PS Structural Permeability in Australian Sedimentary Basins*

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

Search and Discovery Article #11054 (2018)**
Posted March 12, 2018

*Adapted from oral presentation given at AAPG International Conference and Exhibition, London, England, October 15-18, 201

[1]University of Adelaide, Adelaide, SA, Australia (adam.bailey@ga.gov.au)
[2]Beach Energy, Adelaide SA, Australia

Abstract

Declining conventional hydrocarbon reserves have triggered a shift in exploration of energy-rich Australian basins towards unconventional sources, such as coal seam and shale gas, as well as thermal energy from enhanced geothermal systems (EGS). Unconventional play and EGS viability often depends on secondary permeability due to interconnected natural fractures that commonly exert a prime control over absolute permeability due to degraded primary permeability. Structural permeability of the Northern Perth, South Australian Otway, and Northern Carnarvon basins are characterised via an integrated approach combining geophysical wellbore logs, seismic attribute analysis and detailed structural descriptions of core and outcrop. Integration of these methods allows for identification of faults and fractures at a range of scales, providing crucial permeability information. This study raises three significant scientific questions: 1) What are the main factors controlling fracture reactivation in Australian basins? 2) Can 3D seismic attributes be used to identify fractures in the subsurface beyond the wellbore? 3) Are electrically conductive fractures in image logs actually open to fluid flow? We demonstrate distinct correlations between aligned natural structures identified in 3D seismic attribute analysis and natural fractures identified through interpretation of electrical resistivity image logs, implying that similar features at different scales are being identified. Fracture reactivation within the basins, in particular the Otway and Carnarvon basins, is demonstrated to be complex, depending not only on the in-situ stress regime but also fracture fills and pre-existing local and regional structures. Natural fractures identified on image logs as being electrically conductive are generally assumed to be hydraulically conductive. However, core from the Otway Basin shows open fractures are rarer than image logs indicate, likely due to the presence of fracture filling siderite, an iron-carbonate that may cause fractures to appear hydraulically conductive on image logs. The techniques demonstrated in several case studies represent an effective method for assessing regional structural permeability with various levels of data availability. Basinwide structural permeability is constrained using a variety of data, ranging from predominantly image logs supported by 3D seismic, to performing a basin-wide assessment using image logs, 3D seismic, core, and outcrop studies.

References Cited

Bailey, A., R. King, S. Holford, J. Sage, G. Backe, and M. Hand, 2014, Remote sensing of subsurface fractures in the Otway Basin, South Australia: Journal of Geophysical Research: Solid Earth, v. 119/8, p. 6591-6612.

Bailey, A., R. King, S. Holford, J. Sage, M. Hand, and G. Backe, 2015, Defining structural permeability in Australian sedimentary basins: The APPEA Journal, v. 55/1, p. 119-148.

Bailey, A.H.E., 2016, Structural permeability in Australian sedimentary basins (Doctoral dissertation).

Nicol, A., J.J. Walsh, J. Watterson, and P.G. Bretan, 1995, Three-dimensional geometry and growth of conjugate normal faults; Journal of Structural Geology, v. 17/6, p. 847-62.

Peacock, D.C.P., and A. Mann, 2005, Evaluation of the controls on fracturing in reservoir rocks: Journal of Petroleum Geology, v. 28/4, p. 385–96.

Sibson, R.H., 1996, Structural permeability of fluid-driven fault-fracture meshes: Journal of Structural Geology, v. 18/8, p. 1031-1042.

Walsh, J.J., and J. Watterson, 1993, Fractal analysis of fracture patterns using the standard box-counting technique: valid and invalid methodologies: Journal of Structural Geology, v. 15/12, p. 1509-1512.

STRUCTURAL PERMEABILITY IN AUSTRALIAN SEDIMENTARY BASINS

Dr. Adam Bailey[1,2], Dr. Rosalind King[3], Dr. Simon Holford[1], Joshua Sage[3,4], Prof. Martin Hand[3,5]

adam.bailey@ga.gov.au, rosalind.king@adelaide.edu.au, simon.holford@adelaide.edu.au, joshua.sage@beachenergy.com.au, martin.hand@adelaide.edu.au

[1] The Australian School of Petroleum, The University of Adelaide, Australia
[2] Geoscience Australia, Canberra, Australia
[3] School of Physical Sciences, The University of Adelaide, Australia
[4] Beach Energy, Adelaide, Australia
[5] Institute of Minerals and Energy Resources, The University of Adelaide, Australia

S3 Seismic Structure Stress

TRaX Centre for Tectonics Resources and Exploration

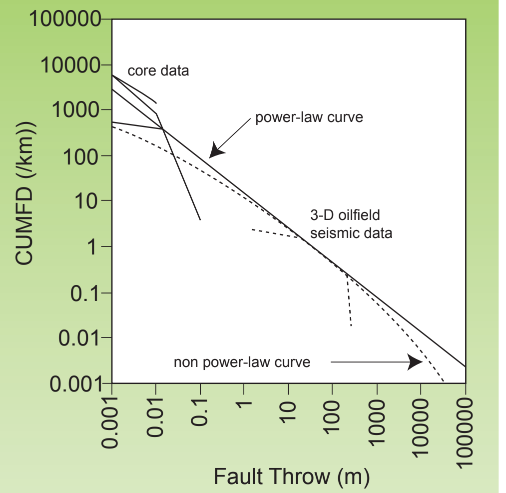
AUSTRALIAN SCHOOL OF PETROLEUM

THE UNIVERSITY of ADELAIDE

BACKGROUND

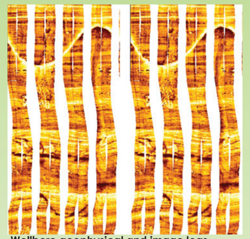
Structural Permeability:

- A secondary permeability provided by structure, generally interconnected networks of natural fractures.
- Natural fractures are common features in the brittle crust.
  - A failure due to stresses exceeding rock strength.
  - Are considered to be scale invariant (Walsh and Watterson, 1993, Nicol et al, 1995).

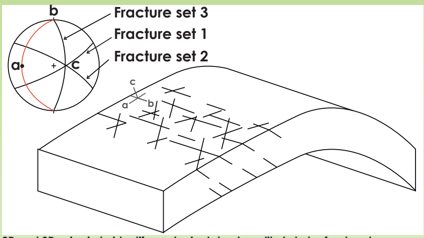


Fractures are scale invariant as demonstrated by this figure, an empirical non-power-law curve overlaying a power-law-curve, showing their relationship to displacement curves for faults mapped from three-dimensional seismic data and core (Nicol et al., 1995).

Fracture Identification:

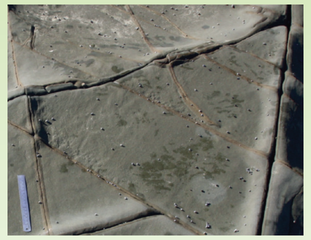


Wellbore geophysical and image logs



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

Recovered core



Surface analogues

Fractures are identified in a range of ways at varying scales including but not limited to wellbore logs, recovered core, surface outcrops, and through the identification of structures likely to host fracture populations.

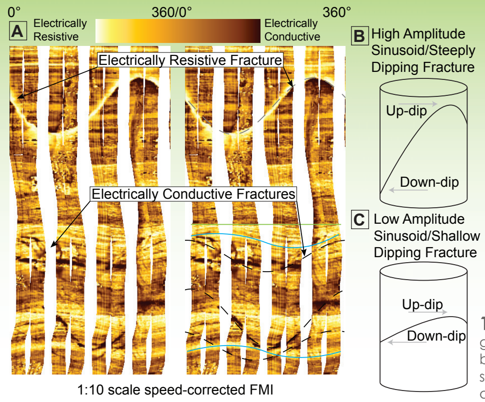
Why the interest?

- When optimally oriented, can serve as fluid flow 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.

(Sibson, 1996)

Natural fractures allow for sub-surface fluid flow such as preserved by these natural dilational fractures formed within a fine grained sandstone unit of the Wilpena Group. Multiple generations of a calcite rich fluid have flowed through these structures, as evidenced by several distinct bands of fracture filling calcite. Pichi Richi Pass, South Australia.

Natural Fractures on Image Logs:



- Electrical resistivity image logs provide a high resolution pseudo-image of the borehole wall.
- Fractures appear as sinusoids, and are classified by their electrical character.
  - Electrically conductive fractures are generally considered to be open to fluid flow, and filled with drilling mud.
  - Electrically resistive fractures are generally considered to be closed to fluid flow,and sealed by cement.

1:10 scale FMI image (A) A section of FMI image highlighting electrically resistive (marked in grey) and electrically conductive (marked in black) fractures. Examples of bedding are marked in blue and an erosional surface is marked in green, illustrating the similarity in appearance between syn-tectonic and pre-tectonic features (Bailey et al, 2014). Schematic diagrams of (B) a highly dipping fracture; and, (C) a shallow dipping fracture intersecting a vertical wellbore.

PROJECT OUTLINE

Aim to identify natural fractures in the sub-surface of energy rich Australian Sedimentary basins.

