Remote Sensing of Subsurface Fractures: A South Australian Case Study*

Adam Bailey[1], Rosalind King[2], Simon Holford[1], Joshua Sage[2], and Martin Hand[3]

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[1]Australian School of Petroleum, University of Adelaide, Adelaide, South Australia, Australia (adam.bailey@adelaide.edu.au)
[2]School of Earth and Environmental Sciences, University of Adelaide, Adelaide, South Australia, Australia
[3]South Australian Centre for Geothermal Energy Research, University of Adelaide, Adelaide, South Australia, Australia

Abstract

South Australia's Penola Trough was used as a natural laboratory for the detection of naturally occurring fractures, following an integrated methodology, which included identification and interpretation of fractures in wellbore image logs and core, and the remote detection of fractures in a 3D seismic volume. In this study, electrical resistivity image logs from 11 petroleum wells were interpreted for structural features, with 508 fractures and 523 stress indicators identified. Stress indicators demonstrate a mean maximum horizontal stress orientation of 127°N in the Penola Trough. Two fracture types were identified: 1) 268 electrically conductive (potentially open to fluid flow) fractures with mean NW-SE strikes, and; 2) 239 electrically resistive (closed to fluid flow) fractures with mean E-W strikes. Core recovered from Jacaranda Ridge-1 shows open fractures are rarer than image logs indicate, due to the presence of fracture-filling siderite. Siderite is iron-rich, electrically conductive cement that may cause fractures to appear hydraulically conductive in resistivity-based image logs. Fracture susceptibility plots created using the defined stress orientation, and previously derived magnitudes, illustrate that the majority of fractures detected are favourably oriented for reactivation under in-situ stresses. However, it is demonstrated that fracture fills exert a primary control over which fractures are open to fluid flow in the sub-surface. As natural fractures generally lie below the resolution of seismic amplitude data, seismic attributes were calculated from the 3D Balnaves/Haselgrove survey and mapped to the target Pretty Hill Formation to enhance observations of structural fabrics. Linear discontinuities likely to represent faults and fractures were identified with orientations consistent with natural fracture orientations identified in image logs, striking E-W and NW-SE. However, these are mostly limited in extent to zones around larger faults and so likely represent damage zones. Additionally, it is unlikely that a large proportion of these fractures are open to fluid flow, given observations from core and image logs. This limits possible fracture connectivity and, therefore, the possibility of significant secondary permeability in the Penola Trough. This integrated methodology provides an effective workflow for the remote detection of natural fractures, and for determining whether those fractures are hydraulically conductive.

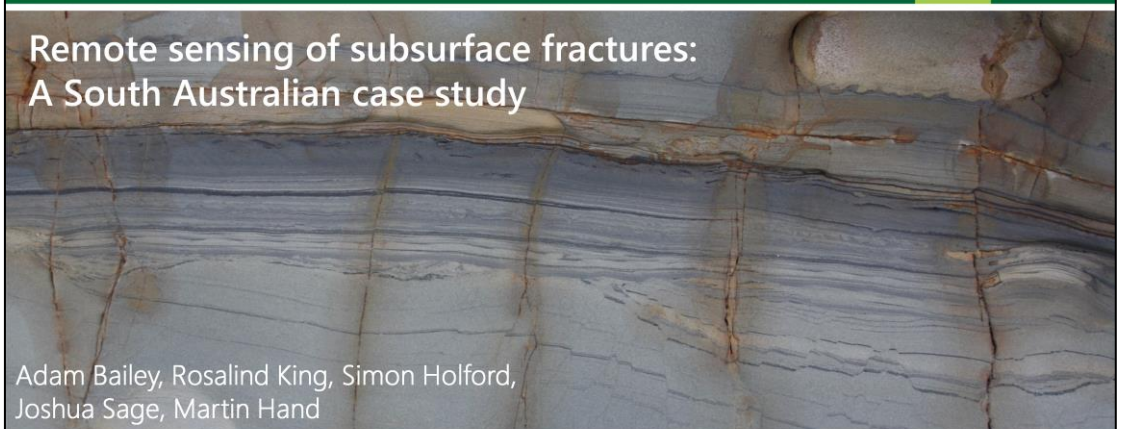
Selected References

Nicol, A., J. Watterson, J.J. Walsh, and C. Childs, 1996, The shapes, major axis orientations and displacement patterns of fault surfaces: Journal of Structural Geology, v. 18/2-3, p. 235-248.

