Click to view movie: The 3D sub-seismic fault network (13.5 mb).

Using Outcrop Geology to Constrain Uncertainties in Three-Dimensional Structural Models of Sub-Seismic Scale Fault Networks*

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Abstract

Three-dimensional (3D) seismic data have insufficient resolution to image faults with throws less than ca. 20 m. Despite their potential impact on reservoir performance, the true 3D structure of sub-seismic scale fault networks has only been determined in exceptional circumstances; for example, by cutting serial sections through faults in unconsolidated sediments or within active opencast mines. A further difficulty has been that most structural datasets from onshore analogues have been collected using traditional mapping techniques, which require the 3D geology and surface topography to be projected onto a 2-D plane (or along a 1-D scan line). Terrestrial laser scanning (TLS) now enables structural geologists to produce 3D representations of geological outcrops ("digital outcrop models"), but faults are generally recorded as intersections on the outcrop surface, rather than planes.

We use a digital outcrop model of sub-seismic scale, post-depositional normal faults from SE Scotland to illustrate a methodology for extrapolating fault surface traces to create a fully 3D fault model. The faults are exposed on the foreshore and in cliffs behind the beach. We created a pseudo-3D seismic grid across the digital outcrop model and extrapolated fault sticks from the surface intersections using geologically driven rules. The cliff section provides constraints on the range of permissible fault dips, fault heights, and the impact of host rock stratigraphy on fault bifurcation. The geometries of larger scale post-depositional normal faults observed in 3D seismic datasets have been used to guide our interpretations of fault tip- and branch-lines. These geological rules provide a

conceptual framework to generate multiple 3D realisations from a single digital outcrop model which could be used to further test the implications of small faults on production flow.

References

De Paola, N., R.E. Holdsworth, K.J.W. McCaffrey, and M.R. Barchi, 2005, Partitioned transtension; an alterantive to basin inversion models: Journal of Structural Geology, v. 27/4, p. 607-625.

Kristensen, M.B., C.J. Childs, and J.A. Korstgard, 2008, The 3D geometry of small-scale relay zones between normal faults in soft sediments: Journal of Structural Geology, v. 30/2, p. 257-272.

Wightman, R.H., J. Imber, and R.R. Jones, 2007, Quantifying fault zone thicknesses and fault rock distribution in Coal Measures sequences using terrestrial laser scan data: GSA Abstracts with Programs, v. 39/6, p. 50.

Using outcrop geology to constrain uncertainties in three-dimensional structural models of sub-seismic scale fault networks?

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FR3DA

Fractured Reservoir 3D Digital Atlas

Durham University

Presenter's Notes:

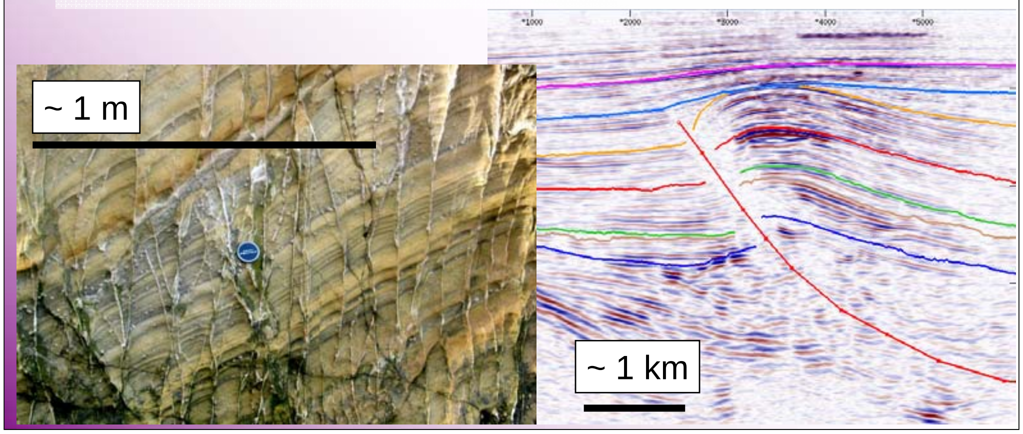
I, Jonathan Long, am a PhD student at Durham University and my talk is on

•Using geological rules and TSL datasets to constrain uncertainty in 3D structural models of sub-seismic scale fault networks

•Which, in real words, just means we are proposing a new way to model SSFN in three dimensions at outcrops by using detailed data collection techniques.

