



THE UNIVERSITY
of ADELAIDE

**Sedimentology, Provenance, and Salt-Sediment
Interaction in the Ediacaran Pound Subgroup, Flinders
Ranges, South Australia**

**John Waldon Counts
B.Sc., M.Sc.**

A thesis submitted for the degree of

Doctor of Philosophy

Australian School of Petroleum

Faculty of Engineering, Computer, and Mathematical Sciences

The University of Adelaide

Adelaide, South Australia

July 2016

*Shiny, speckled, red and sandy,
A bonney layer, quite a dandy
Rippled, stippled, grooved and fluted
On bedding plane for inspection suited.
A layer of red and some uniformity
And nicely opposite a fine unconformity.
Poised to announce the most famous of all
The layer of life, standing tall*

-Terry Krieg

"Bonney Sandstone"

Contents

Figures and Tables	i
Abstract	iv
Declaration	vi
Acknowledgements	vii
Chapter 1: Introduction	1
1.1: Contextual Statement.....	2
Chapter 2: Background and Review of Relevant Literature	8
2.1: Present-day Geography and Recent History	9
2.2: Palaeogeographic Context of the Adelaide Rift Complex	11
2.2.1: Configuration and Breakup of Rodinia.....	12
2.3: Geology of the Centralian Superbasin	16
2.3.1: Overview	16
2.3.2: Basin Fill	18
2.4: Stratigraphy and Sedimentology of the Adelaide Rift Complex	20
2.4.1: Callanna Group.....	21
2.4.2: Burra Group	24
2.4.3: Umberatana Group and Cryogenian Glaciation.....	27
2.4.4: Wilpena Group.....	33
2.4.5: Hawker and Lake Frome Groups.....	42
2.5: Salt-Sediment Interaction in the Adelaide Rift Complex	43
2.5.1: Minibasin Formation and Stratal Architecture	44
2.5.2: Minibasins in the Adelaide Rift Complex	46
2.6: Hydrocarbon-Bearing Analogues for the Adelaide Rift Complex	48
2.6.1: Gulf of Mexico	50

2.6.2 Offshore Brazil	53
2.6.3: Paradox Basin	55
2.7: References.....	58

Chapter 3: Sedimentological interpretation of an Ediacaran delta: Bonney

Sandstone, South Australia 76

3.1: Abstract.....	77
3.2: Introduction	78
3.3: Background	80
3.3.1: Previous Research	80
3.3.2: Study Area	83
3.4: Methodology.....	83
3.5: Results and Interpretation	86
3.5.1: Lithostratigraphic Divisions	86
3.5.2: Facies Analysis and Interpretation.....	92
3.5.3: Process and architectural classification.....	96
3.5.4: Interpretation of stacking patterns and architectural elements	97
3.6: Discussion.....	101
3.6.1: Regional Implications and Significance	101
3.6.2: Approaches to Sedimentological Interpretation with Limited Datasets ...	108
3.7: Conclusions.....	110
3.8: Acknowledgements	111
3.9: References.....	112

Chapter 4: Paleogeography of an Ediacaran Fluvial-Deltaic System: A Case Study Integrating Sedimentology and Provenance

4.1: Abstract.....	119
--------------------	-----

4.2: Introduction	120
4.3: Background	122
4.4: Methodology	126
4.4.1: Field Methods	126
4.4.2: Zircon Analysis.....	127
4.5: Sedimentology	133
4.5.1: Stratigraphy.....	133
4.5.2: Observed Lithofacies	134
4.5.3: Lithofacies Associations	143
4.5.4: Parasequence Interpretation: Integrating Stacking Patterns and Lithofacies	145
4.6: Detrital Zircon Geochronology	147
4.6.1: Bunyeroo Gorge	147
4.6.2: Mainwater Creek.....	149
4.6.3: Castle Rock.....	149
4.6.4: Comparison with Related Formations.....	150
4.7: Discussion.....	150
4.7.1: Sediment provenance.....	150
4.7.2: Implications for Early Life.....	152
4.8: Conclusions.....	158
4.9: Acknowledgements	159
4.10: References.....	160

