Using network topology to constrain fracture network permeability

Rowan Hansberry*
Department of Earth Sciences
University of Adelaide
rowan.hansbberry@adelaide.edu.au

Simon Holford
Australian School of Petroleum
University of Adelaide
simon.holford@adelaide.edu.au

Rosalind King
Department of Earth Sciences
University of Adelaide
rosalind.king@adelaide.edu.au

Natalie Debenham
Australian School of Petroleum
University of Adelaide
natalie.debenham@adelaide.edu.au

SUMMARY

Predicting the interconnectivity and permeability of fractures at any scale remains a fundamental challenge in structural geology. Models which predict the likelihood of fracture opening based on their relation to the stress field can be applied at scales of 100s of metres to kilometres. Increasingly however, an understanding of how networks of the smallest-scale (sub-seismic to mm) natural fractures permit fluid flow in the subsurface appears key to predicting and exploiting these pathways. Here, we apply the nascent method of network topology to natural fracture networks to a fossilised fault damage zone in the Otway Basin. Network connectivity and the potential to percolate fluids has been shown to be directly related to the topology, and intensity of fracturing. This technique is relatively straightforward, provides a range of parameters to define various aspects of a fracture network (e.g. intensity, connectivity), and is independent of the scale and geometry of the structures of interest. We integrate this technique with traditional structural analysis to illustrate the scale of fracturing around a region-scale fault and constrain spatial variation in permeability associated with the fracture network. We also illustrate how elements of this technique might be applied to existing sub-surface data.

Key words: topology, fracture, structural, fault, permeability

INTRODUCTION

Fractures and joints are some of the most ubiquitous features of the shallow crust, providing pathways for economic fluids, and are vital to maintaining the critically stressed nature of the crust (Townend and Zoback, 2000). Analysis of fractured rock, particularly in fault damage zones is often subject to a variety of techniques and terminologies to characterise the properties of individual fractures and their relationships within wider fracture networks. Network topology of has gained popularity over the last five years, as a method for quantitative analysis of fracture and fault networks (Procter and Sanderson, 2018; Sanderson and Nixon, 2015). This technique involves counting the lines, nodes, and areas of a network of linear features, and producing a range of parameters to classify fracture networks. These parameters can be used to compare fracture networks across a locality and quantify their fracture intensity and connectivity (Sanderson and Nixon, 2015). We apply network topology to a natural fracture network in the Eumarella Formation at Castle Cove, Otway Basin, to analyse spatial variation in its potential permeability (Figure 1). In addition, we compare this 2D fracture network to fracture data from the Bellarine-1 wellbore image log which intersected 800 metres of tight sandstones within the Eumarella Formation.

METHODS AND RESULTS

Network topology analysis of a 2D fracture network (such as the cross section exposed at Castle Cove) centres around the fact that the fracture network can be thought of as a finite number of lines—fracture traces on a surface—which either terminate at their tips, or intersect other lines (Sanderson and Nixon, 2015). Sanderson and Nixon (2015) apply the PXY system to provide a system of topological parameters to describe fracture size and abundance (Dershowitz and Herda, 1992). This provides a basis for consistent terminology, where terms such as frequency, intensity, and spacing are often used with overlapping meaning, depending on the property referred to, and the dimension of sampling. The PXY system (Figure 2c) provides a consistent use of terminology, which we adopt for clarity.

To analyse the fracture network in the hanging-wall of the Castle Cove Fault (recently described by Debenham et al. (2018a, 2018b)), high-resolution photography was taken across the 290 m long outcrop (Figure 1). This was then stitched into a single image and imported into ArcMAP in order to digitise the fracture network. The NetworkGT toolkit developed by Nyberg et al. (2018) provides an automated method for developing the nodal topology of a digitised fracture network, reducing the time and error in digitising node and branch types manually. Using this toolkit, a 50 cm sampling grid was generated, and the full range of topological parameters discussed in Sanderson and Nixon (2015) was generated for each grid square across the Castle Cove Fault fracture network, allowing for spatial analysis of topological variation within the fracture network. Digitisation of the natural fracture network adjacent to the Castle Cove Fault, yielded a detailed cross-section of roughly 5000 fractures, which when analysed with the NetworkGT toolkit produced approximately 14,000 nodes.

