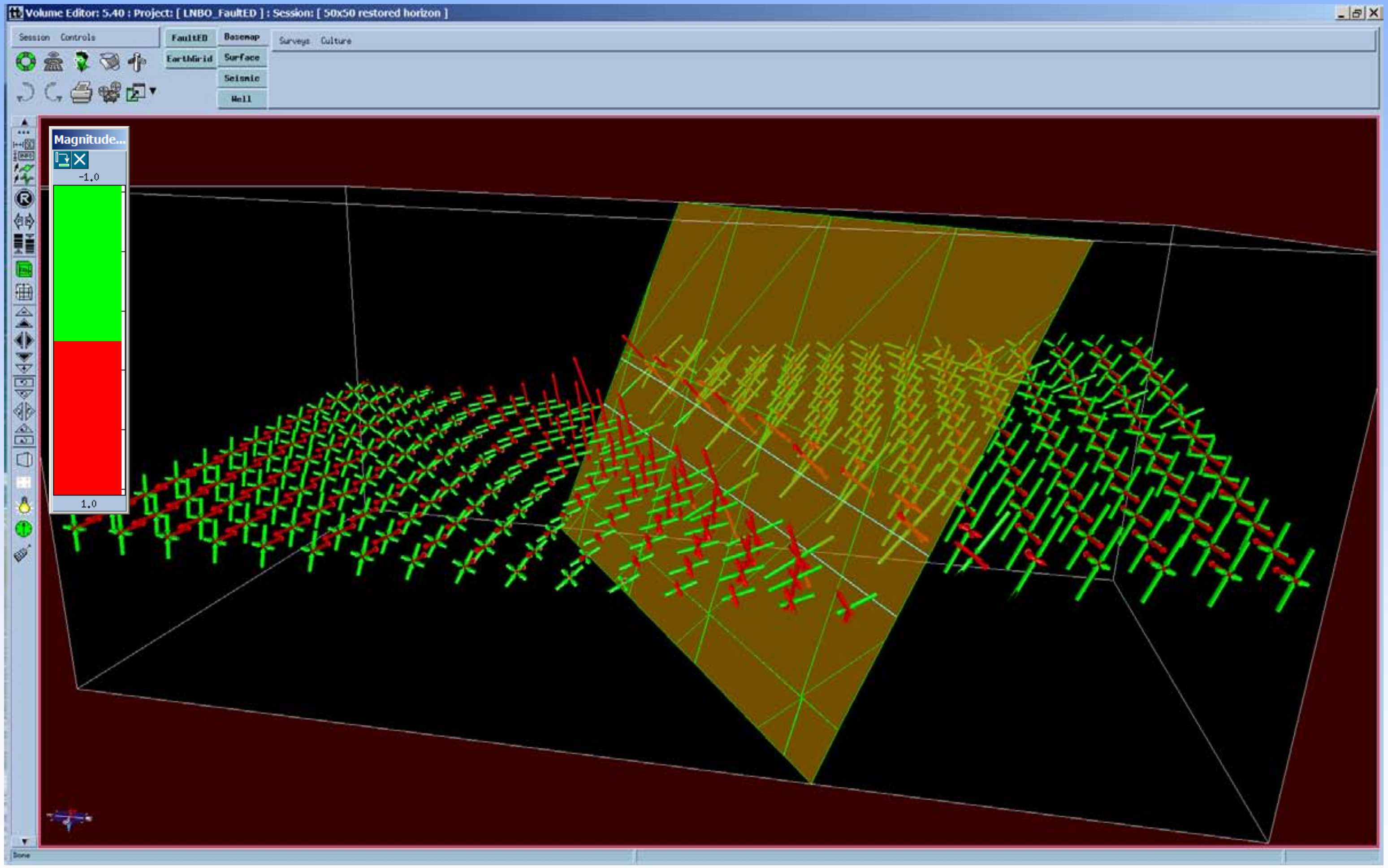
E1 + E2 + minimum principal strain (E3)



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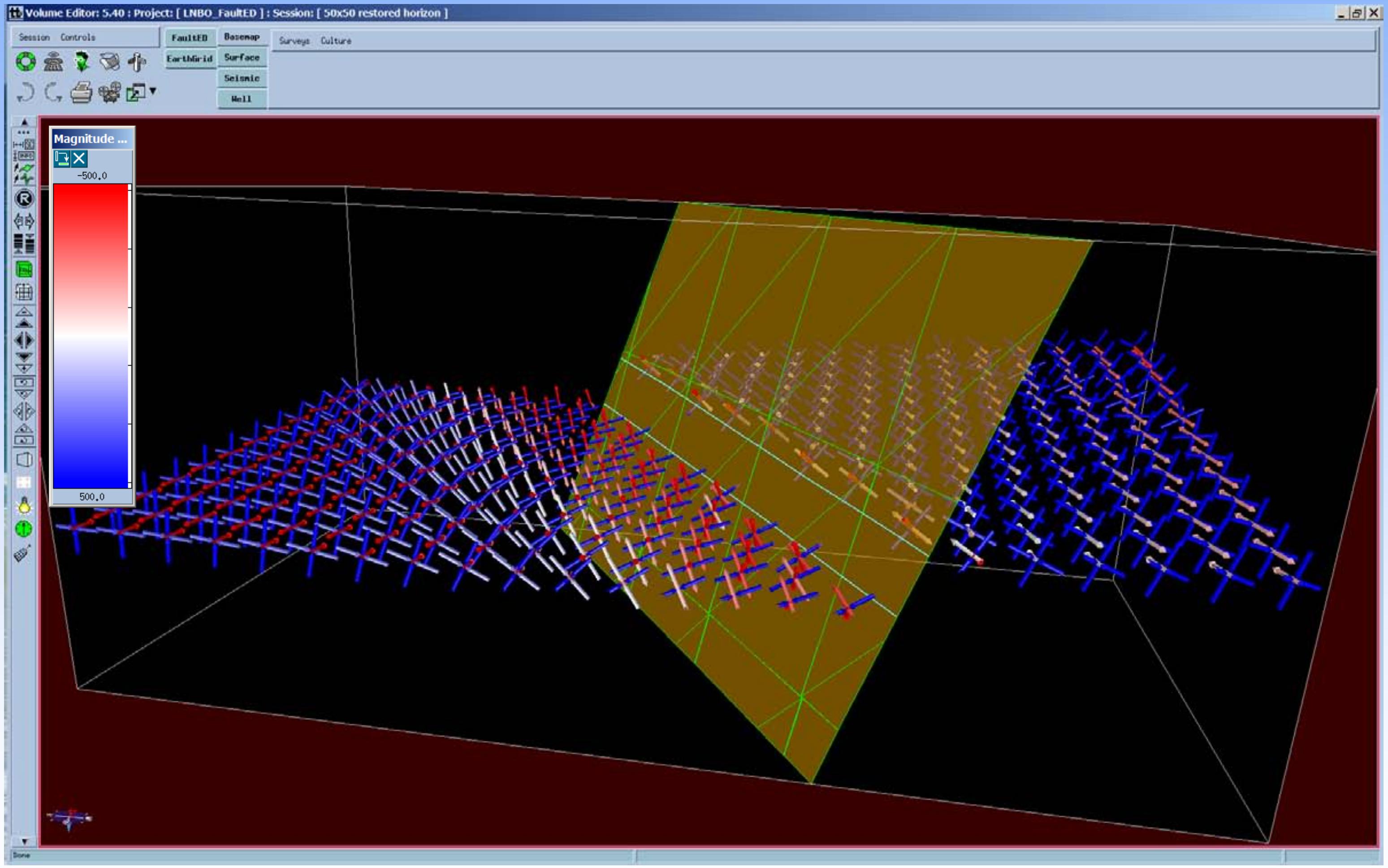
Principal stress directions and magnitudes (coloured Mpa)