Chapter 5: Lateral Variability along the Margin of an Ediacaran Salt-Withdrawal Minibasin.....	166
5.1: Abstract.....	167
5.2: Introduction	168

5.3: Geologic Setting.....	170
5.3.1: The Adelaide Rift Complex	170
5.3.2: Background Sedimentation.....	172
5.3.3: Character and Distribution of Diapirs in the Adelaide Rift Complex	172
5.4: Methodology.....	174
5.5: Observed Facies	175
5.5.1: Facies descriptions	175
5.5.2: Facies distribution	181
5.5.3: Facies interpretations	182
5.6: Discussion.....	186
5.6.1: Environmental controls on facies variability.....	186
5.6.2: Diapiric influence on sedimentary character and depositional processes.....	187
5.6.3: Diapir-related controls on facies change	190
5.6.4: Comparison with diapir-sediment interaction elsewhere	193
5.7: Conclusions.....	195
5.8: References.....	197

Chapter 6: Sedimentology, depositional environments and significance of an Ediacaran salt-withdrawal minibasin, Billy Springs Formation, Flinders Ranges, South Australia.....	203
6.1: Abstract.....	204
6.2: Introduction	205
6.3: Geological Setting	208
6.4: Background	211
6.5: Field And Laboratory Methodology	217
6.6: Observed Lithofacies: Description, Distribution and Interpretation	220
6.6.1: Planar-laminated silty mudstone (Lithofacies Mpl)	222

6.6.2: Convolute-laminated silty mudstone (Lithofacies Mcl).....	229
6.6.3: Lithofacies association 1: Planar-laminated and convolute-laminated mudstones.....	232
6.6.4: Matrix-supported diamictite (Lithofacies Dms).....	237
6.6.5: Lithofacies association 2: Diamictites, outsized clasts and onvolute- laminated mudstones	241
6.6.6: Tabular-bedded sandstone (Lithofacies Stb).....	246
6.7: Discussion and Significance	251
6.7.1: A glacial source for extrabasinal clasts?.....	251
6.7.2: Umberatana Syncline as a salt-withdrawal minibasin.....	253
6.7.3: Relevance to the Ediacaran metazoan assemblage	257
6.8: Conclusions.....	259
6.9: Acknowledgements	260
6.10: References.....	261
Chapter 7: Conclusions	275
7.1: Summary and Implications.....	276
7.2 Future work	280
Chapter 8: Appendices	282
8.1: Files on CD	283
8.2: Supplementary Figures, Chapter 4	284
8.3: Supplementary Figures, Chapter 5	294

Figures and Tables

CHAPTER 2

Figure 1: Present-day satellite view of the Flinders Ranges and surrounds, with geographic regions labelled.....	10
Figure 2: Major proposed reconstructions of cratonic configurations within the Rodinian supercontinent	12
Figure 3: Global palaeogeography at approximately 750 Ma.	15
Figure 4: Present-day Australia, showing the position of the Tasman line and the locations of Proterozoic cratons and basins.....	16
Figure 5: Map showing location of Centralian Superbasin.....	18
Figure 6: Correlations across the Centralian Superbasin. Modified from Walter et al. (1995).....	19
Figure 7: Generalized basin-fill stratigraphy of the Adelaide Rift Complex.....	21
Figure 8: Large stromatolite in the Trezona Formation, a fine-grained unit in the upper interglacial interval.	29
Figure 9: Glacial tillite in the upper Elatina Formation, Brachina Creek.....	30
Figure 10: Tidal rhythmites in the Elatina Formation near Pichi Richi	31
Figure 11: The basal Ediacaran GSSP ("Golden Spike") in Brachina Creek.....	33
Figure 12: A large tepee structure in the Nuccaleena dolomite	34
Figure 13: The Acraman ejecta layer in the Bunyerroo Formation, Bunyerroo Gorge.	35
Figure 14: Google Earth view of the Fortress Hill canyon complex in the Wonoka Formation on Umberatana Station.	39
Figure 15: Fine-grained shales and rapidly deposited sands with load structures in the Ediacara Member in Brachina Gorge.....	40
Figure 16: Dickinsonia, an Ediacaran organism, on display in Parachilna.	40
Figure 17: Vertical burrows in the Parachilna Formation, Parachilna Gorge	42
Figure 18: Minibasins seen in seismic section, Kwanza Basin, offshore East Africa. Courtesy TGS..	44
Figure 19: Various stacking patterns of halokinetic sequences	45
Figure 20: Seafloor topography in the Gulf of Mexico.....	50
Figure 21: Schematic salt geometries in the Gulf of Mexico.....	51
Figure 22: Subsurface structure map of top of evaporite sequence, Campos-Santos region, offshore Brazil.....	54
Figure 23: Deposition model of salt diapirs and minibasins in the Paradox Basin.....	56