Rationale

- Seismic resolution – many faults & fractures are "sub-seismic"
- Need to define the **3D geometries** of sub-seismic faults & fractures to understand their impact on reservoir performance



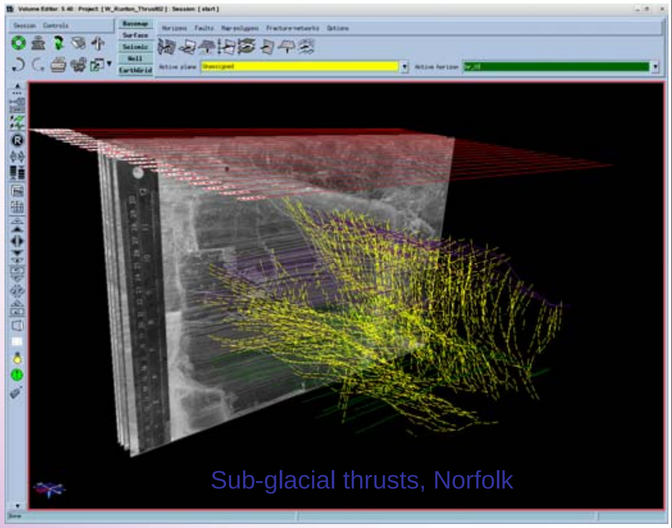
Presenter's Notes:

Simple statement of the overall issue: seismic resolution is a problem; outcrops contain much useful data, etc.

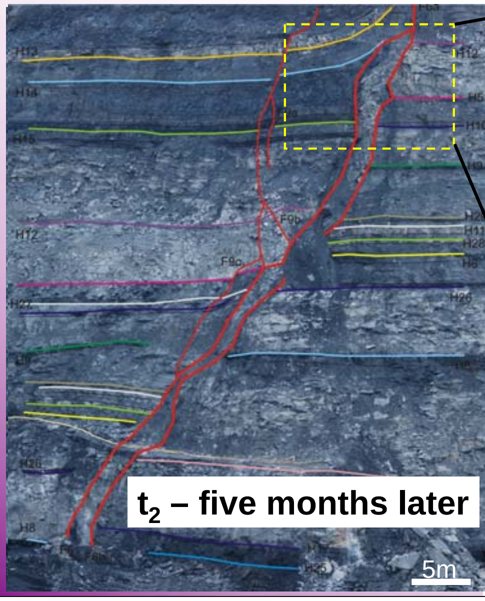
The seismic image is from ConocoPhillips and cleared for display by Neil Grant;note the bright spot in the antiform.

3D fault & fracture geometry – how?

- Reconstruct 3D geometry from serial sections through **soft sediments** (e.g. Kristensen et al. JSG)…



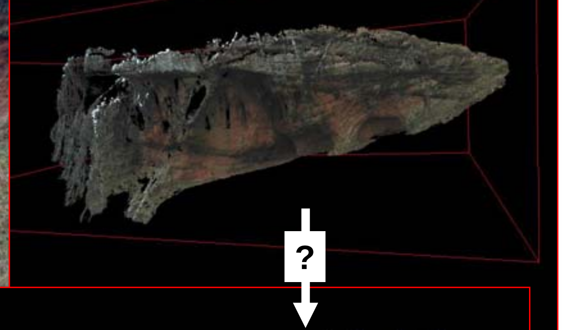
3D fault & fracture geometry – how?