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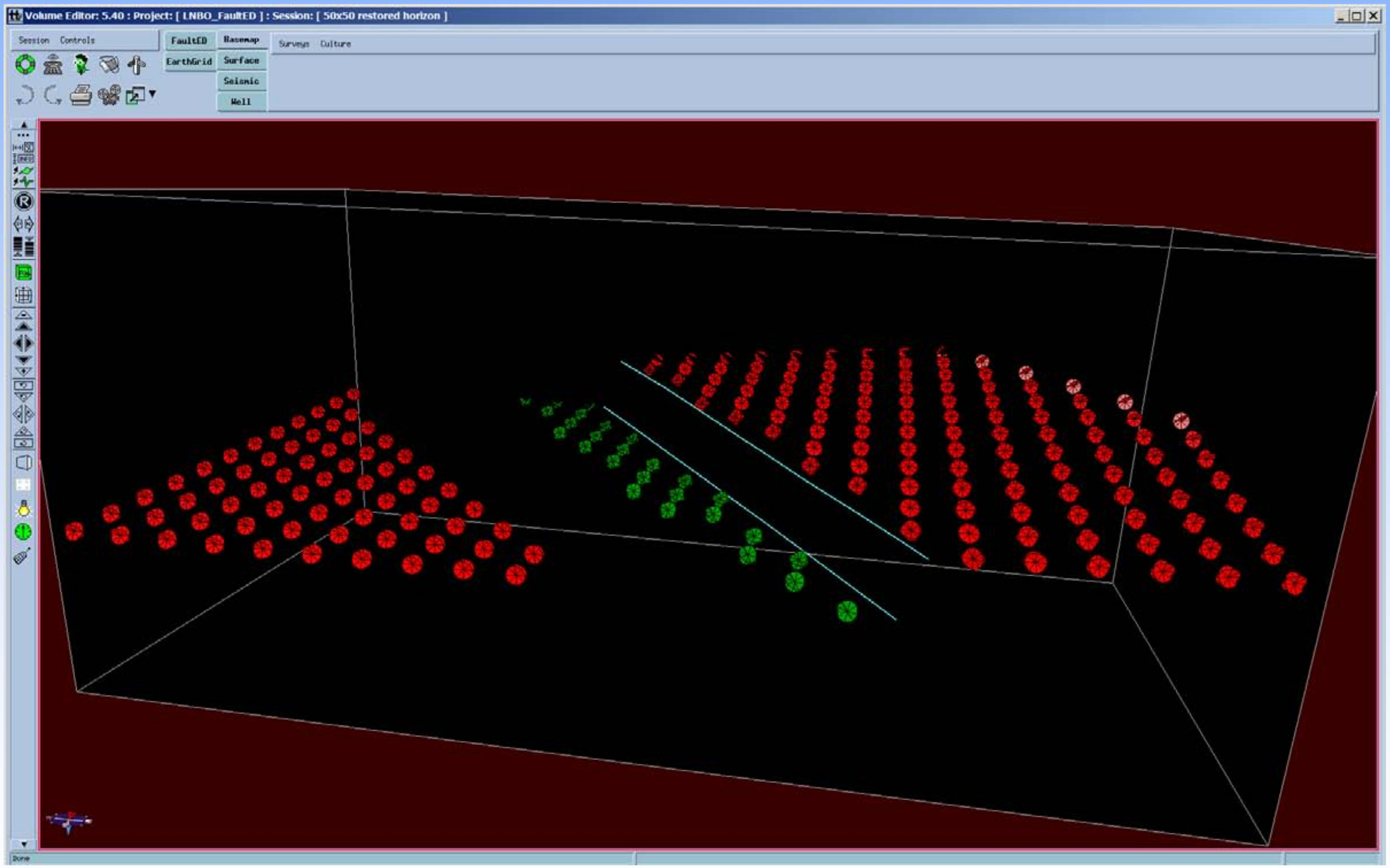
Normal (red) and reverse (green) shear planes



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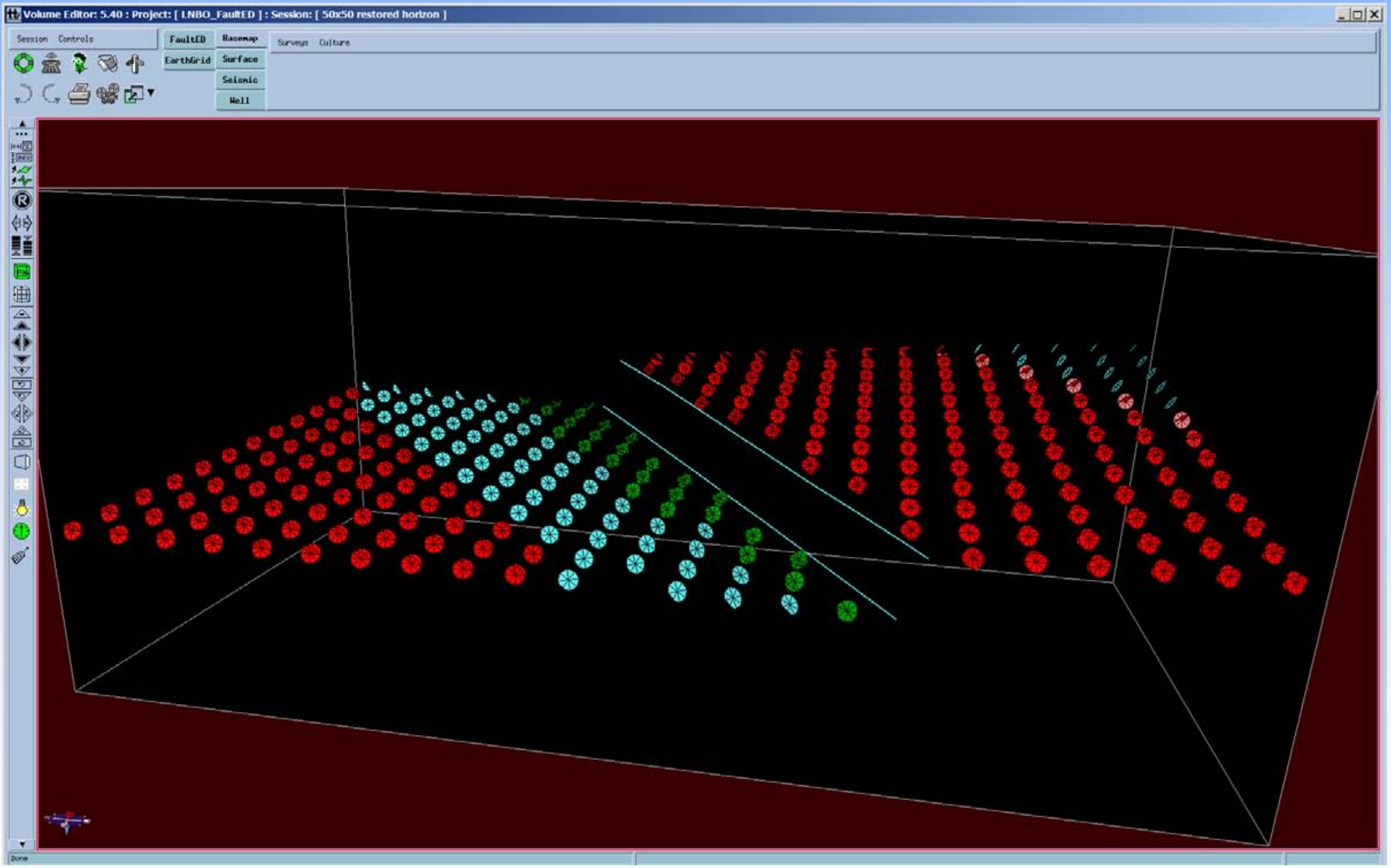
Normal, reverse shear and dextral strike-slip (blue) planes