CHAPTER 3

Figure 1: Stratigraphy of the Adelaide rift complex basin fill, showing the position of the Bonney Sandstone in relation to other units	82
Figure 2: Detailed geological map of the study area and its position within Australia	85
Figure 3: Summary log and palaeocurrents.....	88
Figure 4: Stratigraphic column of the Bonney Sandstone in Bunyerroo Gorge	89
Table 1: Facies found in the Bunyerroo Gorge section of the Bonney Sandstone	92
Table 2: Facies associations found in the Bunyerroo Gorge section of the Bonney Sandstone.....	93
Table 3: Brief definitions of architectural categories.	95
Figure 5: Notation scheme for relative influence of wave, tidal and fluvial processes.	97
Table 4: Summary and classification of shallow marine depositional elements... ..	103
Figure 6: Cartoon showing schematic progradational parasequences sets during a highstand systems tract.....	105
Figure 7: Correlation with Gehling's (1982) Bonney Sandstone measured sections.....	106

CHAPTER 4

Figure 1: (A) Location of Adelaide Rift Complex within Australia. Cratonic provinces in red, basins in yellow. (B) Geologic setting of area of interest, including major structural elements of the region. (C) Regional geologic map of the Northern Flinders.....	121
Figure 2: General stratigraphy and relative rock relationships of the basin fill in the Adelaide Rift Complex.....	123
Figure 3: Measured section MW	128
Figure 4: Measured section CR	129

Figure 5: Representative photographs of Lithofacies A and B.....	131
Figure 6: Representative photographs of Lithofacies C-F.	132
Table 1: Lithofacies and lithofacies associations described in this study.	135
Figure 7: Paleocurrents from the two measured sections of the Bonney Sandstone	137
Figure 8: Detrital zircon geochronology of the Bonney Sandstone, Rawnsley Quartzite, and Billy Springs Formation.....	148
Figure 9: Comparison of probability peaks in figure 8 with selected potential sources for zircons. ...	153
Figure 10: Regional reconstruction of structural and tectonic elements, sediment pathways, and salt-sediment relationships in the Bonney Sandstone. Schematic only; not to scale.	155
Figure 11: Correlation of parasequences and paleogeography over a series of time slices, showing depositional environments over the course of the formation	157

CHAPTER 5

Figure 1: Location of Adelaide Rift Complex within Australia; Geologic context and location of study area.....	171
Table 1: Summary of typical lithologies of formations seen in this study, for comparison with diapir-influenced character seen in the Mt. Frome region.....	174
Figure 2: Local geology of the Mt Frome diapir region	176
Figure 3: Sections and palaeocurrents measured in this study.	177
Table 2: Summary of lithofacies seen in the minibasin.	178
Figure 4: Sedimentologic features seen in the Brachina and Wonoka Formations	179
Figure 5: Lithologic features of the Bonney Sandstone	180
Figure 6: Facies relationship diagram for the Mt. Frome minibasin margin.....	184
Figure 7: Schematic block diagram reconstructions of depositional environments and local palaeogeography in the Mt Frome area over a series of time slices	188
Figure 8: Comparison between observed diapir-margin geometry in the Mt. Frome area and experimental models of growth faulting and salt roller generation.....	193