Odoh, B., J. Ilechukwu, and N. Okoli, 2014, The Use of Seismic Attributes to Enhance Fault Interpretation of OT Field, Niger Delta: International Journal of Geosciences, v. 5, p. 826-834, doi:10.4236/ijg.2014.58073.

S3 Seismic Structure Stress

Remote sensing of subsurface fractures: A South Australian case study



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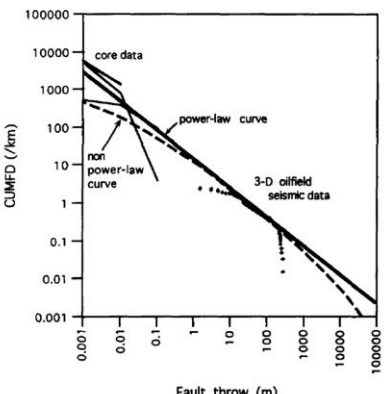
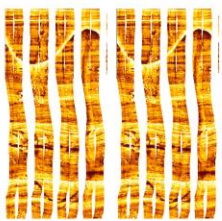
What is a natural fracture?

- Common feature of the brittle crust
- A failure of a rock due to stresses exceeding rock strength
- Are considered to be scale invariant and are often described as being fractal or self similar (power-law relationship)



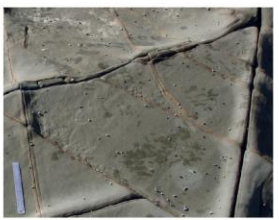
Power-law relationship for fault length and fault throw (Nicol et al., 1996)

How are fractures identified?



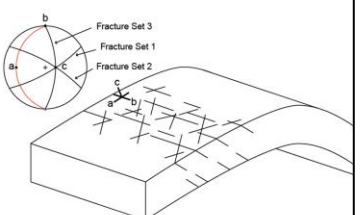
Wellbore geophysical and image logs

Recovered core



Surface Analogues

2D and 3D seismic to identify geological structures that are likely to be fractured



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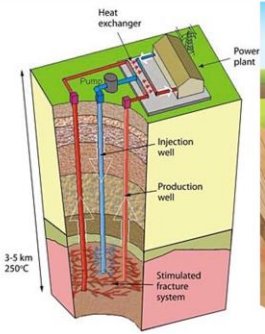
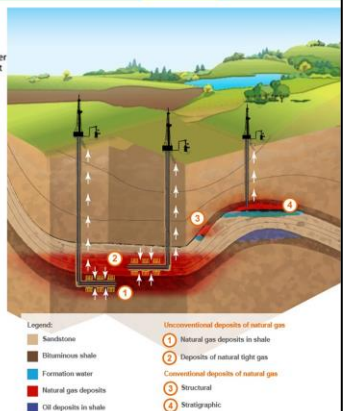
Why are we interested in fractures?

- When optimally oriented, can serve as fluid conduits
- Can provide interconnected, hydraulically conductive networks
- Allow significant fluid transport through low permeability rocks
- Are the primary means for fluid flow in low permeability reservoirs





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A brief outline:

- The Penola Trough
- Methods and Results
  - Natural fractures
    - Image logs
    - Core
    - 3D seismic attributes
- Fault and fracture reactivation
- Open vs. closed fractures
- Seismic attribute mapping
- Fracture fill as a control on structural permeability
- Conclusions

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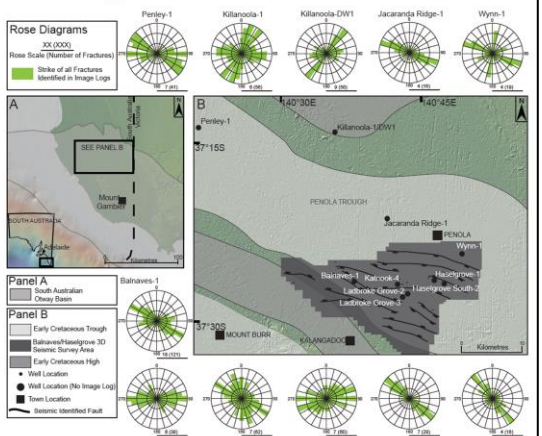
South Australian Otway Basin: The Penola Trough

