Fault and Fracture Networks in the Otway Basin, Victoria; Implications for Structural Permeability

Thesis submitted in accordance with the requirements of the University of Adelaide for an Honours Degree in Geology

Joshua Matthew Sage

November 2013

THE UNIVERSITY of ADELAIDE

ABSTRACT

Over 1900 naturally occurring fractures were recorded in the field, from outcrop of the Eumeralla Formation in the Otway Basin, Victoria, Australia. Two distinctive fracture sets were identified with strike orientations of N-S and NE-SW. Natural fractures were further characterised as open or closed. A total of 623 open fractures in two dominant sets were observed at surface, with mean strikes of N-S and WNW-ESE. A total of 892 closed fractures (generally cemented) in two dominant sets were also observed at surface, also with mean strikes of N-S and WNW-ESE. Further investigation showed that despite a majority of fractures being optimally aligned with the present-day stress field, they remained closed.

Six discrete fracturing events were interpreted in total; Two Cretaceous bedding perpendicular Mode 1 sets; a late Cenozoic vertical Mode 1 set; a late Cenozoic bedding parallel set; a Miocene continuous crack-seal related set; and finally an Early Cretaceous Fault related set, reactivated during the Miocene.

Thin sections revealed multiple generations of fracture cement inferring a crack-seal history or that mineral cement renders the fractures stress insensitive. Failure of fractures to reactivate and remain open to fluid flow in the favourable stress conditions of the Otway Basin has potential to adversely affect and limit the secondary permeability of the system. This also validates the hypothesis that the in-situ stress regime is not always the dominant factor in the propensity for a fracture to be open to fluid flow.

KEYWORDS

Otway Basin, structural permeability, Eumeralla Formation, fracture mechanics, fault.

TABLE OF CONTENTS

Abstract 1
Keywords 1
List of Figures and Tables 4
Introduction 8
Background 10
Geological Setting 10
Diagenesis 16
Geomechanical Background 17
Stress Field Direction 17
Horizontal and Vertical Stress Magnitudes 18
Pore Pressures 19
Rock Strength (Host Rock and Fracture Fill) 20
Mechanical Stratigraphy 21
Methods 22
Observations and Results 23
Fracture Orientations at Field Sites in the Otway Basin 26
Moonlight Head 26
Castle Cove 26
Cape Otway 26
Crayfish Bay 27
Marengo 27
Skenes Creek 27
Wongarra 27
Smythes Creek 27
Cape Patton 28
Cumberland River 28
Lorne 28
Satellite Comparison 28
Fracture Fills and Porosity in the Otway Basin from Thin Section Microscopy 31
Mechanical Stratigraphy and Variations in Lithology 34
Discussion 41
Variation in Fracture Patterns around Local Structures 41
Fold at Cape Otway and Associated Fracture Pattern 41
Fracture Orientations across the Wild Dog Shear Zone 44
Fractures Associated with the Castle Cove Fault 46

General Field Trends of Fracture Sets 49
Tilt Corrected Fracture Sets 49
Implications of Fractures in the Otway Basin: From Past to Present 51
Mechanical Stratigraphy of the Eumeralla Formation 51
Fracture Generation History 52
Implications for Structural Permeability 55
Conclusions 64
Acknowledgments 66
References 67
Appendix A: Extended Methods 72
Field Mapping 72
Structural Data Collection 77
Structural Analysis 77
Structural Permeability 84
Slide Preparation 86
Petrology 87
Porosity 90
Wyllie Time Average Calculations 93
Appendix B: Face Maps and transects 94
Appendix C: Satellite Images 115
Marengo 116
Skenes Creek 117