CHAPTER 6

Figure 1: Map of Australia showing major cratonic provinces, selected sedimentary basins, and Centralian Superbasin.	208
Figure 2: Locator map showing Adelaide Basin and field sites in relation to surrounding basins and cratonic provinces	210
Figure 3: Generalized lithostratigraphy of the Adelaide Rift Complex, Wilpena Group, and Pound Subgroup.	211
Table 1: Summary of salt-withdrawal minibasin studies in published literature, including only those where some component of sedimentology has been described.....	213
Table 2: Comprehensive list and summary of previous investigations of the Billy Springs Formation that discuss sedimentology or stratigraphy.....	215
Figure 4: Geologic map of the field area	216
Table 3: Brief description of stratigraphic units, measured section OSCS.	218
Table 4: Brief description of stratigraphic units, measured section OSCN	219
Figure 5: Stratigraphic sections measured in this study	221
Figure 6: Planar-laminated mudstone in thin-section.....	222
Figure 7: QEMSCAN images of planar-laminated lithofacies, Unit OSCS-G.....	223
Figure 8: Planar-laminated mudstone lithofacies	224
Figure 9: Rhythmite histogram and analysis.....	227
Figure 10: Convolute-laminated lithofacies in thin-section.....	229
Figure 11: X-Ray diffraction analysis of silty mudstones from planar- and convolute-laminated lithofacies	234
Figure 12: Convolute laminated silty mudstone lithofacies: outcrop photos	235
Figure 13: Diamictites, boulders, and exotic clasts found in the Billy Springs Formation	238
Figure 14: Wide range of exotic clasts seen in two 2"x3" thin sections from upper unit OSCS-A	240
Figure 15: QEMSCAN images showing detailed mineralogy of sample in unit OSCS-H, diamictite lithofacies	242
Figure 16: Interbedded sandstone-mudstone lithofacies	247
Figure 17: Sand-dominated lithofacies in thin section	248
Figure 18: Sequence stratigraphic interpretation of the relationship between the Wonoka Formation, Billy Springs Formation, and Wilpena Group	251
Figure 19: Diapirs of the northern Flinders Ranges, cross section, and Gulf of Mexico analogue	258

Appendix

Figure 1: Photos of loading structures and and convolute lamination	284
Figure 2: Representative outcrops of the Pound Subgroup in the northern Flinders Ranges	284
Figure 3: Additional photographs of Lithofacies A1	285
Figure 4: Additional photographs of Lithofacies A2	286
Figure 5: Additional photographs of Lithofacies A3	287
Figure 6: Additional photographs of Lithofacies B1	288
Figure 7: Additional photographs of Lithofacies B2	289
Figure 8: Additional photographs of Lithofacies C	290
Figure 9: Additional photographs of Lithofacies D	291
Figure 10: Additional photographs of Lithofacies F.....	292
Table 1: Summary of youngest individual concordant zircon ages in each sample.....	292
Table 2: Detailed interpretations of sedimentary environments for sediments found in sections CR and MW.....	293
Figure 11: Landscapes and outcrop expression in study area	293
Figure 12: Representative lithologies in the Rawnsley Quartzite and Wilkawillina Formations.....	295
Table 3: Timing of movement of selected diapirs throughout the Adelaide Rift Complex.....	296
Figure 13: Map of diapirs in the central and northern Flinders Ranges	296
Figure 14: Hypothetical movement and cross-section of Mt. Frome diapir.....	297
Figure 15: Typical extrusive salt dome in the Arabian Gulf.....	297