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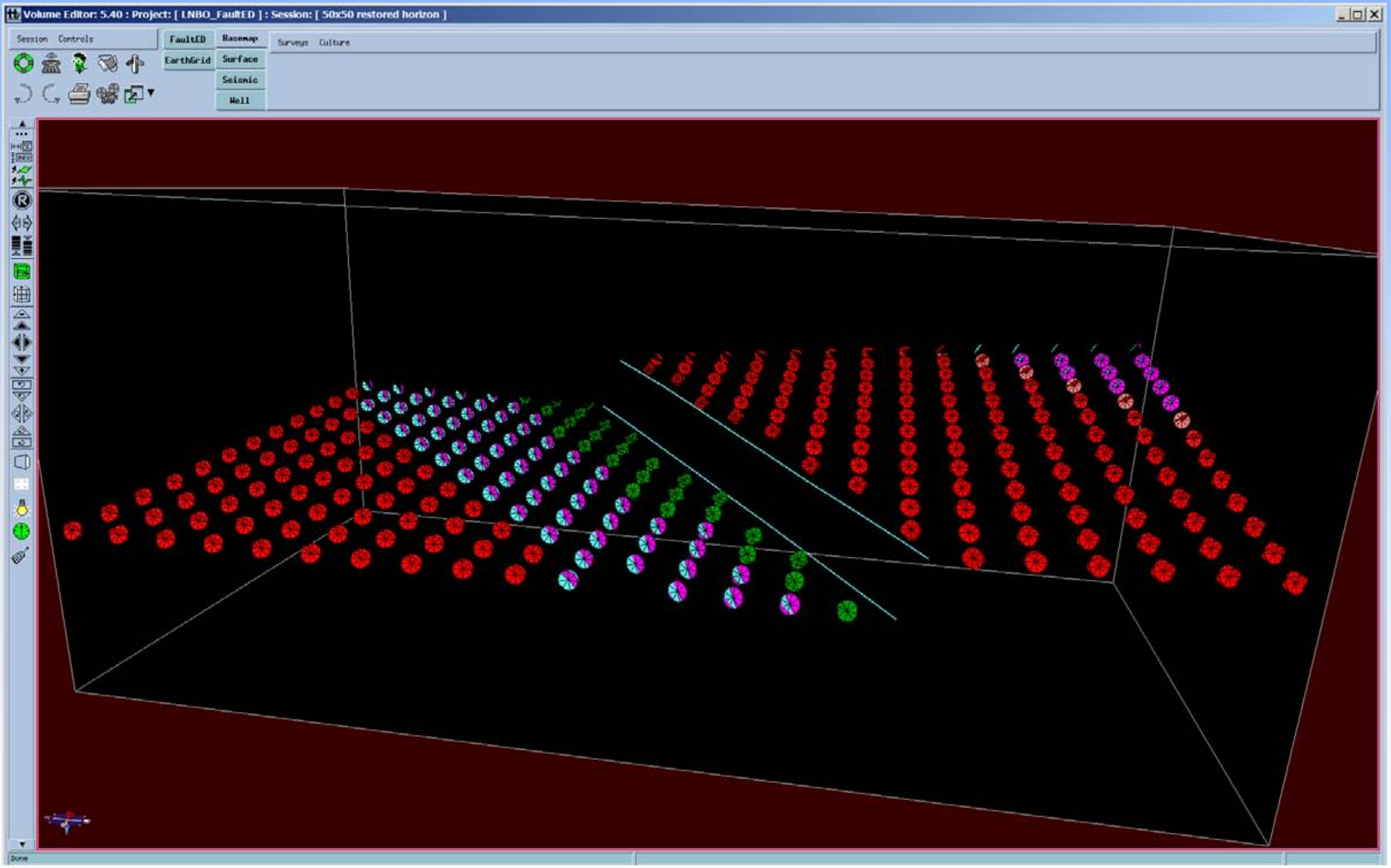
Normal, reverse shear and dextral strike-slip (blue) + sinistral strike-slip (purple) planes



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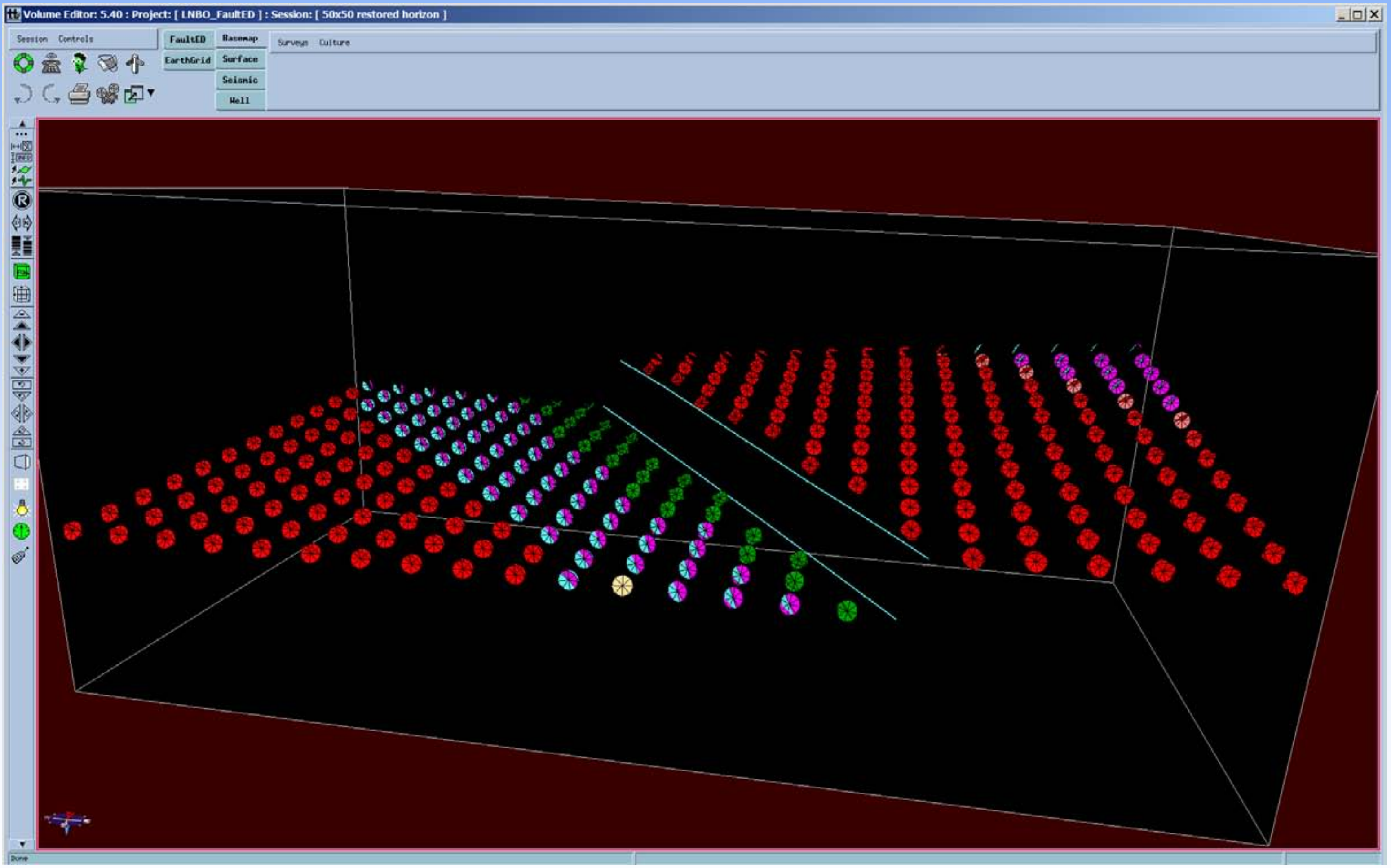
Add in tensile (orange) failure planes – not many



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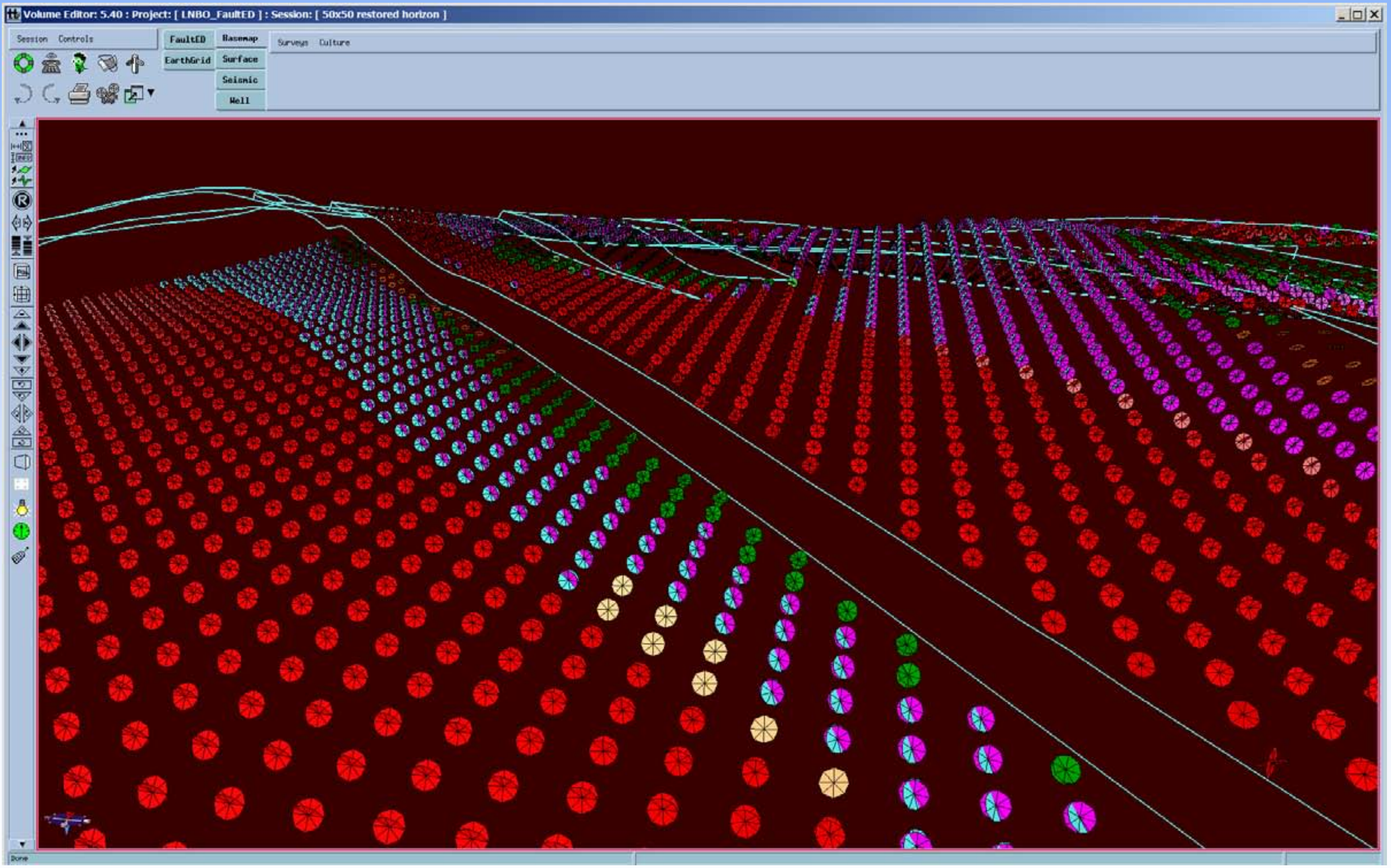