- …or **open cast mines** (e.g. Wightman et al. 2007)
- But limited scope

3D fault & fracture geometry – terrestrial laser scanning (TLS)

Deformation bands, Cumbria



3D topography of outcrop surface; fracture traces in correct XYZ locations

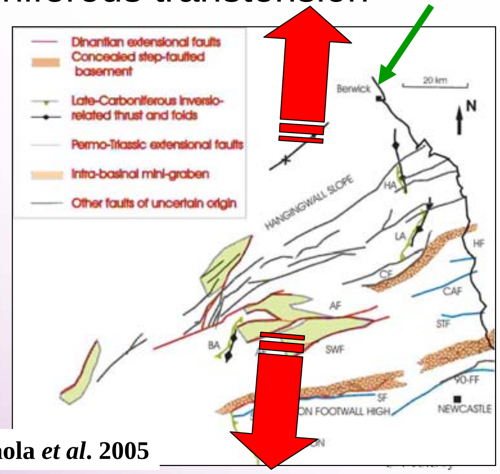
Richard Jones, Ken McCaffrey & Bob Holdsworth

Aim

- Develop a “geologically driven” method for producing **3D fault or fracture surfaces** from laser scan datasets
  – Creating planes from traces
- Sub-seismic scale **post-depositional normal faults**
  – Lamberton, SE Scotland

Lamberton – geological setting

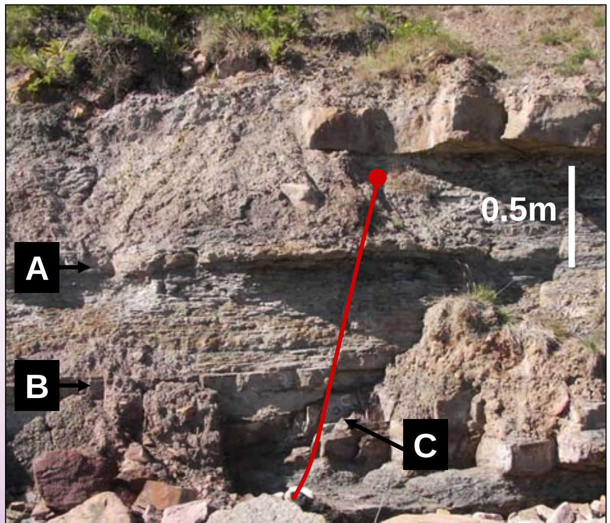
- **Post-depositional normal fault** system
- Developed at northern margin of Northumberland Basin during Late Carboniferous transtension



De Paola *et al*. 2005

Cross-sectional geometry & host-rock lithology

- Interbedded sandstone, shale & coal
- Faults **tip out in shale** above sandstone A
- Maximum throw **~0.3m**
- Focus on deformation in **3 sandstone beds** exposed in wave-cut platform



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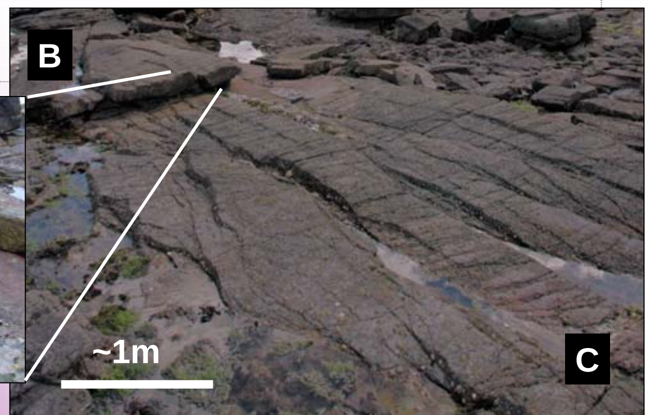
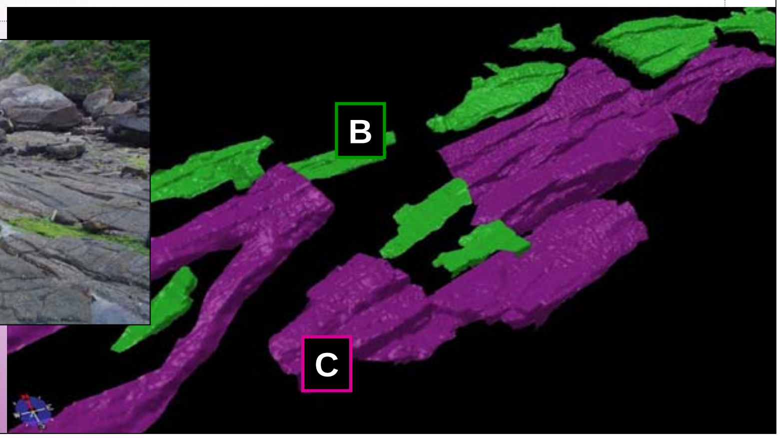
Fault orientation & size

