UNIVERSITY OF ADELAIDE LIBRARY 26/7/05



THE UNIVERSITY OF ADELAIDE

School of Earth & Environmental Sciences,
Geology & Geophysics

NEOTECTONICS OF THE MOUNT LOFTY RANGES (South Australia)

Victor Tokarev

Thesis submitted for the degree of Doctor of Philosophy
in the University of Adelaide, Faculty of Science

February, 2005

TABLE OF CONTENTS

Table of Contents i

List of Figures v

Abstract vii

Disclaimer viii

Acknowledgments ix

CHAPTER 1: INTRODUCTION **1**

1.1 Aim and Objectives 1
1.2 Geological, Tectonic and Geomorphological Backgrounds 2
1.3 Thesis Outline 6

CHAPTER 2: METHODS **8**

2.1 Digital Elevation Model (DEM) 8
2.2 Use of Geological and Geomorphological Cross-sections 12
2.3 Analysis of Planation Surfaces 12
2.4 Lithostratigraphic Analysis of Tertiary and Quaternary Sediments 13
2.5 Use of Global Sea-Level Curve 13
2.6 Combined Method of Palaeoreconstructions 14

CHAPTER 3: PRE-TERTIARY BASEMENT: GEOLOGY AND TECTONICS **15**

3.1 Introduction 15
3.2 Proterozoic Complex 15
3.3 Late Proterozoic to Early Paleozoic Complex 16
3.3.1 .Delamerian Structure 17
3.4 Late Paleozoic Complex 20
3.5 Mesozoic Development 24
3.5.1 Triassic through to Middle Jurassic 24
3.5.2 Mid-Jurassic through to the Cretaceous 25
3.5.3 Mesozoic Igneous Activities 27
3.5.4 Summary of Mesozoic Development 30
3.6 Mesozoic Plate Reorganisation since the Gondwanan Breakup 32
3.6.1 Study Region since the Gondwanan Breakup 34
3.7 Separation of the Australian and Antarctic Plates: Potoroo Extensional Tectonic Regime (~99Ma and ~43Ma) 36
3.7.1 Study Region between 99Ma and 43Ma 39
3.8 Early Tertiary Environment 40
3.9 Pre- Middle Eocene Palaeoplain 41

CHAPTER 4: REGIONAL PALAEORECONSTRUCTIONS: THE MOUNT LOFTY RANGES AND FLANKING ST. VINCENT AND WESTERN MURRAY BASINS 43

4.1 Introduction 43
4.2 Regional Stages 44
4.3 Johannian Stage (~43-37Ma) 47
4.3.1 Johannian Stage in the St. Vincent Basin 48
North Maslin Sand 48
Clinton Formation 51
South Maslin Sand 52
4.3.2 Johannian Stage in the Western Murray Basin 56
Olney Formation 57
4.3.3 Johannian Stage: Conclusion 59
4.4 Aldingan (~37Ma) through to Balcombian Stages (~14Ma) 60
4.5 Aldingan Stage (~37-34Ma) 60
4.5.1 Aldingan Stage in the St. Vincent Basin 61
Tortachilla Limestone 61
Blanche Point Formation 64
Chinaman Gully Formation 66
4.5.2 Aldingan Stage in the Western Murray Basin 69
Buccleuch Formation 69
4.5.3 Aldingan Stage: Conclusion 72
4.6 Willungan Stage (~34-29Ma) 73
4.6.1 Willungan Stage in the St. Vincent Basin 73
Aldinga Member of the Port Willunga Formation 74
Ruwarung Member of the Port Willunga Formation 76
4.6.2 Willungan Stage in the Western Murray Basin 77
Buccleuch Beds 77
4.6.3 Willungan Stage: Conclusion 78
4.7 Early Janjukian Stage (~29-24Ma) 79
4.7.1 Early Janjukian Stage in the St. Vincent Basin 79
4.7.2 Early Janjukian Stage in Intramontane Basins 80
4.7.3 Early Janjukian Stage in the Western Murray Basin 88
Compton Conglomerate 88
Ettrick Formation 92
4.7.4 Early Janjukian Stage: Conclusion 94
4.8 Late Janjukian Stage (~24-21Ma) 95
4.8.1 Late Janjukian Stage in the St. Vincent and Intramontane Basins 95
4.8.2 Late Janjukian Stage in the Western Murray Basin 97
4.8.3 Late Janjukian Stage: Conclusion 98
4.9 Longfordian Stage (~21-16Ma) 99
4.9.1 Longfordian Stage in the St. Vincent and Intramontane Basins 99
4.9.2 Longfordian Stage in the Western Murray Basin 101

4.9.3 Longfordian Stage: Conclusion 103
4.10 Batesfordian-Balcombian Stages (~16-13Ma) 104
4.10.1 Batesfordian and Balcombian Stages in the St. Vincent and Intramontane Basins 104
Munno Para Clay Member of the Port Willunga Formation 105
4.10.2 Batesfordian-Balcombian Stages in the Western Murray Basin 106
4.10.3 Batesfordian-Balcombian Stages: Conclusion 107
4.11 Bairnsdalian and Mitchellian Stages (~13-5.5Ma) 108
4.11.1 Late Miocene Sedimentary Termination, Uplift and Erosion 108
4.11.2 Nature of Miocene/Pliocene Unconformity, Erosion and Exhumation 110
4.11.3 Marine Bed-load Erosion 112
4.11.4 Bairnsdalian and Mitchellian Stages: Conclusion 114
4.12 Cheltenhamian and Kalimnan Stages (~5.5-2Ma) 114
4.12.1 Cheltenhamian and Kalimnan Stages in the St. Vincent Basin 115
Kooyonga Formation 115
Dry Creek Sand 115
Hallett Cove Sandstone 117
4.12.2 Cheltenhamian and Kalimnan Stages in the Western Murray Basin 118
Loxton Sand 120
Parilla Sand 122
Karoonda Surface 123
Norwest Bend Formation 124
Blanchetown Clay 125
4.12.3 Cheltenhamian and Kalimnan Stages: Conclusion 127
4.13 Werrikooian Stage (~2Ma to Present) 128
4.13.1 Werrikooian Stage in the St. Vincent Basin 133
Burnham Limestone 133
Point Ellen Formation 134
Hindmarsh Clay 134
Keswick Clay 137
Gley Clays and Black Earths 138
Glanville Formation 138
Carbonate Pedoderm 139
Pooraka Formation of the St. Vincent Basin 141
St. Kilda Formation 143
4.13.1.1 Werrikooian Stage in the St. Vincent Basin: Conclusion 144
4.13.2 Werrikooian Stage in the Western Murray Basin 145
4.13.2.1 North-Western Murray Basin 145
Blanchetown Clay 146
Bungunnia Limestone 146
Pooraka Formation in the Western Murray Basin 146
Woorinen Formation 148
Molineaux Sand 150

Coonambidgal Formation 150
4.13.2.2 South-Western Murray Basin 151
Coomandook Formation 151
Bridgewater Formation 153
4.13.3 Werrikooian Stage in the Western Murray Basin: Conclusion 155
4.14 Regional Palaeoreconstructions: Conclusion 156

CHAPTER 5: NEOTECTONICS OF THE MOUNT LOFTY RANGES AND FLANKING ST. VINCENT AND WESTERN MURRAY BASINS 159
5.1 Introduction 159
5.2 Neotectonic Plate Reorganisation 162
5.3 Neotectonic Settings 165
5.3.1 Tertiary Extensional Setting: Crustal Segmentation 174
5.3.2 Tertiary Extensional Setting: Strain Accommodation and Transfer Zones 175
5.3.3 Lake Bungunnia: A New Assumption 179
5.3.4 Nature and Regional Significance of Tertiary Strain Transfer Zone 180
5.3.5 Compressional Neotectonic Setting 185
5.4 Neotectonic Setting: Independence versus Inheritance (Discussion) 191

CHAPTER 6: GEOMORPHOLOGY AND LANDSCAPE EVOLUTION OF THE MOUNT LOFTY RANGES 197
6.1 Introduction 197
6.2 Geomorphological Setting of the Mount Lofty Ranges 199
6.2.1 Major Watershed of the Mount Lofty Ranges 207
6.3 Palaeodrainage Reconstructions 210
6.3.1 Palaeodrainage of the Eastern Portion of the Mount Lofty Ranges 211
6.3.2 Palaeodrainage of the Western Portion of the Mount Lofty Ranges 223
6.4 Landscape Evolution of the Mount Lofty Ranges 235
6.4.1 Drainage Initiation (Middle-Late Eocene) 236
6.4.2 Subtle Erosion (Oligocene-Middle Miocene) 237
6.4.3 Landscape Relaxation (Late Miocene–Early Pleistocene) 241
6.4.4 Vigorous Erosion (Mid-Pleistocene-Recent) 243

CHAPTER 7: SYNTHESIS & CONCLUSIONS 246
7.1 Introduction 246
7.2 Three Stage Neotectonic Model 247
7.2.1 Neotectonic Stage I: Crustal Extension (~43Ma to ~15Ma) 247
7.2.2 Neotectonic Stage II: Transitional regime (~15Ma to ~1Ma) 252
7.2.3 Neotectonic Stage III: Crustal Compression (~1Ma to Present) 246
7.3 Conclusion 258

LIST OF FIGURES

Chapter 1

1-1 Location of the study area 3
1-2 Mount Lofty Ranges and flanking St. Vincent and Western Murray Basin with some elements of neotectonic setting (1-s DEM) 4

Chapter 2

2-1 Sample data of 1arc-second DEM of the Mount Lofty Ranges 9
2-2 Sequence of marine floodings of the southern Mount Lofty Ranges 11

Chapter 3

3-1 Basement Delamerian structure of the Mount Lofty Ranges 18
3-2 Restored cross-section of the basement structure in central part of the Ranges 19
3-3 Evidence of the Permian Glacials 21
3-4 Permian glacial deposits of the Troubridge Basin 23
3-5 Cretaceous Berri and Otway Basins in South Australia 26
3-6 Main structural elements of the Australian Southern Rift System 28
3-7 Seaward stepped down chain of half-grabens of the Otway and Duntroon Basins 29
3-8 Tectono-structural elements of the pre-Tertiary basement of southern South Australia. 31
3-9 The impact of the Cetaceous marine inundation on the Australian continent 35
3-10 Seafloor spreading arround Australia 37

Chapter 4

4-1 Regional Stages and Global Eustatic Curve 45
4-2 General trend of the Tertiary tectonic subsidence of the St. Vincent Basin 54
4-3 Geological setting and cross-section of the Willunga Embayment 55
4-4A Geological setting of the Noarlunga Embayment 63
4-4B Projected marine flood at 180m above PSL onto the landscape of the Noarlunga and Willunga Embayments 63
4-5 Composite columnar section of Tertiary units of the St. Vincent Basin 65
4-6 Principal neotectonic model associated with the Tertiary extensional regime 67
4-7 Buccleuch Embayment (SW Murray Basin) 71
4-8 Intramontane Hindmarsh Tiers and Myponga Basins and Meadows-Kuitpo area 81
4-9 Calculation of tectonic subsidence in the southern Ranges (Myponga Basin) 83
4-10 Simulation of the marine floods over the Mount Lofty Ranges at 130m, 180m and 230m with some elements of neotectonic setting 84
4-11 Simulated marine flood at ~350m above PSL over the southern Mount Lofty Ranges .. 85
4-12 Cross-section along the Sellicks Hill Range watershed 87
4-13 Lithostratographic section on the eastern slope of the Mount Lofty Ranges (Cross's Bridge, Bremer Valley) 90
4-14 Inferred marine passage between the St. Vincent and Western Murray Basins over the Mount Lofty Ranges with marine flood simulation at ~250m above PSL 91
4-15 Distribution of the Late Oligocene-Middle Miocene Ettrick Formation and Murray Group Limestones in the Murray Basin 93
4-16 Distribution of the Loxton-Parilla Sands in the Murray Basin 119
4-17 Pliocene marine flood simulation of the Mount Lofty Ranges at ~80m above PSL 121
4-18 Lake Bungannia and structural cross-section of the northern part of the Western Murray Basin 126
4-19 Palaeomagnetic and oxygen isotope stratigraphy of the Quaternary in South Australia 129
4-20 Quaternary oxygen isotope curve correlated with lithostratigraphic units of the St. Vincent Basin 131

4-21 Quaternary oxygen isotope curve correlated with lithostratigraphic units of the SW and NW Murray Basin 132
4-22 The distribution of the Hindmarsh Clay within the Adelaide Plains sub-basin 135
4-23 High resolution benthic oxygen isotope record and the Late Pleistocene sedimentation in the St. Vincent Basin 140
4-24 Principal neotectonic model comparing Tertiary normal faults and Pleistocene reverse faults affecting thickness of sediments 142
4-25 The distribution of the Pooraka Formation in the Adelaide Plains sub-basin 149
4-26 Sand-dune ridges crossing by the Bremer Fault (SW Murray Basin) 152
4-27 Geological section across Murray River Gorge 154

Chapter 5

5-1 Seafloor spreading around Australia with an index of changes in plate motion at the 43 Ma 163
5-2 Seafloor spreading before and after the 43Ma 164
5-3 3D surface and block-diagram of the western margin of the Mount Lofty Ranges 168
5-4 Tertiary neotectonic setting of the southern Mount Lofty Ranges 169
5-5 Principal structural cross-sections of the northern and southern parts of the Ranges ... 171
5-6 Neotectonic setting of the intramontane Barossa Basin 172
5-7 Geological transects of the Barossa Basin and Freeling area 173
5-8 Tertiary Transfer Zone fault terminations 181
5-9 3D visualization of the southern Australian continental margin 183
5-10 Pleistocene compressional deformation on the western and eastern sides of the Mount Lofty Ranges 186
5-11 Active tectonic splay of the Willunga Fault weackness zone at Waterfall Creek (western slope of the Sellicks Hill Range) 188
5-12 Tectonic contact between the Cambrian basement and Pleistocene Ochre Cove Formation in the Cactus Creek (western slope of the Sellicks Hill Range) 188
5-13 Geomorphological cross-sections along the Willunga escarpment 189-190
5-14 Principal Neotectonic model of the Mount Lofty Ranges and flanking embayments... 192
5-15 Oblique contact between neotectonic and basement structures 194

Chapter 6

6-1 Present drainage pattern of the Mount Lofty Ranges in the Adelaide area 201
6-2 Main channel gradients and longitudinal profile of the River Torrens 202
6-3 Geomorphological cross-sections along the River Torrens 205-206
6-4 River systems of the Mount Lofty Ranges 208
6-5 Geomorphological profile along the major watershed of the Mount Lofty Ranges 209
6-6 Geomorphological setting and cross-sections of the Mount Barker area 212
6-7 Collage of aerial photos of the Mount Barker area 213
6-8 Collage of aerial photos of the River Marne water catchment 215
6-9 Double capture of the River Finniss 217
6-10 Drainage pattern of the River Finniss 219
6-11 Two generations of the River Finniss incision 220
6-12 Present and palaeodrainage network of the SE slope of the Mount Lofty Ranges and Monarto Block 222
6-13 Location and geomorphological transects of the palaeo-Carrickalinga Valley 225
6-14 Aerial view at the River Torrens crossing the Eden-Burnside Fault 227
6-15 Outwash fans of the principal streams of the Adelaide area 228
6-16 Possible connection of the River Torrens with Dry Creek (Adelaide area) 230
6-17 Pleistocene palaeodrainage reconstruction surrounding Adelaide 232-233
6-18 Flooding model at ~15m above PSL of the Adelaide area 234

Chapter 7

Summary Chart 259

ABSTRACT

The Mount Lofty Ranges resulted from long-term interaction mainly between neotectonic movements and fluvial processes. This thesis presents an original comprehensive neotectonic study incorporating a structural analysis, lithostratigraphic data interpretations, and various geomorphological investigations. This study begins by introducing a multidisciplinary approach to neotectonic analysis including traditional and advanced methods such as Digital Elevation Models (DEMs). Regional stages were used as an appropriate time-framework for palaeoreconstructions and correlations of basin sedimentation with fluvial stream competence (erosion and sedimentary supply).

In contrast to the traditional hypothesis that Tertiary uplift of the Ranges was due to compressional reactivation of Delamerian structures (~500Ma), this study reveals three principal neotectonic stages associated with specific tectonic regimes: 1) Extensional Stage (Middle Eocene to Middle Miocene); 2) Transitional Stage (Late Miocene to Early Pleistocene); and 3) Compressional Stage (Early Pleistocene to the Present). Several lines of evidence are provided showing the independence of neotectonic structure from basement fabric.

A large region of South Australia was represented by a gently undulating and deeply weathered Palaeoplain during the early Tertiary. In a methodological/analytical first, the global eustatic curve was used to evaluate the altitude of this Palaeoplain (~250-300m above the present sea-level). This study also revealed that the effect of sea-level change onto the landscape during the Tertiary was more significant than previously considered. The initial crustal segmentation (Middle-Late Eocene) involved subsidence of the St. Vincent and Western Murray Basins while remnants of the high-standing Palaeoplain became the Mount Lofty Ranges. Further crustal segmentation and subsidence resulted in the formation of embayments, and intramontane basins such as Meadows-Myponga, Hindmarsh Tiers and Barossa. Fundamental attributes of extensional tectonics such as strain transfer and accommodation zones, tilting and crustal segmentation recognised in the Tertiary tectonic setting.

The major compressional tectonic activity was associated with steep reverse faults on both sides of the Ranges. This compressional neotectonic regime resulted in Pleistocene uplift of the Mount Lofty Ranges that resulted in a major lithological change in the sediments of both the St. Vincent and Western Murray Basins. The young and dissected landscape with a number of stream gorges and waterfalls on both marginal sides of the Ranges is correlated with stream gravels including cobbles, pebbles and slope debris. This compressional neotectonic uplift of the Ranges mainly occurred during the Pleistocene (~1Ma) and continues today as indicated by seismic activity and insitu stress measurements.

DISCLAIMER

This thesis 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 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 Library, being available for loan and photocopying.

.....

Victor Tokarev

AKNOWLEDGEMENTS

First of all, I would like to thanks my supervisor Associate Professor Vic Gostin. His wisdom to patiently guide me has made this work possible. In him I found not only a source of knowledge but also a friend who has been always available when the most needed. Your encouragement, immense support, endless hours of continuing work with me are greatly appreciated and I will always remember that without you this thesis would not be possible, thank you very much.

Special thanks to Mike Sandiford (Melbourne University) for his supervision while he was at the University of Adelaide. Your introduction of computer analysis of DEMs, encouragement and scientific vision of this project was a critical for this thesis. You have always been a scientific inspiration for me and for many of your students, thank you. I believe that the major chapter of the Australian neotectonics has not been written yet and I sincerely hope for our cooperation in this matter.

I wish to thank my university mates and colleagues Jerry Meyer and Trevor Dhu (room mates) for their friendship, these years were as knowledgeable as entertaining, thanks for opening a hidden treasure of the Australian culture and language. Thanks also to Jon Teasdale, Eike Paul, Angelos Mavromatidis, Sandra McLaren, Norell Newman, Ric Daniel, Scott Reynolds and many other students who made my life in this University easier and enjoyable over the years. Thanks to all staff in the Department of Geology & Geophysics for great support, your professionalism and goodwill make this department a warm and friendly place to learn and work. Special thanks to Qianyu Li for a numerous important discussions on Tertiary lithostratigraphy, sea-level fluctuation, neotectonics and everything else.

I want to express my gratitude to Olga Gostin for her encouragement to accomplish this thesis and for her time of careful reading this technical manuscript, your wonderful words and suggestions significantly improved it, thank you very much.

Last but not least, I would like to thank my children for their great understanding of the importance of this thesis for me. I hope it would provide them an example that, despite ups and downs of our life, patience and hard work finally bring some results and satisfaction. Your support and understanding means a lot for me, thank you.

Finally, I would like to thank the examiners for their time to read and careful examination of this thesis.

Chapter 1

INTRODUCTION

1.1 Aim and Objectives

The Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins (Fig. 1-1) preserve a rich record of Australian intraplate neotectonic movements and their effects on landscape evolution and sedimentary basin development in this region of South Australia. However in spite of decades of studies of various aspects of geology, tectonics and geomorphology there is no clear understanding how these Ranges and basin structures were formed. The traditional hypothesis of Tertiary compressional reactivation of basement fabrics is inconsistent with observed neotectonic settings, landscape evolution and Tertiary geological records. The major goal of this study is to develop a new neotectonic model that contributes to our fundamental understanding of how neotectonic motions and deformations operate within this sector of the southern Australian Earth crust. The other main aim of this thesis is to provide a better understanding of the effects those neotectonic movements imposed on landscape evolution and sedimentation.

It is always a challenge to create an internally and externally consistent and plausible neotectonic model based on the integration of comprehensive analyses of structural settings, lithostratigraphy and geomorphology. The combination of traditional and technologically advanced methods such as a high resolution Digital Elevation Model (DEM), spatial morphometry and relevant software packages were used to reach the major objectives of this thesis. These objectives are:

- To define the nature and extent of neotectonic movements in the Mount Lofty Ranges through regional structural analysis (neotectonic setting). Geomorphological data and DEM analysis of river network (eg. stream pattern, main flow direction, shape of river valley and depth of stream incisions), preservation and distribution of planation surfaces and regolith, original watershed and fault-scarp locations were used to verify that landscape development corresponds to the nature and extent of neotectonic movements.
- To define the structural style and amount of neotectonic movements in flanking and intramontane basins utilising methods of structural geology and lithostratigraphic analysis including facies and thickness distribution.

- To correlate basin sedimentation with geomorphological development in the Ranges by the cross-examination of fluvial input into stratigraphic units and stream competence (erosion and sedimentary transport).
- To integrate all available data into a new neotectonic model including structural development, various aspects of landscape evolution and sedimentary environments.

Regional stages comprising basin lithostratigraphic units were used as appropriate time-frameworks for palaeoreconstructions. A pre-Middle Eocene Palaeoplain was identified as the most probable predecessor of the Mount Lofty Ranges and the St. Vincent and Western Murray Basins, all of which were developed as geological structures/neotectonic entities since the Middle Eocene. For the first time, the global sea-level curve was utilised to evaluate the initial altitude of this Palaeoplain. The sea-level curve, as a reference for palaeotopography, was also used for various palaeoreconstructions and the estimation of erosional base-levels during each stage. Rises in sea-level were identified as one of the important causes of the formation of sedimentary accommodation space, supplementary to basin subsidence.

1.2 Geological, Tectonic and Geomorphological Backgrounds

The study area covered about 10 000km² that was restricted by available 1 arc-second DEM data (Fig. 1-2), however some data from neighboring regions and in some instances from the southern Australian continental margin were used to support the developing hypothesis. Some data related to Australian Plate tectonics, such as seafloor spreading, were also used to identify a possible link between plate and intraplate movements and dynamics.

The Mount Lofty Ranges and flanking basins were formed as neotectonic entities during the last ~43Ma. The most recent development of this region occurred in the Quaternary period (~1Ma) which gave rise to recent tectonic structures and landscapes. Almost all these Ranges consist of Precambrian/Cambrian rocks of the Adelaide Geosyncline and Kanmantoo Trough which formed the basement on which the neotectonic structure of the Mount Lofty Ranges was built. The main basement tectonic fabric associated with Adelaide Geosyncline was formed between 750Ma and 500Ma and culminated by the Delamerian Orogeny (~500Ma). Permian fluvioglacial deposits substantially covered this complicated and significantly eroded basement structure. Remnants of the Permian Complex are widely distributed and exposed in the southern part of the Mount Lofty Ranges and are also situated beneath the Tertiary and

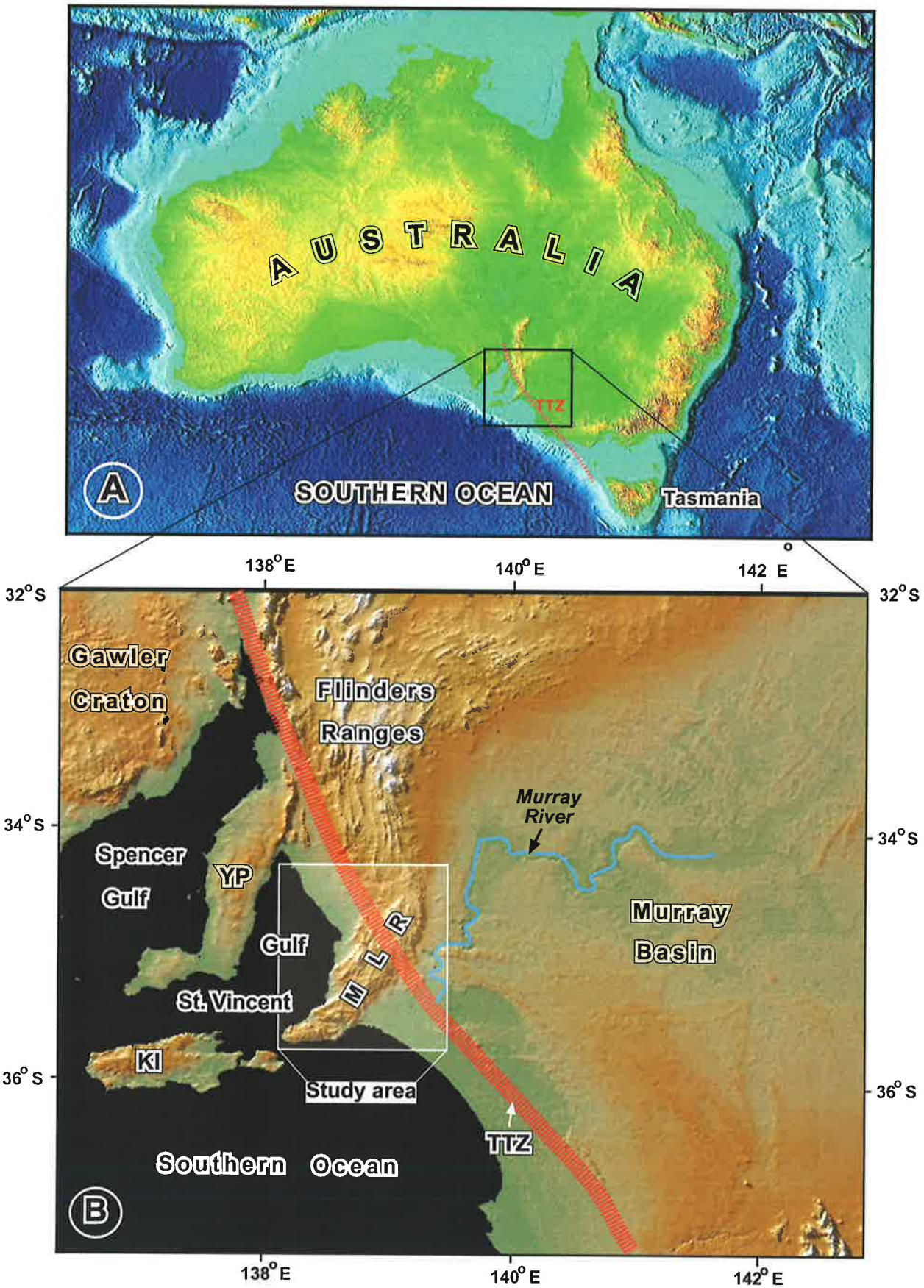


Figure 1-1 Location of the study area of the Mount Lofty Ranges (MLR) and flanking St. Vincent and Western Murray Basins. KI = Kangaroo Island; YP = York Peninsula. TTZ - Tertiary Transfer Zone associated with extensional tectonic regime. A: ETOPO 2min DEM (US NOAA) also showing a possible conection of the TTZ with large fault zone west of Tasmania. B: Regional shaded-relief image derived from 9 arc-second DEM data (Geoscience Australia).

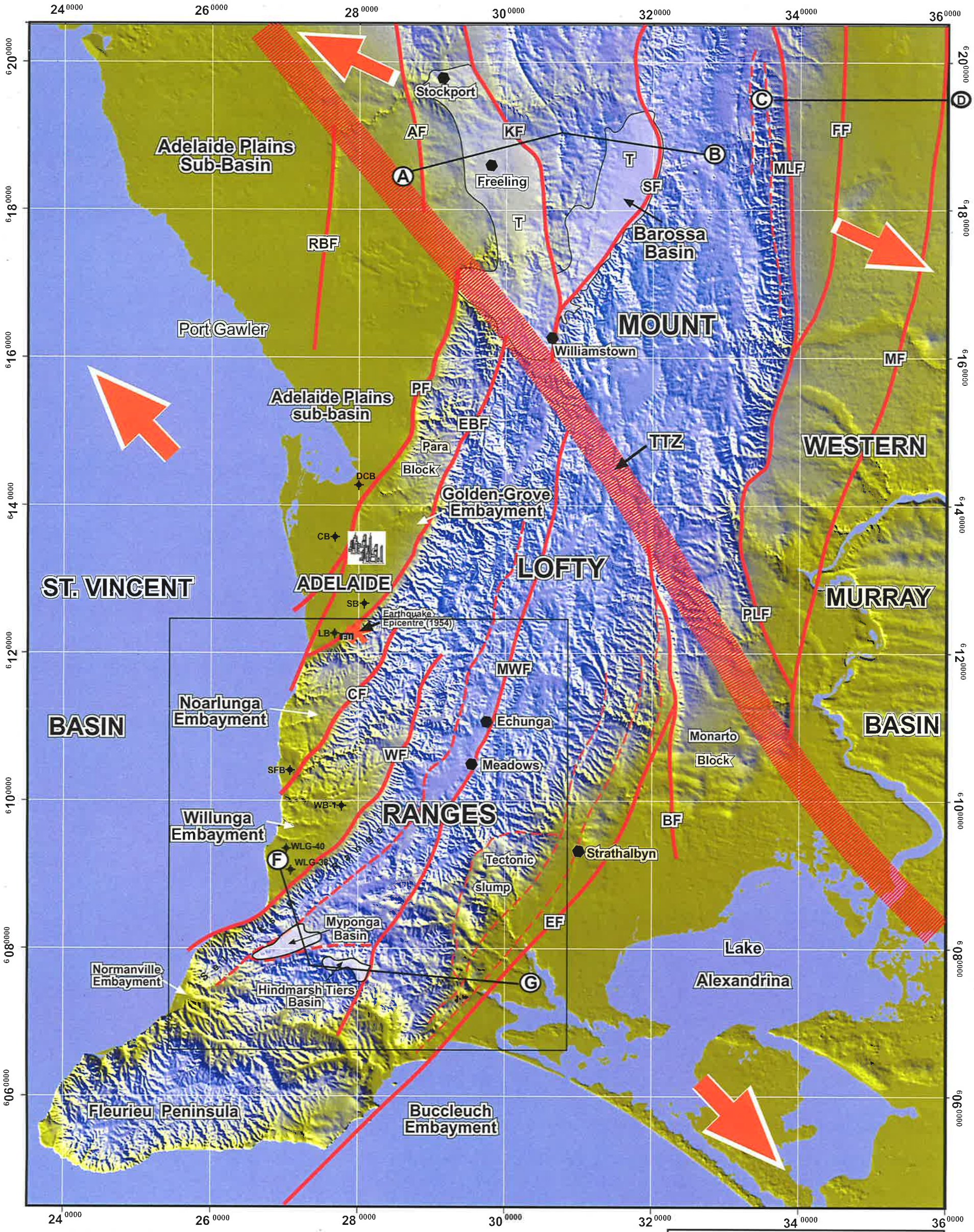


Figure 1-2 Study region of the Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins with some elements of neotectonic setting. TTZ - Tertiary Transfer Zone (see Ch. 5 for definition). Main faults (thick solid red lines) controlled Tertiary sediment distribution and formed according to major direction of tectonic stress distribution (big red arrows). Black outlined box = expanded DEM image of Fig. 5-4. Cross-sections AB, CD and FG are on Fig. 5-5. Shaded relief image derived from 1 arc-second DEM (data courtesy DEH SA). Boreholes: CB = Croydon -2; DCB = Dry Creek, LB = Longyear, SB = Sprinbank (Adelaide area), SFB = Seafort (Noarlunga Embayment); WB and WLG = associated with Willunga Embayment (data courtesy PIRSA).

LIST OF MAIN ACTIVE FAULTS	
Northern segment:	*Southern segment:*
AF- Alma	RBF - Red Bank
KF- Kitchener	PF- Para
SF- Stockwell	EBF- Eden-Burnside
MLF- Milendella	CF- Clarendon
FF- Florienton	WF- Willunga
MF- Morgan	MWF- Meadows
PLF- Palmer	EF- Encounter
	BF- Bremer

Quaternary sediments in the St. Vincent and Western Murray Basins. Permian deposits exposed within the Ranges regularly contributed sandy and coarse material to the fluvial part of the Tertiary and Quaternary basin fill. The geological record of the period between the Upper Permian and the Middle Eocene is missing within the study region. This is attributed to tectonic stabilization with associated deep weathering and landscape planation that resulted in the formation of pre-Middle Eocene Palaeoplain.

The distribution of Tertiary and Quaternary deposits is limited within the Mount Lofty Ranges and is generally associated with the intramontane Barossa, Meadows-Myponga and Hindmarsh Tiers Basins. However a significant amount of these deposits overlies the pre-Tertiary basement with a significant stratigraphic hiatus (>200Ma) in flanking St. Vincent (>600m) and Western Murray (>400m) Basins. Most of the Tertiary and Quaternary terrigenous deposits in these basins are derived from the Mount Lofty Ranges source area by stream and river erosion. Together with carbonate precipitation from marine water, they record major changes in sedimentary environments associated with tectonic events, sea-level and climate changes. Therefore Tertiary and Quaternary lithostratigraphic units provide spatial- and time-frameworks for neotectonic interpretations and palaeoenvironmental reconstructions including landscape and sedimentation (Ch. 4).

Neotectonic movements and deformations have built the major framework of the sedimentary source region of the Mount Lofty Ranges that together with climate and geological setting, controlled the development of palaeo- and current river systems, and thus the landscape/regolith evolution. Neotectonic movements also account for the structural development of the St. Vincent and Western Murray Basins. Down-to-basin block movements together with sea-level rise are the major cause of the Tertiary and Quaternary sedimentary accommodation space. Therefore river systems, coastal zone configuration, sediment and soil distributions, and groundwater reservoirs in this region substantially depend on the style and extent of neotectonic movements. The study region is also exposed to the highest earthquake risk in Australia due to past and present neotectonic activity. In spite of such significance there has been no systematic study of neotectonic movements and deformations in this region. There has been no previous systematic work on the neotectonics of the Mount Lofty Ranges and the flanking St. Vincent and Western Murray Basins.

However there is a long history of structural, tectonic and geomorphological interpretations in

this region (Benson, 1911; Howchin , 1911, 1918, 1933; Fenner, 1927; 1930, 1931; Hossfeld, 1935; Sprigg, 1945, 1946; Stuart, 1969; Twidale, 1976; Veevers, 1984; Cooper, 1985; Benbow et. al., 1995; see details in Ch. 5). The most popular traditional hypothesis of the formation of the Mount Lofty Ranges is Tertiary compressional reactivation of the Delamerian structures (~500Ma old) as outlined in several chapters of the *Geology of South Australia* (Drexel & Preiss, 1995).

In contrast to the traditional hypothesis that Tertiary uplift of the Ranges was due to compressional reactivation of Delamerian structures (~500Ma), this study recognised the independence of neotectonic structure of the Mount Lofty Ranges and sedimentary flanking basins from the pre-Tertiary tectonic fabric. This thesis also revealed three principal neotectonic stages associated with specific tectonic regimes: 1) Extensional Stage (Middle Eocene to Middle Miocene); 2) Transitional Stage (Late Miocene to Early Pleistocene); and 3) Compressional Stage (Pleistocene to the Present).

1.3 Thesis Outline

This thesis consists of seven chapters supported by a number of figures and a list of references. Chapter 2 outlines the methods used in this multidisciplinary study. Some methods are described briefly, but others such as Digital Elevation Model (DEM) are described in more detail. A high-resolution DEM analysis is applied for the first time to the neotectonic study of the Mount Lofty Ranges. Chapter 3 is a brief overview of the pre-Tertiary basement geology and tectonics to provide a better understanding of regional history and basement involvement in the neotectonic process. A brief history of Australian Plate tectonics since the Gondwana break-up outlines the position of the study region in the global tectonic setting, and the concept of a pre-Middle Eocene Palaeoplain is also introduced in this chapter.

Chapter 4 thoroughly examines available Tertiary and Quaternary lithostratigraphic data and provides new interpretations of sedimentary environments in association with a neotectonic setting and crustal movements as well as landscape evolution. The analysis of the lithology and stratigraphy of the sedimentary units is critically important for this study because it provides not only the geological background but also the only available time-framework for all the palaeoreconstructions discussed in this chapter.

Chapter 5 focuses on the neotectonic setting of the Ranges and flanking basins. For the first time, classical attributes of the extensional tectonic settings such as crustal segmentation, strain transfer and accommodation zones and fault terminations are recognised in this region. This new extensional interpretation of the neotectonic setting contradicts the traditional interpretation of the Tertiary compressional reactivation of the basement structure. Because of this, several lines of evidence demonstrating the independence of the neotectonic structure from the basement fabric are provided in the discussion at the end of chapter 5.

Chapter 6 describes the main geomorphological features of the Mount Lofty Ranges such as location of the regional watershed, distribution and preservation of the planation surfaces and various characteristics of the river drainage systems. Most of these features are considered in this thesis as a geomorphological response to neotectonic processes and are used as evidence of the nature and extent of neotectonic movements. The eastern edge of the remnant of pre-Middle Eocene Palaeoplain was reconstructed within the Mount Lofty Ranges. Several river captures were recognised that resulted in the major watershed migration from its original position.

Chapter 7 integrates lithostratigraphic data and interpretations, landscape characteristics and neotectonic settings into a final model that refines the timing of specific tectonic regimes that resulted in the formation of the Mount Lofty Ranges and flanking basins. Cross-examination and correlation of the landscape evolution of the Ranges with flanking and intramontane basin sedimentation resulted in a three-stage neotectonic model.

Chapter 2

METHODS

This thesis utilises a combination of traditional geological and geomorphological methods for the neotectonic analysis of the study area, as well as advanced methods of Digital Elevation Models (DEMs) using relevant computer softwares for the analysis of river drainage systems, and various data visualisation and interpretation.

2.1 Digital Elevation Model (DEM)

Digital elevation models or DEMs are increasingly becoming valuable in numerous applications within the earth, environmental and engineering sciences. The precision of a DEM provides the necessary quality of topographic data for simulating landscape parameters of elevation, slope, aspect and other dimensions. DEM data is normally generated by sampling a regular array of elevation values derived from topographic maps, aerial photographs or satellite images. Two data sets were used in this research: a 9 arc-second DEM at about 250m spatial resolution (Geoscience Australia) and a 1 arc-second DEM (DEH South Australia) covering the Mount Lofty Ranges and surrounding regions. While the former was used for general geomorphological observation and regional analysis, the latter, with a maximum resolution at about 10m, was used more frequently for 3D imaging, drainage network extraction and spatial morphometry.

Digitised contours of the analog topographic maps at scale of 1:10 000 were used to generate 1-s DEM database by the South Australian Department of Environment and Heritage. Subsequently 2.5m contours were registered, vectorised, edited and tagged with elevation values. The original data was gridded using a 100m grid in order to save a significant amount of computer operational memory. The elevation matrix structure of a rectangular grid was used for modelling and constructing the actual DEM. Such an elevation data storage structure uses a point model where every elevation point (Z value) can be assigned to a row (X) and a column (Y) using rectangular coordinates (Fig. 2-1).

Data and image processing were strictly dependent on the algorithm of available software packages such as ENVI, ER Mapper, ESRI, Transform Spyglass and RiverTools. Each of

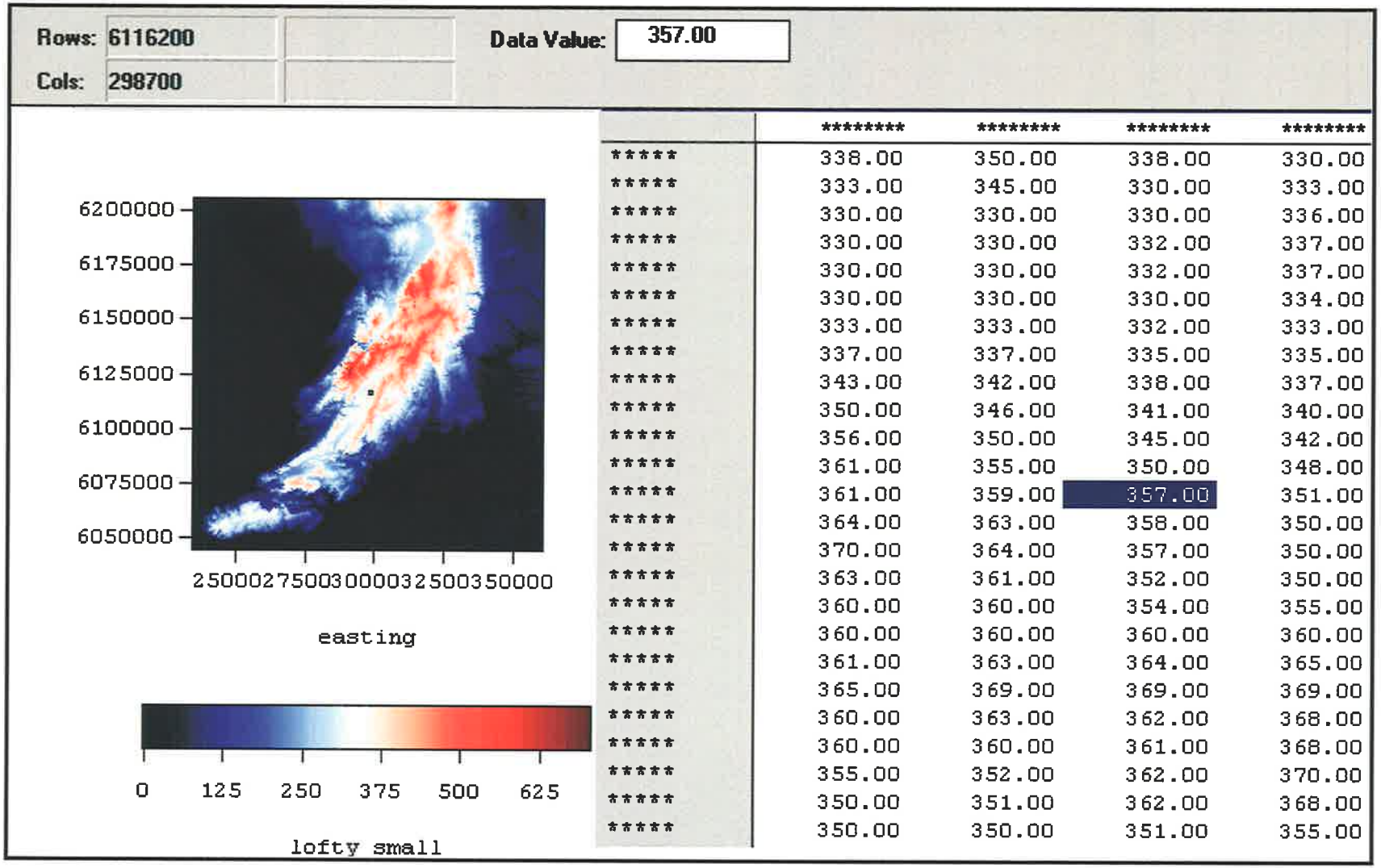


Figure 2-1 Sample data of 1arc-second DEM of the Mount Lofty Ranges (data courtesy SA DEH)

these packages is designed for multipurpose use where DEM is only a tool of spatial analysis. Therefore a combination of these softwares was used depending on the task of neotectonic analysis. ENVI was the most frequently used package for general data processing and various image manipulations such as the selection of area of interest, re-sampling, resizing, re-gridding, filtering and image colour manipulation.

DEM filtering involves smoothing and enhancement functions by using low-pass and high-pass filters respectively. Smoothing reduces or removes details in the DEM, while it highlights major or regional terrain discontinuities. These were normally saved onto disk storage space to economise processing time, or to aggregate or resample the image resolution. However we found that the smoothing process could be useful to derive the average elevation value of the major planation surfaces by the reduced effect of erosion. Alternatively, enhancement was used to highlight landscape details such as fault-scarps and erosional features.

The process of image and data visualisation was used in this study in two contexts. Firstly, the figures presented in this thesis should be an effective means of communicating geological, geomorphological and neotectonic ideas. Secondly, and more importantly, the visualisation process was instrumental in developing the distinctive methodological approach that culminated in the effective use of the DEM for neotectonic analysis. Thus both 2D and 3D visualisation was used to explore various topographic aspects extracted after DEM processing. It was used to highlight major geomorphological units of interpreted landscape such as river basins and watersheds, and also to derive a general view from various sun-angles and to manipulate the vertical exaggeration of shaded relief in the study area.

DEM horizontal slicing was used for accurate spatial location of landscape anomalies. This method was used to delineate the scarp zones associated with active faults. This enabled one to demonstrate how fault movements affected the initial surface in the process of fault-scarp formation. Such a technique is often called "Flood" and is used to demonstrate which areas would be covered by water if water levels were to rise to a particular level. The resulting images of such 'flood simulation' identified the landscape from the selected level up to the highest points of the landscape (Fig. 2-2). The technique of flood simulation was used for palaeolandscape reconstruction associated with particular sea-level stands correlated with the global eustatic curve (Haq et al., 1987, McGowran, 1989; Li et al., 2004).

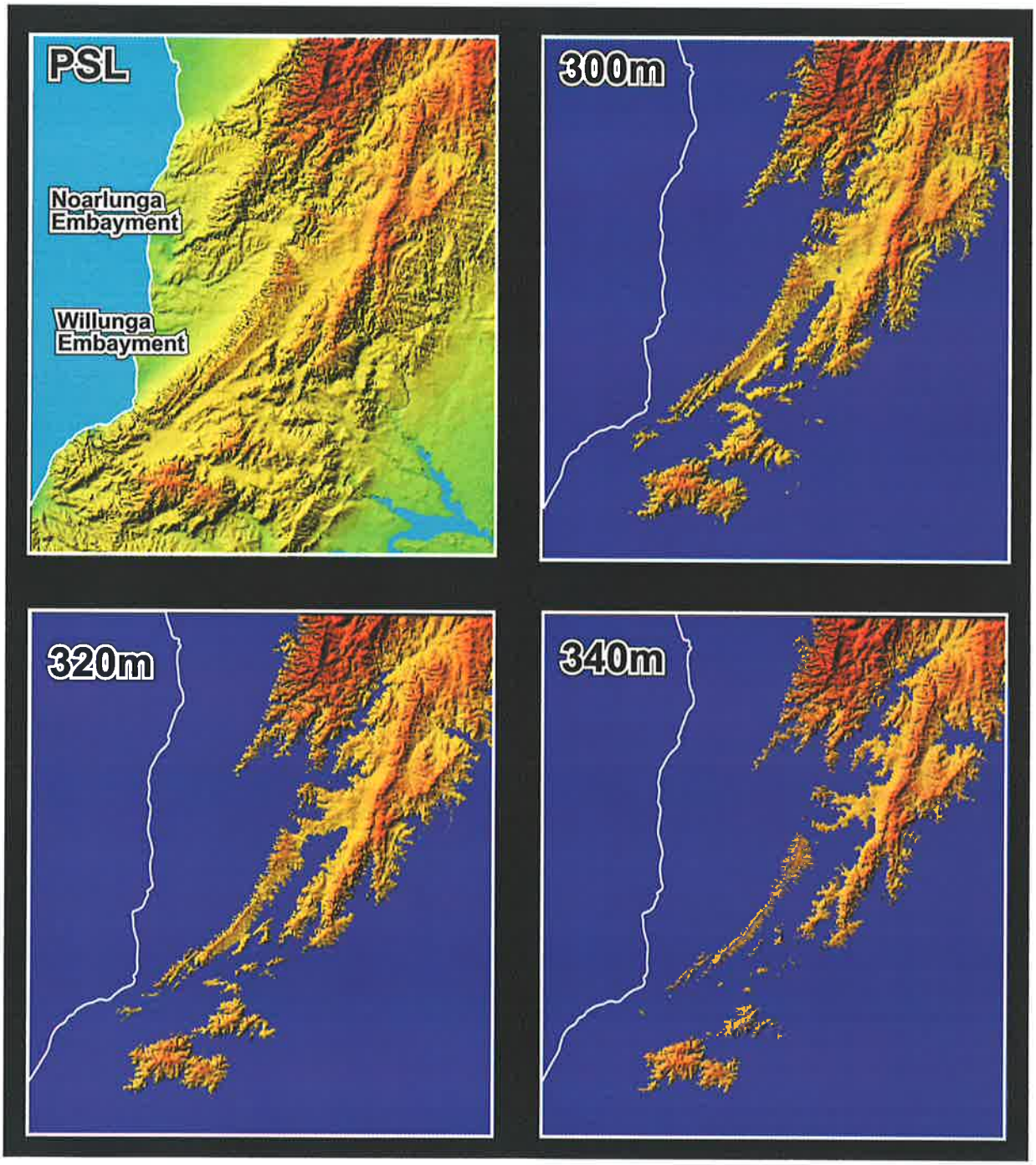


Figure 2-2 Sequence of marine floodings of the southern Mount Lofty Ranges during the Late Oligocene and Middle Miocene, not adjusted for any Pleistocene uplift.

Such a simulation was also used where sediments of a particular age are associated with marine influence in the Mount Lofty Ranges such as in the Meadows-Myponga Basin and on the edges of the flanking sedimentary embayments. While some later tectonic movements apparently affected the palaeolandscape and have to be taken into consideration, the sea-level projection onto DEM often provided the most valuable data on possible altitude and spatial expression of the palaeolandscape.

RiverTools was identified as the most comprehensive analytical software package for drainage system analysis. A 1-s DEM and "RiverTools" package was used to create the drainage pattern, to extract river networks, to analyse channel profiles and some statistical data of the major rivers in the Mount Lofty Ranges. Automated procedure or algorithm embodied in this package was used to delineate basin geometry and to derive flow pathways from DEMs. Unfortunately available data does not provide sufficient resolution to extract correct stream passes over some flat areas formed by Tertiary and Quaternary sediments in the St. Vincent and Western Murray Basins. This was corrected manually using analogue and digital topographic maps.

2.2 Use of Geological and Geomorphological Cross-sections

Cross-sections were used to reconstruct the tectonic structure, locate active faults and to correlate planation surfaces. Cross-sections were also used to calculate the amount of fault displacements. Geological and topographic maps at 1: 50 000 scale were used together to generate a number of cross-sections. Unfortunately, geological maps at 1: 50 000 are not available for the whole study area and therefore geological maps at 1: 250 000 scale and old maps at scale of 1:63 000 were used where appropriate. Hundreds of computer generated geomorphological profiles from the 1-s DEM were created for morphometric analysis and data correlation.

2.3 Analysis of Planation Surfaces

The main watersheds of the Mount Lofty Ranges are a common place for the preservation of the initial planation surfaces. Geomorphological profiles of all main watersheds have been constructed manually using topomaps at 1:50 000 scale to locate old planation surfaces. Computer generated profiles and images (including 3D images) were used for control and

later for regional geomorphological generalisation. In some instances generic images were correlated with airphotos, and features were observed in the field in order to better elucidate their natural expression and then used to correlate planation surfaces. This thesis presents only the final redrawn images and cross-sections using available drawing software packages.

While several methods of absolute dating of planation surfaces are currently available, the mostly erosional features of the Ranges have left little chance for such dating (Watchman & Twidale, 2002). For this reason planation surfaces were correlated with basin lithostratigraphic units providing a time-framework for the principal palaeoreconstructions. The landscape of the Mount Lofty Ranges is a complex combination of young and old landforms and therefore the selection of the principal erosional surface (most representative and recognisable) within this region was crucial. The planation surface with a deep regolith cover on the regional watershed of the Ranges was considered to be a remnant of the pre-Middle Eocene Palaeoplain and was selected for correlation with pre-Tertiary basement surface in the flanking and intramontane basins.

2.4 Lithostratigraphic Analysis of Tertiary and Quaternary Sediments

The analysis of lithostratigraphy was a major method of palaeoreconstruction (Ch. 4). This included the lithology, age and fossil content, thickness and thickness distribution, grain size and sediment sorting. Particular attention was paid to lithological composition, hiatuses and angular unconformities. This analysis provided information on available time-framework, deposition environments, sea-level change, palaeogeomorphology and structural reconstructions and spatial and time correlations of various events.

2.5 Use of Global Sea-Level Curve

The global sea-level curve (Hag et al., 1987) adapted to South Australia by McGowran (1989) and recalculated by Li et al. (2004) was used to estimate the altitude of pre-Middle Eocene Palaeoplain, to assess a marine influence on sedimentary environments and palaeolandscape, and to evaluate a main erosional base during several regional stages. The global sea-level curve was also used to distinguish tectonic influence on the sedimentary accommodation space from the effect of sea-level rise or fall.

2.6 Combined Method of Palaeoreconstructions

The reconstruction of neotectonic and geological history is a rather complex process because it consists of several components. These include:

- character of lithological facies and their thickness together with faunal and other evidence of the unit's age
- sea-level change trends and still-stands for the particular time-interval
- climatic changes including precipitation and vegetation
- character of dominant weathering in particular time-intervals
- landscape evolution including drainage net development and stream competence
- structural component of the earth's crust
- type and amount of neotectonic movements correlated with basin sedimentary pattern and terrain landscape evolution.

We recognise that not every one of these components is currently identifiable for particular time-intervals and that many of them are separate subjects of past, present and likely future studies and considerations. Despite this, the correlation and interpretation of complex data in this thesis is a new attempt to reconstruct neotectonic history of this area and to generate a plausible regional neotectonic model of the Mount Lofty Ranges and its flanking St. Vincent and Western Murray Basins.

Chapter 3

PRE-TERTIARY BASEMENT: GEOLOGY AND TECTONICS

3.1 Introduction

The Mount Lofty Ranges are a neotectonic structure that has been exposed since the Middle Eocene, for some 43Ma. All of the older rocks and structures are related to the pre-Tertiary basement out of which the Mount Lofty Ranges have been built. The aim of this chapter is to provide a brief summary of the geological history, tectonic settings and major events recorded in the pre-Tertiary basement. A number of published papers related to the pre-Tertiary tectonic structure and events have been used (Clarke, 1987; Cockshell, 1996; Flottmann et al., 1994; Flottmann & James, 1997; Jenkins, 1990; Jenkins & Sandiford, 1992; Mancktelow, 1990; Marshak & Flottmann, 1996; Offler & Fleming, 1968; Preiss, 1987; Preiss et al., 1993; Preiss, 1995; Sandiford et al., 1995; Yassaghi, 1998; Yassaghi et al., 2004). For an extended pre-Tertiary tectonic reference, the reader should consult the compilation *The Geology of South Australia* edited by J.F. Drexel & W.V. Preiss (1995).

The pre-Tertiary basement within the Mount Lofty Ranges contains a wide spectrum of rocks and structures formed during distinct periods of basement history: Proterozoic, Late Proterozoic to Early Palaeozoic (Adelaidean Complex), and Late Paleozoic. Brief characteristics of rock complexes and pre-Tertiary tectonic fabric are provided below in order to emphasise their possible role and influence on the nature of the neotectonic structure and landscape of the Mount Lofty Ranges.

3.2 Proterozoic Complex

The oldest Proterozoic rock complex consists of crystalline schists, gneisses and pegmatites exposed in a number of relatively small inliers between Yankalilla and Mount Compass; Crafers and Aldgate and Houghton and Barossa Valley (Ludbrook, 1980; Paul, 1998). These rocks were formed as a result of continental crust formation somewhere between 1600Ma and 900Ma. This time-interval featured long periods of sedimentation, granitic intrusions and a great flow of acid lavas ending with metamorphism. Most structural events including fault movements and folding occurred mainly at the end of tectono-magmatic activity somewhere

about 900 Ma. After the final episode of activity, the region was stabilised followed by significant periods of erosion and probably landscape planation.

3.3 Late Proterozoic to Early Palaeozoic Complex

The Late Proterozoic to Early Palaeozoic is the most prominent period in the geological history of South Australia associated with development of the Adelaide Geosyncline and Kanmantoo Trough dated from ~750Ma to about 500Ma. Large regions of South Australia including the area of the recent Mount Lofty Ranges and flanking basins were initially involved in the process of crustal stretching followed by subsidence and deposition. Thousands of metres of sediments were deposited over the crystalline complexes with great angular and stratigraphic unconformities. The thickness of Adelaidean sediments has been estimated to be up to ~8.5km (Mawson & Sprigg, 1950) and Kanmantoo Group over 10km (Daily & Milnes, 1973). The precise thickness of these sediments remains uncertain because of the allochthonous nature of the Kanmantoo Group (Clarke & Powell, 1989) and thrust kinematics and shortening of the Adelaide Fold-Thrust Belt (Flottmann et al, 1994; Flottmann & James, 1997).

The Adelaide Fold Belt (Mancktelow, 1990; Jenkins, 1990; Jenkins & Sandiford, 1992) or the Adelaide Fold-Thrust Belt (Marshak & Flottmann, 1996; Flottmann et al., 1994; Flottmann & James, 1997) is representing the complex structural fabric that is partly exposed in the present Mount Lofty Ranges and Fleurieu Peninsula and buried by Permian fluvioglacials and the Tertiary and Quaternary fill of the St. Vincent and Western Murray Basins. The Late Proterozoic Adelaidean and Early Cambrian Normanville and Kanmantoo Groups were deposited because of significant crustal attenuation and basin subsidence occurring over 200 million years. A repeated basin extension was apparently accompanied by down-to-basin synsedimentary faults movements (Jenkins, 1990). High-temperature and low-pressure metamorphism followed the Cambro-Ordovician Delamerian Orogeny at about 500 Ma (Flottmann et al., 1994; Sandiford et al., 1995). Regional fold and thrust deformations of the basin sediments were accompanied by great crustal shortening of between 30% and 58% (Flottmann et al., 1994).

The Adelaide Fold-Thrust Belt forms an integral part of the foreland of the extensive Palaeozoic Pacific margin of Gondwana (Dalziel, 1991; Moores, 1991), and it is also the site

of the disintegrated Late Proterozoic Supercontinent "Rodinia" that included Australia, Antarctica and North and South America (Flottmann et al., 1994). Regionally, within the study region, the Adelaide Fold-Thrust Belt is represented by foreland W-NW-verging intensive folds, discretely spaced overthrusts and shear zones (Flottmann & James, 1997).

3.3.1 Delamerian Structure

The Delamerian orogenesis is the most prominent tectonic event in the Late Proterozoic to Early Palaeozoic history that formed the pre-Tertiary basement structure of the study region. Intrusions of various igneous rocks occurred somewhere between 515-490 Ma (Sandiford et al., 1995), while ion microprobe analysis of zircons from a tuffaceous layer in the Normanville Group shows some earlier activity at 526Ma (Cooper et al., 1992). Synmetamorphic deformation in the proximity to igneous intrusives may partly explain a regional structural complexity (Mancktelow, 1990; Sandiford et al., 1995). The Delamerian structural geometry, metamorphic and magmatic complexes are represented in Fig. 3-1. This map clearly shows an arcuate geometry of major folds elongated in N-S direction and restored in balanced structured cross-sections (Fig. 3-2). These cross-sections clearly show the thrust geometry of the main faults that dip eastwards at low angles.

Geochronology of the post-tectonic granites suggests that penetrative deformation had ceased by ~470Ma (Preiss, 1993). Milnes et al. (1977) however, argued that thermal effects persisted until ~420Ma. All the above indicate that a wide mountain belt (a few times wider and several times longer than the Mount Lofty Ranges) was created and sedimentary rocks were intensively deformed and metamorphosed by the end of the Ordovician.

The lack of stratigraphic records between the Ordovician and Late Palaeozoic indicates significant erosion and denudation of the Adelaide Fold-Thrust Belt, and strongly suggests an absence of significant tectonic activity between these periods. From the wide range of information related to the Late Proterozoic-Early Palaeozoic crustal evolution and following Preiss (1987), the most important facts related to this study are summarised below:

- Thick sediments (up to 15km) were deposited during the extensional phases of the Adelaide Geosyncline
- A number of fold and thrust structures were formed later during the crustal contraction and may be interpreted as a multistage reactivated (inverted) extensional structure.

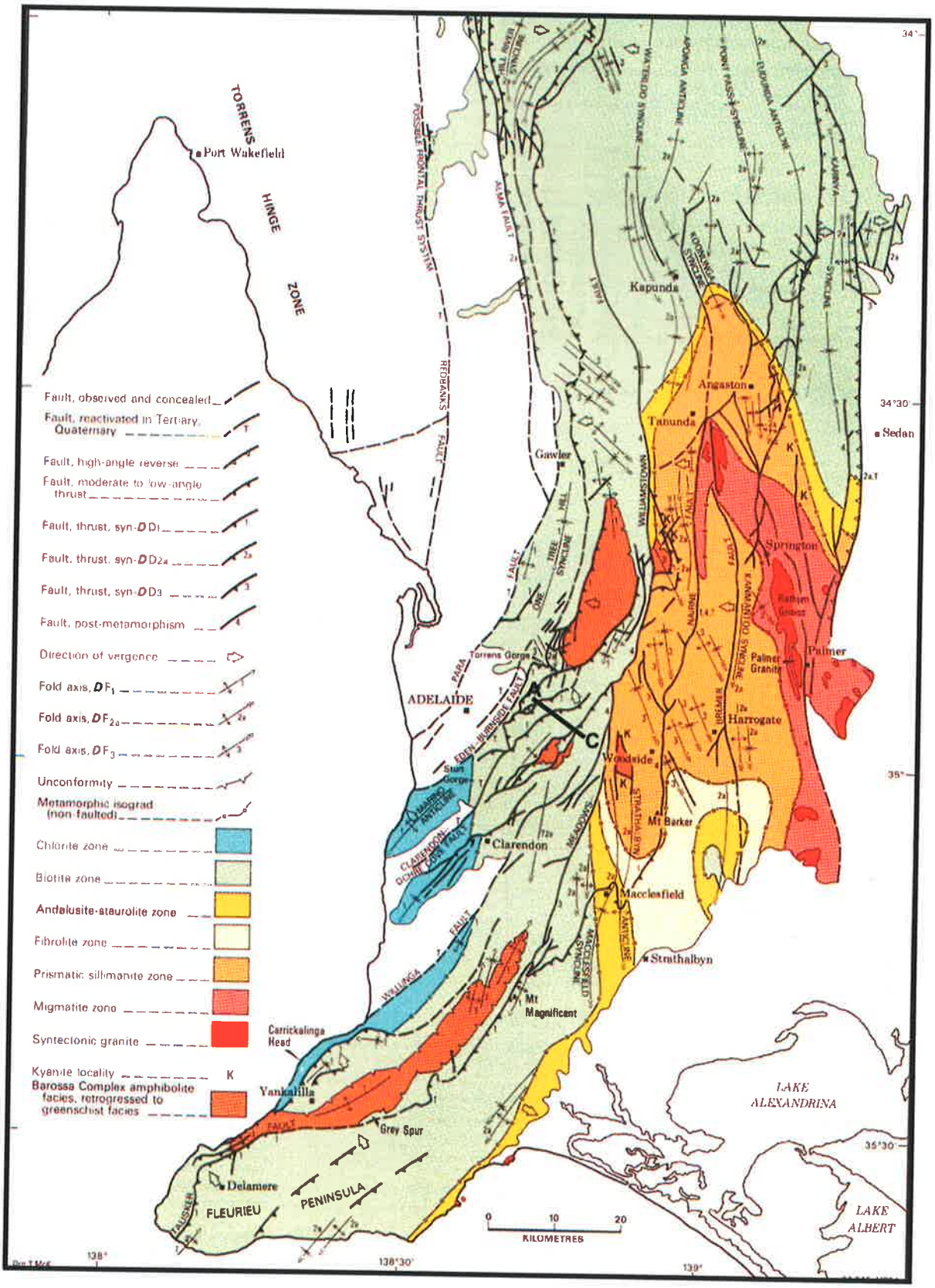


Figure 3-1 Basement Delamerian structure of the Mount Lofty Ranges (after Preiss, 1995). Line A-C = approx. location of the restored cross-sections of Fig. 3-2.

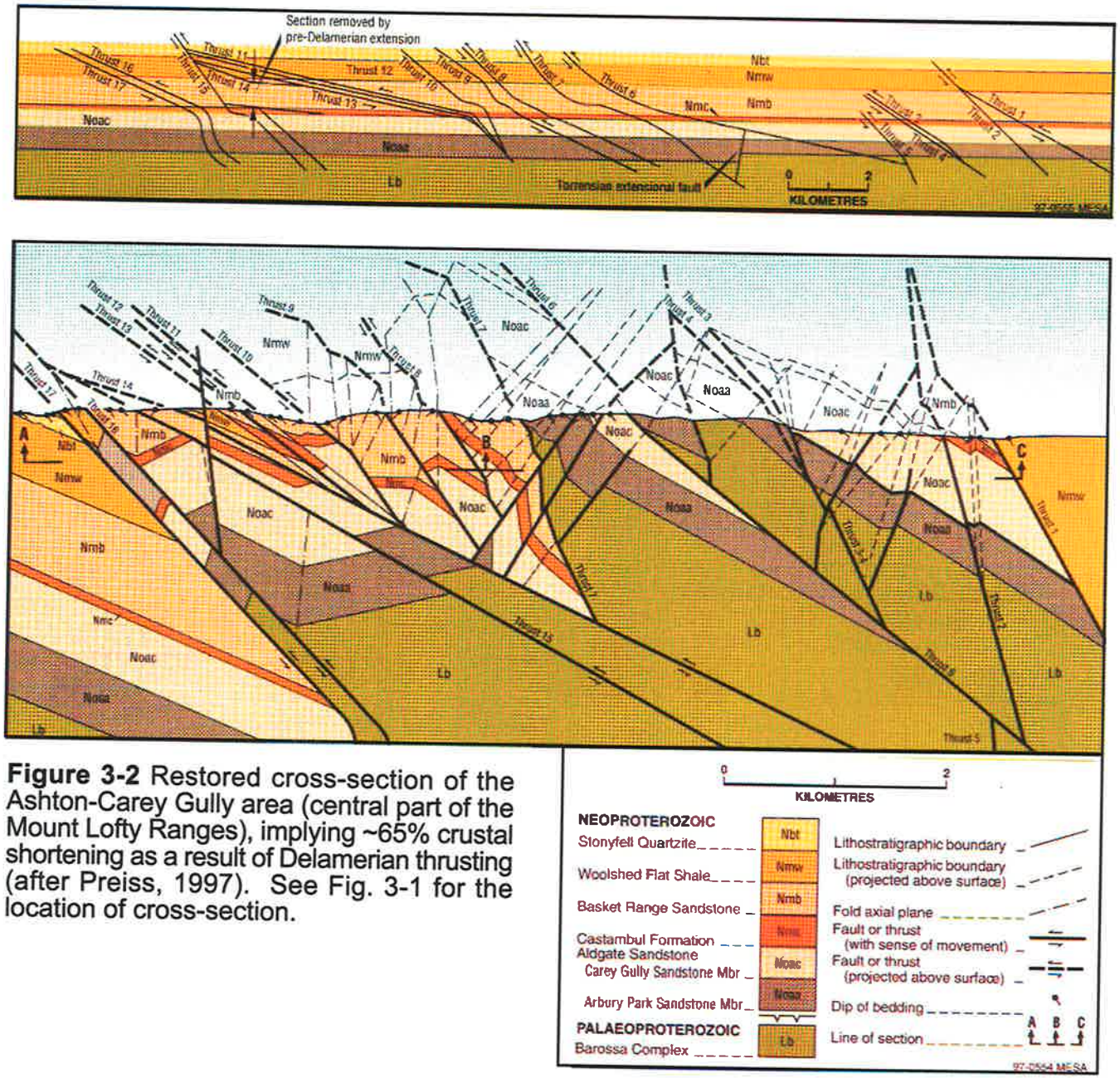


Figure 3-2 Restored cross-section of the Ashton-Carey Gully area (central part of the Mount Lofty Ranges), implying ~65% crustal shortening as a result of Delamerian thrusting (after Preiss, 1997). See Fig. 3-1 for the location of cross-section.

- The Cambro-Ordovician Delamerian Orogenesis is the most prominent tectono-magmatic and metamorphic phase, ending the tectonic evolution of the Adelaide Geosyncline and Kanmantoo Trough at about 500Ma ago.
- The Adelaide Fold-Thrust Belt is the appropriate term to describe the complex Delamerian structure expressed in the basement of the Mount Lofty Ranges represented by a number of folds and low-angle thrusts and shear zones dipping east.
- Significant erosion and denudation occurred before the commencement of the Early Permian glaciation.

Most of the rocks constituting the Mount Lofty Ranges are represented by the Late Proterozoic to Early Palaeozoic Adelaide Geosyncline and Kanmantoo Trough. This fact partly explains why the Mount Lofty Ranges are often associated with the Adelaide Geosyncline. However, the development of Adelaide Geosyncline and Kanmantoo Trough was finalised by the Delamerian orogeny that resulted in a distinctive Adelaide Fold-Thrust Belt structure (eg. Flottmann & James., 1997). Only a small part of this structure is exposed within the Mount Lofty Ranges formed by neotectonic process that is different and completely separated from those resulted in the Adelaide Fold-Thrust Belt.

3.4 Late Palaeozoic Complex

The Late Palaeozoic complex constitutes the upper part of the pre-Tertiary basement and is related to the widespread glaciation of Gondwanaland. While glaciation affected most of the Australian continent, its evidence in the Mount Lofty Ranges is limited. The Inman Valley on Fleurieu Peninsula has the most prominent features of glaciation. This glacially eroded valley contains striated surfaces and remnants of glacial deposits and large erratics. Remarkable imprints of glacial action are also located in the western portion of the Mount Lofty Ranges in the Hallett Cove area south of Adelaide. There are a number of striated and polished bedrock surfaces within the study area (Fig. 3-3). The ice flow striations vary in direction from 280 to 015 degrees (Bourman, 1987; Milnes & Bourman, 1972; Sprigg, 1942) and were interpreted as multiple phases of glaciation (Bowen, 1959). However later studies show that most of the Late Palaeozoic glacial deposits in South Australia contain only one lodgement till, with several flow tills that reflect the progressive decay of the ice-mass (Alley & Bourman, 1984; Bourman, 1987).

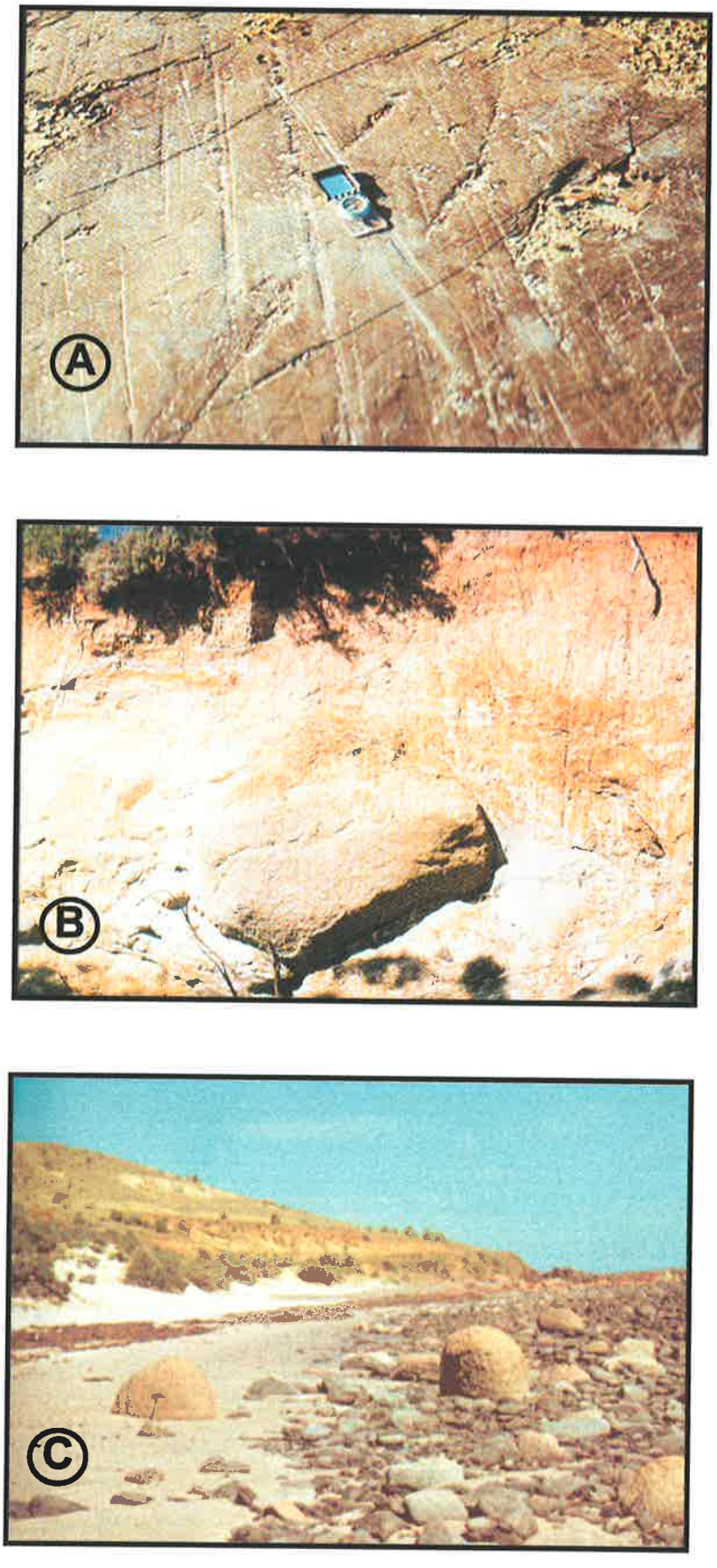


Figure 3-3 Evidence of the Permian Glacials. A: North-west striation on glacially scoured surface of the Late Proterozoic metamorphic complex at Hallett Cove as indicator of general direction of ice movement; B: Granite erratics in glacial deposits at west bank of the Inman River (after Alley & Bourman, 1995). C: Erratics of Encounter Bay Granite and Early Palaeozoic Kanmantoo Group rock complex at the beach north of Cape Jervis derived from the Permian glacial till (after Ludbrook, 1980).

While restricted palaeontologic evidence does not enable accurate age determinations, most of the glacigenic rocks within the study region are Early Permian in age. The lowest part of these rocks may relate to the Late Carboniferous (eg. Alley, 1995) or may straddle the Carboniferous/Permian boundary (Bourman, 1987). The final stage of deglaciation is represented by glacio-lacustrine and glacio-marine sedimentation such as the Cape Jervis Formation dated as earliest Permian (Alley & Bourman, 1995).

The structural relationship of Late Palaeozoic glaciers to Australian intracratonic sedimentary basins has long been recognised in Australian regions (Gravenor, 1979; Veevers, 1984; Veevers & Evans, 1975; Veevers et al., 1982; Wopfner, 1970, 1980). However many South Australian deep basins are of non-structural origin and thin mantles of glacigenic sediments are more common (Alley, 1995). While some landforms such as Inman Valley and Backstairs Passage seem to have been buried by glacial deposits, many other exhumed landforms of post-Permian age may be non-glacial in origin (Bourman, 1987).

All Permian sediments and proposed landforms within the study region were included in an area called the Troubridge Basin (Fig. 3-4). This basin does not have any tectonic significance and only marks the region where the Late Palaeozoic icesheets have passed and left their sediments (Wopfner, 1972). Outlines of the Troubridge Basin show that fluvioglacial deposits probably covered a significant part of the Mount Lofty Ranges and its flanking basins prior to Tertiary erosion and sedimentation. Preliminary results of seismic investigation of Permian deposits in the St. Vincent Basin show that these fluvioglacial deposits covered a much larger area and were significantly thicker than had been considered earlier (J. Bull, 1998, pers. comm.).

The SE to NW direction of ice movements has been well documented and provides important evidence that the Delamerian structure and landscape were already significantly eroded prior to the glaciation that allowed glaciers to pass freely through the meridional Delamerian structure in the study area. It is also important to note that the Troubridge Basin and NW direction of the ice movements remarkably delineated an absence of any structural consistency with both the older Delamerian and the younger Mount Lofty Ranges structures. Thus the Permian glaciation apparently played a significant role in post-Delamerian landscape planation by eroding remnants of local uplifts and filling many shallow valleys and sags.

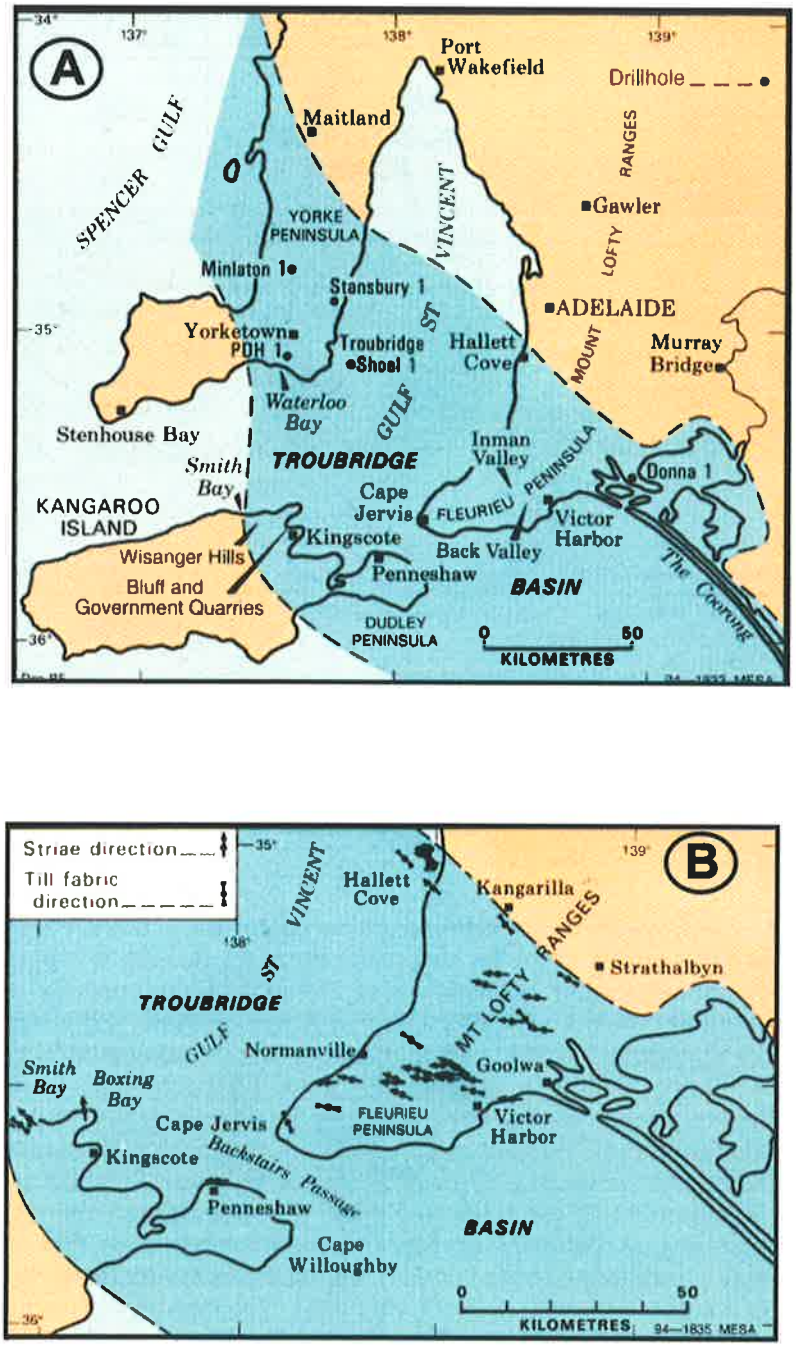


Figure 3-4 A - Approximate limit of Permian glacigene deposits of Troubridge Basin with important sites and drillholes (after Alley & Bourman, 1995). Boundaries are not tectonically controlled. B - Main directions of the Permian ice movement in the Troubridge Basin showing that neither the Adelaide Fold-Thrust Belt not the Mount Lofty Ranges represented any significant barrier to the north-west direction of Permian glacier flow that most probably contributed to further erosion and planation of the Delamerian structures.

The preservation of Permian unconsolidated sediments within the Mount Lofty Ranges and flanking bains highlights the post-Permian relative tectonic quiescence and provides important evidence for post-Middle Eocene evolution of the region. The following summarises some important facts and events of the Late Palaeozoic development in the study area:

- The Adelaide Fold-Thrust Belt did not represent any significant barrier to the north-western direction of glacier movements apparently due to its significant erosion and denudation before the commencement of glaciation.

- Distribution of Permian fluvioglacial deposits does not relate to any tectonic structure but is perhaps associated with irregularities of the post-Delamerian erosion surface.

- Preservation of Permian sediments in the southern part of the study area is evidence of insufficient uplift and erosion to remove these unconsolidated fluvioglacial sediments before and during the formation of the Mount Lofty Ranges.

- The oblique relationship of the fluvioglacial Troubridge Basin with its SE to NW flows to SW-NE strike of the Mount Lofty Ranges indicates that neither regional neotectonic structure nor landscape of the Ranges was associated with the Late Palaeozoic development.

- Permian fluvioglacial deposits within the Ranges were a significant source of the Tertiary polymictic terrigenous deposits such as the North and South Maslin Sands.

3.5 Mesozoic Development

Despite an absence of Triassic, Jurassic and Cretaceous sedimentary records in the immediate study region, there are significant geological and tectonic records of these periods in regions surrounding the study area. A brief review of these records is provided below in order to better understand the general state of the crust and tectonic processes directly or indirectly affected the study region during the Mesozoic.

3.5.1 Triassic through to Middle Jurassic

Relatively limited distribution of Early Triassic deposits in Australia and world-wide allowed Frakes & Rich (1982) to infer a relatively dry climate at this time. Aridisation occurred in spite of slow sea-level rise from the lowest stand near or below Present Sea Level (PSL) in the

Late Permian to ~50m above PSL in the Middle Triassic (long term eustatic curve, Haq et al., 1987). Both Gondwanan Mid-Triassic and Early Jurassic climates correspond to warm temperatures with some variation in seasonality (Barnard, 1973). This time has been classified as a 'warm mode' with progressively more widespread humid climates in Early and Middle Jurassic (Frakes et al., 1992). This corresponds to the slow sea-level rise from about PSL in Late Triassic to ~100m above PSL in the Mid-Jurassic (Haq et al., 1987).

Late Triassic with possible extension to early Jurassic fluviolacustrine and coal deposits are recorded in the western portion of the Flinders Ranges some 60-70km north-east of Port Augusta (Dickinson, 1944; Parkin, 1953; Johns, 1970, 1975a,b; Kwitko, 1995). These sediments are associated with the South Australian Leigh Creek Coalfield and restricted to four small (3-25km) and isolated basins containing hundreds of meters of interbedded gravely sandstones, siltstones, mudstones and coal seams (Kwitko, 1995). All late Triassic to early Jurassic sedimentation apparently occurred in freshwater lacustrine environments with warm and wet climate during coal formation. The restricted sediment distribution suggests that their origin is probably a local phenomenon such as post-diapiric collapse postulated by Lemon (1988) or perhaps represents eruption craters associated with lamprophiric intrusions later filled by sediments (Flinders Diamonds Ltd, Prospectus, 2001). As Kwitko (1995, p.99) points out: "Fluviatile input in these areas occurred under conditions of sluggish drainage and subdued topography" that seems was a regional landscape characteristics with sedimentation as a local phenomenon.

3.5.2 Mid-Jurassic through to the Cretaceous

Despite the continuing long-term sea-level rise up to ~150m above PSL in the Late Jurassic, Frakes et al., (1992) inferred a climatic 'cool mode' to the Middle Jurassic to Early Cretaceous interval, based on ice-rafted deposits in high-latitude regions. They have demonstrated that the southern part of Australia including the study region had mainly seasonally wet to wet conditions. There was a possible extension of the Eromanga Basin from the north into the central part of the present Murray Basin (~150km east of the present Mount Lofty Ranges) in the Early Cretaceous. Terrigenous and shallow marine sediments (up to 600m) occurred in a few troughs and shallow depressions that collectively form the Berry Basin (Fig. 3-5).