- One of three basins formed from the rifting of Australia and Antarctica
- Rifting in the Otway began in the Late Jurassic
- A series of large half-grabens were created
- Characterised by a strike-slip regime, NW-SE orientation



Presenter's notes:
- Rifting began in the Bight Basin in Middle Jurassic, spread to Otway and Gippsland by Late Jurassic
- Penola Trough is defined by large east to west striking normal faults
- extensive inversion and uplift observed through the Otway Basin, however, the Penola Trough shows little evidence of this
- Debate around strike-slip or reverse (King et al 2012)
- Site of ongoing petroleum and geothermal exploration.
- Natural laboratory

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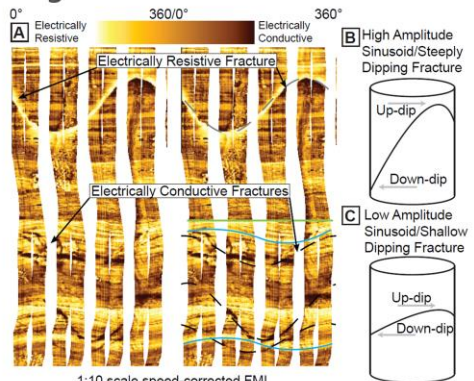
Methods and results: data

- Interpreted 11 electrical resistivity based image logs for natural fractures
    - 508 natural fractures
- Interpreted core from Jacaranda Ridge-1
    - 44 observed fractures
- Seismic attribute modelling of the Pretty Hill Formation in Balnaves/Haselgrove 3D seismic survey
    - A natural structural fabric observed

Methods and results: Fractures on image logs

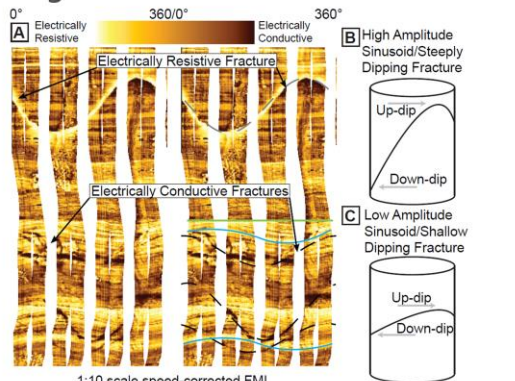
- Electrical resistivity image logs provide a high resolution pseudo-image of the borehole wall
- Fractures appear as sinusoids: Up-dip section represented by peak, down-dip by trough
- Important to distinguish between pre-tectonic and syn-tectonic features



1:10 scale speed-corrected FMI

Methods and results: Fractures on image logs

- Identified as either electrically resistive or conductive:
  - Resistive considered closed
  - Conductive considered open



1:10 scale speed-corrected FMI

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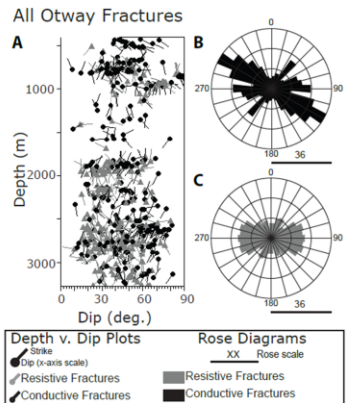
Methods and results: Fractures on image logs

- 508 fractures identified in eleven wells
- Field wide mean E-W strike (100°N-280°N)
  - Conductive fractures – mean NW-SE strike (120°N-300°N)
  - Resistive fractures – mean E-W strike (090°N - 270°N)
- Intermediate dips of 30-60° are the majority of fractures
- Both fracture types are present at all depths



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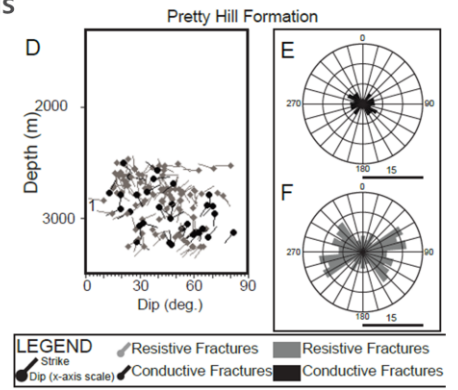
Methods and results: Fractures on image logs

