



**Basin analysis and the geochemical signature of
Paleoproterozoic sedimentary successions in northern
Australia: Constraints on basin development in respect
to mineralisation and paleoreconstruction models**

Alexis Lambeck, (B.Sc, M.Sc)

**Geology and Geophysics
School of Earth and Environmental Sciences
The University of Adelaide**

**This thesis is submitted in fulfilment of the requirements for the
degree of Doctor of Philosophy in the Faculty of Science,
University of Adelaide**

December 2011

Table of Contents

CHAPTER 1 - GEOCHEMISTRY AND MINERALISATION IN THE NORTH AUSTRALIA CRATON.....	1
1.1 THESIS OUTLINE AND SUMMARY OF RESULTS	5
1.2 GEOLOGICAL BACKGROUND.....	6
1.2.1 <i>Tanami region and Pine Creek Orogen</i>	6
1.2.2 <i>Eastern Proterozoic Australia at ~1650 Ma</i>	6
1.3 RESULTS.....	6
1.4 SUPPLEMENTARY APPENDICES.....	8
1.5 REFERENCES.....	9
CHAPTER 2 - PROTEROZOIC TURBIDITIC DEPOSITIONAL SYSTEM (TANAMI GROUP) IN THE TANAMI REGION, NORTHERN AUSTRALIA, AND IMPLICATIONS FOR GOLD MINERALISATION	15
STATEMENT OF AUTHORSHIP.....	15
ABSTRACT.....	19
2.1 INTRODUCTION.....	19
2.1.1 <i>Geological background and regional stratigraphy</i>	23
2.1.2 <i>Gold deposits and gold prospects of the Tanami region</i>	25
2.2 METHODS	26
2.3 FACIES ASSOCIATIONS	29
2.3.1 <i>Facies Association 1 (FA1) and interpretation</i>	29
2.3.2 <i>Facies Association 2 (FA2) and interpretation</i>	29
2.3.3 <i>Facies Association 3 (FA3) and interpretation</i>	35
2.4 REGIONAL STRATIGRAPHIC TRANSECTS AND ISOPACH MAPS	35
2.6 DEPOSITIONAL HISTORY OF KILLI KILLI FORMATION	37
2.7 CONCLUSIONS	39
2.8 ACKNOWLEDGEMENTS	39
2.9 REFERENCES.....	39
CHAPTER 3 - TYPECASTING PROSPECTIVE AU-BEARING SEDIMENTARY LITHOLOGIES OF THE TANAMI REGION, NORTHERN AUSTRALIA.....	43
STATEMENT OF AUTHORSHIP.....	43
ABSTRACT.....	45
3.1 INTRODUCTION.....	45
3.1.1 <i>Geological setting and stratigraphy</i>	47
3.2 SAMPLING AND ANALYTICAL METHODS	51
3.3 GEOCHEMICAL RESULTS.....	52
3.3.1 <i>Major elements</i>	52
3.3.2 <i>Regional chemostratigraphy</i>	56
3.3.3 <i>Stubbins Formation</i>	59
3.3.4 <i>Dead Bullock Formation</i>	59
3.3.5 <i>Killi Killi Formation</i>	59
3.3.6 <i>Ware Group</i>	63
3.3.7 <i>Mount Charles Formation</i>	63
3.4 DISCUSSION.....	63
3.4.1 <i>Suggested evolution of the Tanami region geochemical variations</i>	64
3.4.2 <i>Stubbins Formation: event 1</i>	64
3.4.3 <i>Dead Bullock Formation: event 2</i>	64