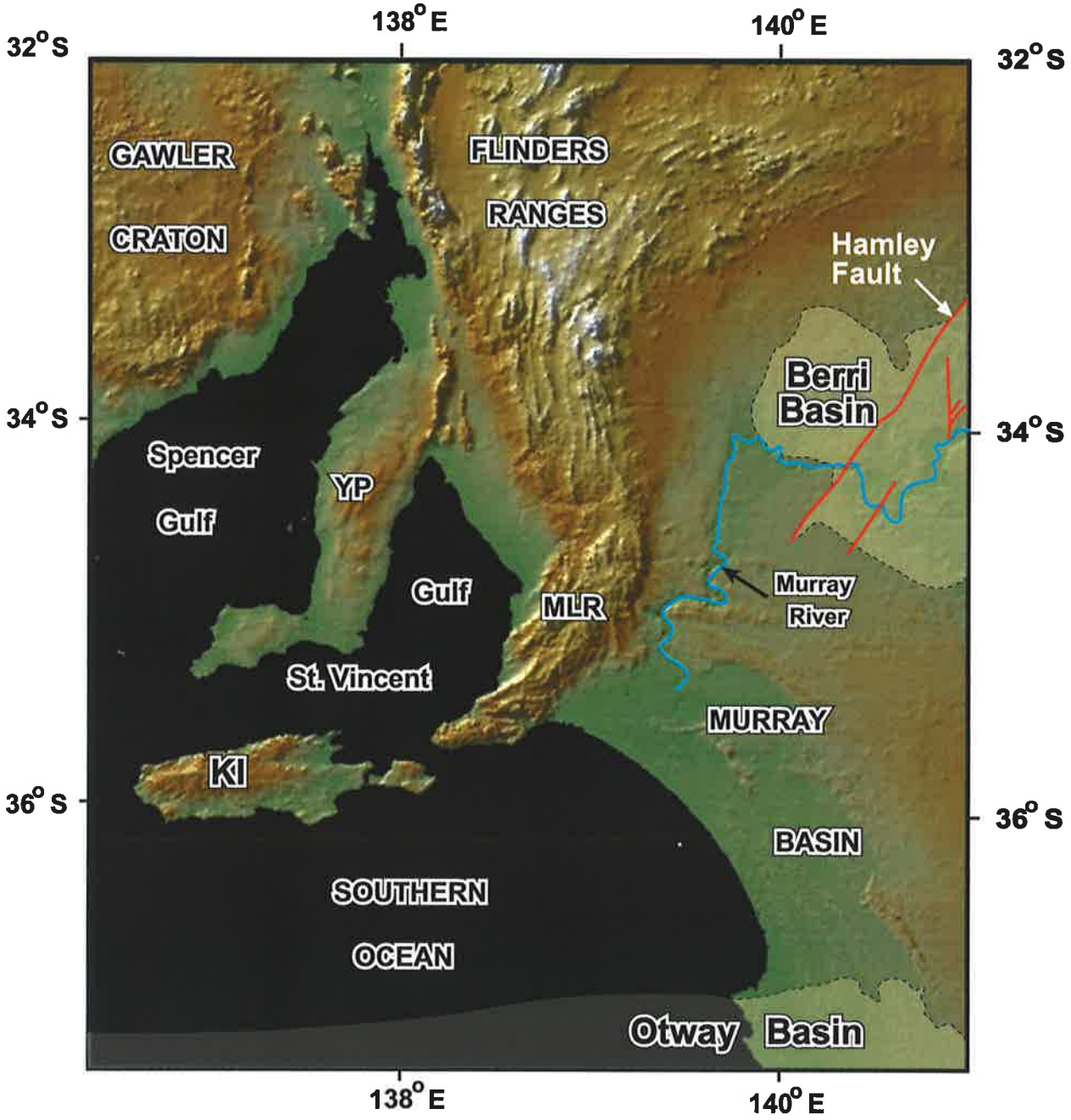


Figure 3-5 Approximate limits of Cretaceous Berri Basin (after Rogers, 1995) and Otway Basin (after Morton, 1995) in South Australia . MLR = Mount Lofty Ranges; KI = Kangaroo Island; YP = York Peninsula. Shaded-relief image derived from 9-s DEM (Geoscience Australia).

By far the major tectonic developments surrounding the study region are the great Jurassic-Cretaceous rifting events that occurred in the southern coastal regions of South Australia collectively named the Southern Australian Rift System (Fig. 3-6). This comprises a number of basins and depocentres that accommodate up to 11km (Ceduna depocentre, Veevers, 1984) of Jurassic-Cretaceous deposits associated with intracontinental crustal extension. Rapid subsidence and sedimentation continually occurred in the Late Cretaceous in the rifted Bight, Duntroon and Otway Basins (Morton, 1995; Hill et al., 1995; Stagg et al., 1999). The seaward stepped down chain of half-grabens in these basins is typically associated with the Late Jurassic and Early Cretaceous crustal segmentation initially intraplate, and later after break-up of Australia and Antarctica (~100Ma), on the incipient southern Australian continental margin (Fig. 3-7).

The Southern Ocean sea floor spreading and transform faults apparently transformed an extensional stress into the continental shelf where a number of troughs and associated basins were also formed. One of the remarkable tectonic features of the extensional stress transfer into the continental crust is the Polda Trough (Stagg & Willcox, 1992). This Trough extends over 400km from the Bight Basin on the continental shelf into the Eyre Peninsula (SW part of Gawler Craton). The onshore position of this Trough with Jurassic sediments indicates that extensional forces affected the highly consolidated Australian continental crust such as the Gawler Craton (Fig. 3-6).

"The period from the mid-Cretaceous to the mid-early Eocene was one of the warmest times in the Late Phanerozoic" (Frakes et al., 1992, p. 83). There was a global sea-level rise that reached its Mesozoic peak (~300m above PSL) in the Late Cretaceous and then sea-level gradually dropped (Haq et al., 1987). However, there were a number of transgressive and regressive pulses associated with relatively short-term (~5.5 million years) fluctuations of sea-level (Frakes et al., 1992).

3.5.3 Mesozoic Igneous Activities

There are no geological records of Mesozoic development within the study area other than the intrusion of kimberlitic pipes in the Echunga and Blanchetown areas. A number of kimberlitic lamprophyres (over 70 outcrops) are also encountered immediately north of the study area in the South Flinders Ranges and elsewhere in the South Australia (Farrand, 1995).

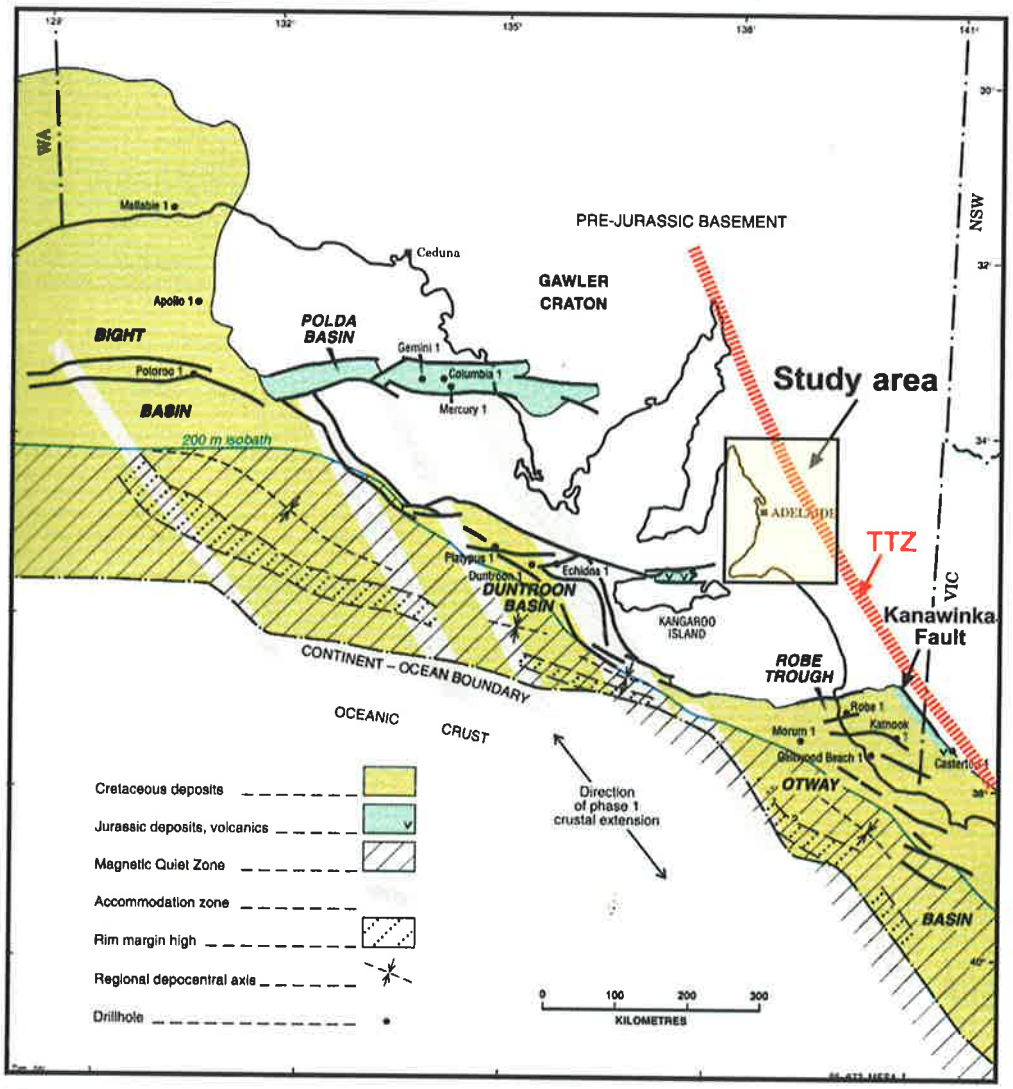


Figure 3-6 Main structural elements of the Australian Southern Rift System in South Australia (after Gatehouse,1995). TTZ - Tertiary Transfer Zone that is consistent with main direction of phase 1 of crustal extension and thus possibly established during the Cretaceous.

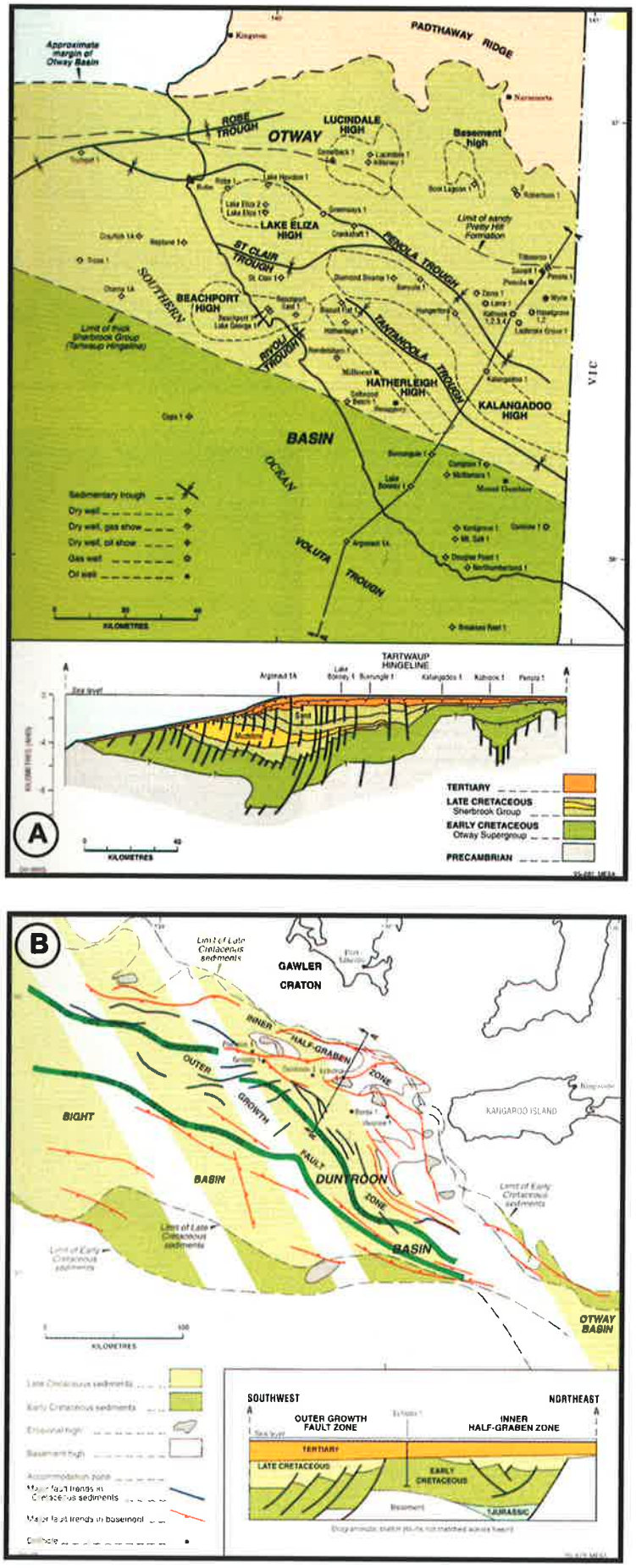


Figure 3-7 A = Seaward stepped down chain of half-grabens of the Otway Basin (after Morton, 1995); and B = structure of the Duntroon Basins (after Hill, 1995) south of the study region showing an extensional style of deformation affected the southern Australian continental margin during the Cretaceous.

A number of U-Pb, K-Ar and Rb-Sr absolute dates of kimberlitic lamprophyres indicate that they were formed sometime during the Jurassic, approximately 170Ma ago (Black et al., 1993; Scott Smith et al., 1984). There is also the Wisanger Basalt outcrop westward from Kingscote on Kangaroo Island. The age of the Wisanger Basalt (~170Ma) obtained by K-Ar determination is the same as most other lamprophyres (McDougal & Wellman, 1976). These extrusions are attributed to the initial separation of Australia and Antarctica by Milnes et al. (1982). This also indicates that an extensional stress regime apparently affected study area and nearby regions however it was not yet resulted in main structural development.

While most of the South Australian lamprophyres were formed at about 70km depth, some of those in the South Flinders Ranges are exceptional, and formed at depths exceeding 120km (Ferguson et al., 1979). This indicates that a weak state of the earth's crust was apparently associated with extensional tectonic stress. Farrand (1995) suggests that lamprophyres are products of thermal activity in the mantle and that their penetration was related to rifting as a precursor to the opening of the Southern Ocean. A few strain transfer zones associated with extensional tectonic regime would be established during this time interval that probably provided an access for lamprophyres and basalts into the upper part of the crust and even onto the surface (eg. Wisanger Basalt). Spatial coincidence of the major extensional transfer zone (Ch. 5) with regional gravity lineament or so-called G2 structural corridor (O'Driscoll, 1981; Farrand & Preiss, 1995) is not accidental but is likely a result of the Jurassic-Cretaceous extensional tectonic regime with associated lithospheric magmatic penetration (Fig. 3-8).

3.5.4 Summary of Mesozoic Development

- Climatic modes inferred to the Mesozoic: warm Triassic to Mid-Jurassic; relatively cool mode from Mid-Jurassic and Early Cretaceous; and the warmest Mid-Cretaceous to Early Tertiary.
- Long-term sea-level rise from below or near PSL in earliest Triassic to its peak (~300m above PSL) in the Late Cretaceous accompanied by tens of short-term sea-level changes resulted in a number of transgressions and regressions during the Mesozoic.
- Local Triassic sedimentation and coal measure sediments occurred in the western flank of

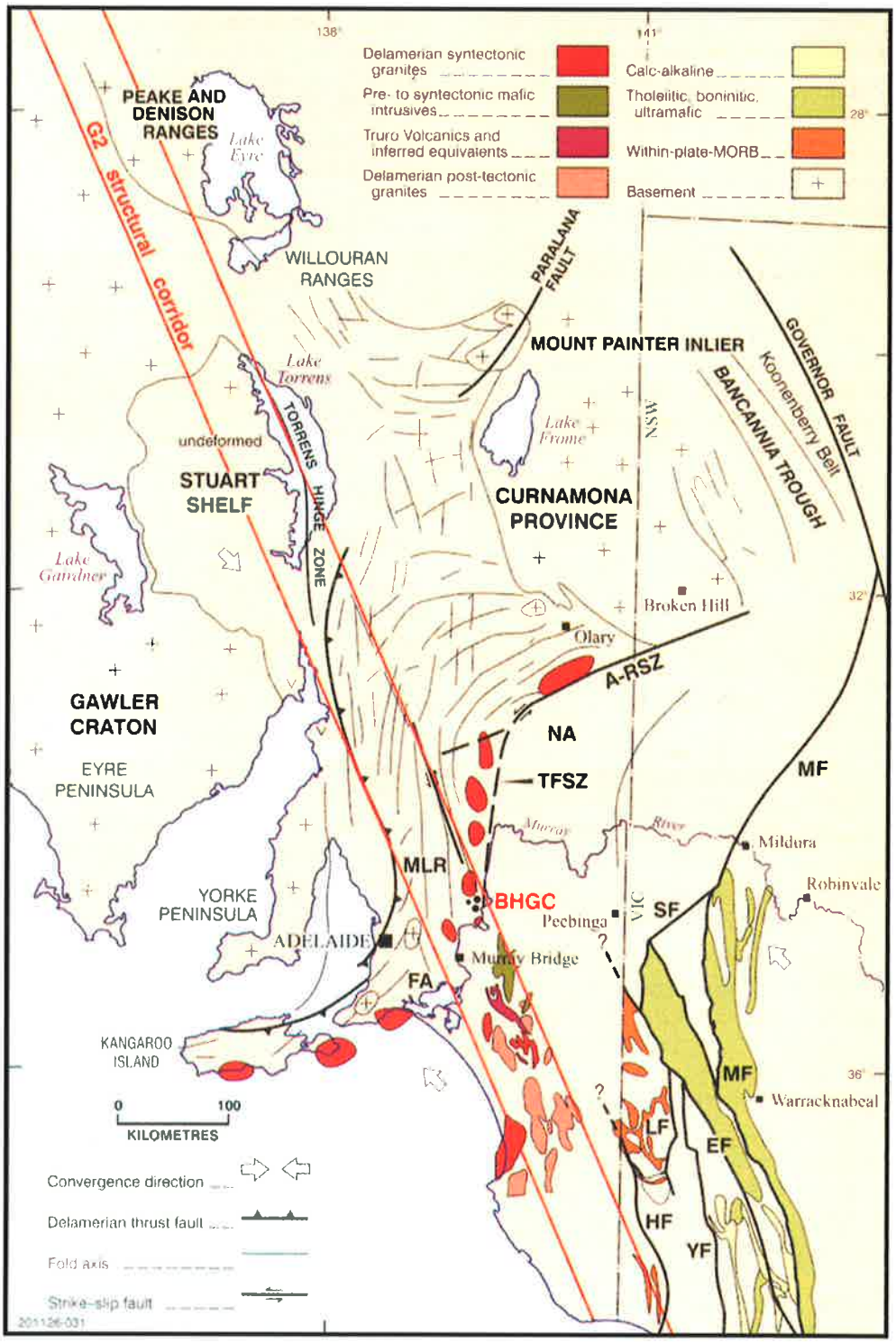


Figure 3-8 Tectono-structural elements of the Pre-Tertiary basement of eastern South Australia (after Preiss, 1999; modified by Burtt & Purvis, 2002). The inferred Tertiary Transfer Zone (TTZ, this thesis) is spatially concurrent with G2 structural and gravity corridor (O'Driscoll, 1981, 1990).

the Flinders Ranges. Most of this occurred in landlocked, relatively stable tectonic and low relief environments.

- Trough systems were formed in the Berri Basin (central part of the present Murray Basin) that accommodated ~600m of Early Cretaceous deposits.
- A number of large rift basins collectively named the Australian Southern Rift System were formed during the Jurassic and Cretaceous on the southern margin of Australian continent.
- The Polda Trough (>400km long and 20-60km wide) was formed as a response to the initial break-up of Gondwana despite strongly consolidated continental crust of Gawler Craton.
- Crustal penetration by Jurassic kimberlitic lamprophyres and basalts surrounding the study region is probably associated with a crustal attenuation due to an extensional stress regime driven by embryonic Gondwanan break-up.

This brief analysis of the Mesozoic geological and tectonic records indicates that the most prominent tectonic movements resulting in basin formations occurred outside the study region. Extensional trough systems were the most common tectonic features constituting the architecture of Mesozoic basins specifically along the incipient Southern Australian Continental margin (eg. Stagg et al., 1999).

Taken together these facts clearly indicate that a substantial continental extension affected the Southern Australian Continental crust including the highly consolidated crust of the Gawler Craton and some areas within the present Mount Lofty Ranges (eg. intrusion of kimberlitic pipes in the Echunga area). The absence of any Triassic-Jurassic and Cretaceous sedimentary records in the study area demonstrates that weathering and landscape planation with a minor role of stream erosion were the most likely processes affecting this region.

3.6 Mesozoic Plate Reorganisation since the Gondwanan Breakup

The Australian Plate has experienced significant changes in plate boundary geometry and relative plate motion directions and velocities since the breakup of Gondwana (Muller et al., 2000). Since this breakup in the Late Jurassic (~156Ma) a major extension occurred along the western, southern and eastern margins of the Australian Plate that was associated with seafloor spreading during most of the Cretaceous (Gaina et al., 1998; 1999; Muller et al., 2000). Enormous stretching forces were apparently involved in the separation of the

Australian from the Indian and Antarctic Plates and the Lord Howe Rise/New Zealand counterparts of Gondwana during this time. If plate boundary forces and drag forces acting along the base of the plate are the primary sources of tectonic stress (eg. Coblentz et al., 1995), then there is reason to believe that substantial extensional rather than compressional stress was generated during the major intervals of seafloor spreading.

Initial separation of Australia from its Gondwanan counterparts occurred by seafloor spreading along the NW margin of Australia in the central part of the Argo Abyssal Plain. This spreading propagated south to the Perth Basin between 156Ma and 132Ma. During this time Argo Land moved NW relative to Australia indicating a SE-NW crustal extension that resulted in the stepped transform structure of the NW Australian margin such as the Exmouth Plateau (Muller et al., 2000).

About 132Ma, the initial spreading between the Australian and Indian Plates suddenly ceased, but the major breakup between Greater India and Australia almost simultaneously commenced along the western Australian margin and propagated further south (Fullerton et al., 1989). At about 120Ma southern Greater India started to separate from Antarctica (Muller et al., 2000). However the time of initial spreading between Australia and Antarctica remains controversial. Stagg & Willcox (1992) determined the initial breakup at ~135Ma from seismic data on the relationship between continental margin sequences and oceanic crust. However more recent studies determine the initial spreading between the Australian and Antarctic Plates at about 100Ma (Muller et al., 2000; Veevers, 2000).

While the Southern Ocean was not yet open along the southern Australian margin in the Late Jurassic and Early Cretaceous, the intracontinental extension resulted in subsidence and formation of the Otway, Bass and Gippsland Basins in the Australian south-east (Muller et al., 2000; Veevers, 1984, 2000). Extensional features in these basins and elsewhere on the southern plate margin indicate variation of the extensional stress orientation mostly in the NW-SE and N-S directions (Muller et al., 2000; Etheridge et al., 1985; Willcox et al., 1992).

All above extensional crustal structures were formed in spite of long-lived subduction of the Pacific Plate beneath the eastern margin of the Australian Plate. "Head-on" Chilean-type subduction persisted up to ~136-131Ma, when it changed to transform margin (Muller et al., 2000). However, Veevers (2000) postulated that "head-on" subduction persisted up to the

99Ma event featuring a major swerve in the direction and rate of absolute motion of the Pacific Plate. Late Jurassic and Early Cretaceous Plate tectonic events are briefly summarised as:

- Initial separation of the Australian/Antarctic and Indian Plates (Argo Abyssal Sector), with significant seafloor spreading and formation of the initial western margin of the Australian Plate (~156–120Ma).
- Seafloor spreading between Greater India and Australia (commenced at ~131Ma).
- Separation of Greater India and Antarctica (commenced at ~120Ma).
- Subsidence and basin formations on the embryonic southern margin (Gippsland, Bass Otway, Duntroon, and Great Australian Bight Basins).
- "Head-on Chilean-type subduction" of the Pacific Plate beneath the eastern margin of the Australian Plate.

This summary clearly indicates that despite the head-on subduction of the Pacific Plate beneath the eastern Australian Plate margin an extensional stress regime was dominant along the western and southern embryonic margins.

3.6.1 The Study Region since the Gondwanan Breakup

In spite of dramatic changes in the Australian Plate configuration, directions and velocity of plate motions during the Late Jurassic and Early Cretaceous, there are no geological records of this time within the study region that might provide any indication of tectonic activity. The nearest record of Early Cretaceous subsidence is associated with the formation of the Berri Basin in the central part of the present Murray Basin, and the Otway Basin SE of the Mount Lofty Ranges (Fig. 3-6).

Palaeogeographical reconstructions of the Australian Cretaceous shorelines indicate that a wide Early Cretaceous (eg. Aptian) transgression directly affected more than half of the Australian Platform (Frakes et al., 1987). However the regions of the present Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins were outside any direct Cretaceous marine influence (Fig. 3-9). This suggests that the study region was situated topographically higher than Cretaceous sea-levels. According to the global eustatic curve (Haq et al., 1987) the study region must have stood at least 300-350m above PSL. Absence of

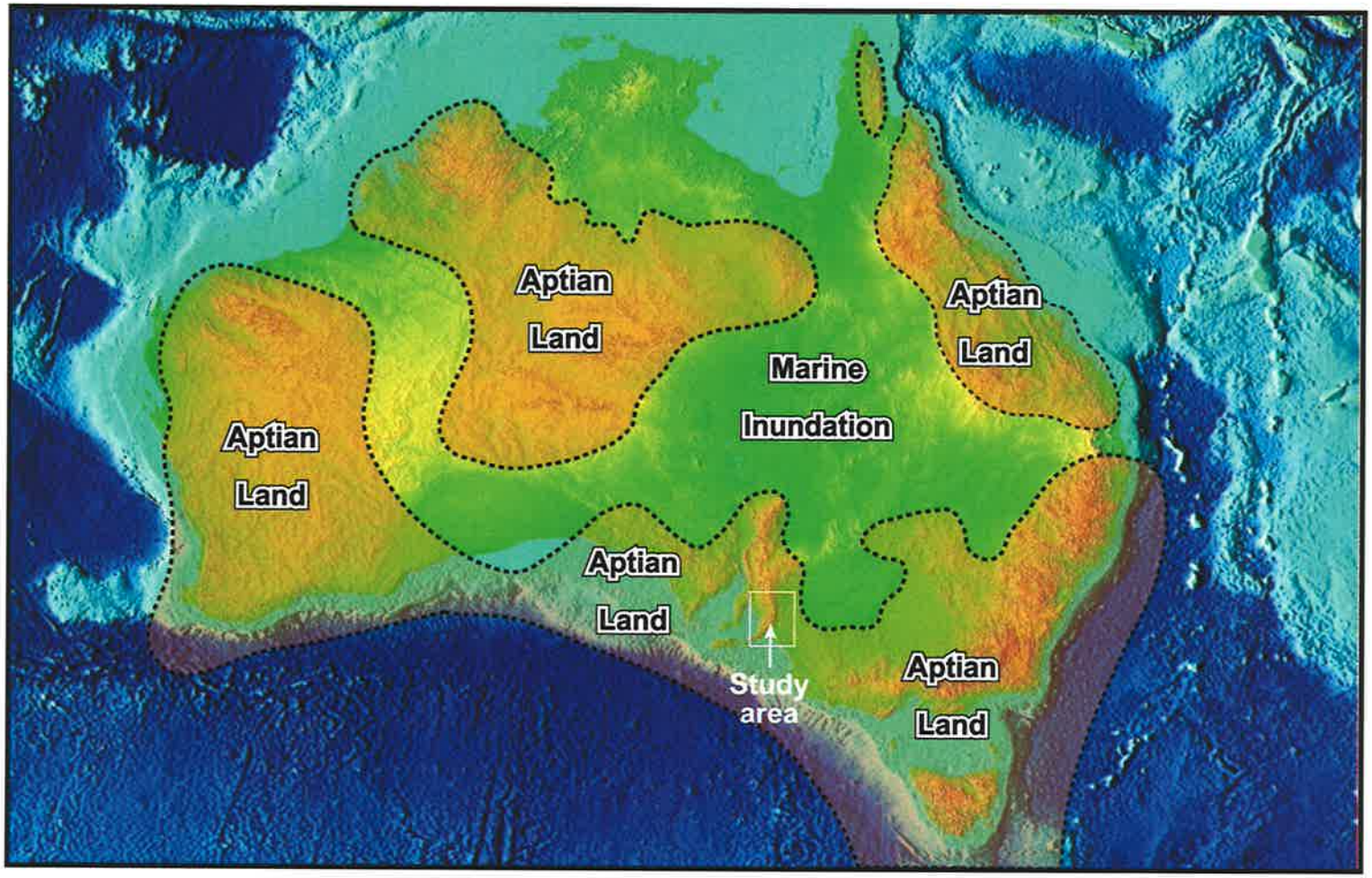


Figure 3-9 The impact of the Cretaceous marine inundation on the Australian continent (~116Ma). Approximate limits of Aptian lands (after Veevers, 2000) showing that the Mount Lofty Ranges, St. Vincent and Western Murray Basins were out of marine influence during maximal marine flood associated with sea-level rise up to ~300m above PSL according to the Global eustatic curve (Haq et al., 1987). 2' DEM image courtesy NOAA USA.

geological records or evidence of structural development along with other factors would testify to a long duration of relative tectonic quiescence and thus development of the relatively high-standing Palaeoplain over the regions of the Mount Lofty Ranges and flanking basins during the Jurassic and Early Cretaceous.

3.7 Separation of the Australian and Antarctic Plates: Potoroo Extensional Tectonic Regime (~99Ma and ~43Ma)

Veevers (2000) distinguished two major tectonic events associated with changes of azimuth and velocity of the Pacific Plate motion at Mid-Cretaceous (99Ma) and Mid-Eocene (43Ma) that drastically changed the tectonic stress regime of the Australian Plate. The interval between these events was introduced earlier as the Potoroo Extensional Regime (Veevers, 1984). Specifically, the 99Ma event produced a change from a "Chilean-type of head-on subduction of the Pacific Plate prior 99Ma to a sinistral oblique Mariana-type subduction between 99Ma and 43Ma. This evoked significant change of azimuth of the Pacific Plate motion (65-70-degree clockwise) between 119-100Ma and 100-94Ma intervals" (Veevers, 2000, p.102).

The seafloor spreading west of Australia indicates that the 99Ma event also drastically changed the spreading direction between India and Australia from NW-SE to N-S (Muller et al., 1998, 2000). Spreading rates between these plates have been significantly increased from 36mm/year to 84mm/year in association with this event (Veevers, 2000).

Giana et al., (1998) describe several short strike-slip faults accompanied by rift zones that developed prior to the opening of the Tasman Sea southeast of Tasmania at about 84Ma. Since then, a crustal extension with associated "rifting and seafloor spreading propagated from the south to north and transferred continental crust from Australia to the Lord Howe Rise" (Muller et al., 2000, p.25). The sigmoidal northward propagation of seafloor spreading, extreme asymmetry of Tasman Sea margins and variation of spreading rates indicate that forces involved in such crustal extension were variable in both azimuth and magnitude during the time of the propagation.

In contrast to the Tasman Sea, the Southern Ocean seafloor spreading was relatively symmetric with only small azimuth variations (Fig. 3-10). Tikku & Cande (1999) noticed that

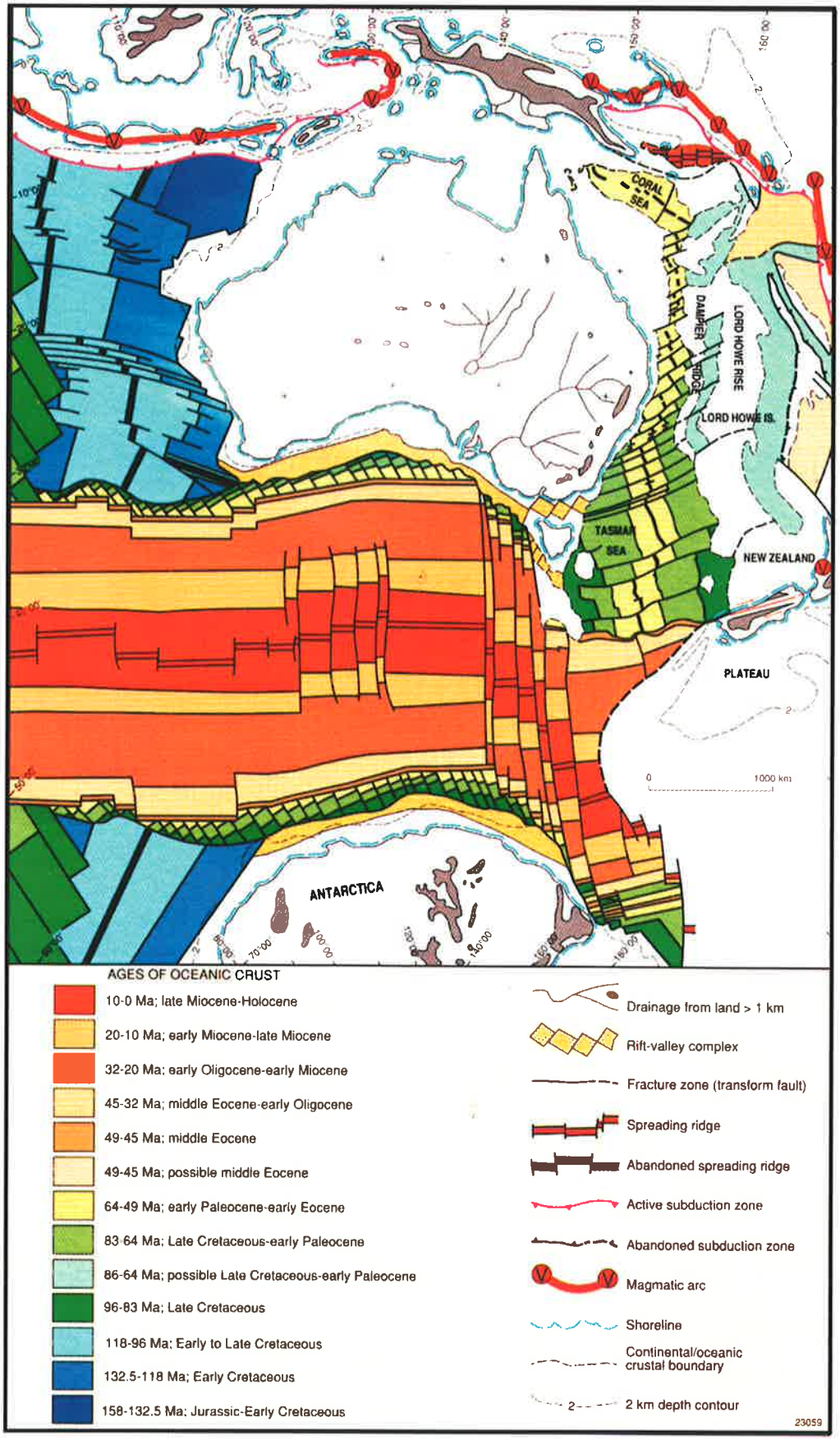


Figure 3-10 Seafloor spreading around Australia (after Scheibner, 1999).

spreading direction between Australia and Antarctic was changed from NE-SW to NNW-SSE at about 61Ma. This change of the spreading direction is perhaps associated with the N to NE change of the motion of the Pacific Plate some time between 65Ma and 61Ma (Muller et al., 2000). Relative symmetry of the Australian and Antarctic margins and similar rates of Southern Ocean seafloor spreading indicate that more or less uniform extensional forces resulted in the separation of Australia and Antarctica (~99Ma to ~43Ma).

Extensional forces driving the Australian Plate lasted up to ~50Ma, when the seafloor spreading ceased along the entire eastern and northern margins of the Australian Plate. Muller et al., (2000) correlate the ending of this extensional regime with new plate reorganisation associated with change in both direction and velocity of Pacific Plate motion. They note that such changes caused oblique compression between the Pacific and Australian Plates. However Veevers (2000) observed continuing NE motion of the Pacific Plate between 48Ma and 43Ma and inferred that the major change of azimuth and absolute motion of the Pacific and Australian Plates associated with anticlockwise swing at ~70-degree occurred at ~43Ma. All the above plate tectonic events during the Potoroo Extensional Regime are summarised as follows:

- Seafloor spreading between the Australian and Antarctic Plates commenced at ~99Ma.
- Spreading acceleration from 36 to 84mm/year between the Indo-Australian and Antarctic Plates occurred at about 99Ma.
- Opening of the Tasmanian Sea as a back arc system was associated with a NW to N swing of the Pacific Plate motion that transformed "head-on" subduction to sinistral oblique subduction, with a significant component of left-lateral strike-slip motions (~84Ma).
- Significant Tasmanian seafloor spreading with sigmoidal northward propagation, rifting and hundreds of kilometres of lateral block movements along transform faults occurred between ~84Ma to ~50Ma.
- Reduction and ending of the seafloor spreading along the entire northern and eastern Australian margins occurred some time between~52Ma to ~43Ma.
- A counterclockwise Pacific Plate swing from N-NE to N-NW possibly caused a change of Southern Ocean spreading from NE-SW to NNW-SSE at about 43Ma.

There is still uncertainty about the age, nature and style of the continental breakup and separation of the Australian and Antarctic Plates. A few models from a classical 'Atlantic' symmetric rift to oblique extension and detachment models have been proposed (Falvey & Mutter, 1981; Veevers, 1984, 1986, 2000; Etheridge et al., 1990; Stagg et al., 1999). Willcox & Stagg (1990) proposed an oblique SE-NW extension as a major cause of the initial formation of the Australian southern margin. They recognised a number of *transfer faults* active along the southern Australian continental margin, which strike SE-NW penetrating the upper crust as far north as the Polda Trough (SW Gawler Craton). According to this model principal crustal movements are associated with left lateral strike-slip movements along the large Tasman Fracture Zone west of Tasmania (Willcox & Stagg, 1990).

3.7.1 The Study Region between 99Ma and 43Ma

In spite of pronounced tectonism in many parts of Australia associated with the extensional Potoroo Regime, there is no record of any tectonic development within the study area, and it is very limited in neighbouring regions. The nearest structures imprinted during the Late Cretaceous are the Otway and Duntroon Basins located on the southern Australian continental margin far south of study area (Figs 3-6; 3-7). These basins were developed as integral parts of the Southern Australian Rift System on the passive continental margin (Willcox & Stagg, 1990; Willcox, 1990; Hill, 1995). Both basins were established possibly in the Late Jurassic but more certain structural development occurred in the Early Cretaceous as a result of intracontinental extension and later in association with the Australian/Antarctic break-up.

There is no doubt that both basins accommodated substantial crustal extension before and certainly during separation of the Australian and Antarctic Plates as a significant amount of sediments was accumulated in these basins. The thickness distribution indicates that the northern parts of the Otway and Duntroon Basins (inner zones) typically accommodated less amounts of subsidence and fault movements than their southern outer parts. This probably related to a reduction of extensional stress propagating northward. The northern limit of effective palaeostress release along the southern passive margin is not uniform and as elsewhere significantly depends on crustal heterogeneity such as variation in density and rheological properties, configuration of plate boundaries and other factors (eg. Zoback et al., 1989). Therefore the stress/strain boundary is not a straight line even if stress distribution was

relatively uniform according to the relative symmetrical seafloor spreading of the Southern Ocean.

The Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins did not record any tectonic activity during the Potoroo Regime. The highly consolidated and brittle crust in this region was apparently beyond the limit of any stress release. The absence of sedimentation together with the eustatic curve suggests that this region was topographically higher than Late Cretaceous and Early Tertiary sea-levels (~250-350m above PSL). Deep weathering and a relatively flat planation surface beneath the Tertiary deposits in these flanking basins and on the major watershed of the Ranges indicate that an extensive pre-Tertiary Palaeoplain was developed over much of southern South Australia including the study area during the Late Cretaceous and Palaeocene.

3.8 Early Tertiary Environment

The Australian climate had been gradually cooling from the warm mode of the Late Cretaceous to Early Tertiary (Frakes et al., 1992), and at the beginning of the Tertiary the climate was approximately 6° C higher than it is today (Barron, 1983). Palaeobotanical records confirm the scenario of warm and wet climate with extensive development of rainforests in the late Palaeocene to early Eocene in southern Australia beyond 60°S palaeolatitude (Kemp, 1978). These data are consistent with warming in high latitude surface waters of the Southern Ocean in this period (Zachos et al., 1994). During the early Eocene, rainforests in the region were diversely angiosperm and their character is distinctly nonseasonal megathermal (>24°C mean air temperature) corresponding to tropical conditions where moisture and light regimes are not limited during one or more seasons (Macphail et al., 1994). All of these factors together with global data (Berger & Vincent, 1981; Berger, 1982; Seibold & Berger, 1993) provide evidence that a warm period prevailed in regions near the nascent Southern Ocean in the early Cenozoic (McGowran, 1989; McGowran et al., 1997).

Long-term global sea-level lowering since the Late Cretaceous was sluggish and sea-level remained at about 200-250m above the PSL during the Palaeocene. However there is no Palaeocene or Early Eocene sedimentary record in the study region including the St. Vincent and Western Murray Basins. The first influx of Middle Eocene sediments into these basins is correlated with the beginning of a new era in the regional neotectonic development. This new

beginning is recorded by the Middle Eocene North Maslin Sand in the St. Vincent Basin (Lange, 1970; McGowran et al., 1970) and by the Olney Formation in the Western Murray Basin (Brown & Stephenson, 1991). Therefore, the regional lithostratigraphic hiatus between the Late Palaeozoic glaciation and Early Tertiary deposition extended for a very long ~200 Ma.

Such a long period is most probably associated with a regional landscape planation, deep weathering and regolith development. Stable tectonic conditions, subdued landscape, deep regolith and an absence of sedimentation indicate that the earth's crust of a large southern portion of South Australia, including the study area, was in or near a state of geodynamic equilibrium (quasi-equilibrium).

3.9 Pre-Middle Eocene Palaeoplain

The Palaeocene to Early Eocene palaeoenvironmental reconstruction of southern Australia (Boeuf and Doust, 1975) shows that at this time the terrain was generally of low relief "like a peneplained land surface". A number of boreholes have encountered a deeply weathered and gently undulating surface beneath the Tertiary sediments in the Murray Basin. This led Brown & Stephenson (1991) to consider that all pre-Tertiary structural elements underlying this basin were levelled to a gently undulating surface formed on a tectonically stable platform. Similarly, a gentle undulating and deeply weathering surface of the pre-Tertiary basement was encountered by drilling in the St. Vincent Basin (Stuart, 1969; Daily et al., 1976; Cooper, 1979; Lindsay, 1981; Selby & Lindsay, 1982). Therefore this pre-Tertiary basement surface in these basins could be reliably established as the basis for further palaeolandscape correlations.

Residual landforms such as bornhardts and a number of weathered planation surfaces are still preserved on the main watersheds of the Mount Lofty Ranges (Sprigg, 1945; Glaessner & Wide, 1958; Twidale & Bourne, 1975; Tokarev et al., 1999). These planation surfaces cut across varied bedrock and are capped by a deep regolith indicating that they are residuals of a formerly extensive palaeoplain that existed before the Tertiary tectonic movements.

The long term (~200Ma) relative tectonic quiescence of the terrain standing above sea-level in association with a wet and warm climate was sufficient to create an extensive palaeoplain

over a large part of South Australia. Therefore all these buried and preserved planation surfaces and some residual landforms are considered here as a final product of long-term planation that are collectively named the pre-Middle Eocene Palaeoplain (non-committal term, Hills, 1961; Ollier & Pain, 2000). This pre-Middle Eocene Palaeoplain was widely distributed in South Australia, including the Mount Lofty Ranges and the St. Vincent and Western Murray Basins. However it is important to note here that neither the Mount Lofty Ranges nor these flanking basins existed as tectonic or geological entities before the Middle Eocene.

In order to determine the topographic position of this Palaeoplain, the global sea-level curve (Haq et al., 1987) adapted to South Australia (McGowran, 1989; Li et al., 2004) has been used. Extrapolation of sea-levels onto the palaeotopography indicate that the pre-Middle Eocene Palaeoplain was situated at least 220-250m above PSL and probably higher if one takes into account the higher Cretaceous sea-level and relative tectonic quiescence since that time. This position of the Palaeoplain emerges as a principal geomorphological level that forms the basis for the development of a new neotectonic model and landscape/regolith evolution of the Mount Lofty Ranges (this thesis; Tokarev et al., 1999; Tokarev & Gostin, in press).

Similar geological, tectonic and geomorphological features to the study region extending on a broader scale suggest that such a high-standing pre-Middle Eocene Palaeoplain existed not only in South Australia but probably also was distributed over a large portion of the southern Australian continental margin from the Western Australia to Victoria. Therefore this case study provides a significant contribution for further broader correlations and establishes a methodological approach to study neotectonics and to develop landscape/regolith models in other parts of the Australian continent.

Chapter 4

REGIONAL PALAEORECONSTRUCTIONS: THE MOUNT LOFTY RANGES AND FLANKING ST. VINCENT AND WESTERN MURRAY BASINS

4.1 Introduction

There is no evidence that the Mount Lofty Ranges existed as a tectonic/geologic entity before the Middle Eocene. The pre-Middle Eocene Palaeoplain is the earliest predecessor of these Ranges and flanking basins that formed following long term (~200Ma) erosion and planation. In this chapter, the age of origin and stages of the Mount Lofty Ranges development are correlated with the time of sedimentation in the flanking St. Vincent and Western Murray Basins. While previous authors such as Benbow et al. (1995, p. 211) held the traditional point of view that "the uplift of the Mount Lofty Ranges resulted from compressional reactivation of meridional to northeast-trending Delamerian structures", this thesis presents the contrary view that:

1. Neotectonic structure is independent of any basement structures
2. Tertiary tectonics was essentially extensional
3. Major uplift of the Mount Lofty Ranges occurred mainly in the Pleistocene-Holocene
4. The landscape of the Mount Lofty Ranges is a result of complex interaction between Tertiary and Quaternary tectonic movements and fluvial and marine erosion.

Most previous works have concentrated on relatively distinct features of the regional tectonic and geological history of this region. Here, for the first time, several aspects such as neotectonic movements and structural interpretations, reconstructions of sedimentary environments and lithostratigraphy, palaeolandscape and river system development, data on eustatic sea-level change and climate are combined and incorporated into the scheme of regional stages. Integrated data have refined the timing of specific neotectonic events and provided a paleogeographic framework for the results. For example the initiation of basin sedimentation discussed here is the result of segmentation of the pre-Middle Eocene Palaeoplain due to subsidence of both St. Vincent and Western Murray Basins that is attributed to regional crustal extension. The stratigraphy of basal North Maslin Sand and the Olney Formation reveals that the regional neotectonic structure was established at the beginning of the Johannian Stage at about 43Ma.

The concept of sedimentary accommodation space is used in this thesis as one of the major and essential factors controlling the depositional environments. "Accommodation space is the space available for potential sediment accumulation which is controlled largely by tectonic movements, changes in sea-level, volcanic activity, compaction and long-term subsidence rates" (Reading & Levell, 1996, p.5). Neither volcanic activity nor sediment compaction has contributed to the formation of accommodation space of the St. Vincent and Western Murray Basins flanking the Mount Lofty Ranges. Because there is a general downward trend of the Tertiary sea-level in the global eustatic curve (Haq et al., 1987; McGowran, 1989; Li et al., 2004) neotectonic subsidence was essential, and is the single obvious factor that must form accommodation space of these Tertiary Basins.

Neotectonic subsidence interacting with climate and sea-level changes determined the major sedimentary environments that are recorded by the lithostratigraphic units. In contrast to compressional uplift, this study reveals that the Mount Lofty Ranges initially were formed as an interbasin region due to subsidence of the flanking basins. The initial stream distribution and its pattern was formed due to tilting of the pre-Middle Eocene Palaeoplain within the Ranges and the flanking basin subsidence. The major rivers of the Mount Lofty Ranges are all superimposed onto the pre-Tertiary basement fabrics and lithologies (Tokarev et al., 1999; see also Ch. 6 of this thesis). Therefore landscape evolution and sedimentary supply were directly dependent on the type of neotectonic movements and newly created structures. Thus the main objective of this chapter is to investigate these movement and structures, and to correlate neotectonic events with sedimentation and landscape evolution. Analysis of lithostratigraphic units provides a spatial and temporal framework for such correlations, and a scheme of the regional stages was used for this purpose.

4.2 Regional Stages

A third order (~ million year) regional bio- and lithostratigraphic framework (McGowran et al., 1997) provides a useful chronostratigraphic reference that has been used for palaeoreconstructions in this thesis. Regional stages have been correlated with the global eustatic curve (Haq et al., 1987) as adapted to South Australia by McGowran (1989) and recently recalculated by Li et al. (2004). In spite of good correlations of regional stages with global eustatic cycles (Fig. 4-1), it is important to note that the beginning or end of any single stage is not necessarily correlated with any particular lithostratigraphic unit. Some units such

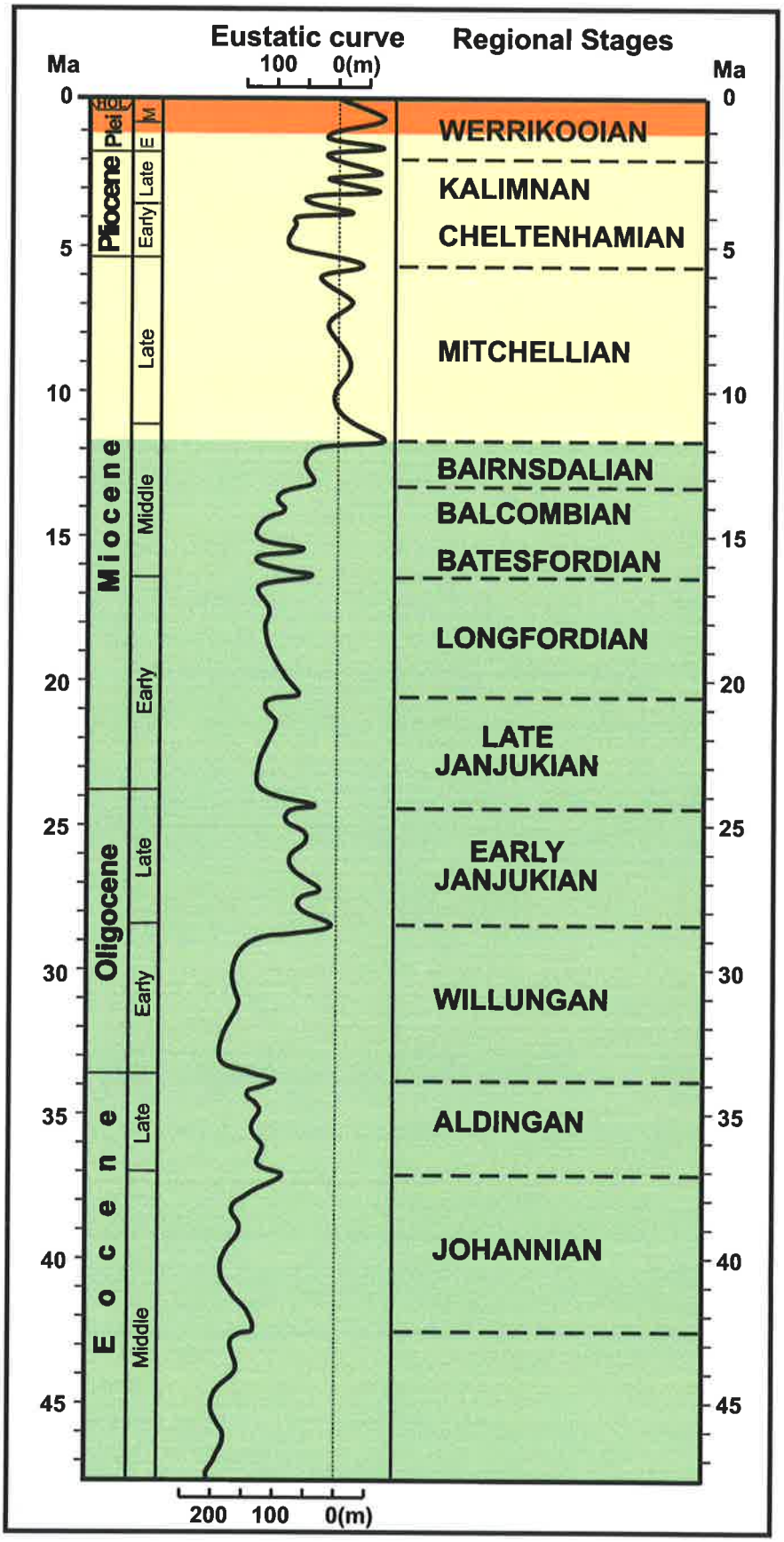


Figure 4-1 Regional Stages (modified after McGowran et al., 1997); Eustatic curve (after Haq et al., 1987; McGowran, 1989; Li et al., 2004); Colour is associated with tectonic regime: green - extensional; yellow - transitional; orange - compressional.

as the Port Willunga Formation and its members may pass through several stages, whereas other units may occupy only part of a single stage. Information on each stage is uneven, therefore some stages are treated briefly and others in some detail.

The concept of regional stages, widely used in Western Europe and New Zealand recognises the need for regional time-scales for palaeoreconstructions (eg. McGowran et al., 1997; Hornibrook et al., 1989). However in southern Australia this concept was abandoned after several unsuccessful attempts to recognise the need of regional stages (Singleton, 1941; Crespin, 1943, 1964; Ludbrook & Lindsay, 1969). Recently McGowran et al. (1997) made a new attempt to resurrect the concept of regional stages as natural divisions of the stratigraphic record. Despite some difficulties in correlating fossil assemblages with classical successions both on-shore and offshore, the benefit of using regional stages as chronostratigraphic reference for regional models such as neotectonic or landscape evolution is obvious.

First at all, there is an almost perfect correlation of regional stages with third order global eustatic curve, emphasising a pronounced effect of global sea-level change on the regional sedimentary environments along the southern Australian continental margin. Second and most important for this study, the stages allow correlation of several events such as sea-level change, neotectonic movements, landscape evolution and sedimentation in various environments within a given time-interval. This make palaeoreconstructions more complete and thus more plausible in comparison to those using only traditional bio-zonation or stratigraphic formations which are often isolated from other environments or restricted by age of fossil assemblages. This study integrates several factors in a regional development model to provide an original view and methodological approach for further neotectonic studies in other regions of Australia.

Each stage described below contains:

1. Records of climate and sea-level change;
2. Lithostratigraphic characteristics of the sedimentary units accumulated within and nearby the study region; and
3. Interpretation of the sedimentary environments correlated with tectonic movements and landscape evolution.

4.3 Johannian Stage (~43-37Ma)

Late Early through early Middle Eocene was the first major cooling episode in the Tertiary before the commencement of the Khirthar restoration (McGowran et al., 1997). Palynological information indicates that the late Middle Eocene was the warmest Tertiary period with a mean annual temperature range of +23-26°C and annual rainfall of ~2000-2500mm (Christophel, 1994; Greenwood, 1994; Rowett, 1997). Such a climate evoked development of the meso-megathermal rainforest which left fossil flora in the palaeochannels of the Maslin Sands encountered in the eastern part of the St. Vincent Basin (Rowett, 1997).

In the study region the Middle Eocene is clearly associated with newly formed accommodation space initially filled by terrigenous or fluviolacustrine formations in both St. Vincent and Western Murray Basins flanking the proto-Mount Lofty Ranges. The absence of marine sediments in the early succession in both basins indicates that the terrigenous deposition occurred on a surface above the Middle Eocene sea-level. Since this level was >200m above PSL (Fig. 4-1), it follows that the sedimentary surface in these basins was at least topographically higher than this level. The Mount Lofty Ranges, as an interbasin source region supplying terrigenous sediments to these basins, must have stood above the sedimentary surface and thus were ~250-300m above PSL.

There is a large pre-Middle Eocene stratigraphic interregnum in evolutionary and biogeographic records not only in the study region but also in the larger Indo-Pacific region including southern and continental Australia (McGowran, 1990; McGowran et al., 1997). Middle Eocene neotectonic plate reorganisation (Ch. 5) was associated with Australia/Antarctic spreading acceleration that significantly changed the tectonic regimes of the exterior and interior parts of southern Australia. This plate reorganisation corresponds to Chron C20-19 (43-41Ma) and is known as the Khirthar restoration, accompanied by strong clustering of tectonic, transgressional and biospheric events (McGowran et al., 1997).

The major stratigraphic event after the pre-Middle Eocene interregnum is the Wilson Bluff marine transgression that simultaneously occurred in three southern Australian basins, namely Eucla, Bight and Otway (McGowran et al., 1997). However, the study region including the St. Vincent and Western Murray Basins and obviously the Mount Lofty Ranges escaped the influence of this transgression apparently because it remained topographically above sea-level

at that time. Meanwhile, there are significant terrigenous lithostratigraphic records in these basins showing that subsidence and initial segmentation of the pre-Tertiary Palaeoplain had occurred during the Johannian Stage. It is important to note that this stage marks the beginning of a new structural development of the St. Vincent and Murray Basins as neotectonic entities. The Mount Lofty Ranges were thus formed as an interbasin region that substantially inherited the landscape of the pre-Middle Eocene Palaeoplain such as gently undulating morphology and position above sea-level.

4.3.1 Johannian Stage in the St. Vincent Basin

This stage comprises the North Maslin Sand, Clinton Formation and South Maslin Sand that accumulated in the St. Vincent Basin.

North Maslin Sand

The North Maslin Sand is a fluviolacustrine basal unit of the Tertiary sequence representing the birth of St. Vincent Basin. These sediments are often preserved in numerous small and shallow depressions, and unconformable overly the highly weathered pre-Tertiary basement. Small sinuous streams left shallow channels in the basement and are also encountered in the lower part of the Tertiary sequence in the Willunga, Noarlunga, Golden Grove Embayments and Adelaide Plains sub-basin (Stuart, 1969; Lindsay, 1981; Rowett, 1997). The W-SW direction of these palaeostreams indicates that the Mount Lofty Ranges were the main source of the North Maslin Sand deposits in the St. Vincent Basin.

Sediments of the North Maslin Sand include rare pebbles (northern margin of Willunga Embayment) and common medium to coarse quartz sands that formed mainly channel-lag deposits in the Noarlunga and Golden Grove Embayments and in the Adelaide Plains sub-basin. These sediments record relatively broad, braided drainage systems that are attributed to relatively active sedimentary environments. However clayey and silt lenses also occur in the North Maslin Sand succession that indicate the presence of small shallow lakes with restricted sediment input. Thus both relatively active and passive sedimentary environments existed in the eastern part of the St. Vincent Basin during the Middle Eocene.

The significant quartz component of the North Maslin Sand points to a substantial amount of deeply weathered rocks that were available in the source area. Polymictic components of this unit and particularly the abundance of rounded shape grains and polished pebbles may suggest

the existence of large, long and high-energy rivers capable of delivering such material. However, earlier palaeodrainage reconstructions (Sprigg, 1945; Rowett, 1997) indicate that there were no such high-energy or long rivers in this region. Our targeted regional geomorphological and lithostratigraphic analysis also shows that the Mount Lofty Ranges were the only sedimentary source since the Middle Eocene. Quartz sand with cross-bedding, poor sorting and various grain shapes, intercalated with silt and clays of the North Maslin Sand are a clear demonstration that these sediments were formed by short and temporary streams in the floodplain type environment near their source areas.

Unconsolidated Permian fluvioglacial polymictic deposits are still preserved in places in the southern part of the Mount Lofty Ranges and Fleurieu Peninsula even after prolonged periods of erosion. According to seismic interpretations, variable fluvioglacial deposits also exist beneath the Tertiary sediments in the Murray and St. Vincent Basins (J. Bull, 1998, pers. comm.). These widespread unconsolidated Permian deposits were therefore the significant source of the North Maslin Sand and particularly its rounded and polished pebbles.

The North Maslin Sand was deposited in a fluviolacustrine environment (Lindsay & Alley, 1995) that accounts for the terrigenous nature of these sediments. Dyson (1998) has proposed a deltaic environment of deposition in the coastal zone of the Willunga Embayment in the mixed tide-wave and flood-tidal zone. However there is clear evidence that marine transgression occurred only after deposition of the North Maslin Sand. An alternation of active and passive environments is typical for early stages of river development in continental interiors with low relief that correspond to the pre-Middle Eocene Palaeoplain. Therefore a fluviolacustrine model in a broader regional setting suitably describes the Middle Eocene depositional environment.

Stuart (1969) pointed out that streams have continually reworked the North Maslin Sands deposited previously (within the unit) by lateral migration and down-cutting followed by vertical filling. The meandering character of streams and lateral redistribution of sediments is evidence of low gradients of stream channels that are typical for floodplain environments that existed in the Middle Eocene in the St. Vincent Basin.

Despite a large amount of available weathered bedrock together with Permian soft fluvioglacial deposits within the source area, only tens of metres of North Maslin Sand (up to

70m) actually accumulated in the eastern deepest part of the St. Vincent Basin. This indicates that available accommodation space rather than volume of available material is more likely to have controlled sediment accumulation. Therefore basin subsidence was a major cause of sedimentary accommodation space creating differentiation of gravitational potential energy along the basin margin and thus initiating stream erosion and sedimentary supply of the North Maslin Sand.

In spite of the relatively wide distribution of the North Maslin Sand, these sediments are localised in separate Embayments such as the Willunga, Noarlunga, Golden Grove Embayments and the Adelaide Plains sub-basin. Each of these embayments is SE fault-bounded. The maximum thickness and distribution of this unit is commonly alongside these bounding faults as in the Golden Grove Embayments next to the Eden-Burnside Fault, and in the Willunga Embayment next to the Willunga Fault. These indicate that while general basin subsidence may correspond to deeper and wider crustal processes, shallow down-to-basin fault movements are apparently associated with upper crustal segmentation.

As there is no slope debris in the North Maslin Sand even adjacent to the bounding faults, it seems that there were no abrupt slopes or fault-scarps. This together with a slight deposit thickening toward the faults indicates low amplitude block movements along normal faults rather than thrusts or reverse faults that would more likely create long lasting and abrupt fault scarps. It is important to remember that there is no alternative to down-to-basin tectonic movements which were required in order to create sedimentary accommodation space in the high-standing pre-Middle Eocene Palaeoplain. Earlier suggestions that the Mount Lofty Ranges were formed as a result of uplift would be highly unrealistic as these did not include the initial high-standing position of the Palaeoplain and because uplift would not contribute to the formation of sizeable sedimentary accommodation space.

The W-SW direction of main channel lags filled by the North Maslin Sand in the St. Vincent Basin floodplain environment (Rowett, 1997) strongly suggests that a gentle west facing slope was probably established in the Mount Lofty Ranges during the Johannian Stage. Thus a gentle W-SW tilting in the Ranges would be consistent with the direction of initial drainage direction and observed lithology of channel lags.

Clinton Formation

The Clinton Formation is mainly associated with lignite and coal development in the St. Vincent Basin during the Middle Eocene-Early Oligocene (Harris, 1970). Widespread lenticular very fine sands, clays, lignites and coals of this Formation are indicators of shallow lake and swamp depositional environments. Oxygen-isotope palaeotemperatures suggest that a warm and subtropical climate prevailed during the deposition of the Clinton Formation (Lindsay, 1981). A warm and wet climate is also favourable for kaolinitic clay genesis. However clay origin demands a long period of chemical weathering in combination with a low erosion rate in the source areas. The abundance of kaolinitic clays and laterite fragments in the Early Tertiary sequence is an indicator of deeply weathered source rocks in the western portion of the Mount Lofty Ranges.

Diessel (1980) pointed out that coal can only accumulate when the depth of fresh water is within a range of no more than a few meters. Greater depths tend to drown the vegetation whilst shallow depths lead to oxidation and hence destruction of the peat. Thus swamps and peat require a limited and shallow accommodation space, with a relatively restricted influx of terrigenous sediments. This very sensitive depositional environment apparently prevailed at the time of the Clinton sediment formation in the eastern part of the St. Vincent Basin.

In comparison with the North Maslin Sand, the formation of Clinton sediments occurred in a lower energy and more tectonically sensitive environment. Clinton sediments normally rest on the deeply weathered pre-Tertiary basement that clearly indicates that sedimentary accommodation space was formed by gentle subsidence. However tens of metres of sediments were actually accumulated suggesting that sedimentation occurred contemporaneously with subsidence and approximately at the same rate. Some swamps occupied saucer-shaped depressions along the fault lines (Lindsay, 1981) indicating that low amplitude down-to-basin block movements also occurred along the normal faults.

All the above strongly suggest that the Mount Lofty Ranges and its western portion in particular were not uplifted during the formation of clayey and coal deposits. Any uplift would increase stream competence (erosion and sedimentary supply) that would have been disastrous for tectonically sensitive environments of swamps and shallow lakes. Therefore, slow basin subsidence and normal fault movements accompanied by gentle westward tilting

of the source area would be the most probable tectonic scenario for the formation of the Clinton sedimentary environment. These tectonic movements affected a gently undulating landscape of the pre-Middle Eocene Palaeoplain and would satisfy all the requirements of coal, lignite and clay sedimentation such as: availability of deep regolith and long lasting chemical weathering, limited access of competent streams and subtle formation of the accommodation space.

South Maslin Sand

The accumulation of the late Middle to early Late Eocene South Maslin Sand is critically associated with the first marine influence on the regional sedimentary environment. These deposits are typical marginal-marine in nature with an abundance of micro- and macrofossils in the upper part of the sequence. The quartzose, glauconitic and pyritic sand lithology is evidence of near-shore depositional environment with restricted open-marine access (Lindsay, 1981).

This is the first time since the Early Permian, and after >200Ma that a marine passage was created into the area. Since there was a general downward trend of global sea-level with a significant drop of about 100m near the Middle and Late Eocene (Fig. 4-1), the single obvious cause for such a marine transgression was subsidence of the St. Vincent Basin accompanied by tilting of the southern Australian continental shelf. This is the simplest and most plausible explanation for the marine transgression into the continental interior basins at a time of global sea-level fall.

The South Maslin Sand forms thin sheet deposits (max. 6m) in the Adelaide area and Noarlunga Embayment that increases southward to over 30 m of an estuarine complex in the Willunga Embayment (Stuart, 1969; Dyson, 1998). Coarse sediments at the base of the South Maslin Sand may indicate that a new and probably major pulse of basin subsidence occurred that lowered the erosional base level and reinforced stream erosion and sedimentary supply. The angularity of grains indicates that sedimentation occurred close to the source area. The occurrence of glauconite and sponge spicules within the Willunga Embayment confirms that the base of this unit represents an extensive marine flooding surface (Fairburn, 1998).

However the basal South Maslin Sand also contains rounded and polished pebbles that apparently have been reworked from Permian fluvioglacial sediments that were widely

distributed in a nearby source. Reworked Permian spores occurring in some samples of the South Maslin Sand (Lindsay, 1981) support such a suggestion. An abundance of limonitic and dark brown carbonate mud with moderately glauconitic and pyritic components in the upper part of the South Maslin Sand are evidence that a large amount of weathered material remained available in the source region in the Late Eocene. Moreover, the absence of fresh fragments of metamorphic Precambrian basement rocks in the South Maslin Sand indicates that deep stream incision had not yet occurred in the western portion of the Mount Lofty Ranges.

There is a rapid lithological change upward in the South Maslin Sand sequence from the basal coarse sands to fine and very fine-grained silty and muddy sands. This is evidence of a relatively rapid decrease of stream competence. If the western Mount Lofty Ranges were uplifted, as some have suggested (eg. Benbow et al, 1995) it would have increased stream competence and immediately evoked deep stream incisions. It would also require a significant time for erosion to reduce stream competence in the source area. This contradicts the observed facts of the available deep regolith in the source area and fine-grained lithology associated with rapid lost of stream competence.

Thus, the initial increase of stream competence at the base of the South Maslin Sand was most likely due to a new pulse of basin subsidence but the reduction of such competence was apparently a response to sedimentary infill of the available accommodation space. This would be consistent with general basin subsidence as a major and essential factor for the marine transgression and creation of the sedimentary accommodation space during a general trend of sea-level fall (Fig. 4-2).

Distribution of the South Maslin Sand shows abrupt limits on the SE side of the St. Vincent Basin embayments associated with the Willunga, Clarendon, Eden-Burnside and Para Faults. This indicates that down-to-basin block movements along these faults continually provided control over sedimentation. However, no debris or slope deposits near the faults were observed or recorded. There are slight increases in thicknesses of sediments toward these faults. Therefore down-to-basin block movements apparently were accompanied by a low-angle tilting of hanging-wall blocks that created additional sedimentary accommodation space near the faults such as Willunga Fault (Cross-section in Fig. 4-3).

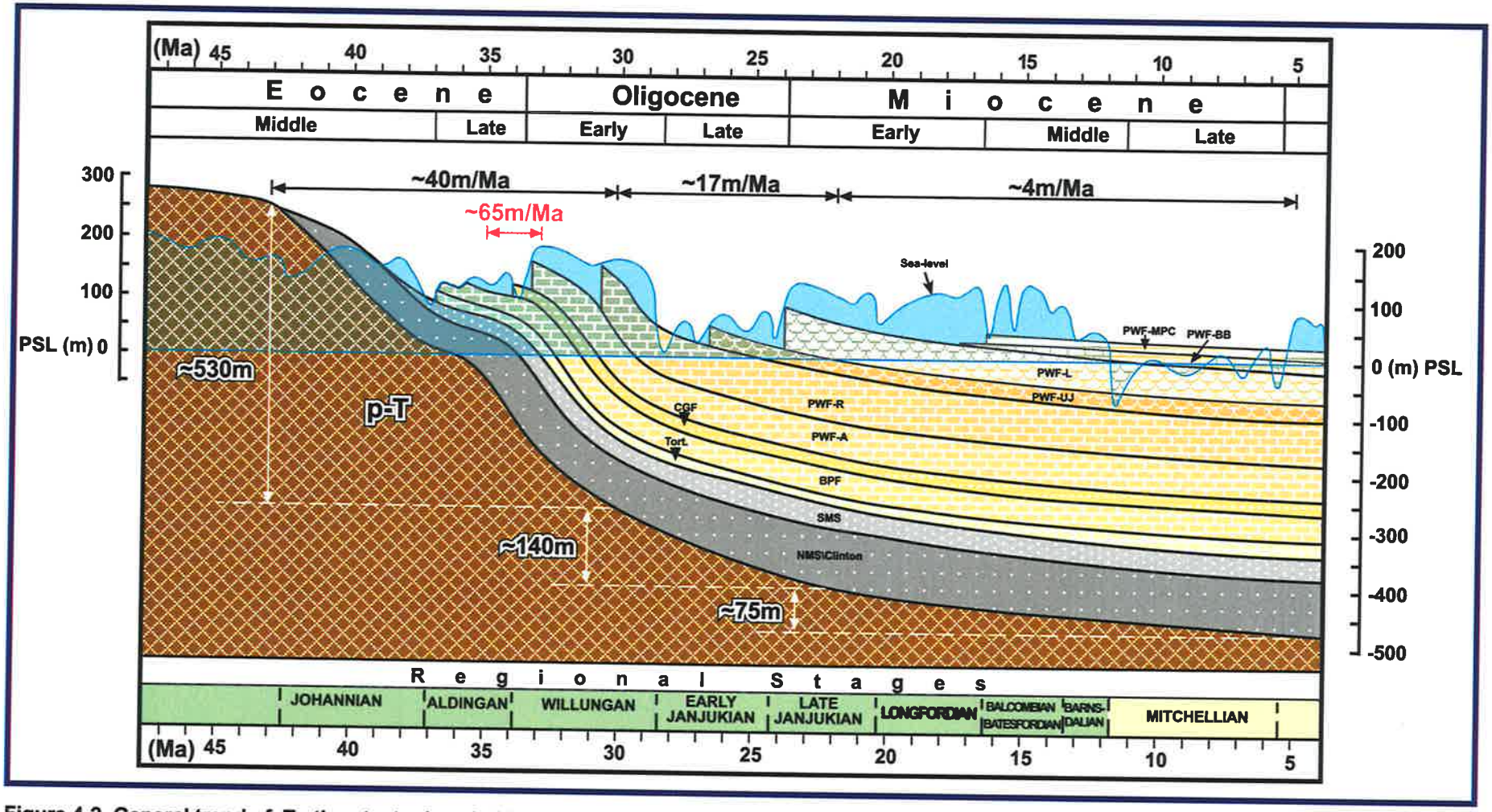
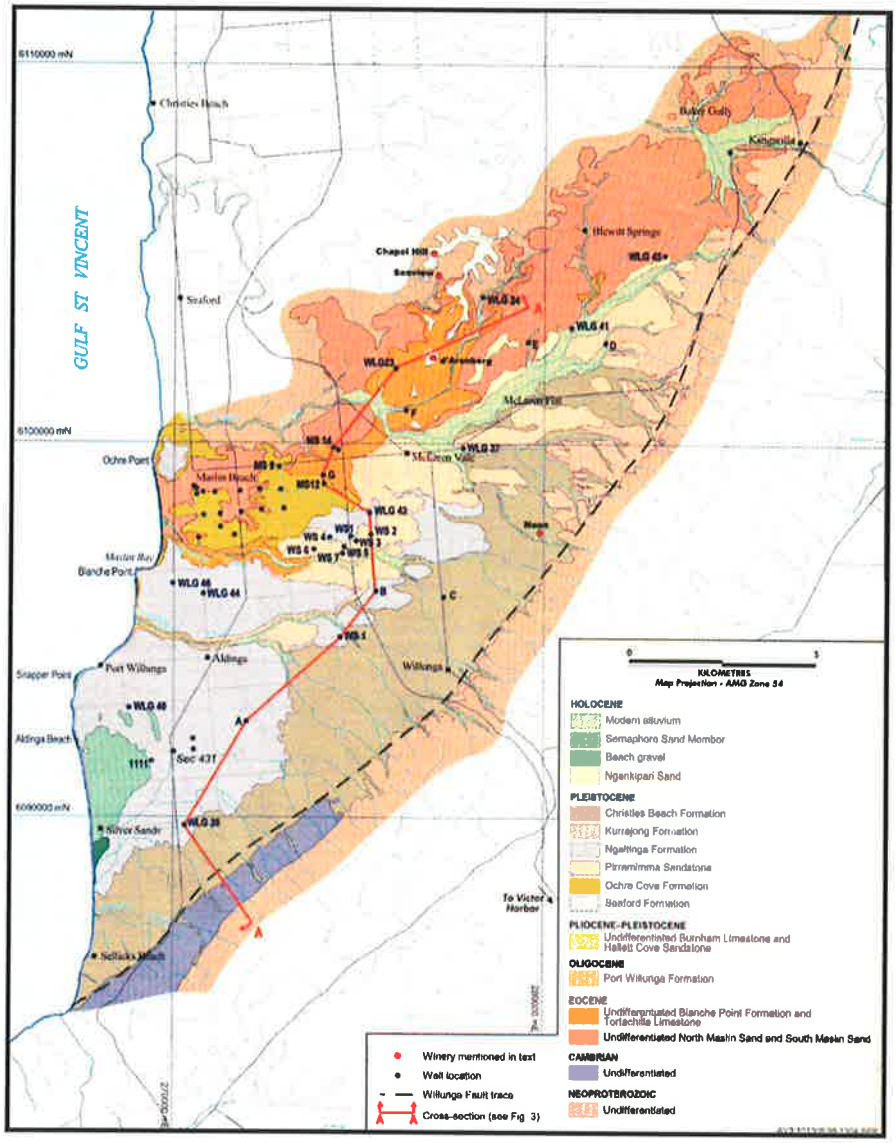


Figure 4-2 General trend of Tertiary tectonic subsidence in the St. Vincent Basin integrated with lithostratigraphic units and Eustatic sea-level. PSL- Present Sea Level; PW-MPC, PW-BB, PWF-L, PWF-UJ, PWF-R and PWF-A are: Munno-Para Clay, Batesfordian-Balcombian, Longfordian and Upper Janjukian Units and Ruwarung and Aldinga Members of the Port Willunga Formation correspondingly; CGF - Chinaman Gully Formation; BPF - Blanche Point Formation; Tort.-Tortachilla Limestone; SMS - South Maslin Sand; NMS - North Maslin Sand; p-T - pre-Tertiary basement. Thicknesses are approximate (after Lindsay, 1981). ~40m/Ma = gradient of subsidence (metres per million years). Global Eustatic curve (after Haq et al., 1987, recalculated by Li et al., 2004). Regional Stages (modified after McGowran et al., 1997). Stages in colour according to neotectonic regime: green - extensional, yellow - transitional.



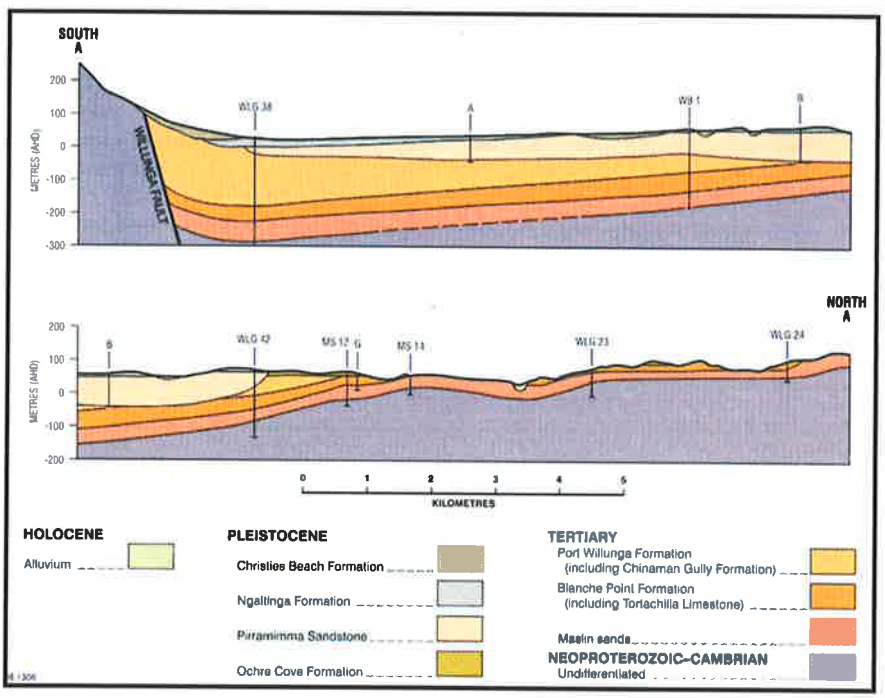


Figure 4-3 Geological setting and cross-section of the Willunga Embayment (after Fairburn, 1998) show increased thickness of Tertiary sediments toward the normal Willunga Fault.

Transitional and conformable contacts of the South Maslin Sand with fluviatile North Maslin Sand in the Willunga Embayment indicate that subsidence continually occurred after the first accommodation space was created. However in several cases the South Maslin Sand directly overlies the pre-Tertiary basement as in the Adelaide area (Miles, 1952) and near Moana Township in the Noarlunga Embayment (Stuart, 1969). This indicates that accommodation space was progressively created in these originally erosional areas that were apparently involved in the process of subsidence or associated with W-SW tilting of the source areas.

In spite of a general absence of angular unconformities between the early Tertiary units in the St. Vincent Basin, Glaessner (1953) stated that the contact between the South and North Maslin Sand in the Noarlunga Embayment is an angular unconformity of a few degrees. In Albert's sand quarry near Noarlunga, the South Maslin Sand overlaps the North Maslin Sand from the SW (Stuart, 1969). This overlap has occurred from the marine side, while the North Maslin Sand is slightly inclined NE toward the main source area. This suggests that a low-angle tilt of hanging-wall block along the Clarendon Fault would result in such an ungular unconformity. These features are consistent with and thus support a normal fault mechanism for the formation of sedimentary accommodation space near the active fault.

All the above data and interpretations indicate that:

1. Basin subsidence was the major cause of the formation of sedimentary accommodation space in the St. Vincent Basin that allowed marine transgression into this continental interior. Some source areas in the western Mount Lofty Ranges were also involved in the subsidence or at least were tilted down toward the basin.
2. Continuing basin segmentation into embayments was due to down-to-basin block movements accompanied by a low-angle tilt of the hanging-wall blocks toward the bounding normal faults.
3. There is no indication of any uplift of the Mount Lofty Ranges but gentle W-SW tilting caused the formation of the western slope of the Ranges following drainage initiation.

4.3.2 Johannian Stage in the Western Murray Basin

Earlier palaeoreconstructions suggested an uplift of the ancestral Mount Lofty Ranges that blocked the western course of the Murray River some time in the Late Palaeocene (Twidale et al., 1978; Veevers, 1984; Benbow et al., 1995). However there is no evidence for such

Palaeocene uplift in the flanking Western Murray Basin. The Warina Sand is the only Late Palaeocene basal unit of Tertiary sequence that has a limited distribution associated with the Renmark Trough (Brown & Stephenson, 1991). This Trough is ~150km from the eastern edge of the Mount Lofty Ranges. The Warina Sand was not encountered by any of hundreds of boreholes between the Ranges and the Renmark Trough (Goode & Williams, 1980; Brown & Stephenson, 1991). Thus the Ranges did not have any relation to the Warina Sand or the Renmark Trough. In contrast to earlier palaeoreconstructions, this study indicates that neither the Mount Lofty Ranges nor the Western Murray Basin existed as geological/tectonic entities until the Middle Eocene.

Tertiary sediments rest on a gently undulating and deep weathering basement of the Western Murray Basin (Brown & Stephenson, 1991). This together with a lack of any lithostratigraphic record beneath the Middle Eocene are evidence that this basin, along with the Mount Lofty Ranges and St. Vincent Basin, was a part of the extensive pre-Middle Eocene Palaeoplain standing about 250-300 above the present sea-level.

The Western Murray Basin is located along the eastern edge of the Mount Lofty Ranges and represents the only western portion of a very large (>30 000km^2) Murray Basin. However this area has specific neotectonic and lithostratigraphic characteristics which distinguish it from other parts of the basin. First at all, the Tertiary and Quaternary lithologies of the Western Murray Basin were closely linked with the development of the Mount Lofty Ranges. Although the Murray and Darling Rivers were major contributors of water and fine-grained sediments, streams and rivers of the eastern slope of the Ranges also provided significant sedimentary supply into this basin. All these streams, together with the marine incursions created a variable and complex sedimentary pattern in the basin during the Johannian Stage. The Olney Formation typifies Johannian sedimentary environment in this basin that spatially and genetically linked it with the eastern portion of the Mount Lofty Ranges.

Olney Formation

Fluviolacustrine deposits of the Lower Olney Formation formed an extensive blanket of laterally discontinuous beds of unconsolidated to poorly consolidated, dark brown, grey or black, carbonaceous silt, sand, clay and coal in the Western Murray Basin (Ludbrook, 1961; Lawrence, 1975; Brown, 1989). Lithologic characteristics of the Olney Formation, as

provided by Brown and Stepherson (1991) have included poorly sorted fine to medium quartz sand, polymictic sand and sandy dolomite that are commonly micaceous, pyritic, ferruginous and intercalated with lignitic brown coals and lignites.

The Olney Formation is widespread and rests on the topographically irregular and weathered pre-Middle Eocene basement (Brown & Stephenson, 1991; Rogers at al., 1995). The base of this Formation was deposited predominantly in fluviolacustrine environments, although micropalaeontological evidence indicates that paralic and minor marine to marginal-marine components are increasingly prevalent toward the top of the Formation (Brown, 1989). Because the age of this Formation varies from Middle Eocene to Middle Miocene, the first marine influence occurred perhaps in the Late Eocene. Deposition of the Olney Formation in the SW part of the basin was restricted to the Middle Eocene-Early Oligocene, where it is replaced up-sequence by marine sediments of the Murray Group (Brown, 1989).