Fracture frequency analysis across the 290-metre cross-section shows that ~50% of fractures occur within the first 70 metres proximal to the fault, indicating the potential effect and extent of the fault damage zone. Frequency is relatively constant (in the range of 5 to 25 fractures-per-metre) over the area 100-290 metres from the fault, which may indicate a "background" or regional fracture frequency. Connections per branch (C_B) also increases at approximately the same distance from the fault, though this is a less obvious change. C_B is a dimensionless

number between 0-2 and provides a useful measure of network connectivity (Sanderson and Nixon, 2015). Beyond roughly 80 metres from the fault C_B varies significantly, however within 80 metres of the fault, variation decreases with far fewer values below 1.5, and approximately 40 metres from the fault all values are >1.5 (Figure 6). Spatially, this is seen as a decrease in occurrence of low-connectivity zones (whiter squares, CB <1), with no low-connectivity zones within approximately 75 metres of the fault.

Calculation of a percolation threshold parameter called B22C or "critical branch intensity" can be calculated for a given sample area or network if the node topology and fracture intensity (B22) is already constrained (Sanderson and Nixon, 2018). This critical branch intensity can then be compared to the branch intensity value in each square of our sampling grid, to create a spatial analysis of percolation potential in the Castle Cove fracture network (Figure 2). Results show that the network is almost uniformly above the percolation threshold over the same 60-70 metres defined as the extent of the fault damage zone.

DISCUSSION

Our results show that network topology is a powerful tool for quantitatively investigating fracture networks in rocks. Grid sampling of network also provides a useful way of visualising results in cross-section, beyond that of traditional structural geology. Fracture intensity (P21) values from the data in this study show a notable increase from a background values within approximately 70 metres of the Castle Cove Fault. We suggest that while the damage zone may be defined as a zone of homogenous high fracture intensity, higher fracture intensity related to Castle Cove Fault may extent heterogenous beyond this limit. Similarly, spatial analysis on percolation potential suggests pathways through the network which are above the percolation threshold may extend well beyond the 70 metres defined as the fault damage zone, suggesting the network may be heterogeneously permeable as much as 150 metres from the fault (Figure 2).

Network topology of pseudo-wells through the Castle Cove section and fractures recorded in the Bellarine-1 image log illustrate the difficulty of applying this technique to such a spatially restricted dataset. While Bellarine-1 intersects more than 300 natural fractures, it captures too few fracture intersections to provide enough data for the nodal topology which the percolation threshold analysis relies on. It does however provide enough data to assess the two-dimensional fracture intensity (P21), with comparisons to the Castle Cove outcrop showing similar values. Given that this parameter in the outcrop example appears to be closely spatially correlated with the percolation threshold, this may provide a rough estimate of the fracture intensity required to percolate fluids.

CONCLUSIONS

This study is a first in spatial analysis of a fracture network using network topology. Both in assessing the networks as an analogue for potential to percolate fluids, and in applying network topology to constrain the nature and extent of a fault damage zone. The NetworkGT tool of Nyberg et al. (2018) allows for the generation of a high-resolution cross-sectional analysis of spatial variation of network topology parameters for a fault damage zone. This method allows relatively quick and easy production of large datasets of fracture populations, topology, and geometry.

Network topology has provided a robust and novel method for assessing the intensity, interconnectivity, and potential to percolate fluids of the fracture network in the hanging-wall of the Castle Cove Fault. Topological analysis of wellbore image log data is significantly hampered by the limited dimension of sampling; however, it can provide a reliable estimate of fracture intensity. To build on these results further case studies using network topology at a variety of scales and sampling dimensions is required before it can be used predictively.

ACKNOWLEDGEMENTS

We wish to thank Björn Nyberg and Casey Nixon at the University of Bergen for their invaluable assistance in network topology methods, and helpful discussions on this work. We would also like to thank the Australian Research Council for funding this work under ARC Discovery Project DP160101158.

REFERENCES

Dershowitz, W. S., and Herda, H. H., Interpretation of fracture spacing and intensity, in Proceedings The 33th US Symposium on Rock Mechanics (USRMS)1992, American Rock Mechanics Association.

Nyberg, B., Nixon, C. W., and Sanderson, D. J., 2018, NetworkGT: A GIS tool for geometric and topological analysis of two-dimensional fracture networks: Geosphere.