- Pretty Hill Formation is a primary target reservoir
  - 133 fractures identified
    - 100 electrically resistive (striking 115°N - 295°N)
    - 33 electrically conductive (striking 100°N - 280°N)



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Presenter's notes:
- Pretty Hill
- **conductive** with approximate northwest to **southeast** strikes
- 100 are **resistive** striking approximately **east to west**

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Methods and results: Fractures in core

- Core from Jacaranda Ridge-1 was examined for natural fractures
- Intersects the Sawpit Sandstone from 2633.0 – 2643.5 mTVD
- Several zones of fracturing were identified
  - 44 fractures observed

Identified fracture type	Number of fractures	Percentages
Open	9	20%
Sealed	29	66%
Siderite fill	6	14%

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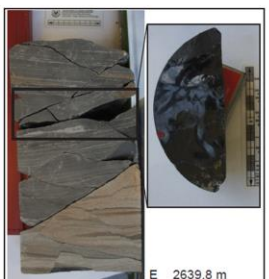
Presenter's notes:
- 44 fractures being observed in the 20.5 m section
- nine fractures were open
- 29 sealed by cataclasites mineral deposition or a fused fault gouge material
- six were sealed with cement that included visible siderite mineralisations

Methods and results: Fractures in core


E 2639.8 m

NOTE: All photos feature an individual scale.

A 2633.0 m

B 2636.5 m

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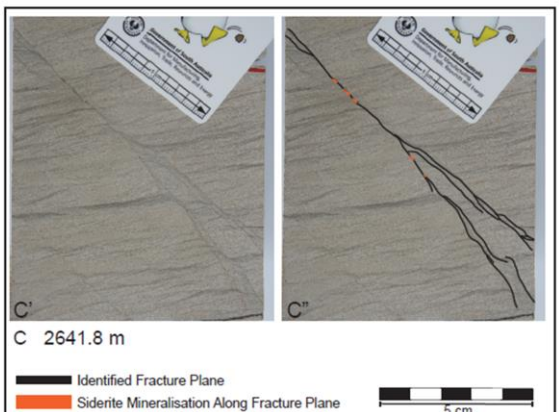
Methods and results: Fractures in core



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Presenter's notes:
- Siderite is an iron-carbonate mineral and so is likely to appear as electrically conductive on image logs

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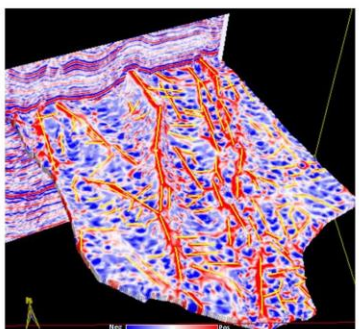
Methods and results: 3D seismic analysis

- The majority of faults and fractures lie below seismic resolution
- Lithologies less than ~25 m thick and faults with throws less than 10-15 m may not be resolved
- Techniques for improved sub-seismic amplitude detection exist
- The primary method is through the calculation of 3D seismic attributes



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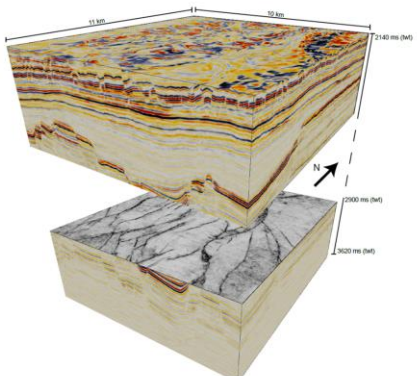
Methods and results: 3D seismic analysis

- Faults and fractures have been successfully mapped with 3D attributes
- Most commonly curvature and similarity, due to established correlations
- However, curvature in seismic data can be due to an array of tectonic features



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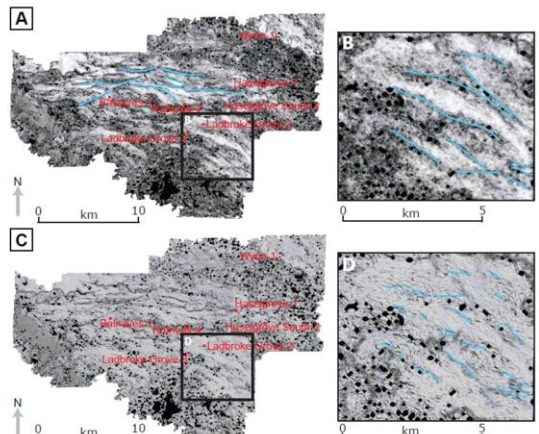
Methods and results: 3D seismic analysis