Stephenson & Brown (1989) have shown that along the SW margin of the basin (eastern slope of the Mount Lofty Ranges) several small coalfields occur within the Olney Formation. They note that these small coal basins represent back swamp deposits between an ancient Murray River and the basin edge. Back swamp deposits are characterised by an abundance of carbonised and pyritic plant remnants, including fossil logs, woody peat, and leaf litter debris intercalated with lignites and coal in this area. The total thickness of the Olney Formation is below 100m with local variations in the Western Murray Basin. In fact, only a few tens of metres relate to the Johannian Stage.

Sedimentary environments of the Olney Formation are similar to those that occur in the St. Vincent Basin in the Middle and Late Eocene. Taking into account that the Western Murray Basin was an integral part of the pre-Middle Eocene Palaeoplain, it follows that subsidence along the eastern portion of the Mount Lofty Ranges was required in order to form the sedimentary accommodation space. Swamp deposits indicate that the rate of subsidence was low to very low and apparently contemporaneous to sediment accumulation. It must be repeated here that coal could only accumulate when the depth of fresh water is within a range of no more than a few metres. Greater depth tends to drown the vegetation whilst shallow depth leads to oxidisation and hence to destruction of peat (Diessel, 1980). Therefore, a high rate of subsidence or uplift near such swamps would be disastrous to the optimal depth of swamps and would interrupt coal formation.

The fact that fluviolacustrine coal and lignite deposits were attached to the western margin of this basin indicates that the initial subsidence providing sedimentary accommodation space occurred along the eastern edge of the Mount Lofty Ranges. The generally fine-grain lithology of the Olney Formation is consistent with a low-gradient of insipient streams which drained the embryonic eastern slope of the Ranges. The absence of steep slope debris and restricted sedimentary supply suggest that the topographically low and gently undulating landscape inherited from the Palaeoplain persisted in the eastern Ranges. In combination these facts indicate that the eastern Mount Lofty Ranges were not likely to have been uplifted as they did not provide competent streams with corresponding sedimentary supply. Thus subsidence was the major cause of the Western Murray Basin formation though it was probably at a low rate. The Olney Formation thus is a result of the first differentiation between the sedimentary accommodation space and source area during the Johannian Stage.

4.3.3 Johannian Stage: Conclusion

Unlike most earlier studies that proposed tectonic uplift as a major cause of the Mount Lofty Ranges, the data and interpretation above lead to the conclusion that the subsidence of the St. Vincent and Western Murray Basins was the initial and major cause of the tectonic differentiation between the sedimentary accommodation space and source region of the Mount Lofty Ranges. The following important points relate to the development of the Mount Lofty Ranges and flanking basins during the Johannian Stage:

- The Mount Lofty Ranges, the St. Vincent and Western Murray Basins did not exist as tectonic or geomorphic entities before the Middle Eocene. All of these regions belonged to the pre-Middle Eocene Palaeoplain standing ~250-300m above the present sea-level (PSL).
- Major tectonic and geomorphological changes occurred in the Middle Eocene due to regional segmentation of the high-standing Palaeoplain into the sedimentary St. Vincent and Western Murray Basins.
- The Mount Lofty Ranges were formed as remnants of this Palaeoplain between the sinking Western Murray and St. Vincent Basins and therefore inherited Palaeoplain altitude and a deeply weathered and gently undulating landscape.
- There is no evidence of uplift of the Mount Lofty Ranges before and during the Johannian Stage. Even if uplift had occurred, it would have been very insignificant in comparison to the effects of basin subsidence. Gentle W-SW tilting was the most probable process of

deformation within the Ranges.

- The total basin subsidence during the Johannian Stage in the St. Vincent Basin can be roughly estimated as about 300m (Fig. 4-2). This conclusion is based on considerations of the initial height of the Palaeoplain, sea-level fall and shallow water depth of this basin, and combined thickness of sediments. Although the subsidence of the St. Vincent and Western Murray Basins occurred simultaneously, the extent of downward movements was slightly less in the Western Murray Basin.

4.4 Aldingan (~37Ma) through to Balcombian Stages (~14Ma)

There are several stages in the regional biostratigraphic framework between the Late Eocene and Middle Miocene that are associated with various foraminiferal and other fossil assemblages (McGowran et al., 1997). In spite of some lithological variations, all sedimentary formations accumulated during these stages in the St. Vincent and Western Murray Basins can be assembled into one carbonate-dominated package.

Well-recorded lithostratigraphic units (Abele et al., 1976; Brown & Stephenson, 1991; Frakes et al., 1987; Lindsay, 1967, 1969, 1981, 1985; Ludbrook, 1971, 1973; Ludbrook & Lindsay, 1969; McGowran, 1978, 1989; 1991a,b; McGowran et al., 1997; McGowran et al., 2004, and many others) provide clear evidence that a marine environment remained dominant in these basins for >20Ma. Although, it was the longest period in Tertiary history associated with carbonate sedimentation, there were significant changes of climate and sea-level. Therefore a study of these changes has been undertaken and sea-levels were projected into the palaeolandscape where it was appropriate, for example in the intramontane Hindmarsh Tiers and Meadows-Myponga Basins containing marine sediments. Such sea-level simulation together with structural analysis provides crucial evidence of neotectonic movements in the Mount Lofty Ranges and establishes the type and magnitude of those movements.

4.5 Aldingan Stage (~37-34Ma)

The Aldingan Stage occupied a time-interval from the Late Eocene to the earliest Oligocene (Fig. 4-1). This stage is clearly associated with a relatively low stand of global sea-level at ~130-150m above PSL in comparison to the previous Johannian and following Willungan Stages (both >180m above PSL). The Aldingan Stage was associated with a long-term transgressive period in a relatively warm climate (Lindsay, 1976; McGowran, 1989). The

Tortachilla transgression was one of the most influential marine impacts on the southern Australian continental margin (McGowran, 1989) while it probably correlated with only a small sea-level rise (~40-50m) at the beginning of this stage (Fig. 4-1). The comparison of the Johannian and Aldingan sea-levels clearly indicates that substantial subsidence or southward tilting must has affected the large southern Australian continental margin. The regional subsidence of the St. Vincent and Murray Basins was apparently an integral part of the Early Tertiary process of tilting/subsidence that affected large portions of this continental margin. The marine entry into these interior basins during the relatively low sea-level period would be difficult to explain without such tectonic effect.

Despite the significant warm-water influence on the sedimentary environments in South Australia the climate was not tropical (McGowran & Lindsay, 1969; Benbow et al., 1995). Harris (1980) suggests that latest Eocene deposition in the St. Vincent Basin was perhaps associated with warm climate, high annual precipitation and rainforest vegetation. Towards the later Eocene there was also the cooling trend of Southern Ocean water, with several short-lived episodes of warming, reflected in the oxygen isotope records (Mathews & Poore, 1980; Shackleton & Kennet, 1975; Shackleton, 1984, 1986). Short-lived warming episodes are correlated with several of the Late Eocene transgressions (McGowran, 1989; McGowran et al., 1992). Carbonate-dominated sediments accumulated during the Aldingan Stage indicate that marine incursions occurred into low-relief marginal areas in the southern Australian continental shelf (Deighton et al., 1976). Similar sedimentation in the interior basins likewise suggests a low and gentle landscape surrounding the St. Vincent and Western Murray Basins and thus extending to the Mount Lofty Ranges.

4.5.1 Aldingan Stage in the St. Vincent Basin

In the St Vincent Basin this stage was associated with accumulation of carbonate-rich facies of the Tortachilla Limestone, Blanche Point and Chinaman Gully Formation.

Tortachilla Limestone

As a basal lithostratigraphic unit of the Upper Eocene-Miocene carbonate package the Tortachilla Limestone is composed mainly of bioclastic material. The Tortachilla marine inundation extended deep into the continental interior and produced significant sedimentary changes from terrigenous (North Maslin Sand and Clinton Formation) and marginal-marine

(South Maslin Sands) into typical carbonate marine environments of the St. Vincent Basin.

Comparison of the lithology of lower and upper parts of the Tortachilla sequence shows that terrigenous input such as quartz and goethite-limonite in the sediments decreases upwards from 20-40% to 5-10%. In contrast, calcite fossil fragments and calcite matrix increase to 95% (Lindsay, 1981). This indicates that the already restricted access of fluvial systems into the Tortachilla depocentres were further minimised in the Late Eocene and implies a further reduction of stream competence in the western Mount Lofty Ranges.

The Tortachilla Limestone occurs in the Willunga, Noarlunga Embayments and Adelaide Plains sub-basin where it is normally located at the base of an undifferentiated Tortachilla/Blanche Point unit. There is variation in thickness of the Tortachilla Limestone from a max. 27.4m in the Adelaide Plains area west of Para Fault, to 4m in the Noarlunga and 0.2-6m in the Willunga Embayments. This indicates that local tectonic movements influenced the sedimentary accommodation space, resulting in continuing basin segmentation into embayments.

In the Willunga Embayment this unit occurs as far north as McLaren Vale, 1.5km SW of Blewitt Spring (Fig. 4-3). Marine inundation is also seen as far east as the southern end of the Happy Valley Reservoir in the Noarlunga Embayment (Fig. 4-4). There is some evidence that the Onkaparinga River during the Early Tertiary was possibly located on the NE margin of the Willunga Embayment south of its modern course (Bourman, 1989). Therefore the relatively large Onkaparinga River could supply terrigenous sediments into the Willunga Embayment during the Late Eocene. However, in spite of a relatively wet climate and large amounts of regolith available in the source area, this longest channel with one of the largest water catchments in the Mount Lofty Ranges supplied only a minimum amount of terrigenous material into the Willunga Embayment during the Tortachilla Limestone accumulation. This points to a very low gradient of the Onkaparinga channel that allowed the rising sea-level (~40m) to flood the lower part of the river and therefore a fluvial sedimentary discharge occurred only somewhere up-steam, far from the present coastal location of this embayment.

Both the very low terrigenous supply and marine inundation into the western portions of the Mount Lofty Ranges clearly indicate that a gently undulating landscape stood near sea-level. It seems that gentle W-SW tilting controlled the insipient drainage pattern in this area.

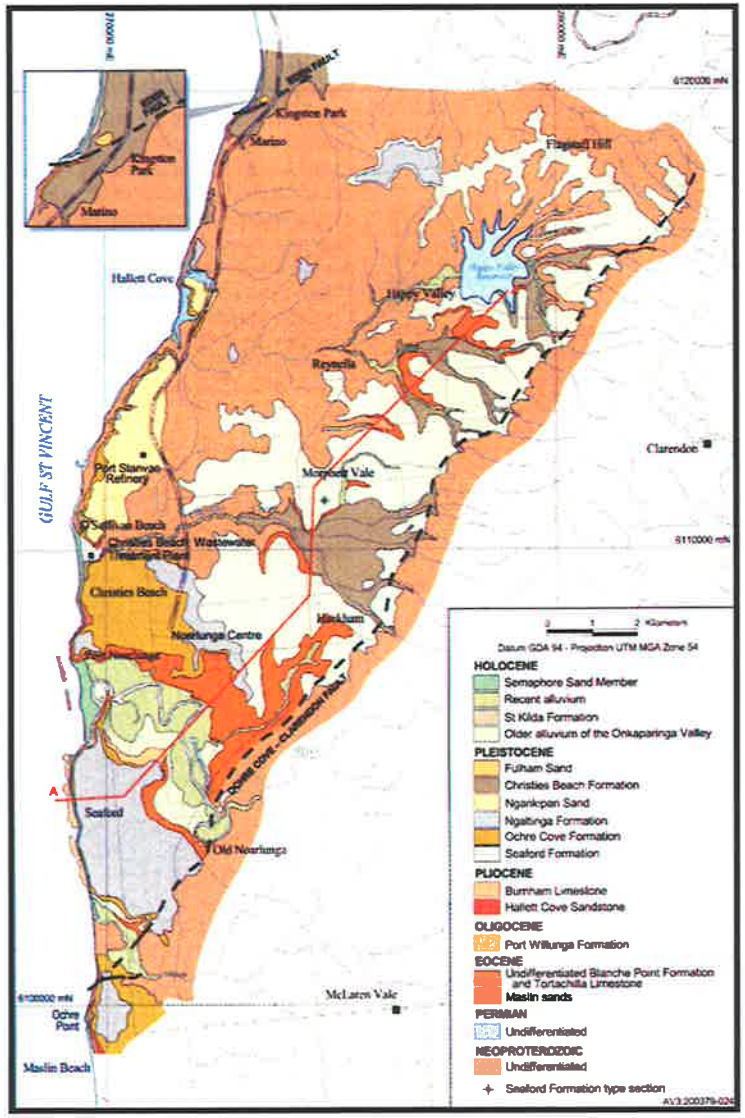


Figure 4-4 A Geological Setting of the Noarlunga Embayment (after Fairburn, 2000)

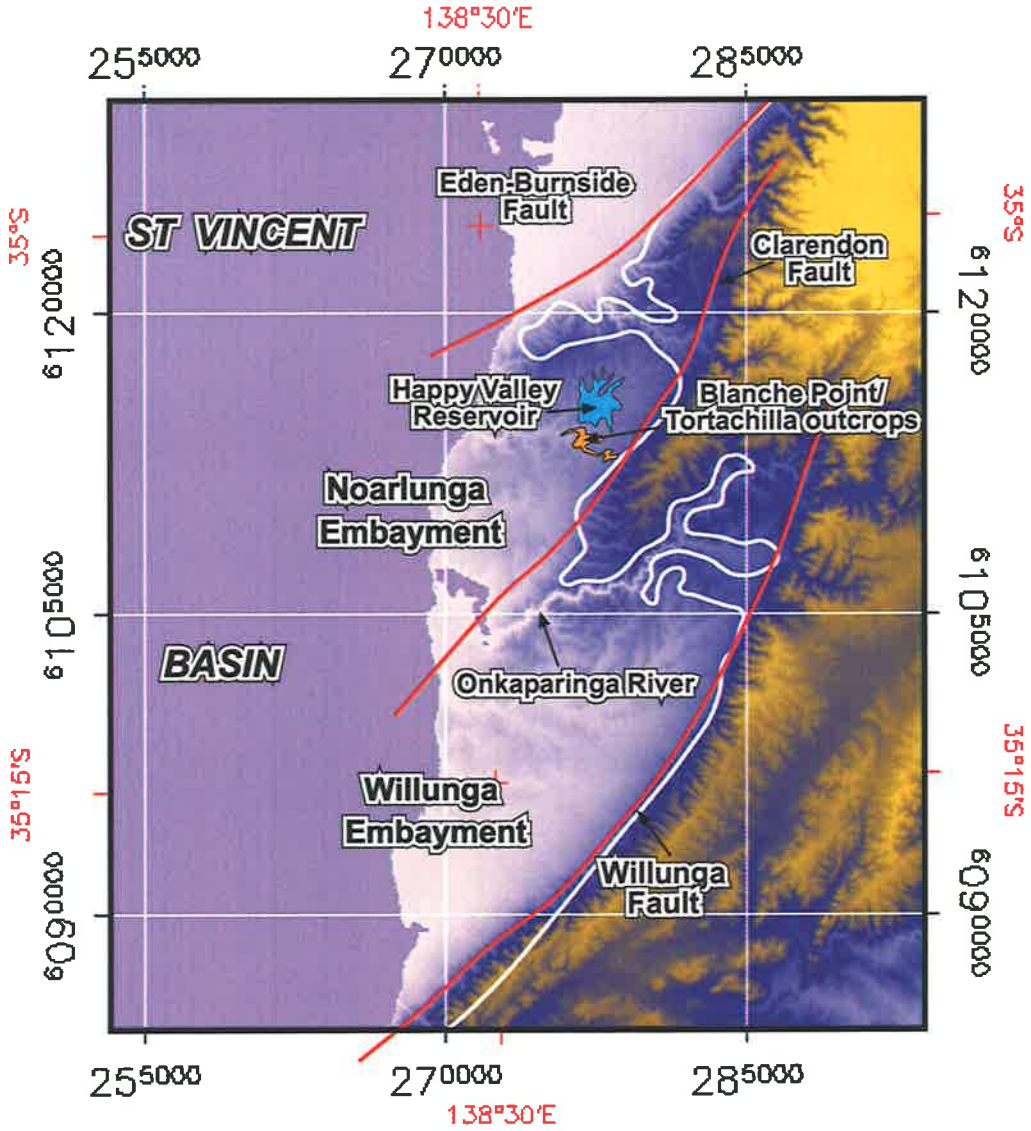


Figure 4-4 B Projected shoreline (white solid line) onto the present landscape of the Noarlunga and Willunga Embayments associated with sea-level above Late Eocene Tortachilla Limestone outcrop (~180m above PSL).

Thickness differences throughout the basin are associated with various amounts of down-to-basin block movements probably along the faults bounding the embayments.

Blanche Point Formation

Blanche Point Formation comprises the Tuketja, Gull Rock, Perkana and Tuit Members developed in the St. Vincent Basin (Fig. 4-5). Blanche Point deposition occurred in a low-energy marine environment in a shelf-like gulf, with restricted access to the open ocean (Lindsay, 1981). The lowest part of this Formation (Tuketja Member) consists of ~ 2m of glauconitic clay and fossiliferous calcareous mudstone and limestone that is associated with the Tuketja Transgression in warm conditions (McGowran, 1989, 1991). Clarke (1994) suggested that sea-level during the Tuketja Transgression was ~20m higher than it was during the Tortachilla Transgression and therefore marine inundation had to extend further into the southern Australian continental margin.

In the St. Vincent Basin the upper parts of the Blanche Point Formation consist of intercalated carbonate-rich and silica-rich sediments. The nature of the silica is still problematic, while volcanic ash was perhaps contributed from distant volcanic centres (Jones & Fitzgerald, 1986). However following Wopfner (1978) it would be reasonable to suggest that the deeply weathered and subdued relief of the Mount Lofty Ranges with sluggish and inadequate drainage surrounding Blanche Point depocentres may have supplied a significant amount of silica. Limited water circulation and anoxic bottom-water might also have increased the decay of organic matter and promoted precipitation of silica (Goldstein, 1959; Peterson & Von der Borch, 1965; Namy, 1974).

There is a clear contact of the Blanche Point sediments with the underlying Tortachilla Limestone and overlying Chinaman Gully Formation. Therefore the accumulation of the Blanche Point Formation occurred during most of the Late Eocene (Fig. 4-5). McKenzie (in Cooper, 1979b, p.92) points out that the Blanche Point Formation in the Willunga Embayment (southern part of the St. Vincent Basin) was deposited at depths of about 50 to 100m, on a muddy marine outer shelf with poor circulation in warm water temperature about 15°C. This assumption is based on ostracode assemblage characteristics and oxygen-isotope palaeotemperatures (eg. Gill, 1968). Depth of water is an important indicator of basin subsidence and was taken into account to calculate the amount of neotectonic movements

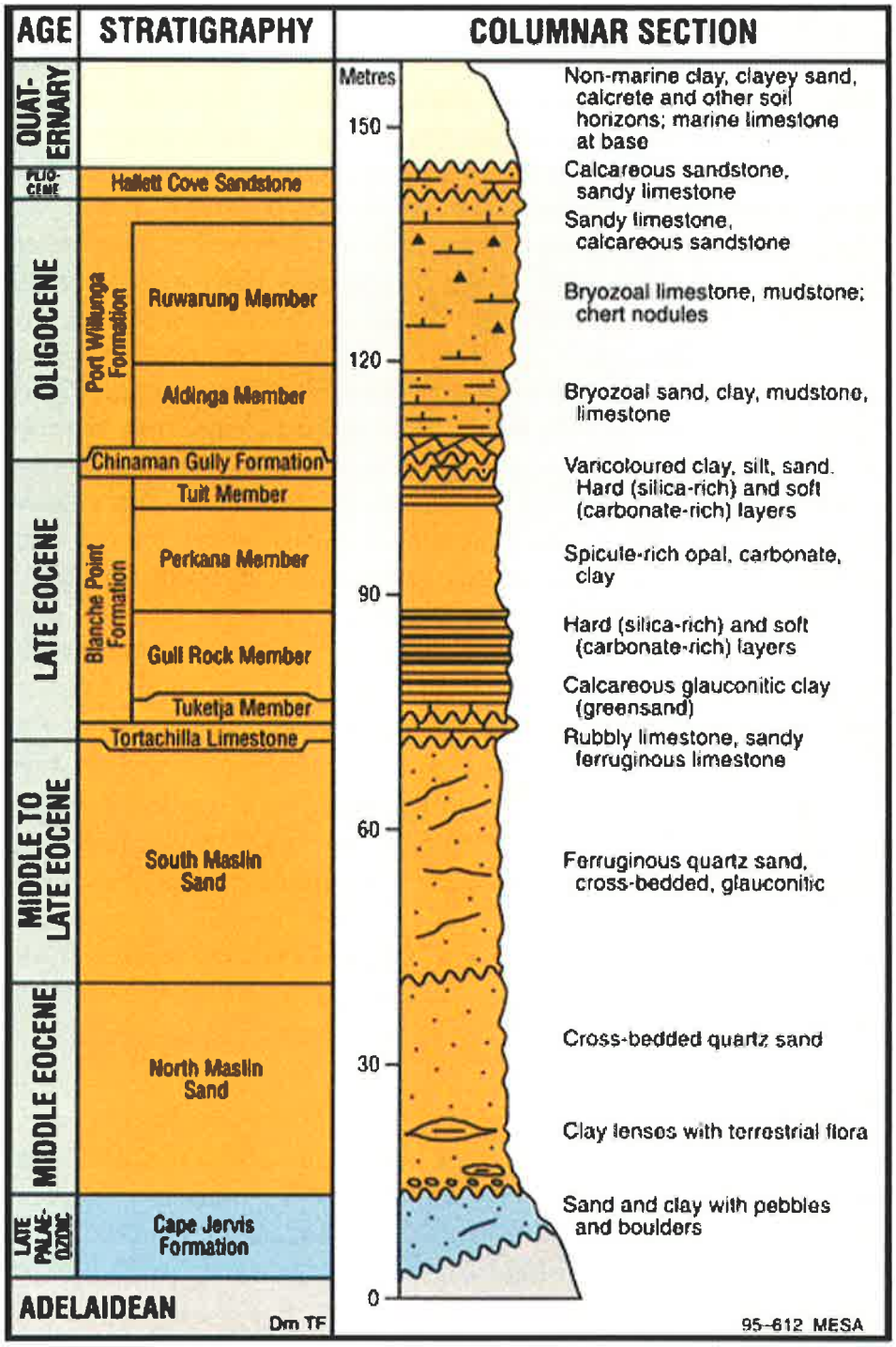


Figure 4-5 Composite columnar section of Tertiary units, Maslin-Aldinga area of the St. Vincent Basin (Lindsay & McGowran, 1986; after Lindsay & Alley, 1995)

providing sedimentary accommodation space (see Fig. 4-2), though it is likely that part of this water depth may be related to sea-level rise.

Sedimentation of the Gull Rock Member of the Blanche Point Formation is associated with intensive accumulation of spicular fossiliferous chert (cherty siltstone, marl and mudstone) and opaline silica matrix that occurred in relatively uninterrupted environments. There is a thickness variation of the Blanche Point Formation within the St. Vincent Basin and also locally within the embayments. There is up to 37m of sediments preserved within the Adelaide Plain sub-basin (Lindsay, 1981), up to 21m in the Noarlunga Embayment and up to 28m in the Willunga Embayment (Cooper, 1979).

The thickness generally increases towards the eastern and SE parts of the three embayments where more marginal sandy facies prevail (Lindsay, 1969, 1981). For example, Reynolds (1953) shows that the thickness of the Blanche Point Formation is only 11m at stratotype Blanche Point (NW part of Willunga Embayment), but increases SE, and near the Willunga Fault it reaches a maximum of 28m (WLG-38 bore record, Cooper, 1979, p.30; see Fig. 4-3 for locations).

The variation in thickness is evidence that there was continuing basin segmentation into the embayments. The thickness increase toward the faults is typical for the extensional terrains with well-developed normal faults (Mandl, 1988). When viewed in plan the arcuate shape of faults with inward curves facing the basin also points to a normal fault mechanism controlling sedimentary accommodation space. Absence of soft sediment deformation in the fault zones also strongly supports down-to-basin block movements along normal faults. A low-angle tilting of hanging-wall blocks (toward the bounding faults) seems to be sufficient to provide extra accommodation space near the faults (Fig. 4-6). These facts related to normal fault interpretations significantly contradict earlier interpretations of the Mount Lofty Ranges as a result of uplift along reactivated Delamerian thrust faults.

Chinaman Gully Formation

This formation occurs on the border of the latest Late Eocene and the earliest Oligocene (Lindsay & McGowran, 1986) and therefore occupies a short interval between the Aldingan and Willungan Stages. There is a sharp lithological change from the highly fossiliferous and silica-rich environment of the Blanche Point Formation to the fine- and coarse-grained sands,

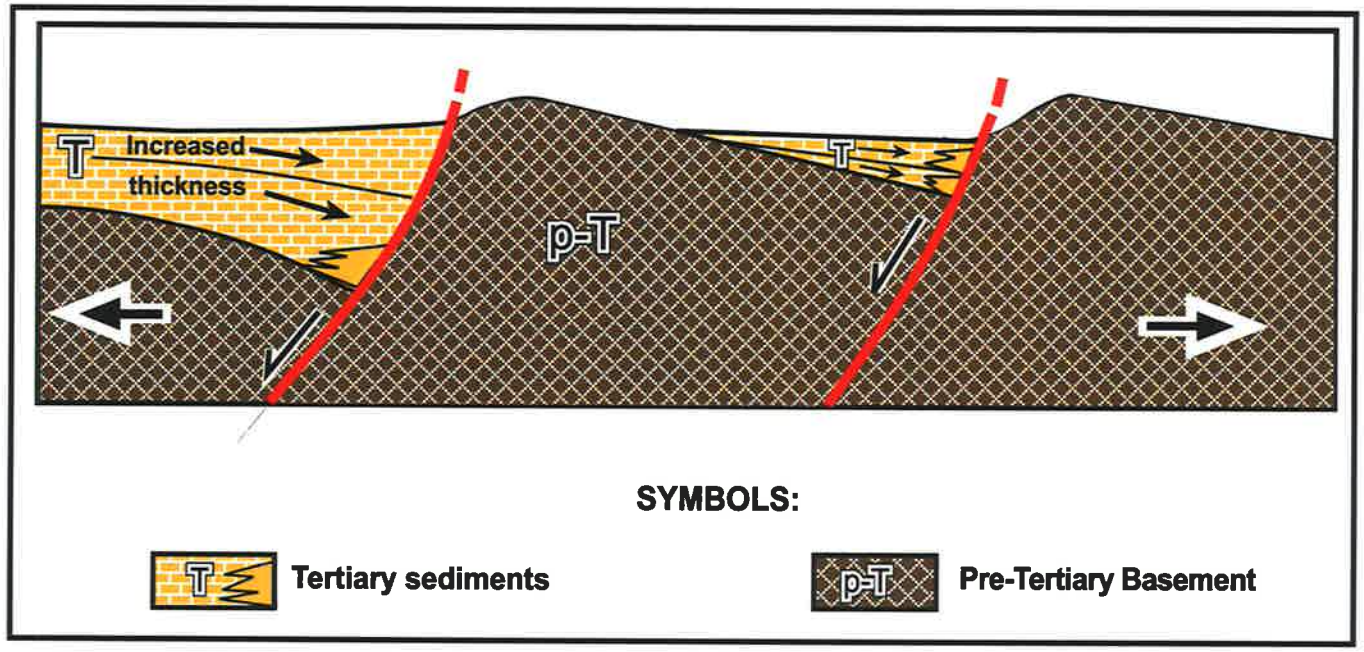


Figure 4-6 Principal neotectonic model of the western portion of the Mount Lofty Ranges and flanking embayments of the St. Vincent Basin. Model is associated with a Tertiary extensional tectonic regime. Increased thickness of Tertiary deposits toward the faults indicates normal fault kinematics with a low-angle faultward tilting of the hanging-wall blocks that creates additional accommodation space near the faults.

silt, carbonaceous clays and lignites of the Chinaman Gully Formation. This indicates a rapid change from the normal marine and marginal-marine to a very restricted marginal-marine and even fluviolacustrine and swamp sedimentary environment (Cooper, 1979). The lithological content of the Chinaman Gully Formation indicates a relatively high but generally fine-grained influx of terrigenous sediments into the St. Vincent Basin. However, ostracode valves, sponge spicules, small molluscs and glauconitic pellets are apparent evidence of significant marine influence at the base of this Formation (Lindsay, 1981; Lindsay & Harris, 1979; Cooper, 1979). Deposition of Chinaman Gully Formation appears to correspond to part of the regressive episode of sedimentation (Quilty, 1977; McGowran, 1978, 1979; Lindsay, 1981) and thus is probably correlated to the latest episode of sea-level drop in the Aldingan Stage. The thickness of this Formation is highly variable but commonly is in the range of 10m (Lindsay, 1981).

There are several notable features of the Chinaman Gully sedimentation in the St. Vincent Basin that provide some information on tectonic movements. First, poorly sorted sand bodies within the Chinaman Gully Formation encountered sub-surface near the Eden-Burnside and the Para Faults allowed Lindsay (1981) to suggest that this Formation as a whole, tended to be developed near the faulted eastern margins of the St. Vincent Basin. Cooper (1979) provided clear evidence of the progressive thickening of the Chinaman Gully Formation from the coastal stratotype (2.1m) towards the Willunga Fault where 8m of sediments were encountered. Similar SE thickness increase was observed near the Adelaide City where the Tandanya Sand Member of this Formation increased from 7.6m to 23m nearby the Para Fault (Lindsay, 1981).

Second, there are common lignite occurrences in the fault-angle depressions such as along the Eden-Burnside Fault in the Golden Grove Embayment (Springbank Bore, Lindsay, 1981, see Fig 1-2 for location). Fault-angle depressions are most probably a result of low-angle tilting of hanging-wall blocks rather than block uplifts along reverse faults. Such tilting would be consistent with both the observed 1° S-SE tilting of the Tandanya Sand Member beneath the Adelaide City (Lindsay, 1981, p.237) and sedimentary thickening towards the faults.

Third, an erosional disconformity between Tandanya Sand Member of the Chinaman Gully Formation with the cherty Gull Rock Member or middle part of the Blanche Point Formation in the Adelaide City area is quite apparent (Lindsay & Harris, 1979). This suggests that the

upper part of the Blanche Point Formation was probably eroded. The terrigenous nature of some sands, clays and lignites, and erosional disconformity indicate that there was a reduction of accommodation space of the St. Vincent Basin during the Chinaman Gully deposition. Such a reduction of accommodation space would result from a major sea-level drop at the end of the Aldingan Stage or due to tectonic factors, or a combination of both causes.

There was ~50m sea-level drop at the end of Aldingan Stage as the eustatic curve indicates (Fig. 4-1). This would suggest that basin water depth of ~50m could correlate with this sea-level drop and would be sufficient for erosion by marine retreat without any tectonic effects. However tectonic uplift of fault blocks in the Adelaide area has been inferred to explain the erosional unconformity between the Chinaman Gully and Blanche Point Formations (Lindsay, 1981). It is hard to accept or reject tectonic uplift as a cause of the erosional unconformity; however it is clear that some reduction of basin subsidence took place in the Late Eocene (Fig. 4-2). If uplift did occur it was probably no more than a few tens of metres (possibly less) that would have been sufficient for temporary exposure of the sedimentary surface and erosion.

4.5.2 Aldingan Stage in the Western Murray Basin

The Aldingan Stage in this basin is associated with continuing sedimentation of the Olney Formation with a clear but gradual change from fluviolacustrine to marginal-marine environments. The marine Buccleuch Beds are the most notable sedimentary feature in the SW part of the Murray Basin during this stage.

Buccleuch Formation

The Buccleuch Formation or Buccleuch Beds represent the first marine transgression into the SW Murray Basin (Rogers et al., 1995). The lithologic characteristics of this Formation provided by Brown and Stephenson (1991) are: poorly consolidated grey-brown carbonaceous clay with limonitic upper surface; overlain by friable carbonaceous sand with thin limestone lenses; further overlain by highly fossiliferous white bryozoan limestone with green-grey glauconitic calcareous clay (marl). Lithologically the Buccleuch Formation is similar to the upper part of the Olney Formation but is distinguished by the lack of quartz sand and mica, and the presence of shells and bryozoal calcarenite (Brown, 1989; Rogers et al., 1995).

The thickness of the Buccleuch Beds is irregular and mainly under 30m, but in places increasing to 78m (Brown & Stephenson, 1991). Good palaeontological evidence dates the marginal-marine depositional environment of the Buccleuch Formation as the Late Eocene-Early Oligocene (Brown & Stephenson, 1991) with possible extension into early Late Oligocene (Rogers et al., 1995). This would indicate that accumulation of the Buccleuch Formation occurred during the Aldingan and probably extended into the Willungan Stage.

A thin bed of fossiliferous and ferruginous sandy limestone near Victor Harbor in the Waitpinga drainage basin at ~70m AHD (Fig. 4-7) is correlated with the middle limestone interval of the Buccleuch Formation (Bourman & Lindsay, 1973) and represents a southern extension of the Murray Basin onto the Fleurieu Peninsula (Rogers et al., 1995). If the shallow marine sediments were accumulated and preserved in this area then the sea-level at about 100m above PSL must be applied without any correction to later uplift, while the global eustatic curve indicates that the sea-level during the Aldingan Stage could be between 100 and 150m above PSL (Fig. 4-1). Thus it seems plausible to consider that the gently undulating landscape of the Fleurieu Peninsula inherited from the pre-Middle Eocene Palaeoplain more likely subsided than was uplifted as higher sea-level during the Johannian Stage did not result in flooding of the Waitpinga basin of Fleurieu Peninsula. If one takes into account that during the Johannian Stage sea-level was ~100m higher than during the Aldingan Stage, then the effect of downward movements on the Fleurieu Peninsula is persuasive.

The formation of accommodation space of the Buccleuch Embayment (Fig. 4-7) was obviously due to subsidence that occurred in the SW part of the Murray Basin and involved the eastern portion of the Fleurieu Peninsula. Specifically, one must take into account that the Buccleuch Formation is associated with the first marine transgression into this Basin. The marine environment of sedimentation was established during the low sea-level stand in comparison to earlier stages. Thus the subsidence of the SW Murray Basin would be an essential factor leading to the formation of accommodation space. In spite of the sea-level drop at the end of the Aldingan Stage, there were no significant changes of sedimentary environment in the Buccleuch Embayment. This would indicate that tectonic subsidence of the Western Murray Basin provided sufficient accommodation space. In contrast, this sea-level fall affected sedimentary environment of the St. Vincent Basin (Chinaman Gully Formation) that suggests a reduction of this basin subsidence.

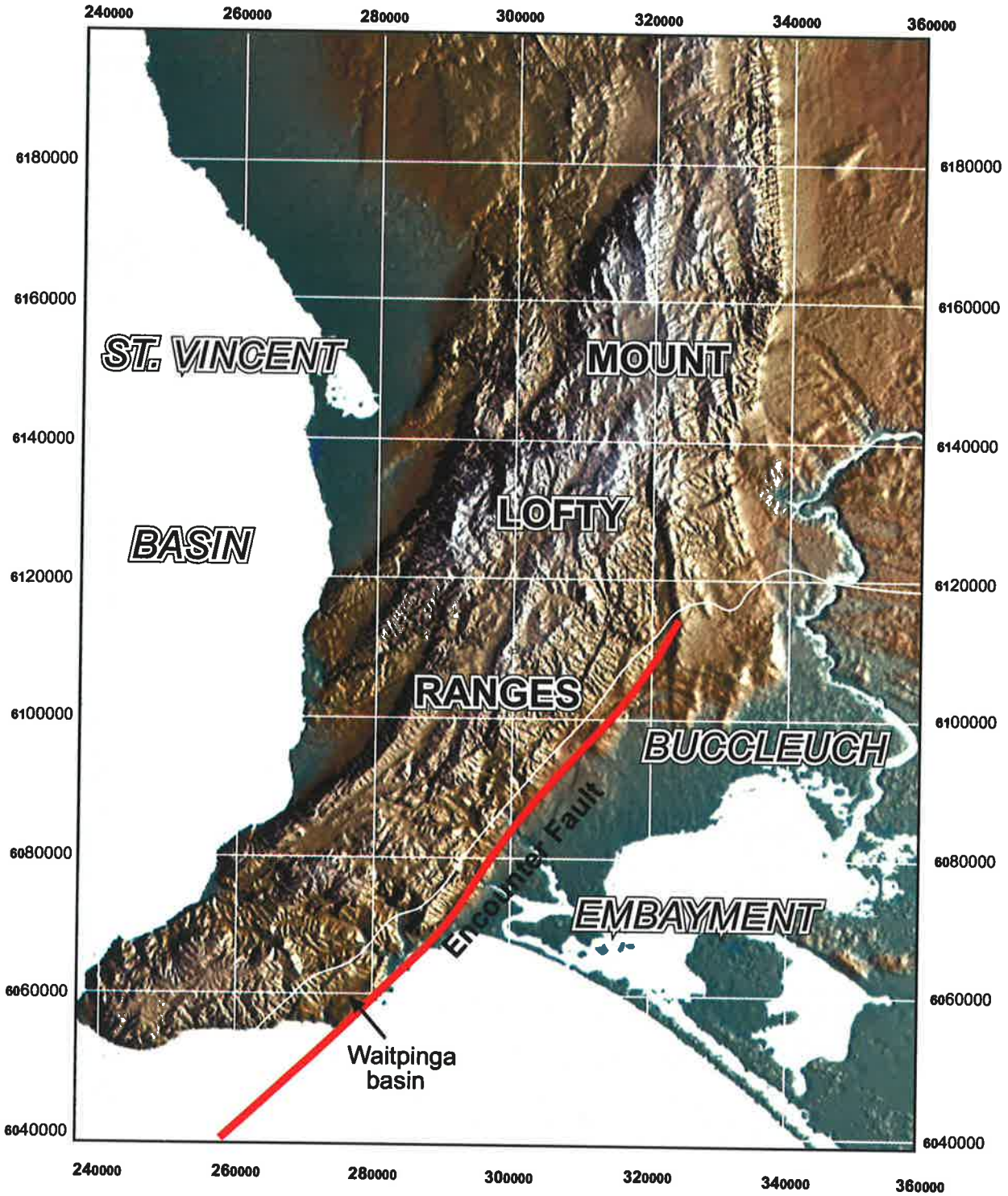


Figure 4-7 Location of the Buccleuch Embayment (outlined white) and Encounter Fault (in red) in the south-western part of the Murray Basin (modified after Brown and Stephenson, 1991). Waitpinga basin contains marine sediments correlated with the Buccleuch Beds (Bourman & Lindsay, 1973). Shaded relief image derived from 1-s DEM.

In summary, the discussion above establishes that:

1. The first marine transgression into the Western Murray Basin is clear evidence of the increased subsidence that also involved the eastern part of the Fleurieu Peninsula.
2. The Buccleuch Embayment is apparently a result of the crustal segmentation of the Murray Basin mainly due to subsidence that exceeds the sea-level drop at the end of the Aldingan Stage.
3. A very restricted sedimentary supply from the SE Mount Lofty Ranges and Fleurieu Peninsula indicates that this source region inherited a low and gently undulating landscape of the pre-Middle Eocene Palaeoplain.

4.5.3 Aldingan Stage: Conclusion

- The St. Vincent Basin was basically a shallow north-elongated depression surrounded by a low and gentle landscape including the area of incipient Mount Lofty Ranges and Fleurieu Peninsula.
- Thickness differences are evidence of *basin segmentation* into the Willunga, Noarlunga, Golden Grove and Adelaide Plains Embayments. Such segmentation was mainly due to down-to-basin block movements along the eastern faults bounding these embayments.
- The increased thickness of sediments toward the bounding faults, formation of fault-angle depressions and the absence of fault-scarp associated deposits indicate that down-to basin block movements along *normal faults* caused an extra sedimentary accommodation space.
- The terrigenous nature of some sand, clayey sediments and lignite indicates that the reduction of accommodation space occurred mainly due to sea-level drop at the end of the Aldinga Stage, while reduction of basin subsidence probably also contributed to the sedimentary surface exposure and following erosion in some areas.
- Differential subsidence occurred in the SW Murray Basin that resulted in the Buccleuch Embayment formation and first marine transgression into the basin during the Aldingan Stage. The subsidence even compensated for the sea-level drop at the end of this stage.
- The gently undulating and deeply weathered landscape inherited from the pre-Middle Eocene Palaeoplain was generally preserved during this stage.
- The marine inundation of the eastern Fleurieu Peninsula clear indicates that some areas of the source area was also involved into the subsidence that lowered initially high-standing Palaeoplain to the level below the sea.

4.6 Willungan Stage (~34-29Ma)

The beginning of the Willunga Stage is associated with a significant sea-level rise of about 100m that reached >180m above PSL (Fig. 4-1). This sea-level stand was the highest since the Wilson Bluff transgression (~220m above PSL) and significantly affected the southern Australian continent margin. It is important to note that this sea-level stand was the last highest for the rest of the Tertiary and Quaternary Periods.

Rapid sea-level rise at the beginning of the Willungan Stage significantly enlarged the sedimentary accommodation space and at the same time apparently flooded lower parts of streams in the Mount Lofty Ranges. This must have reduced river competence (erosion and sedimentary supply) in marginal areas of this source region. However, this sea-level rise alone was insufficient to flood the intramontane Meadows, Myponga and Hindmarsh Tiers Basins during the Early Oligocene. Absence of Early Oligocene sediments in these basins and elsewhere inside the Mount Lofty Ranges indicates that the source region between the St. Vincent and Western Murray Basins was situated at least above this sea-level (>180m above PSL). Therefore tectonic developments occurred mainly on the western and eastern borders of this source region and are associated with basin subsidence and segmentation.

The Willungan Stage is clearly associated with chert-carbonate sedimentation in the intraplate St. Vincent and Western Murray Basins and elsewhere in offshore basins on the southern part of the Australian continent (McGowran et al., 1997). Sedimentation in these basins occurred in typical shallow marine environments in spite of a few episodes of transgression and regression associated with fluctuating sea-level and climatic changes (Lindsay & McGowran, 1986).

4.6.1 Willungan Stage in the St. Vincent Basin

In the St. Vincent Basin the Willungan Stage is associated with formation of the Aldinga Member - a basal unit, and the Ruwarung Member – middle part of the Port Willunga Formation. There are some uncertainties as to the age of the Aldinga and Ruwarung Members in the stratigraphic framework. The most probable age of the Aldinga Member is the uppermost Eocene to Early Oligocene that is close to the Eocene/Oligocene boundary (Lindsay, 1981). This unit is clearly above the regressive interval of the Chinaman Gully Formation and obviously associated with eustatic rise. Therefore, it is most likely that it takes

place at the base of the Early Oligocene (Fig. 4-5). The cherty Ruwarung Member is underlain by the softer Aldinga Member everywhere in the St. Vincent Basin (Lindsay, 1981). Therefore, despite its various age determinations from the Eocene/Oligocene boundary to the middle part of the Oligocene and further up, the Ruwarung Member formed after the Aldinga Member, apparently some time in the Early Oligocene (eg. Lindsay & Alley, 1995).

Aldinga Member of the Port Willunga Formation

The Aldinga Member is a basal unit of the Port Willunga Formation and consists of predominant calcarenite with minor silt, clay and very fine-grained glauconitic quartz sands with abundant fossils, ovoid faecal pellets and sponge spicules. Such composition indicates a relatively passive near-shore neritic environment with restricted access to the open ocean, although some fining-upwards progression probably represents increasing water-depth (Lindsay, 1981).

Sedimentation of the Aldinga Member generally occurred in relatively warm water temperatures (McGowran, 1978). This may be in accord with a small regional rise in palaeotemperatures towards the Early Oligocene, extracted from oxygen-isotope data for benthonic foraminifera (Shackleton & Kennett, 1975; Kennett & Shackleton, 1976). Palynological data indicate relatively high annual precipitation, probably in excess of 1000mm, with sub-tropical rainforest vegetation covering much of southern Australia similar to that in the Eocene (Harris, 1980).

The basal part of the Aldinga Member is coarser than the upper part and contains sub-angular and rounded quartz grains mainly 0.05mm to 0.3mm in diameter (Lindsay, 1981). Significant quartz content dispersed through a finely crystalline matrix indicates that intensive chemical weathering still occurred in the source area. The upper part of this unit, represented mainly by silt and clay, also shows an increase of deep weathering in the source area.

In spite of the relatively high annual precipitation in the region, the erosive capacity of river systems in the Mount Lofty Ranges was apparently low. This allowed streams to supply only fine- to very fine-grained sediments into the sedimentary basins. These facts clearly point to the existence of a subdued landscape of the Mount Lofty Ranges with sluggish drainage systems during the Willungan Stage. A warm climate and abundance of sub-tropical vegetation probably also contributed to the reduction of landscape dissection. However,

topographically this source area was located higher than the erosional base level (up to 180m above PSL) and thus stood ~200-250m above PSL, that is a little lower but still close to the original altitude of the Palaeoplain.

Following the Chinaman Gully Formation regressive episode the Aldinga Member of the Port Willunga Formation represents a new marine transgression into the St. Vincent Basin. Sedimentation occurred in a typical marginal-marine neritic shallow water depth environment, though an increased water depth associated with fining-upwards progression of sedimentary sequence within the Aldinga Member has been identified (Lindsay, 1981). However there is a downward trend of sea-level after the first 100m rise at the Late Eocene/Oligocene boundary. Therefore increased water depth certainly would indicate that it related to increased basin subsidence.

The distribution of the Aldinga Member is fairly consistent throughout the St. Vincent Basin. Thickness of the stratotype Aldinga Member in the Willunga Embayment is about 13m whereas it is only a few metres in the Noarlunga Embayment (Cooper, 1980). While the thickness of this unit is generally constant at 12-15m in the Adelaide area, there are some later erosional truncations as well as significant increases of thickness of this unit. A maximum thickness of the Aldinga Member of 49m in Croydon-2 bore was encountered west from the Para Fault (Lindsay, 1981; see Fig. 1-2 for bore locations). This indicates that down-to-basin block movements along the Para Fault continually occurred and provided additional accommodation space during the sedimentation.

The Eden-Burnside Fault also appeared to be active as a few metres of marginal sands of the Aldinga Member were encountered by drilling near the southern edge of the Golden-Grove Embayment (Eberhard, 1980). There is a significant thickness increase along this fault southward where, at the southern end of the Adelaide Plains sub-basin, 39.5m of the Aldinga sediments were encountered by the Longyear Bore near the Eden-Burnside Fault. However the lithology of this unit at this location consists mostly of fine-grained sediments, from quartz-calcarenite sand (lower part) to calcarenitic sandy mudstone (upper part). There is no indication of any slope debris or other coarse material that may suggest uplift along the Eden-Burnside fault during this time. Thus normal fault morphology with down-to-basin hanging block motions would be the best possible explanation for this significant thickness increase and formation of accommodation space near this fault.

Ruwarung Member of the Port Willunga Formation

The Ruwarung Member consists of hard irregular nodules of fossiliferous spicular chert in a matrix of fossiliferous mudstone. Both nodules and matrix are glauconitic, calcarenitic, quartzose and sandy (Lindsay, 1981, p.293). The glauconitic and cherty nature of this Member is a distinctive feature separating it from the earlier soft (non-cherty) Aldinga Member and also from overlying units. The typical marine origin of the Ruwarung Member is not in any doubt; however the chert formation and environment of deposition is still under dispute, though chert diagenesis is beyond the scope of this thesis.

There is significant uncertainty as to the age of the Ruwarung Member of the Port Willunga Formation that has been dated from the Eocene/Oligocene boundary to earliest Miocene (Lindsay, 1981). However at the boundary between Early and Late Oligocene (also a possible boundary of the Willungan and Early Janjukian Stages) a significant sea-level drop of about 150m occurred according to the recalculated sea-level curve (Fig. 4-1). This was apparently the biggest sea-level drop for the whole Tertiary Period and must have significantly affected the sedimentary environment in the St. Vincent Basin.

The Ruwarung Member is well recognised in the subsurface of the Adelaide Plains with an average thickness of about 23-26m. However, in many places this Member is truncated by a Pliocene-Pleistocene angular unconformity that was recognised as an eroded wedge with reduced thickness (Lindsay, 1981). The maximum known thickness of the Ruwarung Member encountered in the Croydon-2 Bore about 2km west from the Para Fault is about 70m. This anomaly of thickness distribution together with increased thickness of the underlying Aldinga Member strongly suggests that significant down-to-basin block movements occurred along the Para Fault during the Willungan Stage.

In the Willunga Embayment ~15m of this cherty unit outcrops near Port Willunga and it increases toward the Willunga Fault where WB-1 Bore encountered a thickness of 27m (Fig. 4-3). There is also a 10m-thickness increase from 22m near Port Noarlunga to 32m in the Seaford Bore near the Clarendon Fault in the Noarlunga Embayment (Cooper, 1979; Fig. 4-4). Thickness increase thus is clear evidence that down-to-basin block movements along the faults bounding St. Vincent embayments occurred during the Willungan Stage. Gentle tilting of the hanging-wall block was the apparent cause of the extra accommodation space close to

those faults. Taking into account that 1° of tilt provides an extra 17.5m of accommodation space over a distance of 1km, then such minor tilting would be sufficient for the observed thickness increase in the Willunga and Noarlunga embayments and southern part of the Adelaide sub-basin toward the Eden-Burnside Fault. However the thickness anomaly along the Para Fault demands a slightly increased tilting in order to provide accommodation space for ~130m of sediments (Croydon-2 Bore) accumulated during the Willungan Stage.

Altogether the data and interpretation would indicate that:

1. Basin subsidence accompanied by down-to basin block movements along the normal faults such as Para, Eden-Burnside, Clarendon and Willunga was the most probable tectonic process associated with the Willungan Stage in the St. Vincent Basin.
2. The increased thickness of sediments toward these major faults is clearly associated with a low-angle tilting of the hanging-wall blocks that, once again, points to normal fault morphologies.
3. The restricted terrigenous supply indicates that the western Mount Lofty Ranges remained gently undulating and relatively low while clearly above sea-level and thus >180m above PSL.

4.6.2 Willungan Stage in the Western Murray Basin

The Willungan Stage is associated with continuing sedimentation of the Buccleuch Beds in the marine and marginal-marine environments of the SW part of Murray Basin. There was also fluviolacustrine to marginal-marine sedimentation of the Olney Formation north of the Buccleuch Embayment along the eastern edge of the Mount Lofty Ranges. The distribution of the Buccleuch Beds (Fig. 4-7) shows that significant sea-level rise in the Early Oligocene allowed marine transgression to inundate significantly further north into the Basin.

Buccleuch Beds

The Buccleuch Beds commonly overlie and interfinger with sediments of the Olney Formation. However in some places such as Padthaway Ridge and the SE Fleurieu Peninsula, these sediments lie directly on the pre-Tertiary basement (eg. Brown & Stephenson, 1991). This indicates that the enlargement of the sedimentary accommodation space in the Western Murray Basin was apparently due to rapid sea-level rise during the beginning of Willungan Stage.

The distribution of the Buccleuch Beds in the southern part of the Western Murray Basin is mainly restricted on the west by the Encounter Fault (Fig. 4-7). This Fault was apparently a major tectonic boundary between the source area of the southern Mount Lofty Ranges and the Buccleuch Embayment during this stage. However a slight overlap of the fault by marine sediments indicates that uplift along the Encounter Fault did not occur and that probably both sea-level rise and down-to-basin block movements caused the formation of sedimentary accommodation space. There is also an increase of thickness of the Buccleuch Beds south-westward where a maximum thickness of ~78m was recorded (Brown & Stephenson, 1991). It seems that low amplitude scissor-like motion of down-to-basin block movements along the Encounter Fault provided additional accommodation space in the southern part of the Basin.

A mature pedogenic (lateritic and ferruginised) surface was developed on the Buccleuch Beds and elsewhere in this basin (Brown & Stephenson, 1991) at the end of the Willungan Stage. It is most probable that exposure of the marine sedimentary base was associated with dramatic sea-level fall (>150m) almost down to the present sea-level some time near the boundary of Early and Late Oligocene (Fig. 4-1). This sea-level change was the major single sea-level fall in the whole Tertiary Period and would have essentially reduced accommodation space that apparently caused an exposure of a large sedimentary surface to active weathering in the Western Murray Basin.

Thus the Willungan Stage in the Western Murray Basin is almost similar to that in the St. Vincent Basin except that the latest episode is associated with sea-level fall. Marine retreat and exposure of the sedimentary surface to weathering and pedogenesis did not occur in the St. Vincent Basin. This indicates that subsidence of this basin provided sufficient accommodation space despite the substantial sea-level drop.

4.6.3 Willungan Stage: Conclusion

- The main tectonic activity occurred on the western and eastern borders of the Mount Lofty Ranges. There was slow subsidence of the St. Vincent and Western Murray Basins partly compensated by sediment accumulation in both basins.
- Down-to-basin block movements along the Para, Eden-Burnside, Clarendon and Willunga Faults occurred on the western side and along the Encounter Faults on the eastern side of the Mount Lofty Ranges.

- Relatively passive marine and marginal-marine sedimentary environments dominated in both St. Vincent and Western Murray Basins during the Willungan Stage.
- Significant sea-level change at the beginning and end of this stage sufficiently affected sedimentary accommodation space in both basins.
- Predominantly carbonate type of sedimentation is evidence of restricted sedimentary supply. This in turn indicates that a gently undulating landscape with sediment-starved river systems prevailed in the interbasin region of the Mount Lofty Ranges.
- In spite of the significant sea-level rise that was the highest for the rest of the Tertiary and Quaternary it was insufficient to flood intramontane Meadows-Myponga and Hindmarsh Tiers Basins in the southern part of the Ranges. These basins and ranges remained outside any marine influence and thus were topographically >180m above PSL.

4.7 Early Janjukian Stage (~29-24Ma)

The significant and rapid sea-level drop at the end of the Willungan Stage, generally, did not evoke significant changes in the inner-neritic environment of deposition in the St. Vincent Basin. However, there was a remarkable episode of exposure and weathering of the sedimentary surface in the Western Murray Basin, followed by deposition of the Compton Conglomerate and calcareous clays (marl) and silt of the Ettrick Formation.

The most significant changes occurred in the interior parts of the Southern Mount Lofty Ranges associated with marine inundation into the intramontane Meadows-Myponga and Hindmarsh Tiers Basins despite about 100m lower sea-level than it was during the preceding Willungan Stage. A rising sea-level trend with ~50m fluctuations reached ~80m above PSL at the end of the Early Janjukian Stage (Fig. 4-1). No significant climatic changes were recorded from this time interval.

4.7.1 Early Janjukian Stage in the St. Vincent Basin

The major fall of global sea-level at the end of the Willungan Stage was "the biggest since the Gondwana glaciation a quarter-billion years previously" (McGowran et al., 1997). Despite this, carbonate sedimentation continually dominated during the Early Janjukian Stage over the entire St. Vincent Basin. Sedimentation of the cherty Ruwarung Member of the Port Willunga Formation continued during the Early Janjukian Stage. This is strong evidence that the extent of basin subsidence was greater than the major sea-level drop otherwise there

would have been some interruption to sedimentation as occurred in the Murray Basin. Therefore subsidence of the St. Vincent Basin was the major cause of the accommodation space formation that allowed marine sedimentation to occur almost uninterrupted for millions of years in spite of significant eustatic rises and falls.

The neritic environment of deposition of the Ruwarung Member in the St. Vincent Basin had restricted access to the open ocean (Lindsay, 1981). This, together with a calcareous cherty-bearing lithology, clearly indicates that incompetent river systems (with restricted erosion and sedimentary supply) drained the western slope of the Mount Lofty Ranges during the Early Janjukian Stage. It seems that incipient streams were not able to essentially modify the subdued landscape inherited from the pre-Middle Eocene Palaeoplain before a major marine inundation occurred in the southern part of the Ranges.

4.7.2 Early Janjukian Stage in Intramontane Basins

It is particularly important to note again that marine sedimentation commenced during the Early Janjukian Stage in the intramontane Meadows-Kuitpo area, Myponga and Hindmarsh Tiers Basins (Fig. 4-8) in spite of ~100m lower sea-level than it was during the preceding Willungan Stage (Fig. 4-1). This strongly suggests that major downward block movements occurred in the source region of the Mount Lofty Ranges. It seems that crustal segmentation resulted in the formation of a graben-like structure in the interior part of the Ranges that allowed marine transgression into these intramontane basins.

The Myponga Basin covers the largest area of 30km^2, where a significant package of up to 119m of mid-Tertiary marine sediments is preserved. *The Hindmarsh Tiers Basin* is smaller in size (up to 7km^2) but also contains up to 61m of Tertiary marine bryozoal limestone (Furness et al., 1981). Marine Tertiary successions in both basins are associated with middle and upper parts of the Port Willunga Formation. The base of the limestone in the Hindmarsh Tiers Basin has been dated as the Late Oligocene on the basis of foraminiferal fauna determination (Furness, 1975) and correlated with the Early Janjukian Stage (Lindsay & Alley, 1995).

Lithology of the Early Janjukian sequence in the Myponga and Hindmarsh Tiers Basins is represented by white and grey limestones with abundant bryozoa, echinoids, shells and even shark teeth. The terrigenous input was slightly increased at the base and is represented by

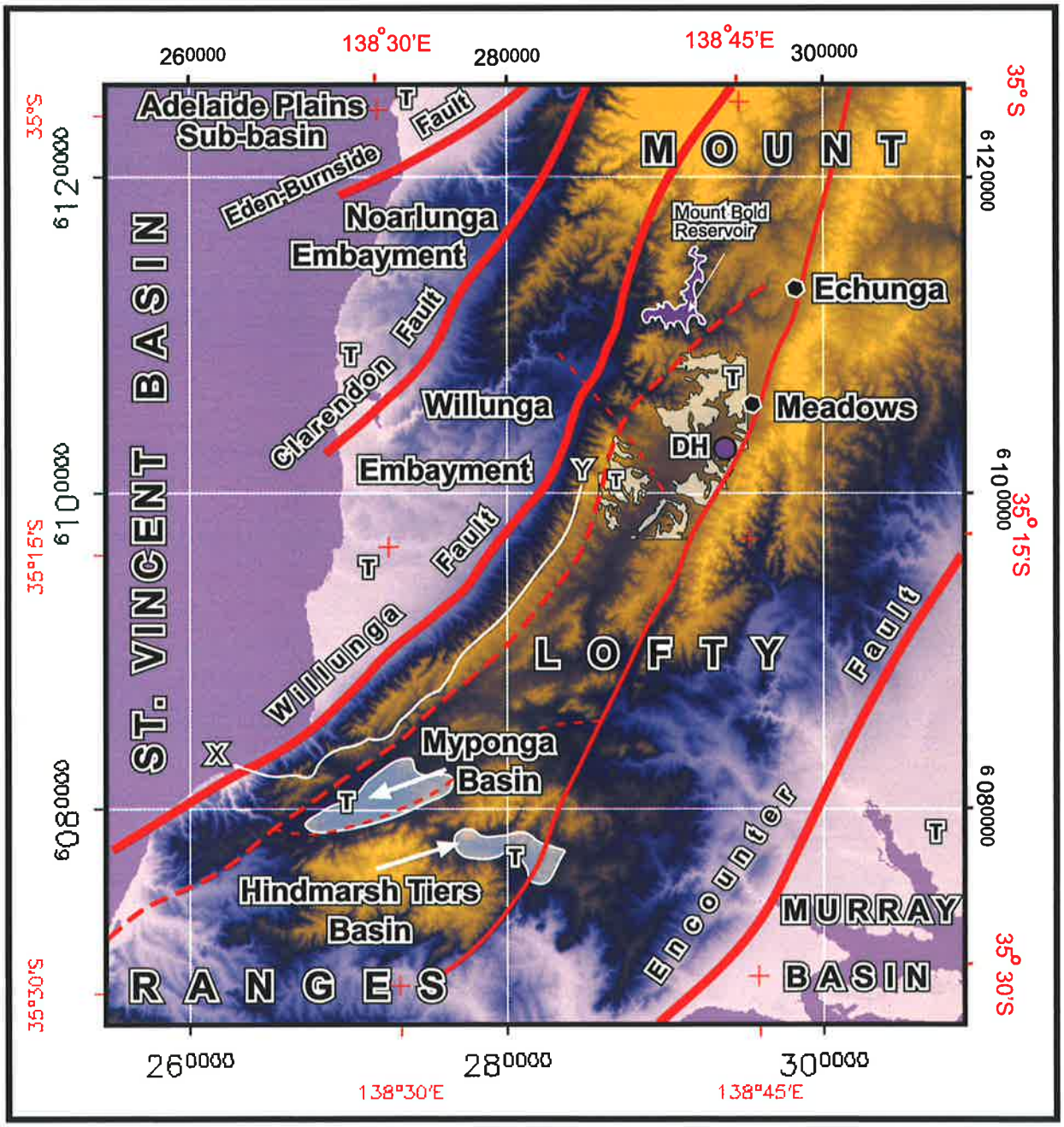


Figure 4-8 Location of the intramontane Hindmarsh Tiers and Myponga Basins and Meadows-Kuitpo area in the southern Mount Lofty Ranges and flanking embayments of the St. Vincent and Western Murray Basins containing marine and marginal-marine Mid-Tertiary sediments (T). DH = Drilling Hole penetrated ~57m of Middle to Late Tertiary sand and sandy clay formed in shallow-marine (possible estuarine) environments (Alley & Lindsay, 1995). Active fault locations are according to DEM interpretation. X-Y (white line) is a cross-section of Fig. 4-12.

calcareous clayey sand with fine-grained (~0.2-0.5mm) and rounded quartz grains, pyrite, ilmenite and metamorphic rock fragments (Furness et al., 1981).

The eustatic curve (Fig. 4-1) indicates that sea-level reached ~80 above PSL at the end of the Early Janjukian Stage. Thus it is certain that such a sea-level rise alone was insufficient to flood interior areas in the Southern Mount Lofty Ranges as they were topographically over 180m above PSL during the Willungan Stage. If one takes into account that tens of metres of sediments accumulated in the shallow marine and marginal-marine environments requiring up to tens of metres of water depth, it follows that tectonic subsidence of the intramontane basins must have been more than 200m during the Early Janjukian Stage (Fig. 4-9). There is no alternative to downward tectonic movements that would explain marine inundation and sedimentation in the interior parts of the Mount Lofty Ranges.

A much wider area than the above basins was obviously affected by tectonic subsidence. Alley & Lindsay (1995, p. 199) provide evidence that middle to late Tertiary marginal-marine sedimentation also occurred in the *Meadows-Kuitpo Valley*. There was a possible connection between the Meadows-Kuitpo area and Myponga Basin during the Oligocene-Early Miocene. A sequence of simulated marine floods demonstrates how the possible marine connection between Myponga and Meadows areas could have occurred (Fig. 4-10). Sedimentation in the Myponga and Hindmarsh Tiers Basins occurred in shallow marine and marginal-marine environments, while in the Meadows-Kuitpo area it may represent an estuarine environment of deposition (Alley & Lindsay, 1995).

At a location ~3km south-southwest of Meadows currently at about 300m above PSL, a drillhole intersected 57m of Tertiary succession (Alley & Lindsay, 1995). If one takes into account that later development of this area involved a relatively uniform uplift and that ~50m of water depth is a realistic estimate of marine environments in these basins then a projected sea-level of ~350m above PSL would be the minimum effect that marine inundation imposed on the Meadows-Kuitpo area and generally on the southern part of the Ranges during the Janjukian Stage (Fig. 4-11).

It is thus clear that a large area of the southern Mount Lofty Ranges was involved in downward tectonic movements, allowing marine inundation deep into this previous source region. The distribution of Tertiary sediments within the Meadows-Kuitpo area seems to be

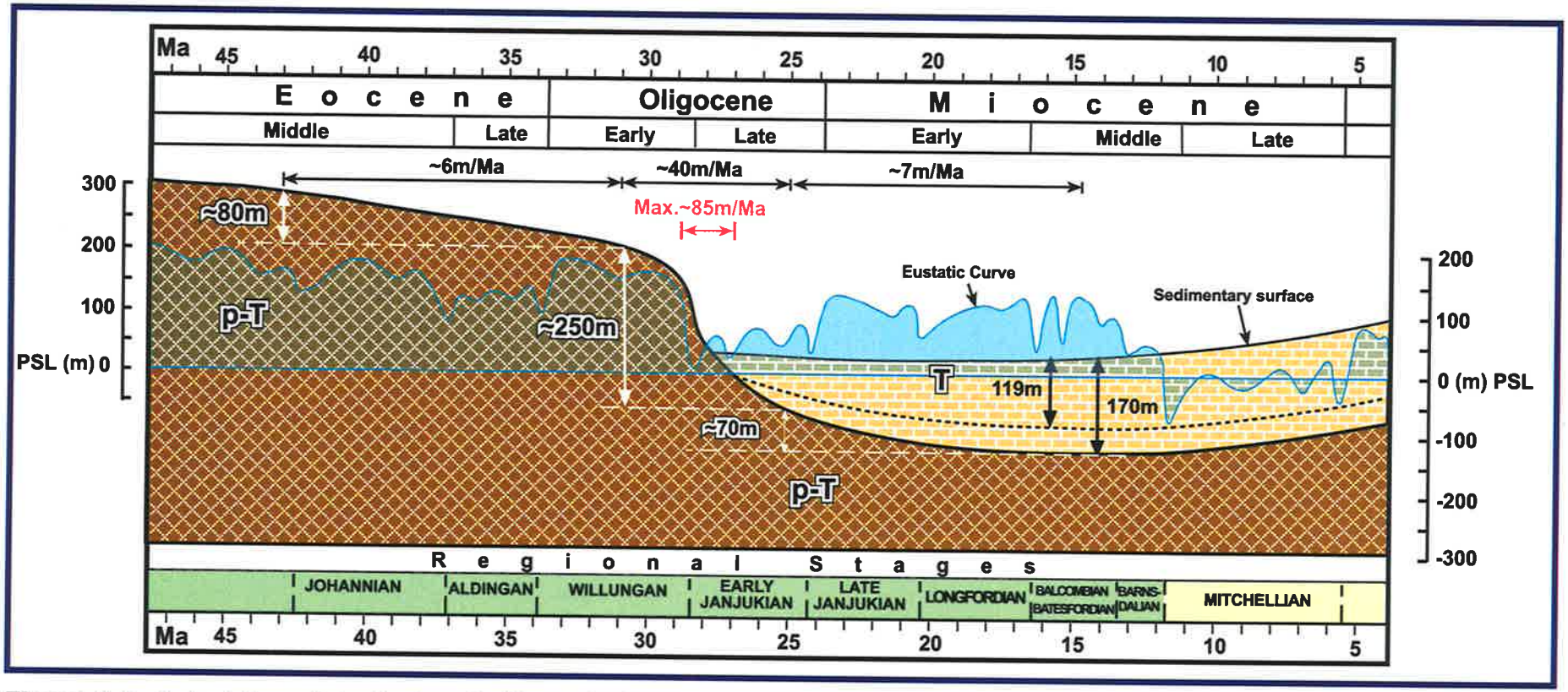


Figure 4-9 Calculation of tectonic subsidence in the southern Mount Lofty Ranges: Integrated sea-level, commencement and termination of marine sedimentation and thickness of Tertiary sediments in the intramontane basins. ~6m/Ma = Gradient of subsidence (max. in red). 119m and 170m = thickness of Mid-Tertiary marine sediments in the Hindmarsh Tiers and Myponga Basins (Furness et al., 1981). The abrupt downward trend of the pre-Tertiary surface is associated with second order crustal segmentation and the formation of basin accommodation space. Global Eustatic curve after Haq et al. (1987), recalculated by Li et al. (2004). Regional Stages after McGowran et al. (1997). Stages in colour according to tectonic regime: green - extensional, yellow - transitional.

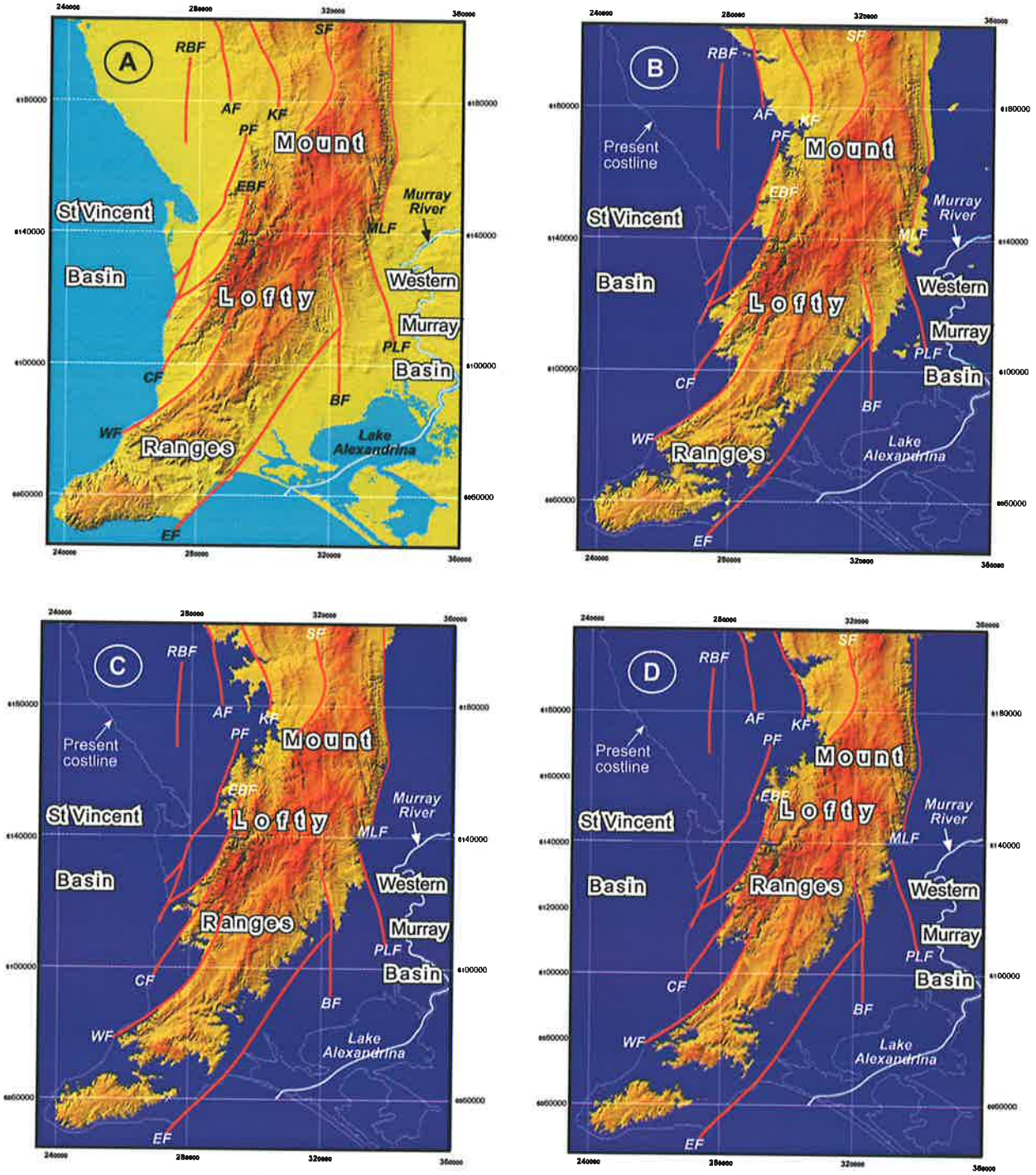


Figure 4-10 Simulation of marine floods of the landscape in the study region of the Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins (not adjusted to any later uplift). A - at PSL; B - at ~130m above PSL; C - at ~180m above PSL and D - marine flood at ~230m above PSL. Shaded relief image with some elements of neotectonic setting derived from 1-s DEM analysis (see Fig. 1-2 for list of active faults).

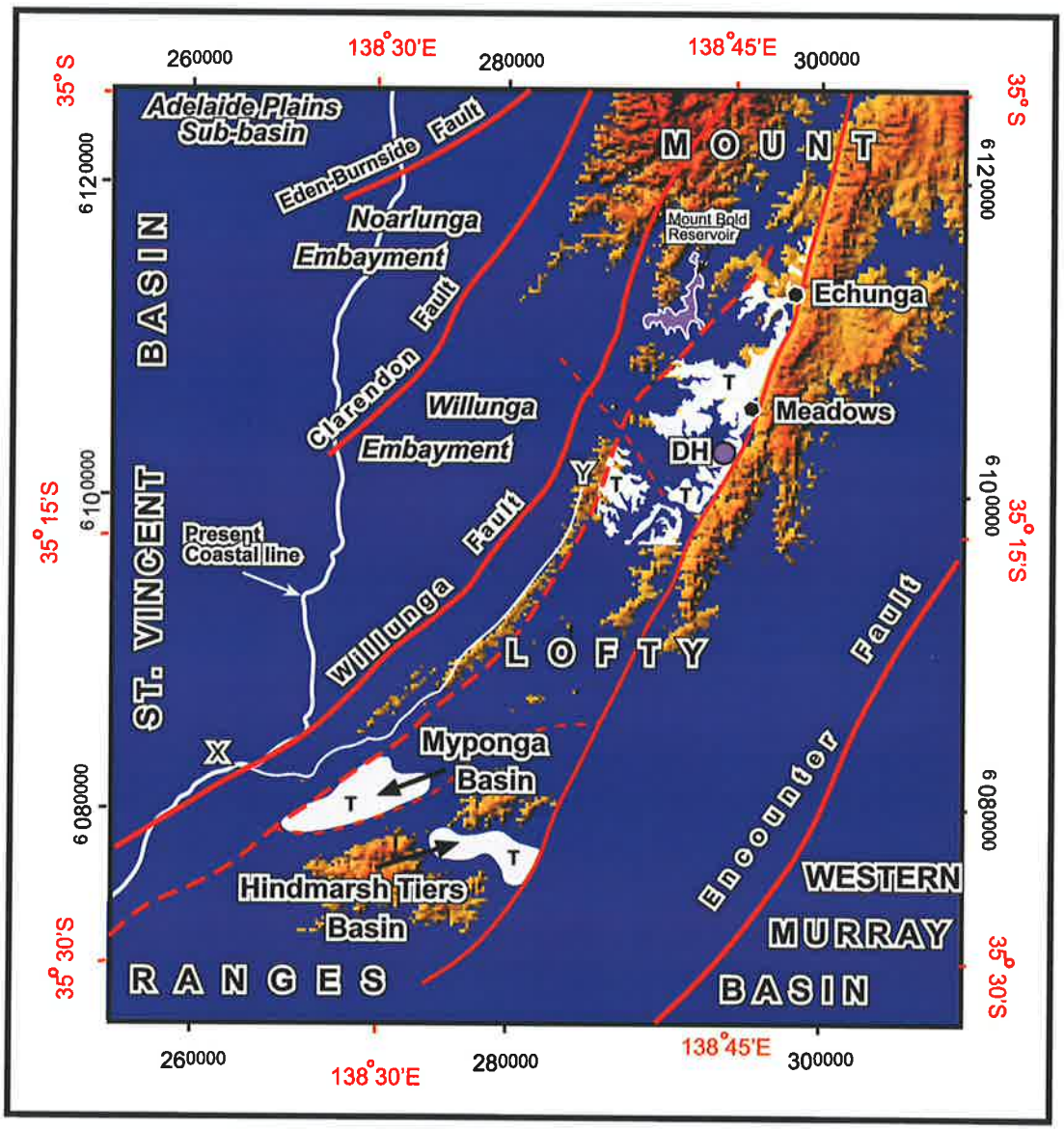


Figure 4-11 Sea-level flood at ~350m above PSL over shaded relief (1-s DEM) of the southern Mount Lofty Ranges (possibly during the associated Mid-Tertiary). DH = Drilling Hole at ~300m above PSL penetrated ~57m of Middle to Late Tertiary sand and sandy clay formed in shallow-marine possible estuarine environments (Alley & Lindsay, 1995). Distribution of Tertiary deposits (T) near Meadows according to Echunga map sheet 1:50000 Geological Series (SA Dept. Mines & Energy; Forbes, 1983). Active Tertiary faults associated with crustal segmentation during the extensional regime. X-Y (white line) is a cross-section in Fig. 4-12. Note: Full DEM image with neotectonic setting in Fig. 5-4.

controlled by the faults, specifically along the western side of the Bull Creek Range passing through Meadows and Echunga (Fig. 4-11). This fault is well expressed in the landscape forming a prominent NE-SW straight-line scarp for tens of kilometres. Structurally this fault is associated with the eastern border of the Tertiary intramontane graben joining Meadows and Myponga Basins. Some structural considerations of this area are provided in Chapter 5 and landscape development in Chapter 6 of this thesis.

There is also some geomorphological evidence of subsidence of the southern Mount Lofty Ranges and Fleurieu Peninsula during the Early Janjukian Stage. Geomorphological observations and study of the regolith (Tokarev & Gostin, in press) indicate that a uniform and remarkably flat planation surface was developed on the top of the Sellicks Hill Range (Fig. 4-12). This surface developed over various lithologies of the pre-Tertiary basement. Only a thin regolith cover (tens of centimetres) of this surface contrasts with significantly thicker regolith (several metres) along the major watershed of central and northern parts of the Mount Lofty Ranges (the most preserved remnants of the Palaeoplain). This indicates that the major regolith associated with the Palaeoplain was stripped from the southern Ranges.

However any fluvial removal of the regolith is inconsistent with the observed flat and uniform surface of the Sellicks Hill Range. A process of marine abrasion is proposed here as the cause of this surface formation. While similar marine abrasion surfaces or platforms are commonly distributed for hundreds of kilometres along the present coast of southern Australia, the formation of such a surface on the Sellicks Hill Range, currently standing at 300-400m above PSL is unusual and demands a specific scenario that would explain the observed facts.

The Sellicks Hill Range is a watershed between the intramontane Meadows-Myponga Basin and the Willunga Embayment of the St. Vincent Basin. The Willunga Fault bounding the western side of this range was active during the initial Middle-Late Eocene crustal segmentation and at least partly responsible for the formation of accommodation space of the Willunga Embayment. However up to the Late Oligocene the Sellicks Hill Range together with interior parts of the southern Mount Lofty Ranges (east of the Willunga Fault) were the source area remaining generally above sea-level (>180m above PSL during the Willungan Stage). The above data demonstrates that the Late Oligocene sedimentation occurred on both the western (Willunga Embayment) and eastern (Meadows-Myponga) sides of the Sellicks Hill Range. Therefore a new pulse of crustal segmentation that resulted in intramontane basin

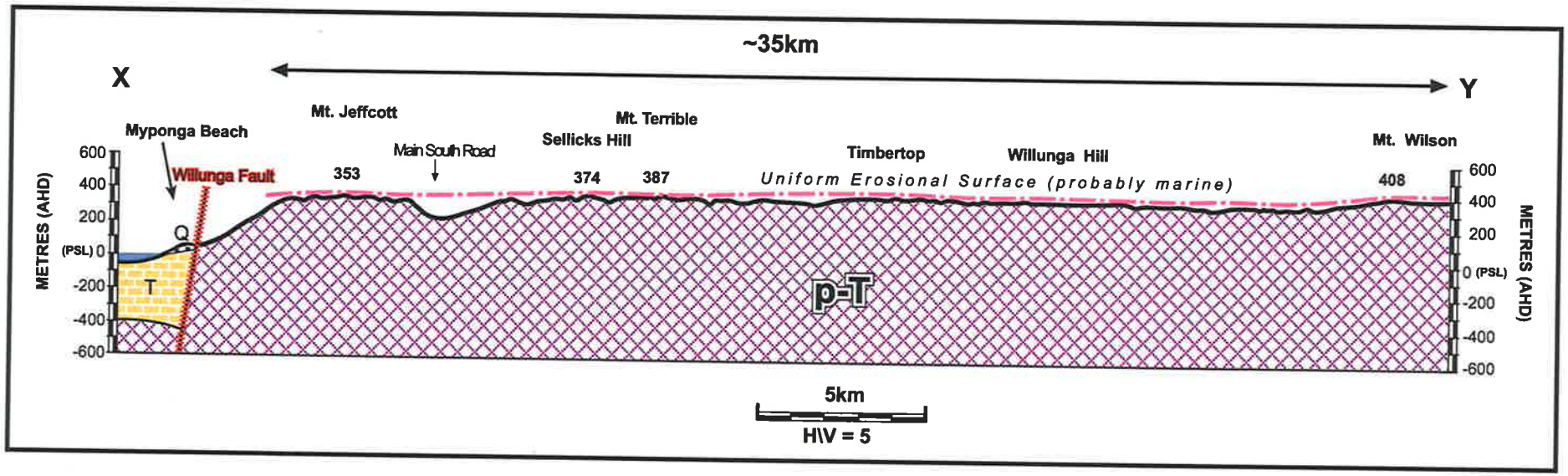


Figure 4-12 Geological-geomorphological cross-section along the Sellicks Hill Range. Uniform planation summit surface developed over 35km along the watershed indicates that marine abrasion was the most probable cause of this surface genesis during the high sea-level. However even highest Tertiary sea-level alone was insufficient to flood over the Ranges, therefore downward tectonic movement such as S-SW tilting is inferred. Differential tectonic movements along the Willunga Fault provided accommodation space for the Tertiary sediments (T). p-T = pre-Tertiary basement (including Permian fluvioglacial deposits). Q = Pleistocene and Holocene predominantly beach deposits. Location of the cross-section X-Y shown in Fig. 4-11.

subsidence occurred during the Early Janjukian Stage. Due to this, the Sellicks Hill Range appeared between two substantially subsiding basins: Meadows-Myponga on the east and Willunga Embayment on the west.

Lindsay & Alley (1995) suggest that there was more likely a marine connection between the intramontane Meadows-Myponga and the St. Vincent Basin rather than with the Murray Basin. Following the marine flood simulation (Fig. 4-11) it would be possible to suggest that at least the southern part of the Sellicks Hill Range (where the uniform and flat surface is preserved) existed as an underwater barrier between the Willunga Embayment and the newly forming Meadows-Myponga Basin. Such an interbasin position inevitably exposed this Range to submarine and marine erosion at least during high sea-level stands that apparently resulted in complete regolith removal and formation of an abrasion platform - a flat planation surface formed simultaneously over a large area (Fig. 4-12). As will be shown in the following section, products of this erosion were moved eastward and deposited as the highly ferruginous Compton Conglomerate in the nearby SW Murray Basin. A thin regolith over the southern Mount Lofty Ranges and Fleurieu Peninsula apparently was formed later after the final marine regression from area when this palaeolandscape was exposed to renewed weathering. The post-Late Tertiary age of the regolith on the summit surface of the Fleurieu Peninsula (Bird & Chivas, 1989) supports the above scenario.

4.7.3 Early Janjukian Stage in the Western Murray Basin

The Early Janjukian Stage commenced in the Western Murray Basin after interruption of sedimentation and exposure of the sedimentary surface to weathering and pedogenesis (Brown & Stephenson, 1991) most probably due to dramatic sea-level drop in the latest Early Oligocene. The Compton Conglomerate is mainly superimposed on this weathered surface, and is overlain by the calcareous Ettrick Formation.

Compton Conglomerate

The Compton Conglomerate is a composite unit typically containing pebbles, sand, glauconitic and calcareous clays packed with a ferruginous matrix. The main clasts are ironstone and quartz pebbles and cobbles up to 20cm in size (Brown & Stephenson, 1991). The abundance of ferruginous material indicates that active stripping of a regolith occurred from a nearby source region. The distribution of this unit is patchy and almost restricted to

the Buccleuch Embayment in the SW Murray Basin (Fig. 4-7), where it disconformably overlies the Buccleuch Beds and partly the Olney Formation. However there are several cases where the Compton Conglomerate directly overlies the pre-Tertiary basements of the eastern slope of the Mount Lofty Ranges such as in the Bremer River valley near Cross's Bridge, Hartley and Monarto (Fig. 4-13). The thickness of the Compton Conglomerate is variable and commonly in the range of 1m to 7m with a maximum recorded of 16m (Brown & Stephenson, 1991).