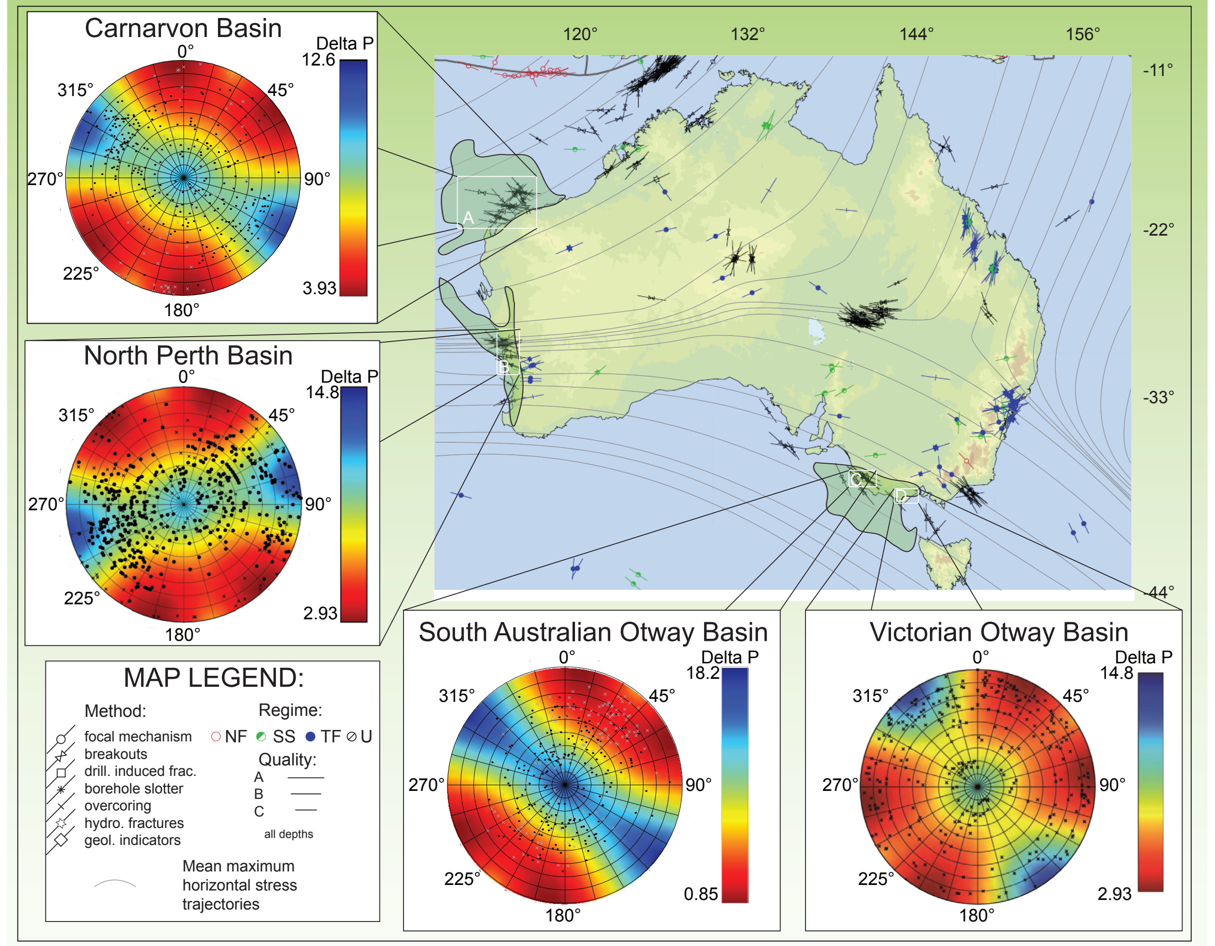
- An integrated approach using wellbore logs, seismic attribute analysis, and detailed structural geology.

Crucial permeability information is obtained through the identification of fractures and faults over a range of scales (mm to km).

New stress information is interpreted, allowing for stress based predictions of fracture reactivation.

Three main questions are raised by these data:

1) Can 3D seismic attributes identify fractures?
2) What factors control fracture reactivation in the studied Australian basins?
3) Are fractures identified as being open in image logs actually open to fluid flow?



Potential structural permeability map showing the study areas across the projected maximum horizontal stress azimuths of the Australian Stress Map. Fractures identified within each study area are presented on stereoplots as poles to planes, with stereoplots coloured by the pore pressure (ΔP) required to create or reactivate fractures under the given stress regime, also plotted as poles to planes. Red areas illustrate fracture orientations that are optimally oriented for reactivation, and blue colours represent fracture orientations least likely to reactivate (Bailey et al., 1015).

REFERENCES:

BAILEY, A., KING, R., HOLFORD, S., SAGE, J., BACKE, G. AND HAND, M., 2014—Remote sensing of subsurface fractures in the Otway Basin, South Australia. Journal of Geophysical Research: Solid Earth, 119 (8), 6,591–612.

BAILEY, A., KING, R., HOLFORD, S., SAGE, J., HAND, M. AND BACKE, G. 2015—Defining structural permeability in Australian sedimentary basins. The APPEA Journal, 55(1), 119-148.

BAILEY, A.H.E., 2016—Structural permeability in Australian sedimentary basins (Doctoral dissertation).

NICOL, A., WALSH, J.J., WATTERSON, J. AND BRETAN, P.G., 1995—Three-dimensional geometry and growth of conjugate normal faults. Journal of Structural Geology, 17(6), 847–62.

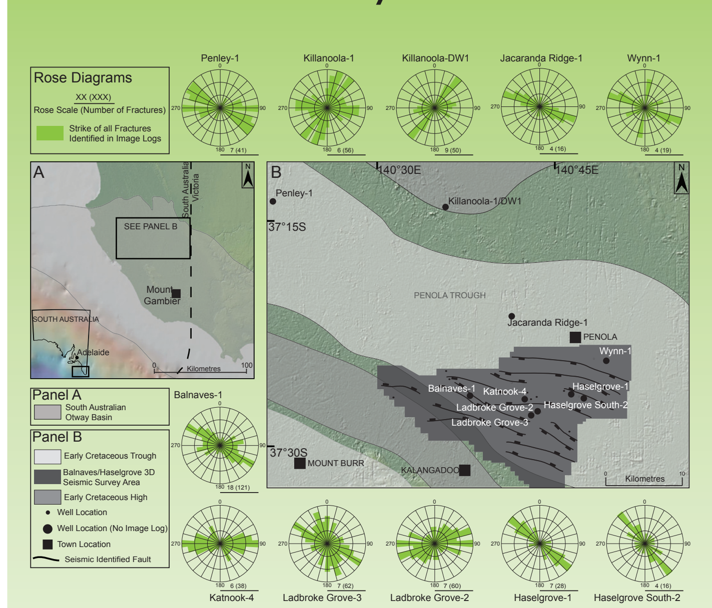
PEACOCK, D.C.P. AND MANN, A., 2005—Evaluation of the controls on fracturing in reservoir rocks. Journal of Petroleum Geology, 28 (4), 385–96.