- Balnaves/Haselgrove survey
  - Good well control
  - Decent quality
- Numerous igneous intrusions
- Dominant E-W fault trend, secondary NW-SE trend
- Attribute mapping of the Pretty Hill Formation



Presenter's notes:
- covers a large area of the Penola Trough, interpreted wells
- relatively good for an onshore survey, several large igneous intrusions shadowing underlying sediments
- Pretty Hill Formation, a primary target reservoir within the Penola Trough, identifies a structural fabric that is mostly constrained to the local area of larger faults

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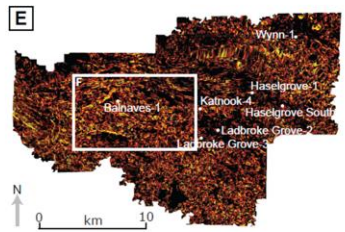
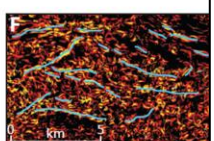
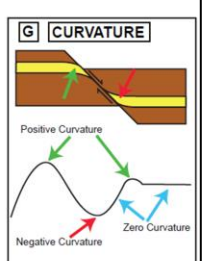
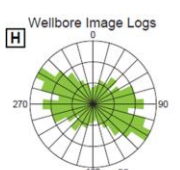
Methods and results: 3D seismic analysis

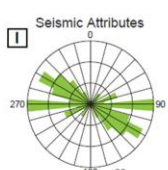
- A structural fabric mostly constrained to the vicinity of larger faults
- Two major trends are identified
  - East to west
  - Northwest to Southeast











Presenter's notes:
- Pretty Hill Formation, a primary target reservoir within the Penola Trough, identifies a structural fabric that is mostly constrained to the local area of larger faults

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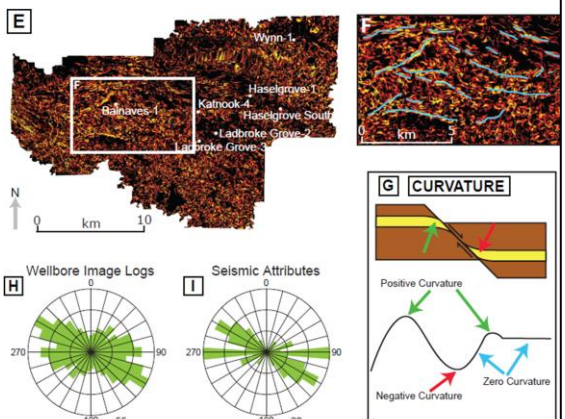
Methods and results: 3D seismic analysis

- Discontinuities and curvature lineations are associated with faults
- Smaller scale attribute features likely represent fractures in fault damage zones
- Orientations match those of the image log identified natural fractures



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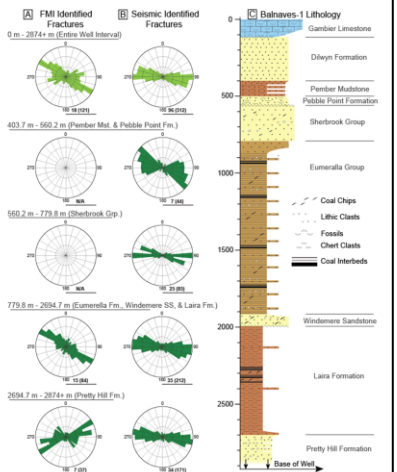
Methods and results: 3D seismic analysis

- Pseudolog of curvature derived lineations for Balnaves-1
- Lineation orientations can be seen to closely reflect, and perhaps predict, natural fracture orientations
- Link between curvature lineations and fracture orientation