Traditionally the sudden appearance of such a conglomerate would be correlated with high stream competence (outwash deposits) and thus rapid uplift and erosion of a nearby source area. However, contrary to uplift, evidence above has suggested that: 1. The subsidence of the southern Mount Lofty Ranges had occurred during this stage and it had not led to any notable increase of fluvial erosion; and 2. There were no large river systems in this source area capable of supplying such coarse gravel. However, the Compton Conglomerate contains both pebbles and enormous amounts of regolith that distinguish this unit from any earlier deposits. Glauconitic and calcareous clays and poorly fossiliferous calcareous sandstones indicate that deposition of the Compton Conglomerate occurred in marine or marginal-marine environment. The Compton Conglomerate thus consists of an extremely variable lithology that was deposited in a very short interval sometime around the Early and Late Oligocene boundary that is at the beginning of the Early Janjukian Stage. A small sea-level rise (up to 60m above PSL) together with significant subsidence (>200m) of interior parts of the southern Mount Lofty Ranges (Fig. 4-9) resulted in marine inundation of this relatively large interbasin region during the Early Janjukian Stage.

As the above scenario (Fig. 4-11) indicates, a large portion of this source region was apparently flooded that resulted in regolith stripping from the drowned landscape by marine abrasion. This would be consistent with a large amount of ferruginous material constituting the Compton Conglomerate. The abundance of Permian fluvioglacial deposits in the southern Mount Lofty Ranges and Fleurieu Peninsula (still present) would thus provide plenty of coarse gravel and sands, which together with regolith now compose the Compton Conglomerate. However the delivering mechanism of such coarse material into the Buccleuch Embayment needs to be determined. The simulated flooding model (Fig. 4-14) at only ~250m above PSL and thus just about 30m above Tertiary sediments of the Myponga

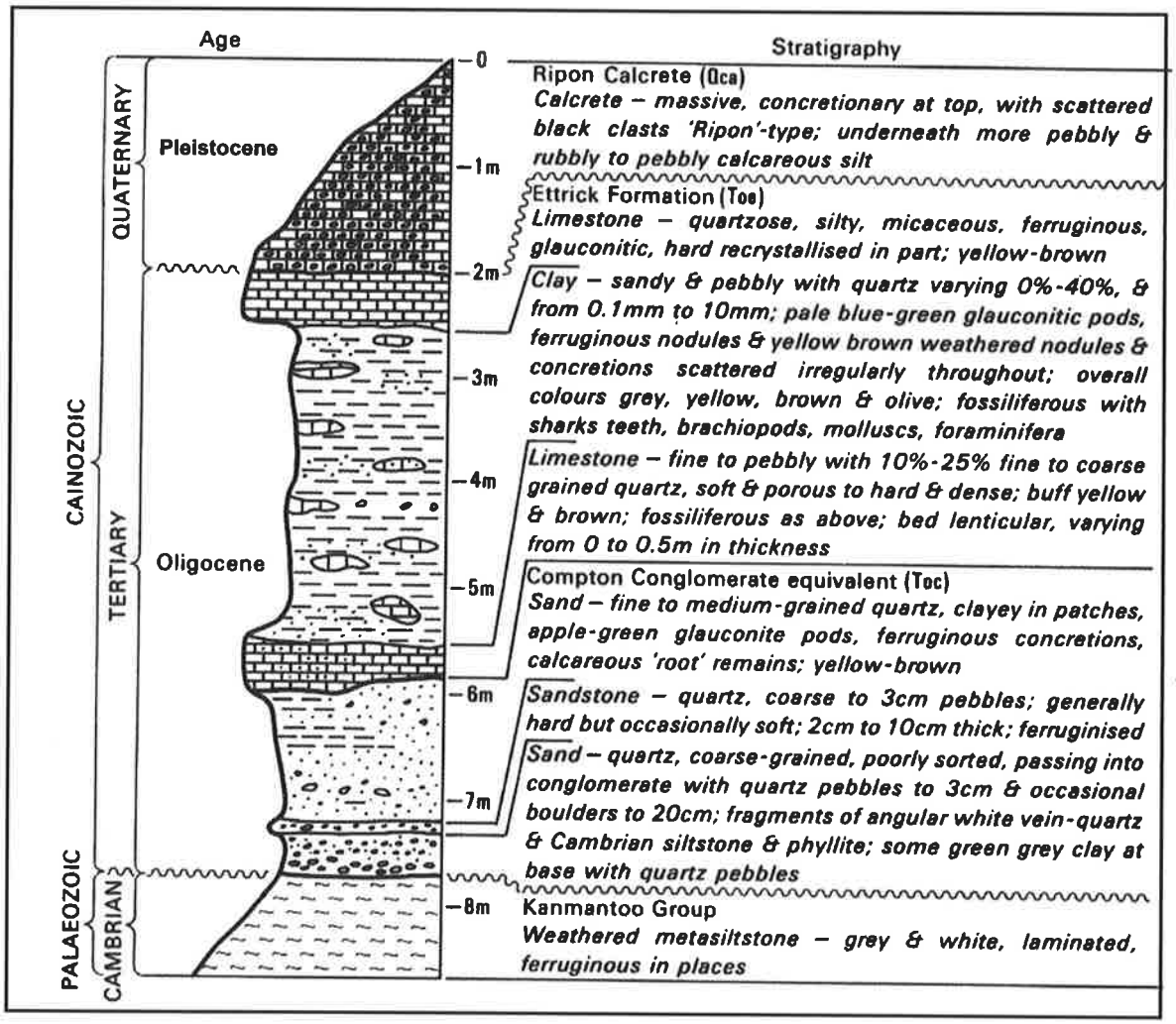


Figure 4-13 Sections exposed in the Bremer River Valley at Cross's Bridge and Hartley and in Kalibar railway cutting Monarto. Exposure of Ettrick Formation underlying by Compton Conglomerate (after Brown & Stephenson, 1991 based on Lindsay & Williams, 1977).

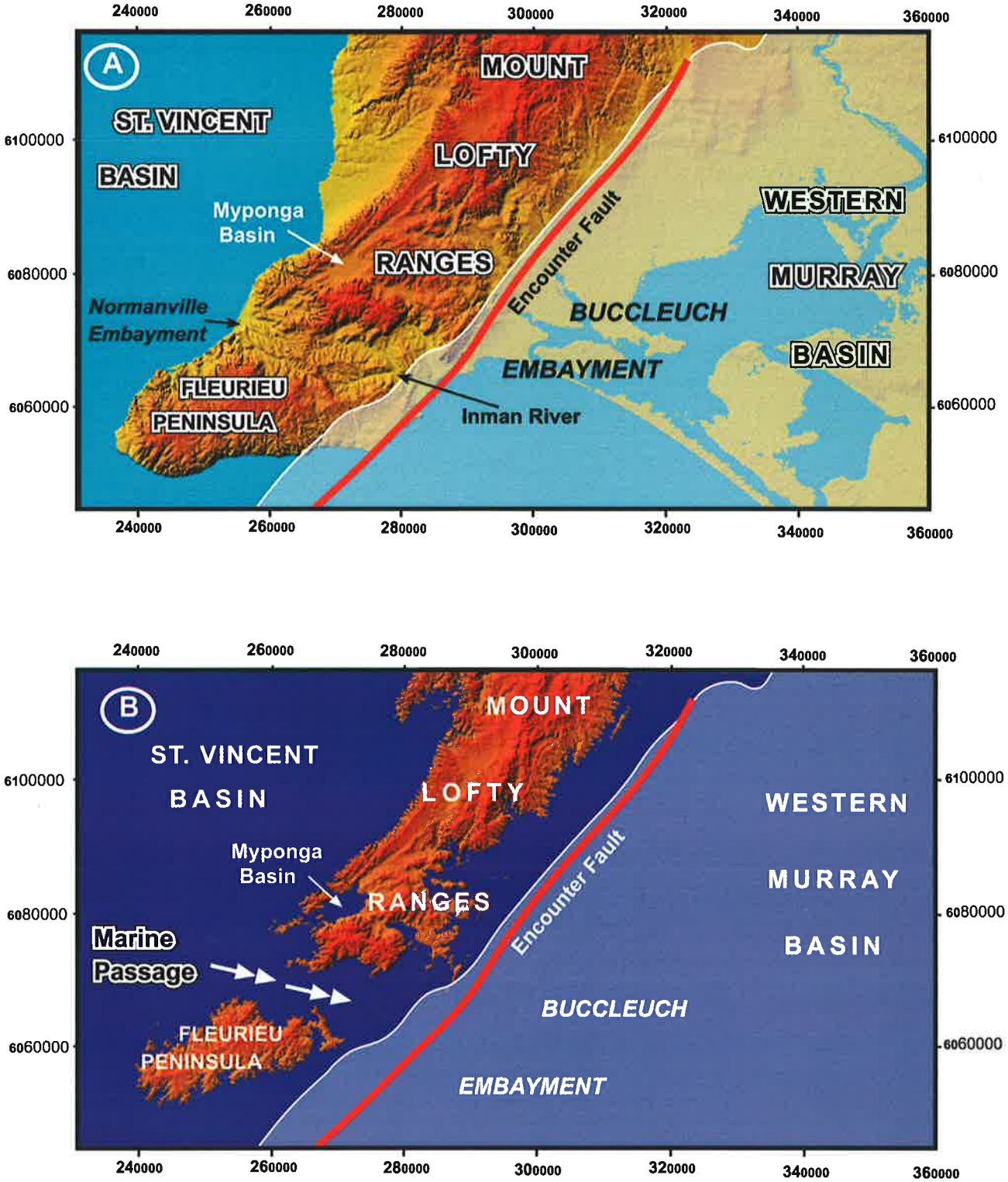


Figure 4-14 Marine flood simulation at ~250m above PSL (B) shows that during the high sea-level there would be a possible marine passage over the Mount Lofty Ranges between the St. Vincent and Western Murray Basin. Strong marine and coastal currents were able to deliver coarse Oligocene Compton Conglomerate into the marine Buccleuch Embayment. A - PSL . Shaded relief image and projected sea-level derived from 1-s DEM analysis.

Basin indicates that at this level a marine passage from the St. Vincent to the Murray Basin already possibly existed (Fig. 4-14B). Strong marine and coastal currents probably surged through the Normanville Embayment and along wide Inman Valley into the Buccleuch Embayment during the Early Janjukian Stage (Fig. 4-14A). These currents would have been considered as the best possible delivering mechanism for the coarse and highly ferruginous Compton Conglomerate.

Thus the environment of the Compton Conglomerate formation would indicate that: 1. It is consistent with downward tectonic movements in the Southern Mount Lofty Ranges and probably Fleurieu Peninsula; and 2. Marine abrasion and strong west to east currents removed a large amount of ferruginous and pebbly deposits from the source area and delivered them into the Buccleuch Embayment during the Early Janjukian Stage.

Ettrick Formation

The Ettrick Formation represents the final episode of the Early Janjukian Stage in the Western Murray Basin. A uniform thickness of 20-30m of these deposits covered a large area (Fig. 4-15). This Formation consists of grey to green glauconitic and highly fossiliferous calcareous clay, silt and sandy clays. The lithology of this Formation is more variable at the base, which includes minor fossiliferous quartz sand, but becoming more calcareous toward the top with micritic limestone intercalations and increasing skeletal calcarenite. The Ettrick Formation conformably overlies the Compton Conglomerate and is discomformable over the Olney Formations and Buccleuch Beds where the Compton Conglomerate is absent (Brown & Stephenson, 1991).

The age of the Ettrick Formation based on a number of fossil determinations is in the range from Oligocene to Early Miocene (Ludbrook, 1957, 1961; Lindsay & Bonnet, 1973; Brown & Stephenson, 1991). The eustatic curve indicates that accumulation of Ettrick sediments occurred during the rising sea-level trend that may have reached ~80m above PSL at the Late Oligocene/Early Miocene boundary. The age of the Ettrick Formation can therefore be correlated with sedimentation in the intramontane Meadows-Myponga and Hindmarsh Tiers Basins. It is also a lithostratigraphic correlative of the Oligocene parts of the Ruwarung Member of the Port Willunga Formation of the St. Vincent Basin (Lindsay & Bonnett, 1973; Lindsay & Williams, 1977). The lithology of these formations clearly indicates that they

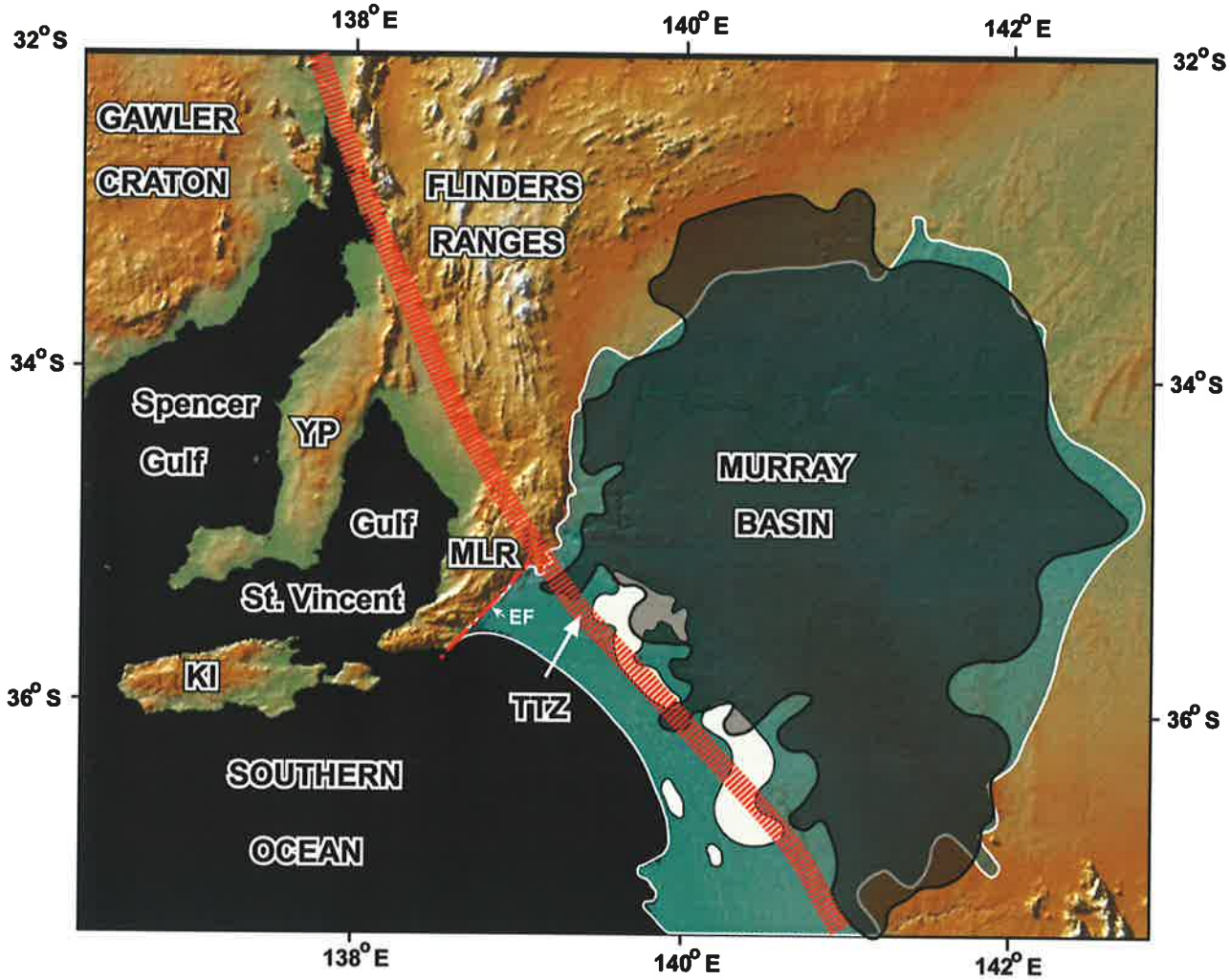


Fig. 4-15 Distribution of the Late Oligocene-Middle Miocene shallow marine Ettrick Formation (dark area with black outline) and Murray Group Limestones (pale-blue area with white outline) based on borehole data (after Brown & Stephenson, 1991). White areas = erosional/non-depositional areas during the Murray Group accumulation. MLR = Mount Lofty Ranges; KI = Kangaroo Island; YP = York Peninsula; EF = Encounter Fault. TTZ = Tertiary Transfer Zone associated with extensional tectonic regime. Shaded-relief image derived from 9-s DEM (Geoscience Australia).

were all deposited in shallow marine environments with a restricted terrigenous supply. It is important to note that the ferruginous supply from the source area was also significantly reduced, even into the intramontane basins. This supports the earlier scenario of marine inundation into the Southern Mount Lofty Ranges that removed the regolith from this source area during the short interval of deposition of the Compton Conglomerate.

The abundance of glauconite and marine fossils indicates that Ettrick sediments were formed in a shallow marine and low-energy environment. Sedimentation of the Ettrick Formation occurred in deeper marine water in the SW part of the Western Murray Basin that gradually changed further northward to restricted-marine and lagoonal environments (Brown & Stephenson, 1991). Because this Formation also developed during the Late Janjukian Stage, further consideration and interpretations will be made later.

4.7.4 Early Janjukian Stage: Conclusion

- The Early Janjukian Stage is one of the most important and recognisable intervals of the neotectonic development of the southern Mount Lofty Ranges.
- Crustal segmentation associated with downward block movements resulted in substantial landscape lowering and formation of sedimentary accommodation space in the intramontane Meadows, Myponga and Hindmarsh Tiers Basins.
- Combination of downward tectonic movements with small sea-level rise resulted in marine inundation, erosion and removal of the old and well-developed regolith from a wide area of the southern Mount Lofty Ranges and Fleurieu Peninsula.
- Strong west-to-east marine currents were the most likely process of gravel and regolith delivery into the SW part of the Murray Basin where the Compton Conglomerate was deposited.
- Subsidence of the intramontane basins is estimated at over 250m during the Early Janjukian Stage. The accommodation space of these basins was only partly filled by dominantly marine carbonate sediments.
- Continuing sedimentation in the marine environments occurred in the St. Vincent and Western Murray Basins due to further basin subsidence.

At the end of the Early Janjukian Stage, a small drop in sea-level of ~40m lowered sea-level to about 40m above PSL. However there is no evidence of any sedimentary interregnum in

the St. Vincent Basin, either in the intramontane Myponga and Hindmarsh Tiers Basins, or in the southern Western Murray Basin. In order to compensate for this new sea-level drop further tectonic subsidence must have affected the southern parts of the Mount Lofty Ranges and flanking basins at the end of the Early Janjukian Stage.

4.8 Late Janjukian Stage (~24-21Ma)

The beginning of the Late Janjukian Stage is associated with the Clifton transgression that occurred along the southern Australian continental margin some time near the Late Oligocene and Early Miocene boundary (McGowran et al., 1997). The global eustatic curve indicates that a new sea-level rise up to 140m above PSL occurred during this transgression. In spite of continuing sedimentation in the St. Vincent, Western Murray and also in the intramontane Myponga and Hindmarsh Tiers Basins, there are no new formal lithostratigraphic units to those in the Early Janjukian Stage. Thus the Early Miocene part of the Port Willunga Formation was deposited in the St. Vincent Basin and in the intramontane basins; and the Ettrick Formation continually accumulated in the Western Murray Basin during the Late Janjukian Stage.

4.8.1 Late Janjukian Stage in the St. Vincent and Intramontane Basins

The Late Janjukian Stage is associated with the formation of the informal Upper Janjukian unit of the Port Willunga Formation represented by glauconitic sandy limestone/calcareous sandstone above the Ruwarung Member. The Upper Janjukian unit is fossiliferous and glauconitic but contains more clayey components than the Ruwarung Member (Lindsay, 1981).

There are some lithological differences of this unit in the Willunga and Adelaide Plains Embayments. In the Willunga Embayment the base of the Upper Janjukian unit is represented by sandy dolomitised limestone and dolomite (Cooper, 1979). The same interval in the Adelaide Plains sub-basin is also represented by dolomitised but coarser sandy limestone/calcareous sandstone with occasional gravelly quartzose bands (Lindsay, 1981). There are thickness differences of these deposits throughout the St. Vincent Basin: average 12m within Adelaide sub-basin; 4.5m in the Noarlunga Embayment, and ~6.5m in the Willunga Embayment (Lindsay, 1981). Meanwhile in the intramontane Hindmarsh Tiers Basin, the total thickness of the Upper Janjukian unit may attain several tens of metres

(Furness, 1975).

The irregular thickness distribution of the Upper Janjukian unit in the Adelaide Plains sub-basin indicates a local tectonic differentiation of block movements. For example, there is a thickness increase from 4m near Port Gawler to up to 25m near the Redbank Fault in the north part of these Plains. The thickness also increases towards the Eden-Burnside Fault from an average of 13m up to 31m near Flinders University (Lindsay, 1981). There is also a significant increase of thickness of the Upper Janjukian unit toward the Willunga Fault from 5m in the vicinity of Snapper Point up to 30m in bore WLG-40 (Stuart, 1969; Cooper, 1979).

These facts allowed Lindsay (1981, p.314) to conclude that this "Upper Janjukian unit thickens towards basin margins and in fault-angle depressions". Such a significant thickness increase must also indicate that down-to-basin block movements occurred and were accompanied by a low-angle tilting of the hanging-wall blocks towards the normal faults bounding embayments. These types of tectonic movements apparently provided extra sedimentary accommodation space near the faults and were thus responsible for the increased thickness. These data again support the extensional Tertiary tectonic setting with normal-fault interpretation (Fig. 4-6).

As with other members of the Port Willunga Formation, this informal Upper Janjukian unit was deposited in a neritic marine environment with limited access to the open ocean (Lindsay, 1981). The Late Oligocene-Early Miocene age of this unit may indicate that sedimentation was continuous during both the maximum sea-level drop and the high stand after the Clifton transgression. The coarser-grained quartzose constituents of this unit represent a higher-energy sedimentary environment that apparently was associated with temporary increased stream competence possible due to sea-level drops.

It is important to note that continuous marine sedimentation also occurred in the intramontane Myponga and Hindmarsh Tiers Basins in the environment similar to that of the St. Vincent Basin during the Late Janjukian Stage. This together with very fine-grained and dominant carbonate lithology clearly indicates that apparently only some high ridges escaped the Late Oligocene–Early Miocene marine transgression associated with relatively high sea-level (Fig. 4-1). The Sellicks Hill Range apparently remained as a natural barrier to sedimentary input into the Willunga Embayment from the northern and eastern parts of the Mount Lofty Ranges

during this stage. However because sea-level was ~60m higher than at its maximum in the preceding Early Janjukian Stage, substantial areas of the southern Ranges must have been submerged. Thus the intramontane basins captured most of these available sediments. This may partly explain the reduced thickness of the Upper Janjukian unit in the Willunga Embayment. However as mentioned for earlier stages the amount of accumulated sediments was primarily dependent on available accommodation space, and only secondarily on the amount of weathered and available material in the source areas. For marine environments such as those dominating during several Oligocene-Early Miocene stages the factor of available accommodation space is even more critical than for the mixed marginal-marine or fluviolacustrine environments. However stream competence or erosional/transportation capabilities directly depend on the energy of the landscape and thus mostly on tectonic activity in the source area, while climate would also be important but only secondary to tectonic factors.

4.8.2 Late Janjukian Stage in the Western Murray Basin

Continuing sedimentation of the green and grey, highly fossiliferous and calcareous clays with minor quartz content of the Ettrick Formation in the Western Murray Basin persisted during the Late Janjukian Stage (Brown & Stephenson, 1991). Increased glauconitic content and abundant marine fossils point to the increased influence of the shallow marine and low-energy environment that dominated over a large portion of this basin (Fig. 4-15).

It is important to note that part of the Ettrick Formation (equivalent to the Upper Janjukian unit) in the Western Murray Basin transgressed onto former erosional areas in the eastern Mount Lofty Ranges. Marine sediments outcrop in the River Marne Valley where they overlap old granites and metasediments (Lindsay, 1981). Ettrick sediments are also present inside the Bremer Valley near the Cross's Bridge and at Monarto (Fig. 4-13) where together with a thin section of the Compton Conglomerate they overlap the pre-Tertiary basement (Lindsay & Williams, 1977).

There was a substantial sea-level rise during this stage and the Clifton transgression would have created extra accommodation space. However if inundation occurred into the previously erosional and slope areas of the eastern Ranges (relatively high slope gradients), it would have more likely increased erosion rather than initiated deposition as sediments would be removed

and redistributed to the lower basin areas, except very rare and specific geomorphological conditions. Therefore sea-level rise alone would have been insufficient to provide the required accommodation space for sediment accumulation in those slope areas. It seems likely that at least some areas of the eastern portion of the Mount Lofty Ranges were also involved in subsidence during the Late Janjukian Stage to account for sediment accumulation and its protection from marine erosion and redistribution.

This scenario/interpretation would account for the lack of significant difference in the sedimentary environment of the Ettrick Formation in the Early and Late Janjukian Stages except for an increase of sea-level and some marine expansion over previous source areas. This again indicates the existence of only a low and gentle landscape of the Mount Lofty Ranges.

4.8.3 Late Janjukian Stage: Conclusion

- Continuing marine sedimentation in the intramontane Myponga and Hindmarsh Tiers Basins indicates that subsidence continually provided accommodation space within the southern Mount Lofty Ranges.
- Downward tectonic movements on the eastern slope of the Mount Lofty Ranges together with sea-level rise contributed to marine expansion over the border of the Western Murray Basin.
- Continuing slow subsidence at about 4m/Ma occurred in the St. Vincent Basin with pronounced local down-to-basin block movements along the normal faults bounding the embayments with possible low-angle tilt of the hanging-wall blocks, specifically along the Para Fault bounding the Adelaide Plains sub-basin.
- Predominantly carbonate deposition in low-energy shallow marine environments with restricted terrigenous supply indicates that relatively low and gently undulating relief of the Mount Lofty Ranges persisted during the Late Janjukian Stage.

There was a sea-level drop from ~120m to ~70m above PSL at the end of the Late Janjukian Stage that apparently reduced the sedimentary accommodation space in the St. Vincent and Western Murray Basins. However even in the intramontane Myponga and Hindmarsh Tiers Basins carbonate marine and marginal-marine sedimentation continued into the Longfordian and later stages.

4.9 Longfordian Stage (~21-16Ma)

The Longfordian Stage began with transgression associated with long-term (~4Ma) gradual sea-level rise from ~70m up to ~150m above PSL at the end of this stage (Fig. 4-1). At least two distinctive episodes of warm climate occurred during the Longfordian Stage (McGowran et al., 1997).

4.9.1 Longfordian Stage in the St. Vincent and Intramontane Basins

There was continuing predominantly marine carbonate sedimentation in the entire St. Vincent Basin and also in the intramontane Myponga and Hindmarsh Tiers Basins during this stage. The informal Early Miocene Longfordian unit of the Port Willunga Formation was accumulated in these basins and has a conformable contact with the Upper Janjukian unit. The lithology of these units is very similar and they are distinguished only biostratigraphically by various foraminiferal characteristics (Lindsay, 1981). These point to the smooth transition from one stage to another and suggest that the basin sedimentary surface must have been below sea-level despite the ~50m drop in sea-level at the boundary of the Late Janjukian and Longfordian Stages (Fig. 4-1).

The Longfordian unit of the Port Willunga Formation is widely distributed within the Adelaide Plains sub-basin. More than 50m of the glauconitic sand and sandy limestone of this unit was penetrated by the Croydon-2 Bore ~2km west of the Para Fault (see Fig. 1-2 for location). Some ferruginous material including the brown and red-brown coloured clayey quartz sand is sometimes present in the succession (Lindsay, 1981). This indicates that deep regolith was still available in the Mount Lofty Ranges. The fine-grained terrigenous input indicates that sluggish drainage systems of the South Para, Torrens and Sturt Rivers were not capable of deep erosion and of delivering coarse sediments into the Adelaide Plains. Thus it seems that low gradient channels were continually associated with a low standing and subdued landscape developed in the western portion of the Mount Lofty Ranges during the Longfordian Stage.

In the Willunga Embayment, the Longfordian unit consists of predominantly carbonate and sandy limestone. Insignificant ferruginous or other terrigenous input indicates that only minor deep regolith was available in the southern Mount Lofty Ranges during this deposition. The drainage systems in this portion of the Ranges were apparently less competent than in the

central part east of Adelaide Plains. This was apparently due to lower landscape nearby the Willunga Embayment possibly covered by the sea. However ~60m of Longfordian sediments was penetrated by drilling (Bore WLG-38) inland of the Willunga Embayment (Cooper, 1979). Such significant thickness of fine-grained carbonate sediments points to intensive formation of accommodation space in this embayment during the Longfordian Stage. Due to increased thickness toward the Willunga Fault the formation of sedimentary accommodation space was apparently related to down-to-basin block movements along this fault with possible low-angle tilting of the hanging-wall block. Generally, the St. Vincent Basin was subsiding during the Longfordian Stage at the same rate ~4m/Ma as it had subsided during the preceding Late Janjukian Stage (Fig. 4-2).

A Miocene carbonate package similar to that of the St. Vincent Basin accumulated in both the Myponga and Hindmarsh Tiers intramontane basins. These sediments were formed in a shallow marine to marginal-marine environment with very restricted terrigenous supply (Furness, 1981). It is important to note that this sedimentation occurred in the middle part of the southern Mount Lofty Ranges that were certainly flooded by marine inundation. Therefore this region was generally low-lying and probably substantially submerged, while some spurs and ridges could appear above sea-level. Despite this, the rate of subsidence within the southern Mount Lofty Ranges significantly dropped from ~ 40m/Ma during the late Willungan and Early Janjukian Stages to ~4m/Ma during the Late Janjukian and Longfordian Stages (Fig. 4-9). However the higher rate of sedimentation (~15m/Ma) in both the Adelaide Plains sub-basin and Willunga Embayment indicates that locally substantial part of the sedimentary accommodation space was formed due to fault movements accompanying the sea-level rise. Altogether the data above indicates that:

1. There is no indication of uplift of the western or southern parts of Mount Lofty Ranges. Restricted terrigenous supply suggests that low and subdued landscape of this source region persisted during the Longfordian Stage.

2. Reduced but continuing basin subsidence including the St. Vincent and intramontane Myponga and Hindmarsh Tiers Basins together with a rising trend of the sea-level and warm climate facilitated production of carbonate sedimentation.

4.9.2 Longfordian Stage in the Western Murray Basin

The Longfordian Stage in the Western Murray Basin is associated with the accumulation of the Murray Group Limestones. This group of units usually overlies the Ettrick Formation in the major part of the Western Murray Basin; however in some places in the southern part of this basin these directly overlie the Buccleuch Beds and Compton Conglomerate. The Murray Group Limestones also onlap directly onto the pre-Tertiary basement in some areas on the western basin margin. The most likely age of the Group is the Early Miocene, however there is a possible transition from latest Oligocene up to Middle Miocene (Brown & Stephenson, 1991). Table 1 shows components of the Murray Group Limestone and their most likely age and occurrence.

In spite of the wide lithological spectrum of this group, generally all members may be divided into two principal types: predominantly limestones and significantly clayey units. The limestones are characterised by higher carbonate content, abundance of fossils and skeletal debris and a wider uniform distribution. The second type consists of poorly lithified clays of various colours with minor fine-grained angular quartz components and patchy distribution, mainly near the basin margins. A combination of calcareous clays and clayey limestone with minor calcareous sandstone containing fine-grained quartz, silt and glauconitic clay are the components of the Morgan Limestone and Cadell Marl, widely distributed in the Western Murray Basin.

The Murray Group Limestones were deposited in the 'Murravian Gulf', a shallow epicontinental sea which flooded the Western Murray Basin from the Late Oligocene to the Middle Miocene (Brown & Stephenson, 1991, p. 134). Most units of the Murray Group apparently accumulated during the marine transgression associated with long-term sea-level rise during the Longfordian Stage. However a low-lying and relatively flat surface of deposition with relatively small fluctuations in base level caused extensive lateral migration of facies boundaries (Brown, 1985).

The Murray Group (including Longfordian and later sediments) is distributed over much of the Western Murray Basin (Fig. 4-15). The combined thickness of these sediments is about 100m; however it is variable in places. For example, in the SW part of the Basin (Buccleuch Embayment) the Group is much thinner possibly due to later Pleistocene erosion. "Generally,

Component Unit	Occurrence (State)	Age
Pata Limestone	S.A.	Middle Miocene
Morgan Limestone	S.A.	Early to Middle Miocene
Cadel Marl Lens of the Morgan Limestone	S.A.	Early Miocene
Finniss Clay	S.A.	Early Miocene
Mannum Formation	S.A.	Early Miocene
Duddo Limestone	Vic., NSW	Late Oligocene to Early Miocene
Gambier Limestone	S.A., Vic.	Late Oligocene to Early Miocene
Naracoorte Limestone Member of the Gambier Limestone	S.A.	Early Miocene

TABLE 1 Age Range of the 'Murray Group Limestone' Units (after Brown & Stephenson, 1991)

the Murray Group Limestones can be considered to form a horizontal sheet of sediments which is locally disrupted by faulting" (Brown & Stephenson, 1991, p.125).

The minor occurrence of fine-grained angular quartz together with patchy distribution of the clay units indicates that only minor erosion and sedimentary supply into the marginal-marine environment occurred along the eastern edge of the Mount Lofty Ranges during the Longfordian Stage. Outcrops of the Murray Group Limestones in the Marne River and Burra Creek (Thomson, 1969a; Firman, 1972; Rogers, 1978) are strong evidence of relatively deep marine expansion into the eastern portion of Ranges. This together with the onlap of Mannum Formation on the Kanmantoo metasediments on the eastern slope of the Ranges (Thomson & Horowitz, 1962) indicates that a low and gentle landscape was inherited from previous stages. While long-term sea-level rise obviously contributed to marine expansion into the eastern portion of the Mount Lofty Ranges, there are no specific geomorphological or lithostratigraphic indications of active uplift during this stage. In contrast, any uplift would impact on the shallow marine sedimentation and probably would redistribute those sediments accumulated on the eastern slope of the Ranges.

Thus, both rising sea-level and slow basin subsidence have contributed to the formation of the accommodation space of the Murray Group Limestones in the Western Murray Basin. However some areas of the eastern portion of the Ranges were probably also involved in the subsidence that facilitated the marine expansion and preservation of soft sediments accumulated during the Longfordian Stage.

4.9.3 Longfordian Stage: Conclusion

- Predominantly carbonate marine sedimentation in the St. Vincent and Western Murray Basins and also in the intramontane Myponga and Hindmarsh Tiers Basins provides strong support for a low and gently undulating landscape of the Mount Lofty Ranges, the southern part of which probably was submerged.
- Long-term gradual sea-level rise accompanied by a low rate of basin subsidence were obvious contributors to the formation of sedimentary accommodation space in all those basins during the Longfordian Stage.
- Both basin sedimentary environments and geomorphological interpretations of the source region indicate that there was a slight but perceptible reduction of crustal extension resulting in only subtle tectonic effects throughout the whole study region.

4.10 Batesfordian and Balcombian Stages (~16-13Ma)

There is no formal or informal division of the Batesfordian and Balcombian Stages in the lithostratigraphic framework. Both stages are represented by an informal substantially carbonate unit overlain by the Munno Para Clay Member of the Port Willunga Formation in the St. Vincent Basin. Bryozoal limestones in the intramontane Myponga and Hindmarsh Tiers Basins and upper part of the Murray Group Limestones in the Western Murray Basin are represented in the same time-interval. Therefore both stages are considered here as a single important interval of Tertiary history. The boundary between the Longfordian and Batesfordian Stages is primarily biostratigraphic and only partly lithostratigraphic (eg. Lindsay, 1981). However the recalculated eustatic curve (Fig. 4-1) indicates that a boundary between these stages may be associated with dramatic sea-level drop at about 15.5Ma.

The Batesfordian Stage began with a short interval of sea-level recovery after the substantial drop of ~100m at the end of the Longfordian Stage. However, there was no sedimentary interregnum and only variable lithology apparently reflecting a rapid reduction and recovery of accommodation space in basin environments. The Batesfordian Stage was apparently associated with a rapid recovery of sea-level to ~130m above PSL with another significant sea-level drop of ~ 80m at the end of this stage that lowered sea-level to ~50m above PSL.

The beginning of the Balcombian Stage was probably associated with a new but also rapid sea-level rise up to the previous ~130m level above PSL after a short low sea-level stand. The rest of the Balcombian Stage was associated with progressive downward trend of sea-level as indicated by the global eustatic curve (Fig. 4-1). There was a warm and wet climate during these stages known as the Miocene climatic optimum (McGowran & Li, 1996, 1998; McGowran et al, 1997).

4.10.1 Batesfordian and Balcombian Stages in the St. Vincent and Intramontane Basins

There are two lithostratigraphic units associated with these stages in the St. Vincent Basin: the informal substantially carbonate 'Batesfordian-lower Balcombian' unit and the formal Munno Para Clay Member of the Port Willunga Formation.

The lithology of the 'Batesfordian-lower Balcombian unit' of the Port Willunga Formation is variable from sandy limestone, quartzose, calcarenitic, sparsely glauconitic clayey limestone

to calcarenitic clay and sandy clay as drilling of the Adelaide Plains shows (Lindsay, 1981). Some benthonic assemblages indicate a warm and shallow water environment (possibly less than 12m deep) of the eastern St. Vincent Basin (Lindsay, 1981 with reference to Chaproniere, 1975). This unit is dated at about Early/Middle Miocene (McGowran, 1978, 1979; Lindsay, 1981).

In spite of significant sea-level fluctuations continuing marine sedimentation also occurred in the intramontane *Myponga and Hindmarsh Tiers Basins*. About 21m of bryozoal limestones represent the same depositional episode in the upper part of the Mid-Tertiary sequence in the Myponga Basin (Glaessner, 1953; Glaessner & Wade, 1958; Lindsay, 1981; Stuart, 1969; Wade, 1958). This marine environment and the sedimentation of limestone is crucial evidence of a very gentle landscape surrounding these basins capable of providing only a very minor terrigenous input.

It seems that the restricted land surface of the southern Mount Lofty Ranges was just above the maximum sea-level stands. However the subsiding basins were likely to have been permanently under marine water thereby providing sedimentary accommodation space during short sea-level falls. These intramontane basins are probably best described as marine lagoons. There is no reason to suggest that uplift affected the southern Mount Lofty Ranges during these or earlier stages. On the contrary, downward tectonic movements must have continually occurred to generate required basin accommodation space during the Batesfordian-Balcombian Stages.

Munno Para Clay Member of the Port Willunga Formation

Sea-level fell to about 50m above PSL at the possible boundary between the Balcombian and Batesfordian Stages and then rapidly recovered to the previous level of ~130m above PSL (Fig. 4-1). This time of sea-level fluctuations is associated with accumulation of the Munno Para Clay Member of the Port Willunga Formation in the St. Vincent Basin (McGowran, 1978, 1979).

About 27m of this unit is encountered in the Claydon-2 Bore in the Adelaide sub-basin. However the Munno Para Clay Member does not occur westward of the Para Fault in the Adelaide City area perhaps partly due to later erosion (Lindsay, 1981). This Member has also been found inland of the Willunga Embayment (WLG-38 Bore) beneath the Pleistocene

unconformity (Cooper, 1979).

Intercalation of the fossiliferous limestone beds with grey and blue clay of the Munno Para Clay in the Adelaide Plains occurred in the restricted but still marine environment and testifies to the fluctuating regime (Lindsay, 1981). Such lithology indicates that there was only restricted erosion and sedimentary supply from the western portion of the Mount Lofty Ranges. McGowran (1978, 1979) suggests that the Munno Para Clay is a local expression of a widespread, regressive, cooler episode between two warm climatic peaks: the Batesfordian and Balcombian.

The absence of any alluvial or other coarse sediments in the Munno Para Clay Member points to the presence of a low and gently undulating landscape in the western portion of the Mount Lofty Ranges. Lack of slope debris even near the major bounding faults such as Para and Eden-Burnside in the Adelaide area, Clarendon in the Noarlunga Embayments and Willunga Fault in Willunga Embayment indicates that only minor and low-magnitude block movements occurred along these normal faults. Such down-to-basin block movements would be more consistent with minor erosion and incompetent streams than with uplift accompanied by reverse fault motions.

4.10.2 Batesfordian-Balcombian Stages in the Western Murray Basin

Various age determinations of the upper part of the Murray Group Limestones (Table 1) indicate that the sedimentation of most members of this group ceased earlier in the Early Miocene or at the end of the Longfordian Stage. However the Morgan Limestone persists to the Batesfordian-Balcombian Stages where the presence of some species of foraminifera indicates that the uppermost part of this unit extended into the Middle Miocene (Lindsay & Bonnett, 1973).

The Morgan Limestone is represented by skeletal and quartzose calcarenite, calcareous clay with minor calcareous sandstone and glauconite. This Limestone is distributed over a large area of the Western Murray Basin where up to a few tens of metres of these sediments accumulated within the shallow marine environment of the 'Murravian Gulf'. The western border of this Gulf is outlined by the marine sediments located close to the eastern slope of the Mount Lofty Ranges. The Morgan Limestone together with the underlying Mannum Formation (commonly undistinguishable) sometimes onlaps the Proterozoic metasediments of

the Kanmantoo Group exposed in the slope areas (Thomson, 1969; Firman, 1972; Rogers, 1978).

Such lithology and distribution indicates that only minor terrigenous input was available during the Batesfordian-Balcombian Stages. Therefore it suggests that a low-lying gently undulating landscape was also a dominant geomorphic feature in the eastern portion of the Mount Lofty Ranges. Thus only subdued subsidence of the Western Murray Basin and probably of some areas of the eastern slope of the Ranges occurred during this stage. There is some indication of a regressive sequence of the uppermost part of the Morgan Limestone associated with marine retreat from the Murray Basin (Ludbrook, 1961; Brown, 1985). However even this did not evoke any additional terrigenous supply. Thus environment of deposition corresponds to subdued tectonics and a low and gentle landscape of the eastern portion of the Mount Lofty Ranges.

The Morgan Limestone represents the last episode of the Oligocene-Middle Miocene marine sedimentation in the 'Murravian Gulf' near the Mount Lofty Ranges because the younger Middle Miocene Pata Limestone occurs only in the deeper Renmark Trough of the central part of the Murray Basin far from this source region (eg. Brown & Stephenson, 1991). Thus the Miocene marine record in the Western Murray Basin terminates sharply in the Balcombian Stage. This is consistent with the end of high sea-level stands and the termination of the climatic optimum (eg. McGowran et al., 1997). It is also consistent with the decline or even disappearance of the rainforest-type flora and the rainforest-type fauna that characterised the Early Miocene of inland Australia (Martin, 1991; Kershaw et al., 1994; Archer et al., 1994, 1996). Analysis of the global eustatic curve (Fig. 4-1) shows that a real trend of sea-level fall and thus termination of high stands occurred at the end of the Balcombian Stages.

4.10.3 Batesfordian-Balcombian Stages: Conclusion

- The lithostratigraphic record strongly suggests that only subdued tectonic movements such as low-magnitude basin subsidence occurred during these stages.
- The landscape of the Mount Lofty Ranges remained gently undulating with sluggish drainage systems capable of delivering only very-fine terrigenous sediments into the St. Vincent and Western Murray Basins and also into the Myponga and Hindmarsh Tiers

intramontane Basins.

- Some areas of the eastern portion of the Mount Lofty Ranges also experienced subsidence as evident from marine expansion into those areas.

The sudden termination of sedimentation almost simultaneously in all these basins is attributed here to the major fall in sea-level that occurred after the Middle Miocene climatic optimum. However a substantial reduction of crustal extension that was unable to provide any further accommodation space also contributed to this termination.

4.11 Bairnsdalian and Mitchellian Stages (~13-5.5Ma)

Following the significant sea-level fall from ~140m above PSL (the Middle Miocene climatic optimum) to ~70m below PSL (end of the Bairnsdalian Stage) there is no record of sedimentation either in the St. Vincent and Western Murray Basins or in the intramontane Myponga and Hindmarsh Tiers Basins between ~14Ma and ~5.5Ma. The main part of the Bairnsdalian Stage is associated with rapid sea-level drop from ~60m above PSL to ~70m below PSL. Such a substantial sea-level fall, in addition to preceding falls, inevitably affected the shallow marine environments of all these basins by rapid and apparently complete marine retreats. If one takes into account that tectonic subsidence was significantly reduced at the end of the preceding Balcombian Stage as the above data indicates (Figs 4-2; 4-9), then it would follow that a retreating sea exposed basin sedimentary surfaces to weathering and erosion.

4.11.1 Late Miocene Sedimentary Termination, Uplift and Erosion

It is important to note that at the end of the Bairnsdalian Stage sea-level fell below the PSL, the first time for the entire previous Tertiary Period (Fig. 4-1). This evoked a termination or interruption of sedimentation in some interior basins along the southern Australian continental margin. At the beginning of the Mitchellian Stage however, sea-level recovered up to PSL but remained at the low stand with some 20-30m fluctuations above and below PSL. Because of the Late Miocene lithostratigraphic interregnum in the study region, available information from neighbouring regions and further from the southern Australian continental margin and its slope was used and incorporated into this thesis.

Since the sea-level falling trend took place in the Middle Miocene, there was a sedimentary

termination in many onshore and nearshore basins along the southern Australian continental margin (Abele et al., 1976, 1988; McGowran, 1979, Brown & Stephenson, 1991). Lithostratigraphic hiatuses and erosional low-angle unconformities have been recognised between latest Middle Miocene and Pliocene sedimentary packages onshore in the Gippsland, Bass and Otway Basins (Dickinson et al., 2001, 2002), in the Murray Basin (Brown & Stephenson, 1991), in the St. Vincent Basin (Lindsay & Alley, 1995) and also along the continental slope in the Great Australian Bight (Li et al, 2004).

However the time of sedimentary termination varied from ~14Ma in the St. Vincent and Murray Basins (McGowran et al., 1997; Brown & Stephenson, 1991), to 11-10Ma in the Port Phillip and Hamilton area of the Otway Basin, and even to ~8Ma in the Gippsland Basin (Dickinson et al., 2002). This indicates that regional tectonic deformations must be an important factor in triggering this termination. Otherwise, if termination of sedimentation was due only to sea-level drop, it would have occurred simultaneously in all those basins.

There is a general belief that mild uplift in the Late Miocene resulted in sedimentary termination, erosion and formation of low-angle unconformities in the St. Vincent and Murray Basins. Similar uplift in the Eucla and Gambier Basins also resulted in cessation of sedimentation and sub-aerial exposure of the sedimentary surface followed by karst development and erosion (Benbow et al., 1995). A general low-angle unconformity (<1-5°) between the Middle Miocene and Pliocene sedimentary packages was also recorded in the Otway, Port Philip/Torquay and Gippsland Basins (Dickinson et al., 2001). Thus, there is no doubt about tectonic involvement in the formation of the Miocene/Pliocene unconformity or the presence of Late Miocene tectonic deformations in all those basins. However there is no direct evidence of uplift in the St. Vincent or Western Murray Basins. The only deformation recorded in the Late Miocene is a low-angle unconformity that is not necessarily associated with uplift.

Dickinson et al. (2001) argue that the Late Miocene tectonic uplift in Victoria (particular in the Otway and Strzelecki Ranges) was more significant than the later Pliocene-Recent uplift. These authors propose a Late Neogene uplift and exhumation in the range of over 600m associated with a compressional tectonic regime. Similar erosion of ~1000m around the Otway Ranges was suggested by Cooper & Hill (1997). The existence of exhumation, gentle folding and reverse faulting associated with basin inversion along the eastern sector of the

continental margin (east of the Gambier Embayment) as presented by Dickinson et al. (2001, 2002) is completely accepted here. Complimentary to this, Fig. 4-9 suggests that the southern parts of the Mount Lofty Ranges probably were also up-warped as the marine inundation into the intramontane Myponga and Hindmarsh Tiers Basins has never re-occurred since the Middle Miocene. However an estimated ~100m uplift of the source area, or alternatively flanking basins subsidence during the Late Miocene would have been sufficient to protect the southern Mount Lofty Ranges from the Pliocene marine transgression. Meanwhile a putative 600-1000m of uplift and erosion of the Victorian south-western ranges (Cooper & Hill, 1997; Dickinson et al., 2000) seems speculative and perhaps exaggerated, if one takes into account the nature of erosion and sea-level stands during the Late Miocene.

4.11.2 Nature of the Miocene/Pliocene Unconformity, Erosion and Exhumation

There is a general consensus about the low and fluctuating sea-level during the Late Miocene (Fig. 4-1). This has been confirmed by a number of unconformities and lithostratigraphic hiatuses in the Great Australian Bight (Li et al., 2004) and also by the well-developed canyons incised into the southern continental shelf (Holdgate et al., 2000; Gallagher et al., 2003). Therefore sea-level changes in the Late Miocene may be correlated with the global eustatic curve and used as direct evidence of neotectonic movements that occurred along the southern Australian continental margin.

Information extracted from deep ocean drilling records in the Great Australian Bight indicates that a total of 15 unconformity-bounded hiatuses comprise the Neogene lithostratigraphic sequence (Li et al., 2004). Six of these hiatuses are related to the Late Miocene-Early Pliocene. A stepwise model of the evolution of the southern Australian margin since the Middle Eocene has been proposed (Li et al., 2003) and extended to the Neogene (Li et al. (2004). This model infers that hiatuses coincide with third-order sequence boundaries corresponding to sea-level fluctuations at time scales similar to the global pattern (eg. Haq et al., 1987). Therefore global eustatic control on sequence boundaries is considered to be the most important factor, though regional tectonic movements may complicate this.

It seems plausible that major stream erosion occurred somewhere on the continental shelf or even slope a few hundreds kilometres away from the study region during Late Miocene low sea-level stands. However it would be odd to suggest that the Mount Lofty Ranges did not

supply any terrigenous sediments into the emptied flanking basins. Palynological dating of the upper part of the Rowland Flat Sands in the Barossa Basin is clear evidence that fluviolacustrine sedimentation did actually occur during the Early to Late Miocene (Alley, 1995a). This indicates that most of the sedimentary supply from the Mount Lofty Ranges, albeit minimal, was not preserved in these flanking basins. That stream erosion that picked up and removed all late Middle and Late Miocene sediments from the basin flat sedimentary surface seems to be very unrealistic. First, there was no significant stream erosion as it has to occur somewhere on the continental slope or shelf according to the low sea-level stand as the major base of erosion. Second, there was a noted climatic deterioration toward the dry mode with increasing aridity and diminishing precipitation by the end of the Middle Miocene and during the Late Miocene (Martin, 1977, 1991; Truswell & Harris, 1982; McGowran, 1987). Third, there was a restricted source region of the Mount Lofty Ranges with an apparent low and undulating landscape (see previous stages) unable to generate large drainage systems. Therefore sedimentary discharge of mainly fine-grained sediments by starved streams from the Mount Lofty Ranges most probably occurred in the vicinity of slope areas of the Ranges on the flat sedimentary surfaces of the flanking basins.

The absence of any Late Miocene sediments in the St. Vincent and Western Murray Basins (within the study region) indicates that these sediments were completely removed from these flanking basins. However the mechanisms of basin erosion and delivery of these sediments to the continental shelf and beyond are still unclear. One may suggest that these sediments were removed from the onshore St. Vincent and Western Murray Basins and delivered onto the continental shelf by stream erosion during the low sea-level stands. However the flat basin morphology associated with exposed sedimentary surface and basin-wide uniform Miocene/Pliocene unconformity in these inland basins significantly contradicts such a suggestion. If the Miocene/Pliocene unconformity was formed by fluvial erosion, it would not be as wide and uniform as it is, because stream erosion is spatially restricted to vertical channel incision and thus unable to form laterally uniform (almost flat) and basin-wide erosional features. This is an additional argument to those three above rejecting fluvial erosion as the major process that removed late Middle and Late Miocene sediments and formed the Miocene/Pliocene erosional unconformity.

4.11.3 Marine Bed-load Erosion

In contrast to basin stream erosion it is more probable that shallow marine bed-load erosion removed minor Late Miocene fluvial input together with the upper part of the Middle Miocene sedimentary package during the repeated marine regressions that formed the Miocene/Pliocene unconformity. Marine bed-load erosion would also have provided a satisfactory mechanism of sediment delivery onto the continental shelf, where Miocene sediments are widely distributed and are not restricted only to the canyons. Similar marine erosion would also have contributed to incomplete stratigraphic sections and hiatuses on the southern Australian continental shelf, stripping Late Miocene sediments in places due to sea-level fluctuations.

Analogous to the Miocene/Pliocene unconformity in the St. Vincent Basin, relatively flat, wide and laterally uniform unconformities are common throughout several onshore and near-shore basins in the SE sector of the Australian continental margin (Dickinson et al., 2002). This indicates that a large region, if not the entire southern Australian continental margin, experienced similar processes of non-deposition/erosion apparently associated with several long-term and perhaps a number of short-term marine retreats that would be associated with marine bed-load erosion during the Late Miocene.

According to structural reconstructions (Dickinson et al., 2002) the basin erosional surface may be correlated with planation surfaces on the Otway and Strzelecki Ranges. In addition to such reconstructions, a lithological analysis of Tertiary sediments allowed these authors to suggest that "the Cretaceous blocks had not been uplifted and exposed to significant erosion until the end of the Miocene" (Dickinson et al., 2002, p.31). Without reference to the nature of erosion those authors then concluded that about 600m to 1km of soft sediments were stripped from these highlands. This erosion was supposed to occur during a relatively short time-interval (end of the Miocene to Pliocene). Once again, it must be noted that the stripping of large amounts of sediments almost simultaneously from a very broad region would be very problematic (if not impossible) by simple stream erosion in the absence of large and powerful river systems over such a short time-interval. In contrast, the preservation of a number of erosional flat surfaces well-developed on the relatively soft Lower Cretaceous sediments in the Otway and Strzelecki Ranges indicates that they are also probably the result of laterally wide bed-load marine erosion rather than a product of fluvial processes. Therefore it seems

likely that basin-wide low-angle erosional unconformities and well-developed planation surfaces in these highlands are mainly the result of the same intensive process of marine bed-load erosion that possibly occurred during several Late Miocene marine retreats and only secondarily (laterally restricted) related to stream erosion.

There is a general consensus that Mid-Miocene and older strata in inland and near-shore basins along the southern Australian continental margin were formed in shallow marine environments with a water depth of only a few tens of metres (eg. Li et al., 2004). The projection of the Mid-Miocene sea-level onto these regions would demonstrate that the sedimentary surface was initially higher or even significantly higher (>100m above PSL) than when it was exposed to Late Miocene erosion. If we believe that a significant part of the sedimentary section was stripped by marine erosion, then the Late Miocene low sea-level would have required ~100m of crustal subsidence in order to provide marine access to all these basins and particularly to the highland regions.

Thus a possible explanation for marine access and bed-load erosion would be as follows: low magnitude downward movements (~100m) reduced the altitude of landscape (including sedimentary surfaces) to approximately present sea-level that would be just about average level for the Late Miocene sea-level fluctuations. Subsidence was then probably slowly replaced by inversion with gentle folding, reverse faulting and also by minor uplift in some areas that was also accompanied by erosion. It would be reasonable to suggest several alternating episodes of downward and upward crustal movements (epeirogenic tectonic movements) during the Late Miocene. If one takes into account that 1° of tilting provides 17.5m/km of subsidence then a regional southward tilting (including the continental shelf) would be sufficient to lower previously higher surfaces down to Late Miocene sea levels (close to PSL). The low-angle Miocene/Pliocene unconformity (1-5°) recorded in the study region and other basins along the continental margin would be thus associated with such tilting providing marine excess to those basins and possibly to other erosional regions. This scenario is consistent with observed offshore Late Miocene fine-grained lithology, onshore sedimentary interregnum and geomorphological settings and also with low sea-level stands during the Late Miocene. It would also provide a more plausible mechanism for significant regional erosion and the formation of extensive erosional surfaces and low-angle unconformities rather than rapid Late Miocene uplift accompanied by substantial fluvial

erosion without adequate sedimentary response.

This scenario can be applied to the formation of the Miocene/Pliocene unconformity in the St. Vincent and probably SW Murray Basins. If the subsidence of the southern Mount Lofty Ranges had ceased at the beginning of the Late Miocene it would have been sufficient to protect the intramontane Myponga and Hindmarsh Tiers Basins from Pliocene marine inundation associated with sea-level rise. However gentle up-warping of this area of the Ranges could also be considered as one of the possible Late Miocene scenarios. Such a scenario would require interchange of subsidence and uplift during the Mitchellian Stage and thus probably interchange of extensional and compressional tectonic regimes referred to here as a "transitional tectonic regime". Further details relating to the Late Miocene-Pliocene 'transitional tectonics' are provided in Chapter 5.

4.11.4 Bairnsdalian and Mitchellian Stages: Conclusion

- The long-term Late Miocene-Early Pliocene sedimentary interregnum in the study region was associated mainly with substantial sea-level falls.

- A wide, uniform and low-angle erosional Miocene/Pliocene unconformity in the St. Vincent and SW Murray Basins was formed by marine bed-load erosion during several marine retreats associated with fluctuating sea-levels.

- The low and subdued landscape of the Mount Lofty Ranges drained by low-gradient sediment-starved streams was preserved during these stages with possible up-warping in the range of 100m.

4.12 Cheltenhamian and Kalimnan Stages (~5.5-2Ma)

The beginning of the Cheltenhamian Stage is associated with a significant sea-level rise from ~40m below to ~80m above PSL in the earliest Pliocene according to the recalculated eustatic curve (Fig. 4-1). This level was significantly higher than it was even during the Late Miocene maxima. There were also several dramatic changes of sea-level up and down within the 100m range during the Kalimnan Stage (Late Pliocene). Significant rises in sea-level (compared to the immediate preceding stage) resulted in widespread marine transgression onto the inland basins and generally onto the low-lying and gently undulating landscape of the southern Australian margin.

Despite some deterioration of the Miocene warm and wet climate (since the Middle Miocene climatic optimum), the Early Pliocene climate remained relatively stable and warmer than the Late Pliocene which was associated with the expansion of the Antarctic ice sheet. Gallagher et al. (2003) have written: "Palaeobotanical proxy data (mainly from south-eastern Australia) indicate that the regional climate oscillated between warm-wet and cool-dry phases, with an overall cooling-drying trend through the Pliocene, and by the end of the Late Pliocene climates and environments were similar to present day settings".

4.12.1 Cheltenhamian and Kalimnan Stages in the St. Vincent Basin

The Cheltenhamian and Kalimnan Stages in the St. Vincent Basin are associated with marine transgression and accumulation of the Kooyonga Formation, Dry Creek Sand and Hallett Cove Sandstone representing the Pliocene sedimentary succession in this basin.

Kooyonga Formation

The Kooyonga Formation is a basal Early Pliocene unit that mainly consists of a very fine grey silt, muddy and very fine-grained quartz sand and silty limestone. The unit is noticeably glauconitic and contains a fair proportion of fragments of mollusc, ostracode, foraminifera, bryozoan and other faunal constituents (Lindsay, 1981). The thickness of this unit varies from a few metres up to 30m in the Croydon-2 Bore west of Adelaide City. The distribution of this unit is patchy and limited to the sub-surface of the Adelaide Plains west from the Para Fault. The unit commonly intertongues with the Dry Creek Sand and was integrated into the Dry Creek Sand (Lindsay & Alley, 1995).

Dry Creek Sand

The Dry Creek Sand is a fossiliferous shelly sand unit widely distributed sub-surface within the Adelaide Plains sub-basin and typically occurs at the base of the Hallett Cove Sandstone in the vicinity of Adelaide City (Lindsay, 1981). The thickness of the Dry Creek Sand varies from a few metres up to 43 m (Dry Creek Bore type-section, Lindsay & Alley, 1995). Highly fossiliferous yellow sand up to 1m thick at the base of the Pliocene sequence at Blanche Point and in outcrop near the Port Willunga (Reynolds, 1953) may represent the same depositional event as the Dry Creek Sand in the Willunga Embayment (Lindsay, 1981). Deposition of this unit generally occurred in a shallow marine embayment with a very restricted marine access

(Ludbrook, 1959; Lindsay, 1981).

In spite of the abundance of fossils in this unit there is little fauna that may provide a clear age to the Dry Creek Sand. The Early to Late Pliocene age of the Kooyonga Formation integrated into the Dry Creek Sand is based on various benthonic fauna and rare planktonic species determinations (Ludbrook, 1961, 1963, 1973; Lindsay, 1977, 1981). This unit certainly occurred before the Hallett Cove Sandstone that typically overlies it.

The fine-grained lithology of the Dry Creek Sand indicates that only a gently undulating landscape with starved streams prevailed in the adjacent Mount Lofty Ranges. However the highly ferruginous content suggests that deep regolith was formed or preserved in this landscape before the Early Pliocene. This is also consistent with a low and gently undulating landscape of the Ranges during the preceding stages. Substantial local thickness is likely attributed to a new pulse in accommodation space formation. Irregular thickness and distribution of the Dry Creek Sand indicate that available accommodation space varied from place to place, apparently due to local variations of downward tectonic movements. The increased thickness of the Dry Creek Sand west of the Para Fault and its absence east of this fault indicates that down-to-basin block movements along the Para Fault provided the main sedimentary control. Normal fault geometry and possible fault-ward tilt of a subsiding hanging-wall block were the most likely structural characteristics of this accommodation space.

The Early Pliocene marine transgression and possible marine retreats associated with high fluctuating sea-level during the Late Pliocene (Fig. 4-1) apparently resulted in the redistribution of fine-grained terrigenous sediments and their mix with various carbonate bio-facies. However it is certain that preservation of tens of metres of the Dry Creek Sand was due to the formation of local accommodation space by downward tectonic movements along the well-established Para Fault. This leading one to the conclusion that a new pulse of crustal extension affected the study region that resulting in new subsidence in the St. Vincent Basin in the Early Pliocene, after a prolonged period of erosion/non-deposition. Thus the subsidence accompanied by sea-level rise was the main cause of the accommodation space formation during the Cheltenhamian Stage.

Hallett Cove Sandstone

The Hallett Cove Sandstone is a basin-wide sedimentary feature mostly outcropping in the present coastal zone from the Willunga Embayment in the south to the Adelaide Plains sub-basin in the north. The thickness of this unit is very irregular: from several centimetres to a maximum of 12.2m in the southern part of Adelaide City (Lindsay, 1981), with an average of a few metres.

The Hallett Cove Sandstone contains abundant marine fossils, mostly molluscs and foraminifera. However there is no distinct species available for accurate age determination (eg. Lindsay, 1981). This Formation is sometimes interbedded with the upper part of the Dry Creek Sand (Ludbrook, 1973, 1980). The overlying Early Pleistocene Burnham Limestone defines the upper boundary of the Hallett Cove Sandstone. Thus the Late Pliocene age of the Hallett Cove Sandstone may be considered to be certain.

This Formation at its type location in the Hallett Cove Conservation Park (south of Adelaide) is only about 1m thick and consists of "pale grey/pale brown, coarsely quartzose and richly fossiliferous calcareous sandstone" (Lindsay, 1981, p.352). At this locality the unit occasionally contains pebbles and boulder-size clasts at the base that Sprigg (1942) identified as reworked Permian glacial erratics widely distributed in this area. The lithology of this unit outcrops near the Port Willunga Jetty and comprises ~4m of fine-grained sands interbedded with six hard bands of calcareous sandstone or sandy limestone (Reynolds, 1953).

In the vicinity of Adelaide City the Hallett Cove Sandstone generally occurs as calcareous quartz sandstone/sandy limestone. Several samples recovered from the drill cores in the Adelaide CBD show that this unit consists mainly of detrital quartz grains and calcitic shell fragments cemented by a granular dolomitic matrix (Lindsay, 1981). The detrital quartz grains are generally between 0.05mm and 0.5mm in diameter and sub-angular to sub-rounded in shape. However the distribution of this unit in the Adelaide area is patchy because of its later exposure to erosion, weathering and karstification (Lindsay, 1981).

The sedimentary environment of the Hallett Cove Sandstone is typically shallow marginal-marine and probably represents a warm transgressive episode (Lindsay, 1976; McGowran, 1978, 1979). However, some of the benthonic foraminifera and other fossils may indicate that the marginal-marine environment was a sheltered to estuarine or lagoonal environment (eg.

Murray, 1973). Taking into consideration the global eustatic curve (Fig. 4-1) one has to suggest that the Early Pliocene accommodation space of the St. Vincent Basin was formed due to sea-level rise. However the Late Pliocene sea-level was close to PSL and accompanied by high magnitude fluctuations (~100m). Such fluctuations have to be considered as a major cause of rapidly changing environments of deposition followed by sediment redistribution. Well-mixed fine-grained terrigenous and carbonate sediments forming the Hallett Cove Sandstone would have been consistent with such changing environments.

The irregular and insignificant thickness (a few metres average) of the Hallett Cove Sandstone indicates that the Late Pliocene was not a sedimentary productive interval. This perhaps was due to insufficient accommodation space that leads to the suggestion of a very subtle basin subsidence associated with the Kalimnan Stage (Late Pliocene). The generally fine-grained lithology of all Pliocene units of the St. Vincent Basin indicates that incompetent streams were capable of supplying only minor terrigenous sediments from the adjacent Mount Lofty Ranges during the Pliocene. This, in turn, suggests that the western portion of the Ranges remained topographically low and apparently still gently undulating, and perhaps preserving a deep regolith from the previous stages.

4.12.2 Cheltenhamian and Kalimnan Stages in the Western Murray Basin

The commencement of Pliocene sedimentation in this basin is associated with the formation of the extensive Loxton-Parilla Sand that generally covers a large part the Murray Basin (Fig. 4-16). The Loxton–Parilla Sand is a composite unit consisting of various lithologies associated with complex sedimentary environments including shallow marginal-marine, estuarine and fluvial (Firman, 1965, 1966b, 1972, 1973). Firman recognised that the Lower Loxton Sand was formed in marginal-marine and estuarine environments, while the Upper Loxton Sand was associated mainly with fluvial input, or even entirely of fluvial origin. However, further investigation including fossil content shows that sedimentary environments were more complex and alternating and that such a simple division does not reflect all the changes in the environment (Lawrence, 1975; Macumber, 1983; Brown & Stephenson, 1991). Therefore a composite nature of the undifferentiated Loxton-Parilla Sand unit seems to be appropriate for regional analysis and interpretations (eg. Brown & Stephenson, 1991). However in South Australia it is possible to differentiate this unit into the Early Pliocene Loxton Sand and Late Pliocene Parilla Sand units (Firman, 1972; Rogers, 1978, 1980).

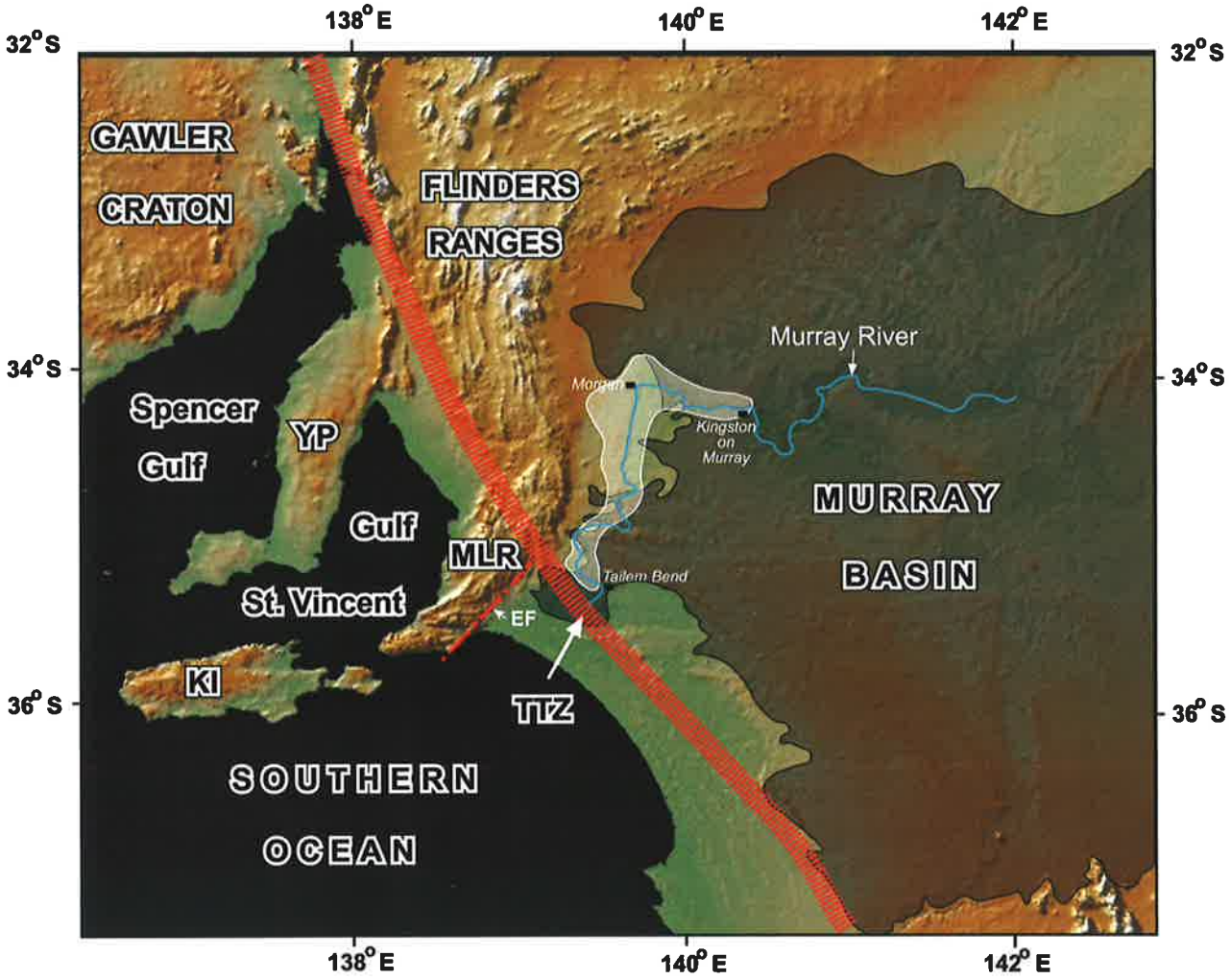


Figure 4-16 Distribution of the Pliocene Loxton-Parilla Sands (undifferentiated) (dark area with black outline) and Norwest Bend Formation (light area with white outline) based on borehole data (after Brown & Stephenson, 1991). MLR = Mount Lofty Ranges; KI = Kangaroo Island; YP = York Peninsula; EF = Encounter Fault. TTZ = Tertiary Transfer Zone associated with extensional tectonic regime. Shaded-relief image derived from AGSO 9-s DEM.

Loxton Sand

The Loxton Sand in South Australia is mainly represented by purplish-brown, fine- to coarse-grained, calcareous, shelly and quartz sands situated at the base and lower parts of the succession in the southern part of the Western Murray Basin. Further north in this Basin the Loxton Sand is represented by more clayey and fine-grained quartz sand, grey-brown in colour (Rogers, 1978, 1980). This section of the Loxton Sand according to Firman (1972) was supposed to have formed in a shallow marginal-marine environment that gradually changed to an estuarine complex. The upper part of this unit is represented by red, yellow and brownish fine to coarse-grained quartz sand formed in a fluviolacustrine environment (Firman, 1972; Rogers, 1978, 1980). Thickness of the Loxton Sand is highly variable from a few metres to a maximum of ~60m. The distribution of this unit is very wide and recognised almost everywhere in the Western Murray Basin except some areas in the south-west (eg. Pinnaroo Block), where it was completely removed by later erosion (Rogers, 1978, 1980; Brown & Stephenson, 1991).

The generally spherical, rounded and sub-rounded quartz grain shapes indicate that the majority of quartz particles travelled a long distance or were reworked before they were deposited. However the abundance of ferruginous material in the poorly sorted micaceous and quartz sand suggests the presence of a deeply weathered landscape nearby providing sediment source such as the Mount Lofty Ranges. The presence of marine fauna, at least in the lower parts of the Loxton Sand, indicates that marine access into most of the Western Murray Basin was available during the Early Pliocene. This seems to be related to a marine transgression associated with a sea-level rise up to ~80m above PSL (Fig. 4-1), after a prolonged period of non-deposition/erosion. However irregular thickness distribution and its increase toward the Para Fault, for example, as well as sediment preservation were apparently due to local tectonic movements providing extra accommodation space in some local areas of the Basin.

Rapid increase of sea-level at the beginning of the Early Pliocene must have evoked marine transgression not only into the Basin areas but also onto the low landscape of the Mount Lofty Ranges. The simulation of the Early Pliocene marine flood (maxima) at ~80m above PSL demonstrates that even the present landscape of the Ranges, uplifted mainly later in Pleistocene, would be profoundly affected by such marine transgression shown in (Fig. 4-17).

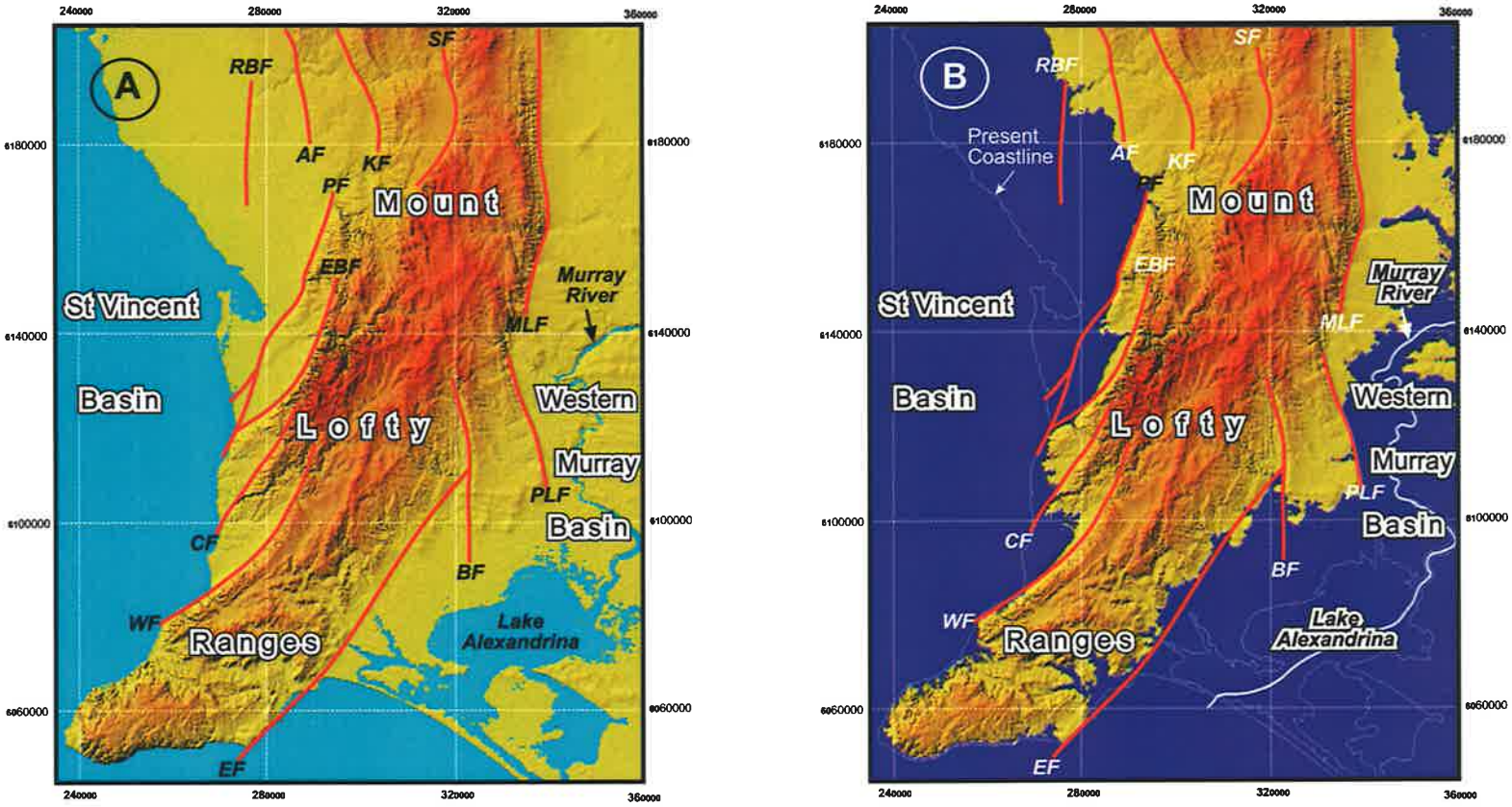


Figure 4-17 Possible effect of the Early Pliocene marine transgression on the landscape in the study region of the Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins. A = shaded relief image at PSL with some elements of neotectonic setting (see Fig. 1-2 for list of active faults) derived from 1s DEM analysis. B = 80m marine flood without correction to the Pleistocene uplift.

It is then reasonable to suggest that the low and gently undulating Pliocene landscape would have been even more flooded if correction for later uplift were made. Such marine drowning of the Pliocene landscape inevitably evoked marine erosion of regolith together with remnants of soft Permian sediments, but only from slopes of the Mount Lofty Ranges as marine inundation did not occur in the interior parts of the Ranges including the Myponga and hindmarsh Tiers Basins. Thus drowned slopes of the Ranges would supply ferruginous material and medium to coarse-grained content of the Loxton Sand in the SW part of the Murray Basin where a deeper marine environment supposedly formed.

The Loxton Sand often formed as composite strandplains associated with shallow-marine and sand beach-ridge systems during the regressive cycles or marine retreats (Brown, 1983). These strandlines are presently well-expressed in the landscape and clearly identifiable on the satellite Landsat imagery and DEM images of the Murray Basin (eg. Brown & Stephenson, 1991; Sandiford, 2003a).

Parilla Sand

The Parilla Sand is represented by unconsolidated to weakly compacted mainly fine to medium-grained quartz sand with the presence of sandy clay generally of grey, pale-brown and yellowish colour. The Parilla Sand is more clayey, less micaceous and more fine-grained than the Loxton Sand and it does not contain marine fauna (Firman, 1972, 1973; Rogers, 1978, 1980; Rogers et al., 1995).

The average thickness of this unit is 15m in the Western Murray Basin that may increase up to 30m somewhere east of Renmark (Firman, 1972). The Late Pliocene age of the Parilla Sand is defined mainly by the stratigraphic relationships with the underlying Loxton Sands, and interfingering with the Norwest Bend Formation containing Pliocene fauna. It is clearly overlain by the Late Pliocene-Pleistocene Blanchetown Clay. Brown and Stephenson (1991) considered that the Parilla Sand was formed some time between 4Ma and 2.8Ma during the regressive cycle associated with low sea-level stands. A fluvial to fluviolacustrine sedimentary environment was attributed to this unit containing a significant part of reworked Loxton Sand (Firman, 1972, 1973; Rogers, 1980). The Parilla Sand often accumulated in inter-ridge lake-like environments, but it also occurred in the ridge cutting channels (eg. Brown and Stephenson, 1991). The eustatic curve (Fig. 4-1) indicates that there were

possibly several marine retreats and inundations associated with high fluctuating sea-levels. The accumulation of ~15m of the Parilla Sand implies relevant sedimentary accommodation space associated with a subtle basin subsidence that resulted in sediment preservation during the low sea-level and marine retreats.

The absence of coarse sediments (except those of the Early Pliocene marine erosion) along the western margin of the Western Murray Basin suggests that the eastern portion of the Mount Lofty Ranges supplied mainly fine-grained sediments such as sandy clays integrated into the Loxton-Parilla Sand. The comparison of grain-sizes of these sediments (including coarse-grained) with those of the Pleistocene deposits such as the Pooraka and Hindmarsh Clay Formations clearly indicates that Pliocene stream competence (erosion and sedimentary supply) in the eastern Mount Lofty Ranges was markedly lower than it was in the middle and late Pleistocene. If one takes into account a drying climatic trend toward the Pleistocene, then there is no indication of any prominent landscape and thus an absence of uplift of the Ranges during the Pliocene. On the contrary, locally increased thickness of the Loxton-Parilla Sand indicates that low magnitude subsidence locally provided extra accommodation space and thus aided the preservation of sediments in the Western Murray Basin especially during marine retreats.

Karoonda Surface

The ferruginised or ferricrete zone developed over the top of the Loxton-Parilla Sand in the Western Murray Basin was called the Karoonda Surface by Firman (1973). The characteristics of weathering profile provided here is after Brown & Stephenson (1991, p.158). They noted that the weathered lateritic profile of the Karoonda Surface (up to 15m thick) often consists of a sandy white kaolinitic and gibbsitic matrix locally capped by pisolitic duricrust of ferricrete and silcrete cement. Beneath the upper metre or so of red-brown soil, the sands are mottled with yellow and red clay and well-developed pedoderms. These grade down into soft friable sandstone. The surface is supposed to be pedogenic in origin (Coaldrake, 1951; Blackburn et al., 1965, 1967). However part of this thick profile may be formed by ferruginisation of sands cemented by iron oxides deposited from groundwater (Macumber, 1983). The importance of this surface is that its profile contains a large quantity of weathered and ferruginous material apparently brought by streams from a deep weathered landscape of the eastern Mount Lofty Ranges. This, in turn, would indicate

that the landscape of source areas was still deeply weathered probably topographically low and gently undulating (Ch. 6).

Norwest Bend Formation

The Norwest Bend Formation is the last Tertiary unit with a direct marine influence on the Western Murray Basin north of the Pinnaroo Block (Fig. 4-16). The Formation consists of abundant shell detritus with a quartz sand matrix and grades from sandy limestone to calcareous sandstone (Brown & Stephenson, 1991). The Formation occupies a restricted bend along the Murray River course between Kensington and Morgan (east to west) and between Morgan and Tailem Bend (north to south) down the river course (Fig. 4-16). The average thickness of the Norwest Bend Formation is about 5m, but 1m to 2m is most common, and 12m is the maximum (Brown & Stephenson, 1991).

The Formation locally disconformably overlies the Loxton Sand and was deposited in a narrow Late Pliocene estuarine environment (Ludbrook, 1963; Lindsay & Bonnett, 1973). Stephenson (1986) suggests that because Lake Bungunnia (Blanchetown Clay) was developed over the Norwest Bend Formation its deposition must have occurred before 2.5Ma. This formation is the facies equivalent of the Hallett Cove Formation of the St. Vincent Basin and thus Late Pliocene in age (Ludbrook, 1959, 1963).

The estuarine deposition of the Norwest Bend occurred in the drowned valley of the ancestral Murray River due to the Late Pliocene marine transgression (Brown & Stephenson, 1991). This marine transgression occurred despite the sea-level being some 60m lower (at its maxima) than its early Pliocene predecessor and was probably associated with high sea-level stands. Several sea-level fluctuations in the range of 100m occurred during the Late Pliocene (Fig. 4-1). These would change the basin sedimentary environment from river-dominated to marginal-marine-dominated and back again and would shift large river deltas such as that of ancestral Murray for hundreds of kilometres up and down the main channels. Taking into consideration all of the above, the following scenario of the Pliocene deposition in the Western Murray Basin is proposed:

1. Marginal-marine deposition of the major part of the Loxton Sand occurred during the Cheltenhamian Stage (Early Pliocene) due to rapid increase of sea-level up to ~80m above PSL that drowned the gently undulating landscape of the Western Murray Basin. The

eastern slopes of the relatively low landscape of the Mount Lofty Ranges were also significantly affected by the marine inundation.

2. Due to sea-level fall and high fluctuations during the Kalimnan Stage (Late Pliocene) the sedimentary environments alternated between marginal-marine to dominant fluviolacustrine where the latest Loxton and Parilla Sands were deposited. However it did not exclude several possible marine incursions into the basin associated with sea-level maxima. Such marine incursions followed by retreats apparently reworked and redistributed mainly fine-grained sediments. This would explain a very wide and sheet-like distribution of the Loxton-Parilla Sands.
3. As the Norwest Bend is restricted to the present course of the Murray River it may suggest that this course was already established during the Pliocene. Is seems that river banks together with a broad and probably flat sedimentary surface were near the PSL that could allow the Murray River to incise into the Loxton-Parilla sediment during the Late Pliocene marine retreats and also to drown river channels during the marine incursions. While the distribution of the Norwest Bend Formation is locked to the present course of the Murray River it does not exclude that a shallow restricted-marine gulf was formed during its deposition (eg. Lindsay & Bonnett, 1973).