3.4.4 Killi Killi Formation: event 3.....	66
3.4.5 Ware Group deposition: event 4.....	66
3.4.6 Mount Charles Formation: event 5.....	67
3.5 IMPLICATIONS FOR GOLD EXPLORATION.....	67
3.6 CONCLUSIONS.....	69
3.7 ACKNOWLEDGEMENTS.....	69
3.8 REFERENCES.....	70
CHAPTER 4 - ARE IRON-RICH SEDIMENTARY ROCKS THE KEY TO THE SPIKE IN OROGENIC GOLD MINERALISATION IN THE PALEOPROTEROZOIC?.....	75
STATEMENT OF AUTHORSHIP.....	75
ABSTRACT.....	77
4.1 INTRODUCTION.....	77
4.1.1 Geological setting of Paleoproterozoic rocks from northern Australia.....	78
4.1.2 Paleoproterozoic gold deposits.....	80
4.2 GEOCHEMICAL DATA.....	83
4.3 GEOCHEMICAL MODELLING.....	85
4.4 GLOBAL CONTEXT WITH IMPLICATIONS FOR GOLD PROSPECTIVITY.....	88
4.5 COMPARISON OF TANAMI REGION WITH THE PALEOPROTEROZOIC OF SOUTH DAKOTA (USA) AND THE WEST AFRICA CRATON.....	88
4.6 CONCLUSIONS.....	91
4.7 ACKNOWLEDGEMENTS.....	91
4.8 APPENDIX; ANALYTICAL METHODS.....	92
4.9 REFERENCES.....	93
CHAPTER 5 - AN ABRUPT CHANGE IN ND ISOTOPIC COMPOSITION IN AUSTRALIAN BASINS AT 1650 MA: IMPLICATIONS FOR THE TECTONIC EVOLUTION OF AUSTRALIA AND ITS PLACE IN NUNA.....	99
STATEMENT OF AUTHORSHIP.....	99
ABSTRACT.....	101
5.1 INTRODUCTION.....	101
5.1.1 Geological setting and stratigraphy.....	104
5.1.2 Syn-sedimentary "pinkites" in the Mount Isa Province.....	105
5.2 SAMPLING AND ANALYTICAL METHODS.....	106
5.3 TRENDS IN SM-ND AND U-PB ISOTOPE DATA.....	112
5.4 TECTONIC SETTING OF THE ~1650 MA MAGMATIC SOURCE.....	114
5.5 1690 – 1640 MA MAGMATISM IN AUSTRALIA; A SOURCE OF DETRITUS?.....	115
5.5.1 Possible sources from Proterozoic Australia.....	115
5.5.2 Possible sources from outside of Australia.....	116
5.6 CONCLUSIONS.....	117
5.7 ACKNOWLEDGEMENTS.....	117
5.8 REFERENCES.....	117
5.9 SUPPLEMENTARY DATA.....	123
CHAPTER 6 - CONCLUSIONS.....	127
6.1. SEDIMENTARY BASINS DEPOSITED DURING NUNA SUPERCONTINENT AMALGAMATION.....	127
6.2. SEDIMENTARY BASINS DEPOSITED NUNA SUPERCONTINENT BREAK-UP.....	129
6.3 REFERENCES.....	130
APPENDIX: SUPPLEMENTARY U-PB ZIRCON DATA COLLECTED DURING A. LAMBECK'S PHD PROGRAM.....	131