Procter, A., and Sanderson, D. J., 2018, Spatial and layer-controlled variability in fracture networks: Journal of Structural Geology, v. 108, p. 52-65.

Sanderson, D. J., and Nixon, C. W., 2015, The use of topology in fracture network characterization: Journal of Structural Geology, v. 72, p. 55-66.

Sanderson, D. J., and Nixon, C. W., 2018, Topology, connectivity and percolation in fracture networks: Journal of Structural Geology, v. 115, p. 167-177.

Townend, J., and Zoback, M. D., 2000, How faulting keeps the crust strong: Geology, v. 28, no. 5, p. 399-402.

Debenham, N., King, R. C., & Holford, S. P. (2018a). The influence of a reverse-reactivated normal fault on natural fracture geometries and relative chronologies at Castle Cove, Otway Basin. Journal of Structural Geology, 112, 112-130.

Debenham, N., Farrell, N. J., Holford, S. P., King, R. C., & Healy, D. (2018b). The permeability structure of fault zones in sedimentary basins: a case study at the Castle Cove Fault, Otway Basin. The APPEA Journal, 58(2), 805-808.

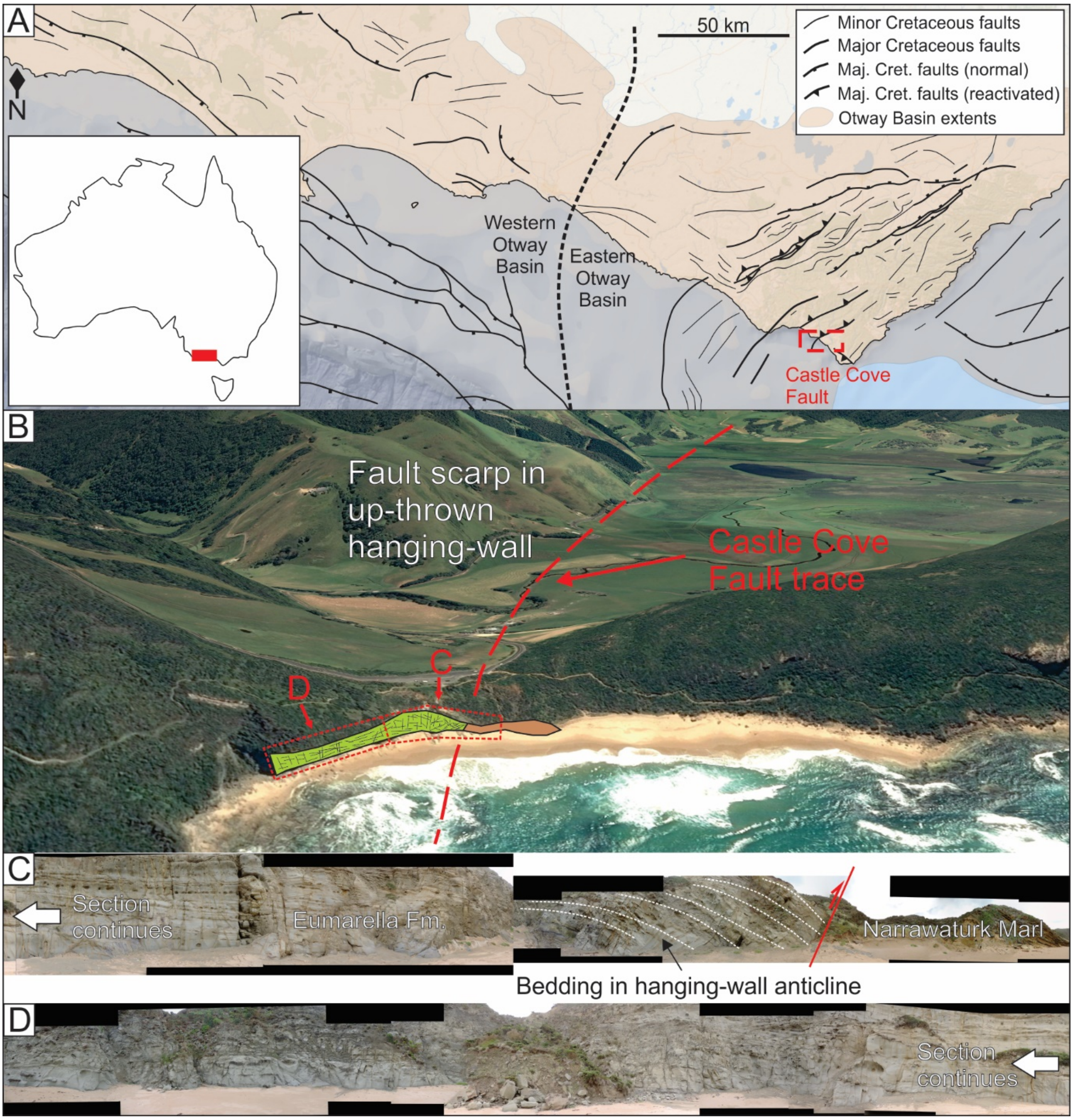