Firman (1972) has suggested that a minor down-warp led to this marine transgression and deposition. Thus despite fluctuating sea-levels, some downward tectonic movements may have caused the formation of accommodation space and preservation of the Norwest Bend sediments. The western limit of the Norwest Bend Formation is closely associated with the Morgan Fault along which a fault-angle depression apparently was formed. Taking into account substantial sea-level fluctuations and only a few metres of thickness of Norwest Bend sediments, one may suggest that minor down-to-basin block movements along active normal faults possibly occurred in the Western Murray Basin. The fine-grained lithology of all the above Pliocene units suggests a very minor (if at all) tectonic activity in the source area of the Mount Lofty Ranges during the Cheltenhamian and Kalimnan Stages.

The Blanchetown Clay

The Blanchetown Clay is associated with development of a large fresh-water Lake Bungunnia (Fig. 4-18). "The lithology of this unit is presented by greenish grey, red-brown silty to sandy clay, with many local variations. It contains thin beds of quartz sand and some thin micrite

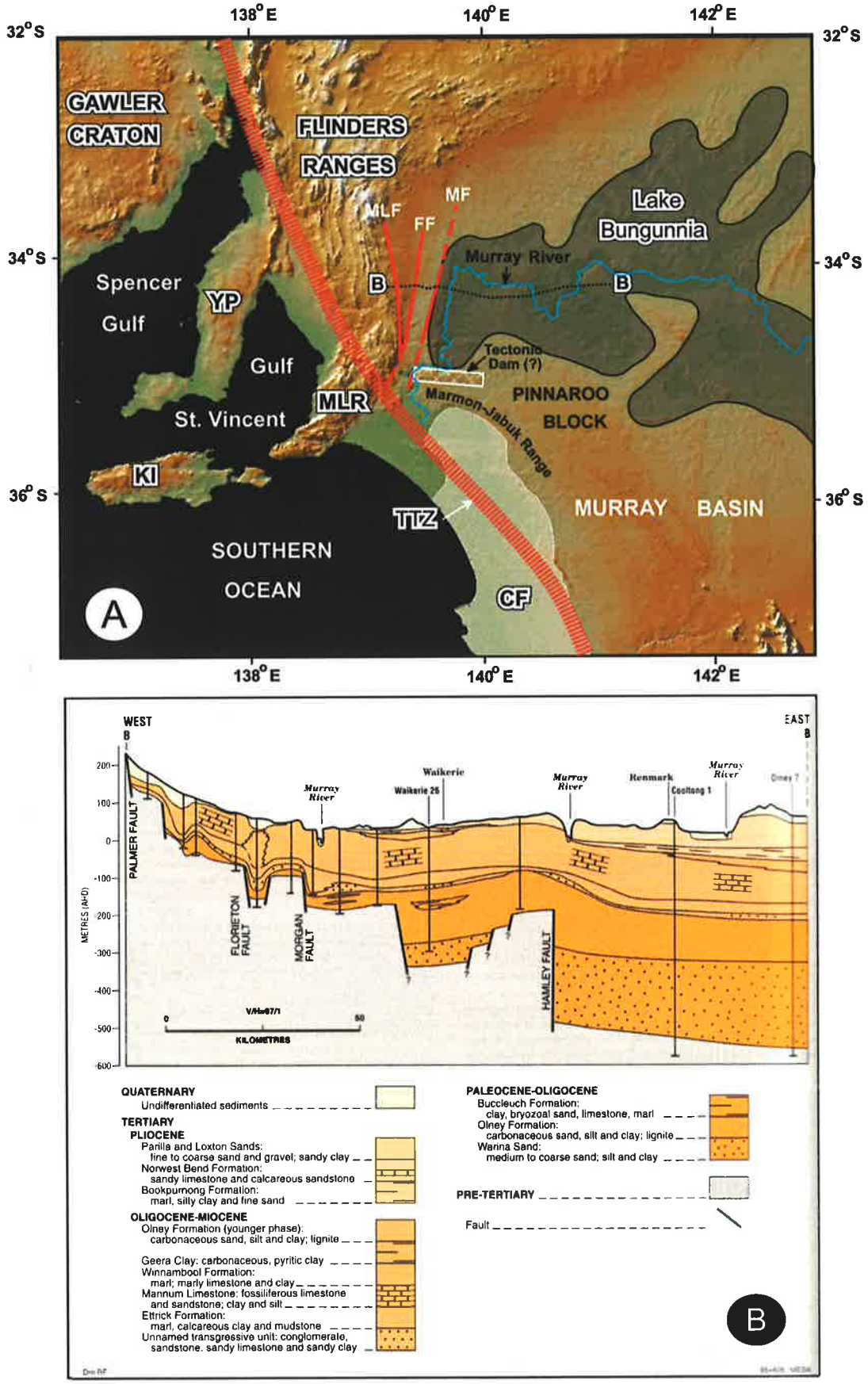


Figure 4-18 A: Location of the Late Pliocene-Early Pleistocene Lake Bungunnia (dark area with black outline, after Rogers, 1995) and distribution of the Coomandook Formation (CF, light area with white outline) in the southern part of Murray Basin (after Brown & Stephenson, 1991). MLR = Mount Lofty Ranges; KI = Kangaroo Island; YP = York Peninsula. MF, FF, PF are Morgan, Florienton and Palmer Faults (modified after Rogers et al., 1995). TTZ = Tertiary Transfer Zone. TTZ and faults are associated with extensional tectonic regime. Shaded-relief image derived from 9-s DEM. **B:** Structural cross-section (B-B) through the Western Murray Basin (after Rogers et al., 1995). Normal fault geometry of the Palmer, Florienton and Morgan Faults and down-to-basin block movements along these faults are clear demonstration of Tertiary extensional tectonic regime.

lenses, and it commonly contains gypsiferous, siliceous and calcareous nodules" (Brown & Stephenson, 1991, p.205). The distribution of the Blanchetown Clay is very wide but patchy and is heavily dependent on the topography of the Western Murray Basin (Stephenson, 1986).

The age of this Formation was established by using magnetic reversals (Bowler, 1980). The oldest part of the Blanchetown Clay was determined as >2.4Ma, and the youngest part as <0.7Ma. Therefore the establishment of Lake Bungunnia was related to the Late Pliocene Kalimnan Stage, but its presence extended well into the Early Pleistocene and thus to the last Werricooian Stage. The average thickness of the Blanchetown Clay is a few metres but it exceeds 20m in places (Brown & Stephenson, 1991).

The Morgan Fault that probably created accommodation space of the Norwest Formation seemed to be active and also formed a natural western barrier to Lake Bungunnia. Possible down-to-basin block movement along this fault also created shallow but steady accommodation space for this lake. At the same time the construction of large coastal barriers in the south during times of low sea-levels (Belperio & Bluck, 1990) provided an additional obstacle to the flow of the River Murray. In combination these two factors led to the formation of Lake Bungunnia. However Stephenson (1986) initially proposed a tectonic dam associated with the Pinaroo Block uplift that should not be excluded from consideration provided in Ch. 5.

Following the formation of Lake Bungunnia, the fluviolacustrine environment in the Western Murray Basin was maintained for about 2Ma with only minor and apparently seasonal changes. Therefore the fine-grained lithology (mostly clay) of Blanchetown sediments in the western extremities of this lake provides conclusive evidence of relative tectonic stability and the low and subdued landscape of the eastern Mount Lofty Ranges during the Kalimnan Stages (Late Pliocene).

4.12.3 Cheltenhamian and Kalimnan Stages: Conclusion

- Early Pliocene sea-level rise resulted in marine transgression that formed a marginal-marine environment in both the St Vincent and Western Murray Basins.
- Maximum tectonic activity was associated with local down-to-basin block movements along the earlier established Para Fault (Adelaide Plains sub-basin) recorded by faultward increased thickness of the Dry Creek Sand. The Morgan Fault was probably also active

and provided a limited accommodation space for the Norwest Bend Formation and Blanchetown Clay in the Western Murray Basin during the Kalimnan Stage.

- Several marine retreats from, and incursions into the Western Murray Basin were associated with significant sea-level fluctuations during the Late Pliocene.
- Only subtle tectonic subsidence in both the St. Vincent and Western Murray Basins was required to satisfy Pliocene marginal-marine, estuarine and fluviolacustrine sedimentary environments.
- Fine-grained lithology (with abundant ferruginous material) and low rate of deposition point to a relatively stable tectonic regime, at least without significant uplift of the Mount Lofty Ranges. Such lithology and environment of depositions would have been consistent with the relatively low, gently undulating and deeply weathered landscape of this source region.

Finally, it is important to note that in contrast to the Western Murray Basin there was a more stable marine presence in the St. Vincent Basin that persisted during the entire Pliocene and even into the Early Pleistocene (Burnham Limestone). This suggests that subsidence of the St. Vincent Basin was more persistent during the Kalimnan Stage than it was in the Western Murray Basin.

Despite the relatively high Early Pliocene sea-level there is an absence of marine sediments in the intramontane Myponga and Hindmarsh Tiers Basins that indicates that the Mount Lofty Ranges segmentation apparently ceased earlier some time in the Middle-Late Miocene. Since that time these intramontane basins never again experienced marine inundation and thus remained above sea-level during the Cheltenhamian-Kalimnan and the following Quaternary Werrikooian Stage.

4.13 Werrikooian Stage (~2Ma to Present)

The Werrikooian Stage is generally associated with the Pleistocene and Holocene, however it may have extended back into the last part of the Late Pliocene as the Pliocene/Pleistocene boundary is placed at ~1.7Ma (eg. Berggren et al., 1985). The Pleistocene divisions used here follow the officially recognised magnetic polarity intervals adapted by Belperio (1995) to South Australia (Fig. 4-19). The Brunhes-Matuyama palaeomagnetic reversal (0.78Ma) is used as the Early-Middle Pleistocene boundary, and the beginning of the last interglacial

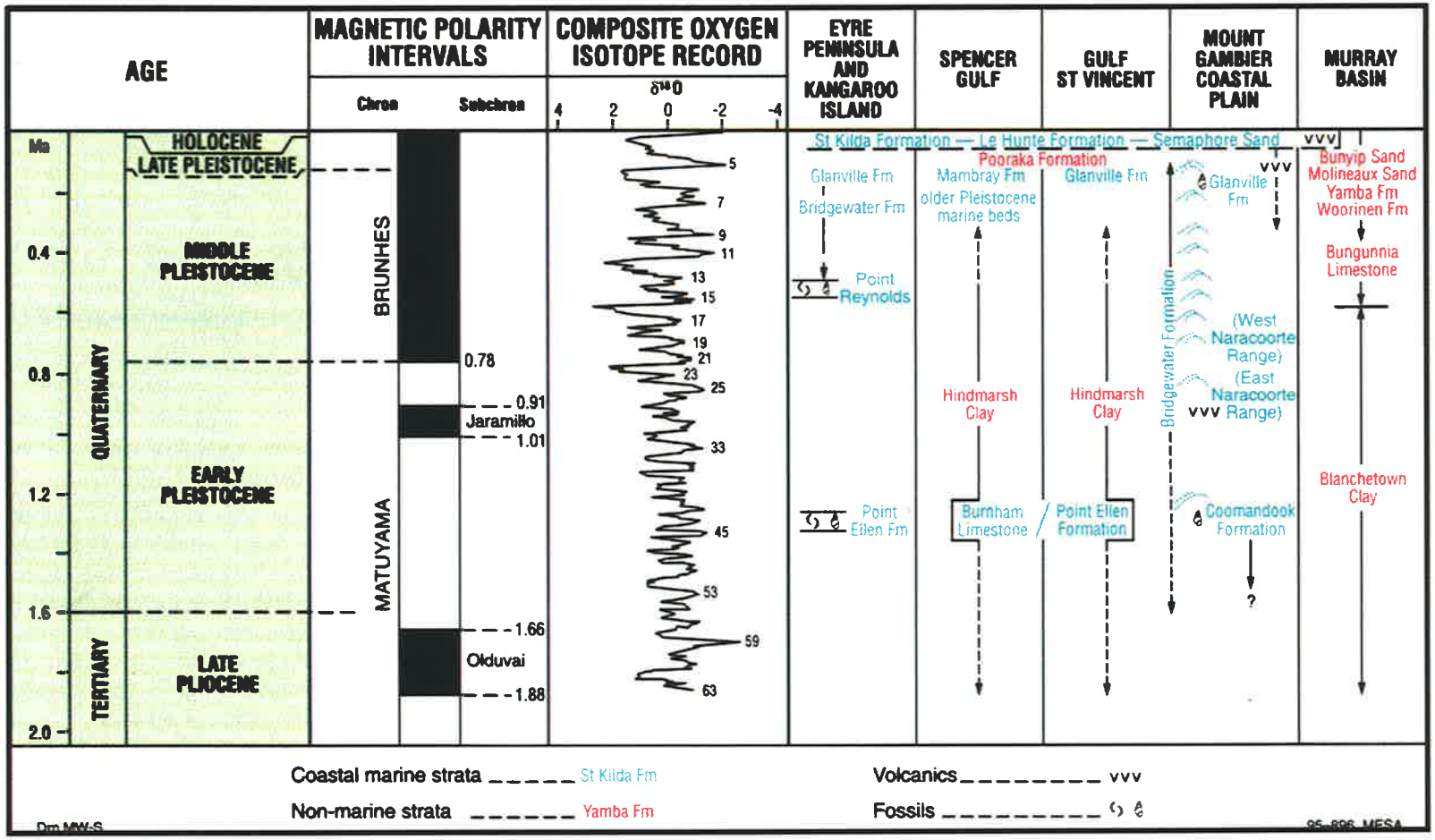


Figure 4-19 Palaeomagnetic and oxygen isotope stratigraphy of the Quaternary with correlations of major coastal marine and non-marine units in South Australia (after Belperio, 1995). Black chron is normal polarity.

(~120Ka) as the Middle-Late Pleistocene boundary. The Holocene is traditionally held as the last 10 000 years in geological history.

"The record of sea-level is only really acceptably known for part of the late Quaternary, perhaps the last 400Ka" (Williams et al., 1993, p.76). In comparison with the late Quaternary record the older evidence is often obscured by tectonics and is beyond the limit of precise age determination. However the composite isotope curve for the last 2Ma was used for correlations of probable sea-level with sedimentary units of the St. Vincent Basin (Fig. 4-20) and the Western Murray Basin (Fig. 4-21).

It seems that the advance and retreat of land glaciations provided a fundamental control on both palaeoclimatic and sea-level fluctuations. Twenty-seven glacial-interglacial cycles are recognised in the deep ocean isotope record since the Early Pleistocene (Belperio, 1995). The Early Pleistocene records indicate low-amplitude fluctuations in oxygen isotope differences between glacial and interglacial maxima but the Middle and Late Pleistocene are associated with high-amplitude and frequency cycles (Shackleton et al., 1984; Williams et al., 1993). There was a dominant 41Ka *obliquity cycle* during the Matuyama magnetic chron from 2.47Ma to 0.7Ma, while the 100Ka orbital *eccentricity cycle* (both are Milankovitch cycles) was dominant during the Brunhes magnetic chron (Ruddiman et al., 1986; Williams et al., 1993).

Detailed investigation of the Late Quaternary sea-levels and sedimentary environments recorded in South Australia (Cann et al., 1988; Gostin et al., 1988; Murray-Wallace et al., 1993) show that since 260Ka there were only two brief episodes when sea-level could reach the PSL: ~220Ka, and ~120Ka – being the penultimate Interglacial (Figs 4-20; 4-21). Therefore most of the records associated with marine activity must occur beneath the present sea-level except those that have emerged as a result of tectonic uplift.

Frakes et al. (1992) revealed that the general increase in desert and grasslands area is a manifestation of the biomass destruction trend on land due to climate change from warm and wet to a colder and dry mode since the Middle Miocene. The Late Miocene-Pliocene climate deterioration with seasonal winter-dominated rainfall gradually progressed into the Pleistocene (Bowler et al., 1982; Frakes et al., 1992). However the Quaternary climate has also undergone dramatic wet and dry fluctuations due to periodic glaciation accompanied by

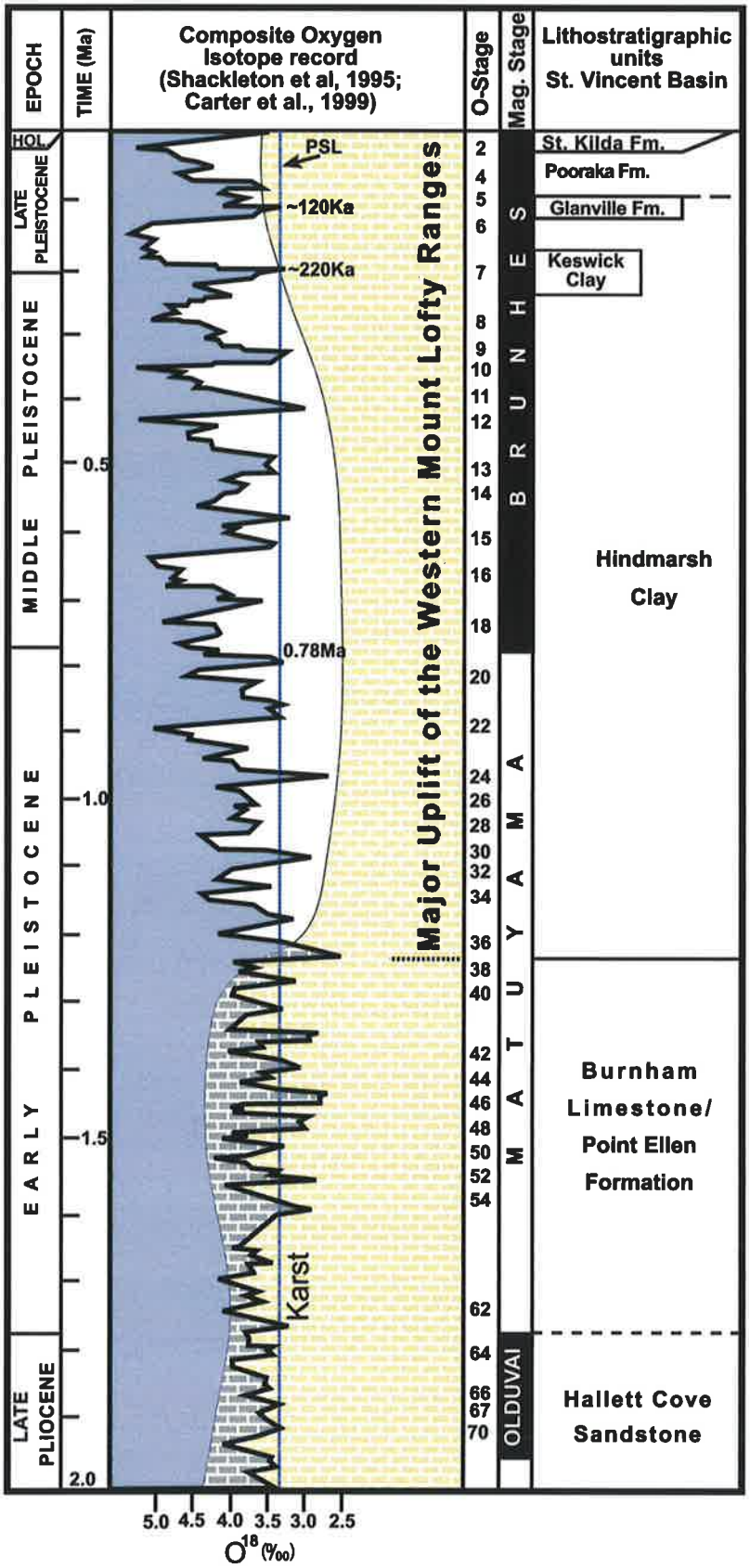


Figure 4-20 Quaternary Oxygen isotope curve superimposed on the sedimentary base of the St. Vincent Basin correlated with lithostratigraphic units (Sheard & Bowman, 1996) and palaeomagnetic stages (adapted from Belperio, 1995).

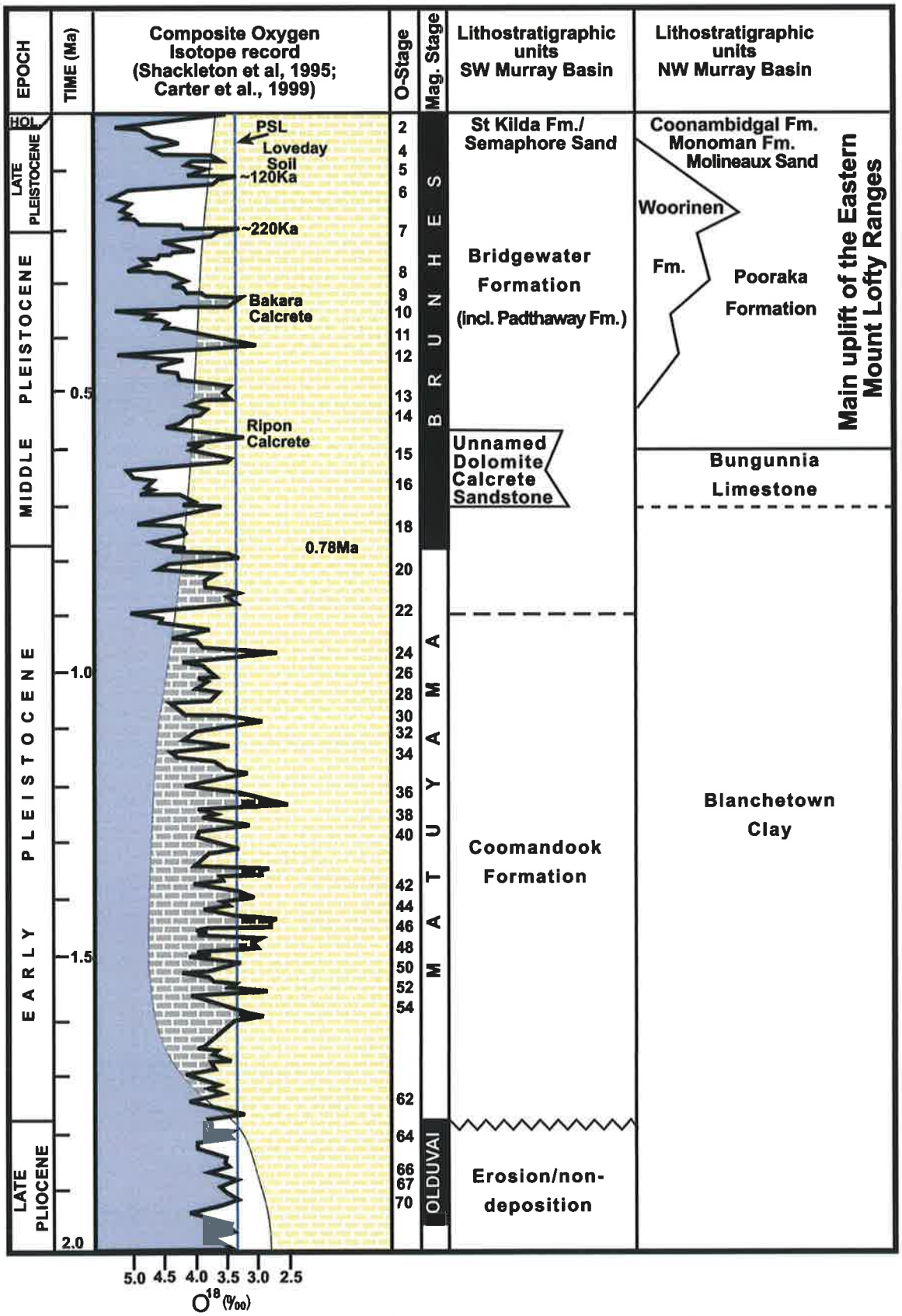


Figure 4-21 Quaternary Oxygen isotope curve superimposed on the sedimentary base of the SW Murray Basin correlated with lithostratigraphic units (after Brown & Stephenson, 1991) and palaeomagnetic stages (adapted from Belperio, 1995). Sedimentary base of the NW part of the Murray Basin (north of the Marmon -Jabuk Range) was above the Quaternary sea-level and thus terrigenous for the entire Period.

sea-level change. These changes, in turn, significantly affected near-shore and interior basin sedimentation including the study region.

4.13.1 Werrikooian Stage in the St. Vincent Basin

The Werrikooian Stage in the St. Vincent Basin incorporates a complex interaction between sea-level and climate change associated with the advance and retreat of glaciations and superimposed tectonic movements. Rivers and streams flowing into the basin responded to tectonic and climatic changes by a significant and variable fluvial erosion and specific sedimentary supply. These together resulted in accumulation of several Quaternary lithostratigraphic units and the formation of various types of soil recorded all these changes. These were correlated with detailed composite oxygen isotope curve available for this period (Figs 4-19; 4-20). The western portion of the Mount Lofty Ranges shows the greatest geomorphic response to these changes during the second part of the Werrikooian Stage.

Burnham Limestone

Thin 0.5m to 1m white silty limestone and calcareous clay occurring at the top of the Hallett Cove Sandstone was defined as the Burnham Limestone (Firman, 1976). It often contains sand and rubble from the underlying Hallett Cove Sandstone and therefore is lithologically hard to distinguish. However, the irregular contact of the Burnham Limestone, such as the infill of karst spaces into the calcareous Hallett Cove surface is a distinctive characteristic in the Adelaide City area. The type section of the Burnham Limestone near Marino Railway Station (south of Adelaide City) is represented by ~0.5m thick pale grey micritic limestone above the 0.5m of orange-brown sparsely fossiliferous calcareous Hallett Cove Sandstone (Firman, 1976). Firman also differentiated Burnham Limestone in the Willunga Embayment where it is about 1m thick and lies above 4m of the Hallett Cove Sandstone.

The Early Pleistocene age of the Burnham Limestone is based on the determination of mollusc bearing sandy-limestone in Maslin Bay (Ludbrook, 1984). The lithology of the Burnham Limestone indicates that accumulation occurred in the shallow marginal-marine environment (Lindsay, 1981). A calcrete crust and karst surface beneath this unit and on top of the Late Pliocene Hallett Cove Sandstone is probably associated with a temporary marine retreat followed by exposure of the sedimentary surface to weathering and karstification.

Point Ellen Formation

The Point Ellen Formation is represented by fossiliferous limestone exposed at the southern limit of the study region at Cape Jervis on the Fleurieu Peninsula (Ludbrook, 1983; Milnes et al., 1983). This Formation is equivalent to the Early Pleistocene Burnham Limestone, and it contains an abundance of fossil molluscan fauna, bryozoa, echinoids and foraminifera, most of which are not age diagnostic. However the absolute age of this formation from a sample collected on southern Kangaroo Island was determined as 1.2Ma (Belperio, 1995).

Despite the absence of precise sea-levels for the Early Pleistocene, the composite oxygen isotope curve (Fig. 4-20) provides some indication of climatic and sea-level change. Since commencement of the Early Pleistocene (~1.7Ma) sea-level probably rose (at least during the maximum warm periods) between composite Oxygen isotope stages 54 and 36 (Fig. 4-20). This period is probably associated with accumulation of the Burnham Limestone and Point Ellen Formation.

Hindmarsh Clay

According to Sheard and Bowman (1996, p.36) the Hindmarsh Clay is "predominantly clay, but is often sandy, silty, micaceous and even gravelly, and it contains lenses of these materials where fluvial influences have been pronounced." The clay mineralogy is highly variable but illite and kaolinite are dominant. "In the Adelaide-Golden Grove Embayment the clays are dominantly smectite-illite and significant kaolin with some randomly interstratified clay minerals and vermiculite". The abundance of silt, clay, gravel, pebbles and boulders are common within the Hindmarsh Clay and widely distributed in the Adelaide Plains sub-basin of the St. Vincent Basin. The thickness of coarse-grained lenses within the Hindmarsh Clay varies from 0.5m to 10m within this sub-basin (Sheard and Bowman, 1996). Selby & Lindsay (1982) believe that the Pleistocene alluvial deposits (Hindmarsh Clay) are coarser than more recent deposits probably attributed to climatic change involving decrease in rainfall.

The distribution of the Hindmarsh Clay within the Adelaide Plains sub-basin (Fig. 4-22) apparently extends well beyond the present shoreline into the St Vincent Basin (Glaessner & Wide, 1958; Belperio, 1985; Sheard & Bowman, 1987). Average thickness of the Hindmarsh Clay is less than 10m in the middle of the Golden-Grove area, increasing to 100m southward. Only several metres of Hindmarsh Clay are currently preserved north of the present course of

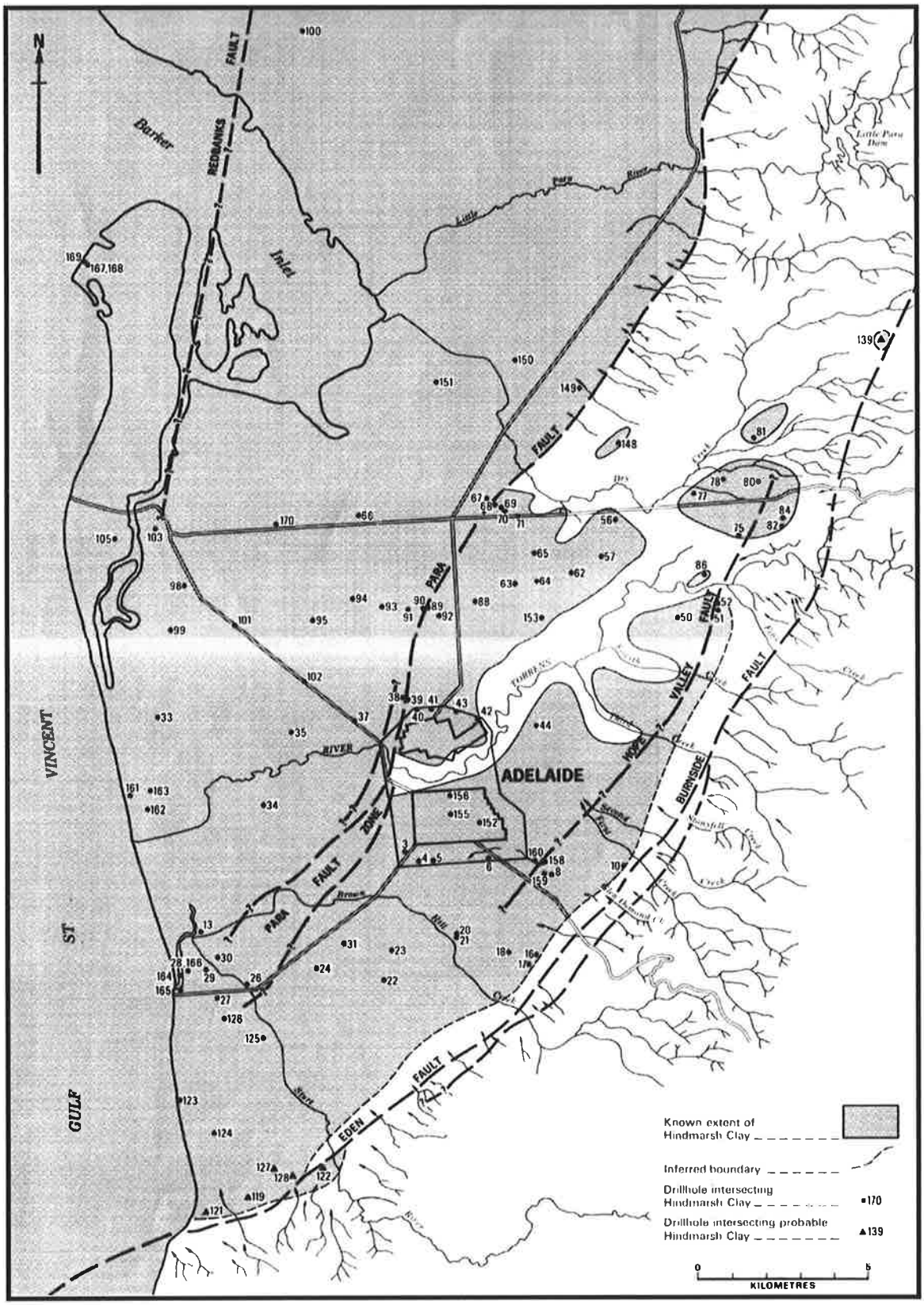


Figure 4-22 Distribution of the Hindmarsh Clay Formation in the Adelaide area (after Sheard & Bowman, 1996).

the Torrens River on the Para Block between the Eden-Burnside and Para Faults (Fig. 4-22). Thickness of this formation rapidly increases west of the Para Fault where it exceeds 100m (Lindsay, 1969).

The Hindmarsh Clay usually unconformably overlies the Late Pliocene Hallett Cove Sandstone/Burnham Limestone elsewhere in the St. Vincent Basin. Firman (1966b) assigned a Pleistocene age to this Formation based on discoveries of remnants of Diprotodon and Macropus. The basal fossiliferous sand of this unit was also related to the Early Pleistocene by Ludbrook (1984). The terrigenous nature of the Hindmarsh Clay provides poor stratigraphic control. However, according to available data this unit was most probably deposited after the accumulation of the Early Pleistocene Burnham Limestone. If the Burnham Limestone is associated with an Early Pleistocene high sea-level stand, then it would be logical to assume that the Hindmarsh Clay was formed after episode 36 of the Oxygen isotope curve (Fig. 4-20) and after a maximum extent of marine influence. Therefore the commencement of the Hindmarsh Clay deposition would occur some time after 1.2Ma that was typically associated with a general sea-level fall and occurred in fluvial and fluviolacustrine environments (interval with sedimentary base-level below PSL in Fig. 4-20).

The upper age limit of the Hindmarsh Clay is uncertain because of the absence of stratigraphic control and its complex relationship with Late Pleistocene units such as the interglacial marginal-marine Glanville Formation, the terrigenous Keswick Clay and Pooraka Formation. However, most probably Hindmarsh Clay deposition persisted at least up to the Last Interglacial (~120Ka) and may continue to the present. Therefore the duration of deposition may be roughly estimated as about 1Ma to 1.2Ma.

Taking into consideration this time interval, the rate of sedimentation of the Hindmarsh Clay can be roughly estimated from a few metres per million years and up to 100m/Ma. The last estimate is the highest rate of sedimentation in the St. Vincent Basin since it was formed in the Middle Eocene. If the total thickness of the pre-Pleistocene package is about 600m, then the average Tertiary sedimentation rate can be estimated as only ~15m/Ma. The earliest fluviolacustrine and estuarine rate of deposition of the North and South Maslin Sand and Clinton Formation was roughly between 10m/Ma and 20m/Ma. The carbonate Late Eocene-Middle Miocene package was formed approximately at the same rate of 10-20m/Ma, while some episodes may have been more productive than others (Lindsay, 1981). However the

Late Pliocene Hallett Cove Sandstone and Early Pleistocene Burnham Limestone were formed at the rate of only ~2.0m\Ma. Thus the deposition of the Hindmarsh Clay was about 5-10 times faster than sedimentation during the Middle Eocene–Middle Miocene, and significantly faster than that during the Late Pliocene-earliest Pleistocene.

The data above provide conclusive evidence that a significant change in the environment occurred during the deposition of the Hindmarsh Clay. Was this related to climate change or other non-tectonic causes? Apparently not, because there was no marked difference in climate between the deposition of the Late Pliocene-earliest Pleistocene and the Late Pleistocene (Hindmarsh Clay) aside from a slightly drier and colder trend. This would have provided even less rainfall and thus less available water for stream erosion and sedimentary transport. No other non-tectonic causes for the drastic change in sedimentary environment were identified in this region. On the other hand, the coarse lithology of the Hindmarsh Clay including boulders and pebble-size clasts clearly indicates that the competence (erosion and sedimentary supply) of rivers and streams flowing into the St. Vincent Basin was substantially higher than any other neotectonic period in the study region. This would strongly suggest that the erosional response of streams and rivers was therefore due to an increased gravitational potential energy associated with the uplift of the western portion of the Mount Lofty Ranges.

Keswick Clay

The Keswick Clay is a lithostratigraphic unit that overlies the Hindmarsh Clay mainly on the Para Block. It consists of yellow-grey to green-grey clays occasionally with yellow to reddish mottles. Lenses of fine-grained sand and silt with thickness of 0.5-6.8m occur where proximal to alluvial fans or creeks (Sheard & Bowman, 1987). For purposes of this neotectonic analysis, this unit is best included with the upper part of the Hindmarsh Clay, but showing "post-depositional reduction in oxygen-poor groundwaters" (Sheard & Bowman, 1996, p.35). The distribution and accumulation of the Keswick Clay indicates that it probably postdates the Pleistocene movements along the Para Fault (Sheard and Bowman, 1987). However the fluviolacustrine nature of the Keswick Clay indicates that it would correspond to the tectonic blockage of Pleistocene drainage of the western slope of the Ranges including the palaeo-Torrens River associated with uplift along the Para Fault. Reverse motions along the Para Fault probably generated a gentle eastern tilt of the Para Block surface toward the Eden-

Burnside Fault that blocked the general westward flow and created a temporary swamp-like environment of the Keswick Clay on the Para Block. Therefore the formation of the Keswick Clay probably was contemporaneous with movements along the Para fault, specifically with transformation of normal fault to reverse progressively from the north to south (see palaeodrainage reconstructions in Ch. 6).

Gley Clays and Black Earths

Sheard & Bowman (1996, p.32) distinguish the lagoonal type of the Gley Clays west of the Para Fault, from the Gley Clays that overlie Keswick Clay or Hindmarsh Clay between the Eden-Burnside and Para Faults. These clays and soils have thicknesses of up to 6m and show moderate to high salinities. The distribution of the Black Earth cracking clay soils generally overlies the Gley Clays. These units were formed on alluvial fine-grained sediments and indicate a slow drainage and periodic wetness. For all the above clays and related soils, a fluviolacustrine-swampy environment attributed that would have been consistent with the proposed above tectonic blockage of the Pleistocene drainage by the reverse Para Fault movements.

Glanville Formation

The Glanville Formation is widely distributed in subcrop on the Adelaide Plains and consists of marine shelly sand, sandy marl and sandy clay (Ludbrook, 1976; Sheard & Bowman, 1996). These typical marginal-marine sediments represent the Last Interglacial high sea-level stand near the present sea-level (Fig. 4-23). The 5.5m thickness of this Formation is generally uniform throughout the Adelaide Plains. However, it is important to stress here that a seaward thickening of the Glanville Formation was encountered on- and offshore by drilling (Belperio, 1985a; Belperio & Baterman, 1986; Belperio & Rice, 1989).

It seems that the Glanville Formation was accumulated in a relatively short time interval associated with the Last Interglacial. There are various absolute age determinations of the Last Interglacial in Australia and around the world. However most of these determinations in South Australia fall in the interval between 132 000 and 110 000 years BP (Belperio & Murray-Wallace, 1984; Murray-Wallace & Kimber, 1987, 1990; Murray-Wallace et al., 1988, 1991; Murray-Wallace & Belperio, 1991; Huntley et al., 1993). There were however, at least three other episodes of marine inundation into the St. Vincent Basin that resulted in thin

interstadial marine sequences before the final Holocene sea-level rise to its present level. Hails et al. (1984) have suggested that about 105 000 years BP sea-level reached a maximum height of 8m below PSL and at about 80 000 years BP it was ~14m below the PSL. Some time between 45 000 and 30 000 years BP some interstadial marine sequences occurred in the St. Vincent Basin when the maximum sea-level reached ~22m below PSL (Cann et al., 1988; Belperio, 1995), however recent review has cast some doubt on this dating (Cann, pers. comm.). The sea-level curve (Fig. 4-23) indicates that marine retreats occurred between these interstadial episodes and during low sea-level. Limited paleosols and weathering, along with an abundance of calcareous mud indicate that the ephemeral lagoonal and lacustrine environment persisted in the deep parts of the St. Vincent Basin during the maximum low stands.

Bourman et al. (1999) used the Glanville Formation as an important indicator of Late Pleistocene–Holocene tectonic movements along the coastal zone in the eastern St. Vincent Basin. These authors discovered and investigated a sequence of sediments in a small former marine embayment in the Normanville area, ~70km S-SW of Adelaide. They used stratigraphic, thermoluminescence and other methods of age determination, indicating a last interglacial age correlated with the Glanville Formation. Originally deposited close to sea-level, these near-shore deposits have been elevated to 12m above PSL at Normanville. Further geomorphological and sedimentological evidence of the last interglacial shoreline was correlated elsewhere in South Australia: Dry Creek (+0.4m to PSL), Sellicks Beach (+4 to5m), Victor Harbor (+6m) and +2m at Hindmarsh Island (Bourman et al., 1999). While this data is fragmentary rather than systematic it provides important evidence of uplift of the eastern margin of the St. Vincent Basin during the latest Pleistocene and Holocene.

Carbonate Pedoderm

Despite the generally soft (loose) character of Glanville sediments they have often been cemented into a hard surface calcrete layer. This calcrete or lime-impregnated layer may be correlated with the extensive 'Carbonate Pedoderm' covering most of the Para Block (Sheard & Bowman, 1996). Both the calcrete and carbonate pedoderm probably formed after marine retreat and during the sea-level low stands which exposed the sedimentary surface and the nearby landscape. During the last glacial maximum and associated aridity, strong westerly winds apparently transported fine carbonate silts eastwards from the Gulf St. Vincent creating

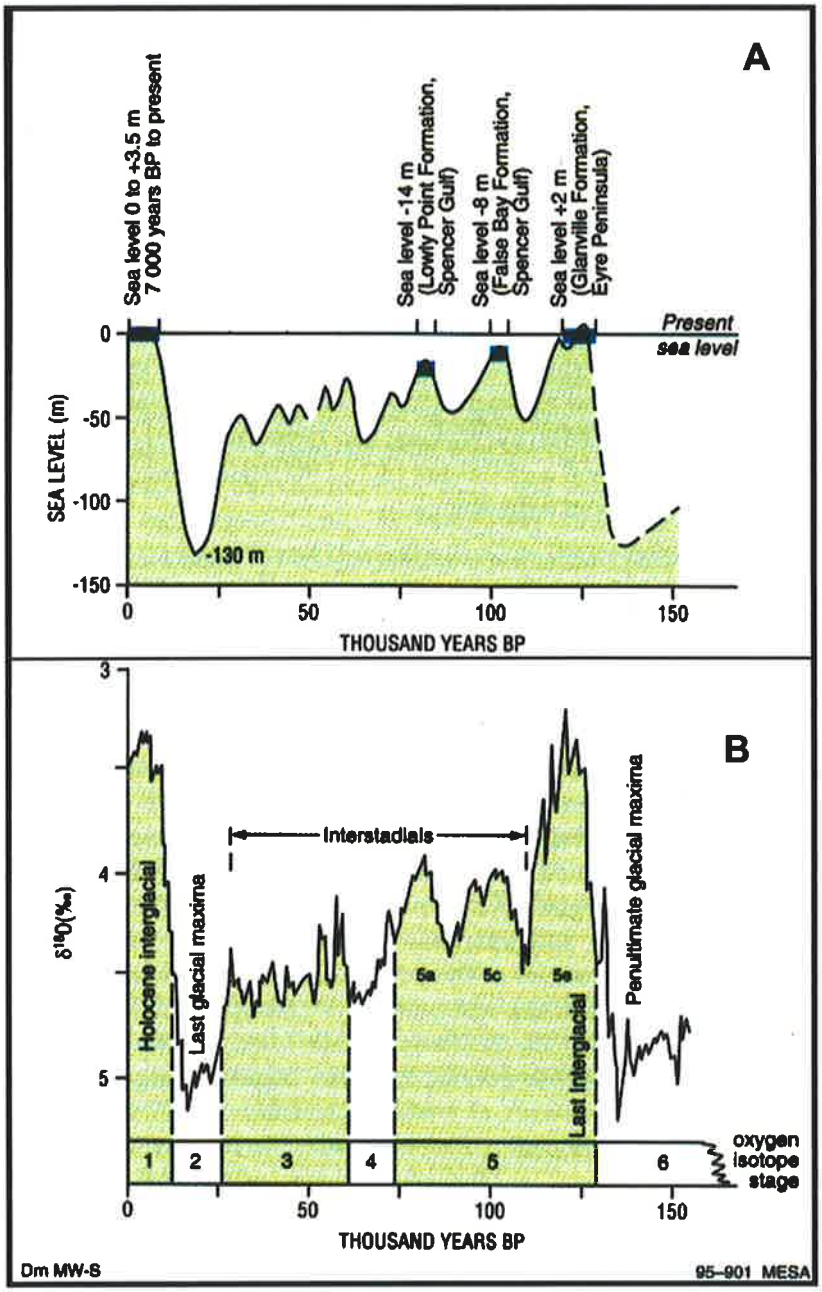


Figure 4-23 A = Sedimentary record of Late Pleistocene high sea-level events in the St. Vincent Basin (after Belperio, 1995). B = High resolution benthic oxygen isotope record (after Shackleton, 1986).

this carbonate blanket above the Para Block (Sheard & Bowman, 1996).

The carbonate blanketing of the Para Block between the Para and Eden-Burnside Faults was long recognised as a result of aeolian redistribution of marine, lagoonal and lacustrine carbonates of the St. Vincent Basin (Crocker, 1946; 1952; Aitchison, et al., 1954; Firman, 1967; Selby & Lindsay, 1982; Sheard & Bowman, 1996). The common thickness of the Carbonate Pedoderm is 0.1 to 2m; mixed with soils and other sediments it may reach 4m (Sheard & Bowman, 1996). A wide band of relatively thick pedoderm in the western part of the Para Block indicates that the Para Fault was a natural barrier to this aeolian transport. However the Para Block was topographically low enough to allow wind to transport carbonate silt all over the Para Block up to the Eden-Burnside fault-scarp.

Pooraka Formation of the St. Vincent Basin

"The Pooraka Formation consists of sandy clay and clayey to sandy silt with interbeds and layers of clay, sand, gravel, pebbles, cobbles and boulders" (Sheard and Bowman, 1996, p.29). This variable lithology suggests that the environments of deposition were similar to those of the Hindmarsh Clay. The distribution of the Pooraka Formation (Fig. 4-24) shows that it occupied similar depocentres to the Hindmarsh Clay with minor differences in the Adelaide area.

These environments integrated fluvial and swamp systems that formed distinct plains on the Para Block as well as further west of the Para Fault. This unit overlies the Hindmarsh Clay, Keswick Clay and also the Glanville Formation. The thickness ranges from 0.3m to 3m between the Eden-Burnside and Para Faults and about 6m to 8m west of Para Fault (Sheard and Bowman, 1996). This indicates that major sedimentary discharge occurred into the Adelaide Plains, escaping the growing Para Block. The insignificant thickness of the Pooraka sediments may indicate a limited time of deposition in comparison to the Hindmarsh Clay. Callen et al. (1995, p.242) noted that "this unit represents a more time-specific Late Pleistocene resurgence of alluvial and fluvial sedimentation". Other definitions of the age of the Pooraka Formation are: ~35 000 years BP (Williams, 1973); between ~30 000-20 000 years BP (Belperio & Baterman, 1986).

If the duration of this unit deposition is about 10 000 years as Belperio & Baterman (1986) have suggested, then deposition occurred at a moderate to very high rate. Allowing for

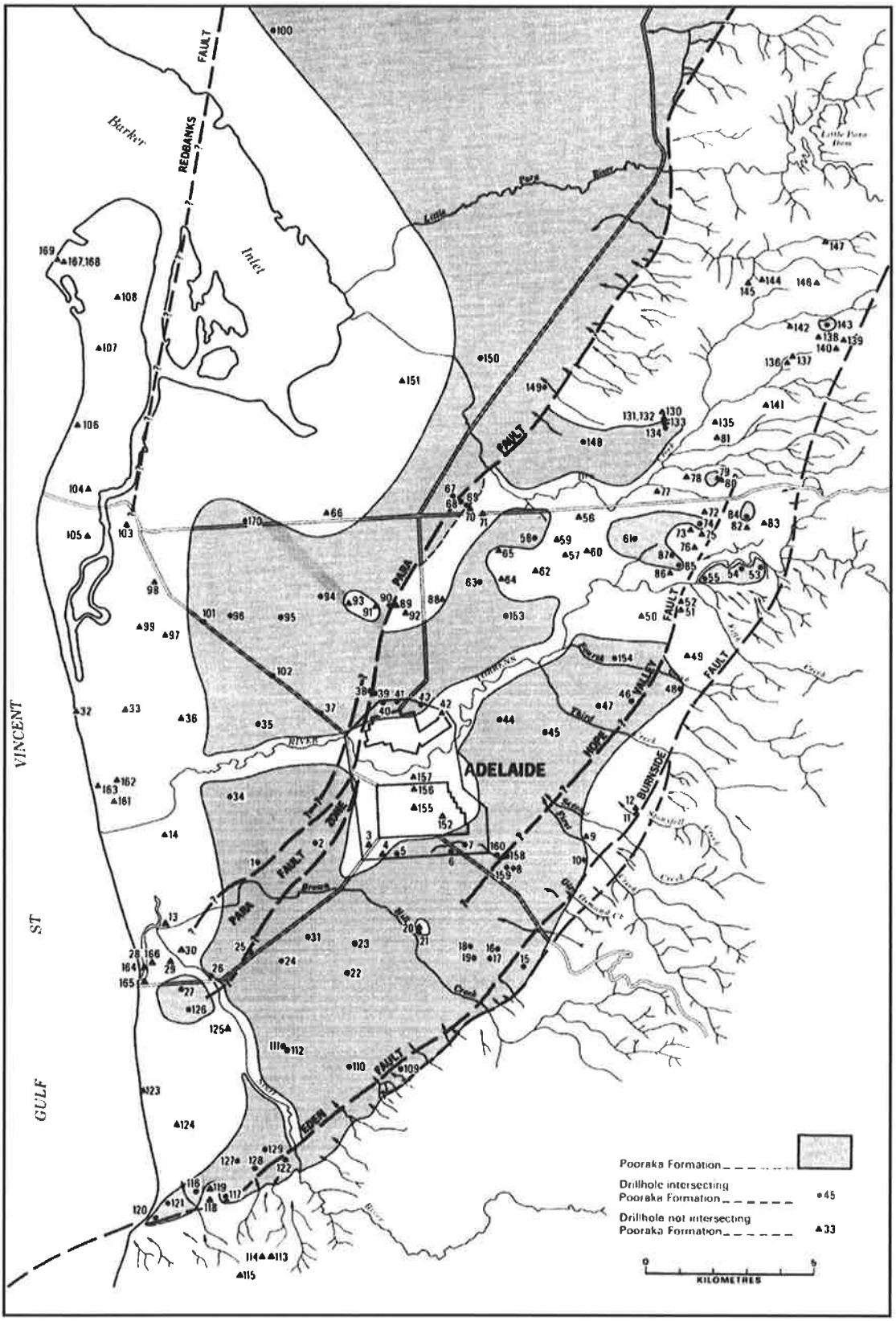


Figure 4-24 Distribution of the Pooraka Formation in the Adelaide area (after Sheard & Bowman, 1996).

discrepancy in the duration of deposition, the rate of this local deposition still remains extremely high. This together with some coarse lithology of the Pooraka Formation indicates continuing active erosion and sediment supply attributed here to the continuing growing of the western portion of the Mount Lofty Ranges in the latest Pleistocene.

St. Kilda Formation

Since ~30 000 years BP sea-level dropped dramatically to about 130m below PSL in association with the Last Glacial Maxima at about 20 000 years BP (Fig. 4-23). Such a significant drop inevitably resulted in complete marine retreat from the St. Vincent Basin exposing sedimentary surfaces to weathering and erosion. Despite the reduction of stream competence associated with a dry and cool climatic trend and a shifting major base of erosion from the study region to the southern Australian continental slope, there was continuing terrigenous supply from the western Mount Lofty Ranges and ongoing aeolian transport from the Basin.

After the Last Glacial Maximum sea-level rose rapidly and a new marine transgression entered the St. Vincent Basin at about 9000 years BP (Belperio, 1995). This flooding most probably redistributed all soft terrigenous sediments (both fluvial and aeolian) filling channels and depressions, and rapidly smoothing any basin roughness. At about 7 000 years BP sea-level reached the present sea-level, thus establishing the present shallow marine environment.

The St. Kilda Formation is associated with this marine environment and is represented by various sedimentary facies including biogenic carbonates full of biota such as algae, foraminifera, molluscs and bryozoa. Coastal aeolian and estuarine deposits as well as back-barrier lagoonal facies were also developed (Firman, 1966a; Belperio, 1988a,b, 1995; Belperio et al., 1984; Sheard & Bowman, 1996). Cann & Gostin (1985) have noted that all facies and members of this formation represent a Holocene active sedimentary environment that is persisting up to the present. The description of facies below is generally after Sheard & Bowman (1996).

The marine sandy facies are represented by fine to medium grained quartz sand mixed with calcareous marine shells and a seagrass component in different proportions. "A basal transgressive gravel and occasional thin gravel beds also occur within the unit, especially near ancestral and present day rivers or creek outlets" (Sheards & Bowman, 1996, p.23). These

authors note that thickness of the marine sand facies is between 1m and 10m, and is widely distributed throughout the St. Vincent Basin. This indicates a very high rate of Holocene sedimentation.

Coastal Barrier Dune Facies are widely distributed along the coastline especially within the Adelaide sub-basin. The aeolian nature of these sand dunes is apparent but in places it is mixed with fluvial input and facies derived by storm surges. The sand dunes are up to 10m high and a few tens of metres wide.

Backbarrier Lagoonal Facies are represented by mixtures of aeolian clays and silt with fluvial sands and occasional gravel developed behind the coastal dunes. Organic-rich clays and mud are also common. Sedimentation also occurs in wetland zones by both marine and fresh water ponded during storms and high rainfall. A thickness of 1m to 2m is most common.

Estuarine Facies are associated with river and creek discharge into the marine and near-shore environment. They are represented by various sediments such as silt, clay, mud, sand and gravel delivered by streams, to calcareous shell sands of aeolian and storm input. Mangrove and swamps are often developed nearby in saline conditions. Most of the estuarine facies are associated with relatively large rivers and creeks such as the Gawler, Dry Creek, Torrens, Sturt, Brownhill and Onkaparinga flowing from the western Mount Lofty Ranges.

4.13.1.1 Werrikooian Stage in the St. Vincent Basin: Conclusion

- Fine-grained calcareous lithology and low rate of sedimentation of the Hallett Cove Sandstone/Burnham Limestone and Point Ellen Formation indicate that an almost stable tectonic regime was established during the latest Pliocene-earliest Pleistocene. Thus the western Mount Lofty Ranges apparently remained as an interbasin region of low and gently undulating relief exposed to deep weathering and very minor erosion at the beginning of the Werrikooian Stage.
- Coarse-grained lithologies and high rate of deposition of the Hindmarsh Clay and Pooraka Formation in the St. Vincent Basin, in contrast, indicate that drastic increase of stream competence due to uplift began in the western portion of the Ranges sometime about 1.2Ma.
- Steep fault-scarps with associated deep stream incision and extensive slope debris along the active Tertiary boundary faults in the western Ranges occurred as a result of

transformation of normal faults such as Eden-Burnside, Clarendon and Willunga into reverse faults.

- The basin-ward increased thickness of the Glanville Formation near Port Adelaide indicates that reverse block motions along the northern part of the Para Fault dragged up both foot-wall and hanging wall blocks. This fault mechanism is consistent with the nature of Pleistocene deposition, sediment distributions and palaeodrainage reconstruction within the uplifted Para Block.

- Substantial terrigenous input at increased rates into the Basin is evidence of significant tectonic activity corresponding to the mid-late Pleistocene uplift of the western portion of the Mount Lofty Ranges that apparently continues into the present as seismic activity of this region indicates.

4.13.2 Werrikooian Stage in the Western Murray Basin

During the last 2Ma the Werrikooian Stage in the Western Murray Basin is associated with various depositional environments such as shallow marginal-marine, lacustrine, fluvial, aeolian, colluvial and pedogenic. This resulted in several major lithostratigraphic units recording complex interactions of tectonics, sea-level and climatic change (eg. Brown & Stephenson, 1991). However there are two different areas in the Western Murray Basin: the north-western associated mainly with fluviolacustrine environments and the south-western associated with predominant marginal-marine environments of deposition. The so-called Pinnaroo Block is the divide between these two areas (Fig. 4-18).

4.13.2.1 North-Western Murray Basin

The beginning of the Werrikooian Stage is related to continuing development of Lake Bungunnia that formed about 2.5Ma ago and dominated the entire early Pleistocene up to 0.6Ma (Brown & Stephenson, 1991). Stephenson (1986) notes that climate was at least twice wetter than during the Holocene since the lake could not have existed under the present climatic conditions. Minor fluctuations of generally wet climate caused major lakeshore migrations.

Blanchetown Clay

The Blanchetown Clay is the primary unit associated with development of the fresh-water megalake Bungunnia. The main characteristics of this unit were described under the Kalimnan Stage but may be supplemented by some details and interpretations of its Early Pleistocene development relevant to a better understanding of tectonic factors affecting the study region.

The Blanchetown Clay was deposited in the fluviolacustrine environment and is represented by fine-grained sediments such as silty to sandy clay, while in marginal areas near the eastern Mount Lofty Ranges, coarse-grained sand and gravelly outwash may be included (Brown & Stephenson, 1991). A very broad distribution of sediments in the shallow fresh-water lake (Fig. 4-18) indicates that it was deposited over a gently undulating landscape. Thicknesses of one to a few metres of these sediments would be consistent with such landscape characteristics. However, local increased thickness up to 20m may indicate creation of extra accommodation space due to local subsidence.

Bungunnia Limestone

The Bungunnia Limestone is a thin 'end-member' of the Blanchetown Clay composed almost entirely of carbonates (dolomitic limestone) apparently recording: a) a drying lake and b) a very restricted (clastic-starved) sedimentary supply in the Early Pleistocene (eg. Brown & Stephenson, 1991, p.209). This indicates that a subtle tectonic regime or even temporary tectonic stabilisation corresponded to this sedimentary environment in the Western Murray Basin. These also suggest that sedimentary starved streams drained the gentle and low landscape of the eastern Mount Lofty Ranges.

Pooraka Formation in the Western Murray Basin

The Pooraka Formation of the Murray Basin is represented by colluvial and high-level alluvial deposits such as gravel and sand, clayey sand and clay and also includes residual material from the weathered basement. Poorly sorted clasts are often cemented by calcrete, iron or silica matrix (Brown & Stephenson, 1991). These sediments are typically attached to the western margins of the Murray Basin and widely distributed along the north-eastern piedmont of the Mount Lofty Ranges and southern Flinders Ranges. The colluvial part of this

formation contains various lithologies that are poorly sorted and unconsolidated. Morphologically the Pooraka deposits are low- to high-angle outwash fans formed by temporary (seasonal) streams. Lag deposits such as conglomerate, gravel and sand along the modern stream channels represent the alluvial part of the Pooraka Formation. Thicknesses of up to 30m occur, but 1m to 5m are most common (Rogers, 1980). The top part of these deposits (1-2m) is usually more fine-grained represented by sandy clays.

The stratigraphic position of this Formation is clearly above the Blanchetown Clay and thus it must be younger than Lake Bungunnia which ceased to exist at about 0.6Ma (Stephenson, 1986). Because the Holocene analog of such deposits as the Pooraka Formation is assigned to the Coonambidgal Formation, Firman (1973) regarded the top of the Pooraka Formation (Callabona Clay) as a boundary between the Late Pleistocene and Holocene.

It is important to note here that despite the similar nature of the Pooraka Formation in many regions such as in both the Western Murray and St. Vincent Basins, the age of these deposits is different. In the St. Vincent Basin a significantly shorter interval between 30Ka and 20ka was allocated to this unit (Belperio, 1985a, 1988a,b, 1995; Sheard & Bowman, 1996). Taking into account the age and nature of the deposits in the Murray Basin it would be best to consider that the lower parts of the Pooraka Formation in the Murray Basin correlate with the upper part of the Hindmarsh Clay in the St. Vincent Basin.

The Pooraka Formation in the Murray Basin forms the most extensive fanglomerate deposits in the entire Tertiary and Quaternary history of this Basin. Most deposits are attached to the eastern slopes of the Mount Lofty Ranges and are associated with the present day drainage system. Tectonic uplift of the Ranges is the major cause of these deposits that would have drastically increased stream gradients and thus erosion and sediment supply (stream competence) since the Middle Pleistocene. Climate change was only a secondary factor that may or may not have amplified the effects of tectonic uplift. If climate change had been a primary cause, then fanglomerates would have occurred earlier in the Late Pliocene or Early Pleistocene, when climatic fluctuations became severe (see oxygen isotope curve Fig. 4-21). Since such coarse conglomerate lithologies were never recorded during the earlier stages, the Pooraka Formation represents the highest stream competence defined here as an erosional response to the major uplift of the eastern Mount Lofty Ranges.

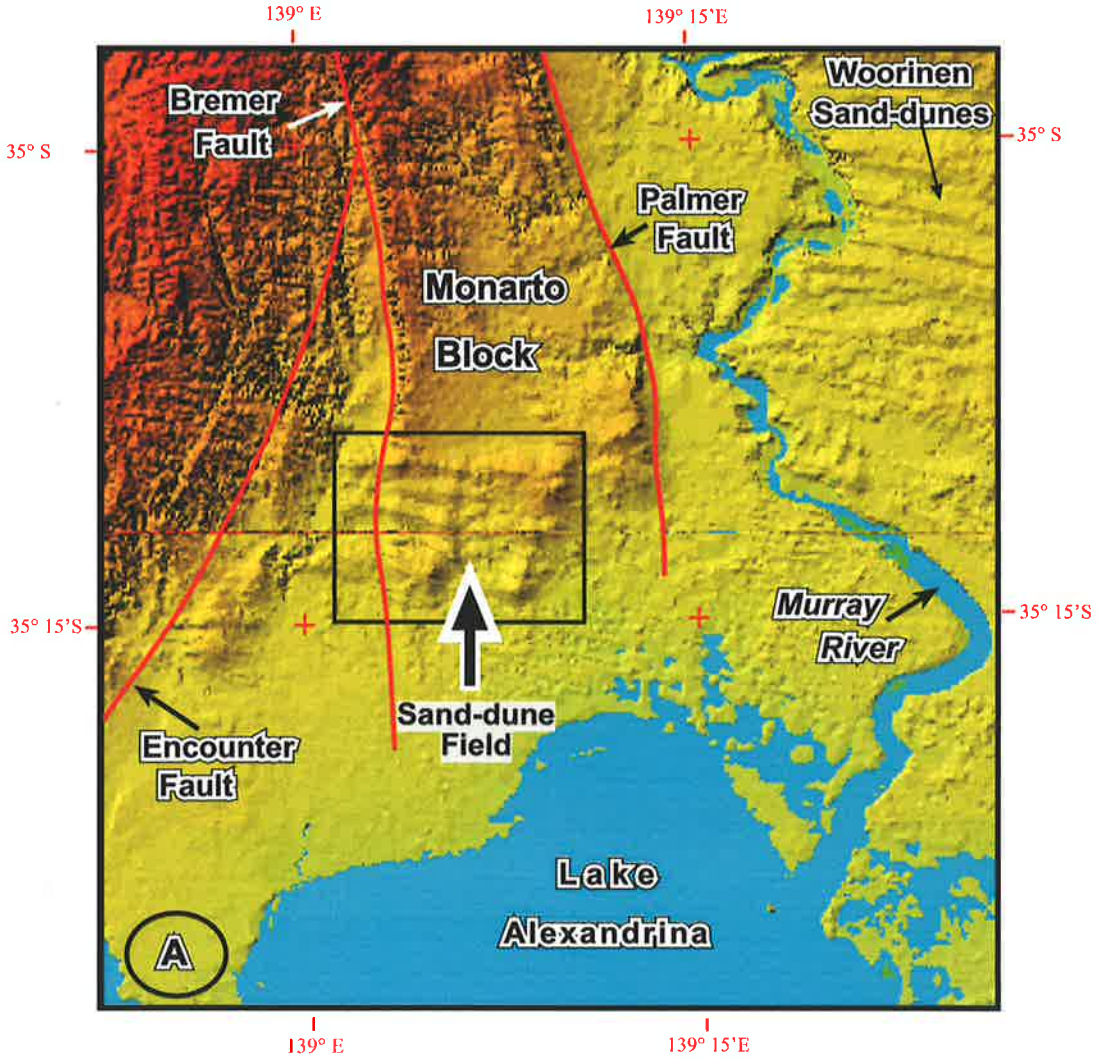
Rubble along the steep fault-scarps is evidence that uplift occurred along faults closely associated with Tertiary active faults. Reverse motions along these faults, such as along the Milendella Fault (Bourman & Lindsay, 1989), are probably associated with a new tectonic rearrangement due to the commencement of a compressional regime that resulted in the major uplift of the Ranges. Sedimentary discharge of streams and rivers draining the eastern slopes of the Ranges occurred rapidly onto the relatively flat surface of the Western Murray Basin. Therefore most coarse deposits of the Pooraka Formation are concentrated along the western margin of the basin and gradually become finer-grained eastward. Since deposits similar to those of the Pooraka Formation extend into the latest Pleistocene and further there is reason to suggest that uplift of the Ranges gradually continued up to the present time as will be demonstrated below.

Woorinen Formation

Since the ending of Lake Bungunnia about 0.6Ma the large surface of this former lake was exposed to pedogenesis. Active wind erosion of soft sediments resulted in their redistribution throughout the Basin. Aeolian sediments consisting mainly of red-brown siliceous silty sand and calcareous silty clay represent the Woorinen Formation (Brown & Stephenson, 1991). Red palaeosols with sandy clay component are common throughout this unit. Calcrete horizons are also a common feature of the Woorinen sand dunes.

These deposits formed extensive dunefields "represented by discontinuous chain of east-west oriented longitudinal dunes and sand sheets" (Brown & Stephenson, 1991, p.230). These dunefields formed almost all the aeolian landscape of the Western Murray Basin except those associated with the more recent Holocene Molinaux Sand. The thickness of the Woorinen deposits is highly variable from a few centimetres to several metres. Sand dunes themselves are up to 100m wide and up to 1km long with irregular dune morphology (Brown & Stephenson, 1991).

While these deposits are a primary geomorphological feature of the Western Murray Basin, their nature does not provide any information useful for neotectonic analysis. However such dunes could be used as evidence of the Late Pleistocene-Holocene uplift in some areas. There are three or four sand dunes that cross the Bremer Fault on the south-eastern corner of the Monaro Block (Fig. 4-25). The formation of aeolian sand dunes is very sensitive to the



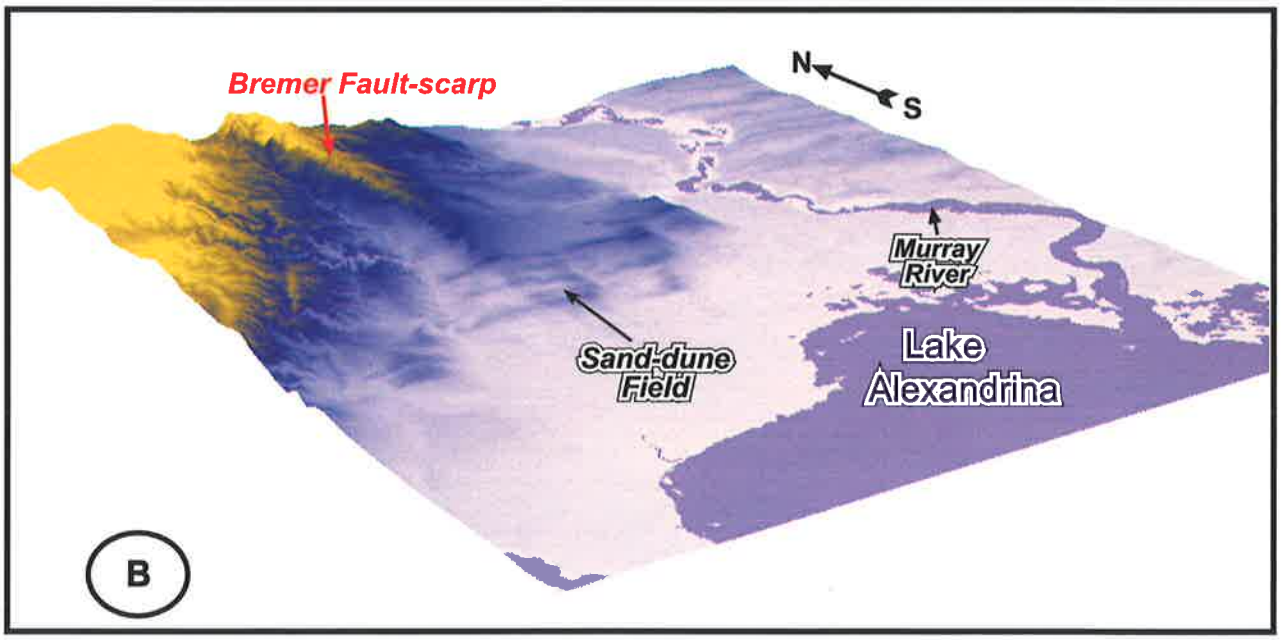


Figure 4-25 **A** = Shaded relief image of the Monarto Block with neotectonically active faults in the SW Murray Basin. Sand-dune ridges (?Woorinen Formation) probably deformed along the Bremer Fault. **B** = Bird's 3D view at the Monarto Block from SW (10 x vertical exaggeration).

roughness of relief and it therefore seems likely that initially these dunes were formed on the relatively flat surface of the Monaro Block extending westward up to eastern slopes of the Mount Lofty Ranges. The shape of aeolian dunes such as height is commonly the same or at least similar along its strike. If the summit of a single dune originally was at the same or similar altitude then tens of metres of displacement would be attributed to the uplift of the Monarto Block along the Bremer Fault. This would thus indicate that the uplift of the Monarto Block occurred sometimes in the Late Pleistocene-Holocene. However there are no absolute age determinations of these sand dunes.

Molineaux Sand

The Molineaux Sand is essentially the same as the above Woorinen unconsolidated aeolian unit and represents the next generation of dunefields in the Western Murray Basin. The composition of the dunes is slightly different to that of the Woorinen Formation and they consist of highly spherical fine to medium-grained siliceous sand (Brown & Stephenson, 1991). Palaeosols and calcrete horizons are usually absent in the dune profiles.

The sand is siliceous and reworked from the Woorinen deposits. It forms extensive tongue-shaped dunefields and sand plains throughout the basin and locally caps the Bridgewater and Woorinen Formations, but interfingers with modern alluvium such as the upper part of the Pooraka and St. Kilda Formations. Therefore the Molineaux Sand is mostly Holocene of age (Brown & Stephenson, 1991). Despite the wide distribution and thick deposits (up to 20m locally) there is a little information that can be used for the purpose of neotectonic analysis.

Coonambidgal Formation

"Unconsolidated, grey, red-brown silt, silty clay, sand and gravel represent this Formation. Most of the sand and gravels are poor sorted, consisting of polymictic assemblages of quartz and lithic clasts and are normally micaceous. In highland valleys the gravel includes cobbles and boulders" (Brown & Stephenson, 1991, p.276). All these features represent deposition in the modern river systems but also include early Holocene and probably part of the latest Pleistocene. These alluvial sediments are widely distributed along the Murray-Darling River tributaries that drain the eastern slopes of the Mount Lofty Ranges.

The thickness of the Coonambidgal Formation is variable but usually several metres. The

River Murray valley near the Murray Gorge contains at least 15 to 20m of fine-grained sand that overlies a further 20m of coarse-grained sediments (Ludbrook, 1960; Firman, 1973; Twidale et al., 1978; Brown & Stephenson, 1991). Firman (1973) separated the lower, mostly coarse-grained part into the Monoman Formation that was probably formed as a fluvial input after significant river incision (up to 70m below PSL) and associated with sea-level drop (last glacial maximum). Thus the Coonambidgal Formation formed as a response to fluctuating sea-level from 17 000 to 6000 years BP, and the overlying sediments (mostly fine-grained) belong to the Monoman Formation (Fig. 4-26).

The interpretation of a large volume of data by Brown & Stephenson (1991) indicates that the Coonambidgal Formation was formed in complex sedimentary environment including fluvial, fluviolacustrine, channel and floodplains in the Western Murray Basin during the Late Pleistocene and Holocene. The lithology of this Formation is significantly varied and depends on location. Most streams and rivers draining the eastern portion of the Mount Lofty Ranges carried coarse-grained sediments that deposited immediately at the slope break. Further basinward, only suspended sediments were transported because of rapid drop of channel gradient in the Western Murray Basin. The high competence of streams and rivers flowing from the Mount Lofty Ranges indicates that this source region was continually growing during the Late Pleistocene and Holocene.

4.13.2.2 South-Western Murray Basin

The development of the south-western part of the Murray Basin differs from the north-west by being associated with marine influence of the sedimentary environment during the Werrikooian Stage.

Coomandook Formation

The lithology of this formation is represented mainly by "fossiliferous calcarenite in grey and cream colour, with medium-grained quartz sand (mainly reworked Loxton-Parilla Sands), calcareous sand, sandy clay, lithic clast (mainly limestone), and abundance of calcareous skeletal debris" (Brown & Stephenson, 1991, p.210). The main part of this lithology was reworked from older (Tertiary) carbonates, while the fine-grained clay and silt were probably primary.

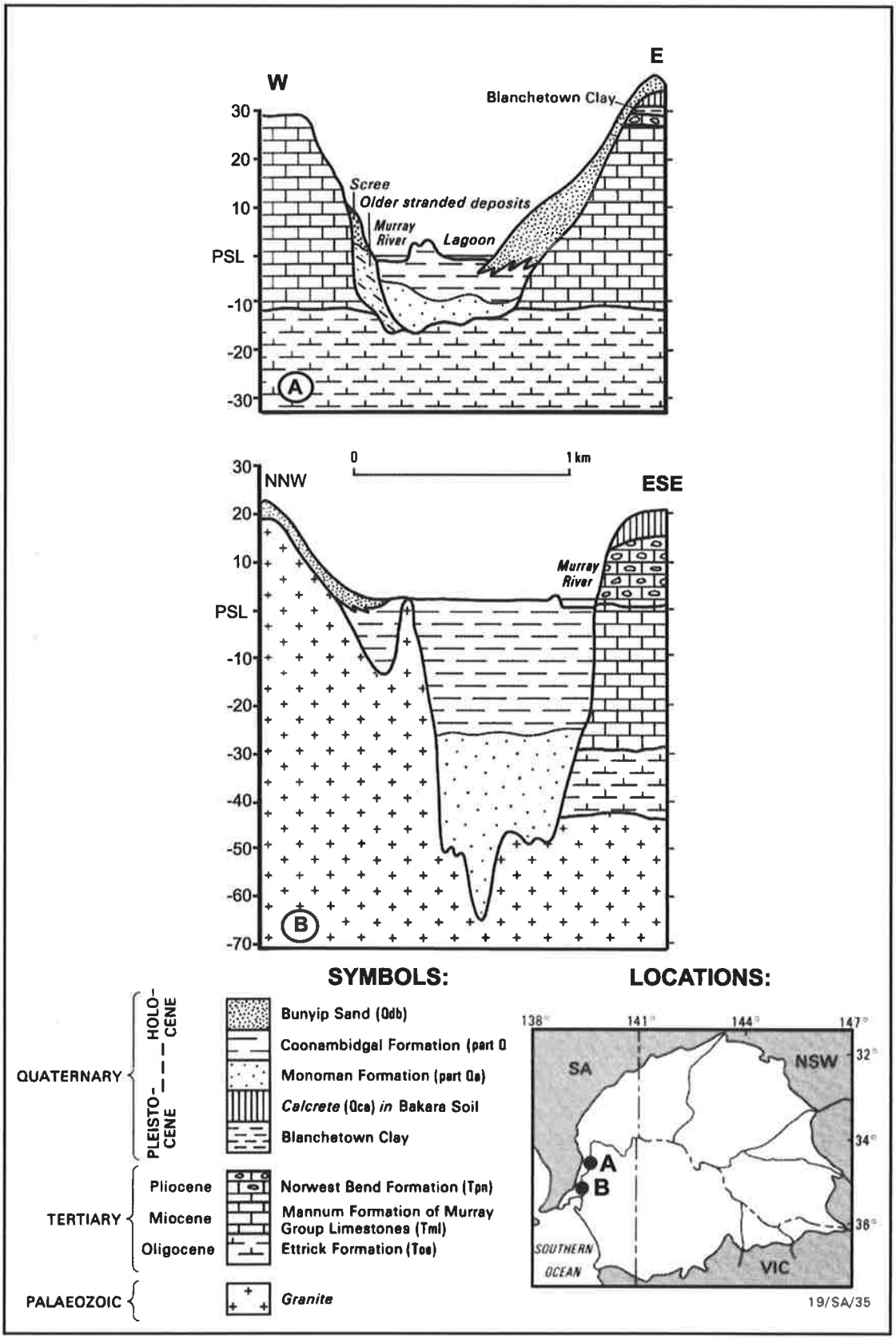


Figure 4-26 Geological sections across the Murray River Gorge (after Brown & Stephenson, 1991)

The distribution of this Formation is restricted by the Buccleuch Embayment and extended SE to the Gambier Embayment of the Otway Basin. The Pinnaroo Block thus was a barrier to the extension of this Formation to the interior parts of the Murray Basin (Fig. 4-18). The thickness of the Coomandook Formation varies and reaches to 75m (Brown & Stephenson, 1991). The thickness of this Formation progressively decreases eastwards, and Belperio (1995) shows that it also thins southward to near Robe, where the younger Bridgewater Formation directly overlies the Miocene limestone.

The Coomandook Formation was deposited in a typical marginal-marine high-energy environment as the lithology and abundance of fossils indicate (Brown & Stephenson, 1991). However there are no direct age-diagnostic fossils in these deposits. Rogers (1980) has suggested that the base of this unit may be as old as the Late Pliocene. Ludbrook (1984) studied fossil assemblages and noted that the Early Pleistocene age of this Formation was more likely. The unit is probably older than 0.9Ma because of the clear relationship with the overlying Bridgewater Formation (Brown & Stephenson, 1991).

It seems that the age and marine lithology of the Coomandook Formation would make it roughly correlate with the Burnham Limestone and Point Ellen Formation of the St. Vincent Basin. All of these units were associated with relatively high sea-levels. The great thickness of the Coomandook Formation indicate that extensive accommodation space was created apparently due to downward tectonic movements along the SW edge of the Murray Basin probably in association with long-lived Encounter Fault.

The thickness distribution may indicate that there was also a SW tilting of the subsiding blocks that preserved the sediments from marine erosion during the sea-level fluctuations. In the absence of subsidence of the Buccleuch and Gambier Embayments, high-energy waves of the open ocean would have immediately redistributed coastal sediments along the continental shelf. Thus it would not have been possible to accumulate and preserve up to 75m of soft calcareous shallow-marine sediments without tectonic subsidence.

Bridgewater Formation

The Bridgewater Formation is associated with bioclastic barrier shoreline deposits. These are related to specific Pleistocene sea-level highstands and are preserved between Robe and Naracoorte (Fig. 4-27). Thirteen stranded ridges of 15m average height, rise up to 60m above

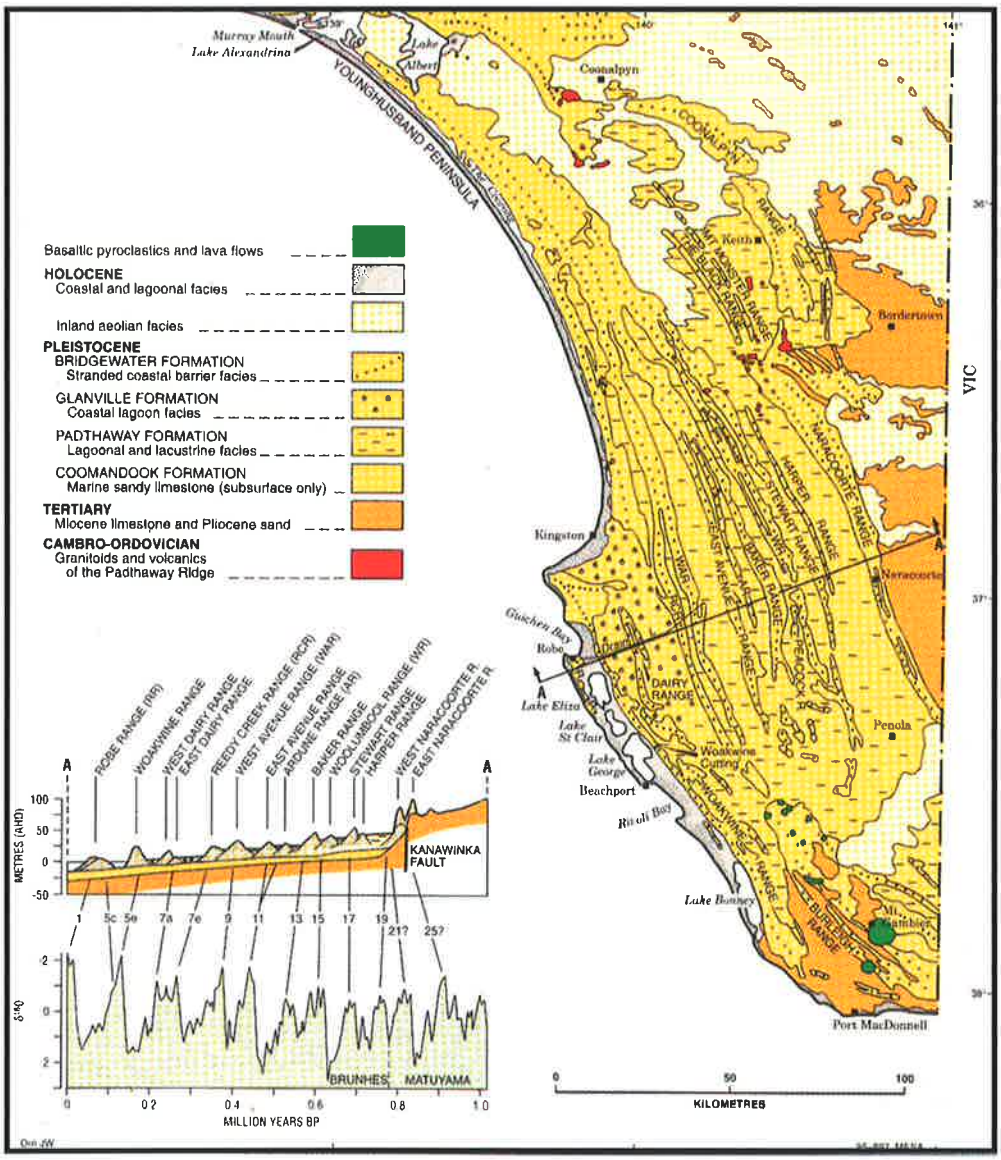


Figure 4-27 Geology of the southern Murray Basin and correlation of shoreline sequences with oxgen isotope stages (after Belperio, 1995)

PSL. "It is preserved as conspicuous subparallel topographic ridges across the coastal plain and continental shelf of the southern Murray Basin and Gambier Embayment of the Otway Basin" (Belperio, 1995, p.222).

Lithology of this formation is represented by "fine to coarse-grained calcareous sand or calcarenite. It consist of an average of 50% carbonate and 50% quartz sand, but carbonate content can rise to 100%" (Brown & Stephenson, 1991, p.223). Older coastal dunes usually contain more quartz sands and are located inland from the present coast. Younger stranded ridges are more calcareous and located near the present coast. The youngest Younghusband Ridge is the modern analog of the Pleistocene Bridgewater Formation coastal sand dunes (eg. Cook et al., 1977; Brown & Stephenson, 1991). Some composite ridges contain calcarenite and palaeosol remnants such as the Ripon Calcrete (Firman, 1967), the Bakara Calcrete and the Peebinga Soil (Rogers, 1980) in South Australia. These were formed in relatively stable environmental conditions when coastal dune build-up temporary ceased and soils formed.