SIBSON, R.H., 1996—Structural permeability of fluid-driven fault-fracture meshes. Journal of Structural Geology, 18 (8),1,031–42.

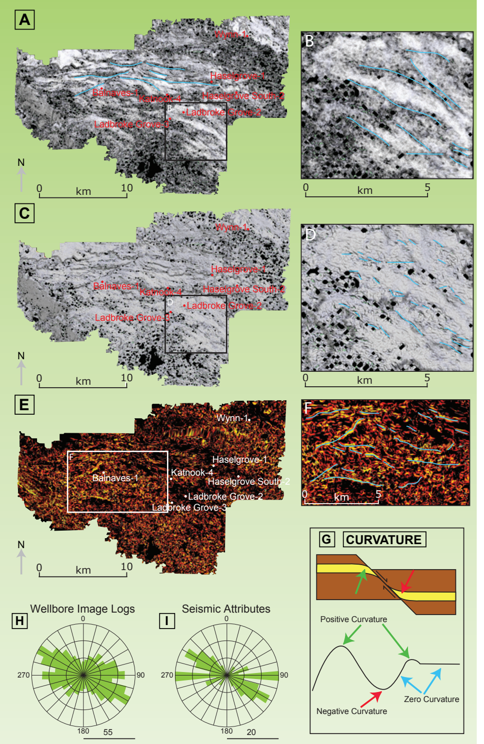
WALSH, J.J. AND WATTERSON, J., 1993—Fractal analysis of fracture patterns using the standard box-counting technique: valid and invalid methodologies. Journal of Structural Geology, 15 (12), 1,509–12.

CASE STUDIES

South Australian Otway Basin:



Map of the South Australian Otway Basin Study Area: (A) Regional map of the SA Otway Basin (B) The study area is spread across the Penola Trough Well locations are marked and are concentrated in the Balnaves/Haselgrove seismic. Major faults interpreted in the seismic volume are marked. Rose diagrams (with individual scales) showing fracture orientations highlight relatively consistent fracture strikes within the Penola Trough.



Three-dimensional seismic attributes draped over the interpreted Pretty Hill Formation horizon interpreted on the Balnaves/Haselgrove 3D seismic (A) The minimum similarity attribute highlights discontinuous events (such as the major faults marked in blue), and (B) discontinuous zones between the larger lineations (highlighted in blue). (C) The ridge enhancement attribute also highlights discontinuities and can be seen to show more detail on both the larger faults as well as the smaller discontinuous zones seen in the similarity attribute, (E) The maximum positive curvature attribute highlights upthrown fault blocks whereas the maximum negative curvature highlights downthrown fault blocks (see curvature inset); when viewed in combination it can be seen that features likely to represent faults are shown by two lineations representing slightly offset curvature maximums rather than the single lineation associated with displaying only the most positive or the most negative curvature. (F) Strong curvature features are clearly represented in the data as distinctly oriented lineations (marked in blue). Fracture strike orientations are presented as rose diagrams for both image log identified fractures (G) and seismic attribute identified fractures (H).

Photographs of natural fractures in Penola Trough core from the well Jacaranda Ridge–1: (A) High-angle fractures sealed with undefined clays (inset shows slip indicators). (B) High-angle fractures filled with a cataclasite formed through slip and appearing to preserve at least partial fracture porosity.(C) High-angle clay-filled fractures showing partial siderite mineralisation along the fracture plane. (D) An open fracture (note the siderite present within the surrounding reservoir rock of the Sawpit Formation). (E) Low- to moderate-angle fractures in the vicinity of the fault intersected by core (inset showing the smooth material coating one of several fracture planes, likely to be fused gouge materials).

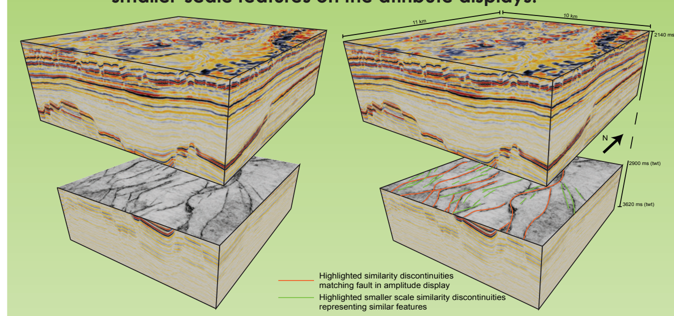
Acknowledgements:

The authors would like to thank the Australian Petroleum Production and Exploration Association (APPEA), the Australian Society of Exploration Geophysics (ASEG) Research Foundation (RF12P01), and the South Australian Centre for Geothermal Energy Research (SACGER) for their generous and ongoing support. Thanks also go to Ikon Geomechanics (JRS Suite©) and dGb Earth Sciences (OpendTect™) for their generous provision of academic licenses. Finally, thanks go to the South Australian Department of State Development and the Western Australian Department of Mines and Petroleum for the provision of the open-file data used.