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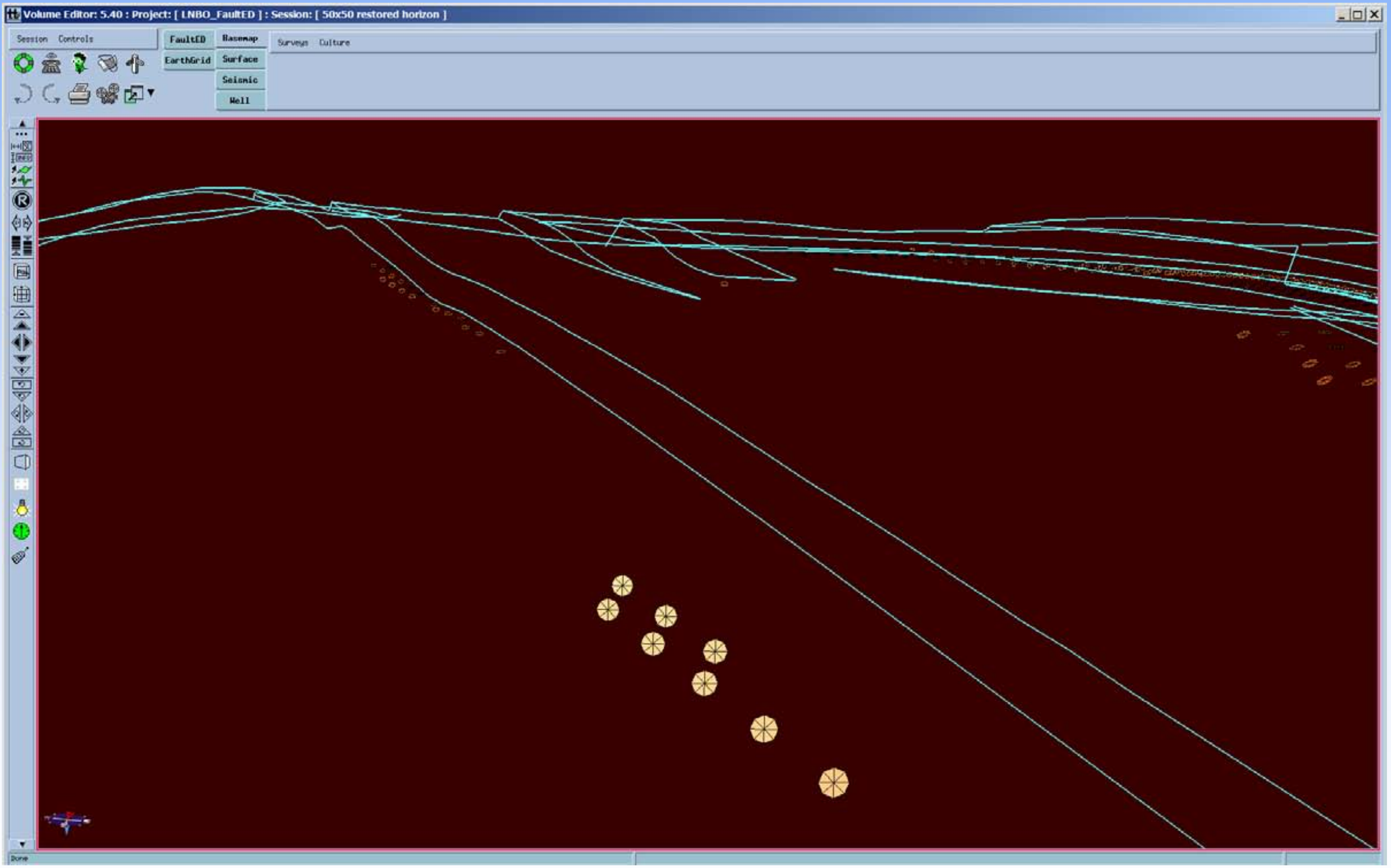

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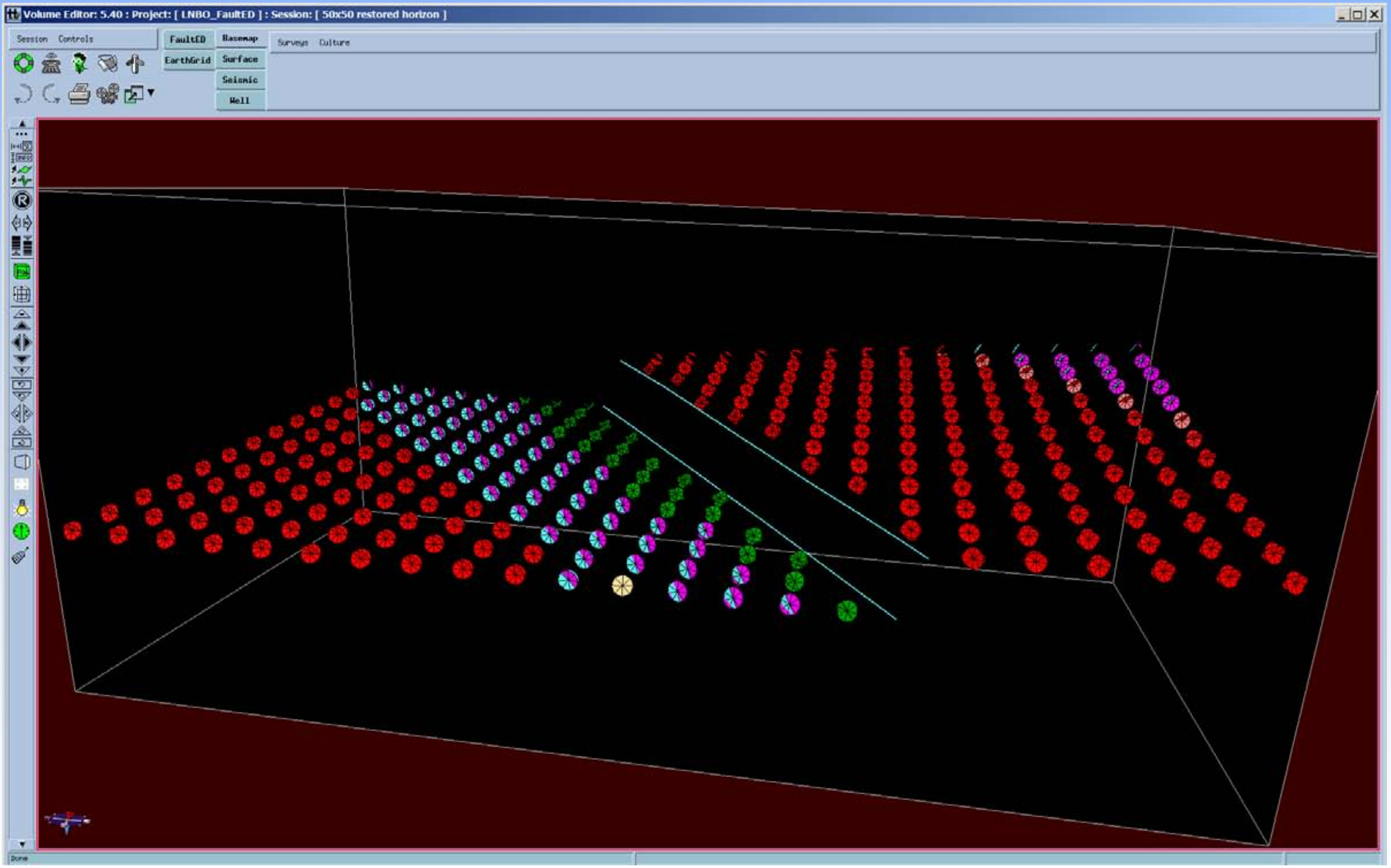
All failure planes