- Fault polygons
- Faults are **highly segmented**
- Bedding sub-horizontal, but dip is variable – ramps

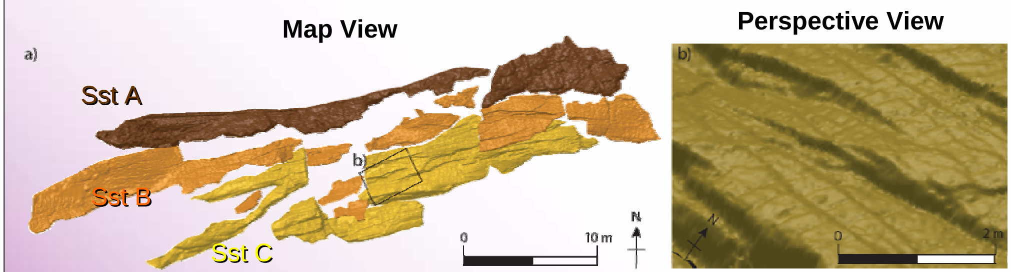


Data capture

- Used TLS to create **high-resolution Digital Elevation Model** (DEM)
- Imported meshed DEM into TrapTester to create fault polygons



Data quality – but then what?



- Meshed surfaces retain important structural information e.g. fault tip locations, bed dip variations
- But fault model limited by height of fault polygons – how can we extrapolate fault network into 3D volume above / below outcrop surface?

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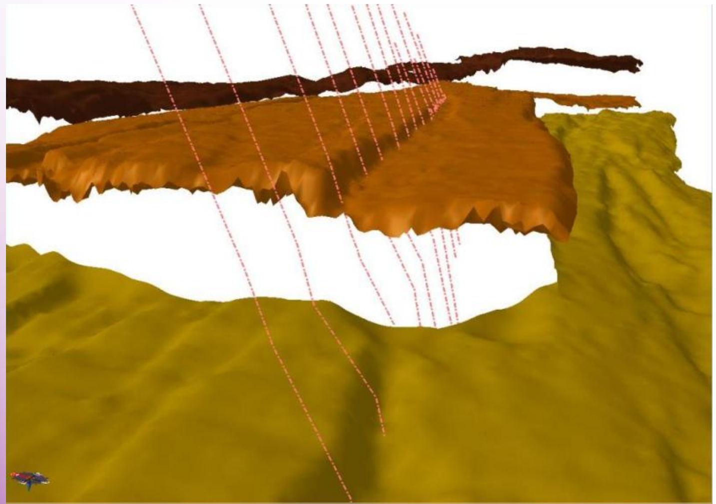
Presenter’s Notes:

There is high detail at one horizon but the problem is that we need to extrapolate the fault network into 3D space.

Is there a better way to extrapolate the fault surfaces?

Methodology



"Geological rules"

- Why use geological rules?
  - Rules are used to guide the extrapolation process
  - Potentially allows multiple realisations
  - More "realistic" models than simply extending fault tip lines??

Schematic cross section

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Presenter's Notes:

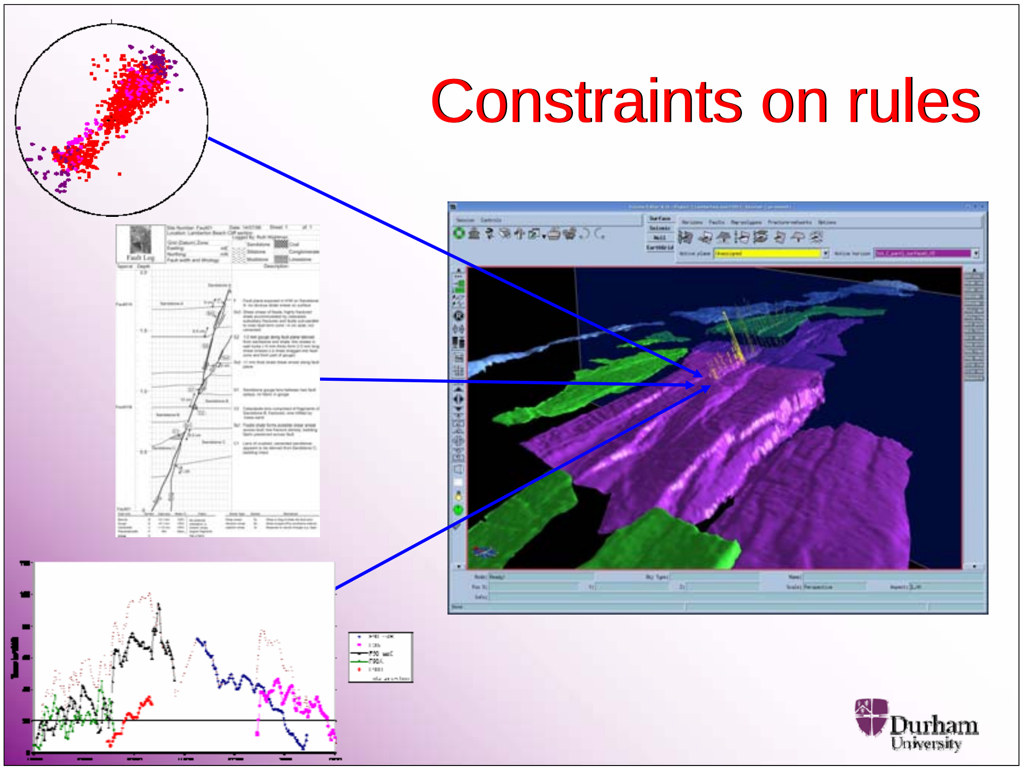
•The first question to answer when modelling:

> •Is what I am modelling actually telling me about what Is being modelled? So in this case does the model produced actually represent the SSFN or is it just random?

•To answer this question we have used geologically defined rules, with high quality data, to make the model as meaningful as possible.

•So Why use rules? Rules are used to guide the model so they can be repeated As Interpreter based extrapolation needs boundaries just like computer based modelling

•To define the rules we used as much data as could be collected from the outcrops at Lamberton, so that the modelled fault network would be as representative as possible of the real fault network



Constraints on rules
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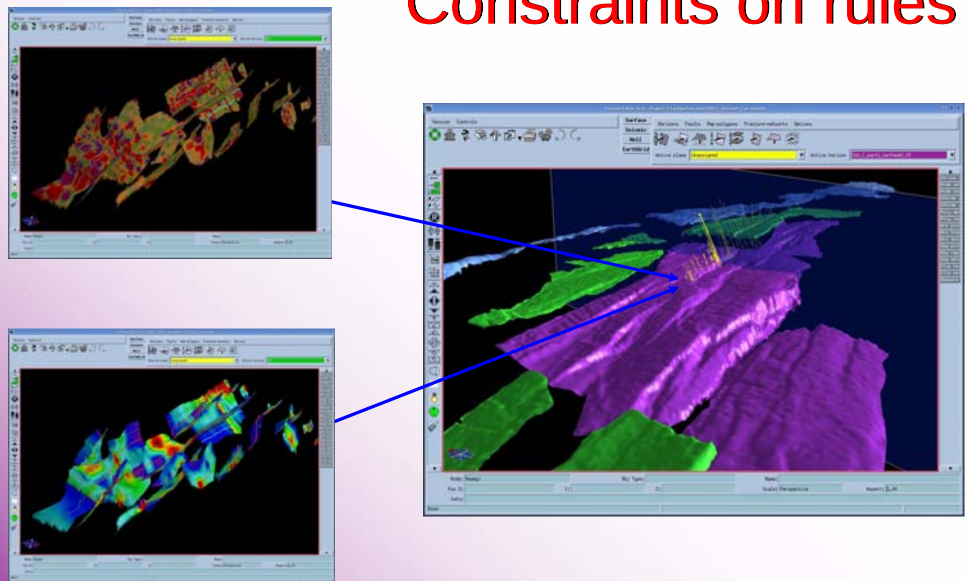
Constraints on rules