The thickness of the Bridgewater Formation ranges from 2m to 70m, with an average of 15-40m (Brown & Stephenson, 1991). It seems that the thickness of this Formation is a direct function of sea-level fluctuations and compares with its magnitude. The coastal zones during the glacial maxima were probably located further south somewhere in continental shelf or break. However during the interglacial intervals with a high sea-level stands marine inundation into the south part of the Murray Basin resulted in the formation of coastal stranded ridges (Fig. 4-27). While there is a variation of these ridges age from the Early Pleistocene to Holocene, most of the available absolute age determinations of the Bridgewater Formation fall into the range of between 780 000 years and Holocene (Belperio, 1995). In spite of some possible tectonic involvement in dune ridge formation (eg. Belperio, 1995; Brown & Stephenson, 1991), it seems that these tectonic movements were only a secondary force in comparison with the effects of sea-level change.

4.13.2.3 Werrikooian Stage in the Western Murray Basin: Conclusion

- Early Pleistocene sedimentation in the south-western part of the Murray Basin occurred in the shallow marginal-marine environment south of the Marmon-Jabuk Range while fluviolacustrine sedimentation associated with megalake Bungunnia dominated in the north-western part of the basin.

- Minor influence of tectonic subsidence probably associated with westward tilting of the southern part of the basin south of Pinnaroo Block resulted in increased thickness and preservation of the Coomandook Formation in the Late Pliocene-Early Pleistocene.
- Sea-level changes resulted in stranded sand dune formation (Bridgewater Formation) in the southern part of the basin.
- Mostly fine-grained and calcareous sedimentation (Blanchetown Clay and Bungunnia Limestone) are considered here to be the result of subtle tectonic subsidence along the Morgan Fault and north edge of the Pinnaroo Block that formed sedimentary accommodation space of Lake Bungunnia.
- The appearance of coarse lithologies of the Pooraka Formation and steep slope debris is roughly coincident with the end of Lake Bungunnia and record a new regional tectonic rearrangement associated with commencement of the compressional tectonic regime sometime after about 0.6Ma.
- The compressional tectonic regime probably resulted in the major uplift of the eastern Mount Lofty Ranges.
- Mid-Pleistocene tectonic uplift accounted for increased competence of streams that dissected the eastern slope of the Ranges as recorded by the wide distribution of Pooraka fanglomerates along the western margin of the Murray Basin.
- Continuing supply of coarse fluvial deposits together with wide distribution and formation of slope debris in the Late Pleistocene and Holocene clearly indicate that uplift of the eastern Ranges continues to the Present.

4.14 Regional Palaeoreconstructions: Conclusion

All data and palaeoreconstructions described in this chapter indicate that the Mount Lofty Ranges together with flanking and intramontane basins are the result of the complex interaction of neotectonic movements, sea-level and climatic change. These are major factors responsible for the ~43Ma of transformation of the high-standing pre-Middle Eocene Palaeoplain into the variously dissected landscape of the Ranges and sedimentary filled basins. Sedimentary accommodation space and dissection of the source area were attributed to the specific style and extent of neotectonic movements wherever possible. Ten main regional stages were distinguished in the Tertiary-Quaternary history in association with specific lithostratigraphic intervals, eustatic sea-level stands, neotectonic setting and

landscape features.

For the first time details of the eustatic curve were incorporated in palaeoreconstructions of the study region and these revealed that marine inundations and retreats played significantly more important roles in the Tertiary history of the Mount Lofty Ranges than previously considered. Specifically, marine erosion is presented here as a major process for regolith removal from the southern Mount Lofty Ranges, that together with reworked Permian fluvio-glacials formed the Oligocene Compton Conglomerate in the Buccleuch Embayment of the Murray Basin. Marine erosion is proposed in this thesis as the major cause of the uniform summit surface of the Sellicks Hill Range formed during the Oligocene-Early Miocene Stages. Marine bed-load erosion is inferred here to explain the long-term lithostratigraphic hiatus and nature of the Middle Miocene/Pliocene uniform unconformity in the St. Vincent and other basins. Together data and interpretations identify a few distinct episodes in the Tertiary-Quaternary history of the Mount Lofty Ranges and the flanking and intramontane basins. These episodes are:

- **Middle to Late Eocene**: Segmentation of the Palaeoplain by the subsidence and formation of the St. Vincent and Western Murray Basins. Remnants of the Palaeoplain formed the interbasin source region of the proto-Mount Lofty Ranges. Further basin segmentation into embayments was associated with down-to-basin block movements along normal faults. Basin subsidence followed by incipient erosion of the source region resulted in the formation of an initial fluviolacustrine environment of deposition that progressively was replaced by marginal-marine and shallow marine sedimentation in the St. Vincent and Western Murray Basins. Despite the general downward trend of the eustatic curve there was a progressive increase of marine influence on the study region due to further basin subsidence.

- **Oligocene-Middle Miocene:** Further crustal segmentation of the source region is accounted for the establishment of the intramontane Meadows-Myponga and Hindmarsh Tiers Basins (Early Janjukian Stage). Rapid increase of sedimentary accommodation space in these basins occurred due to downward block movements and southward tilting of the southern Mount Lofty Ranges. Subsequent shallow-marine and marginal-marine environments of deposition in both flanking and intramontane basins were associated with slow but continued basin subsidence. Possible minor sedimentary alterations were mainly due to sea-level change. Restricted fluvial input associated with low and gently undulating landscape

correspond to regional southward tilting that reduced the altitude of inherited Palaeoplain remnants within the Mount Lofty Ranges.

- **Middle Miocene-Early Pliocene:** Tectonic stabilisation together with substantial sea-level drop resulted in sedimentary termination throughout the whole region. Marine advance into the basins during the high sea-level stands and retreats followed by sea-level falls initiated bed-load erosion and formation of the Middle Miocene/Pliocene stratigraphic and erosional unconformity. Regional southward and low-angle tilt (including continental shelf) apparently provided marine access to the basins and also contributed to the Middle Miocene/Pliocene ungular unconformity (1-5°).

- **Pliocene-Early Pleistocene:** Sea-level rise evoked a new marine transgression into the St. Vincent and SW Murray Basins after the prolonged interval of sedimentary interregnum. Thin and generally fine-grained sediments were formed in shallow marginal-marine, estuarine and fluviolacustrine environments. Some local subsidence mainly along normal faults affected sedimentary accommodation space such as in the Adelaide area along the Para Fault and along the Encounter Fault in the SW Murray Basin resulted in an increased thickness of sediments and their preservation. Down-to-basin block movements along the Morgan Fault together with stable position of the Pinnaroo Block possibly caused the formation of Lake Bungunnia in the Murray Basin (end of the Kalimnan Stage). Restricted terrigenous supply into both St. Vincent and Western Murray flanking basins indicates that the Mount Lofty Ranges remained as the source region with relatively low and undulating relief up to ~1Ma (western portion) and ~0.6Ma (eastern portion).

- **Pleistocene-Holocene:** Hindmarsh Clay, Pooraka and Coonambidgal Formations contain gravels, cobbles and pebbles. These together with widely distributed slope debris represent the most coarse-grained deposits for the entire Tertiary and Quaternary with the highest rate of sedimentation. There was only an increasingly drying climatic trend during the Pleistocene. Thus the coarse lithology clearly indicates a dramatic increase of stream competence attributed to the uplift of the source region during the last million years. Deep stream incision into the marginal areas of the Ranges with a number of gullies and waterfalls are stream erosional responses to the Pleistocene-Holocene uplift of the Mount Lofty Ranges.

Chapter 5

NEOTECTONICS OF THE MOUNT LOFTY RANGES AND FLANKING ST. VINCENT AND WESTERN MURRAY BASINS

5.1 Introduction

For the purposes of this research "Neotectonics" can be defined as the study of young tectonic events (crustal movements and deformations) that have occurred or are still occurring in the study region after significant tectonic quiescence or geodynamic equilibrium. "Neotectonic events have formed Tertiary and Quaternary crustal structures and are strictly connected with the configuration and evolution of the present topography" (modified after Neotectonic Commission of INQUA, 1998).

There is a long history of structural interpretations of the Mount Lofty Ranges and flanking Basins. Howchin (1911, 1918) initially postulated a broad folding that preceded differential uplift of peneplained fault blocks to form the Mount Lofty Ranges. He considered that the Tertiary St. Vincent Basin was formed as a trough or graben. Later, Fenner (1927, 1930) re-enforced the horsts and graben interpretations of this region by suggesting that the Mount Lofty Ranges were formed as a horst-type structure with associated drainage development and sedimentation. Both Howchin (1918) and Fenner (1927) postulated a relatively young age of uplift of the Mount Loft Ranges (Kosciusko Uplift). However Fenner (1930) also considered that Tertiary marine sediments originally covered much of the Ranges. This opinion was adopted by Sprigg (1945) but was rejected later by Glaessner (1953), Campana and Wilson (1954) and Glaessner and Wade (1958).

Fenner (1930, p.9) writes: *"Block mountains such as the Mount Lofty and Flinders Ranges had to do with normal faults and were associated with tensile stresses. In detailed field investigation of these ranges as landscape features, there is much to suggest that the movements have been thrust movements, that compression and not tension has been the dominant factor"*. In the conclusion of his study of the major structural and physiographic features of South Australia he also writes that "The dynamics of these features are unknown, they may be due either to tension or to compression" (Fenner, 1930, p.10). In regard to structural observation within the study region Sprigg (1945, p.288) notes that block structure of the Mount Lofty Ranges is apparent and that the block fault pattern is simple one; it is considered that the form of block subsidences, the vertical hade and the arcuate plan of the

faults are indicative of tensional stress. Cooper (1985, p.39) in his structural and tectonic considerations of the St. Vincent Basin provided several lines of evidence that the extensional tectonism has been a major factor behind the evolution of this basin and that the tensional faulting in the Cainozoic have been superimposed on much older compressional structures. Thus both extensional and compressional tectonics affecting structural development of the Mount Lofty Ranges and flanking sedimentary basins were recognised.

However without further structural and tectonic considerations the Tertiary compressional reactivation of the Delamerian structures (~500Ma old) became the most popular traditional hypothesis of the Mount Lofty Ranges formation as outlined in several chapters of the *Geology of South Australia* (Drexel & Preiss, 1995). Benbow et al. (1995, p.211) noted that "Uplift of the ancestral Mount Lofty and Flinders Ranges and downfaulting within and adjacent to the Ranges probably resulted from compressional reactivation of meridional to north-east trending Delamerian structures in the Middle to Late Eocene". Rowett (1997) following this hypothesis, suggested that the asymmetric St. Vincent Basin fill is a response to growth of the Mount Lofty Ranges along the compressional reactivated Palaeozoic faults. Ultimately the regional seismicity was also correlated with the Mount Lofty Ranges elevation, and both were considered to be the result of reactivation of ancient tectonic structures (Love et al., 1995).

One of the main objectives of this thesis is to integrate the best available information into a neotectonic model that would improve our understanding of the processes that formed the Mount Lofty Ranges and flanking sedimentary basins. Therefore this study incorporates analysis of the latest information on sea-level changes, correlation of lithostratigraphic units with erosional events, field geological and geomorphological observation as well as structural and DEM analyses that together have produced a new model of neotectonic development in this region.

The previous chapter provided some details of neotectonic movements associated with specific Tertiary and Quaternary regional stages based mainly on the analysis of the lithology and sequence stratigraphy in various neotectonic settings, and highlighted the effect of sea-level changes on local sedimentary environments and landscape. This chapter incorporates all those details and specifically the analysis of the neotectonic settings into a new regional conceptual neotectonic model.

Traditionally the Mount Lofty Ranges and flanking basins were considered to be entirely the result of Tertiary compressional tectonics. However, in contrast, this new model provides evidence that a substantial part of the Tertiary was associated with an extensional tectonic regime. The crustal compression that resulted in major block uplifts of the Ranges followed by corresponding erosional and sedimentary responses is considered here to have occurred only during the Pleistocene and Holocene (last million years). Three principal regional neotectonic stages are recognised: 1) Extensional Stage (Middle Eocene to Middle Miocene); 2) Transitional Stage (Late Miocene to earliest Pleistocene); and 3) Compressional Stage (Pleistocene to the Present). Since it is reasonable to presume that a link must exist between Plate tectonic movements and intraplate deformations, an attempt to understand this link is also made here.

Chapter 3 of this thesis (Pre-Tertiary Basement) demonstrated that there is no record of any tectonic developments over 200Ma in the study region before the Middle Eocene. This was a period of tectonic quiescence. Even the geological predecessor such as the Permian fluvioglacial period does not contain any record of significant tectonic activity. It is therefore important to stress here and once again, that not only the Mount Lofty Ranges but also the neighbouring St. Vincent and the Western Murray Basins did not exist as tectonic entities before the Middle Eocene. A long sedimentary interregnum and deep regolith cover over the gently undulating landscape beneath the Tertiary sediments in these basins and over corresponding planation surfaces in the Ranges, are seen as evidence of a gently undulating and deeply weathered pre-Middle Eocene Palaeoplain that formed a large part of South Australia. The global eustatic curve (Haq et al., 1987) adapted to southern Australia (McGowran, 1989; Li et al., 2004) clearly indicates that such a Palaeoplain was topographically higher than 250m above PSL before the neotectonic movements affected this region. Such a Palaeoplain altitude provides a reference base-level for the calculation of the amount and definition of style of neotectonic movements. This topographic level of the pre-Middle Eocene Palaeoplain associated with the global eustatic curve was not available during earlier palaeoreconstructions (eg. Fenner, 1930; Sprigg, 1945, 1946) and was ignored later (eg. Benbow et al., 1995).

The Middle Eocene was a critical time that is associated with the commencement of the structural development and landscape evolution of the Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins (Cooper, 1985; Tokarev et al., 1999; Tokarev & Gostin,

in press). It was the first time since the Late Permian (after ~200Ma of interregnum) that sedimentation commenced in these basins. It is also important to note that the Middle Eocene and later marine transgressions into these basins were contemporaneous with *general sea-level falls* according to the global eustatic curve (Fig. 4-1). Therefore the formation of sedimentary accommodation space was clearly due to basin subsidence. However a subsidence or at least a southward tilting of a large part of the southern Australian continental shelf and margin must be also inferred in order to provide marine access into these inland basins.

5.2 Neotectonic Plate Reorganisation

A brief overview of pre-Tertiary Australian Plate tectonics has been provided in Chapter 3; whereas this chapter highlights major neotectonic plate events. The first significant plate neotectonic event occurred at ~43Ma. This event is associated with a change of azimuth and rate of absolute motion of the Pacific Plate. From their study of the Emperor Seamounts-Hawaiian volcanic chain, Dalryple & Clague (1976) initially postulated a 40-degree swing to the left of the north part of the Pacific Plate at ~43Ma. However Veevers (2000) recognised a 70-degree anticlockwise twist of the Pacific Plate. This swing and interaction between Pacific and Australian Plates apparently evoked a change in the direction of the Australian Plate motion from WSW-ENE between 48-43Ma, and to the north since 43Ma and an acceleration of the Australian Plate absolute motion was also observed (Figs 5-1; 5-2). This involved northward acceleration of the Australian Plate correlated with changes in the rate of the Southern Ocean seafloor spreading from 0.8mm/yr prior to 44Ma to 3.0mm/yr until ~ 40Ma (Royer & Rollet, 1997). The initial subduction of the northern margin of the Australian Plate along the Papua/New Guinea edge also occurred some time in the Late Eocene (Hill et al., 1993). In spite of the recognition of these significant plate-tectonic events their effects on the southern Australian margin and intraplate regions such as the Mount Lofty Ranges and flanking St. Vincent and Western Murray Basin have remained poorly understood.

An attempt to show the influence of the Southern Ocean widening on the southern Australian continental margins was made by Deighton et al. (1976). They showed that establishment of oceanic and also of continental marginal basins directly corresponded to the break-up of Australia and Antarctica. While seafloor spreading correlates well with the Southern Ocean palaeomagnetic framework, tectonic and depositional events on the southern Australian margin are not strictly contemporaneous with spreading (Weisell & Hayes, 1972; Falvey &

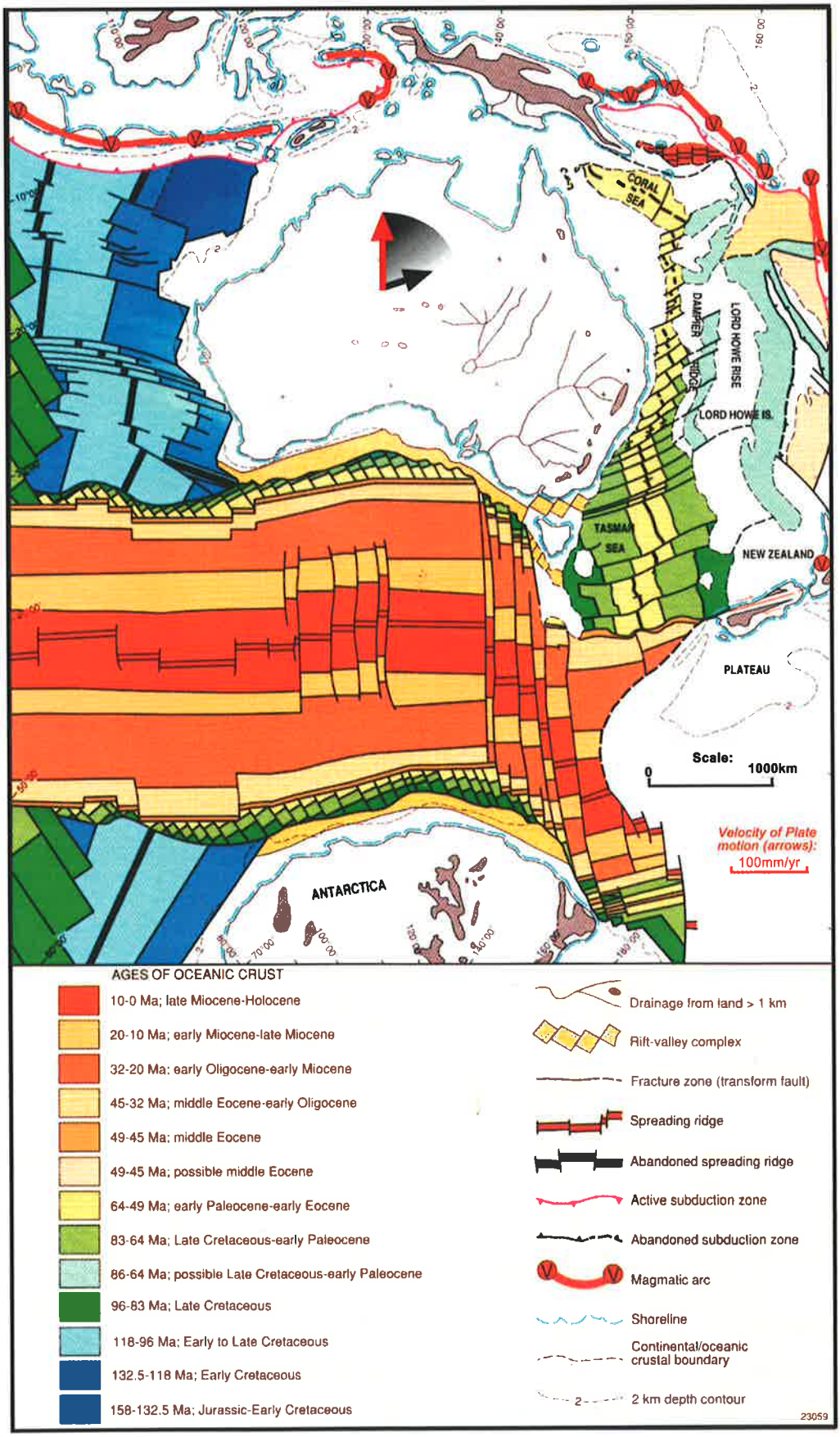


Figure 5-1 Seafloor spreading around Australia (after Scheibner, 1999). Arrows = the direction and velocities of the Australian Plate motion: black - between 48Ma and 43Ma; red - between 43Ma and 25Ma (after Veevers, 2000).

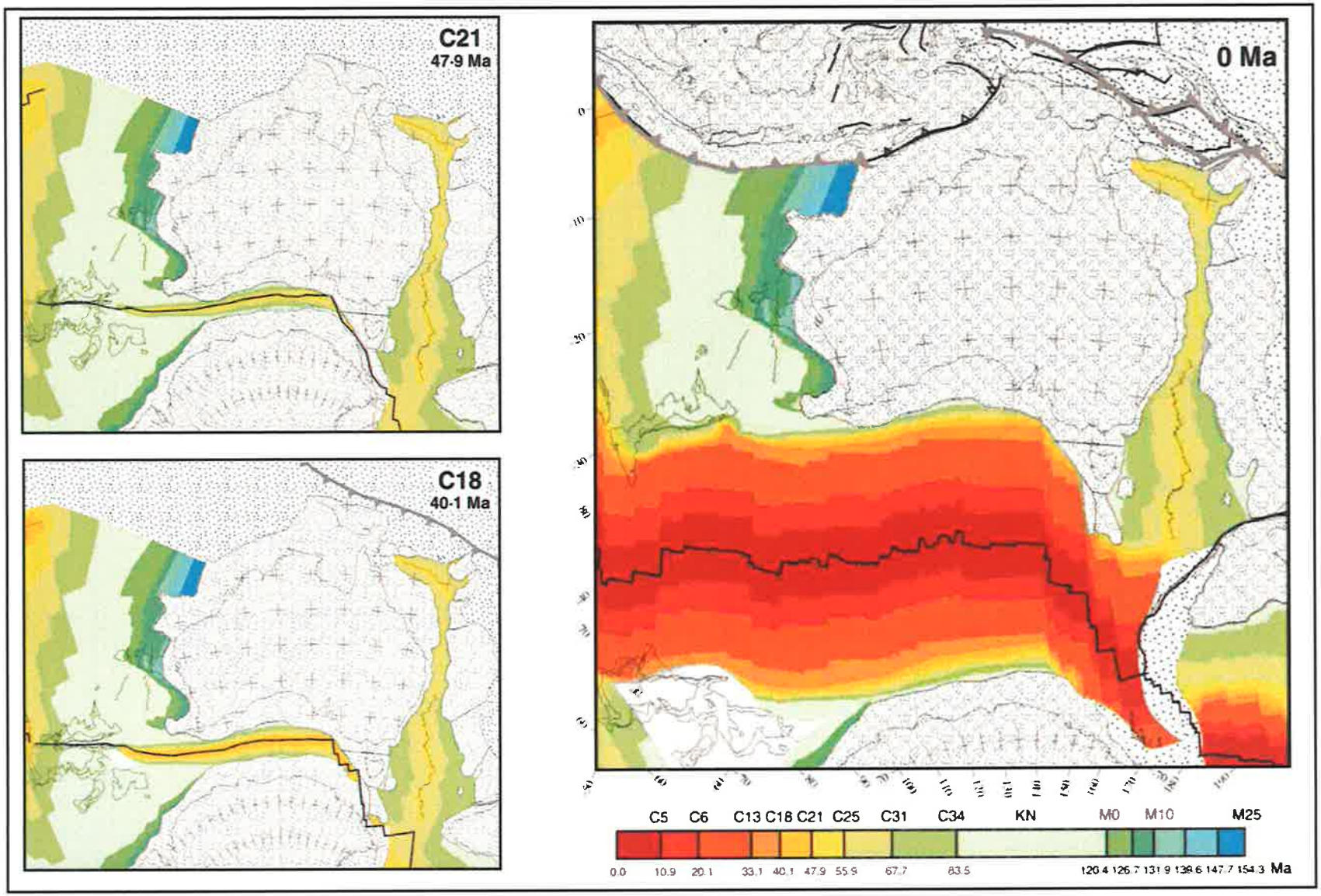


Figure 5-2 Seafloor spreading immediately before and after the 43Ma tectonic plate reorganisation and its present state (after Muller et al., 2000).

Mutter, 1981; Deighton et al., 1976; Veevers, 1984, 2000; Muller et al., 2000).

The 43Ma event significantly changed the direction and also the rate of Australian and other plate motions. Veevers (2000) has calculated that only 12% of all seafloor spreading between Australia and Antarctica occurred during the Potoroo extensional regime (96Ma-45Ma) with dominantly SSW to NNE direction of the Australian Plate motion. However, 88% of the spreading was associated with a predominantly S-N direction between 45Ma and the Present.

The Pacific Plate twist at 43Ma possibly caused an oblique compression between the Australian and Pacific Plates (Muller et al., 2000). The amalgamation of the Australian and Indian Plates and their collision with the Euro-Asian Plate at ~43Ma (Liu et al., 1983; Veevers, 2000) may have also contributed to the compressional state of the Australian crust. However the great acceleration of the Australian Plate northward and the total amount of Southern Ocean seafloor spreading (88%) during the Tertiary and Quaternary are unlikely to have been a total response to these presumed compressional events in the north and east of the Australian Plate, and thousands of kilometres from the southern Australian continental margin. First, plate collisions do not suggest any necessary acceleration of plate motion toward the collisional front, and second, the Southern Ocean seafloor spreading itself is a result of large-scale lithospheric stretching rather than compression, while some possible compression associated with upwelling of magma along the mid-oceanic ridge perhaps affected nearby regions.

Nevertheless there is a perfect correlation between initial sedimentation in the St. Vincent and Western Murray Basins and the 43Ma plate tectonic changes, in particular the acceleration of the Australian and Antarctic Plates break-up (eg. Cooper, 1985). In spite of such good time correlation between the first neotectonic development in the study region and the 43Ma plate tectonic events, there is no satisfactory tectonic model that provides links between plate motions and the appearance of the Mount Lofty Ranges or its flanking basins. This thesis makes an attempt to understand a possible link between plate tectonic motion and regional structural development in the study area. Before any such relationship can be made, the actual Tertiary neotectonic setting of the study region needs to be described.

5.3 Neotectonic Settings of the Mount Lofty Ranges and Flanking Sedimentary Basins

The main objective of this study is to generate a regional neotectonic model that would be consistent with geological and neotectonic settings and also with general landscape evolution.

Therefore the major emphasis is on relatively large structural elements, while detailed characteristics of small structures at the scale of individual blocks are beyond the scope of this thesis and are referred to only where relevant.

Chapter 4 has already provided evidence that the neotectonic history of the Mount Lofty Ranges is significantly more complex than a simple and entirely compressional uplift, as was traditionally considered. Two essentially different neotectonic settings such as Tertiary *extensional* (Middle Eocene-Middle Miocene), and Quaternary *compressional* (Pleistocene-Holocene) were identified in the study region. Minor deformations with relevant geological and geomorphological developments during the Late Miocene to early Pleistocene are referred to here as *transitional* tectonic setting.

The present Mount Lofty Ranges are a north-south elongated structure typically comprising a system of tilted blocks variously uplifted relative to the flanking St. Vincent and Western Murray Basins. The southern end of the study region forms the Fleurieu Peninsula, while Kangaroo Island (beyond of study area) is also an integral part of this SE convex arcuate system of blocks (Fig. 1-2).

The neotectonic structure of the Mount Lofty Ranges consists of a number of tectonic blocks of varying size that were tilted, subsided and uplifted to various degrees during the Tertiary and Quaternary. These blocks experienced multiple motions both downward and upward, mostly along the bounding faults. The common size of tectonic blocks is from a few km² to several of tens km². In spite of the asymmetric shape of the blocks, their elongation is typically N-S, corresponding to the fault pattern.

Field investigations show that the major elongated geomorphological features such as steep slopes, river valleys and watersheds do not correspond with pre-Tertiary basement lithology or tectonic fabric (Tokarev et al., 1999; see also discussion at the end of this chapter). This, together with a superimposed pattern of the main drainage systems, indicates that the major pronounced landforms are associated with active faults bounding relatively large tectonic blocks. Such association is consistent with a rigid basement unable to form flexural and fold structures on a small scale. Hence the formation of major landforms of the Ranges is clearly associated with block movements along faults during the Tertiary and Quaternary. Regional and local tilting of planation surfaces were also an important part of neotectonic processes that affected both the uplifted and subsided blocks.

Because it is clear that major landforms of the Mount Lofty Ranges (except a number of bornhardts or monadnocks) were associated with neotectonic block movements, the pattern of main faults (Fig. 1-2) was extracted from 1 second DEM and correlated with geological setting. This fault pattern clearly indicates that the western border of the Mount Lofty Ranges adjoining the St. Vincent Basin is not a straight line but consists of several sub-parallel curved faults such as the Willunga, Clarendon, Eden-Burnside and Para (Figs 1-2; 5-3). These faults are easterly bounding the corresponding Willunga, Noarlunga, Golden-Grove and Adelaide Plains embayments containing most of the Tertiary sediments.

The eastern border of the Ranges adjoining the Western Murray Basin is more straightforward, particularly in the north and south where it is associated with the corresponding Milendella and Encounter Faults. Other major eastern faults are Bremer and Palmer, bounding the uplifted Monarto Block that is oblique to the main strike of the eastern edge of the Ranges (Figs 1-2; 4-26). It seems that both the Bremer and Palmer Faults are superimposed over Tertiary structures, and were active only during the last Werrikooian Stage (mostly Pleistocene). The Morgan and Florieton Faults in the NW part of the Western Murray Basin are semi-parallel to the eastern edge of the Ranges while mostly buried by Late Tertiary and Quaternary sediments (Fig. 4-18B).

However these faults are clearly defined by the results of drilling that show their important role in the Tertiary and possible Pleistocene development of the NW part of the Murray Basin. The long-lived Encounter Fault is the major structural feature located near the SE slope of the Ranges and separates these from the SW part of the Murray Basin known also as the Tertiary Buccleuch Embayment (Fig. 4-7). It seems that the younger Bremer Fault truncates the NE extension of the Encounter Fault.

The Mount Lofty Ranges contain a few prominent intramontane sedimentary basins such as Meadows-Myponga and Hindmarsh Tiers, filled by Mid-Tertiary marine, marginal-marine and fluvial sediments in the south, and the Barossa Basin in the north containing only fluvial sediments (Fig. 1-2). There are several linear geomorphological features within the Mount Lofty Ranges interiors that are presumably associated with active faults. Two such faults delineate the intramontane Meadows-Myponga and Hindmarsh Tiers Basins containing ~170m and 119m of Mid-Tertiary sediments respectively (Fig. 5-4). Tertiary Meadows Fault is located along the western foot of the Bull Creek Range and is partly coincident with the

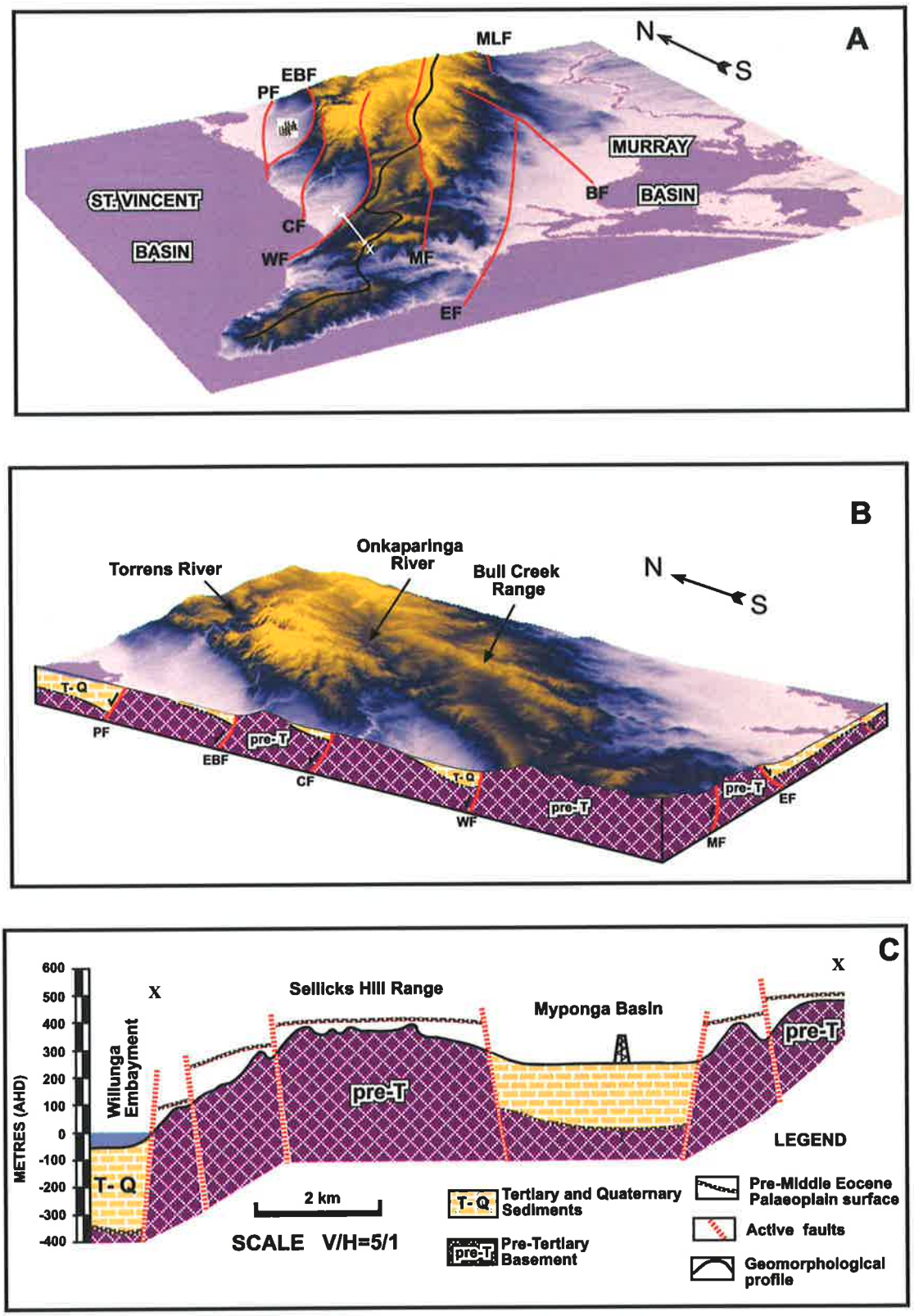


Figure 5-3 Southern-western portion of the Mount Lofty Ranges. A = 3D surface of the southern Ranges with some active faults (red lines), major watershed (black line) and location of transect X-X. B = Block-diagram of the western portion of the Mount Lofty Ranges together with structural reconstructions. Active Faults: PF = Para, EBF = Eden-Burnside, CF = Clarendon, WF = Willunga, MF = Meadows, EF = Encounter, BF = Bremer and MLF = Milendella Fault. C = Geological transect (X-X) crossing of the Sellicks Hill Range and graben-like structure of the intramontane Myponga Basin.

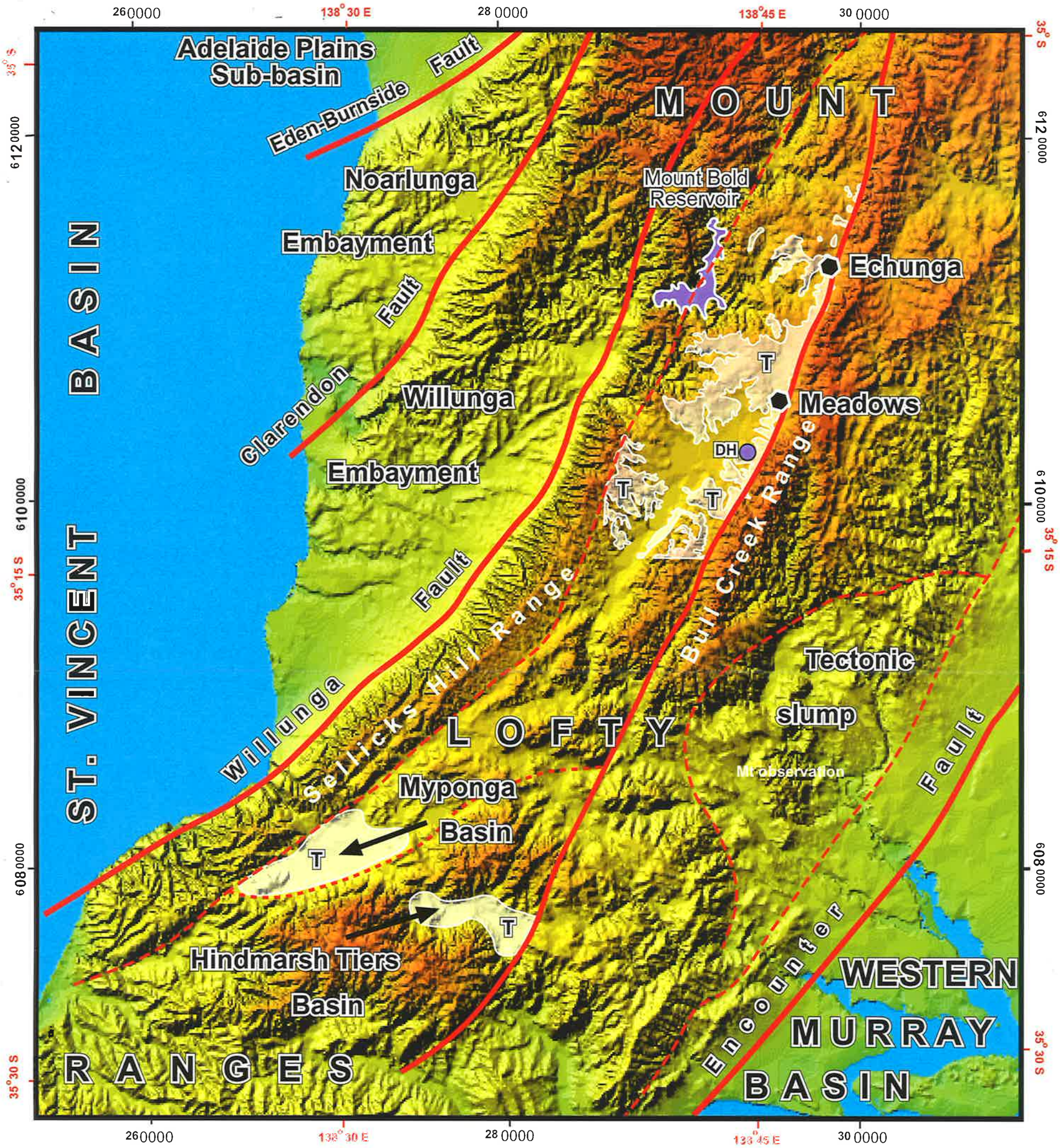


Figure 5-4 Tertiary neotectonic setting of the southern Mount Lofty Ranges, flanking and intramontane basins containing Tertiary sediments. Shaded areas - the distribution of the Tertiary sediments (T) according to Echunga and Noarlunga map sheets: 1:50000 Geological Series; SA Dept. Mines & Energy (Compilers: Forbes, 1983; Belperio, 1985). DH = Drilling Hole (Meadows-Kuitpo area) at ~300m above PSL penetrated ~57m of Middle to Late Tertiary shallow marine sediments (Alley & Lindsay, 1995). Intramontane Myponga and Hindmarsh Tiers Basins contain 170m and 119m of Tertiary marine sediments respectively (Furness et al., 1981). Active Tertiary faults are associated with crustal segmentation during the extensional regime. Fault locations are according to 1-s DEM interpretation and to the Tertiary sediment distribution.

Meadows-Williamstown basement Fault. Another unnamed fault along the eastern edge of the Sellicks Hill Range also seems to have been active during the Tertiary, being well defined in the landscape, and also controlled the sedimentary accommodation space of the Meadows-Myponga area (Fig. 5-4). These two faults collectively formed a graben-like structure (referred to here as the Meadows-Myponga Basin) where Tertiary marine and non-marine sediments have been accumulated and preserved (Figs 5-3C; 5-5B). However a few smaller and less significant faults probably complicated this interior setting.

In the north of the study region the intramontane Barossa Basin contains more than 140m of Tertiary and Quaternary fluviolacustrine sediments (Alley, 1995a). This basin is bounded by the Stockwell Fault in the east. An amphitheatre-like escarpment facing the basin is formed along this fault in association with normal fault geometry and down-to-basin block dynamics during the Tertiary There are other neotectonic faults such as Kitchener, Alma Faults, and Redbank Fault further west of the Barossa Valley (Fig. 5-6). Some parts of these faults are defined well in the landscape but others are mostly buried under Quaternary sediments. However each of these faults formed and controlled specific accommodation space for Tertiary sediments and can be identified as neotectonically active with normal fault geometry (Figs 5-5A; 4-6).

There is a weathered zone located at about 140m above PSL beneath the Tertiary and Quaternary sediments in the Barossa Basin (Alley, 1995a) that apparently belonged to the pre-Middle Eocene Palaeoplain (Fig. 5-7). If one takes into account that this zone would correlate well with the weathered summit surface on the major watershed (also a remnant of the Palaeoplain) that is located about 450m+ above PSL, then ~300-400m of neotectonic movements is implied. Most of these movements are related to the Barossa Basin subsidence along the normal Stockwell Fault that formed basin sedimentary accommodation space (Fig. 5-7, transect B-B).

There are only a few places where neotectonic fault and deformations can be directly observed in the study region. This has created a controversy continuing for decades about the nature and morphology of neotectonic faults and deformation. The most controversial issue is an absence of any Tertiary compressional deformations of sediments within the zone of active faults on the borders of the Ranges (mostly represented by rigid pre-Tertiary basement) with flanking embayments filled by soft and unconsolidated sediments. However there is clear

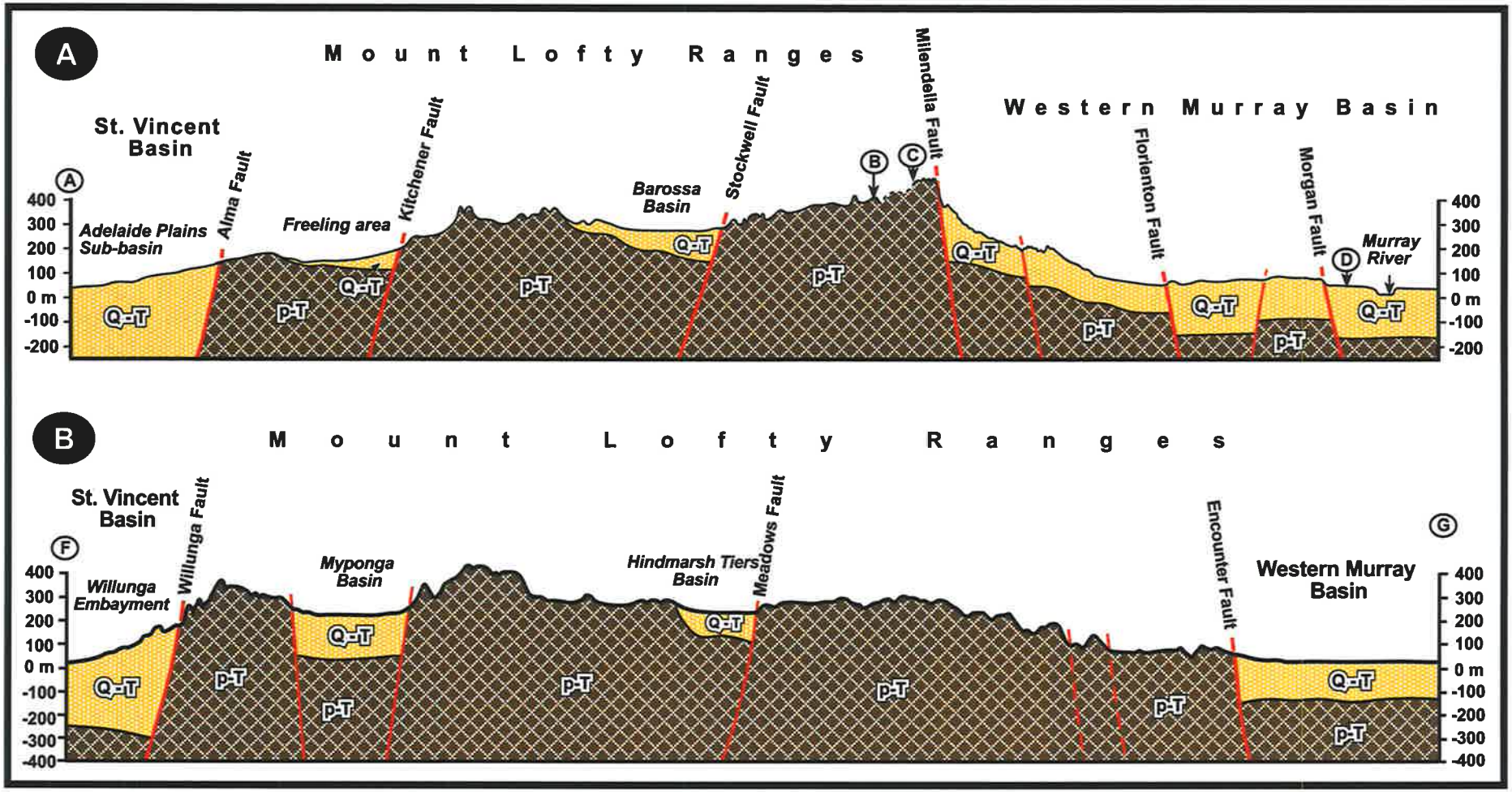


Figure 5-5 Principal structural and geomorphological cross-sections of the northern (AB-CD) and southern (FG) segments of the Mount Lofty Ranges, flanking and intramontane basins. A = based on interpretation of drilling data of Adelaide Plains (Belperio & Bateman, 1986); Freeling area and Barossa Basin (Scott, 1989; Alley, 1995) and NW Murray Basin (Rogers et al., 1995, see also Fig. 4-18B for details); B = drilling data of the Willunga Embayment (Cooper, 1979), Myponga and Hindmarsh Tiers Basins (Furness et al., 1981) and SW Murray Basin (Lablack, 1989; Sheard, 1979). Q-T = Quaternary and Tertiary sediments. p-T = pre-Tertiary basement. Cross-section locations are on Fig. 1-2.

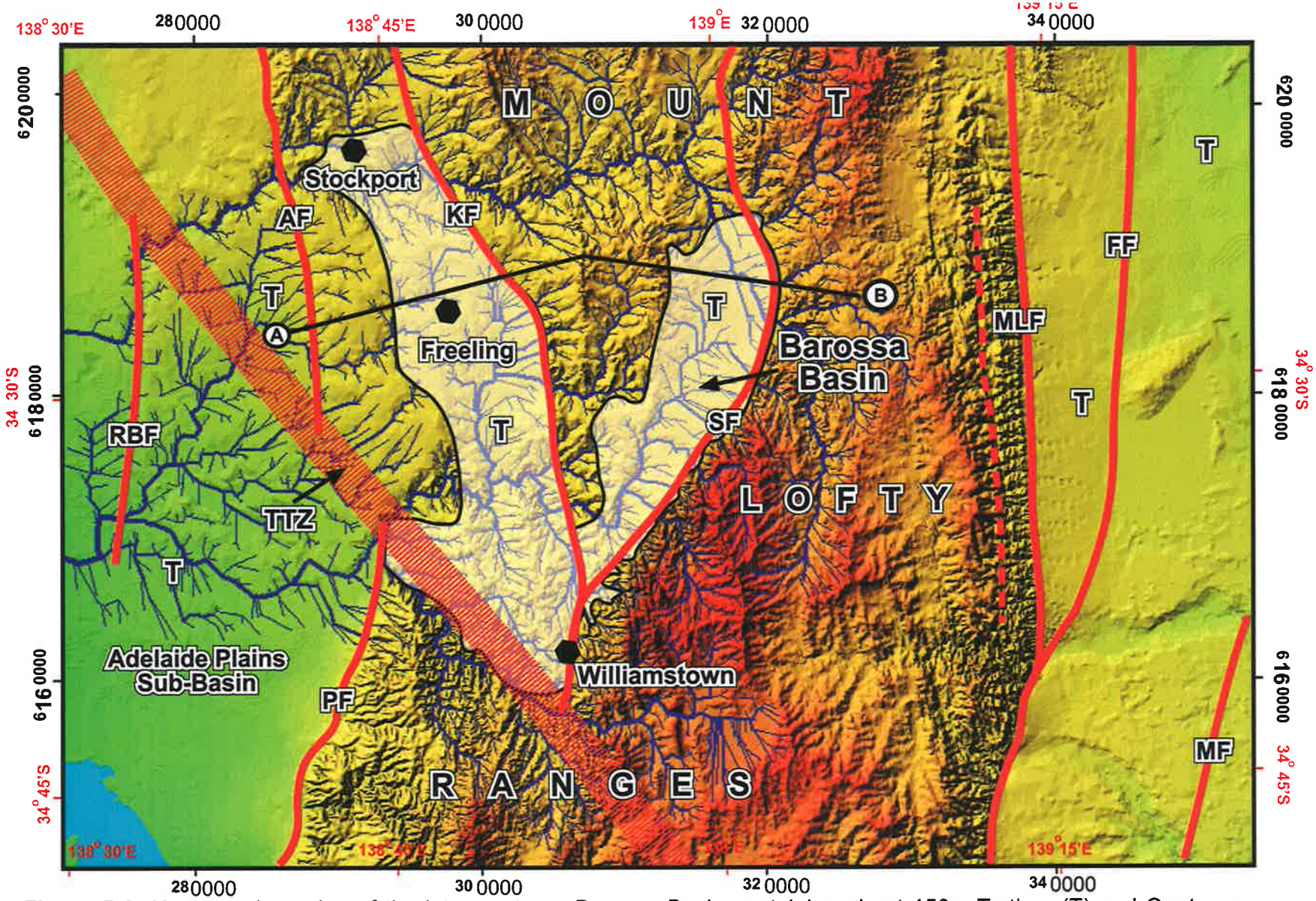


Figure 5-6 Neotectonic setting of the intramontane Barossa Basin containing about 150m Tertiary (T) and Quaternary fluviolacustrine sediments formed in fault-angle depression associated with down-to-basin block movements along active faults. Neotectonic faults from west to east: RBF = Redbank; AF = Alma; PF = Para; KF = Kitchener; SF = Stockwell; MLF = Millendella; FF= Florieton; MF = Morgan. TTZ = Tertiary Transfer Zone. Distribution of Tertiary sediments in the Barossa Basin and Freeling area after Alley (1995a). Active Fault locations according to DEM interpretation and Tertiary sediment distribution. AB = cross-section in Fig. 5-5A. Shaded relief image and drainage pattern derived from 1-s DEM (data SA DEH).

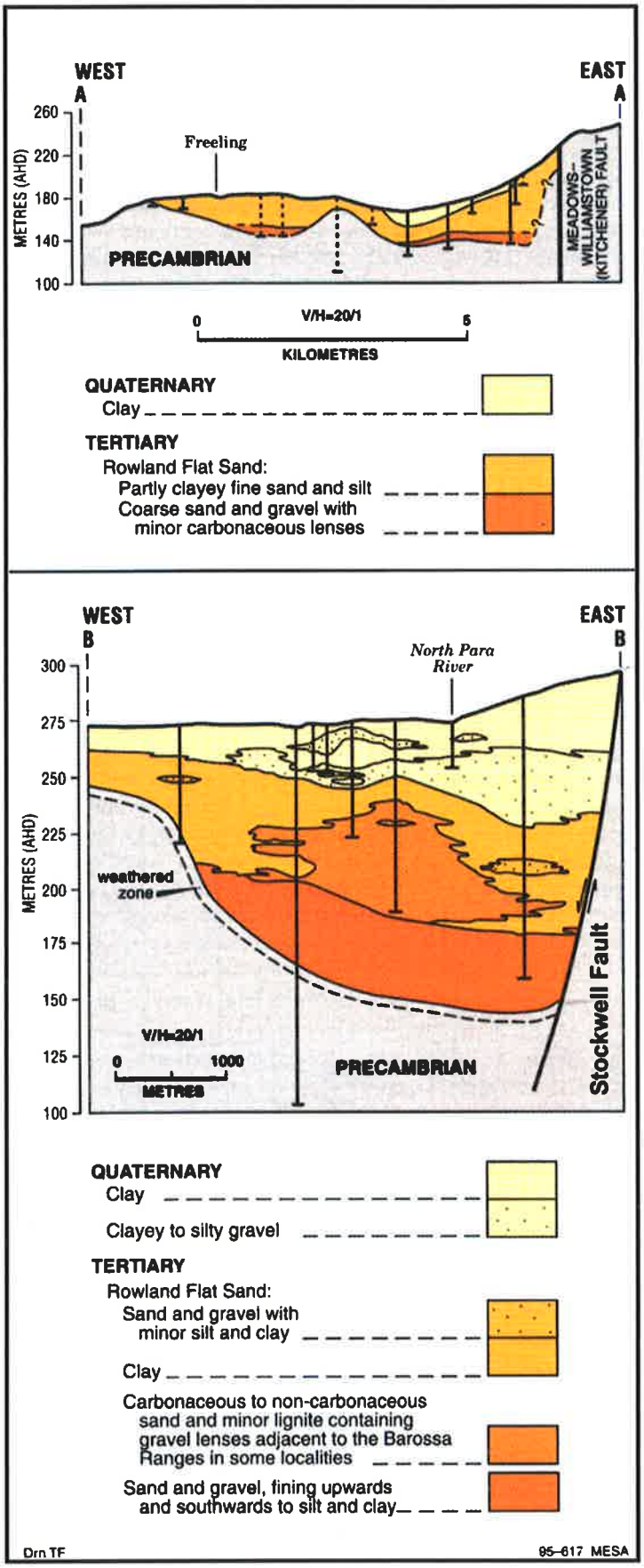


Figure 5-7 Geological transects of the Freeling area and intramontane Barossa Basin containing Tertiary sediments (after Scott, 1989; Alley, 1995). Sedimentary accommodation space of the Barossa Basin is clearly associated with down-to-basin block movements along normal Stockwell Fault; (Transect locations are in Fig. 5-6).

evidence of post-Mid-Pleistocene reverse faults and deformation associated with a compressional tectonic regime on both western and eastern sides of the Ranges (eg. May & Bourman, 1984; Bourman & Lindsay, 1989; Sandiford, 2003). In this thesis, the author has methodically collected all available information and made an analysis of both extensional and compressional settings within the study region. As a result the Tertiary extensional neotectonic setting is distinguished from the Pleistocene compressional setting while both settings are spatially interconnected.

5.3.1 Tertiary Extensional Setting: Crustal Segmentation

To better understand the extensional processes that have affected the study region, a number of published results from extensional terrain studies were examined and the terminology was adapted from many examples in western North America (eg. Faulds & Stewart, 1998) and elsewhere in the world (eg. Gibbs, 1984; Bosworth, 1985; Etheridge et al., 1985, 1987, 1988, 1990; Rosendahl, 1987; Colletta et al., 1988; Morley, 1989; Morley et al., 1990; Wernicke, 1990, 1992; Patton et al., 1994; Moustafa, 1996).

Crustal segmentation is a typical process of extensional tectonics that significantly depends on the spatial distribution of tectonic stress. The magnitude of stress release significantly depends on crustal heterogeneities and may be observed on a range of scales (Faulds & Varga, 1998). The magnitude of stress required for extensional strain release is usually significantly less than that required for the formation of compressional structures in any particular state of the crust. Thus the consolidated metamorphic basement of the Mount Lofty Ranges was less resilient to extensional stress than to compressional basement reactivation. The extensional settings within the study region were observed as second and third orders of crustal segmentation.

1. The first order of tectonic crustal segmentation (continental scale) is apparently related to the separation of the Australian and Antarctic continents.

2. The second order of tectonic crustal segmentation (regional scale) affected the study region and resulted in a division of the Pre-Middle Eocene Palaeoplain into subsiding sedimentary basins. A large remnant of this Palaeoplain stood above these subsiding basins forms the proto-Mount Lofty Ranges and served as a source region. Regional tilting, that is also a common attribute of extensional tectonics, affected this interbasin source region. Gentle S-SW tilting as recorded by the regional river-pattern and major watershed formation on the

eastern portion of the Ranges, resulted in asymmetry of this Palaeoplain remnant with initially higher eastern and lower western edges to this region.

3. The third order of tectonic crustal segmentation (local scale) is the subdivision of the St. Vincent and Murray Basins into embayments and local depositional structures. It also resulted in further segmentation in the Mount Lofty Ranges and imprinted as block structures with various degrees of block tilting and multiple movements. The intramontane basins such as Hindmarsh Tiers, Meadows-Myponga and Barossa containing Tertiary deposits are the product of this segmentation.

It is important to note that second and third orders of crustal segmentation did not occur simultaneously in the entire study region. Although some basin segmentation into embayments apparently occurred at the same time as the Palaeoplain segmentation (Middle-Late Eocene), the third order of segmentation that affected proto-Mount Lofty Ranges began some time during the Late Oligocene (Early Janjukian Stage) when the intramontane Meadows-Myponga and Hindmarsh Tiers Basins were formed. This delay of crustal segmentation in the interbasin region of the Mount Lofty Ranges is probably related to additional stress accumulation required to break the solid metamorphic basement on this scale. Some basement faults such as the Williamstown-Meadows Fault possibly served as zones of crustal weakness. However this example is a rare exception rather than the rule, because of a general absence of any expression of fundamental basement structures in the neotectonic setting and landscape (Tokarev et. al., 1999). For example, the major Nairne Fault of the basement structure that separated the Adelaide Geosyncline from Kanmantoo Trough did not show any neotectonic activity or geomorphological expression. Thus the neotectonic setting is substantially independent from the major basement fabric (see also discussion at the end of this chapter).

5.3.2 Tertiary Extensional Setting: Strain Accommodation and Strain Transfer Zones

There are two fundamental elements in the structural architecture of crustal segmentation of extended terrains: strain accommodation zones and strain transfer zones. The semantics of strain accommodation and strain transfer zones can be found in Faulds & Varga (1998).

The strain accommodation zone in the extensional environment is a group of structures that accommodate the transfer of strain. Most of the accommodation zones are associated with normal-fault systems and attendant tilt-block domains. These zones can trend parallel,

oblique and even perpendicular to the main direction of crustal extension (Faulds & Stewart, 1998).

Most *strain transfer zones* are associated with steeply dipping faults or fault zones that trend parallel or oblique to the main direction of extension and accommodate some components of strike-slip motion that are not always essential. In other words, these faults typically facilitate a transfer of strain between non-aligned systems of normal faults (Gibbs, 1984). Most of these zones do not accommodate the physical separation between extended terrains but simply transfer strain between two originally separated loci of extension (Frauds & Varga, 1998). In this and some other ways, transfer zones are similar to oceanic transform faults. This similarity between the transform faults and extensional strain transfer zones has long been recognised (eg. Wernicke, 1992; Faulds & Varga, 1998). Some major transfer zones in extended terrains such as in the Basin and Range Province (USA) have been interpreted as intracontinental transform faults (Davis & Burchfiel, 1973; Ligget & Childs, 1977; Faulds et al., 1990). Researches in this field have noted that most transfer zones accommodate upper-crustal heterogeneities in strain and may function in a way similar to that of transform faults, inasmuch as they link separate loci of crustal extension. Curiously, while transform faults are currently often associated with oceanic crust, one of the first definitions of transform faults was made for the continental sector of the San-Andreas Fault (Wilson, 1965).

As a result of this study, a strain transfer zone and a number of strain accommodation zones associated with normal faults and attendant tilted blocks were recognised in the study region. The strain transfer zone obliquely divides the study region into two large sectors: northern and southern (Fig 1-2). These are distinguished by the strike of accommodation zones that are probably adapted to slightly different directions of stress distribution. Each of these sectors is also divided into segments according to the morphology of strain accommodation zones.

The SW segment comprises the SW portion of the Mount Lofty Ranges and flanking embayment. This sector accommodated NW dipping normal fault motions that formed several half-graben embayments such as the Willunga, Noarlunga, Golden-Grove and the southern part of the Adelaide Plains, which are bounded on their eastern side by arcuate boundary normal faults (Fig. 1-2). The similar polarity of all these structures indicates synthetic geometry of these accommodation zones. Both synsedimentary fault displacements and block tilting have accommodated SE-NW transfer of crustal extension between non-aligned border faults: Willunga, Clarendon, Eden-Burnside and Para.

The SE segment is mainly associated with the Encounter Fault that separates the SE part of the Ranges from the Buccleuch Embayment of the Western Murray Basin (Fig. 4-7). A few smaller normal faults parallel to the Encounter Fault were also identified on the eastern slope of the Ranges (Figs 1-2; 5-4). The major Encounter Fault was active during the early stages of the neotectonic structural developments and is recognised as the NW border of the Buccleuch Embayment (Brown & Stephenson, 1991). The SW-NE strike of this fault thus indicates that SE-NW extension must have led to the formation of this accommodation zone. It is not clear how far NE this fault extended, because significantly younger movements (most likely Pleistocene) along the Bremer Fault have overprinted the original Tertiary tectonic setting.

It was observed that a relatively large tectonic slump that perhaps consists of several small blocks including Mt. Observation (in the central part) affected the eastern slope of the Ranges within this SE segment (Fig. 5-4). This tectonic slump formed a relatively smooth landscape distinguished from the relief of neighbouring areas of eastern slope of the Ranges and also south and north of this slump. Block sliding toward the basin is consistent with the proposed extensional setting and probably associated with curvilinear shape of the strain accommodation zone (or normal fault) at the head of such slump. Collectively all these faults including the Encounter Fault along the SE slope of the Mount Lofty Ranges formed the SE segment of the extensional strain accommodation zones. Because accommodation zones in this segment most probably dip SE and thus in opposite directions to those developed in the SW segment (eg. Willunga, Clarendon, Eden-Burnside and Para) the antithetic character of these segments is indicated. However the strike of all these accommodation zones along both western and eastern slopes of the Ranges is semi-parallel and thus consistent with SE-NW transfer of crustal extension (Fig. 1-2).

The NW segment accommodates more western dipping fault motions along the Stockwell, Kitchener, Alma and Redbank Faults than faults of the SW sector dipping NW (Fig. 5-6). This indicates that these non-aligned faults of the NW segment probably accommodated the E-W transfer of extension between them. The Transfer Zone thus clearly distinguishes SW and NW segments that accommodate slightly different directions of extensional strain transfer (Fig.1-2).

The NE segment is associated with the Palmer and Milendella Faults developed along the NE border of the Mount Lofty Ranges with the Western Murray Basin. However two other faults such as Florieton and Morgan strike parallel to this border and were clearly identified beneath the Quaternary sediments (Fig. 4-18). A cross-section in this figure clearly demonstrates a stepped down block-structure that accommodated down-to-basin block movements along these normal faults. Thus all these non-aligned parallel faults with attendant blocks formed accommodation zones of this segment in response to the E-W extensional strain transfer.

Because accommodation zones in the NW and NE segments dip in opposite directions, an antithetic geometry of these segments is also indicated. However all zones in both these segments are semi-parallel and thus have accommodated the same E-W transfer of extension between non-aligned faults bounding the subsided basin blocks on both sides and within the Mount Lofty Ranges (Figs 1-2; 5-6)

The strain transfer zone identified here and plotted on the DEM images (eg. Figs 1-2; 5-6) is oblique to the north-south elongated block-structure of the Ranges and typically terminates several faults on both sides of this zone. Fauld & Stewart (1998) noted that lateral termination of normal fault systems is a fundamental component of extensional systems. On the basis of other studies that addressed normal fault terminations (eg. Crittenden et al., 1980; Frost & Martin, 1982; Gans et al., 1989; Wernickie, 1990; Dickinson, 1991) they concluded that "most of the normal fault systems terminate within either transfer or accommodation zones, and that transfer and accommodation zones are largely responsible for the regional crustal segmentation of extended terranes" (Fauld & Stewart, 1998, p.vi). Hudson et al. (1998) and Axen (1998) have emphasised that transfer zones in Nevada and Utah do not correspond to discrete faults or fault zones, but instead incorporate large regions of distributed shear. All these indicate that the relationships between the transfer and accommodation zones are quite complex and often exposed to heterogenous distribution of strain. In the study area of the Mount Lofty Ranges, this would possibly explain why the proposed transfer zone does not correspond to all observed fault terminations.

The curvilinear Willunga and Clarendon faults bounding the Willunga and Noarlunga Embayments terminate in the pre-Tertiary core of the western portion of the Mount Lofty Ranges south of the transfer zone. However the Eden-Burnside and Para Faults bounding the Golden-Grove and Adelaide Plains Embayments typically terminate within the transfer zone.

The southern terminations of all these faults of the SW segment are probably somewhere beneath the waters of Gulf St. Vincent within the accommodation zones that are typical for extensional tectonic settings (see above). The transfer zone also typically terminates the Meadows Fault (eastern border of the Meadows-Myponga graben) in the interior part of the Ranges (Fig. 1-2). Note: While the neotectonic Meadows Fault and Williamstown-Meadows basement Fault are spatially very close they were distinguished on the basis of their role in the Tertiary structure and according to their geomorphological expression and control of the Tertiary sediment distribution.

It is not necessary to consider that all neotectonic faults are long-lived. Some of them apparently were active only during the earlier stages while others appeared during later stages. However the major faults such as those bounding sedimentary embayments were apparently long-lived through the entire Tertiary period and probably served as crustal weakness zones during the Quaternary. All of them are clearly recognised on DEM images of the Mount Lofty Ranges as elongated geomorphological features identified here as fault-scarps or escarpments.

5.3.3 Lake Bungunnia: A New Assumption

The absence of marine access into the NW part of the Murray Basin is evidence of a barrier between the freshwater Lake Bungunnia and the SW part of the basin during the latest Pliocene-Early Pleistocene. The barrier may be associated with tectonic uplift of the Pinnaroo Block (eg. Stephenson, 1986; Brown & Stephenson, 1991), or the building of large coastal sand dunes during low sea-level (Belperio & Bluck, 1990). In either case, this barrier must have been strong and above the Late Pliocene-Early Pleistocene sea-level that was generally near or below PSL. There is not much evidence to suggest that actual uplift of the Pinnaroo Block occurred, while it was obviously a tectonically stable structure.

If one takes into account the normal fault geometry of the Morgan Fault (Fig. 4-18), then Lake Bungunnia would be formed as a result of down-to-basin block movements along this fault. Down-to-basin block movements would be attributed to the Pliocene new pulse of low-magnitude crustal extension providing a new accommodation space in the St. Vincent Basin (Dry Creek Sands and Hallett Cove Sandstone) and also for the Blanchetown Clay of Lake Bungunnia. Thus Lake Bungunnia could be formed as a result of subtle subsidence between the Morgan Fault and the relatively stable Pinnaroo block in the south, even without this

block's uplift. However in either case (uplift or subsidence) only a few tens of metres of tectonic movements were required to form this lake. The coastal build-up sand barriers (eg. Belperio & Bluck, 1990) could also have contributed to this Lake formation but only secondarily to tectonic factors because it seems that sand dunes would be too weak to sustain such a megalake for about 2Ma, especially during the wet seasons that were at least twice wetter than those today (Stephenson, 1986).

5.3.4 Nature and Regional Significance of the Tertiary Strain Transfer Zone

The above data demonstrate the importance of the transfer zone for the Tertiary tectonic setting and formation of the Mount Lofty Ranges and their flanking and intramontane basins. However on a broader scale, the proposed transfer zone perhaps accounts for the sharp NE termination of the northern edge of Gulf St. Vincent and also Spencer Gulf. It is important to emphasise that the NW extent of this transfer zone terminated a number of non-aligned faults such as the Ardrossan, Templeton, Whitwarta, Redbanks, Alma, Para and Eden-Burnside faults mapped as major structural elements of the St. Vincent Basin (Fig. 5-8). The SE extent of the transfer zone coincides with the Padthaway Ridge in the southern part of the Murray Basin associated with the northern limit of the Otway Basin. The Kanawinka Fault as a northern limit of this Basin would be thus an integral part of the proposed transfer zone (Fig. 3-6). The strike of the strain transfer zone is coincident with a main direction of Phase-1 (Jurassic-Cretaceous) of crustal extension and parallel to a number of NW striking transfer faults that resulted in >300km of initial intracontinental crustal extension as a precursor of the southern Australian continental margin (Stagg et al., 1990; Wilcox & Stagg, 1990). Thus transfer zone in the study region would be an integral part of intracontinental extensional system associated with tectonic development of the southern Australian continental margin.

The recognition of a strain transfer zone provides a reliable mechanism of crustal extension and segmentation for the formation of Tertiary structures of the study region that is consistent with geological, structural and geomorphological data. This leads to a better understanding of why the topographically high pre-Middle Eocene Palaeoplain was segmented into an 'en echelon' set of non-aligned subsiding blocks forming the sedimentary embayments of the St. Vincent and Western Murray Basins. According to this extensional model, the initial Mount Lofty Ranges were formed as an interbasin region between the subsiding St. Vincent and Western Murray Basins. As a result of this study all fundamental attributes of extensional tectonics such as crustal segmentation, transfer and accommodation zones, uniformly dipping

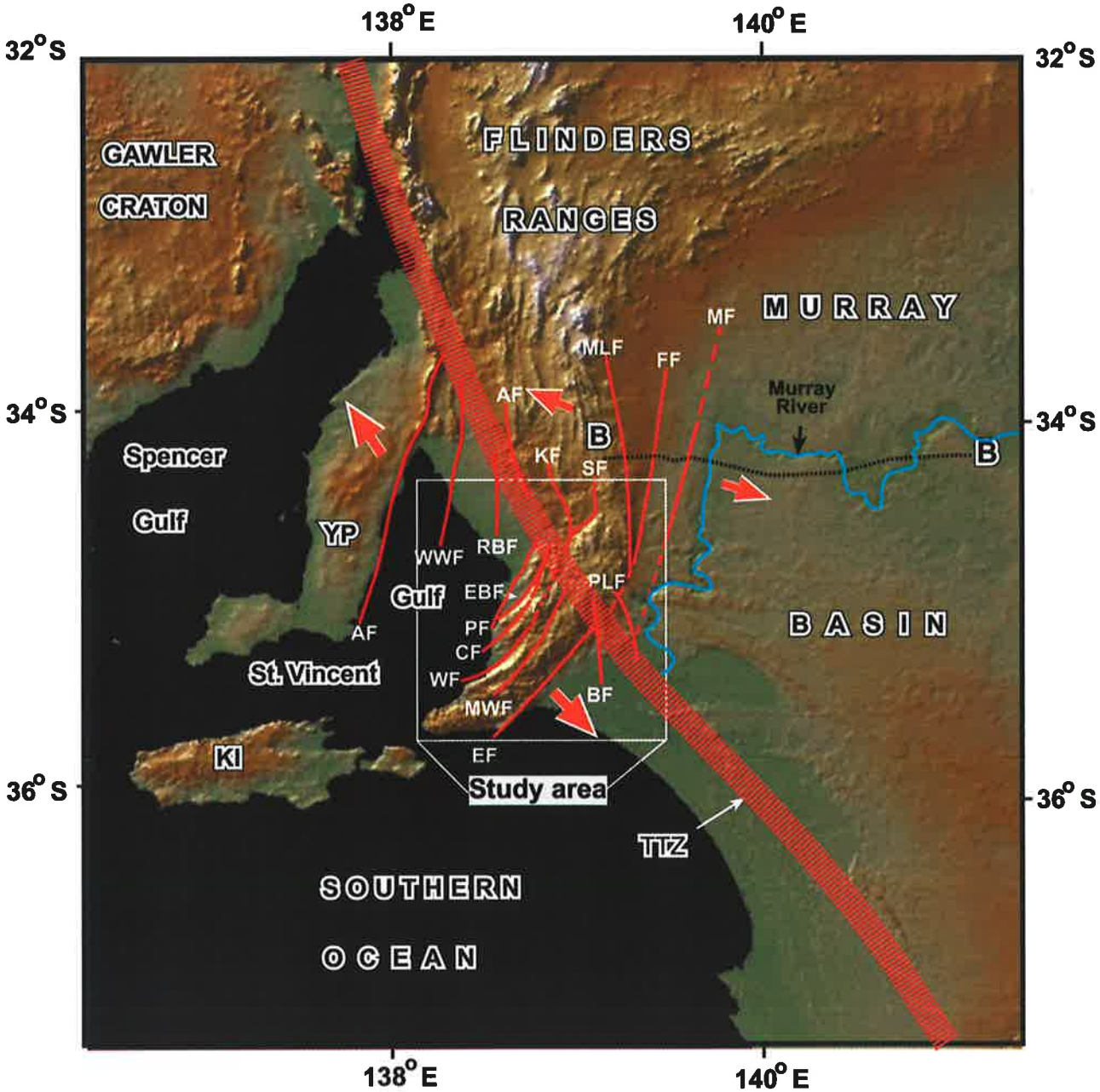


Figure 5-8 Termination of a number of neotectonically active faults (accommodation zones) by the inferred Tertiary Transfer Zone (TTZ). Faults south of TTZ: AF- Androssan, WWF- Whitwarta, RBF- Redbanks, PF- Para, EBF- Eden-Burnside, CF- Clarendon, WF- Willunga, MWF- Meadows, EB- Encounter, BF- Bremer. Faults north of TTZ: AF- Alma, KF- Kitchener, SF- Stockwell, MLD - Milendella, Florieton, MF- Morgan, PLF- Palmer. Red arrows indicates possible direction of the Tertiary extensional strain transfer between non-aligned system of normal faults. B-B: geological transect (Fig. 4-18) YP -York Peninsula; KI - Kangaroo Island. Image derived from 9s DEM.

and non-aligned systems of normal faults and their terminations and gentle tilting of attendant tectonic domains were recognised for the first time in the study region.

In contrast to earlier models (eg. Willcox & Stagg., 1990) the southern extension of the inferred transfer zone is probably coincident with the major fracture zone located immediately west of Tasmania (Fig. 5-9). The connection of the strain transfer zone (study area) with a large Tasmanian Fracture System would plausibly explain the structural difference between the fully-developed rift systems of the outer Otway and Duntroon Basins (west of the zone) and the eastern failed rift systems such as the Victorian inner Otway and Bass Basins (eg. Hill et al., 1995).

If a link between the proposed transfer zone and the Tasman Fracture System existed then it would divide the southern Australian continental margin into two major sectors: eastern and western. While both sectors were initially affected mainly by extension, the compressional palaeostress regime was more pronounced within the eastern sector during the Tertiary as basin inversion, gentle folding and reverse faults were recognised within the SE Australian basins (Dickinson et al., 2001, 2002). In contrast, the fully-developed rift systems of the western sector were most probably associated with the dominant extensional stress not only during the Potoroo (Jurassic-Cretaceous) tectonic regime (Veevers, 2000) but also during the whole Tertiary. The great thickness of Mesozoic and Cainozoic sediments in the Great Australian Bight, Duntroon and outer Otway Basins and elsewhere within this sector clearly points to great subsidence and fully-developed rift systems as the major cause of the sedimentary accommodation space. Therefore the western sector probably accommodated a significantly larger magnitude of extension than the eastern sector of the southern Australian continental margin.

Such differentiation of the southern Australian continental margin is possible associated with an interaction between the Australian and Pacific Plates during which the subduction of the Pacific Plate (as a major plate boundary force) probably generated an E-W to SE-NW compressional stress field. This would reduce the effect of the crustal extension associated with separation of the Australian and Antarctic Plates within the SE sector of the continental margin between the Tasmanian Fracture System and the zone of subduction. However substantial extensional stretching was dominant within the western sector of the Australian continental margin that later (after 43Ma plate neotectonic event) resulted in great

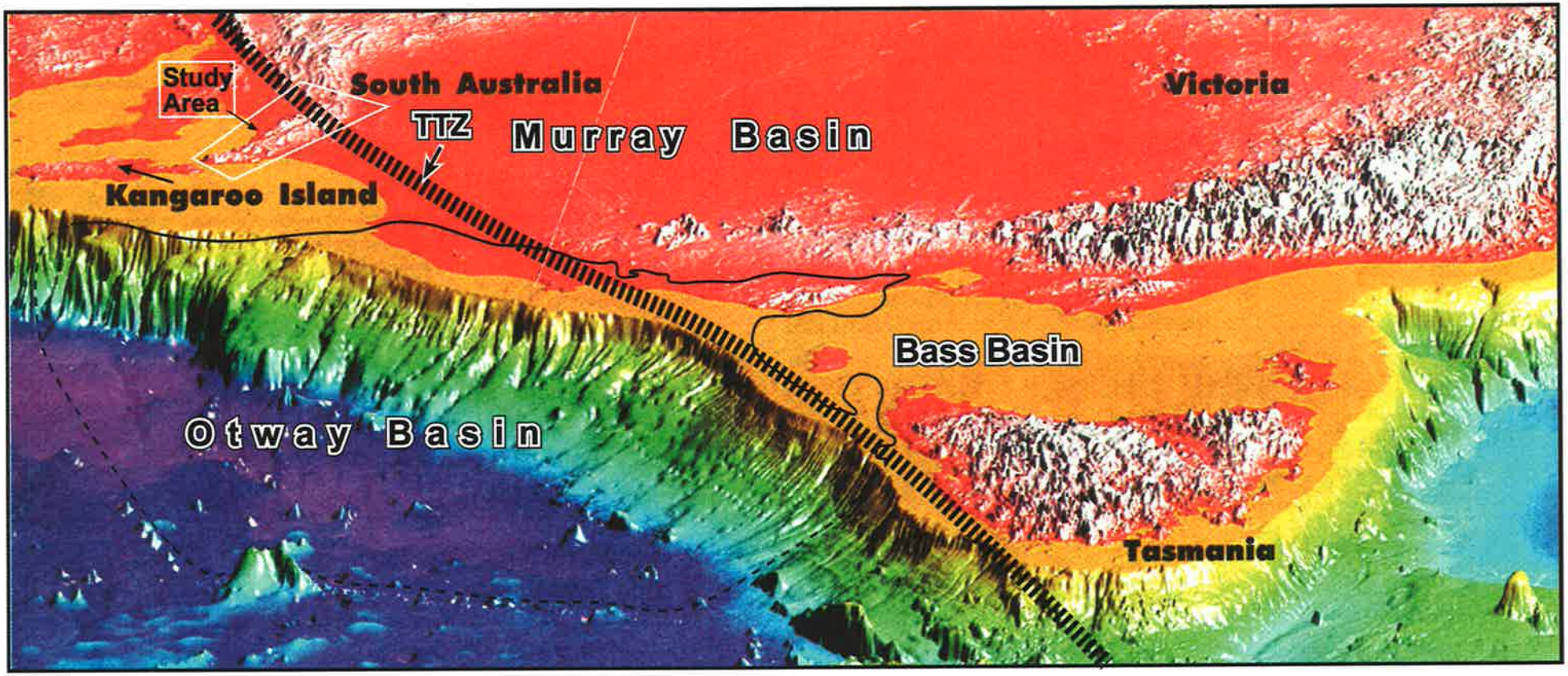


Figure 5-9 3D visualisation of the southern Australian continental margin with possible southward extension of the proposed Tertiary Transfer Zone (TTZ) and some elements of the crustal structures eg. Otway Basin (black solid line = limit of inner part , dashed line = approx. limit of outer parts). Image courtesy Geoscience Australia (not to scale).

acceleration of seafloor spreading between Australia and Antarctica during the Tertiary. In this sense the Tasmanian Fracture System together with the proposed transfer zone in the study region would be critical boundaries in distribution of palaeostress and thus account forthe arcuate configuration of the southern Australian continental margin.

By definition and analogy with transform faults, the transfer zones are steeply dipping faults or fault zones that trend parallel or oblique to the main direction of crustal extension (eg. Gibbs, 1984). Such zones represent deep structures of crustal weakness and when they are once established they can be later deactivated or reactivated depending on the state of the stress field (magnitude and main direction of distribution). Furlong et al. (2001, p.79) noted that "change of velocity of plate motion could push a previously stable offset of transform faults across the limit, causing a new evolutionary path through the parameter space and lead to transform split and new segments to form". The change in azimuth of the Australian Plate motion from SW-NE to dominantly S-N direction at ~43Ma (Fig. 5-1) would significantly contribute to opening and reactivation of SE-NW trending transfer zones established on the incipient southern continental margin earlier during the Jurassic and Cretaceous. The SW-NE direction of the plate movement before the 43Ma event was about perpendicular to the main strike of all those earlier-established transfer zones and this would be considered as the cause of tectonic quiescence in the study region including the St. Vincent and Western Murray Basins. Thus the 43Ma switch to NW azimuth of the Australian Plate movement together with a substantially increased rate of absolute plate motion would push the weakened transfer zone over the limit of the crustal strength and would trigger crustal segmentation in the study region. This would explain the contemporaneous commencement of structural development in the study region with acceleration of the Southern Ocean seafloor spreading.

Thus the proposed Tertiary Transfer Zone obliquely crossing the Mount Lofty Ranges and spatially concurrent with the Tasmanian Fracture System was apparently established during the earlier stages of intracontinental extension in the Late Jurassic and Early Cretaceous. The strike of this zone is the most probably concordant with the major SE-NW direction of this crustal extension (eg. Stagg et al., 1999). However different orientation of the extensional structures in the SE sector (Otway, Bass and Gippsland Basins) from NNE-SSW (Etheridge et al., 1985) to N-S (Hill et al., 1995) and to SE-NW (Willcox & Stagg, 1990) indicates that a complex stress field was already formed within the eastern sector during the intracontinental stage. If one takes into account convincing evidence of a steady SE-NW direction of

extension from the Naturaliste Plateau to Tasmania (Muller et al., 2000; Willcox & Stagg, 1990) then the differentiation of the southern Australian continental margin into western and eastern sectors had probably already occurred on the incipient continental margin.

Following the drastic change of Australian Plate motion from SE-NW to mainly S-N in association with the break-up between Australia and Antarctica at ~99Ma (eg. Muller et al., 2000; Veveers, 2000) there was no evidence of any structural development within the study region up to the Middle Eocene despite the formation of substantial sedimentary accommodation space (thousands of metres) along the emerging southern continental margin. This time interval is referred to here as the relative tectonic quiescence that would indicate that the magnitude of extensional stress was insufficient to break consolidated metamorphic basement within the study region. It would have been directly or indirectly related to predominant NS to SW-NE directions of the Australian Plate movements during the extensional Potoroo Regime (Ch. 3). Plate reorganisation at ~43Ma in both direction and rate of absolute movements most probably changed stress/strain ratio that reactivated the earlier-established SE-NW striking transfer zones. These resulted in a new structural development in the study region associated with intraplate crustal segmentation. The inferred strain transfer zone played a major role in neotectonic rearrangement in the study region and it also associated with plate tectonic development. *Thus this transfer zone is attributed in this thesis as the most probable and a spatially and chronologically consistent link between the Plate and Intraplate tectonics.*

5.3.5 Compressional Neotectonic Setting

Despite the recognition of all fundamental attributes of extensional tectonics, some compressional neotectonic elements are also present in the neotectonic setting of the study region. The rigid metamorphic core of the pre-Tertiary basement inhibited neotectonic folding and thus accounted for the absence of folds in both Tertiary extensional and Quaternary compressional environments. The most significant example of reverse fault action is on Sellicks Beach of the Willunga Embayment (Fig. 5-10A). The almost vertically bedded Mid-Tertiary section of the Port Willunga Formation at the southern end of Sellicks Beach is recognised as a post-Middle Pleistocene compressional deformation along the zone closely associated with the Willunga Fault (eg. May & Bourman, 1984; Bourman & Lindsay, 1989; Sandiford, 2003).