The lead author is grateful to Geoscience Australia for their support in attending AAPG ICE 2017.

Question 1) Can 3D seismic attributes identify fractures?

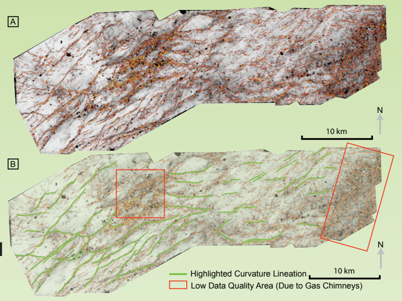
- Distinct natural structural fabrics are observed on dip-steered, median-filtered 3D sesmic from three Australian Basins
  - Observed structural fabrics are composed of sub-seismic amplitude scale faults and fractures
- Large scale faults are easily matched to prominent attribute features, however, the same cannot be done for smaller-scale features on the attribute displays:



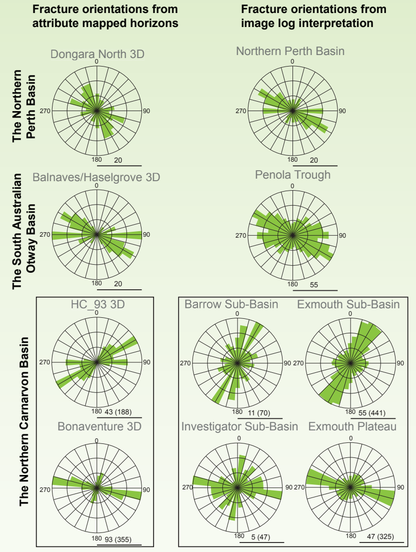
Block diagram from the Carnarvon Basin showing the similarity attribute compared to seismic amplitude data: Large extensional normal faults are evident in the amplitude data of the inline and crossline, however, these are not easily interpreted in the amplitude z-slice (at 2140 msTWT) when compared to the minimum similarity attribute (at 2900 msTWT, light values are highly similar while dark values are dissimilar), which clearly highlights the large faults as well as smaller structural features not present in the amplitude data.

- Structural fabrics are identified as:
  - Discontinuities in the similarity attribute
  - Linear ridges on the ridge enhancement attribute
  - Prominent lineations in curvature attributes
- Systematic geological features should be represented on multiple attribute displays, as observed.
- Established power-law relationship of fractures allows for the correlation of similar features at different scales.

- Investigated surveys clearly show attribute features to occur in the same location
- Attribute features, such as the high ridge values, and curvature lineations, share orientations as
- It is, therefore, likely that they are identifying a systematic geological feature preserved within the data

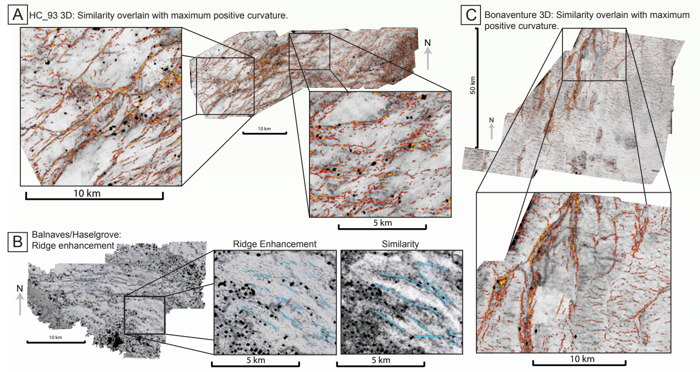


3D seismic attributes draped across the top Barrow Group of the HC_93 3D survey, Carnarvon Basin. (A) Peak values of the most positive curvature attribute overlaying the minimum similarity attribute. (C) Lineations likely to represent faults and fractures highlighted on the overlain attributes. Zones of low data quality are outlined in red.



- Interpreted attribute features additionally occur at the same strike orientations as natural fractures interpreted on image logs.
- It is likely that these are similar geological features, being observed over different scales.

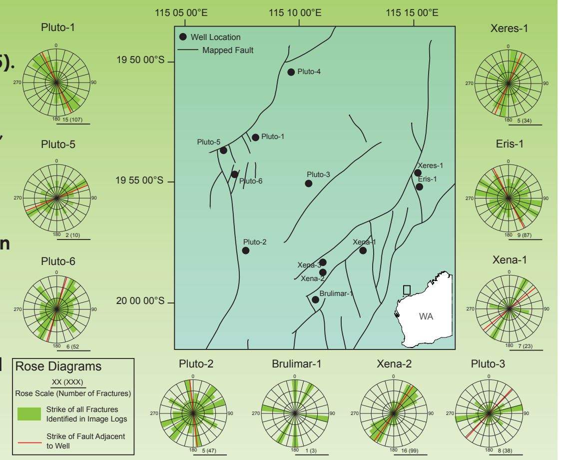
Fracture orientations from both wellbore image log and seismic attribute interpretation: Fracture orientations interpreted on attribute mapped surfaces in 3D seismic surveys from each of the study areas are compared to fracture orientations interpreted on electrical resistivity based image logs. Rose diagrams feature individual scales and display only the fractures interpreted in the formation that was attribute mapped in each survey.