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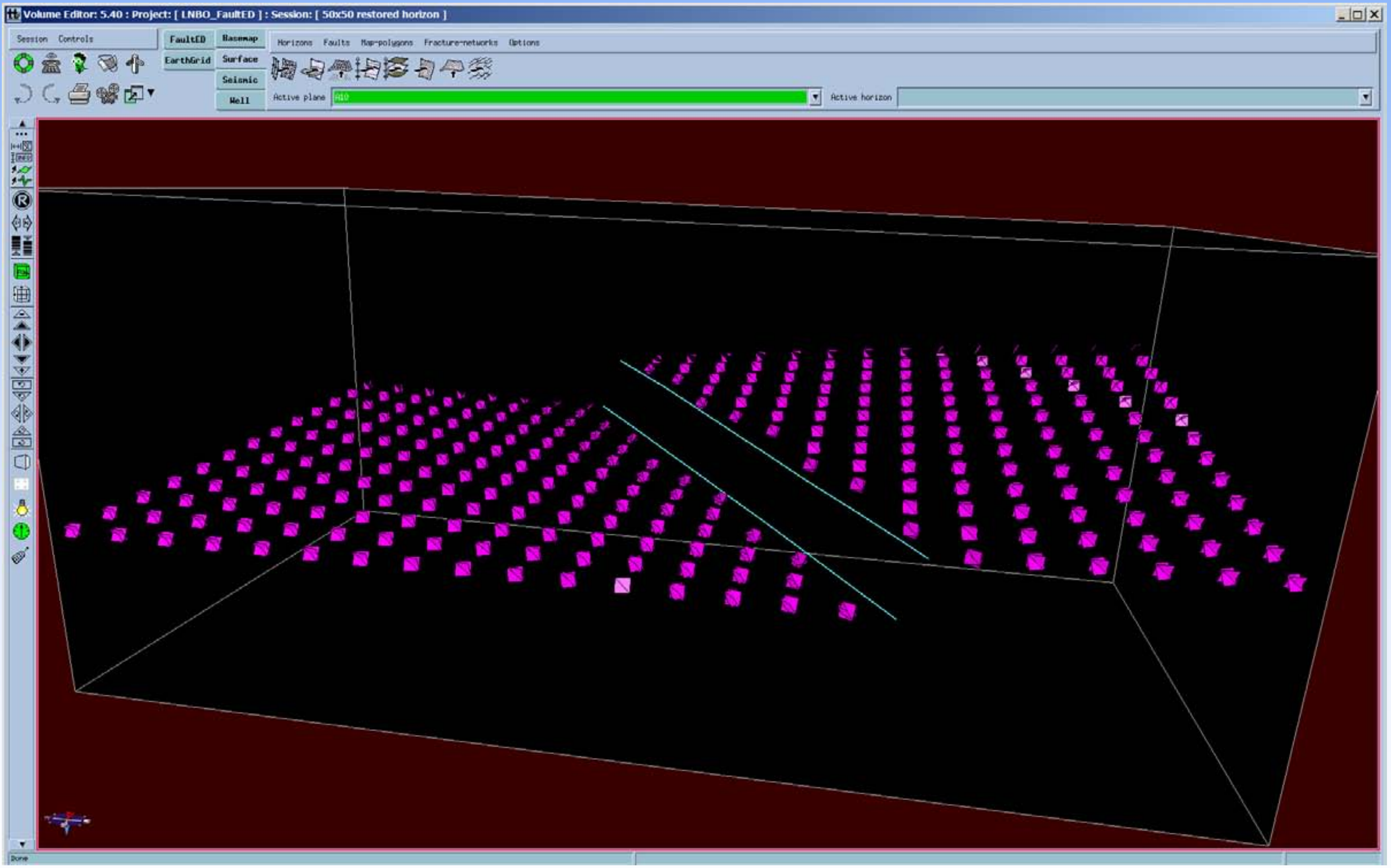
All failure planes converted to fracture networks



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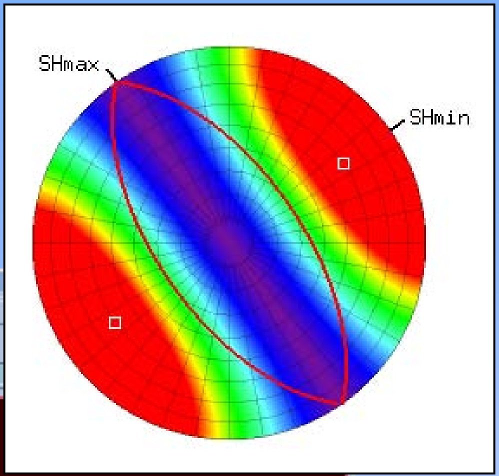
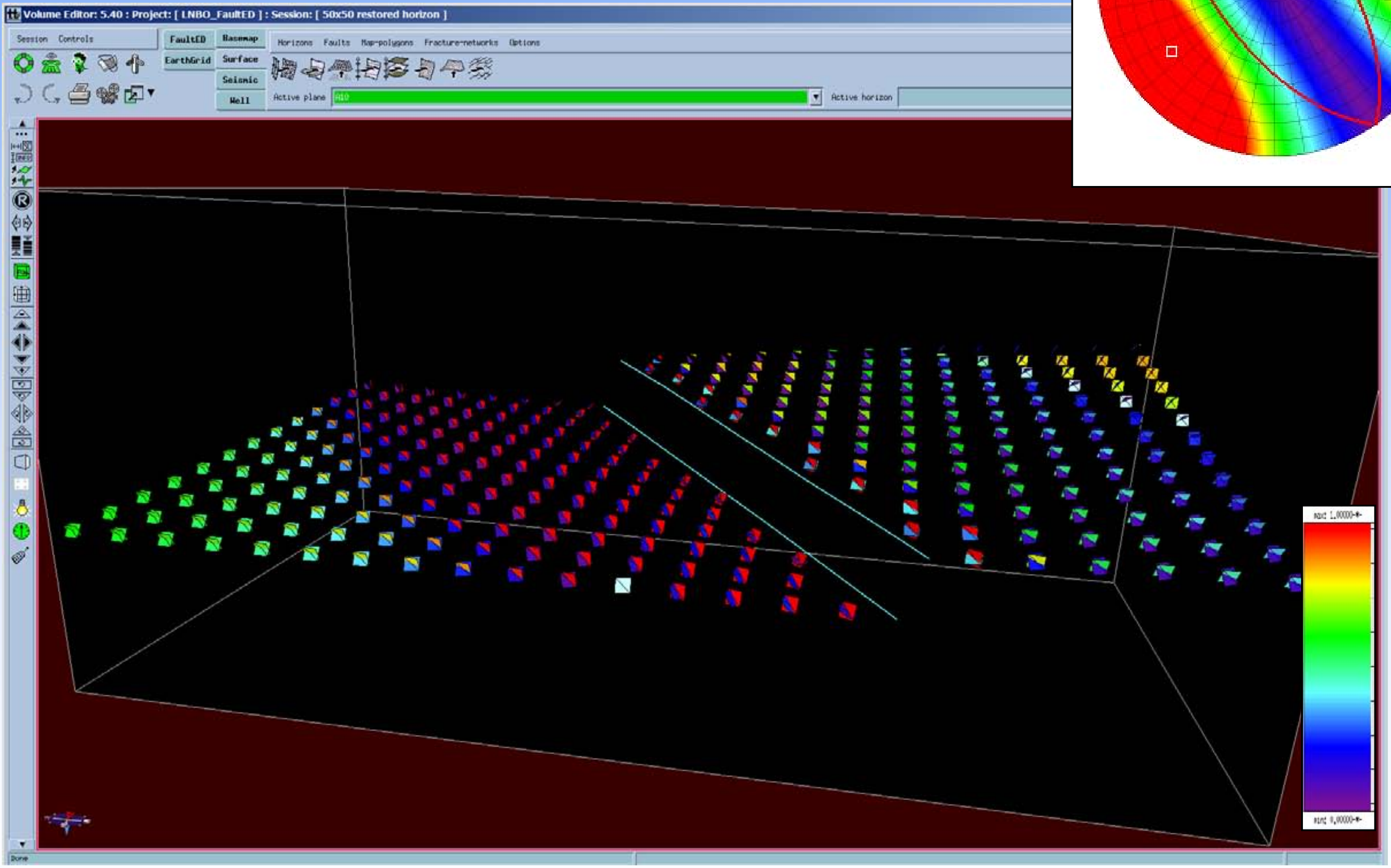
Slip stability ~ fracture permeability