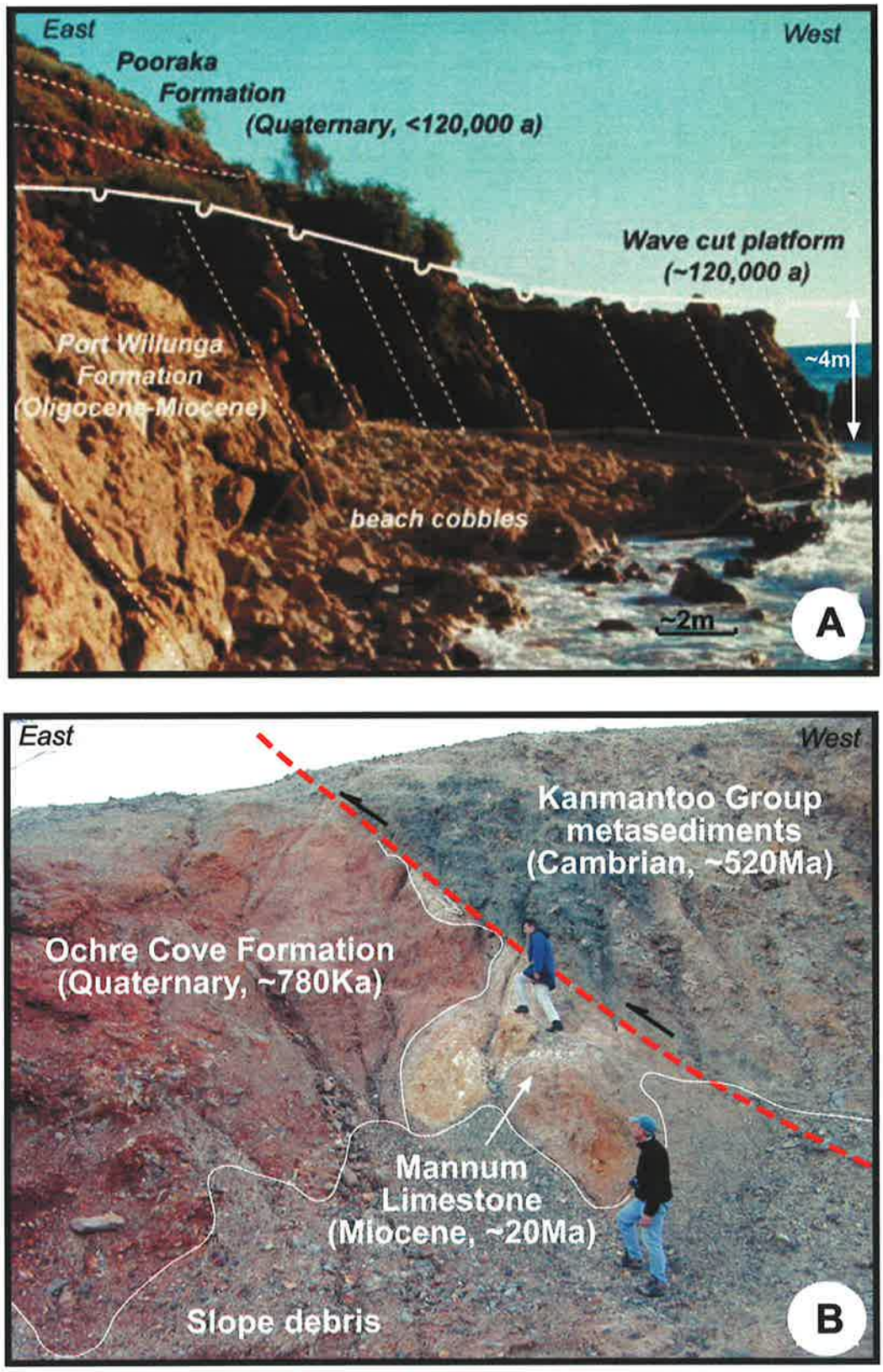


Figure 5-10 Pleistocene compressional deformations on the western and eastern sides of the Mount Lofty Ranges. A = Sellicks Beach (Willunga Embayment). Steeply dipping carbonate package of the Port Willunga Formation (Oligocene-Miocene) overlain by the boulder conglomerate of the Pooraka Formation (Late Pleistocene, ~35Ka) above the wave-cut platform (~120Ka). Deformation is associated with reverse faults along the Tertiary Willunga boundary Fault possible served as crustal weakness zone during the Pleistocene. B = West of Cambrai, thrust fault along the Tertiary Milendella Fault on the eastern border of the Mount Lofty Ranges and Western Murray Basin. Basement metasediments thrust over Pleistocene fanglomerate (after Sandiford, 2003; described by Bourman & Lindsay, 1989).

In regard to this deformation, Lemon & McGowran (1989) note "that near vertical or even overturned bedding on the downthrown side of the fault can only occur if the fault is reverse because the deformation along any normal fault cannot be steeper that the angle of the fault plane". Thus the deformation of the Port Willunga sediments is apparently due to block movements along a reverse fault. One possible splay is exposed as a steep east-dipping brecciated zone (<1m) within the Cambrian metamorphic basement in Waterfall Creek, some tens of metres south of the coastal platform (Fig. 5-11). However there is clearer evidence of the reverse fault in the nearby Cactus Canyon (one of the deepest creeks in this area) at ~150m above PSL. On the left side of this creek the metamorphic basement is clearly in contact with Pleistocene gravel along a steep splay also dipping SE (Fig. 5-12). Despite similar reverse motions of these faults, it appears that they are spatially disconnected. There several possible splays and geomorphological benches at various topographical levels collectively formed the Willunga escarpment (Fig. 5-13). Thus it appears that rather than one master fault, several new reverse splays were formed along the initially normal Willunga Fault (Tertiary) during the Quaternary compressional stage.

It is not clear when the deformation of the Oligocene-Miocene sedimentary package on Sellicks Beach occurred because there is no actual fault exposure at this site. Because the bench of the wave-cut platform (Fig. 5-10A) is associated with the last interglacial maximum (125Ka, May & Bourman, 1984) the deformation must have occurred before this event. In the Cactus Canyon the metamorphic basement is thrust over the Middle Pleistocene gravels of the Ochre Cove Formation. The Brunhes/Matuama magnetic reversal (0.78Ma) was defined at the top of this section (Bourman pers. comm., 1998). Thus it is most probable that compressional reverse fault block movements along the Willunga Fault are post-Middle Pleistocene. This is consistent with the earlier interpretation of fault movements at Sellicks Beach also defined as Mid-Pleistocene (May & Bourman, 1984; Bourman & Lindsay, 1989).

Evidence of the compressional tectonic setting on the eastern side of the Mount Lofty Ranges is associated with the Milendella Fault west of Cambrai at about 160m above PSL (Bourman & Lindsay, 1989; Sandiford, 2003). At this location the metamorphic basement of the Kanmantoo Group sediments is thrust over the Pleistocene fanglomerate overlying the Early Miocene Mannum Limestone at the base of the footwall block (Fig. 5-10B). In contrast to steep reverse faults along the Willunga Fault, the Milendella reverse fault displays a western dip of about 45° (Bourman & Lindsay, 1989; Sandiford, 2003). Bourman & Lindsay (1989)



Figure 5-11 One of several active splays of the Willunga Fault weakness zone within the Cambrian basement at the left bank of Waterfall Creek, showing EW reverse fault motion possibly associated with Pleistocene compressional regime . Outcrop location is just a few hundred metres from Sellicks Beach where Tertiary sediments are deformed (Fig. 5-10A).

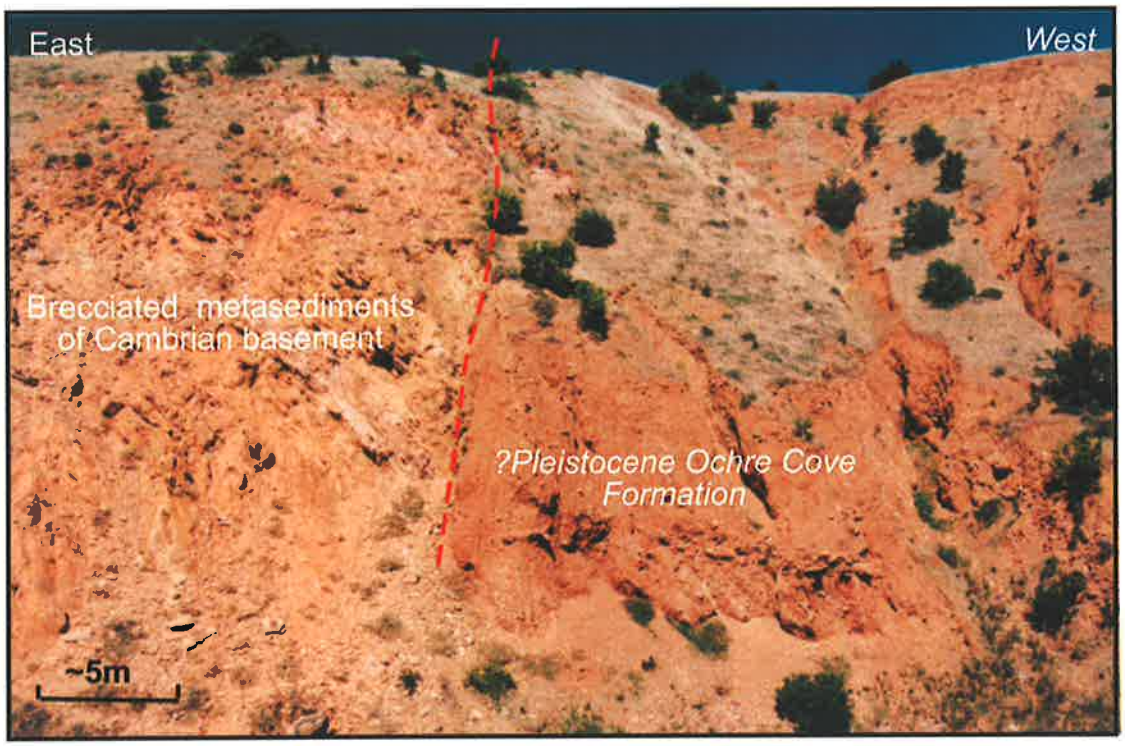
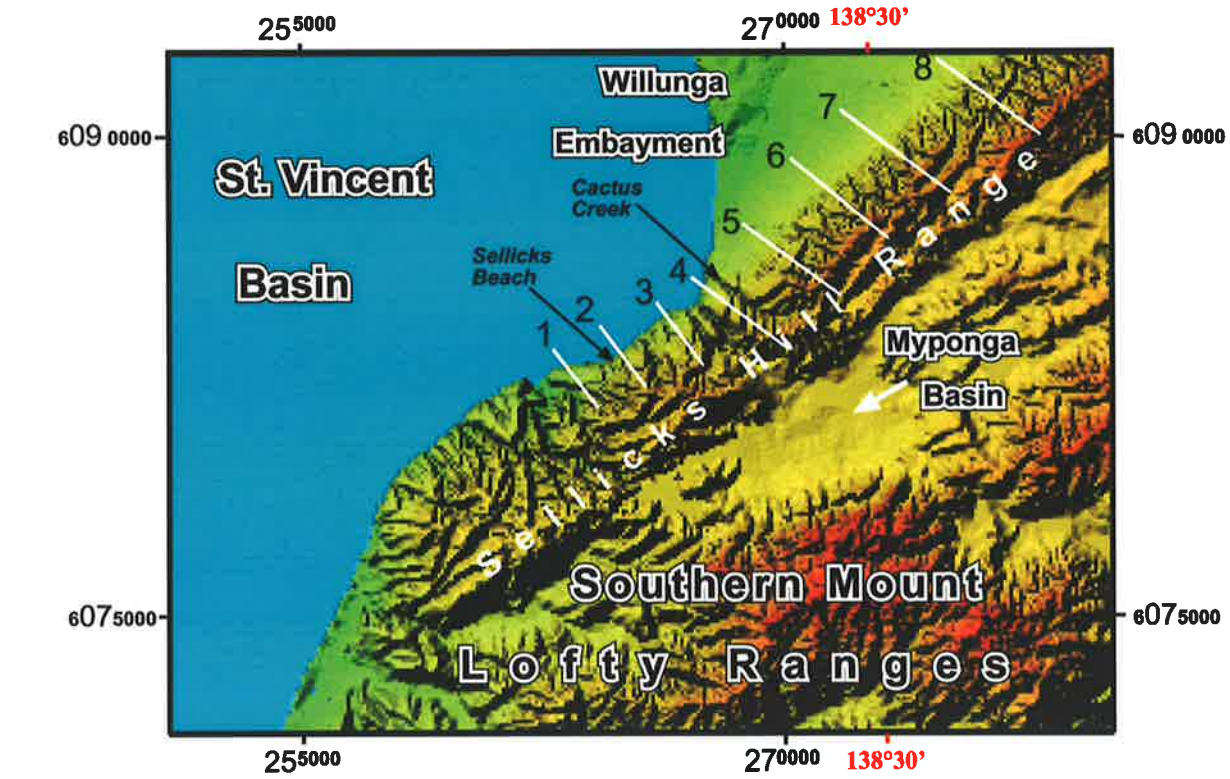


Figure 5-12 Contact between the Cambrian basement and Pleistocene Ochre Cove Formation slightly steeply dipping eastward indicating reverse fault motion at the left bank of Cactus Creek on the western side of the Sellick Hill Range possible associated with one of splays along the Willunga Fault weakness zone. Vertical field of view is about 40m.



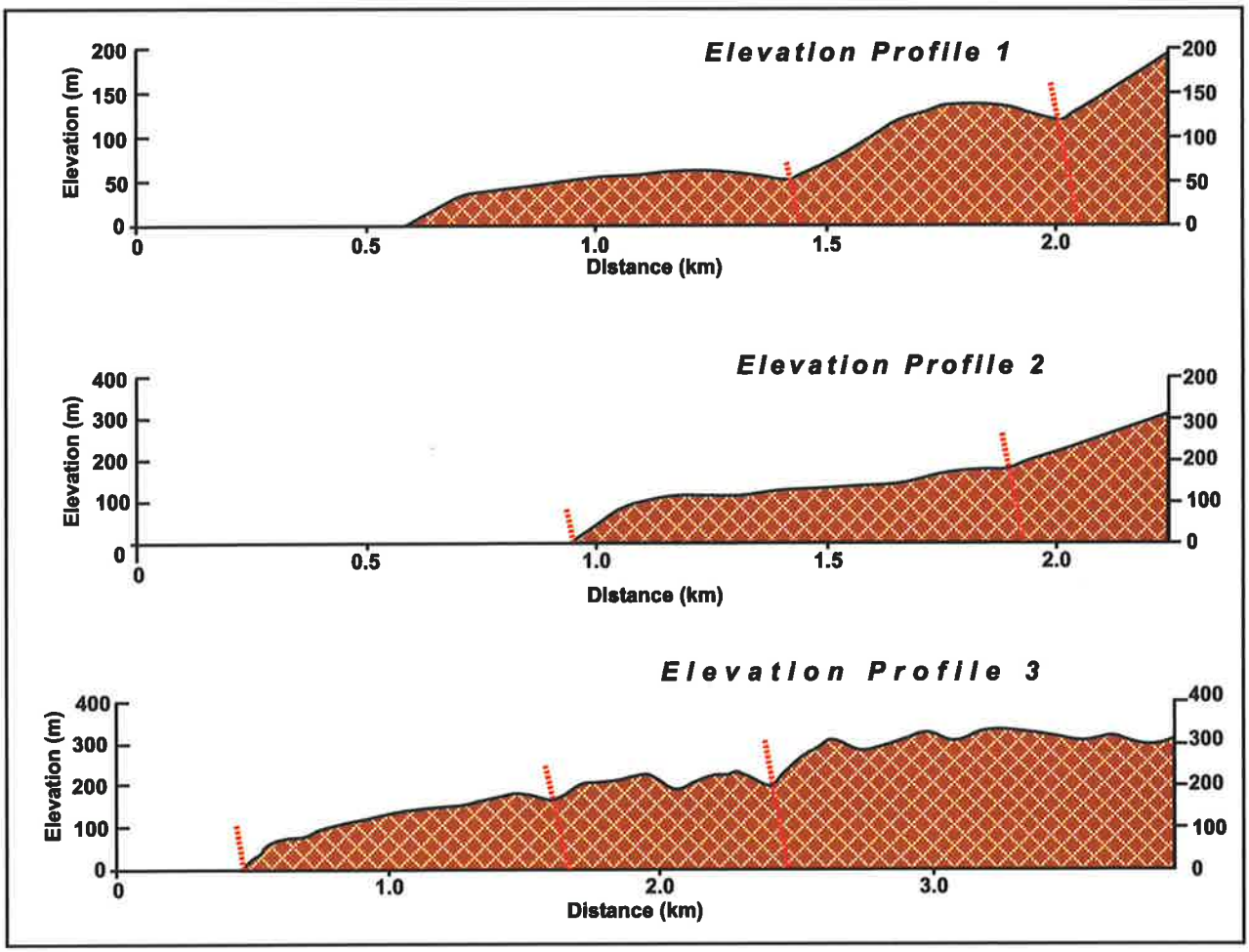


Figure 5-13 Geomorphological cross-sections along the Willunga escarpment show geomorphological benches possibly associated with several splays rather than master reverse fault along the Tertiary Willunga Fault weakness zone (see next page for continuation)

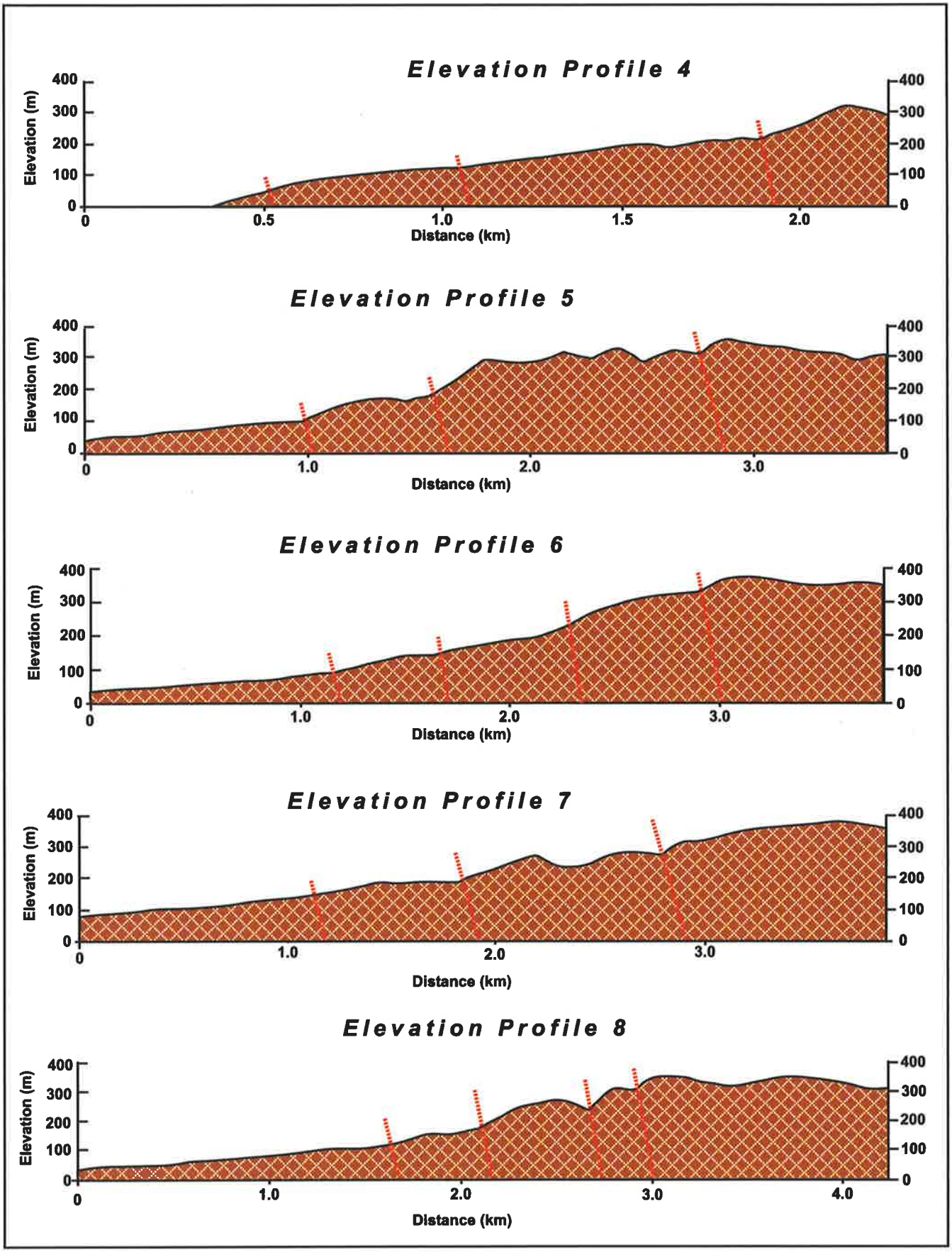


Figure 5-13 (Continued) Geomorphological cross-sections along the Willunga escarpment show geomorphological benches possibly associated with several splays rather than master reverse fault along the Tertiary Willunga Fault weakness zone.

correlated the mottled ferruginous clay, calcrete and gravels at this exposure along the Milendella Fault with those developed on the Willunga scarp and inferred a Middle Pleistocene age for these sediments. The similar time of reverse fault activity on both sides of the Mount Lofty Ranges led Bourman & Lindsay (1989) to postulate a Pleistocene phase of reverse faulting.

There is no further direct evidence of compressional setting in the study region. However several faults that are expressed well in the landscape are probably associated with reverse block movement that resulted in the Pleistocene uplift of the Mount Lofty Ranges. The most visible effect of such block uplifts is associated with the western portion of the Ranges along the Eden-Burnside Fault. The relatively steep western slope with a number of waterfalls and deeply incised valleys is clear evidence of recent uplift along this fault. There is also a similar geomorphological evidence of Pleistocene block uplifts along the Para and Clarendon Faults on the western side of the Ranges, and along the Bremer and Palmer Faults on the eastern side of the Ranges that probably resulted from compressional strain release (see Ch. 6).

There is some geological evidence of the possible Pleistocene uplift along the Para Fault near Port Adelaide associated with a seaward increased thickness of the Glanville Formation (Belperio & Baterman, 1986; Belperio & Rice, 1989; Sheard & Bowman, 1996). This indicates that there was a switch from original Tertiary normal fault movements usually providing extra sedimentary accommodation space near the fault, to reverse fault motions that probably dragged up both foot-wall and the edge of hanging-wall blocks attached to this active fault. This created a slight seaward dip of the sedimentary surface on the hanging-wall block and led to an increased thickness of sediments seaward. The model comparing Tertiary normal faults and Pleistocene reverse faults affecting thickness of sediments is shown in Fig. 5-14.

5.4 Discussion of the Neotectonic Setting: Independence versus Inheritance

There is long lasting speculation about compressional reactivation of the basement structures within the study region. The most popular points of view are reflected in several chapters of the *Geology of South Australia* (Drexel & Preiss, 1995, see p.160 for details). A young and dissected topography along the margins of the Ranges located above the flanking sedimentary basins led to the view that the Mount Lofty Ranges are the result of uplift. The Delamerian Thrust-Fold Belt in the core of the Ranges is the most accessible structure for direct

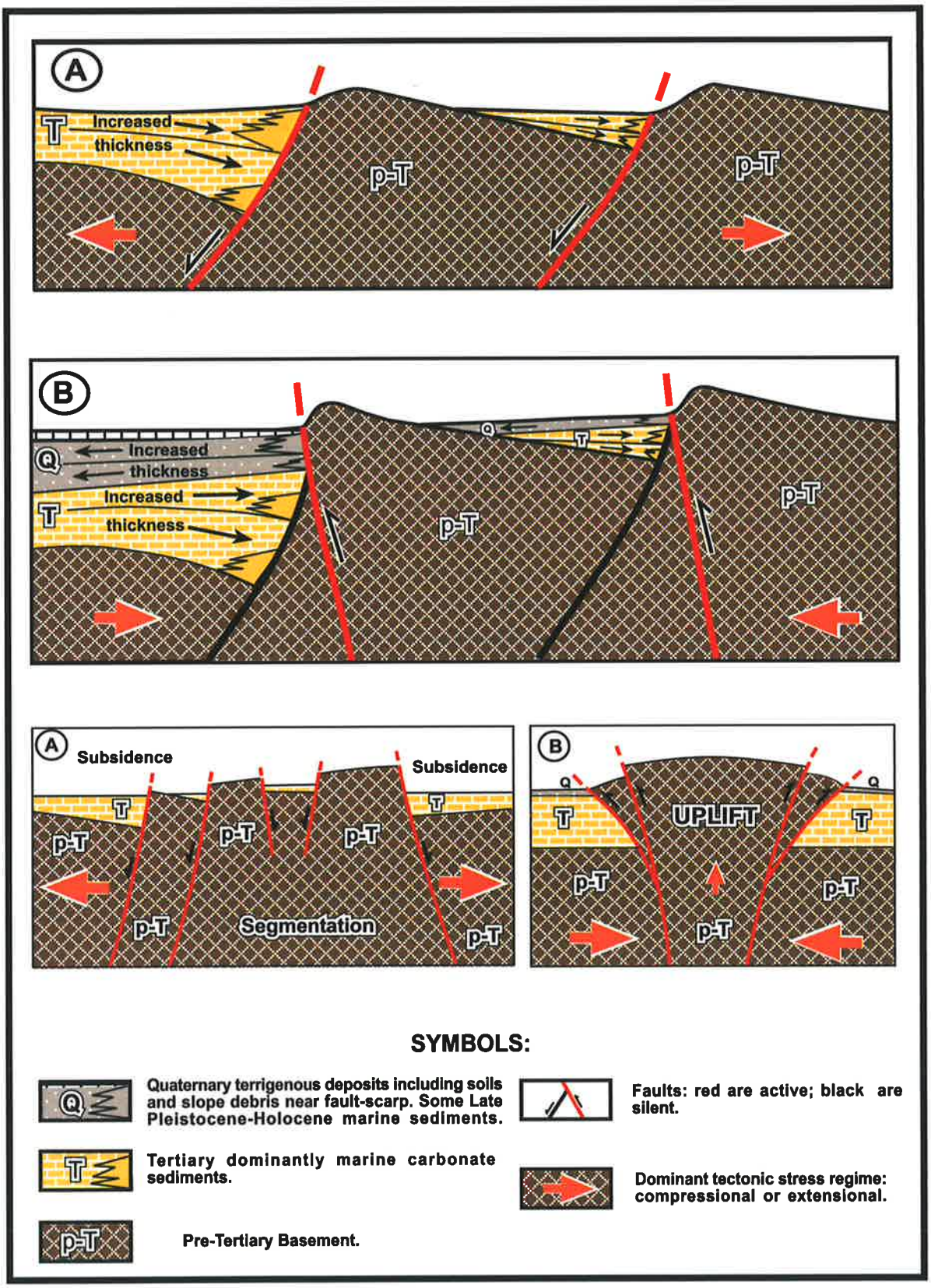


Figure 5-14 Principal neotectonic model of the Mount Lofty Ranges and flanking embayments. **A** = Tertiary extensional regime. Increased thickness of Tertiary deposits toward the faults indicates down-to-basin block movements along normal faults accompanied by low-angle hanging-wall block tilting toward faults. **B =** Quaternary compressional regime. Increased thickness of Quaternary deposits from the fault indicates dragging-up of the hanging-wall block along the reverse fault.

observation. These together led to the widespread interpretation that because basement compressional structure is uplifted and exposed to erosion, then the concept of neotectonic compressional reactivation would be the most likely explanation of the exposure of the pre-Tertiary basement. Despite the dominance of such an interpretation for decades, there is a very low degree of certainty in regard to neotectonic, geomorphological and kinematic reasons for this concept in scientific papers, and references are often made to earlier speculations without spatial correlation of events and/or time considerations.

A number of faults are recorded on geological maps as a result of mapping basement structures. However, most of these basement faults were not active during the Tertiary and are not spatially consistent with those manifested in the landscape of the Mount Lofty Ranges. It seems that most of the pre-Tertiary basement structural elements such as thrusts, shear zones and folds within the Ranges are oblique to and superimposed by neotectonically active blocks and faults. Yassaghi et al. (2004) have provided clear evidence of such obliquity of neotectonic structures to the Delamerian structures of the Adelaide Fold-Thrust Belt (Fig. 5-15). Most importantly, the development of main river systems within the Ranges almost completely ignores basement structures and even lithology. The major pattern of river systems is oblique to and often perpendicularly superimposed onto the basement fabric, even over such fundamental zones as the Nairne Fault – a border between the Adelaide Geosyncline and Kanmantoo Trough. There are several lines of tectonic, geological and geomorphological evidence that challenge the hypothesis of the Tertiary compressional reactivation of ~500Ma old Delamerian structures.

1. The configuration of the neotectonic block-structure is oblique to the Delamerian fabric thrusts, folds and shear zones (eg. Yassaghi at al., 2004). For example, the neotectonically active Eden-Burnside Fault (eastern border of the Tertiary Golden-Grove Embayment) obliquely cuts the North Summit, Greenhill-Montacute Heights, Morialta Shear Zones and their associated thrusts (Fig. 5-15). If there were compressional reactivation of ancient Paleozoic faults resulting in growth of the Mount Lofty Ranges, then kinematics similar to the Delamerian thrust fault would be expected and the geometry of neotectonic faults would have to be spatially consistent with these Palaeozoic faults. In reality, there are no links between neotectonic block configurations and the Delamerian structures.

2. It is clear that the basement Delamerian structure extended beneath the neotectonically formed St. Vincent and Western Murray Basins. The traditional hypothesis of compressional

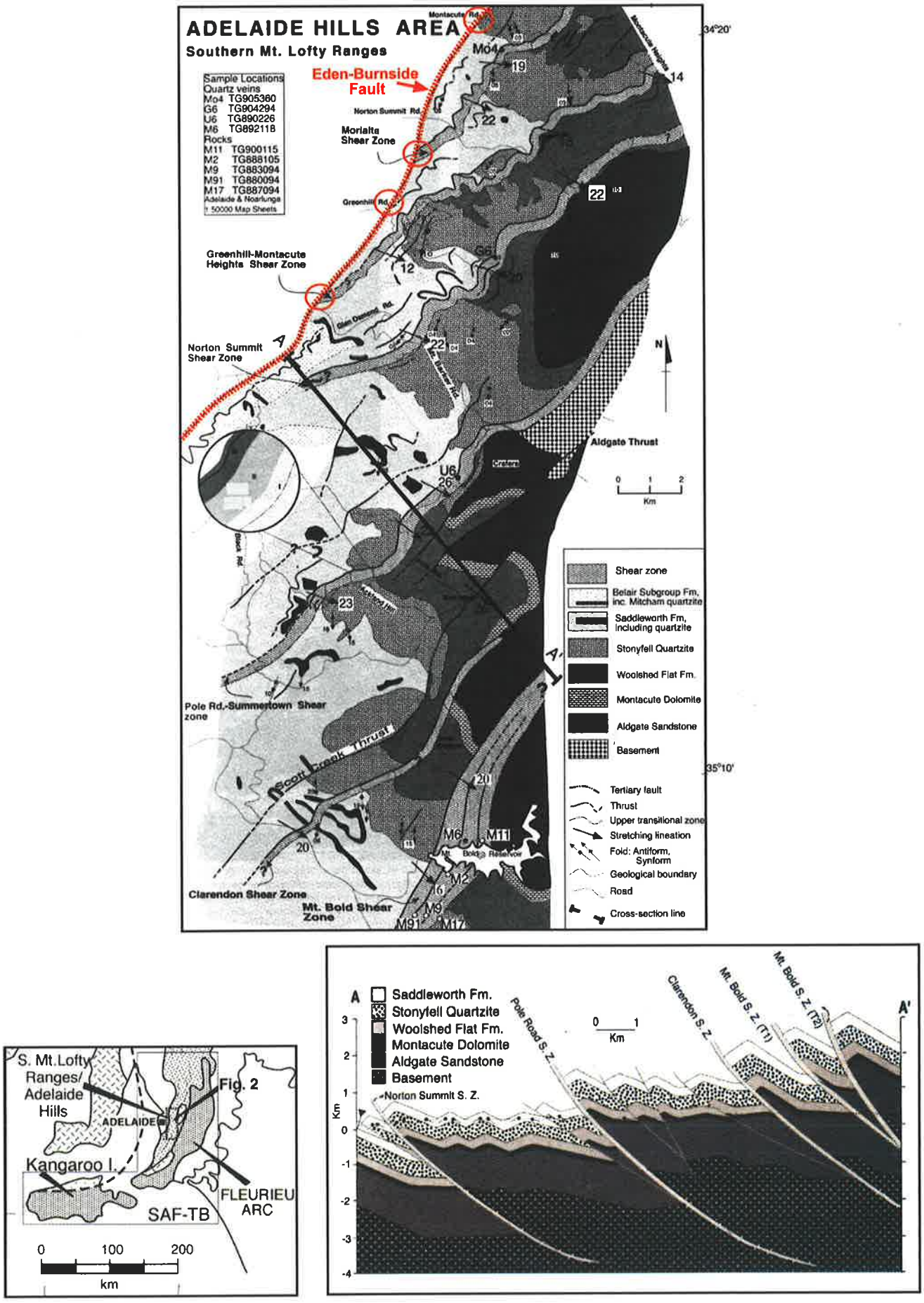


Figure 5-15 Oblique contact between neotectonic structure (Eden-Burnside Fault - red line) with Delamerian thrust and shear zones shown in structural cross-section A-A' (after Yassaghi et al., 2004).

reactivation of basement structures cannot explain why low-angle thrusts and shear zones dipping E-SE resulted in uplift of the Mount Lofty Ranges whilst at the same time this basement subsided to form both flanking basins without any deformations of Early and Mid-Tertiary sediments.

3. The neotectonic block-structure of the Mount Lofty Ranges itself is quite different to the Adelaide Thrust-Fold Belt which contains a number of low-angular decollements accompanied by shear zones with SE to NW block movements (Preiss, 1987; Sandiford & Jenkins, 1990; Flottman et. al., 1994; Yassaghi, 1998; Yassaghi et al., 2004). The dynamics that form steep faults bounding neotectonic blocks is different to tectonic processes resulting in basement low-angle thrust and decollements formed Delamerian fabric. No evidence of crustal shortening was ever recognised in the Tertiary structure, and thus it does not suggest any inheritance of basement structure. In contrast to major SE to NW tectonic movements that formed Delamerian structures, even Pleistocene block-movements that resulted in uplift of the Mount Lofty Ranges (Fig. 5-14B) are quite different. For example the Milendella Fault displays west to east (opposite to the Delamerian movements) displacements along the relatively steep western dipping thrust (Bourman & Lindsay, 1989; Sandiford, 2003).

4. The "downfaulting" within and adjacent to the Mount Lofty and Flinders Ranges (Benbow, 1995, p.211) suggests an occurrence of down-to-basin block movements (Glossary of Geology, 1975) that are commonly associated with normal fault kinematics in the extensional environment, rather than with compressional tectonics. However down-to-basin block movements and associated faultward tilt of the hanging-wall blocks are also recognised in this thesis as the most common Tertiary structural features developed on the margins of the Mount Lofty Ranges and sedimentary embayments (see Ch. 4). Such neotectonic features recorded by faultward increased thickness of sediments are typical attributes of normal fault kinematics associated with crustal extension (Mandle, 1988).

5. Compressional tectonics normally results in a reduction of sedimentary accommodation space with the widening and uplift of the source areas that significantly increase stream competence (erosion and sediment transport). However the lithology and spatial distribution of the Late Eocene to Middle Miocene sediments indicate that widening of sedimentary accommodation space actually occurred in the study area. The marine transgression into the intramontane basins and persistence of marine and marginal marine sedimentary environments in these basins for more than 10Ma are clear evidence of this. In contrast to

growth of the Ranges, the increased carbonate content of Tertiary units from Late Eocene to Middle Miocene indicates a decrease of stream competence upwards of the sequence that is not likely associated with the uplift of source area of the Mount Lofty Ranges.

6. If compressional tectonics were the cause of the basin and range formation, we should expect some fold deformations of soft Tertiary units on the borders with the consolidated Proterozoic basement, at least in a similar manner to that occurring at Sellicks Beach or along the Milendella Fault during the Pleistocene. However, before the Mid-Pleistocene, there are no apparent Tertiary deformations associated with the major neotectonic faults bounding the Willunga, Noarlunga, Golden Grove and Adelaide Plains embayments and on the margin of the Ranges with the Western Murray Basin. Thus the sub-horizontal bedding of the Middle Eocene to Miocene sequence in the flanking and intramontane basins more certainly suggests normal fault geometries of boundary faults with low amplitude synsedimentary kinematics rather than compressional reactivation of pre-Tertiary basement structures.

Thus unlike earlier studies the above data and interpretations in this thesis demonstrate that the neotectonic block-structures of the Mount Lofty Ranges and flanking St. Vincent and Western Murray Basins were formed initially as a result of Tertiary crustal extension, and therefore it must be considered as independent of thrust-fold basement fabric.

A new independent neotectonic model proposing Tertiary crustal extension and segmentation provides the most plausible structural and kinematic solutions for the simultaneous formation of the Ranges and flanking basins. This model incorporates spatial and temporal correlations of neotectonic movements with erosional features in the Mount Lofty Ranges and sedimentary patterns and environments in the flanking St. Vincent and Western Murray Basins (Ch. 4). Detailed analysis of time sequences suggests that the major compressional uplift of the Ranges was related to the Pleistocene (~1Ma). If some compressional reactivation did occur, it must be related to this latest stage of neotectonic developments. However possible Pleistocene tectonic reactivation, to some extent, would be mainly associated with Tertiary fault zones as the most reliable weakness zones of consolidated basement. A three-stage neotectonic model incorporating neotectonic, sedimentary and landscape evolution will provide further details and considerations in chapter 7. The next chapter 6 adds further evidence of the proposed neotectonic setting and development within the study region, by focussing on the geomorphological elements and landscape evolution.

Chapter 6

GEOMORPHOLOGY AND LANDSCAPE EVOLUTION OF THE MOUNT LOFTY RANGES

6.1 Introduction

The present-day morphology of the Mount Lofty Ranges is considered here as a legacy of ~43Ma duration of complex interaction between neotectonic movements, erosion and deposition. The main goal of this chapter is to generate a plausible landscape evolution model that integrates all data and interpretations. While the analysis below focuses mainly on regional geomorphological aspects, some correlations with neotectonic and sedimentary environments are inevitable.

As shown in previous chapters and in earlier work (Tokarev et al., 1999), there have been many interpretations of the landscape evolution of the prominent upland system of the Mount Lofty Ranges. However the model of landscape evolution presented in this thesis differs considerably from those proposed earlier. By incorporating correlated neotectonic, erosional and sedimentary events it is the most complete interpretation of the Mount Lofty Ranges landscape evolution to date.

Most earlier works interpret the preservation of gently undulating and deeply weathered planation surfaces or remnants of old Palaeoplain as essential characteristics of the uplifted landscape of the Ranges. The age of such surfaces is controversial and varies from ~200Ma (Twidale, 1976a, 1983, 1991, 1994) to about 1-2Ma (Fenner, 1927, 1930). Multiple and multicyclic models of the landscape and laterite were also developed, and various ages of planation surfaces were recognised (Bourman, 1973, 1989, 1993a, 1993b, 1995).

Sprigg (1945, 1946) made a significant contribution to the detailed geomorphological study of the western and central parts of the Mount Lofty Ranges and provided valuable information on many morphological features, statistics, and drainage development of this region. He also supported a structural definition of the Mount Lofty Ranges as a horst initially covered by Tertiary deposits. In 1945 he wrote: "*In the early Tertiary Period much of South Australia had been reduced to a base surface, that is, a surface 'old and fully dissected'. This surface was then buried by Tertiary lacustrine and marine deposits ("overmass" sediments). Block faulting commenced late in the Tertiary. Differential*

negative and positive movements of the various blocks, particularly those near Adelaide resulted in warping and tilting. The new cycle of erosion thus initiated led to the removal of much overmass sediments as well as most of the ancient erosion surface. The topography in the vicinity of the major fault escarpments is young and well dissected" (p.315).

Twidale and Bourne (1975) made an attempt to fill the gap of geomorphological research on the eastern portion of the Mount Lofty Ranges. The data presented in that paper sought to answer: "How did this landscape evolve? Of what age and origin are the plains? What is the nature of the scarps that separate the high from the low plains?" (p.203). As a result of various considerations, the summit planation surface (Tungkillo Surface) well preserved on the eastern edge of the Ranges, was dated as early Tertiary. However some mesas and single conical hills standing above the main summit surface were referred to as the "Whalley Surface" of older, or even much older age (Mesozoic or even Triassic).

It is not unusual to find some elements of very old landscapes such as buried Permian valleys in the southern Mount Lofty Ranges or the Early Jurassic/Triassic laterite surfaces in Kangaroo Island (Daily et al., 1974). However it does not follow that the landscape evolution of the Mount Lofty Ranges was continuous since that time because these elements do not have any genetic links with structural or geomorphological development of the Mount Lofty Ranges. Surfaces such as Whalley and Tungkillo (Twidale & Bourne, 1975) together with a number of other monadnock/bornhards can be considered as remnants of a pre-Tertiary Palaeoplain. However, as shown in this thesis (Ch. 3, 4 and 5), the Mount Lofty Ranges as a geological/neotectonic entity can be traced only to the Middle Eocene with specific genetic links between neotectonic structure and geomorphological setting of this source area, and sedimentation in the flanking and intramontane basins. Thus the landscape evolution of this entity is not older than the Middle Eocene.

In recent years in Australia there has been renewed interest in the study of landscape evolution associated with regolith development and environmental applications. Various local and regional models of Landscape/Regolith evolution were developed as a result of CRC LEME (Cooperative Research Centre for Landscape Environments and Mineral Exploration) activity. However the neotectonic part of these models remains substantially underdeveloped. This thesis provides a new approach to landscape evolution of the Mount Lofty Ranges where neotectonic and geomorphological approaches are crucially integrated

and adequately represented. Some results of this approach were presented at several conferences and published (eg. Tokarev et al., 1999; Tokarev & Gostin, in press). However later study revealed many new details, and the work has been expanded and modified so that an improved model of landscape evolution is provided below.

6.2 Geomorphological setting of the Mount Lofty Ranges

Two major elements of the regional geomorphological setting, notably *river systems and watersheds,* are considered here as most fundamental for the long-term regional landscape evolution in the study area. Planation surfaces (both newly formed and inherited), river channels and other smaller scale elements such as catchment hill-slopes were also examined but considered to be of minor importance in the regional geomorphological setting.

Most of the rivers are incised into the pre-Tertiary basements of the Mount Lofty Ranges. There are only a few areas where channels are incised through the Tertiary or Quaternary fill. The largest area where stream incision has occurred through the Tertiary/Quaternary sediments is associated with the intramontane Meadows-Myponga and Hindmarsh Tiers Basins in the southern part of the Ranges (Figs 1-2; 5-4). The Para River in the NW sector has also undergone incision into the earlier terrigenous deposits of the intramontane Barossa Basin (Fig. 5-6). However the most common examples of stream incision through both marine and terrigenous sediments are currently located on the marginal areas of the St. Vincent and Western Murray Basins.

River channels are the most active geomorphological elements of fluvial systems. They are very sensitive to any tectonic or climatic changes and are almost constantly involved in landscape development. There are two principal river channels: active and passive as determined by the degree of interaction between catchment hill-slopes and water flow. Where sediments are delivered from the slopes into active channels, they are almost instantaneously removed from the valleys, while passive channels are not able to do this because of insufficient water flow or channel gradient. This often results in sediment storage and formation of valley sedimentary bottom flats. In the sedimentary basins surrounding the Mount Lofty Ranges the passive state of drainage systems are often expressed as floodplains. The main factors determining passive or active channels are climatic (rainfall) and tectonic movements. While it is recognised that climate change has modified the hydrological characteristics of streams and vegetation over space and time, its

effects are difficult to distinguish within the study area. Therefore tectonic movements are considered here as the major factor that affected channel gradients while climatic changes are considered as relatively uniform throughout the region.

The transformation of active into passive channels is common for most streams escaping from the Ranges onto the flat areas of the Western Murray Basin. Such changes are clearly associated with a rapid decrease of channel gradients. Similar changes also occur on the western borders of the Ranges with flanking embayments of the St. Vincent Basin. For example, Dry Creek and Torrens River channels discharge immediately west of the Para Fault where their channel on the Adelaide Plains can be defined as passive. However there is increased channel activity near the Para Fault and within the Para Block recorded by stream incision through Pleistocene and earlier deposits into the basement (Fig. 6-1). Such incision is associated with Late Pleistocene tectonics involving the Para Block uplift along Para Fault. However the most dramatic increase of channel gradient is associated with the Torrens River. The gradient of this river channel changes from ~4m/km (Para Block) to about 30m/km (near the knick point) that is clearly associated with uplift along the Eden-Burnside Fault (Fig. 6-2). Most active channels associated with increased gradients were also identified along the Stockwell, Para, Eden-Burnside, Clarendon, Willunga, Milendella and other boundary faults elsewhere in the study region (see Fig. 1-2 for active fault locations).

A clear example of a passive channel is also associated with the middle reaches of the Para River in the intramontane Barossa Basin (Fig. 5-6). A number of streams, including the south and north main trunks of the Para River, partly discharged into an area of the Barossa Valley immediately west of the Stockwell Fault. Accumulation of more than 100m of fluvial sediments in the floodplain and fluviolacustrine environments of this basin (Alley, 1995a) clearly indicates that the Para River was not able to remove all sediments delivered from the hill-slopes. Lithostratigraphic units indicate that subsidence and sedimentation in this basin were, at least partly, contemporaneous.

There are clear genetic and spatial links between neotectonic movements, geomorphological development and sedimentation in this basin. Basin subsidence, associated with down-to-basin block movements along the active Stockwell Fault bounding this basin in the east, is an essential factor in the formation of the sedimentary accommodation space.

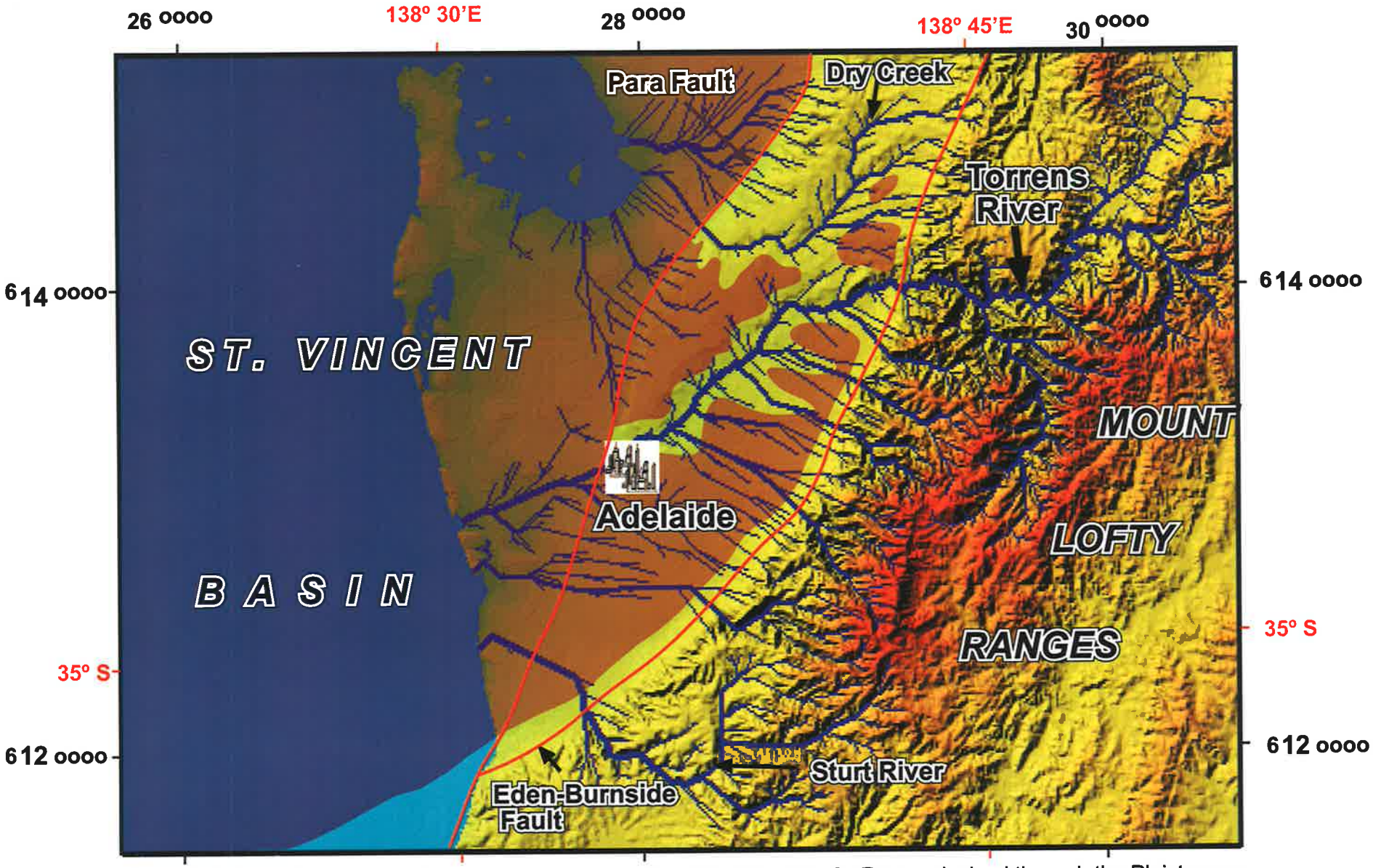


Figure 6-1 Present drainage pattern in the western portion of the Mount Lofty Ranges incised through the Pleistocene Hindmarsh Clay Formation (in brown) in the Adelaide area (Para Block between Para and Eden-Burnside faults). Distribution of the Hindmarsh Clay Formation modified after Sheard & Bowman (1996). Shaded relief image derived from 1-s DEM (SA DEH dataset).

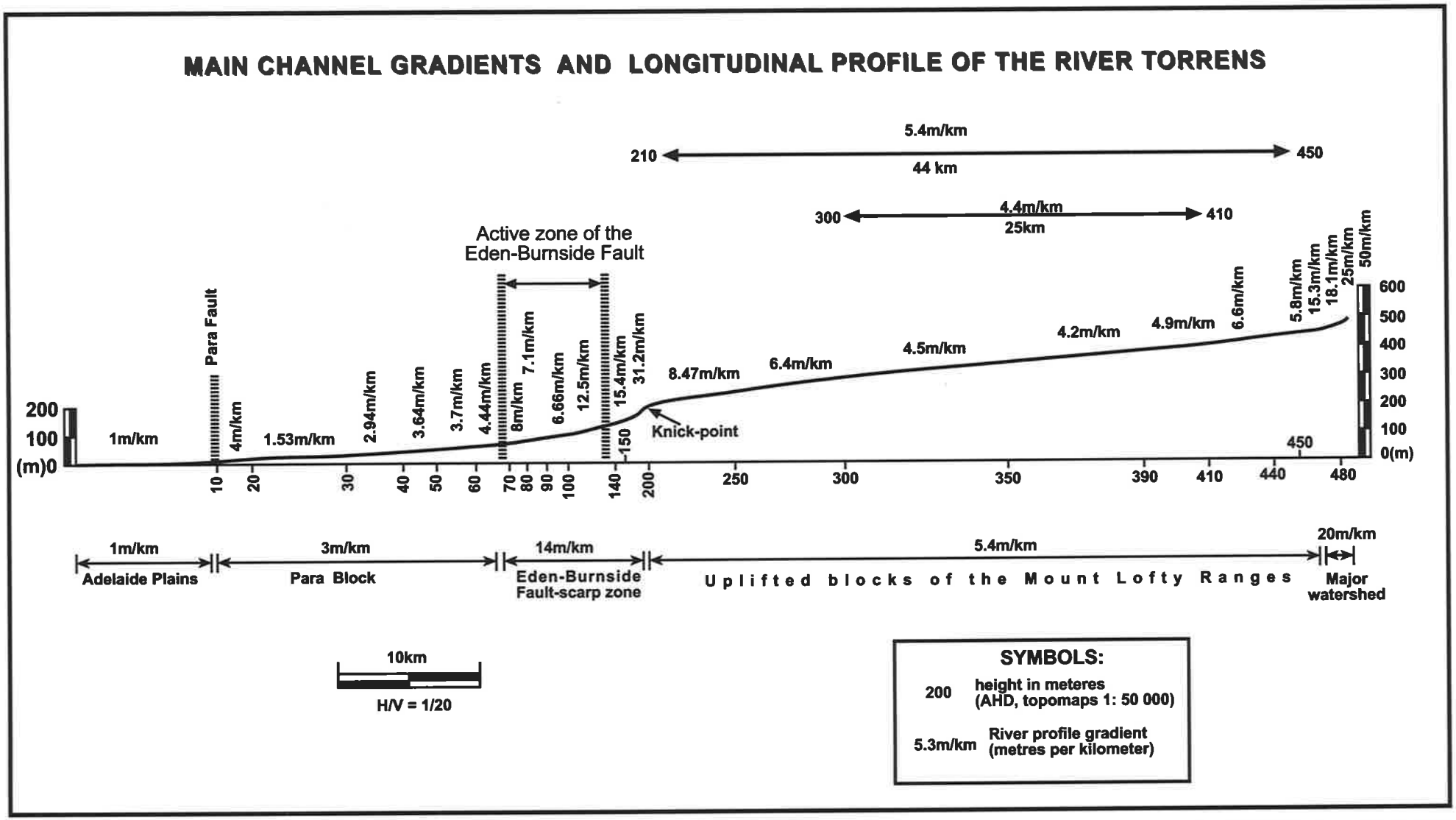


Figure 6-2 Main channel gradients and longitudinal profile of the River Torrens. The maximum channel gradients of ~ 31m/km is associated with Pleistocene activity along the Eden-Burnside Fault. Gradient of ~5.4m/km above the knick-point is associated with general preservation of the Tertiary landscape in interior parts of the Mount Lofty Ranges.

These movements resulted in segmentation of the pre-Middle Eocene Palaeoplain into the sedimentary source and accumulation areas, triggering the development of slope and drainage systems. The remnants of the Palaeoplain as a gently undulating and deeply weathered surface beneath the Tertiary sediments of the Barossa Basin are recorded in a number of drill-holes (Cobb, 1986; Alley, 1995a). This weathered surface or zone dips toward the Stockwell Fault from ~240m above PSL near the western border of the Barossa Basin to ~150m above PSL near this fault in a distance of 6-7km (Cross-section B-B, Fig. 5-7). This cross-section also clearly demonstrates the normal fault geometry of the Stockwell Fault, and that down-to-basin block movements were the main cause of the formation of sedimentary accommodation space in this basin and thus responsible for the passive state of river system within it. However the deep weathered profile on the gently undulating surfaces such as Whalley and Tungkillo on the major watershed is well-recognised immediately east of the Barossa Basin (Twidale & Bourne, 1975). The correlation of such surfaces buried in the basin and exposed within the watersheds has been made in order to calculate the total amount of neotectonic movements in this area (Ch. 5). Down-to-basin tectonic movements along the active Kitchener Fault formed the sedimentary accommodation space in the Freeling area that resulted in slightly increased thickness of the Tertiary and Quaternary units toward the fault (Fig. 5-6 and transect A-A in Fig. 5-7).

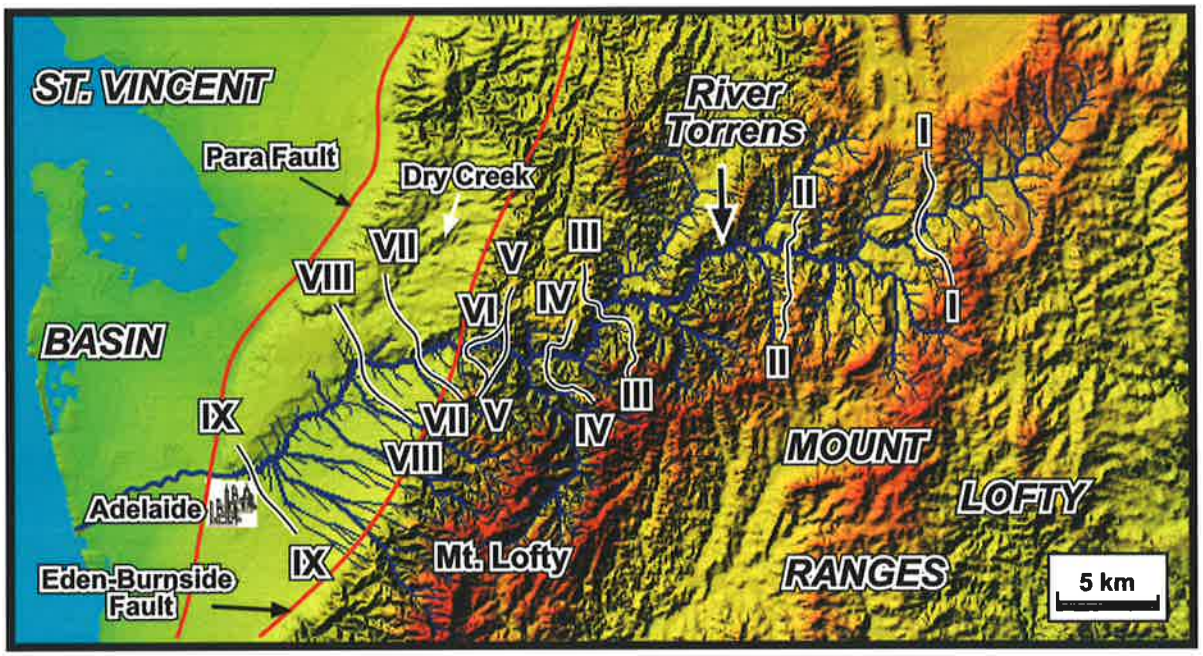
These examples demonstrate that channel activity in the study region is clearly associated with specific elements of the neotectonic setting and the type and amount of neotectonic movements. There were a few distinctive episodes in the long-term landscape evolution of the Mount Lofty Ranges when active channels or their parts became passive for some time and vice versa. Most such changes occurred due to neotectonic movements; however several dramatic changes in the southern part of the Mount Lofty Ranges are corresponded to sea-level fluctuations as the major erosional base-level rose or fell. Some of these episodes have already been identified as increased and decreased stream competences (Ch. 4) but others such as long-term geomorphological changes will be highlighted later in this chapter.

River valleys are important elements of the geomorphological setting of the Mount Lofty Ranges. Fenner (1930) compared the young topography of the stream valleys in the western part of the Ranges with the gentle and mature topography of upstream areas of the Onkaparinga and Torrens Rivers. This thesis also identifies the clear contrast between the

deep stream incision in the marginal areas of the Ranges that formed V-shape valleys and the mild incision and lateral erosion in the interior parts of the Ranges that formed shallow and wide valleys. Valley cross-sections along the River Torrens (Fig. 6-3) demonstrate that the narrow V-shape valley was developed within the active western boundary of the Ranges associated with the Eden-Burnside Fault (cross-sections IV-IV to VI-VI), while broader and shallower valleys are located in interior central parts of the Ranges (cross-sections I-I and II-II). Both types are common for other river valleys developed in pre-Tertiary bedrock without the visible influence of basement lithology or tectonic fabric.

There is a third type of relatively shallow valley with relatively steep banks and flat-bottoms developed in Tertiary and Quaternary sediments. Valleys of this type are often young and are indicators of recent uplift of areas such as the Para Block near Adelaide where such valleys developed. The narrow Murray River valley between Morgan and Tailem Bend developed in the Western Murray Basin (also known as the Murray River Gorge) is an example of a large scale of river incision through Pleistocene and Tertiary fills (Fig. 4-26). However the nature of the Murray River Gorge is different from other gorges developed within the Ranges such as the Torrens River Gorge and Onkaparinga Gorge on the western edge and several gorges on the eastern slope of the Ranges. These gorges are associated with head-ward steam incision into the pre-Tertiary basement within the zone of active faults, while the Murray River Gorge was developed mainly due to sea-level fluctuations with a possible minor tectonic interference (eg. Firman, 1972; Twidale et al., 1978).

The *size of the drainage basins* directly corresponds to the duration of their evolution, if other geological, neotectonic and climatic conditions are similar. The largest river systems in the Mount Lofty Ranges are considered here as the oldest, and thus the most important for long-term landscape evolution. Only major river systems were chosen as appropriate representations of geomorphological units containing linear and spatial pathways for Tertiary and Quaternary sediment movements from the source region of the Mount Lofty Ranges into the basins. Although there are hundreds of smaller rivers and creeks actively involved in the landscape evolution of the Mount Lofty Ranges, most of them are relatively young and represent only the latest stage in this evolution. Thus the Para, Torrens, Onkaparinga and Myponga Rivers flowing into the St. Vincent Basin are the most representative geomorphological units within the western portion of Ranges. The Marne, Bremer, Finniss and Angas Rivers flowing into the Murray Basin are the most representative



Principal location of the Torrens valley cross-sections.

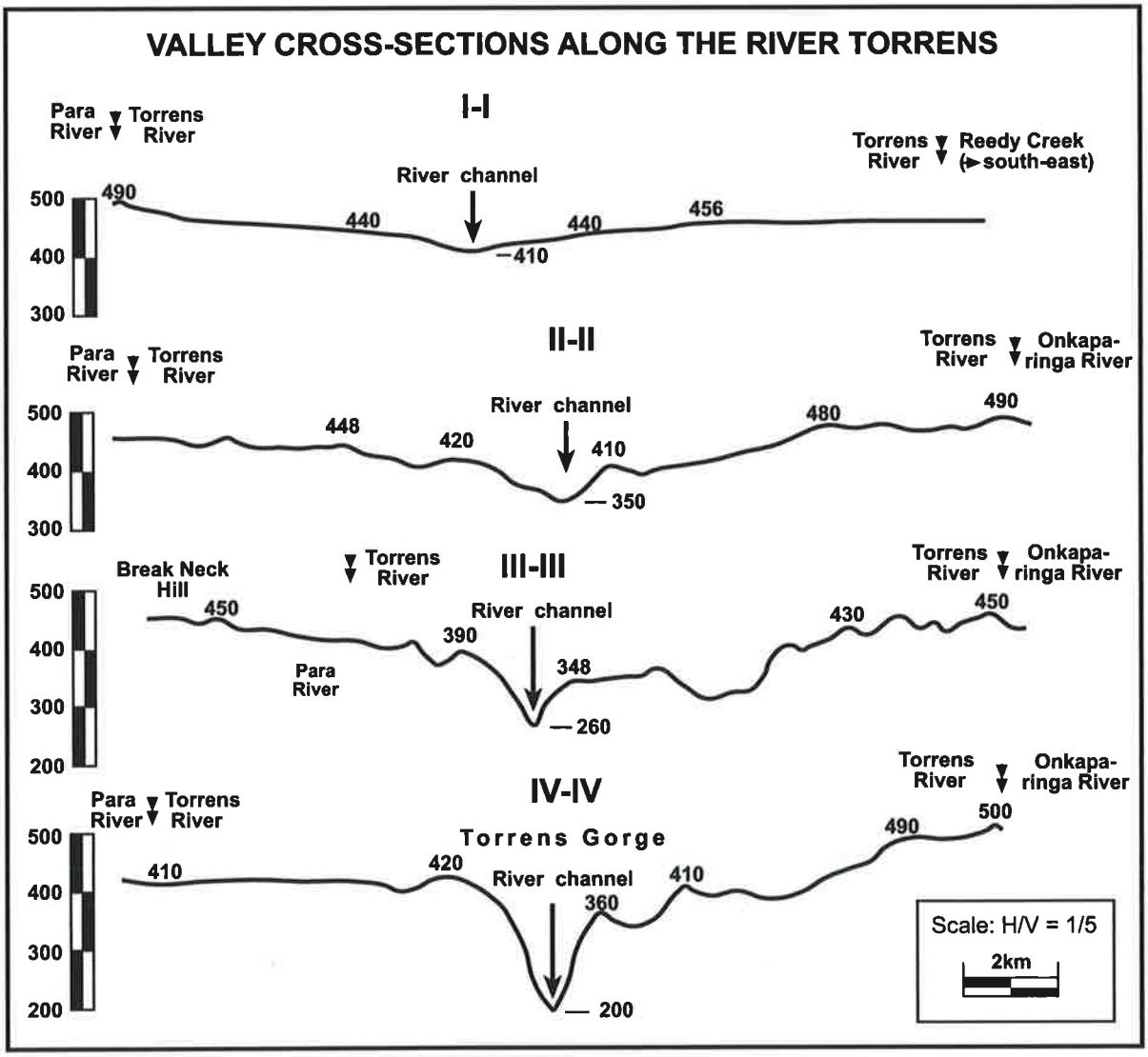


Figure 6-3 (Part 1) Geomorphological cross-sections along the River Torrens. (see part 2 for symbols)

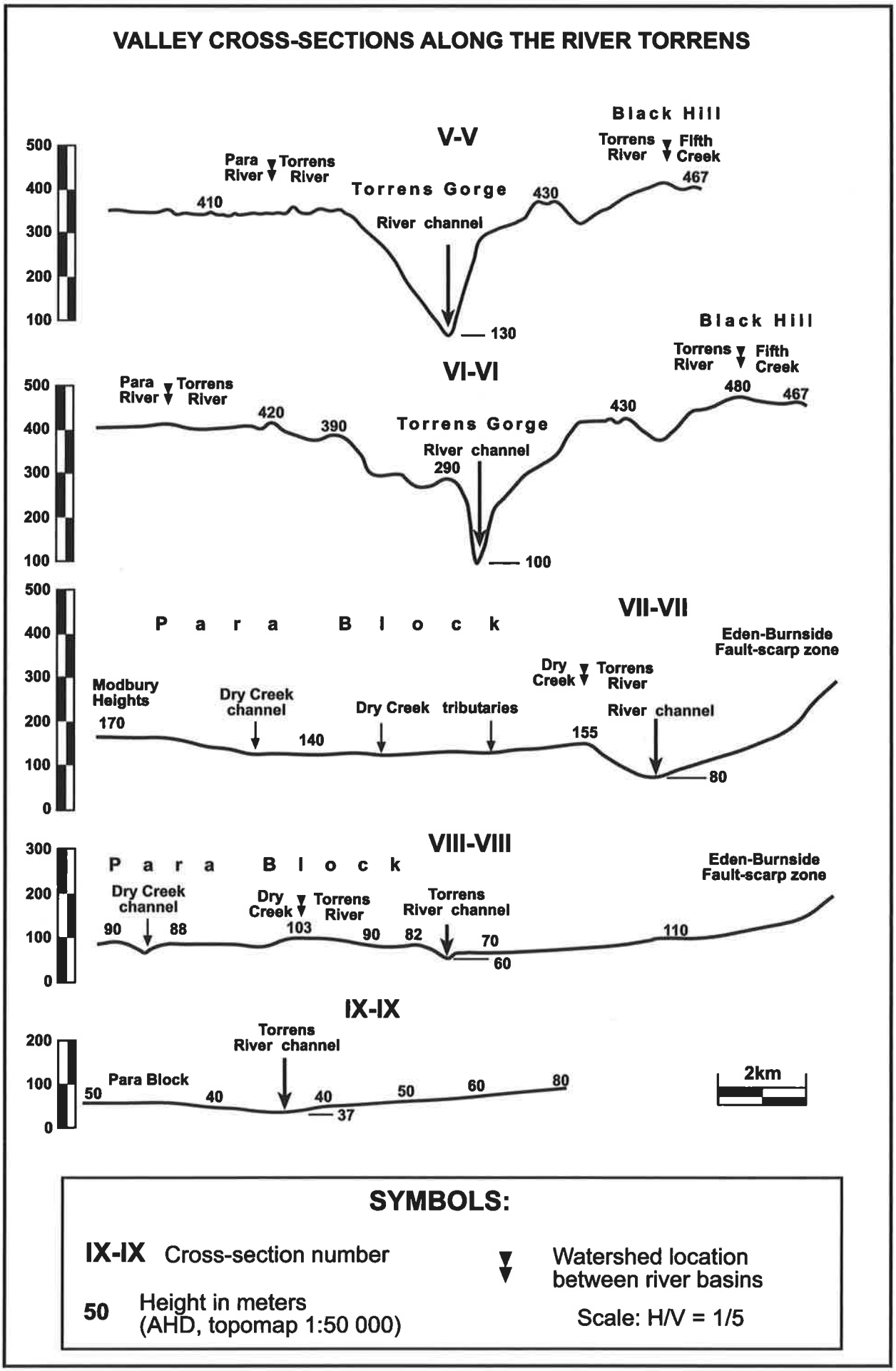


Figure 6-3 (Part 2) Geomorphological cross-sections along the River Torrens

on the eastern slope of the Ranges. The major regional watershed has divided the western and eastern river systems. Spatial distribution of these and other streams and their patterns are derived from 1-s DEM analysis and shown in Figure 6-4.

6.2.1 Major Watershed of the Mount Lofty Ranges

The regional watershed of the Mount Lofty Ranges strikes generally SW-NE with some local lateral variations (Fig. 6-4). The largest part of this watershed is situated in the eastern part of the Ranges in the central and northern parts of the study area. However in the south as will be shown later, this watershed was relocated to the western portion of the Ranges, to the Sellicks Hill Range. The general altitude of this watershed summit surface is about 450-500m above PSL with the relief of this surface being just several tens of metres, but often less, and persisting over 100 kilometres along the major watershed (Fig. 6-5).

The watershed crosses a variety of pre-Tertiary lithologies ranging from pre-Cambrian metasediments to Permian fluvioglacial deposits and deeply weathered regolith. These lithologies would be expected to show significant differences in erosional resistance. However geomorphological analysis shows remarkable preservation of a flat and uniform planation surface often capped by deep regolith along this watershed. The major watershed also crosses the main tectonic fabric of the Adelaide Thrust Fold Belt, including a tectonic window of the Mesoproterozoic metamorphic basement, metasediments of the Adelaide Geosyncline and Kanmantoo Trough. It crosses a number of basement faults and folds, including the Nairne Fault which is a major Paleozoic structure separating the Adelaide Geosyncline from the Kanmantoo Trough. These facts clearly demonstrate that neither basement physical properties nor their structural fabric provided any primary control on the location of the watershed and on the distribution of drainage systems.

The interpretations of neotectonic settings (Ch. 5) show that a large portion of the pre-Middle Eocene Palaeoplain, at least south of the transfer zone (Fig. 1-2) was affected by gentle W-SW tilting. As a result of this tilting, a wide and gentle western slope was formed in the interbasin region of the proto-Mount Lofty Ranges that substantially inherited the altitude and morphology of the Palaeoplain. In contrast to the western slope, the narrow eastern slope of the Ranges was probably formed as a result of the differential subsidence of the Western Murray Basin along several sub-parallel normal faults. According to this neotectonic scenario, the major watershed was formed along the eastern and highest edge of



Figure 6-4 River systems of the Mount Lofty Ranges. Location of watersheds: Thick solid white line = present major watershed (between westward and eastward flowing systems) ; Thinner white lines = second order watersheds (berween major rivers and creeks). Thick dashed white line = main palaeowatershed (where it is different from the present watershed). Red dashed line = reconstructed edge of the pre-Middle Eocene Palaeoplain remnant. River captures: Darks shaded areas = by eastern flowing streams; White shaded area = Myponga River capture. Stream patterns and shaded relief image generated from 1-s DEM.

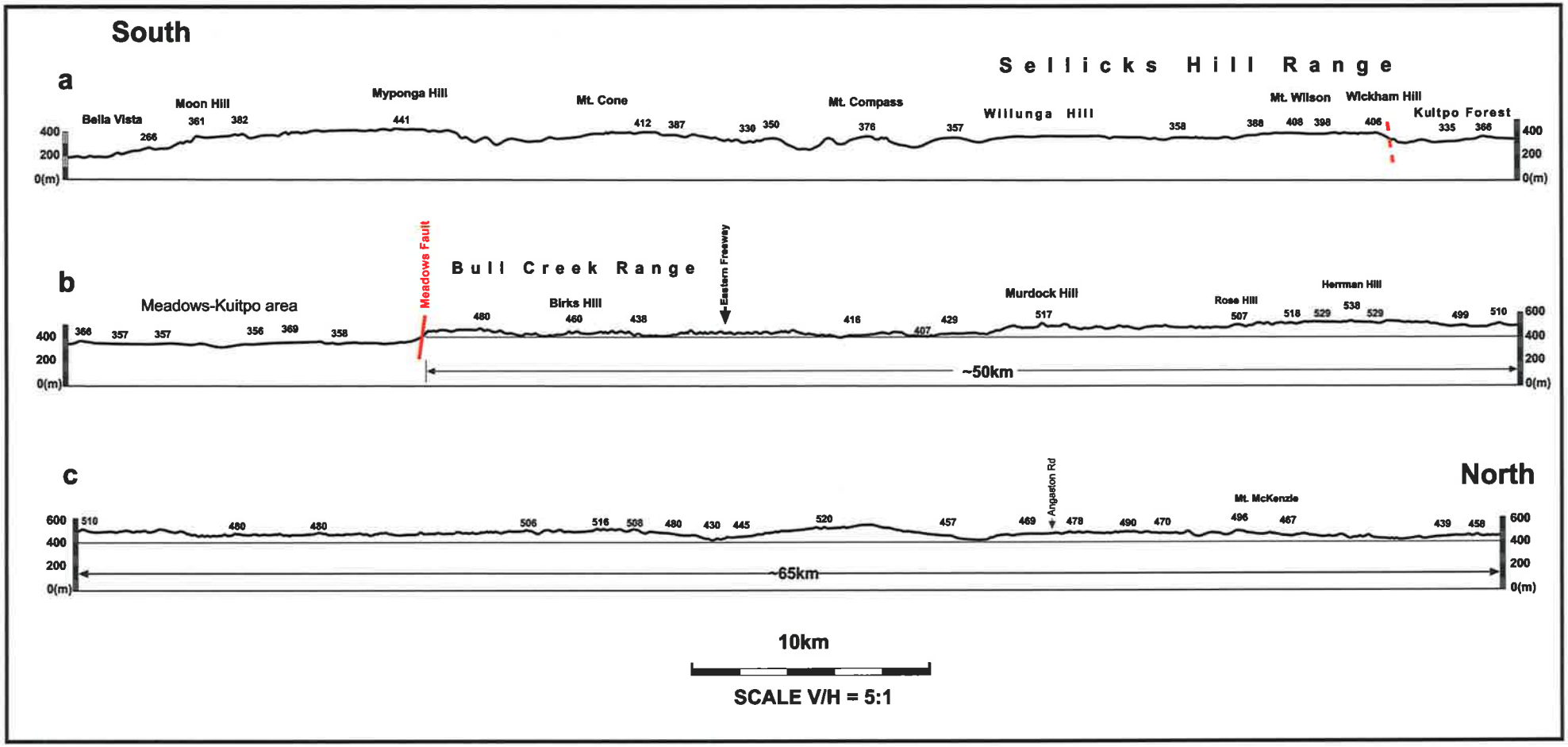


Figure 6-5 Geomorphological profile along the present major watershed of the Mount Lofty Ranges (without Fleurieu Peninsula) dividing western and eastern flowing river systems. It shows remarkable consistency of relatively flat summit surface in altitude (400-500m above PSL) and relief (within 100m), specifically north of the Meadows Fault (section - c), that is correlated with the preservation of the pre-Tertiary Palaeoplain surface. Location of the major wateshed is shown on Fig. 6-4.

the Palaeoplain remnant preserved for some time from the headward stream erosion propagating from both subsided flanking basins.

6.3 Palaeodrainage Reconstructions

The data above indicate that the main geomorphological setting of the Mount Lofty Ranges corresponds directly to both extensional and compressional neotectonic settings. Unfortunately there are no dated river sediments or terraces that would directly indicate the age of the palaeochannels. However viewed regionally the correlation of stream input into the basin sediments along with geomorphological features in the source region suggests some general trends of palaeodrainage development partly outlined in Chapter 4.

Earlier palaeodrainage investigations (eg. Fenner, 1930; Sprigg, 1945) suggested the controversial hypothesis of the Tertiary tectonic uplift of the Mount Lofty Rangers with possible reactivation of the pre-Tertiary basement that influenced Tertiary palaeodrainage. Rowett (1997) produced a report investigating palaeodrainage in the St. Vincent Basin and the Mount Lofty Ranges and incorporated a large amount of geological data including drilling results, lithostratigraphic and some geophysical investigations. A method of topographic generalised contouring was used to identify a number of possible Tertiary palaeochannels in this region. Following the traditional hypothesis of the Tertiary reactivation of the basement structure, this report inferred the major control of the Delamerian fabric on the Early Tertiary palaeodrainage in the Mount Lofty Ranges (Rowett, 1997). However the final map of inferred Tertiary palaeodrainage in this report clearly indicates that the major regional pattern of Tertiary drainage is antecedent to the Delamerian structures. Our earlier investigations also confirm that most of the drainage systems within the Ranges obliquely or even perpendicularly cross the Delamerian and older tectonic fabric (Tokarev et al., 1999). There are several arguments contradicting the Tertiary reactivation of Delamerian structures shown at the end of Chapter 5 of this thesis.

In contrast to all earlier geomorphological studies, this thesis utilises a high resolution DEM (1 arc-second) and several software packages for data processing and visualisation. The 'River Tools' software package has been used for drainage analysis. These together with the use of sea-level curves reveal some new features of river system and general landscape evolution within the study area.

6.3.1 Palaeodrainage Reconstructions of the Eastern Portion of the Mount Lofty Ranges

Active headward erosion of streams flowing into the Murray Basin is associated with higher channel gradients than those formed on the initial gentle western slope. This was probably the main cause of stream incision into the inferred edge of the Mount Lofty Ranges tectonic domain, and even through the major watershed at a few locations that changed the initial watershed configuration (Fig. 6-4). The inferred eastern edge of the Palaeoplain is derived from geomorphological analysis including major and second order watershed configurations, stream patterns, and channel gradients. It was observed that when stream headward erosion passed over the edge there is an abrupt change of stream pattern from narrow dendritic to wide complex and often centripetal-like pattern, with the centre location near the knick-point of the major channel. The flow direction of lower order tributaries is often perpendicular or even opposite to the main channel flow eg. headwater areas of the River Marne, Mount Barker Creek and Finniss River (Fig. 6-4). These changes are attributed to landscape differentiation between slope areas of the eastern Mount Lofty Ranges (neotectonically defined) and the preserved, at various degree, gently undulating surface of the pre-Middle Eocene Palaeoplain.

For example, the relatively steep and narrow dendritic pattern of Mount Barker Creek (largest tributary of the Bremer River) in the slope area is abruptly changed to wide centripetal-like pattern in the vicinity of Mount Barker Township (Fig. 6-6). There is an unusual U-turn of the Western Flat Creek and other upper tributaries of Mount Barker Creek that are often opposite to the main trunk direction of this creek. Geomorphologically a gently undulating area surrounding the township is associated with the preserved Palaeoplain that the major Mount Barker channel reached only when it passed over the initial edge close to the knick-point (Fig. 6-6). Two elevation profiles demonstrate that a chain of separated high hills including Mt. Barker (~500m) and Bonython Hill (~450m) is higher than the major watershed located west of Mount Barker Township (Fig. 6-6). This chain would be associated with an original edge of the Palaeoplain (Fig. 6-7). All these, together with the unusual pattern of upper tributaries of the Mount Barker Creek suggest that this creek eroded westward over the edge of the Palaeoplain.

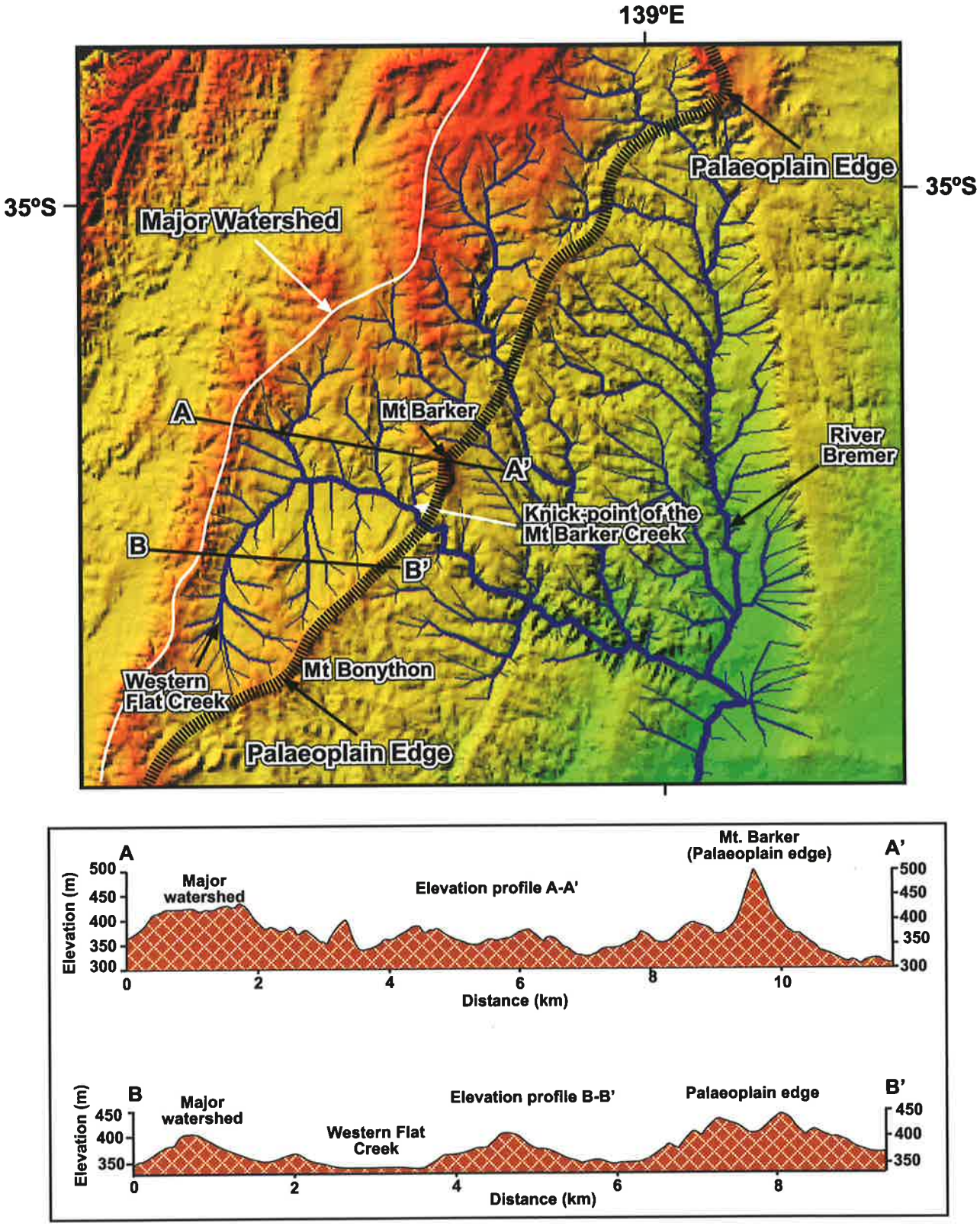


Figure 6-6 Geomorphological setting and cross-sections of the Mount Barker area. White line = location of the major watershed. Black dashed line = inferred edge of the pre-Middle Eocene Palaeoplain remnant. Drainage pattern and shaded relief image derived from 1-s DEM. Elevation profiles demonstrate that an altitude of the Palaeoplain edge is similar or even higher then the major watershed and thus Mount Barker area (between the watershed and this edge) would be attributed to a modified Palaeoplain surface.