List of Figures

1.1 PROTEROZOIC MAP OF AUSTRALIA	2
1.2 TIME-SPACE DIAGRAM OF PROTEROZOIC AUSTRALIA	3
2.1 LOCATION OF TANAMI REGION	20
2.2 SOLID GEOLOGY OF PROTEROZOIC UNITS IN THE TANAMI REGION	21
2.3 REGIONAL STRATIGRAPHY OF THE TANAMI REGION	22
2.4 PHOTOGRAPH ILLUSTRATING POORLY EXPOSED TANAMI REGION	22
2.5 EAST–WEST TRANSECT OF THE TANAMI REGION	27
2.6 NORTH–SOUTH TRANSECT OF THE TANAMI REGION	28
2.7 ISOPACH OF THE DEAD BULLOCK FORMATION	30
2.8 ISOPACH OF THE COMBINED KILLI KILLI FORMATION – WARE GROUP ASSEMBLAGE	31
2.9 EXAMPLE PHOTOGRAPHS OF FACIES 1 – 6	32
2.10 EXAMPLES OF MEASURED STRATIGRAPHIC SECTIONS OF THE CALLIE MEMBER AND KILLI KILLI FORMATION	34
2.11 SCHEMATIC CARTOON ILLUSTRATING THE EAST-WEST LATERAL FACIES RELATIONSHIPS OF THE KILLI KILLI FORMATION	36
3.1 SOLID GEOLOGY OF PROTEROZOIC UNITS IN THE TANAMI REGION	46
3.2 REGIONAL STRATIGRAPHY OF THE TANAMI REGION	48
3.3 TRIANGULAR DIAGRAMS OF TANAMI REGIONAL GEOCHEMISTRY	55
3.4 DOWNHOLE GEOCHEMICAL PLOTS	57
3.5 REGIONAL GEOCHEMISTRY PLOT	57
3.6 REGIONAL RARE EARTH ELEMENT PLOTS	58
3.7 PROSPECT RARE EARTH ELEMENT PLOTS	58
3.8 ϵ_{Nd} VALUES OF REGIONAL STRATIGRAPHY	62
3.9 SCHEMATIC TECTONIC RECONSTRUCTION MODEL OF TANAMI REGION	65
3.10 TOTAL GOLD TONNAGE PLOTTED TO GEOCHEMISTRY	68
4.1 PALEOPROTEROZOIC NORTHERN AUSTRALIA CRATON	79
4.2 TOTAL ORGANIC CARBON (TOC), TANAMI REGION	84
4.3 TOTAL IRON AS Fe_2O_3T VERSUS SiO_2 , TANAMI REGION	86
4.4 PERCENTAGE OF FeO OF Fe_2O_3T , TANAMI REGION	86
4.5 MODELLING OF A TYPICAL OROGENIC GOLD FLUID	87
4.6 TECTONIC RECONSTRUCTION OF COLUMBIA SUPERCONTINENT	90
5.1 REGIONAL CHRONOSTRATIGRAPHIC COLUMNS OF PROTEROZOIC AUSTRALIA	102
5.2 TERA-WASSERBURG CONCORDIA DIAGRAM EASTERN SUCCESSION DOLERITE	107
5.3a PHOTOGRAPHS OF PEPERITES, WESTERN SUCCESSION	107
5.3b PHOTOGRAPHS OF PEPERITES, WESTERN SUCCESSION	107
5.4 RARE EARTH ELEMENT PLOTS OF VOLCANICS IN PROTEROZOIC AUSTRALIA	113

List of Tables

2.1 FACIES CHARACTERISTICS OF THE TANAMI GROUP	33
3.1 SUMMARY OF TANAMI REGIONAL STRATIGRAPHY IN RESPECT TO TOTAL GOLD	49
3.2 REPRESENTATIVE GEOCHEMICAL SAMPLES FROM TANAMI REGIONAL STRATIGRAPHY.....	53
3.3 SM-ND ISOTOPE DATA FROM TANAMI REGIONAL STRATIGRAPHY	60
4.1 AVERAGE CHEMICAL COMPOSITIONS FOR ROCK FORMATIONS.....	81
4.2 AVERAGE OROGENIC FLUID COMPOSITION FOR MASS TRANSFER MODELLING	87
5.1 SM-ND ISOTOPE DATA FOR EASTERN AUSTRALIA	108
5.2 WHOLE-ROCK GEOCHEMISTRY OF SYN-SEDIMENTARY ‘PINKITES’	110

Abstract

Secular changes in the characteristics of sedimentary basins and their associated mineral deposits in Proterozoic Australia are directly related to the evolving global tectonic regimes and global changes in atmospheric and oceanic redox states. Identifying these secular changes provides critical information to assist in applying first pass techniques for regional exploration in Australia. The break-up and formation of the Nuna supercontinent is recorded within sedimentary basins within Proterozoic Australia. Sedimentary basins deposited between 1910 Ma and 1810 Ma formed during the Nuna supercontinent amalgamation and host orogenic gold mineralisation, whereas those deposited between 1710 Ma – 1575 Ma are directly associated with the break-up of Nuna and host lead-zinc mineralisation.