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Parameter	Scale range	Parameter range			Comments	Certainty
		Max:	Min:	Avg:		
Fault dip (outcrop scale)	> 1m - < 30 m	70°	55°	60°	Steeper angles are observed in thicker sandstone units, whereas the lower angles are found in interbedded sandstone and shale (approx 10cm thick units).	2
Fault dip (fault interactions)	< 1 m - > 1 cm	20°	5°	10°	Mainly occurring at locations where the overlapping faults have breached, breaching is normally associated with a shale units which allow the accommodation of the near horizontal offset.	3
Fault height (above wave cut platform)	< 30 m	2.5 m	15 cm		Above the wave cut platform, fault depth is unconstrained.	3-4
Fault throw (observed)	< 1 m	183mm	0 mm	44 mm	Maximum off set observed at Lamberton, not including the boundary faults.	2-3
Fault length (observed)	< 55 m	3.2m	0.2m	0.8m	Only faults that show both tip lines are recorded, some faults extend outside the study area.	3
Fault spacing	< 55 m	0.56 m	0.13 m	0.25 m	Observations from a set of 4 sampled lines	3
Overlap distance (relay structures)	< 55 m	1.62 m	0.165 m	0.73 m	Taken from a population of 21	2-3
Separation distance (relay structures)	< 55 m	0.48 m	0.026 m	0.1 m	Taken from a population of 21	2-3

Certainty Scale	Incomplete knowledge of process/theory [a]	Incomplete knowledge of system [b]	Uncertain quality [c]	Uncertain meaning [d]	Conflict [e]	Variability [f]
1 (V. high)	The process/theory is well established	All the data is collected and used	The data reliability[h] is well known and quantified	The data is clearly understood and is well established	All data sources[i] agree	The data points towards a single conclusion
2 (High)	Accepted process/theory; high consensus	All available[g] data is collected and used	The data reliability is partially known and is quantified	The data is mostly understood; high consensus	Good agreement between different data sources	The data points towards a couple conclusions but one is more valid than the others
3 (Mod)	Accepted process/theory; low consensus	High quality sampling of the available data	The data reliability is known but is qualitative	Basic trends in the data are understood; low consensus	Moderate agreement between different data sources	The data points towards a multiple conclusions but one is more valid than the others
4 (Low)	Preliminary process/theory	Moderate sampling of the available data (1D, 2D sampling)	The data reliability is partially known but is qualitative	Educated speculation of the meaning of the data	Weak agreement between different data sources	The data points towards multiple conclusions but some are more valid than others
5 (V. low)	Crude speculation	Poor sampling of the available data (point sampling)	The data reliability is not known and is qualitative	The meaning of the data is unknown; crude speculation	No agreement exists between different data sources	The data points towards multiple conclusions each equally valid

Constraints on rules

- Different structural geologists may disagree on choice of rules…
- …but key point is that they provide a geological basis for extrapolating fault surfaces
- Traceable decisions & multiple realisations

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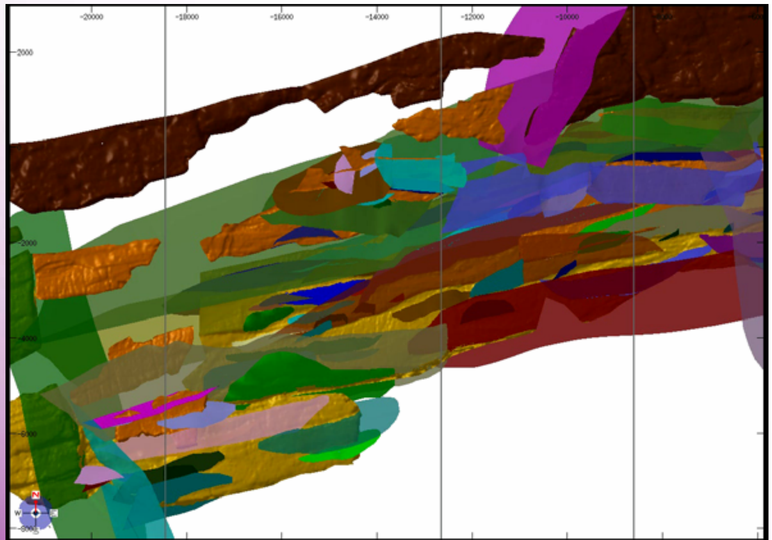
The 3D Sub-Seismic Fault Network



How “correct” is the model?