LIST OF FIGURES AND TABLES

Figure 1. Location map of the Otway Basin, Victoria, Australia. Locations of wells referred to in this study are also shown (Olangolagh-1, Minerva-1 and Bellarine-1).... 12
Figure 2. Stratigraphic column for the Otway Basin (after Krassay *et al*. (2004)), including lithostratigraphy (Geary & Reid 1998) and basin phases and super-sequences (Krassay *et al*. 2004)..... 13
Figure 3. Three-dimensional Mohr Diagram with Griffith-Coulomb failure envelope overlain, showing possible fracture planes within the stress regime and the associated change in pore pressure (ΔPp) required for that plane to fail (after Dewhurst *et al*. 2002). The position of the fracture plane (solid black circle in the grey shaded area) is dependent on the relative orientation of the plane and the principle stresses. The change in pore pressure is used to determine the propensity for that plane to fail. 20
Figure 4. Map showing field sites studied in the Otway Basin, Victoria, Australia, numbered 1 to 11. Insets are rose diagrams (with numbers corresponding to field site on map) which show the strike directions of all fracture planes measured. Large-scale structures and lithological information adapted from Duddy (1994). 25
Figure 5. Rose diagrams comparing fracture strikes measured at outcrop and inferred from satellite imagery (for satellite images see Appendix C). a) Rose diagram of strikes of all closed fractures taken from Marengo. b) Rose diagram of strikes of all open fractures inferred from satellite imagery of Marengo. c) Rose diagram of strikes of all fracture planes taken from Marengo. d) Rose diagram of strikes of all fractures inferred from satellite imagery of Marengo. 29
Figure 6. Rose diagrams comparing fracture strikes measured at outcrop and inferred from satellite imagery (for satellite images see Appendix C). a) Rose diagram of strikes of all closed fractures taken from Skenes Creek. b) Rose diagram of strikes of all open fractures inferred from satellite imagery of Skenes Creek. c) Rose diagram of strikes of all fracture planes taken from Skenes Creek. d) Rose diagram of strikes of all fractures inferred from satellite imagery of Skenes Creek. 30
Figure 7. a) Photomicrograph of calcite vein fill from Cape Otway, Victoria, Australia, showing various calcite grains with sets of twins (Sample JS-07). b) Example of Type I (thin twins) twins from the Northern Subalpine Chain, France (figure adapted from Ferrill *et al.* (2004)). c) Example of Type II twins (tabular thick twins) from the Northern Mountain thrust sheet in the Great Valley, Central Appalachian Valley and Ridge Province (figure adapted from Ferrill *et al.* (2004)). 31
Figure 8. Photomicrographs of calcite vein fills at Moonlight Head. Dashed red line represents fracture/host rock boundary. Other coloured lines represent median lines of crack-seal events (green represents first event, blue represents second event, orange represents third event) a) Section of Sample JS-01 showing at least one (possibly two) crack-seal events. b) Section of Sample JS-02 showing a more complex crack-seal history with at least three crack-seal events. 32
Figure 9. Photomicrographs of thin sections of samples from the Otway Basin used for porosity calculations. a) Porosity was calculated to be 7.15 % for Sample JS-04 from Moonlight Head. b) Porosity was calculated to be 0.36% for Sample JS-07 from Cape Otway. 33
Figure 10. a) Fracture densities in the Eumeralla Formation at different sites in the Otway Basin compared with the maximum depth at which the site had been buried. The

average fracture density from the Eumeralla Formation interval from Bellarine-1 has been included from Tassone *et al.* (in press). b) Fracture densities ranges within different lithologies shown by average grain sizes. 37
Figure 11. Section of face map drawn at Cape Patton. Note very fine grained/silt, finely laminated and finely bedded layers interbedded with fine to medium grained, thickly bedded, well-rounded and well-sorted volcanogenic sands. (For complete map see Appendix B) 38
Figure 12. Section of face map drawn at Marengo. Note conglomerate lens with fine grained clasts inside a coarse grained matrix, clasts up to 10 cm, sub-angular to rounded. Lens is hosted in fine grained, thickly bedded but finely laminated volcanogenic sands. (For complete map see Appendix B) 39
Figure 13. Section of face map drawn at Moonlight Head. Note medium to coarse grained, thickly bedded (20 to 30 cm), less finely laminated (2 to 5 mm) well-rounded and well-sorted volcanogenic sands, interbedded with cross bedded conglomerate bearing lenses (20 to 30 cm) with clasts (1 to 10 cm) within a course grained sand matrix. Clasts appear to be those of similar fine to medium grained units. (For complete map see Appendix B) 40
Figure 14. Data collected from Cape Otway. a) Fracture pattern associated with folding with accompanying stereographic projection of the orientations of the coordinate system (a, b and, c), fracture planes (black great circles) and the bedding (red great circle) (adapted from Twiss & Moores 2007). Fracture pattern observed at Cape Otway appeared very similar to this typical fold fracture pattern. b) Fracture planes of open fractures observed at Cape Otway (black great circles) and poles to fracture planes (black open squares). Red great circle represents bedding. c) Fracture planes of calcite filled fractures observed at Cape Otway (black great circles) and poles to fracture planes (black dots). Red great circle represents bedding. 42
Figure 15. Rose diagrams showing a) All fracture plane strikes at Cape Otway and b) All fracture plane strikes at Crayfish Bay. Note that radial intervals are not at the same scale. 45
Figure 16. Structural data from Castle Cove. a) All fracture planes measured ~14 m from the Castle Cove fault (black great circles) and poles to fracture planes (black dots). b) All fracture planes measured ~173 m from the Castle Cove fault (black great circles) and poles to closed fracture planes (black dots) and poles to open fracture planes (black squares). c) Rose diagram of all fracture strikes measured ~14 m from the Castle Cove fault. D) Rose diagram of all fracture strikes measured ~173 m from the Castle Cove fault. 47
Figure 17. Photograph of orthogonal fracture relationship to monoclinal folding of Eumeralla Formation adjacent to the Castle Cove Fault, Castle Cove, Victoria. Photograph looking north. 48
Figure 18. Stereonet of unfolded bedding data at sites along the Otway Coast. a) Cape Otway, average fracture planes of three separate fracture sets identified in calcite filled fractures (black dashed great circles), average bedding from site where data were collected (red great circle) and fracture plane orientation after bedding is unfolded (solid black great circles). Angles between Fracture Sets 1 and 2 are 87.2° and 92.8°. b) Skenes Creek, average fracture planes of two separate fracture sets identified in fractures (black dashed great circles), average bedding from site where data were collected (red great circle) and fracture plane orientation after bedding is unfolded (solid black great circles). Angles between Fracture Sets 1 and 2 are 84.9° and 95.1°. and c)