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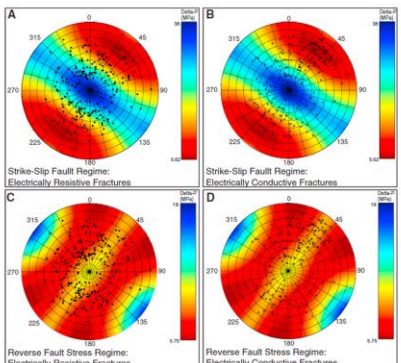
Fault and fracture reactivation

- Fracture susceptibility plots use the same principles as Mohr circles to assess failure likelihood
- Majority of image-log identified fractures plot in high likelihood areas
- Applies to both electrically resistive and conductive fractures



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Presenter's notes:
- Siderite has been previously identified in the three basins
- Identifying siderite not as simple as looking for electrically conductive fractures not oriented for reactivation
- It is equally likely such fractures could be stress-insensitive fractures
- Fractures inferred to be open to fluid flow are also possibly reactivated by high mud weights during well operations, and may not be representative of the fracture away from the wellbore

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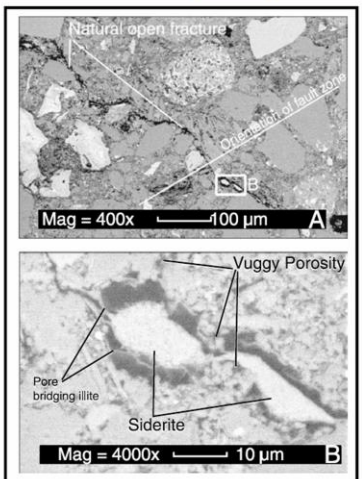
Open vs. Closed fractures

- Many fractures plot as "susceptible," when they are clearly closed
- Majority of fractures in core are closed, but a large proportion of image log fractures are electrically conductive
- Siderite, an electrically conductive mineral, is seen as a fracture fill in core
- Siderite cementation may preserve partial fracture permeabilities



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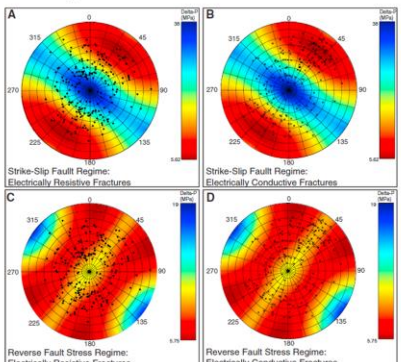
Fracture fill as a control on structural permeability

- Previous studies have shown fracture fills to be significantly stronger than the surrounding host rock
- Reactivation is governed by the level of cementation along the fracture plane
- Likelihood of reactivation depends on not only fracture orientation within the stress field, but also the nature of fracture closure



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Presenter's notes:
- significantly stronger than the surrounding host rock due to preferential cementation
- Fault strength can increase above that of the host lithology through significant cementation, resulting in the creation of new fractures within the host rock, rather than reactivation of existing fractures, due to deformation from reactivation being preferentially partitioned into the weaker host sediments
- these strengthened fractures are likely represented in fracture reactivation plots as optimally oriented resistive fractures

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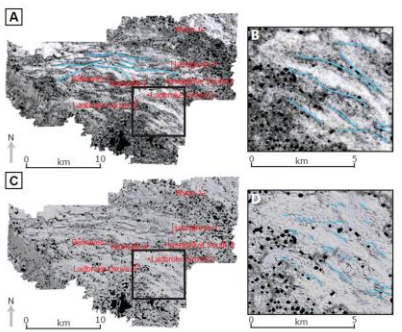
Seismic attribute mapping

- A pervasive natural fabric is identified on the top Pretty Hill Formation
- Fabric can be correlated to natural fractures in image log and core
- Interpretation can therefore be extended regionally
- Fractures seen to be concentrated around larger structures in fault damage zones
- Very little crossover or linkage is seen between these areas
- A larger network of fractures at depth is therefore considered to be unlikely



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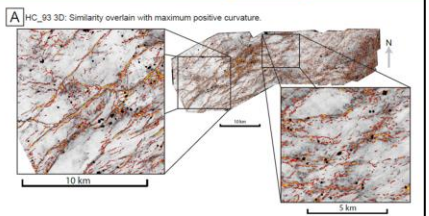
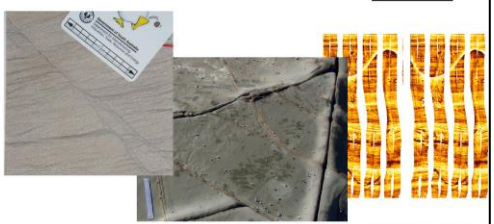
Concluding remarks