Fracture network coloured according to slip stability in contemporary stress field

Slip stability based on stress field from surrounding boreholes





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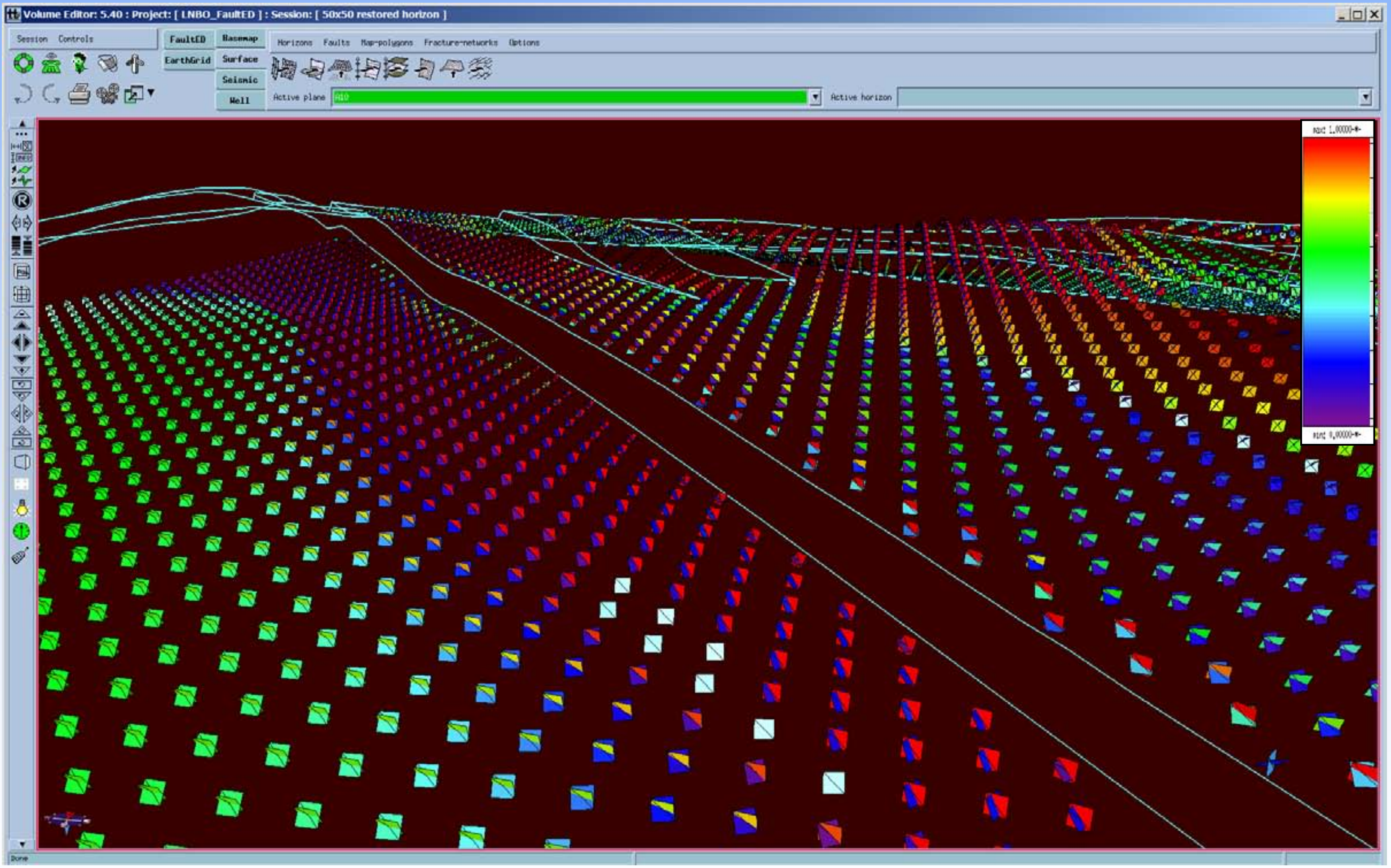

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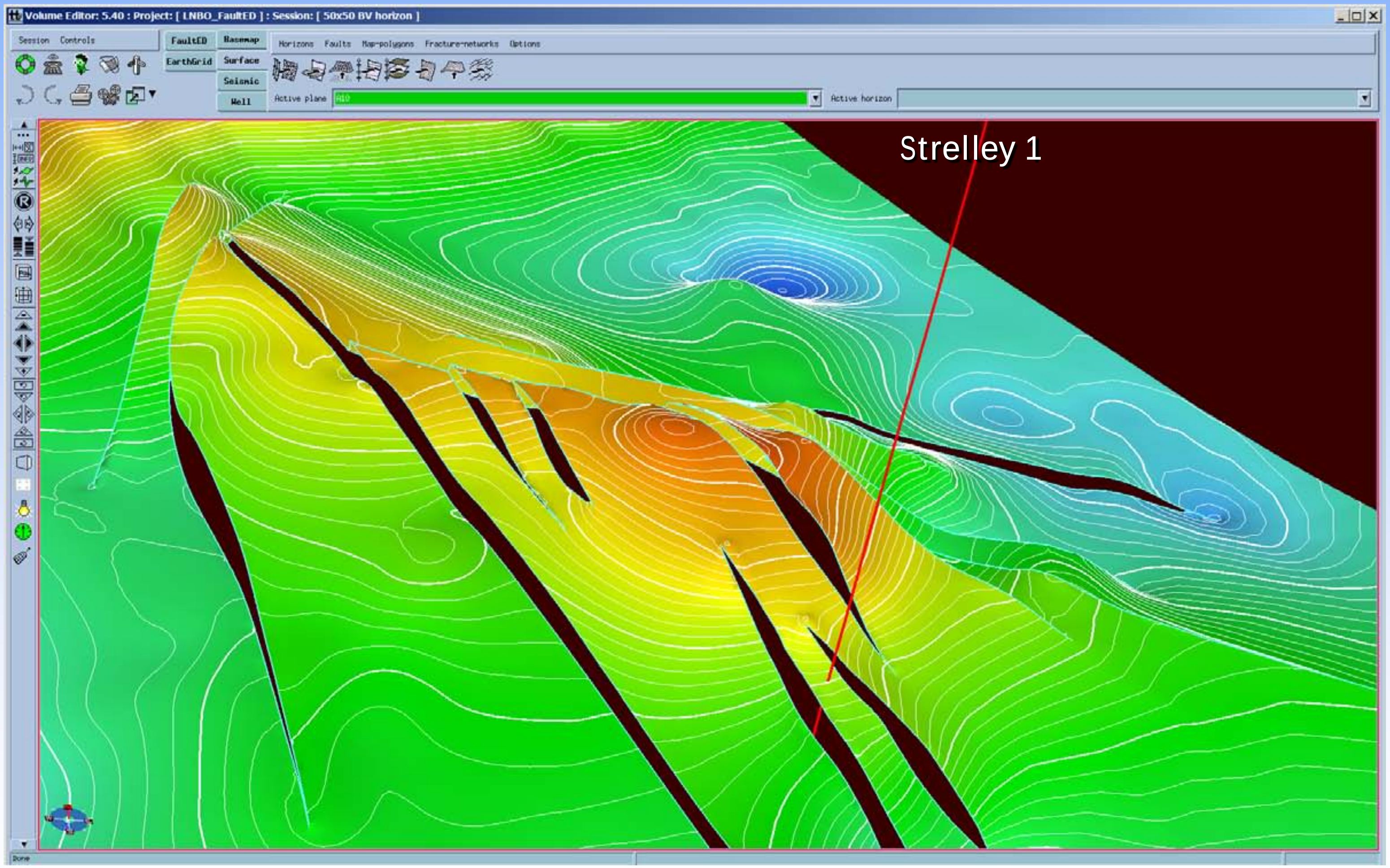
So how will this help us with the placement of a new well?