Cumberland River, average fracture planes of two separate fracture sets identified in fractures (black dashed great circles), average bedding from site where data were collected (red great circle) and fracture plane orientation after bedding is unfolded (solid black great circles). Angles between Fracture Sets 1 and 2 are 83.1° and 96.9°. 50
Figure 19. Schematic thermal history for sites along the Otway Ranges (Calculated from vitrinite reflectance data and apatite fission track analysis (AFTA) with major events including the mid-Cretaceous cooling and the late Tertiary cooling (Adapted from Duddy (2003)). Temperature at which Type I and Type II calcite twins is also plotted as well as interpreted ages for fracture sets in the field site (dashed lines show areas of lower confidence). 54
Figure 20. Shale unit average sonic transit time vs. shale unit midpoint depth below ground level/seabed plot for shale units of the Eumeralla Formation, including the normal compaction trend zone of uncertainty (grey band) (adapted from Tassone *et al.* (in press). Superimposed is the value for the shale unit average sonic transit time for Sample JS-01 (Cape Otway) calculated from the samples porosity and typical shale values from Rider and Kennedy (2011) using the 'Wyllie Time Average' equation (Wyllie *et al*. 1956)..... 56
Figure 21. Rose diagrams showing a) strikes of all natural fractures from the field area and b) all natural fractures within the Eumeralla Formation from well Bellarine 1 (grey circles represent discontinuous fractures, grey triangles represent continuous fractures and grey squares represent full well bore fractures) (Tassone *et al.* in review). Note that radial intervals are not at the same scale. 58
Figure 22. Rose diagrams showing a) strikes of all fractures (black circles represent poles to fracture planes) ~173 m from the Castle Cove Fault, b) strikes of all fractures (black circles represent poles to fracture planes) ~14 m from the Castle Cove Fault and c) all natural fractures within the Eumeralla Formation from well Minerva 1 (grey circles represent discontinuous fractures, grey triangles represent continuous fractures and grey squares represent full well bore fractures) (Tassone *et al.* in review). Note that radial intervals are not at the same scale. 58
Figure 23. Plots of fracture susceptibility for reactivation under the Otway Basin stress conditions at 1 km depth in a strike-slip fault stress regime, with a maximum horizontal stress orientation of 144 (Tassone *et al.* in review). Delta P represents the value of pore pressure increases (in MPa) required to move the Mohr Circle to failure. High values (blue) are the furthest from the failure envelope, and therefore represent a low likelihood of reactivation. Low values (red) are the closest to the failure envelope and require the smallest change in pore pressure, and are thus at high likelihood of reactivation. These values also represent orientations of new faults/fractures to form. Poles to fracture planes (represent by x) are included on each plot and are representative of the fracture type in the title. 61
Figure 24. Differential hardness between host rocks and fracture fills in the Otway Basin. a) Hardened calcite fracture cements at Moonlight Head, showing preferential weathering of host rock compared to fracture cement. b) Hardened FE-rich alteration halos around some open fractures showing preferential weathering unaffected host rock and to varying extents the fracture itself. 63

Table 1. Stress gradients for the strike slip fault stress regime described in the Otway Basin (Tassone 2013). 19
Table 2. Fracture data collected from 11 sites in the Otway Basin. 23
Table 3. Breakdown of fracture data collected from each of the 11 sites in the Otway Basin. 23
Table 4. Fracture sets interpreted from data from each of the 11 sites in the Otway Basin. 24
Table 5. Fracture density data, average bedding and lithological variations at field sites in the Otway Basin, Victoria, Australia. Maximum burial temperatures were determined from vitrinite reflectance data by Duddy (1994). 35