Figure 1. (A) Location of Castle Cove study area in the Victorian Otway Basin (inset location in Australia). (B) Isometric view of Castle Cove from Google Earth™ showing extent of Cretaceous Eumarella Formation outcrop mapped for this study. Fault trace and scarp of the Castle Cove Fault are highlighted. (C and D) Stitched photographic panorama of outcrop from which fracture network was mapped in ArcMAP.

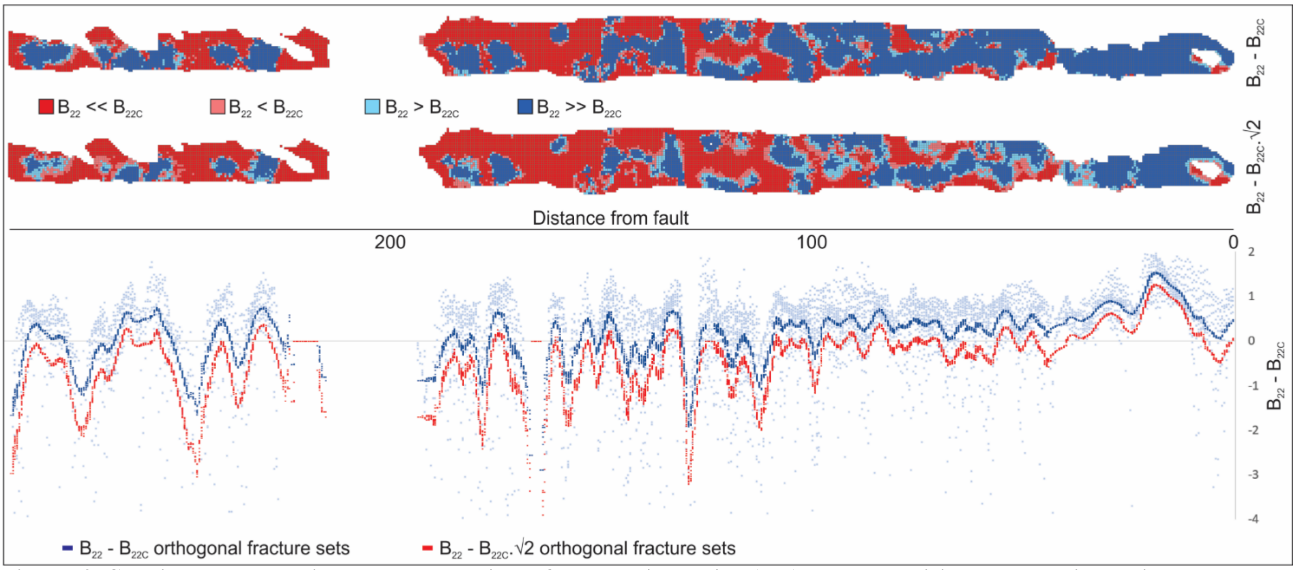

Figure 2. Spatial and graphical representation of branch intensity (*B_{22}*) and the critical branch intensity threshold for percolation (*B_{22C}*). The two sample grid maps (top) are coloured according to *$B_{22} - B_{22C}$* (i.e. if the branch intensity is greater than threshold), blue indicates the value is above the percolation threshold for the topology of that sample area. This is present from both *$B_{22} - B_{22C}$*, and *$B_{22} - B_{22C}.\sqrt{2}$*, suggested by Sanderson and Nixon (2018) as a potential confidence limit. The same data is presented on the plot (bottom), with the y-axis showing where the branch intensity minus the percolation threshold is positive and hence the network can percolate fluids.