- Fractures which are optimally oriented for reactivation within the stress field are not necessarily hydraulically conductive
- Siderite is present as a fracture fill in core, making it likely many "conductive" fractures identified on image logs are actually sealed





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Presenter's notes:
- an integrated geological and geophysical approach making use of wellbore image log data, 3D seismic attribute analysis, and observations of both core and outcrop
- an effective method by which structural permeability can be assessed with various levels of data availability
- Each basin has different controls on the initial formation of fractures and which fractures are likely to be open to fluid flow at the present day

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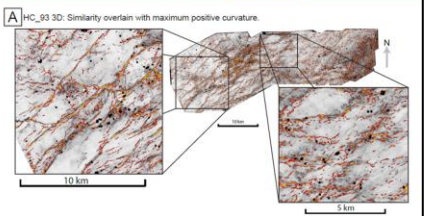
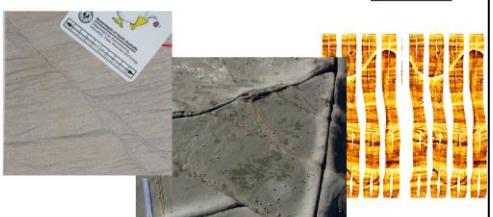
Concluding remarks

- Fracture fills control which fractures are likely to be open in the sub-surface
- Seismic attributes can be correlated to natural fractures identified in image logs and core, and used to make regional assessments of fracture networks





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Acknowledgements

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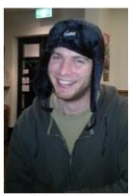
Mr Joshua Sage

Dr Rosalind King

Dr Guillaume Backé

Dr Simon Holford

Prof. Martin Hand

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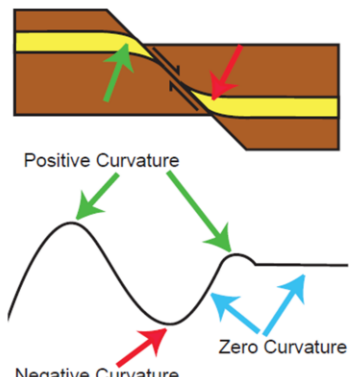
Fractures in 3D seismic: Curvature

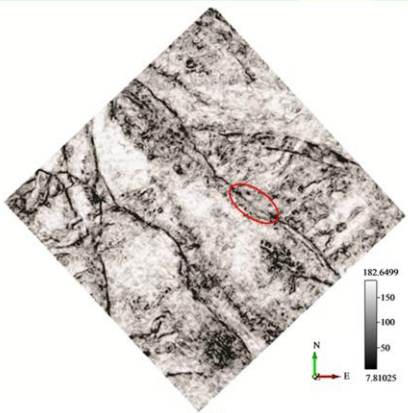
- The degree that a surface deviates from being planar
- Of greatest interest are most positive and most negative curvatures
- Fault trend definition is enhanced, with structures appearing as distinct lineations on the attribute draped surfaces



S3 Seismic Structure Stress

Fractures in 3D seismic: Similarity

- A form of coherency expressing how much two trace segments look alike
- Identical traces have a similarity of one, completely discontinuous traces have similarity of zero
- As fractures and faults are discontinuities, they are likely to be highlighted

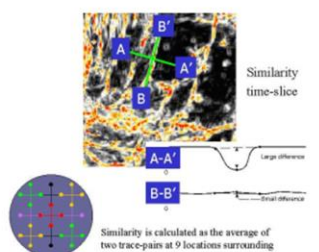


Full-steered minimum similarity, O^T Field, Niger Delta (Odoh et al, 2014)

Fractures in 3D seismic: Ridge Enhancement

- Compares neighbouring similarity values in six directions and outputs largest ridge value
- Majority of points feature small values
- When a discontinuity is crossed, a large ridge is calculated perpendicular to the fault direction