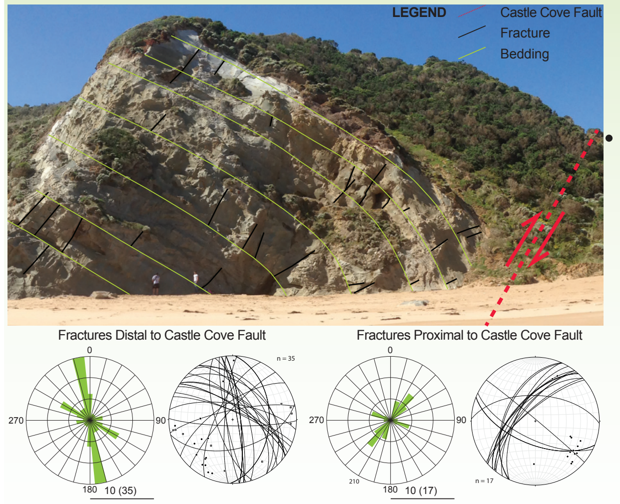
3D seismic attribute analysis highlights fault damage zones within the studied surveys: (A) lineations and discontinuities on the overlain similarity and maximum positive curvature attributes in the Northern Carnarvon Basin HC_93 survey show several areas where attribute features are congregated around larger structural features in the attribute display. Areas further removed from these are seen to lack the lineations or discontinuities likely to represent faults and fractures, and so are likely to be largely undeformed. The same is seen in the Otway Basin Balnaves/Haselgrove seismic survey (B) and in the Northern Carnarvon Basin Bonaventure seismic survey (C). Bonaventure, however, can be seen to have many curvature lineations and similarity discontinuities that run perpendicular to and between the larger structural features.

Question 2) Factors controlling reactivation in Australian basins:

- Fractures form and reactivate in response to factors including stress, rock strength, and pore pressure (Peacock & Mann, 2005).
  - Reactivation can be modelled when these are known, or through using idealised relationships.
  - Predictions of fracture reactivation are made for each basin, however, thisonly allows for limited explanation of identified fracture characteristics.
- Understanding the tectonics of a basin is essential for understanding fracture orientations.
  - Regional Structure: Demonstrated well in the Carnarvon Basin (see "Case Studies: Carnarvon Basin').
    - Set 1 fractures are electrically conductive and strike sub-parallel to the in-situ stress regime. They are likely formed (or reactivated) by the in-site stresses.
    - Set 2 fractures are electrically resistive and concentrated in areas featuring large inversion structures. They parallel the inversion structures and are likely a result of the compressional events that formed them.



Map of the location of wells featuring interpreted FMI logs in the northern Carnarvon Basin's Rankin Platform and Dampier Sub-basin and the proximity of those wells to local structural features. Rose diagrams are for fracture orientations from each well, compared to the strike (red line) of the fault adjacent to that well. Well Brulimar-1 lacks a line due to the low number of identified fractures.

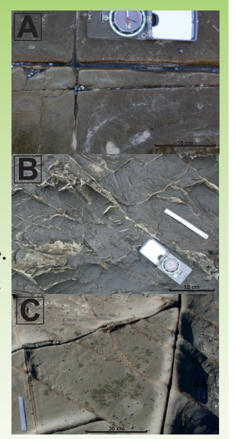


North facing photograph of the orthogonal fracture relationship to monoclinal folding of the Eumeralla Formation adjacent to the Castle Cove Fault in the Victorian Otway Basin. Structural data measured at the site is presented as rose diagrams showing fracture strike and stereoplots showing dip and dip direction. On stereoplots, fractures are represented as both great circles and poles to planes; black dots represent closed fractures and unfilled black squares represent open fractures. Distal fractures are approximately 173 m from the fault, and fractures measured proximally are approximately 14 m from the fault.

- Local Structure: Highlighted well in the Carnarvon Basin's Rankin Platform And Dampier Sub-Basin (above) and the Victorian Otway Basin (left).
- Rankin Platform and Dampier Sub-Basin
  - Fractures identified on electrical resistivity image logs from 10 petroleum wells are interpreted to occur at all orientations, demonstrating no dominant trends.
  - Reflect neither in-situ stress orientations no the dominant structural trend of the basin.
  - Can be seen to closely reflect the strike orientations of adjacent structures.
  - Natural fracture populations may, therefore, be more dependent on local structure than regional trends.
- Victorian Otway Basin
  - The Castle Cove Fault (Left) is a NE-SW striking normal fault that has been inverted into a monocline.
  - Fracture orientations and densities change proximal to the fault, from NNW-SSE strikes change to SW-NE strikes.
  - Proximal fractures share strike orientations with the fault, and soare likely related to fault formation or reactivation.
  - Fracture density changes from 3.7 fractures/m distal to the fault, to 4.5 fractures/m proximal, possibly representing a fault damage zone.