Sediments in northern Australia deposited during the Nuna amalgamation, and before the Great Oxidation Event, consist of fine-grained iron-rich/mafic mudstones and siltstones which are geochemically characterised by high FeO contents, high Cr/Th and low Th/Sc values. This sedimentary assemblage includes the gold-bearing succession of the Dead Bullock Formation, Tanami region and Koolpin Formation, Pine Creek Orogen. This contrasts with the regionally overlying stratigraphy, which is characterised by low Cr/Th and FeO values and high Th/Sc values. These rocks are also characterised by lower abundances of gold deposits. These geochemical characteristics have successfully been applied by Newmont Tanami Operations to help design future drill programs in the Tanami region.

Sedimentological analysis has been applied in the poorly exposed Tanami basin. The results of these studies, in combination with isopach maps derived from seismic data, litho-geochemistry and U-Pb SHRIMP geochronology, have been used to establish a depositional model for gold-bearing Palaeoproterozoic rocks of the Tanami region. The identification of stratal surfaces between the Dead Bullock Formation (Callie Member) and the Killi Killi Formation permits a better understanding of stratigraphic architecture. The Killi Killi Formation consists of coarser grains in the northwest compared to the southeast which suggests that sediment was transported from the northwest. The maximum thickness of the Tanami Group is recorded in the northwest which then fines/thins to the southeast to a position south of the Callie Mine. The Callie Member was deposited as part of a condensed section below storm wave base. The conformably overlying Killi Killi Formation was also deposited below storm wave base and forms part of a low stand system tract.

Claystone and mudstone within the Killi Killi Formation are prospective for epigenetic gold deposits hosted by reduced mudstones (i.e., Callie style deposits). Within the Killi Killi Formation and the Callie Member, gold potential is enhanced by deep crustal faults that intersect black claystone forming overbank deposits of the Killi Killi Formation or condensed sections of the Callie Member. The claystone forms potential redox boundaries for oxidised gold bearing-fluid. Targeting the position of these thrust faults within claystone environments could help refine gold exploration methods in the Killi Killi Formation.

Possible analogies to iron-rich claystone in the Tanami province are suggested with similar iron-rich successions in the Pine Creek Orogen. Deposition of these iron-rich rocks in northern Australia may have involved similar processes that deposited iron-rich rocks between 2100 to 1800 Ma at Homestake, U.S.A., Ghana, West Africa, and Guyana, South America. Between ~2400 Ma to ~1850 Ma Superior-style BIF deposit were

deposited in many areas around the world, but after about 1800 Ma a global rise in oxygen content of the oceans led to the end of deposition of banded iron formations and iron-rich sediments. This transition from iron-rich sediments to iron-poor sediments corresponds to a general change in mineralisation style and correlates with the Nuna supercontinent break-up. Orogenic gold in northern Australia halted by ~1810 Ma, replaced by a major period of lead-zinc mineralisation between 1710 – 1575 Ma which is associated with the Nuna supercontinent break-up.