Top reservoir horizon (contour interval = 10 m)



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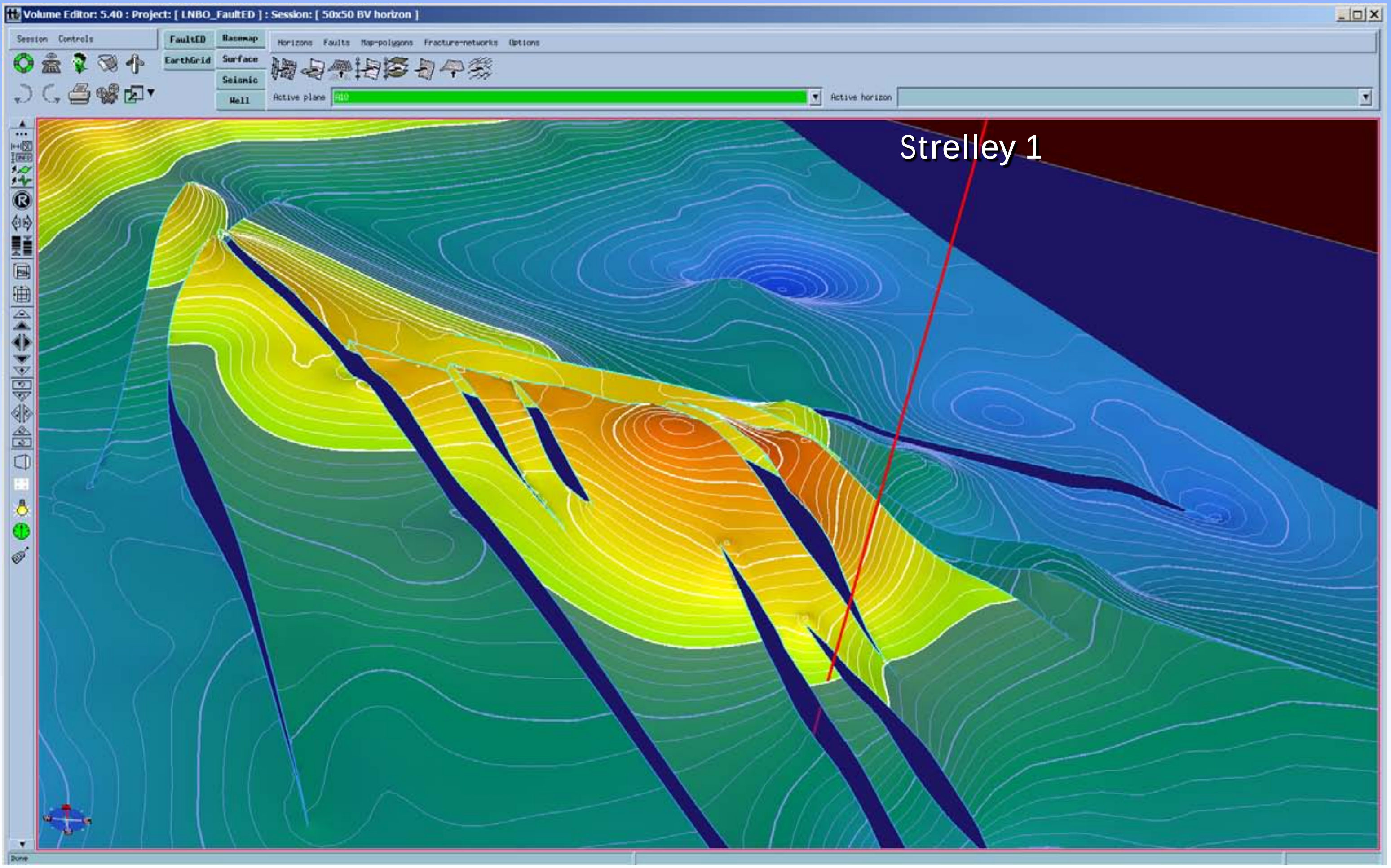
Top reservoir horizon (contour interval = 10 m) + closure if FWL at well.



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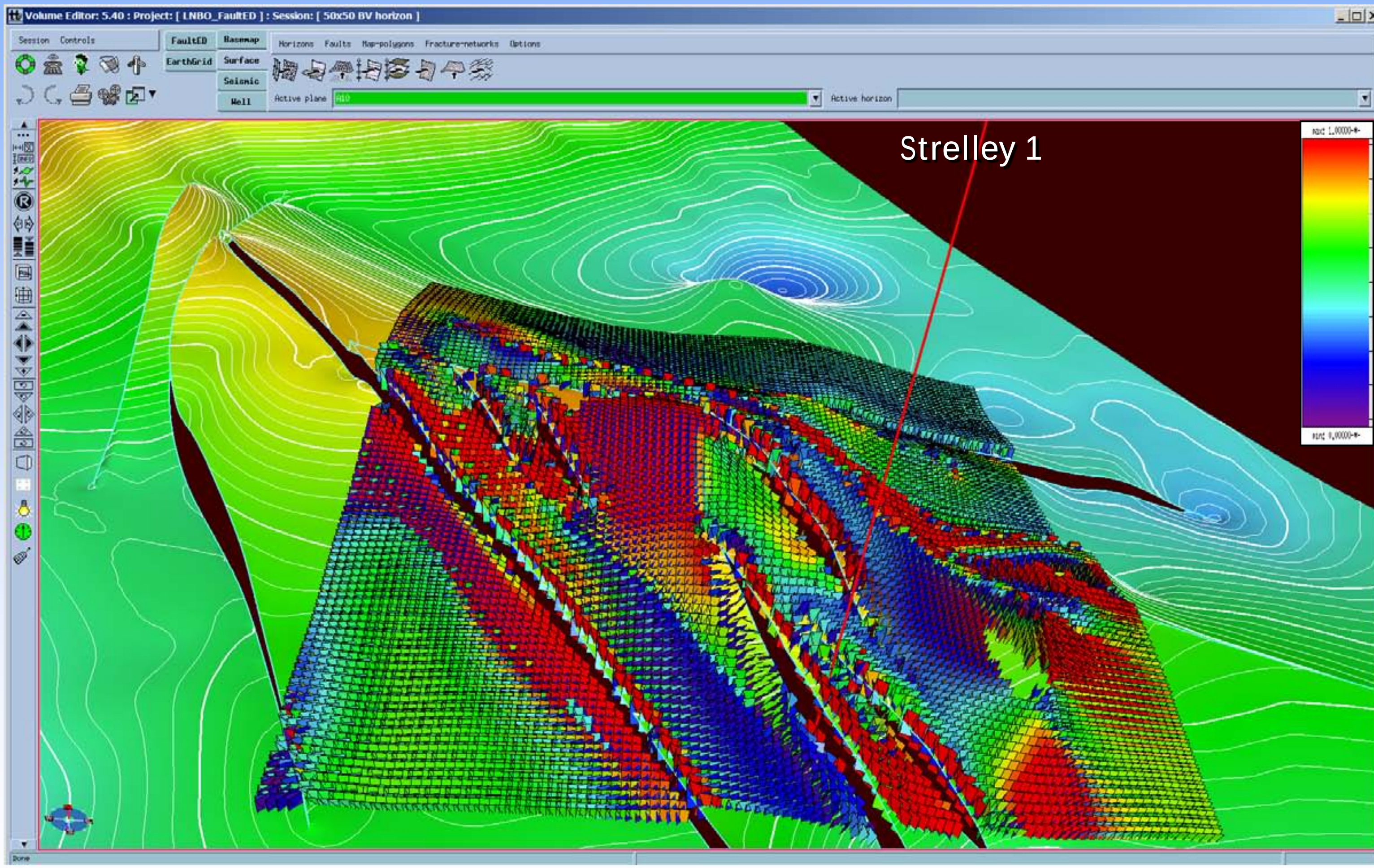
Top reservoir horizon with fractures / slip stability