Abstract

Much of our understanding of the sedimentary character and stratigraphic architecture of subsurface sedimentary deposits is derived from field-based studies of similar depositional systems exposed in outcrop. In South Australia, excellent surface exposures in the Neoproterozoic-Cambrian Adelaide Rift Complex provide a unique opportunity to examine a series of clastic sediments deposited in an ancient fluvial-deltaic to deep marine setting. Through extensive field and laboratory work, this study documents the sedimentology, stratigraphy, provenance, facies distribution and salt-sediment interaction of the upper Bonney Sandstone and Billy Springs Formation. These sediments formed part of the margin of the Australian subcontinent during the Ediacaran, a key time in Earth history just prior to the development of multicellular life. Field investigations reveal that the Bonney Sandstone is primarily comprised of sands and shales, often in progradational parasequences that become progressively sand-dominated upward. The formation thickens significantly to the north through the preservation of additional sediments that contain abundant fluvial features, suggesting a northern depocentre in the basin. Zircon data indicate that sediments may be sourced from the distant Musgrave Province and enter the basin from a large deltaic system in the northwest. These results provide substantial new information as to the palaeogeography of South Australia during this time, and are the product of interpretation using multiple lines of evidence and the study of numerous localities.

Throughout the Adelaide Rift Complex, salt diapirs penetrated the basin fill and formed adjacent rim synclines (minibasins) due to withdrawal of underlying salt. Salt-tectonized, passive-margin settings are significant components of hydrocarbon

systems in some of the world's most productive regions, yet these features are rarely exposed in outcrop as they are here. In the far northern Flinders Ranges, the Umberatana Syncline is interpreted as a salt-withdrawal minibasin that formed in a deeper-water setting. The map-view exposure of the structure allows the depositional processes and products in the minibasin interior to be studied in a way not possible elsewhere; deepwater minibasins are very rarely exposed at the surface. Field and petrographic work reveals a mud-dominated minibasin fill containing mass-flow deposits of varying stages of maturity, ranging from clast-bearing convolute-laminated slumps to sandy turbidites. In a more proximal setting, numerous measured sections along the margin of the Mt Frome minibasin clearly show that sediment character is influenced by diapir activity and the shedding of diapir-derived clasts. Lateral facies variability is controlled by growth faulting and diapir topography, with increased abundance of diapiric material near faults and highs, as well as thinning, onlap, and rotation of sediment blocks. These results, as well as those from elsewhere in the basin, are highly applicable to the prediction of reservoir, source, and seal quality in similar geologic settings in the subsurface.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works. I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

John Waldon Counts

Date

Acknowledgements

I wish to thank the many people who have supported me personally and professionally throughout this project. First, I would like to thank my spouse Shelagh Jessop for coming with me to Australia and being understanding during the long process of writing this thesis. I would also like to thank my parents, grandparents, and family for their constant support, which has come in many different forms over the years. Third, I would like to thank my academic advisor, Kathryn Amos for many technical comments and helpful discussions, and for supporting my application to come to the University of Adelaide in the first place. Thanks are also due to Peter McCabe, and Bob Dalgarno, who provided much helpful advice over the course of this PhD.

Many other thanks are due to those who contributed to this thesis:

- Bruce Ainsworth, Jim Gehling, Ric Daniel and Vic Gostin for many technical discussions that impacted this work significantly
- My former advisor and excellent field partner Steve Hasiotis
- My fellow PhD candidates, research colleagues, and coauthors- Sara Moron, Tessa Lane, Jess Trainor, Frank Rarity, and Rachel Nanson
- Field assistants Claudia Valenti, Koyejo Oyinloye, and Limeng Liu
- Flinders Ranges landowners Barbara and Warren Fargher (Wirrealpa Station), Edie and Gina Nichol (Maynard's Well Station), and Jenny and Chris Mahoney (Umberatana Station)
- DEWNR for granting scientific research permits to Ikara-Flinders Ranges National Park and Vulkathunha –Gammon Ranges National Park

Funding for this thesis is provided in part by the American Association of Petroleum Geologists Nancy Setzer Murray Memorial Grant and a University of Adelaide International Postgraduate Research Scholarship. I acknowledge the traditional inhabitants of the land on which this research was conducted.