Question 3) Are open fractures in image logs open to fluid flow?

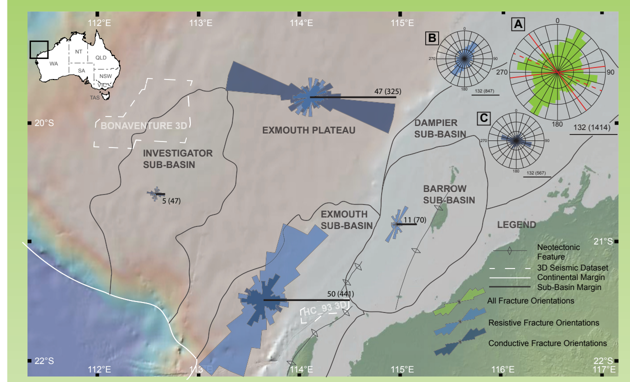
- Electrically resistive fractures have been correlated with hydraulic conductivity.
- However, it could equally be explained by the presence of electrically conductive minerals such as siderite.
  - Siderite is an iron carbonate often seen as a fracture filling cement in Australian basins
- Detailed understanding of fracture fills is therefore required.
  - The Otway Basin is a prime example: Many non-optimally oriented fractures appear conductive, and many optimally oriented fractures are not.
  - Previous studies have shown fracture fills to be significantly stronger than the host rock.
  - Reactivation is therefore governed by the level of cementation along the fracture plane.
  - Likelihood of reactivation depends not only on fracture orientation within the stress field, but also the nature of fracture closure.
- Otway Basin core demonstrates that open fractures are rarer than image logs suggest (20% of observed fractures in core were open, 53% of observed fractures on image logs are 'open').
- Outcrop observations in the Victorian Otway Basin suggest that siderite is a pervasive fracture fill throughout the basin (Right).
  - 28% of identified fractures are sealed with siderite cement.
  - Many fractures that appear open at surface are heavily weathered and may be misidentified
  - Halos around many open fractures suggest transport of iron rich fluids
  - The majority of identified siderite filled fractures are optimally oriented, and yet remain sealed.
- Siderite is identified in the Northern Perth Basin as a fracture fill, and is likely to exist in the Carnarvon Basin.
- It is likely that many fractures on image logs are electrically, though not hydraulically, conductive.
- Care must be taken when using image logs to characterise fractures; physical samples from core or outcrop should be interpreted alongside image log interpretations where possible.



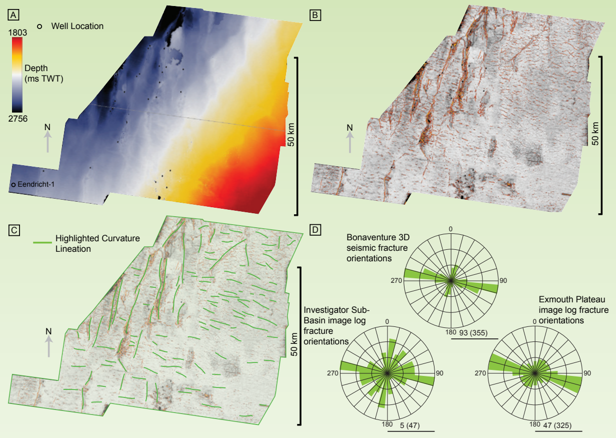
Fractures observed in an outcrop of Otway Group sediments in theVictorian Otway Basin: (A) heavily weathered fractures that appear open at the surface and lack any visible evidence of fracture fills, but which may preserve fills below oceanic detritus; (B) hardened calcite filled fractures preferentially weathering; and, (C) hardened iron-rich halos surrounding both siderite filled and open fractures.

CASE STUDIES

Northern Carnarvon Basin:

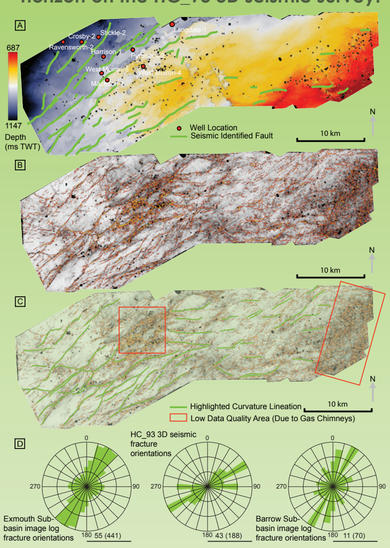


Interpreted natural fracture orientations in the four structural domains of the Carnarvon Basin Presented as frameless rose diagrams scaled to the largest dataset. (A) Rose diagram showing the strike orientation of all fractures identified on image logs (including the predicted orientations for fracture formation under the present-day in situ stress regime; solid red lines represent shear fractures and dashed represent tension fractures) and rose diagramsshowing strike orientations of electrically resistive (B) and electrically conductive (C) fractures.