Basins that formed in the present day eastern part of Proterozoic Australia during Nuna break-up are characterised by an abrupt change in Sm-Nd isotopic characteristics of sediments at ~1650 Ma. Prior to ~1650 Ma, these rocks have bulk $\epsilon_{Nd}(1650 \text{ Ma})$ values of -8 to -6, interpreted to imply a relatively evolved sedimentary source. Sedimentary rocks that accumulated between 1650 Ma – 1600 Ma are characterised by bulk $\epsilon_{Nd}(1650 \text{ Ma})$ values of -2 to -1, indicating a more juvenile sedimentary source. Although Proterozoic felsic magmatism is known in eastern and central Australia, these rocks are either too young or too evolved to have acted as a source for juvenile detritus that characterises the sedimentary successions after ~1650 Ma, which indicates either a source exogenous to present day Australia or a source that was present within Proterozoic Australia that has been lost from the geological record. Juvenile felsic magmatic rocks with ages of around 1650 Ma are known in Laurentia and Baltica, both of which have been interpreted to have been adjacent to Australia at ~1650 Ma. Either of these sources could have been a source of juvenile detritus into Australian Proterozoic basins, but existing data are insufficient to be able to distinguish between these possibilities. Alternatively, the source could have been an endogenous source within Proterozoic Australia. Evidence of such a source may be preserved as "pinkites", thin felsic layers with a probable magmatic origin that are present in parts of the stratigraphy of interest. Present data do not allow discrimination of these three possible sources of juvenile detritus that were introduced into Proterozoic Australian basins at ~1650 Ma.

Sediment hosted Mt Isa-style Zn-Pb-Ag sediments can potentially be fingerprinted by Sm-Nd isotopic data. Future exploration could use this important isotopic boundary at 1650 Ma as an exploration tool for Mt Isa-style deposits in the Mt Isa Inlier, the Etheridge Province, and elsewhere in Proterozoic Australia.

Acknowledgements

By undergoing this PhD through Geoscience Australia and based at Adelaide University I have had the benefit of many people to ‘bounce ideas’ around and talk geology with, so I’m grateful to a lot of people who all collectively played a part in my PhD program. First and foremost I’d like to thank Geoscience Australia for supporting my PhD program, I’m grateful to the support given by James Johnson, Russell Korsch and GA Senior Management throughout my PhD program.

Secondly I’d like to thank my PhD supervisor at Geoscience Australia, David Huston, who was a fantastic help. Dave’s unfaltering willingness to help out was greatly appreciated, especially during those ‘Huston, I have a problem’ moments! I’m also very grateful to Dave Champion for providing me with endless chats about geochemistry...and fishing. Time in the field was always fun with George Gibson and George’s endless debates about geology. Andrew Retter provided much tireless enthusiasm in the field and Andrew’s attention to detail made field work a really fun and enjoyable experience. Lesley Wyborn is also thanked for many thought provoking chats and Lesley’s willingness ‘to bounce ideas around’ was much appreciated. Terry Mernagh was always happy to have chats about geochemistry and the dark art of ‘geochemical modelling’. Tony Meixner’s skills at GOCAD were greatly appreciated...as were endless chats about 24 hour mountain biking...

At Adelaide University, Karin Barovich and Martin Hand had the tough job of dealing with all my questions and work from afar and my endless stream of emails and ‘stuff’ to read through. I’m very thankful to Karin and Martin for those thought provoking questions and conversations through out my PhD program and with the brief time Martin and I spend ‘kicking rocks’ together in the Mount Isa region. David Bruce’s tireless work in the labs at Adelaide University was also greatly appreciated, as was his attention to detail.

At Geoscience Australia; Richard Blewett, Peter Maher and John Wilford were always up for a run and a chat and a great way to break-up the day. Chats over coffee with Paul Henson about geology and ‘life outside’ of geology were also fun times. I’m very grateful to the Liz Webber, and Bill Pappas’s geochemistry team, their help and willingness was greatly appreciated over the years! The GA geochronology group provided a fantastic resource and I’m entirely grateful to them all, especially Keith Sircombe, Andrews Cross, Chris Carson, and Chuck Magee for endless discussion down in the SHRIMP lab. Patrick Burke’s enthusiasm to keep the SHRIMP running was also greatly appreciated. Chris Foudulis and his team in the zircon separation group also provided much enthusiastic support. At the University of Western Australia, Annette George provided many thoughtful suggestions and comments through out my PhD.