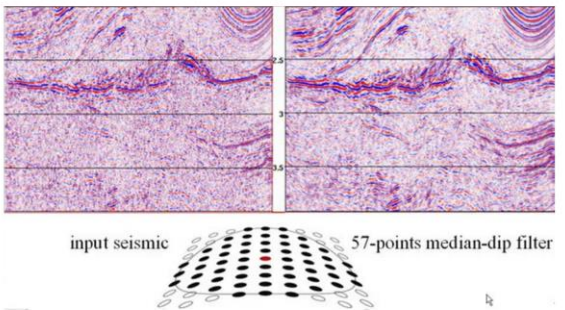
$$\sum \frac{Values\ either\ side}{2} - centre\ value$$



The Ridge Enhancement Filter (OpendTect, 2014)

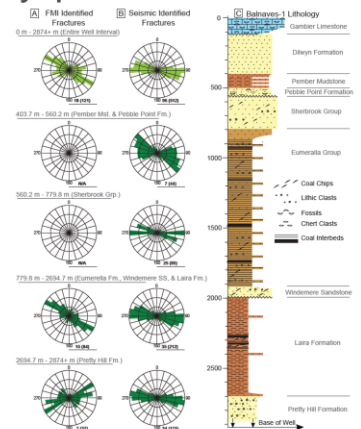
Fractures in 3D seismic: The dip-steered median filter

- Guides attributes along a 3D surface of approximately equal seismic phase
- Median filter replaces the centre amplitude in a dip-steered circle with the median value
- Effectively filters noise and provides an edge-preserving smoothing



Dip-steered median filter applitcation (OpendTect, 2014)

Key questions: Can 3D seismic attributes identify fractures?

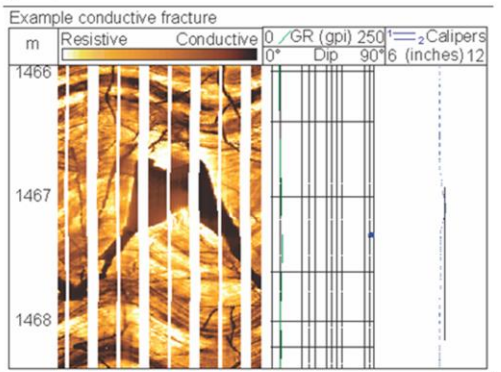


- A pseudo-log of attribute features highlights the strong correlation between fractures identified on image logs and the identified structural fabrics, even on a small scale
- Fracture orientations are predicted by the seismic attribute analysis
- It is likely that attributes are detecting these fractures, and can be used to estimate extent and potential connectivity of natural fractures

S3 Seismic Structure Stress

Key questions: Are open fractures actually open?

- Fractures in resistivity image logs are generally categorised as either electrically resistive (closed) or electrically conductive (open)
- Numerous studies have correlated electrical conductivity with hydraulic conductivity
- Examples can be seen in Australian basins, however, the assumption may not always be correct



Presenter's notes:
- The power-law relationship makes it likely that those smaller-scale features are due to similar geological phenomena

S3 Seismic Structure Stress

Methods and results: In-situ stresses

Orientation determined through image-log analysis

- Maximum horizontal stress orientation of 127°N
- Previously reported as 125°N

Nelson et al. (2006) suggest a strike-slip fault regime

King et al. (2012) suggest a reverse fault regime

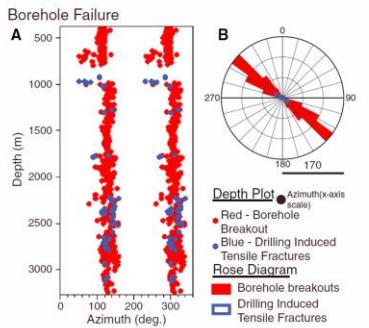


Figure 3. (a) A depth versus dip plot illustrating the depths at which each identified failure (either breakout or drilling-induced tensile fractures) was observed and the stress orientation interpreted from it, and (b) a Rose diagram illustrating the mean NW-SE maximum horizontal stress orientation derived for the South Australian Otway Basin from both borehole breakouts and drilling-induced tensile fractures.

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Presenter's notes:
- In the Northern Perth and Otway Basins, increased fluid flow has been observed in areas hosting large numbers of electrically conductive fractures.
- Northern Perth Basin: fluid losses interpreted as drilling mud being conducted away from the wellbore by open natural fractures
- Otway Basin: increased fracture densities have been demonstrated to correlate to increased gas flows in petroleum wells