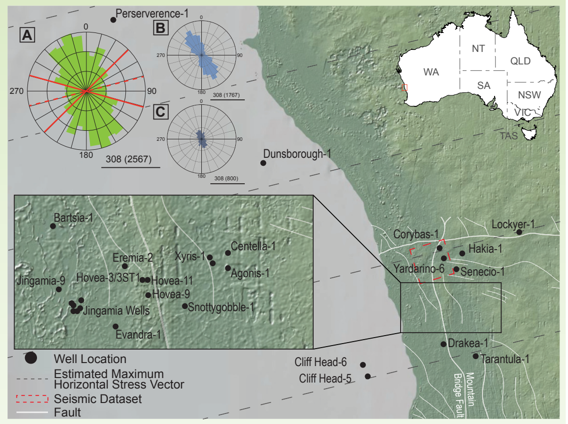
3D seismic attributes draped across the top Barrow Group horizon on the Bonaventure 3D seismic survey (A) Depth to the top Barrow Group horizon (TWT) showing well locations. (B) Peak values of the most positive curvature attribute overlaying the minimum similarity attribute. (C) Lineations likely to represent faults and fractures highlighted on the overlain attributes. (D) Rose diagrams showing the strike orientations of natural fractures identified on image logs from the Investigsator Sub-basin and Exmouth Plateau, compared to those identified from attribute analysis of the Bonaventure seismic dataset.

3D seismic attributes draped across the top Barrow Group horizon on the HC_93 3D seismic survey.

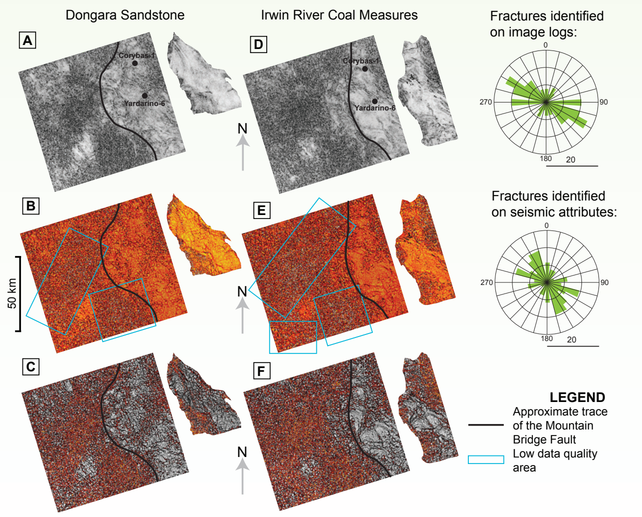


(A) Depth to the top Barrow Group horizon (in two-way time) showing well locations within the dataset and locations of faults intersecting the horizon. (B) Peak values of the most positive curvature attribute overlaying the minimum similarity attribute. (C) Lineations likely to represent faults and fractures highlighted on the overlain attributes. Zones of low data quality are outlined in red. (D) Rose diagrams showing the strike orientations of natural fractures identified on image logs from the Exmouth and Barrow sub-basins, compared to those identified from attribute analysis of the HC_93 seismic dataset.

Northern Perth Basin:



Map of the Northern Perth Basin Study Area: Showing regional structure, estimated maximum horizontal stress trajectory, and the location of wells and 3D seismic data used in this study. The figure includes: (A) a rose diagram showing the strike orientation of all fractures identified on image logs (including the predicted orientationsfor fracture formation under the present-day in situ stress regime; solid red lines represent shear fractures and dashed represent tension fractures); and, (B) and (C) rose diagrams showing the strike orientations of electrically conductive fractures.



Results of Seismic Attribute Processing from the Dongara North 3D Survey: 3D seismic attributes for both timeslices and interpreted horizons representing the Dongara Sandstone and Irwin River Coal Measures(A) Dongara Sandstone showing the similarity attribute; (B) Dongara Sandstone showing the maximum negative curvature attribute; (C) Dongara Sandstone showing the maximum positive curvature attribute; (D) Irwin River Coal Measures showing the similarity attribute; (E) Irwin River Coal Measures showing the maximum negative curvature attribute; and, (F) Irwin River Coal Measures showing the maximum positive curvature attribute. Rose diagrams represent strike orientations of fractures in these formations identified on image logs and through attribute analysis. Blue squares represent areas of particularly poor data quality.

CONCLUSIONS

- An integrated geological and geophysical approach utilising wellbore image log data, 3D seismic attribute analysis, and observations of both core and outcrop is demonstrated to reliably identify natural fracture networks
  - Does not produce a 'one-size-fits-all' model.
  - Each basin is demonstrated to be unique, with different controls over both fracture initiation and reactivation.
  - Reactivation can become complex, with stimulation of existing fractures beingunlikely due to fracture fills rendering existing fractures stress insensitive.
  - Consider basins in isolation, using available data to make an independent assessment.
- The outlined techniques represent an effective method for assessing structural permeability with varying elvels of data availability.
- It is unlikely that natural fracture orientations can be mapped in a simple and reasonable manner on a continental scale, due to the number of variables involved in their formation and reactivation, including:
  - Location,
  - Structural development,
  - Fracture fill,
  - Lithology,
  - Proximity to local structures.
- A general overview of the dominant fracture orientations (with respect to the in situ stress regime) for each basin is presented in a simple form.
- Detailed assessments of the fracture sets described can be found in *Bailey et al., 2016.*