- No doubt that the realisation here does not match reality!
- But how “right” (or wrong) is it?

Presenter’s Notes:

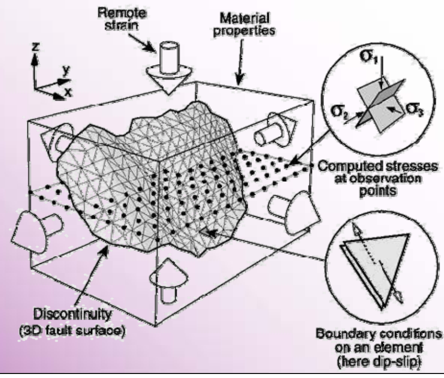
•One advantage of modelling is that multiple realisations can be made from the same raw data as the rules that are used are based on ranges in values. For example, the dip range within a sandstone unit greater than 30cm thick could range from $55\text{-}65^{o}$, so in different realisations the output of these different parameters can be modelled to see if they produced any significant change in the fault network and therefore the potential flow model.

•This technique could be used to investigate if small scale fault variations. For example are the faults linked along horizontal branch lines or do they link along more complex branch line shapes? affect the flow of hydrocarbons within a reservoir. Or are only the general features of a fault network needed--are faults linked at small scales or not?

•The significance of this would be to ascertain how much detail is needed to represent the proportion of the fault network that affects fluid flow within reservoirs and what is unnecessary detail. This will save time and money in investigating SSHF or on the flip side it will highlight that small scale SSFN are important in flow modelling and more work should be done.

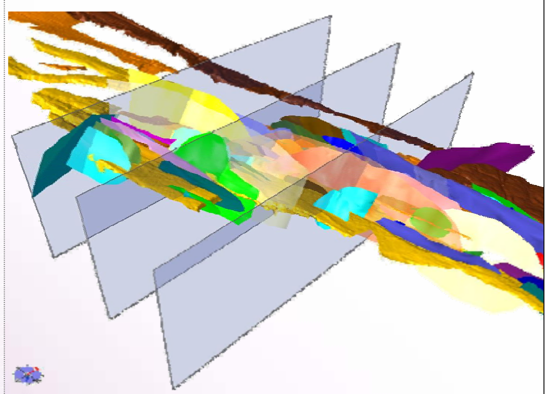
Testing the model?

- Kinematic restoration e.g. 3D Move?
- Geomechanical modelling e.g. FaultED?
- Forward modelling?



Conclusion

- Method to create 3D models from "typical" outcrop analogues of faulted reservoirs
- Allows multiple realisations with traceable decision making
- Potentially testable