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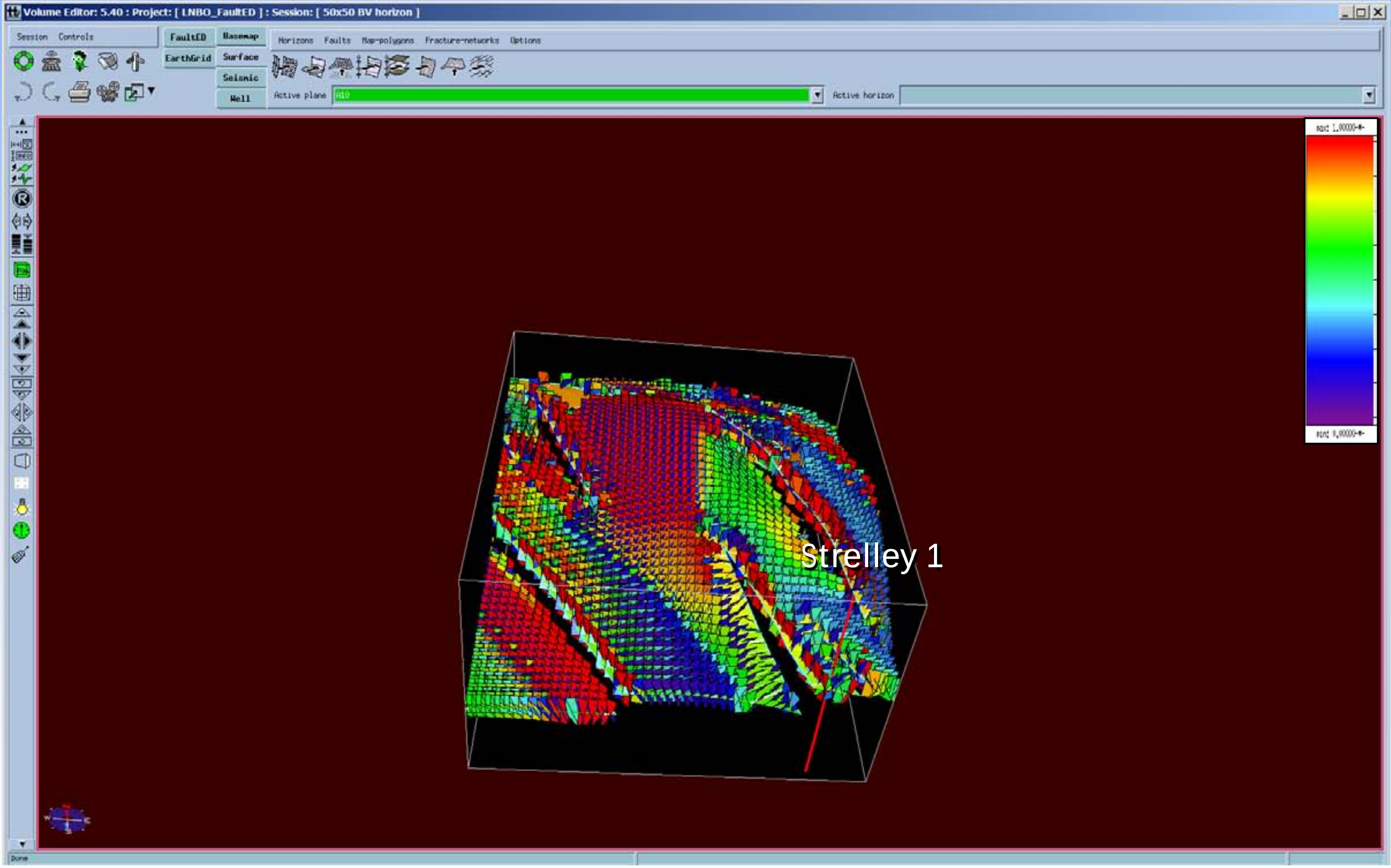

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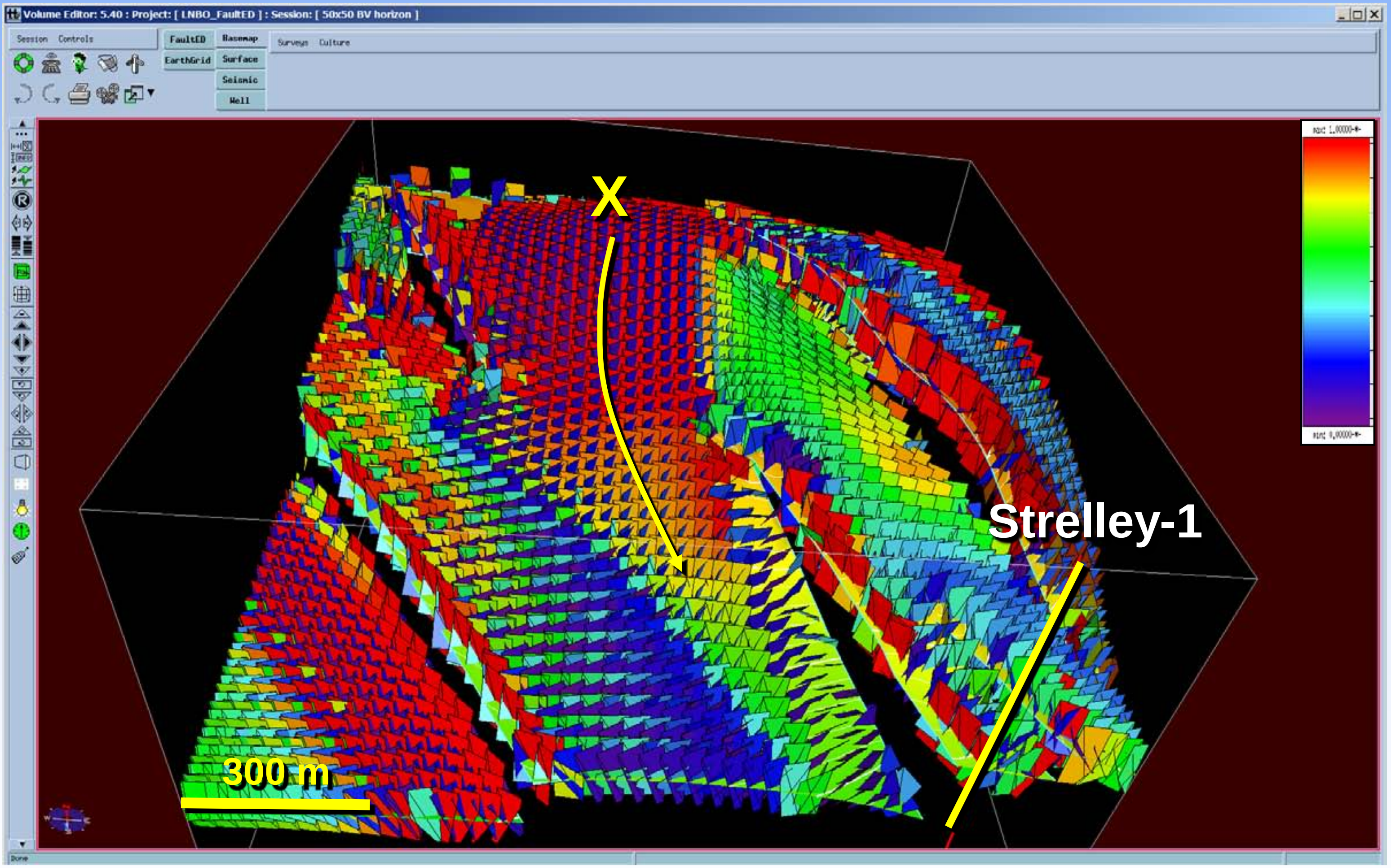

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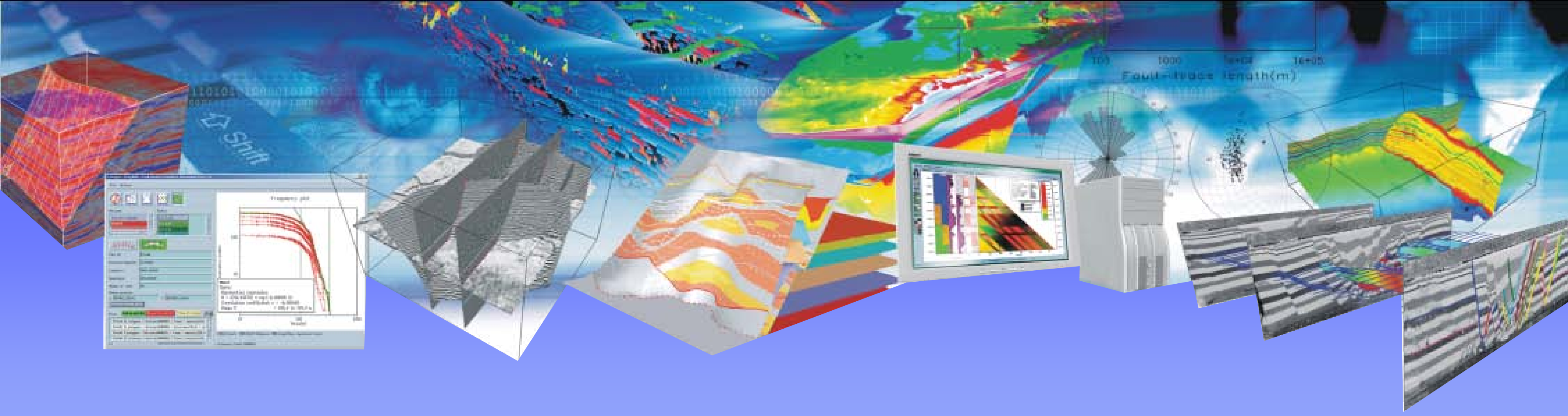

THANKYOU FOR YOUR ATTENTION

Pete. Boult (GINKGO)
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