I am especially grateful to Ian Withnall and Allan Parsons from the Geological Survey of Queensland who put up with my endless stream of questions while ‘kicking-rocks’ in the field. The logistical support from GSQ while working in the Mount Isa Inlier was greatly appreciated during my PhD program. The GSQ team were always happy to talk geology and have a beer & BBQ with at the ‘GSQ house’ in Mount Isa.

My loving wife Andrea is also thanked for her all her support during my PhD program. I’m very grateful to Andrea’s understanding of me disappearing off to remote places for weeks at a time with only brief and random sat phone conversations. Our two young children, Adah and Ashby, were always up for giggles and were a great way to really remember what’s important in life!

Finally thanks to the University of Florida, Mike Perfit and David Foster for providing me with a 'quiet space' in the department to finish writing up my PhD.

Publications and selected conference Abstracts

Peer reviewed Journal Articles

- Lambeck, A.,** Huston, D., and Barovich, K., 2010, Typecasting prospective Au-bearing sedimentary lithologies using sedimentary geochemistry and Nd isotopes in poorly exposed Proterozoic basins of the Tanami region, Northern Australia: *Mineralium Deposita*, v. 4, p. 497–515.
- Lambeck, A.,** Mernagh, T. and Wyborn, L., A, I., 2011. Are iron-rich sedimentary rocks the key to the spike in orogenic gold mineralization in the Paleoproterozoic? *Economic Geology* 106 (3): 321-330.
- Lambeck, A.,** Barovich, K., George, A.D., Cross, A. Huston, D., and Meixner T. Defining basin architecture in the poorly exposed Tanami Proterozoic turbiditic basin, northern Australia with implications for gold mineralisation (in press, *Australian Journal of Earth Science*)
- Lambeck, A.,** Barovich, K., Gibson, G.M. and Huston, D., in review. An abrupt change in Nd isotopic composition in Australian basins at 1650 Ma: implications for the tectonic evolution of Australia and its place in Nuna. (in review. *Precambrian Research*).
- Lambeck, A., Cross, A.,** SHRIMP U-Pb detrital & volcanic zircon results, Georgetown Inlier, Mt Isa, Eastern Succession. (will form a future GA Record).

Selected Conference Abstracts

- Lambeck, A.,** Gibson, G., Neumann, N., Huston, D. 2008, An integrated sedimentological, geochemical and geochronological analysis of Georgetown: Constraints on basin development and paleo reconstructions. Abstracts. Australian Earth Sciences Convention 2008.
- Lambeck, A.,** Parsons, P., Barovich, K., Hand, M., Withnall, I., Huston, D., Neumann, N. and Carson, C. 2009, Sm-Nd isotopic fingerprinting defining a ~1650 Ma reference boundary in Mt Isa and Georgetown: Implications for Zn-Pb exploration. *Digging Deeper*, Abstracts, 2 December 2009, pg 12-15.
- Lambeck, A.,** Huston, D., Neumann, N., Barovich, K. and Hand M., 2010, Reconstruction of the Australia-Laurentia link at 1650 Ma: constraints from Sm-Nd data from the Georgetown, Mount Isa, Curnamona, Yavapai and Mazatzal Provinces . Specialist Group in Tectonics and Structural Geology, Geological Society of Australia, Abstracts 25–29 January 2010, pg. 39.
- Lambeck, A.,** Neumann, N., Barovich, K., Hand, M., Huston, D., Carson, C., Gibson, G., Withnall, I., and Parson, A., 2010, An Australian tectonic reconstruction at ~1650 Ma: A Baltica link. Abstracts. Australian Earth Sciences Convention 2010, pg. 132.
- Lambeck, A.,** Mernagh, T. and Wyborn, L., A,I., 2010. The Spike in Orogenic Gold Mineralization in the Paleoproterozoic: Linked to Anomously Iron-Rich Sedimentary rocks? Society of Economic Geology annual conference Keystone, Colorado pg 13.

Declaration

This thesis contains no material that 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 any other person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University and Geoscience Australia libraries, being available for loan and photocopying.

Alexis Lambeck