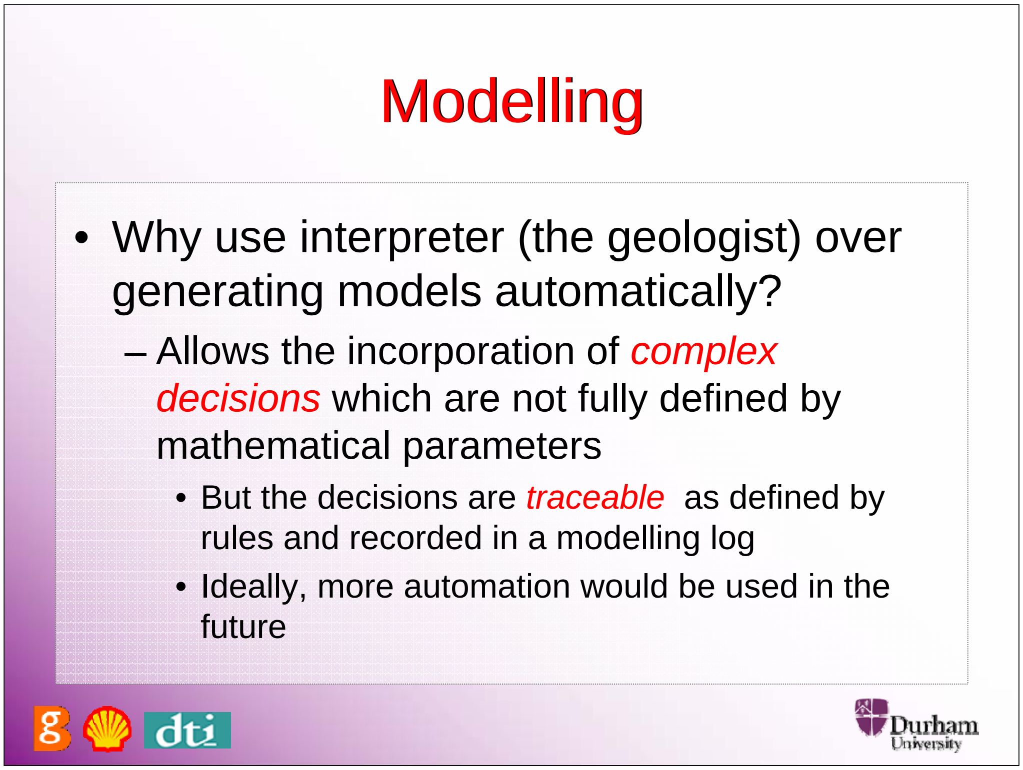
Presenter's Notes:

The final conclusions are:

•This modelling technique can utilise existing outcrops of fractured reservoirs--and is not limited to mines or soft sediments, therefore expanding the possible analogue sites that can be studied; this may be more comparable to actual reservoir rocks.

•The technique also takes advantage of highly accurate 3D data, which reflects the complexities observed in naturally faulted rocks, therefore making the resultant fluid flow model more representative of the real flow conditions.

•Finally as just mentioned, multiple realisations can test the effect of small-scale faults variations on fluid flow; this can be used to help guide research efforts in the future.



Presenter’s Notes:

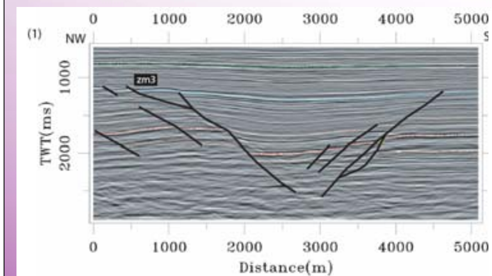
•One question could be asked: Why did we use interpreter over computer modelling techniques, and the answer is: it allows the incorporation of *complex decisions* which are not fully defined by mathematical parameters, but it is important to add that the decisions are *consistent* as defined by rules mentioned earlier. Ideally computer based interpretations would be used in the future, as it is easier to build them by hand following inputs that can be later turned into a computer model, for if it does not work you haven't wasted your time programming.

•Associated errors allows different parts of the model to be *compared*, in relation to its quality, and allows an *informed decision* to be made on the *reliability* of the flow readings.

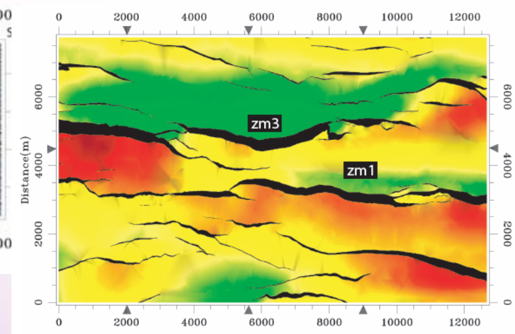
The modelled fault network #1

- Realistic model
  - Retains the *complexity* of *naturally* faulted rock

Cross Section



Map View



Presenter's Notes:

•Here we have a cross section and map view through the modelled seismic volume, and as you can see, it retains the natural complexities seen in comparable seismic data sets, such as faults networks from the IMF, which show similar features both in cross section as well as map view.