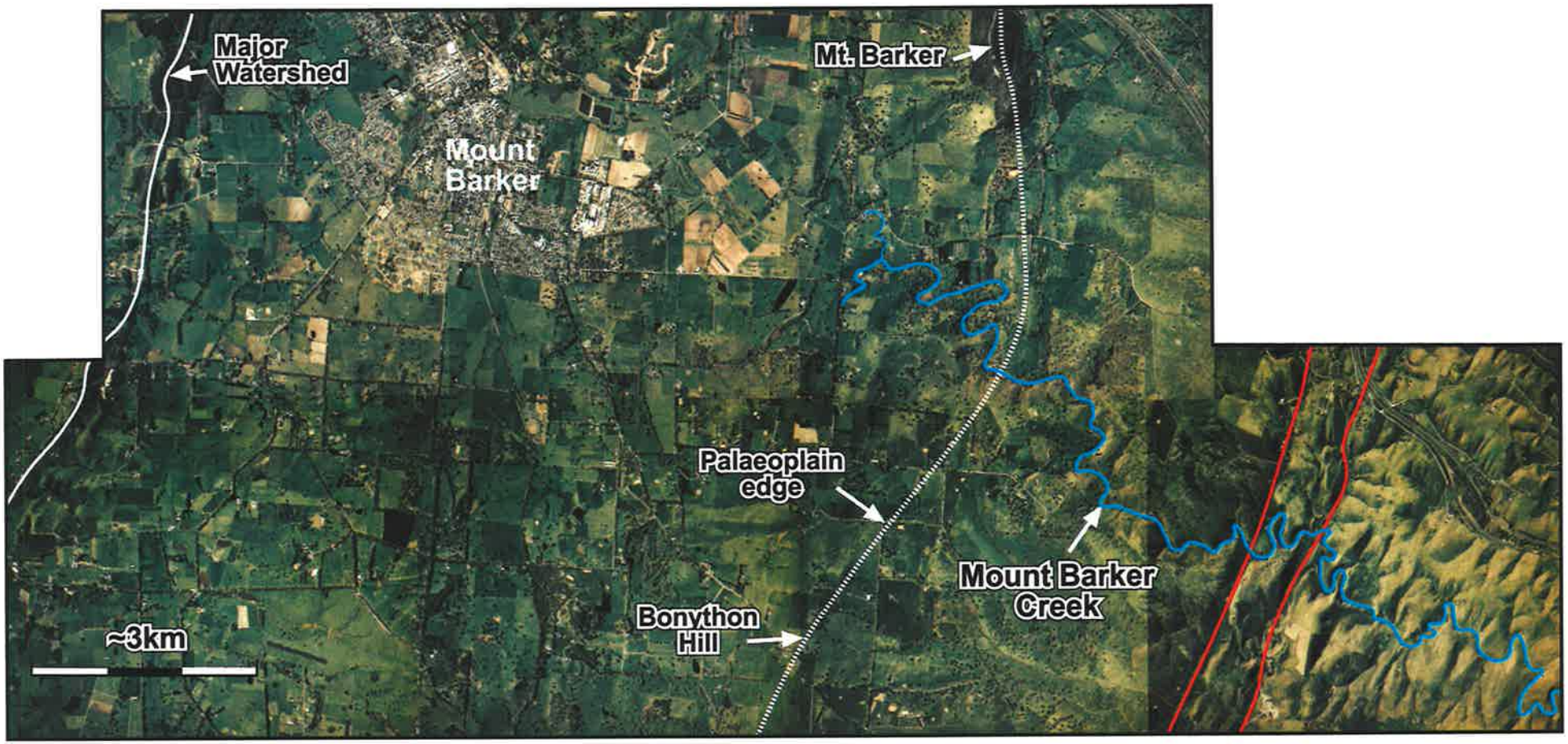


Figure 6-7 Collage of aerial photos of the Mount Barker area shows: location of the major watershed (white solid line west of the Mount Barker township) and inferred edge of the Palaeoplain (white dashed line E-SE of the township). Gently undulating Palaeoplain landscape possibly preserved from intensive headward erosion of the Mount Barker Creek between the watershed and the edge . Red lines represent active faults along the eastern slope of the Mount Lofty Ranges. Drainage pattern shown in Fig. 6-6. (Photos courtesy SA DEH).

There are several places within the eastern Mount Lofty Ranges where river capture may be considered. However there are only two locations with specific geomorphological settings where river captures were observed in association with the river erosion through the major watershed. The Marne River flowing into the Western Murray Basin in the NE of the study area not only eroded into the inferred edge of the Palaeoplain but also cut through the palaeowatershed that resulted in a capture of the upper tributaries of the North and South Para Rivers (Fig. 6-4).

Two specific geomorphological features have been considered as the most important in association with this river capture. Firstly, there is no apparent watershed between the upper tributaries of the Marne River and the South and North Para Rivers due to relatively flat and wide areas on both sides of the present watershed. Secondly, there is an unusual westward diversion of the present major watershed from its normal relatively straight SW-NE strike that persists over hundred of kilometres. The location of the palaeowatershed is along the ridge between Sommer Creek (northern largest tributary of the River Marne) and the southern straight channel of the North Para River. The average altitude of about 450m above PSL of this ridge and its general N-S strike are fairly consistent with the of the major watershed immediately south of the Marne River. It is also important to note that there is a high sinuosity of meandering main trunk of the Marne River crossing the fold-thrust structures of the metamorphic basement (Fig. 6-8). This is clear evidence that this channel was developed initially on the gently undulating or possibly flat surface most likely associated with the pre-Tertiary Palaeoplain. It is also strongly support the independence of river system development from the pre-Tertiary basement fabrics of the Mount Lofty Ranges.

There is another a larger-scale river capture in the central part of the southern Mount Lofty Ranges associated with development of the Finniss River (Fig. 6-4). The northern part of Bull Creek Range (Fig. 5-4) is a source area for large rivers such as Bremer (including Mount Barker Creek), Angas and the upper tributaries of the Finniss River flowing into the Murray Basin (Figs 6-4). However the northern part of the Bull Creek Range is also a source for a number of eastern tributaries of the Onkaparinga River flowing westward into the St. Vincent Basin. Thus the location of the major watershed of the Mount Lofty Ranges along this Range is obvious and corresponded well to the major neotectonic setting (Fig. 5-4). Despite the fact that this range strikes SSW-NNE without significant changes in altitude



Figure 6-8 Collage of aerial photos of the Marne River water-catchment shows: 1) Deeply dissected landscape associated with active Millendella Fault (in red) on the border of the Western Murray Basin and the Mount Lofty Ranges; and 2) Meandering major channel of the Marne River crossing fold-thrust structure of the pre-Tertiary basement. (Photos courtesy SA DEH)

or configuration for tens of kilometres, the major watershed abruptly turns west and relocates onto the Sellick Hill Range, which is topographically lower than the Bull Creek Range (Fig. 6-4). Such watershed relocation is inconsistent with the main neotectonic setting indicating that there is a graben-like Meadows-Myponga Basin between these two Ranges. River-net analysis clearly demonstrates that currently both eastern and western sides of the southern part of the Bull Creek Range are drained by tributaries of the Finniss River including the Meadows Creek. It seems that a double capture by the River Finniss occurred in the vicinity of Mt. Magnificent (Fig. 6-9). Headward erosion of the River Finniss cut through the major palaeowatershed and initially captured Blackfellows Creek (capture 1) which according to the strike of the main channel and general landscape configuration, flowed in a NE to SW direction and apparently joined the Meadows Creek on the way into the Myponga Basin. After the Blackfellows Creek was captured there was a brief time-interval before the headward erosion of the Finniss River reached and captured the Meadows Creek (capture 2). As the Meadows and Blackfellows Creeks occupied a substantial water-catchment area (Meadows-Kuitpo) including even some sites on the eastern slope of the Sellicks Hill Range, the large-scale of this river capture resulted in relocation of the major watershed from the Bull Creek Range onto the Sellicks Hill Range (Fig. 6-4).

There are a few important factors relating to this capture and generally to the significant modification of the original landscape of the southern Mount Lofty Ranges. The first factor relates to the preservation of unconsolidated Permian fluvioglacial deposits that are unable to resist headward stream erosion with even a low competence. These Permian sediments are still widespread in this area, and their distribution within the southern Mount Lofty Ranges was apparently much broader before the modification of the palaeolandscape.

The second factor contributing to landscape modification concerns the Oligocene-Miocene marine inundation into the Meadows-Myponga and Hindmarsh Tiers Basins. The simulation of marine floods using 1-s DEMs (Figs 4-10; 4-13) shows that a significant part of the southern Mount Lofty Ranges probably was submerged during high sea-level stands. Bed-load erosion associated with marine retreats from the southern Ranges was inferred as a major cause of removal of regolith and Permian deposits from this area into the SW part of the Murray Basin (Buccleuch Embayments). This resulted in the formation of the Compton Conglomerate part of which still present in outcrop in the Bremer River Basin (Fig. 4-13).

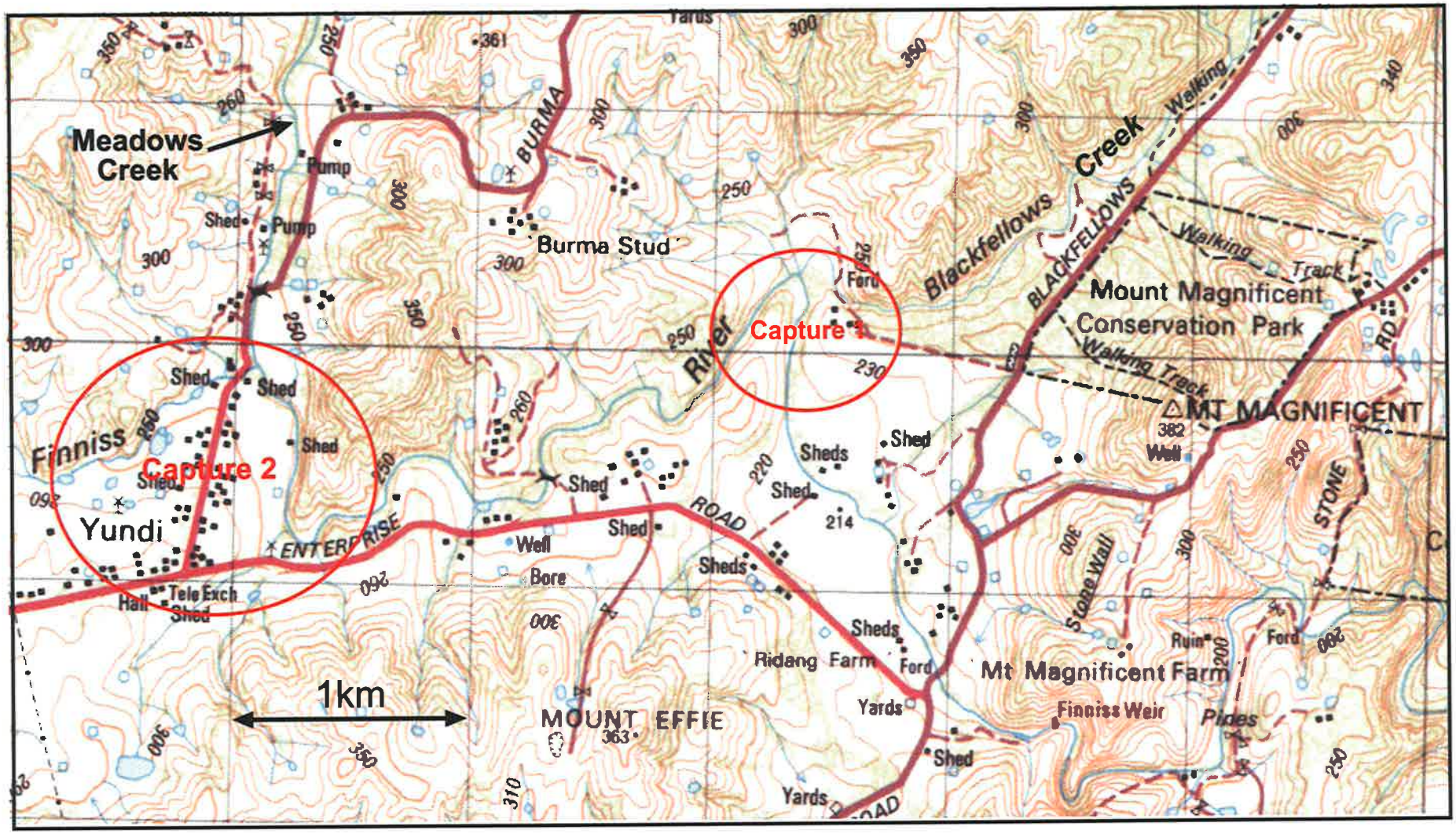


Figure 6-9 Double capture by the Finniss River in the vicinity of Mt. Magnificent.

The unusually wide and well-developed Inman and Bangala River Valleys are postulated as a possible marine passage between the St. Vincent and Western Murray Basins during the Mid-Tertiary (Fig. 4-13; Tokarev & Gostin, in press). However the lower part of the Finniss River was most probably also subject to marine invasion with consequent slope erosion. It is not clear when the Finniss River actually cut through the major watershed and captured streams in the Meadows-Kuitpo area. However if this capture occurred some time in the Oligocene-Middle Miocene then the marine passage from the Meadows area to the Western Murray Basin along the Finniss River would be possible (see marine flood at 350m Fig. 4-11). Thus powerful marine flows amongst other factors would have contributed to the landscape modification in this part of the southern Mount Lofty Ranges.

The third neotectonic factor is apparently the most important for landscape modification of the southern Mount Lofty Ranges. As it shown in Chapters 4 and 5, neotectonic movements such as crustal segmentation resulted in the formation of the intramontane Meadows-Myponga and Hindmarsh Tiers Basins. This together with regional southern tilting and differential Western Murray Basin subsidence (along the Encounter Fault) resulted in a reduced altitude of the proto-Mount Lofty Ranges (interbasin Palaeoplain remnant). These tectonic movements predefined the major geomorphological setting, such as location of the eastern edge and slope, major watershed and generally river-net development in this area.

In contrast to other sites of the Palaeoplain edge along the eastern side of the Mount Lofty Ranges there is a coincidence of the major palaeowatershed with the Palaeoplain edge within the Finniss River catchment (Fig. 6-4). Such a coincidence is associated with an unusual tectonic slump that occurred between the Encounter Fault and projected line of the Palaeoplain edge in this area. This slump is probably bounded on the west by faults or several splays forming an amphitheatre-like structure convex to the west, along which down-to-basin tectonic block movements occurred (Figs 6-10; 5-3). This would be additional to the above factors that predefined progressive Finniss River headward erosion into the Palaeoplain edge and through the major watershed. This combination of factors significantly reinforced the Finniss River erosional potential that resulted in the large-scale capture of streams in Meadows-Kuitpo area.

Geomorphological transects of the Finniss River valley (Fig. 6-11) indicate that two generation of the valley could be identified: the first generation that is associated with a

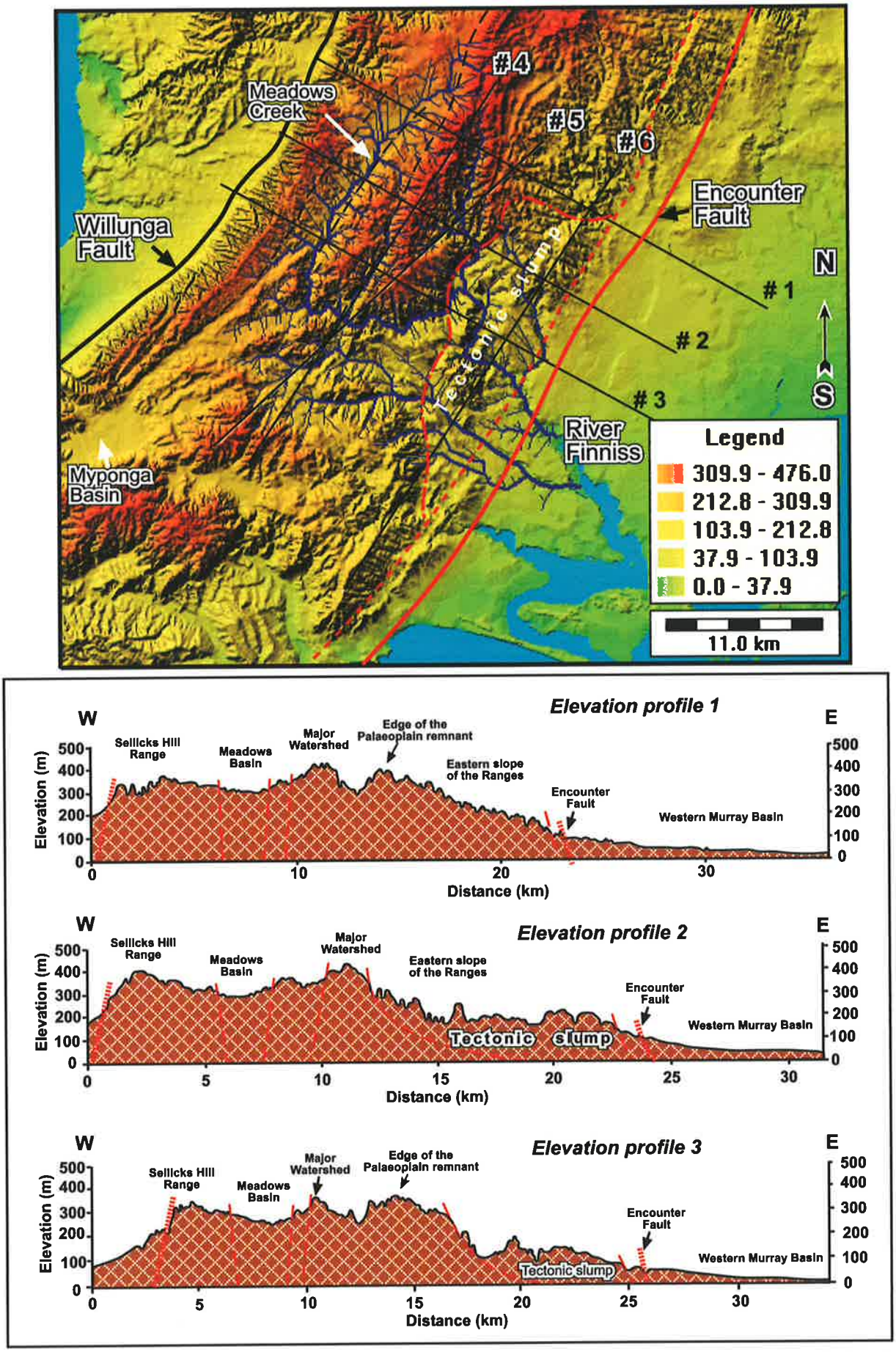


Figure 6-10 Drainage pattern of the Finniss River and shaded relief image derived from 1-s DEM. Elevation profiles show landscape differentiation associated with neotectonic movements and headward stream erosion (see Fig. 6-11 for other profiles).

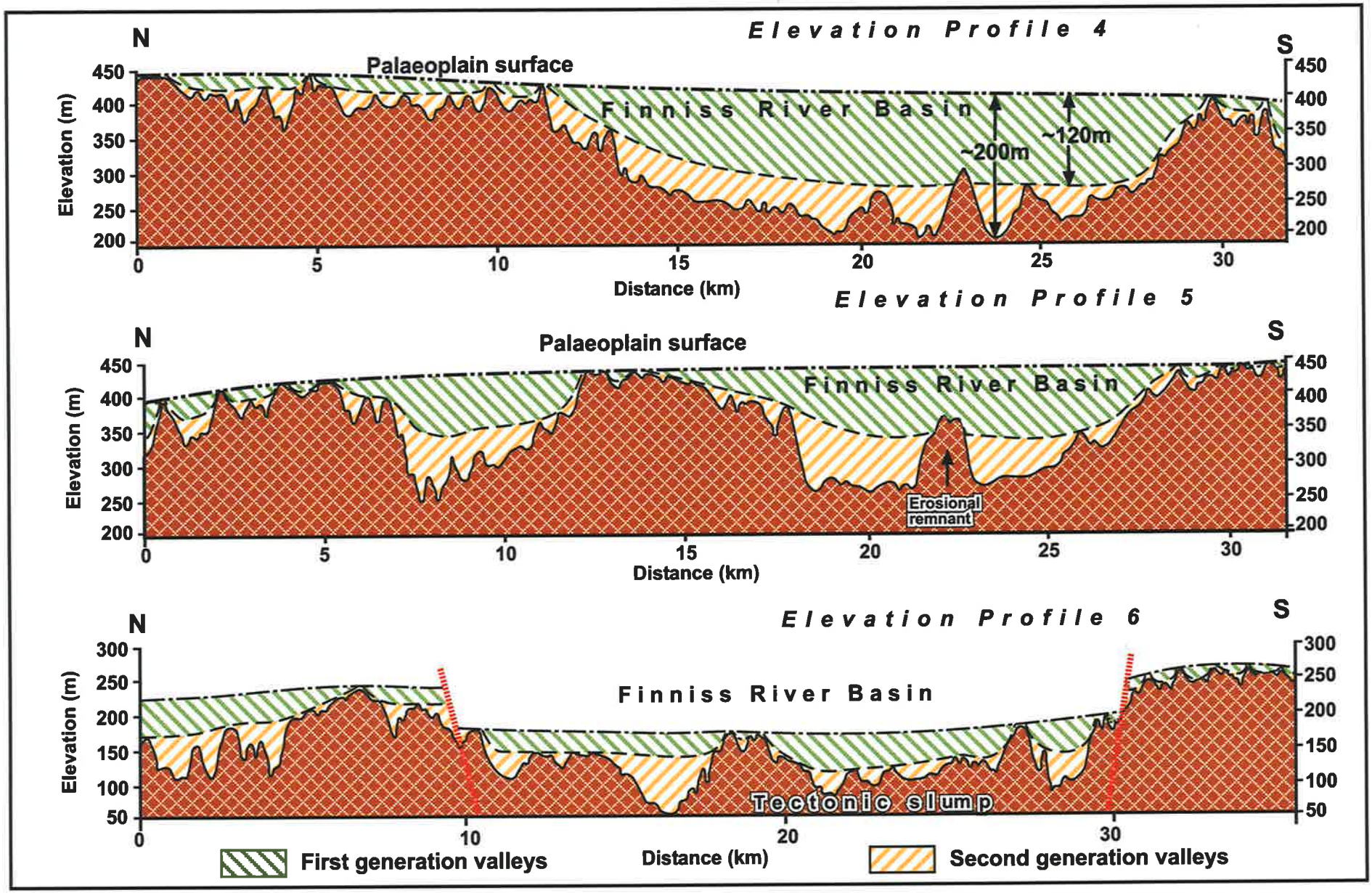


Figure 6-11 Two generations of the Finniss River incision into the eastern slope of the Mount Lofty Ranges. First generation is most probably associated with a generally low and gently undulating Tertiary landscape. The second generation is related to general uplift of the Ranges during the Mid-Pleistocene-Holocene. (see Fig. 6-10 for elevation profile locations)

broad valleys with relatively gentle banks; while the second generation is associated with narrow valleys with relatively steep banks. The wide first generation valleys are interpreted here as being formed during the Tertiary when a gently undulating landscape inherited from the Palaeoplain allowed low gradient streams to meander resulting in lateral erosion and formation of such broad valleys. The total incision of the River Finniss streams (up to 200m) occurred during the Tertiary and thus continued for tens of millions of years. In contrast to this, the second generation of valleys were developed relatively fast, and most probably during the last 0.5-1Ma in association with the Pleistocene uplift of the Mount Lofty Ranges. In spite of fact that the second generation valleys inherited meandering character of Tertiary river channels, their relatively steep banks with often V-shape valleys and occasional waterfalls are consistent with more recent uplift of the Ranges along the active boundary faults.

The above examples of palaeodrainage interpretation are all related to the long-term landscape evolution (millions of years) on the eastern margin of the Mount Lofty Ranges. However there is more recent evidence of palaeodrainage modification associated with the Late Pleistocene uplift of the Monarto Block in the Western Murray Basin (Fig. 4-25). The relatively straight southward main channel of the Bremer River almost perpendicularly cuts the lower part of the Mount Barker Creek and several other neighbouring streams flowing eastward from the Ranges and westward from the Monarto Block. The Bremer River follows the strike of Bremer Fault bounding the eastern edge of the Monarto Block (Fig. 6-12A). All western tributaries of the Bremer River are associated with a relatively steep but topographically low Bremer Fault-scarp. All these western tributaries are markedly short in comparison to eastern tributaries which occupy substantial water catchments on the SE slope of the Mount Lofty Ranges (eg. Mount Barker Creek). This indicates that the development of the western tributaries of the Bremer River occurred during relatively short time-interval. However both high orders steams and valley size of streams flowing from Monarto Block (east of the Bremer Fault) to the Murray River are inconsistent with such a short-time development and also with a low relief of the landscape of this block.

According to the neotectonic interpretation presented in this thesis (Ch. 5) the initial formation of the eastern slope of the Mount Lofty Ranges was due to differential subsidence of the Western Murray Basin along the Encounter Fault currently obliquely cut by the Bremer Fault (eg. Figs 4-25A; 5-3A). This along with the occurrence of Oligocene-Early

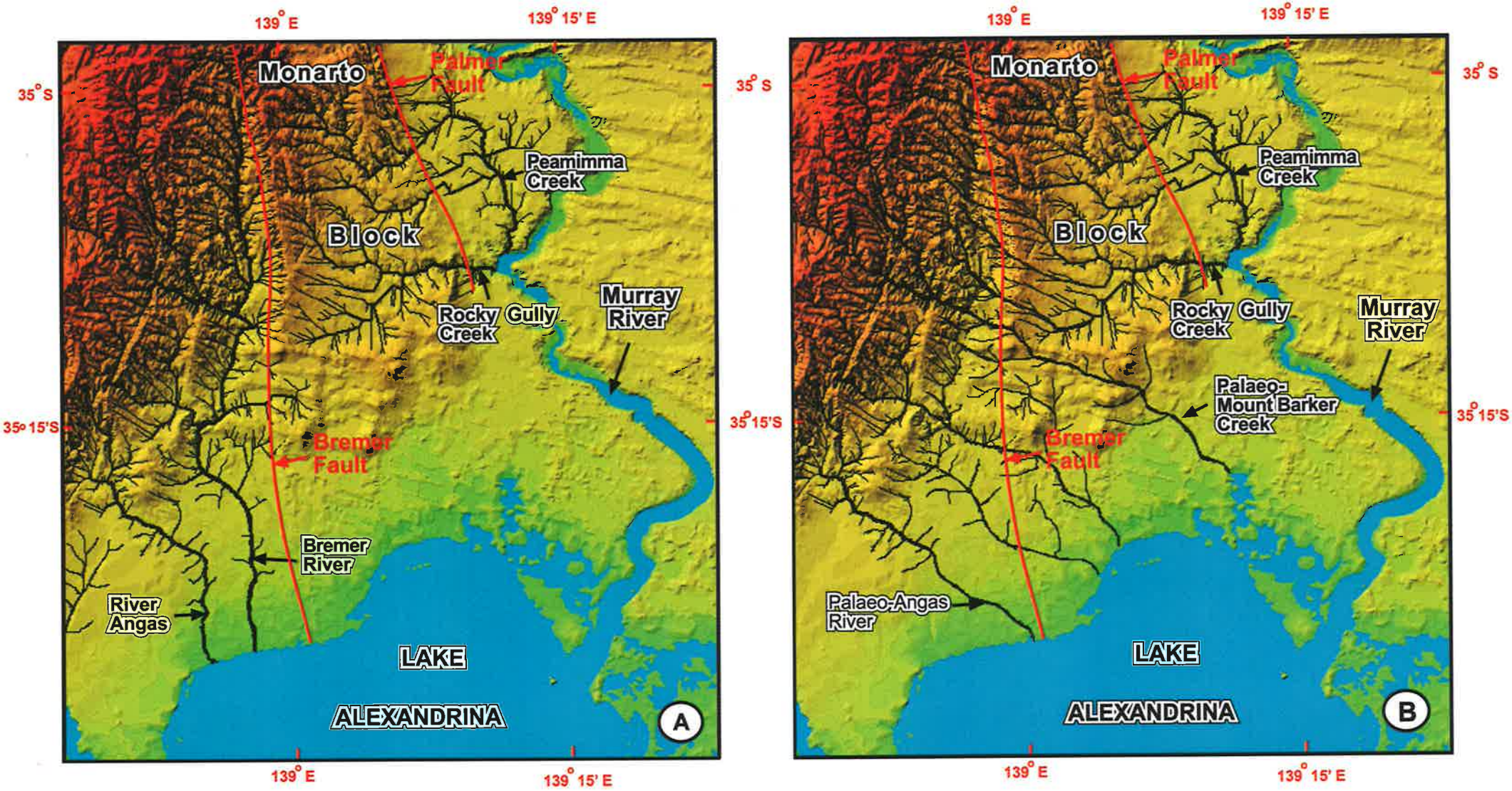


Figure 6-12 **A:** Present drainage network of the south-eastern slope of the Mount Lofty Ranges and Monarto Block, **B:** Reconstructed drainage prior to Late Pleistocene faulting and Monarto Block uplift. Stream patterns and shaded relief image derived from 1-s DEM.

Miocene near-shore sediments near Cross's Bridge in the Bremer Valley (Lindsay & Williams, 1977) and a number of palaeoreconstructions (Brown & Stephenson, 1991) indicates that the Monarto Block most probably was not exposed in the Tertiary landscape. This leads to the suggestion that the initial eastern flow of palaeostreams on the eastern slope of the Ranges would include the Monarto Block. The reconstructed palaeodrainage of this area shows a good spatial and stream-order correlation on the eastern slope of the Ranges with those developed on the Monarto Block (Fig. 6-12B). Therefore the lower part of the Mount Barker Creek and other streams could initially flow over the Monarto Block down to the Murray River. Moreover, if our interpretation of deformations of sand dunes by the Bremer Fault is correct (Ch. 4; Fig. 4-25) then the time of this block's uplift and palaeodrainage modification would occur during the Late Pleistocene-Holocene. The relatively rapid block uplift along this fault apparently blocked off a number of streams, flowing from the relatively steep eastern slope of the Ranges. This resulted in the formation of the Bremer River.

6.3.2 Palaeodrainage Reconstructions of the Western Portion of the Mount Lofty Ranges

Earlier palaeodrainage reconstructions provided evidence of a generally east to west drainage pattern on the western slope of the Mount Lofty Ranges (Benson, 1911; Fenner, 1930; Howchin, 1933; Sprigg, 1945; Aitchison et al., 1954; Sheard & Bowman, 1996; Rowett, 1997). The Gawler and Little Para Rivers, Dry Creek and Torrens River with its five tributaries and Brownhill Creek and Sturt River all flow westward antecedent to basement fabric. These rivers delivered most of the Tertiary and Quaternary terrigenous deposits into the northern and central parts of the St Vincent Basin. The Field River, Christie Creek and Onkaparinga Rivers delivered most of the terrigenous sediments into the Noarlunga Embayment. Pedlar and Drain Creeks together with a number of small streams flowing from the western slope of the Sellicks Hill Range are all drained into the Willunga Embayment. The Myponga River formed the largest water catchment in the southern part of the Ranges amongst other streams such as Carrickalinga Creek, Bungala and Yankalilla Rivers flowing into the southern part of the St. Vincent Basin (Fig. 6-4).

There are a number of possible small stream captures within the western slope of the Mount Lofty Ranges associated with headward erosion cutting through the boundary fault-scarps.

However only a few large captures lead to significant modification of the geomorphological setting. The Myponga River cuts through the Sellicks Hill Range and most probably captured a large catchment area within the intramontane Myponga Basin (Fig. 6-4). It seems that after the marine withdrawal from the Meadows-Myponga Basin in the Middle Miocene a new river system was formed by a number of small streams flowing from the eastern slope of the Sellicks Hill Range as well as from the western slope of the Bull Creek Range (Figs 6-4; 5-4). These streams inevitably formed a master stream flowing S-SW following the regional tilting, and probably along the axis of the intramontane Meadows-Myponga Basin toward the major base of erosion - the Normanville Embayment.

The northern tributary of the Carrickalinga Creek located along the Main South Road is the most likely prototype of that master stream outlet (Fig. 6-13). The upper tributaries of the so called in this thesis proto-Carrickalinga River were possibly located as far north as Meadows or even Echunga (see Fig. 5-4) before the multiple captures from the east (Finniss River) and from the west, such as Echunga Creek (eastern tributary of the Onkaparinga River) and the Myponga River dismembered it. If the proto-Carrickalinga River existed, it would be similar to or even larger than the present Onkaparinga River (Fig. 6-4). It is important to note that in contrast to most rivers and stream of the Mount Lofty Ranges formed mainly by headward erosion, the proto-Carrickalinga River could have been formed by an assemblage of a number of small streams on the bottom of a neotectonically formed graben-like structure of the Meadows-Myponga Basin. However without absolute dating and detailed correlation of erosional and terrigenous sedimentary features, the time of river captures and even the existence of this river remain hypothetical. Meanwhile geomorphological transects crossing northern tributaries of the Carrickalinga River show that such a river would be associated with two main periods of incision (Fig. 6-13). A valley about 2-3km wide and up to 100m deep valley was formed apparently some time in the Late Tertiary. The width/depth ratio of this valley is at least 20 to 1 that indicating that it was associated with lateral erosion and thus a low channel gradient and a low-energy landscape would be attributed to this period of incision. It follows that the second period is associated with only a few to several tens of metres of incision mainly concentrated along the main channel that formed a valley up to 1km wide narrowing to a few hundred metres with a V-shape northward (transect 3-3', Fig 6-13). This would probably indicate that the second type of incision occurred in a relatively short time-interval associated with more recent uplift.

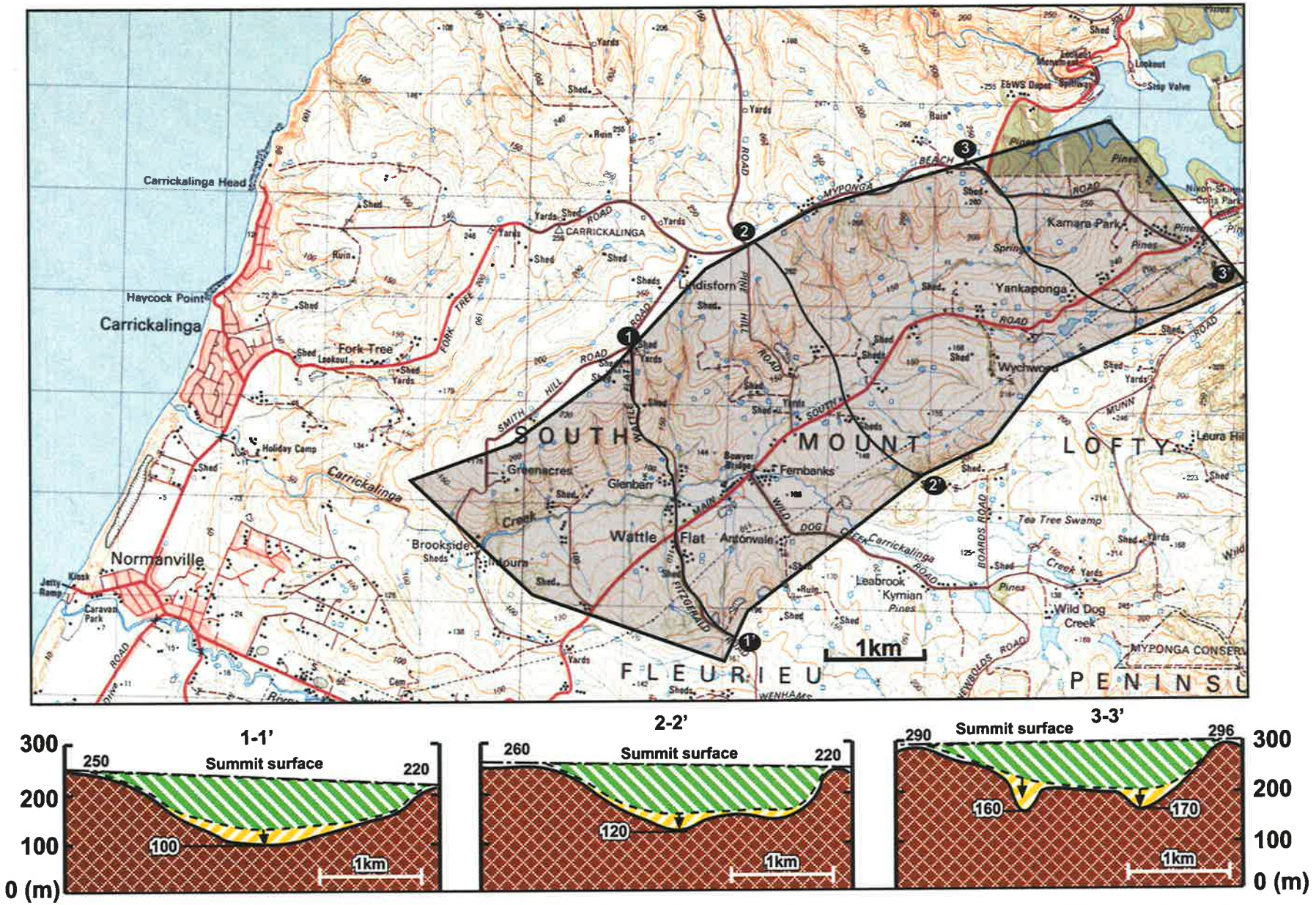


Figure 6-13 Location of the Palaeo-Carrickalinga valley in the southern part of the Mount Lofty Ranges. Geomorphological transects shows two stages of stream incision: undifferentiated Tertiary (green) and Pleistocene to Present (yellow).

There is also some uncertainty concerning the course of the lower Torrens River in the vicinity of Adelaide. Earlier reconstructions of the palaeo-Torrens considered that it flowed from the Mount Lofty Ranges through the Torrens Gorge (Figs 6-14, 6-3), then south-westward, obliquely crossing the Para Block in the same location as at present (Fig. 6-1). The occurrence of relatively large alluvial fans encountered near Port Adelaide were attributed to Dry Creek and the palaeo-Torrens River (Fig. 6-15). In order to explain the location of these relatively large alluvial fans, a ~ 45° turn north-westward of the palaeo-Torrens from its current course immediately west of North Adelaide was proposed (Aitchison et al., 1954; Sheard & Bowman, 1996). However, there is an occurrence and widespread distribution of Hindmarsh Clay and Pooraka sediments (Fig. 4-22 and 4-25) and other informal Pleistocene fluviolacustrine units on the western side of the Para Block north of the present Torrens River course (Sheard & Bowman, 1996). A number of streams flowing from the western slope of the Mount Lofty Ranges including First, Second, Third, Fourth and Fifth Creeks could not have delivered these fluvial sediments as the River Torrens (the major base of erosion in this area) would intercept all sedimentary input from these streams. Thus the occurrence of sediments on the western side of the Para Block between the Para Fault and the present course of the River Torrens would remain largely unexplained if the Torrens River had maintained its present position during the Pleistocene.

There is no doubt that two large alluvial fans near the Outer Harbour and Port Adelaide (Fig. 6-15) must have belonged to powerful streams capable of erosion and delivery of large masses of sediment. Ever since data on these alluvial fans were published (Aitchison et al., 1954) it has been considered that the Outer Harbour fan belongs to the Dry Creek and that the Port Adelaide fan belongs to the palaeo-Torrens River (Sheard & Bowman, 1996). However the relatively small size of the Dry Creek basin (~87km², DEM account) along with a low gradient of channels and shallow stream incision into the basement lead to serious doubts as to the ability of the Dry Creek to deliver such a large amount of coarse sediments to form the Outer Harbour alluvial fan.

In contrast, the size of the Torrens drainage basin is ~ 490km² or at least 5 times that of Dry Creek. The Torrens River main channel has a high channel gradient of 25-32m\km associated with the uplifted western portion of the Mount Lofty Ranges along the Eden-Burnside Fault (Fig. 6-2). The Torrens steam incisions into the basement are significantly deeper than that of Dry Creek. If one takes into account the much greater competence of the

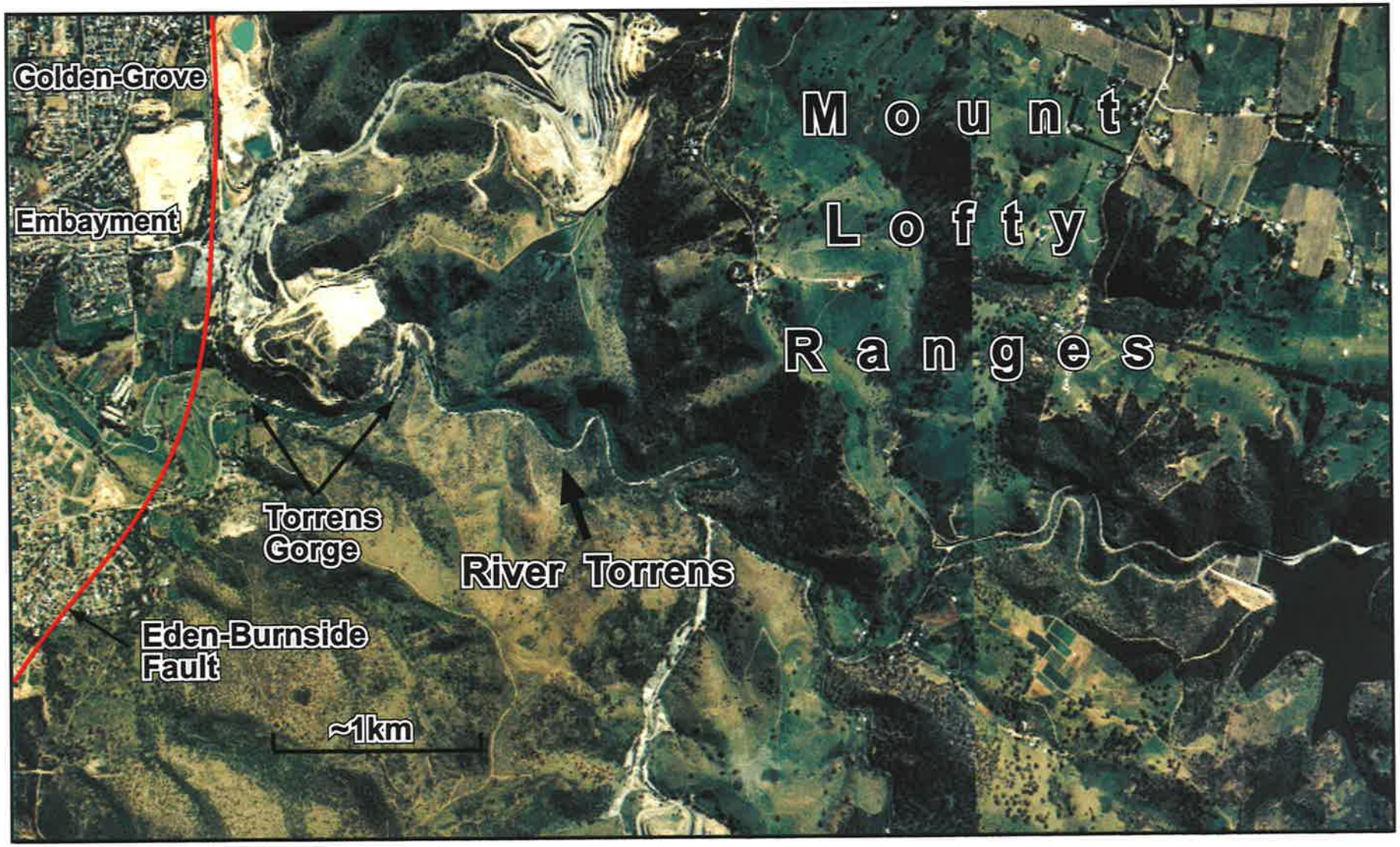


Figure 6-14 Aerial view at the River Torrens crossing the neotectonically active Eden-Burnside Fault forming the boundary between the Mount Lofty Ranges and Golden-Grove Embayment.

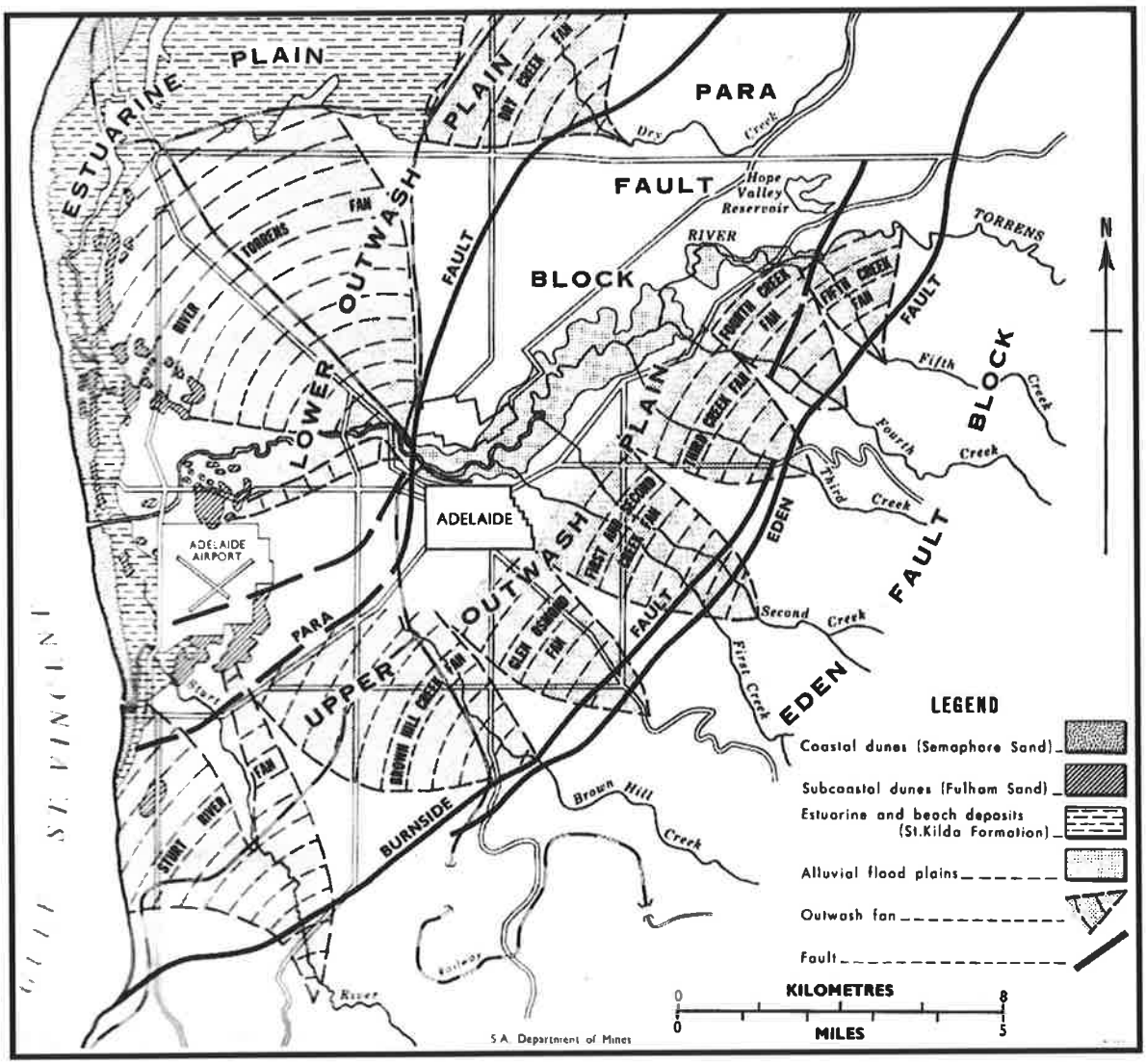


Figure 6-15 Outwash fans of the principal streams of the Adelaide area (after Aitchison et al, 1954).

Torrens River in comparison to Dry Creek then it seems reasonable to suggest that the Torrens River was capable of crossing over the originally gently undulating surface of the Para Block directly west from the Torrens Gorge. The delivery of large amounts of alluvium to the Outer Harbour fan by the palaeo-Torrens River would thus be more realistic and consistent with observed data.

Detailed geomorphological analysis suggests that there is no real topographic barrier between upper streams of the Dry Creek and the main channel of the River Torrens immediately west of the Torrens Gorge (Fig. 6-16). Taking into account the relatively flat original surface of the Para Block, the connection between the Torrens River and the upper tributaries of the Dry Creek outlined in this figure seems to be quite possible and it is consistent with general NW direction of most other streams escaping from the western portion of the Mount Lofty Ranges onto the Para Block (Fig. 6-15). According to this scenario Dry Creek would then have been a northern tributary of the palaeo-Torrens which deposited the Outer Harbour fan.

This reconstruction would furthermore explain the occurrence of a large amount of the Pliocene Dry Creek Sand (>40m thick) immediately south of the Dry Creek as these would also represent mixed marginal-marine and fluvial deposits delivered by a well-developed palaeo-Torrens River. In addition to those above a relatively large field of the Pleistocene Hindmarsh Clay Formation was intersected by several drillholes north-west of the Torrens Gorge (Fig. 4-22). In the absence of other large streams in this area these sediments could be correlated with sedimentary discharge (possible temporary outwash fan) of the River Torrens escaping from the Ranges onto the Para Block. This location of the Hindmarsh Clay deposits is well-correlated with the outlined initial direction of the River Torrens (Fig. 6-16). However the results of drilling (Fig. 4-24) clearly demonstrate that this field was probably even larger but was significantly eroded after the deposition of the Pooraka Formation (~35Ka). The erosional gap between drillholes 74 and 84 (Fig. 4-24) ones again indicates that there was a stream capable of such erosion and it also coincided with the proposed direction of the palaeo-Torrens (Fig. 6-16).

Taken in conjunction these data lead to a new scenario that would imply that the First, Second, Third and Fourth Creeks initially flowed from the western portion of the Ranges onto the Para Block and perhaps further west into the Adelaide Plains (similar to the present

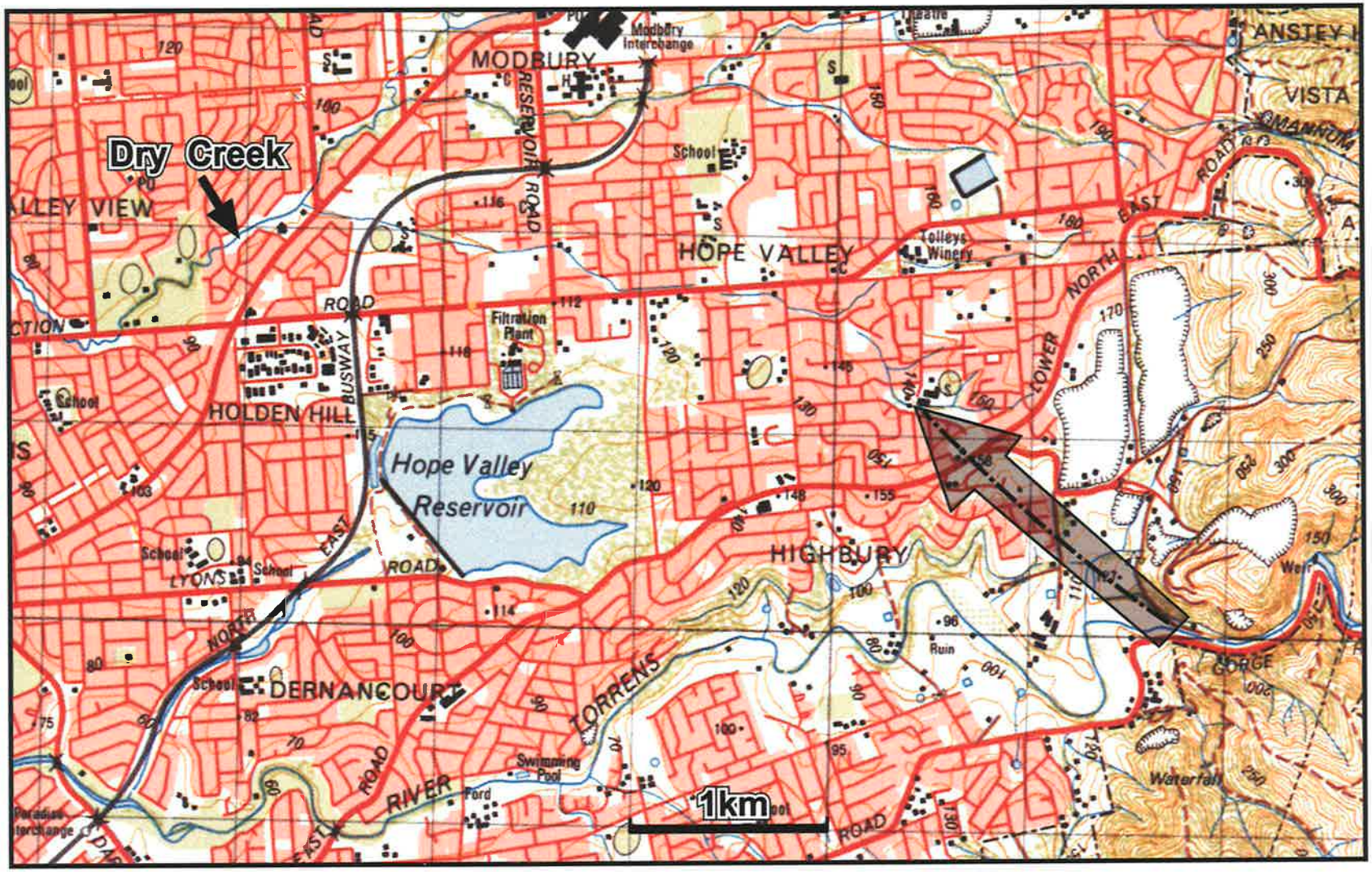


Figure 6-16 Possible connection of the River Torrens (west of the Torrens Gorge) with Dry Creek upper tributaries.

Brownhill Creek and Sturt River) independently of the Torrens River which partly discharged onto the Para Block (Fig. 6-17A). This would also explain the presence of the widespread deposits of the Hindmarsh Clay, Pooraka Formation and other units preserved within the Para Block between the Para Fault and the current course of the Torrens River (see also the Werrikooian stage of Ch. 4). This scenario probably includes most of the Pleistocene as deposits of the Pooraka Formation covered most of the Para Block as far north as Modbury Heights and perhaps further north (Fig. 4-24).

There are several intriguing erosional features associated with stream incisions into the Pooraka Formation. One such notable feature is associated with remnant of the NE-SW elongated erosional channel incised into the Pooraka Formation on the western portion of the Para Block some 4km north-west of, and parallel to, the present Torrens River course (Fig. 4-24). It extends ~5km from Dry Creek southward along the Para Fault. The width of this erosional feature is similar to the present Torrens Valley. This may indicate that the southern diversion of the palaeo-Torrens from direct westward flow into the Outer Harbour to its present course occurred in a few stages following deposition of the Pooraka Formation (Fig. 6-17 B, C and D). Thus most of the erosional features and relocation of the River Torrens within the Para Block occurred during the latest Pleistocene and Holocene as the most common age of the Pooraka Formation is ~35 000 years (Williams, 1973; Belperio & Baterman, 1986; Sheard & Bowman, 1996). It follows that the Para Block uplift is to some extent associated with the Para Fault transformation from Tertiary normal fault to the Late Pleistocene reverse fault that resulted in a low-angle NW-SE tilting of the Para Block surface.

According to geomorphological analysis the manifestation of the reverse component of this fault is associated with the fault-scarp zone. The northern part of the Para Fault forms a prominent escarpment. This escarpment slowly looses geomorphological expression southward and finally disappears beneath the Quaternary sediments SW of Adelaide City. However careful DEM analysis shows that there is a continuation of the Para Fault between the City and Marino that formed a straight-line terrace at ~15m above PSL (Fig. 6-18). This fault-line crosses a number of Quaternary depositional units and is not associated with a possible palaeo-coastal zone (neither erosional no depositional). Therefore it was most probably formed by more recent S-SW propagation of the reverse component of the Para Fault. The location of this fault is probably newly formed, and distinct from the Tertiary

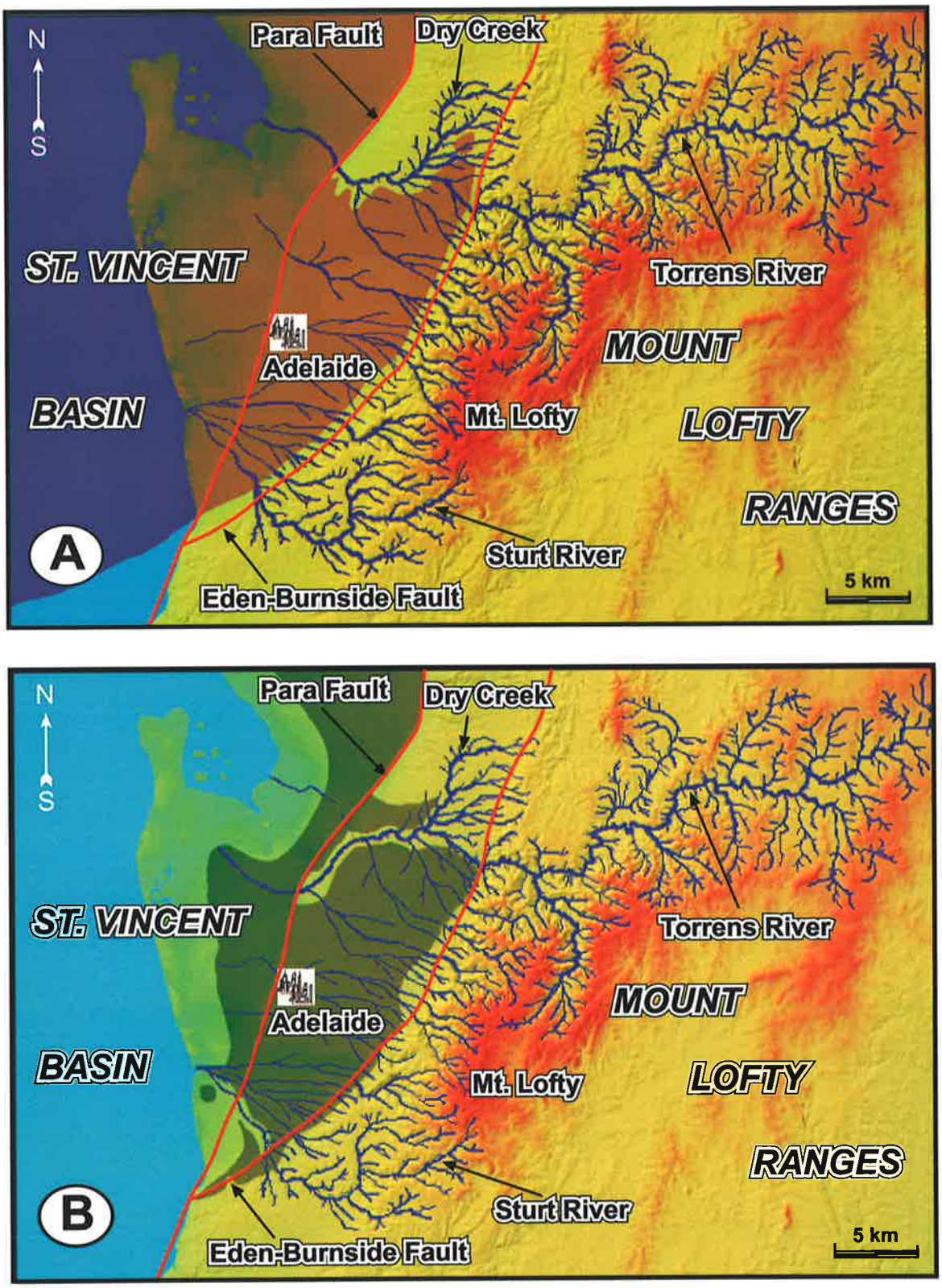


Figure 6-17 Pleistocene palaeodrainage reconstruction surrounding Adelaide. Original drainage derived by DEM analysis and plotted onto shaded relief image. A = Drainage associated with Pleistocene Hindmarsh Clay Formation (khaki color); B = Drainage associated with Late Pleistocene Pooraka Formation (dark green color), specifically with erosional channel north of Adelaide (distribution of these Formations modified after Sheard & Bowman, 1996; see Figs 4-22, 4-24 for original settings).

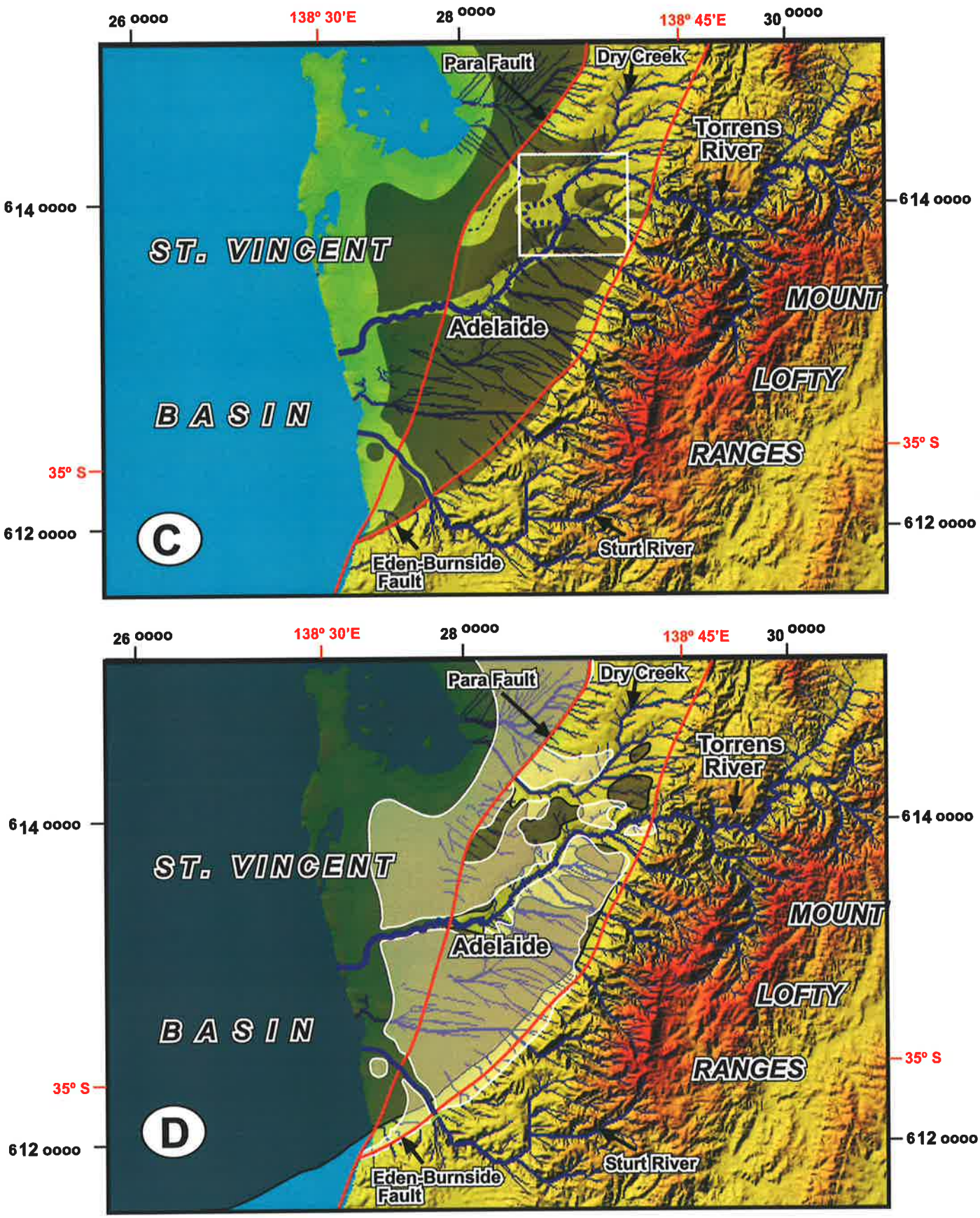


Figure 6-17 (continued) Pleistocene palaeodrainage reconstruction surrounding Adelaide. C = Drainage associated with erosional features in the Pooraka Formation (white box); D = Present day drainage pattern and its relationship with both Hindmarsh Clay Formation (dark green with black outline) and Pooraka Formation (outlined in white).

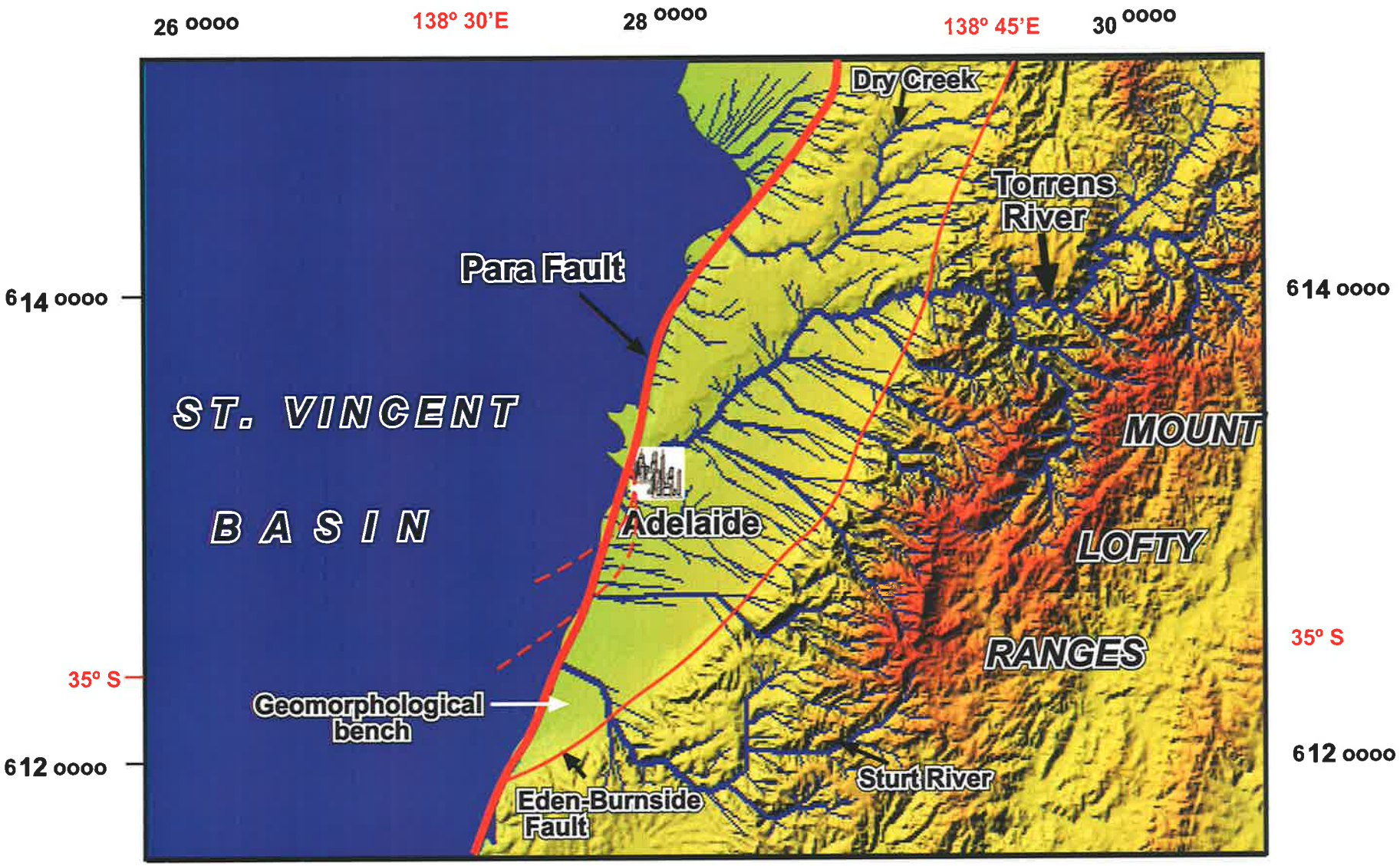


Figure 6-18 Flooding model at ~15m above PSL shows a perfect correlation of the geomorphological terrace or bench south of Adelaide with S-SW extension of the Para Fault (red solid line). Tertiary active branches of this fault shown in red dashed lines.

splitting faults. All these examples of palaeodrainage reconstruction demonstrate that: 1. The development of river systems in the study region was significantly dependent on the character and amount of neotectonic movements. Even a low magnitude of movements along the northern extent of the Para Fault re-organised the most powerful drainage system of the Torrens River; and 2. The palaeodrainage modification on both sides of the Ranges such as in the Adelaide and Monarto areas associated with the palaeo-Torrens and Bremer Rivers was due to uplift along the active faults such as Para and Bremer during the late Pleistocene and Holocene.

Following the identification of a new branch of the Para Fault (Fig. 6-18) with a probable reverse component it is important to note that the location of this fault is in a very densly populated area of western Adelaide suburbs and just about a kilometre from the Adelaide CBD. If one takes into account the thick unconsolidated sediments of this area (including loose sands and thick soils), high ground-water table and the most recent activity of this fault then the zone of the Para Fault and specifically it newly formed S-SW branch must be considered as one of the most dangerous for calculating earthquake hazard in the Adelaide Region.

6.4 Landscape Evolution of the Mount Lofty Ranges

In many models of landscape evolution a clear definition of the age and initial state of the landscape is critical. In this study the initial state is defined as a gently undulating and deeply weathered pre-Middle Eocene Palaeoplain that stood ~250-300m above PSL (see Ch. 3). The global eustatic sea-level was used as a reference point for the estimation of the general altitude of this Palaeoplain. The Palaeoplain concept in the study region suggests that the gently undulating surface has undergone deep weathering for a long time (>200Ma) as recorded beneath the Tertiary deposits in the basins as well as on the summit surfaces of the Ranges.

The link of erosional features with particular sedimentary units and their distribution is another critical step in understanding the nature of long-term landscape evolution. Chapter 4 provides characteristics of the lithostratigraphic units associated with particular regional stages as a time-framework for links between sedimentation and erosion. While such links are well established for some sedimentary sites, at other locations they are not so obvious and may be reconstructed generally or with a lesser degree of certainty. Therefore some

regional generalisations have been used, and four regional episodes or time-intervals of landscape evolution are identified. These episodes are:

- Drainage initiation (Middle-Late Eocene)
- Subdued erosion mainly associated with basin subsidence (Oligocene-Middle Miocene)
- Landscape relaxation associated with transitional tectonic regime (Late Miocene-early Pleistocene) and
- Vigorous erosion associated with major uplift of the Ranges (Mid Pleistocene-Recent).

6.4.1 Drainage Initiation (Middle to Late Eocene)

Drainage initiation is considered here as a function of: 1. Crustal segmentation that divided the Palaeoplain into the areas of the flanking sedimentary St. Vincent and Western Murray Basins and the interbasin sedimentary source area of the proto-Mount Lofty Ranges; and 2. Regional slope formation due to S-SW gentle tilting of the Palaeoplain remnant (western slope) and by differential subsidence of the Western Murray Basin (eastern slope). Further crustal segmentation involved the formation of sedimentary embayments of the St. Vincent Basin significantly complicated transitional zone between the proto-Mount Lofty Ranges and this basin. These together formed the topographic difference between the source area and the accommodation space of the sedimentary basins.

The sudden appearance of the fluvial North Maslin Sands after a long period of sedimentary interregnum (>200Ma) clearly indicates that the Middle Eocene was the crucial time for the initiation of a drainage network. The distribution of the Middle-Late Eocene terrigenous sediments demonstrates that the major stream discharge mainly occurred immediately off the western edges of the Mount Lofty Ranges near the Willunga, Eden-Burnside and Para Faults. Deposits of the time-equivalent to the Maslin Sands and Clinton Formation in the Barossa Basin are probably associated with down-to-basin block movements along the Stockwell Fault that formed the sedimentary accommodation space in that basin.

The fluviolacustrine lithology and age of the lower Olney Formation (Ch. 4) along the eastern edge of the Mount Lofty Ranges indicates that eastern flowing river systems were established simultaneously to those on the western slope of the Ranges. The swampy sedimentary environment of the lower Olney Formation is almost identical to that of the Clinton Formation in the eastern St. Vincent Basin. Such environments were associated

with a very restricted sediment supply from a gently undulating source area. This indicates that low-magnitude, down-to-basin neotectonic movements affected the Palaeoplain and created a very shallow accommodation space for coal and lignites. The localisation of these sediments near the faults or in fault-angle depressions (eg. Lindsay, 1981) shows that part of such accommodation space occurred due to block movements along the normal faults. The absence of debris and slope deposits indicates that fault-scarps were not essential characteristics of the landscape during this initial geomorphological stage.

The prevalence of fine-grained fluvial input into the central and southern parts of the St. Vincent Basin (North and South Maslin Sands) indicates that competence of embryonic streams on the western slope of the Ranges was higher than those on the eastern, especially in the southern part. Regional geomorphological analysis (Tokarev et al., 1999) demonstrates that all eastern rivers flowing from the Mount Lofty Ranges are significantly shorter than those flowing into the St. Vincent Basin. The difference of total channel length and basin sizes on the eastern and western slopes of the Ranges is attributed to the asymmetry of the neotectonic structure of the source region. The wide and gentle western slope of the Ranges was formed mainly due to gentle W-SW tilting affecting a large portion of the proto-Mount Lofty Ranges, although the narrow eastern slope was most probably formed by low-magnitude subsidence of the Western Murray Basin. Thus the greater size of river water catchments on the western slope contributed to greater stream competence resulting in coarser sediments of the North Maslin Sand than those of the lower Olney Formation delivered by short streams of the eastern slope of the Ranges.

Summarising all the above, the development of neotectonic structures due to segmentation of the pre-Middle Eocene Palaeoplain and W-SW tilting of the proto-Mount Lofty Ranges (interbasin remnant of the Palaeoplain) was the major cause of the drainage initiation that occurred some time in the Middle-Late Eocene.

6.4.2 Subdued Erosion (Oligocene to Middle Miocene)

The Oligocene-Middle Miocene sedimentation in all flanking and intramontane basins was clearly associated with a carbonate type of deposition in shallow marine environments. A minor terrigenous supply through the Mid-Tertiary succession is evidence that a gently undulating landscape within the proto-Mount Lofty Ranges inherited from the Palaeoplain persisted after the drainage initiation took place. However some monadnocks of the pre-

Middle Eocene Palaeoplain such as the Mt. Pleasant, Mt. Torrens, Spring Mount, Mt. Compass and perhaps several others could have been more eminent than the general subdued relief. Such landscape was subject to mild erosion during this time-interval. In contrast, a highly differentiated relief as proposed by Benbow et al. (1995) would not correspond to the fine-grained and predominant carbonate sediments accumulated in flanking and especially in the intramontane basins.

Downward movements of the southern part of this source region permitted the Oligocene marine inundation deep into these Ranges. Following this inundation the shallow marine and marginal-marine environments were established in the Meadows-Myponga and Hindmarsh Tiers Basins that dominated for more than 10Ma. This would be consistent only with a low and undifferentiated landscape of the interior parts of the southern Ranges. Simulations of marine inundation (Figs 4-10; 4-11; 4-14) clearly demonstrate that marine influence on landscape evolution was significantly greater than previously considered. These simulations also demonstrate that marine inundation probably covered the large southern part of the Mount Lofty Ranges and Fleurieu Peninsula at least temporarily during the high sea-level stands (Ch. 4; Tokarev & Gostin, in press). Marine bed-load erosion has also significantly contributed to landscape modification in these areas.

It is important to note here that a low and gently undulating landscape with only subdued drainage systems in the Mount Lofty Ranges persisted throughout the Tertiary up to the Middle Miocene. Concerning the Miocene landscape of these Ranges, McGowran & Li (1997, p.6) write: "It is likely that the uplands between the Murray and St. Vincent Basins, including Kangaroo Island, were hardly more than very low hills during Early-Middle Miocene time".

The asymmetry of neotectonic structure is attributed to regional SW tilting of the pre-Tertiary Palaeoplain remnant (proto-Mount Lofty Ranges) and differential subsidence of the Western Murray Basin. These were the primary cause of palaeodrainage distribution along both western and eastern slopes. However tectonic block movements along numerous short and long-lived faults mainly in marginal areas have significantly complicated the initial regional and local geomorphological settings. Although neotectonically active faults often form elongated landforms, slope debris that could be associated with prominent fault-scarps are absent in the Mid-Tertiary succession, even near the most active faults bounding the St.

Vincent Basin embayments. Therefore normal fault kinematics with down-to-basin block movements and a contemporaneous sedimentary fill of accommodation space was required in order to reduce the effect of fault-scarp formations during the Oligocene and Middle Miocene.

Using the global sea-level curve (Haq et al., 1987) adapted to southern Australia (McGowran, 1989; Li et al., 2004) as a reference, it is possible to suggest that the gently undulating landscape in the southern parts of the Mount Lofty Ranges would be topographically ~150m above PSL as there was marine inundation of this area. Because of the generally low-angle of the S-SW tilting one may suggest that the original surface in the Mount Lofty Ranges rose to the north and east. This would be consistent with the major watershed location and also with the regional pattern of river systems. If such tilting affected the whole study region of the Mount Lofty Ranges then, at first approximation, the altitude of the Miocene landscape would be estimated as:

1. The southern Ranges near Myponga and Hindmarsh Tiers Basins stood about 100-150m above PSL in order to provide marine access into these basins;
2. The altitude of the major watershed area somewhere in the middle part of the Ranges (upper reaches of the Torrens and Onkaparinga Rivers) can be roughly estimated as ~150-200m above PSL. Some monadnocks such as the Mt. Pleasant and Mt. Torrens occurred in this area and perhaps stood higher that these estimates;
3. In the northern part of the study region somewhere east of the Barossa Valley the Mount Lofty Ranges stood at about 200-250m above PSL. That would provide the stream competence to deliver coarse Tertiary sands into the Barossa Basin. Such landscape altitude is similar to the initial altitude of the pre-Middle Eocene Palaeoplain.

In spite of uncertainty in estimating palaeolandscape altitudes the scenario above would be consistent with the lithological characteristics of sediments in all the Tertiary basins as well as with the regional neotectonic setting and proposed down-to-basin type of movements that created sedimentary accommodation space. Moreover the eustatic sea-level and marine inundation, river-net patterns and other geomorphological characteristics are all also consistent with such postulated landscape altitudes and structural asymmetry of the Ranges. The increased thickness of the regolith from tens of centimetres in the south to tens of

metres in the NE of the Mount Lofty Ranges also supports regional tilting and these palaeolandscape estimates.

The above characteristics of the reconstructed palaeolandscape significantly contradict Benbow et al. (1995) who proposed a high and differentiated Miocene landscape of the Mount Lofty Ranges with local relief of 250-430m in the south and 350-450m in the north, much higher than at present. Taking into account that the Early and Middle Tertiary climate was significantly wetter with higher rainfall than at present, the marked preservation of a number of planation surfaces capped by regolith within the Mount Lofty Ranges (Fenner, 1930; Sprigg, 1945; Twidale & Bourne, 1975) does not correspond to such an elevated and differentiated Tertiary landscape. Furthermore, neither flanking nor intramontane Tertiary basins contain coarse sediments associated with the postulated high topography of this region. The only unit containing coarse sediments is the Oligocene Compton Conglomerate occurring in the Buccleuch Embayment of the SW Murray Basin. However the nature of this unit was more likely associated with marine influence on the southern Mount Lofty Ranges than with high and differentiated landscape (see Ch. 4).

McGowran et al. (2004) demonstrates that not only the Mount Lofty Ranges but the entire western portion of the southern Australian continental margin was developed as a gently undulating region with shallow marine, flood plain, fluviolacustrine and carbonate lake environments during the Middle Tertiary. Shallow marine sedimentation (<20m water depth) is associated with the Middle Miocene Nullarbor Limestone in the Eucla Basin (Li et al., 2004). Similar shallow marine conditions apparently applied to the Middle Miocene sedimentation of the Melton Limestone formed in the Pirie Basin in northern Spencer Gulf (Alley & Lindsay, 1995a). The Munno Para Clay Member of the Port Willunga Formation completed the Miocene sedimentation in the St. Vincent Basin (Lindsay, 1981). The Cadell Marl and Finniss Clay Members of the Murray Group Limestones were the most common sediments at this time in the Western Murray Basin (Brown & Stephenson, 1991). The Gambier Limestone was formed in the Gambier Embayment as well as in the shallow marine environments of the onshore Otway Basin before sedimentation ceased (Smith et al., 1995). All these Miocene carbonate sediments contain only a very minor terrigenous input. Not a single unit of those sediments points to the existence of a high and differentiated landscape near to these basins. On the contrary, all evidence suggest that only a low and

gently undulating landscape of source areas, including the Mount Lofty Ranges, could have provided such a limited terrigenous supply to the sedimentary basins.

Thus contrary to earlier interpretations this thesis establishes that the Ranges were formed as remnants of the high-standing pre-Middle Eocene Palaeoplain set between the subsiding St. Vincent and Western Murray Basins. Regional S-SW tilting of this interbasin region accompanied the crustal segmentation along a set of normal faults that together with the subdued erosion and mild development river systems modified the inherited gently undulating and deeply weathered Palaeoplain landscape during the Oligocene-Middle Miocene.

6.4.3 Landscape Relaxation (Late Miocene to Early Pleistocene)

Holbrook & Schumm (1999) noted that rivers are extremely sensitive to subtle or even incipient and smaller-scale epeirogenic tectonic changes in modern and ancient settings and that resultant river sediments are a useful decrypting tool for palaeotectonic and geomorphological reconstructions. However there is no lithostratigraphic record at all in the flanking and intramontane basins within the study region between ~14Ma and ~5.5Ma.

This sedimentary interregnum was probably associated with a dramatic sea-level fall in the Middle Miocene that resulted in marine withdrawal not only from all the basins in the study area but apparently also from a large part of the southern Australian continental shelf. The Miocene reduction of tectonic activity, including the reduction of sedimentary accommodation space (Figs 4-2; 4-9) also contributed to the absence of a sedimentary record. However it would be unrealistic to suggest that all sediment supply ceased simultaneously in all basins and specifically from the Mount Lofty Ranges to the flanking basins. The combination of significant sea-level fall, change of tectonic activity and drying climatic trend (after the Middle Miocene climatic optimum) substantially reduced not only stream erosional activity in the study region but arrested landscape development as a whole. This period is referred to here as landscape relaxation and was most likely associated with very slow erosion and also with an increased rate of deep weathering in the Mount Lofty Ranges, and on all exposed sedimentary surfaces in the study region.

Surprisingly, there is no record of accumulation of even fine-grained sediments delivered by starved streams from the Mount Lofty Ranges into the flanking basins during the Late

Miocene. While one can infer an uplift of the basin sedimentary surface in order to explain erosion and the Miocene/Pliocene unconformity, Chapters 4 and 5 of this thesis reveal that the absence of any sedimentary input in the flanking basins is related to marine bed-load erosion during the retreats associated with Late Miocene sea-level low stands. The model of marine bed-load erosion requires the lowering of the shelf and the basin sedimentary surface in order to provide marine access to these inland basins. Regional southern tilting provides a suitable mechanism for such surface lowering that is also consistent with the regional 1-5° of angular Miocene/Pliocene unconformities.

As there were fluctuations in sea-level during the Late Miocene resulting in marine transgressions and retreats (Fig. 4-1), the sedimentary surface in the St. Vincent and Western Murray Basins would be placed at about Present Sea-level. However the southern Mount Lofty Ranges including the intramontane Myponga and Hindmarsh Tiers Basins were possible warped to ~100m above PSL as it is required to protect the intramontane Myponga and Hindmarsh Tiers Basin from the Pliocene marine inundation. Such tectonic rebound would have increased the altitude of the landscape, and perhaps stream competence on the marginal areas if it was associated with bounding faults. However there is no sedimentary record or any other evidence of substantial uplift of the Ranges during the Late Miocene.

Pliocene Cheltenhamian-Kalimnan Stages were apparently associated with a significant sea-level rise from ~40m below to ~80 above PSL at the beginning of the Pliocene. This was the major cause of the marginal-marine environments in both the St. Vincent Basin and the southern part of Western Murray Basin. Such sea-level rise inevitably affected the low and subdued landscape of the Mount Lofty Ranges that mainly resulted in coastal marine erosion and accumulation of medium and coarse-grained sands at the base of the Early Pliocene (eg. Loxton Sand in the SW Murray Basin).

Perhaps some localised down-to-basin block movements also occurred along the Para Fault creating a new accommodation space for Dry Creek Sands in the Adelaide Plain sub-basin. Palaeodrainage reconstruction in this area (see above) shows that the terrigenous input of the Dry Creek Sands into the marginal-marine environment of the Adelaide Plains sub-basin was most probably delivered by the palaeo-Torrens River with Dry Creek as a northern tributary. Such an interpretation would be consistent with the amount of sediments and lithology of this unit.

The lithology of the Hallett Cove Sandstone, Loxton-Parilla Sand and Blanchetown Clay accumulated in flanking basins during the Late Pliocene indicates that subdued streams were capable of supplying only fine-grained sediments into both the St. Vincent and Western Murray Basins. There is no evidence that may indicate that uplift with consequent erosion affected the region during the Pliocene. On the contrary, the reduction of grain size and only fine-grained lithology of the Late Pliocene units accumulated nearby the source clearly indicates that the Mount Lofty Ranges remained as the interbasin region with a low and still gently undulating landscape. The large amount of silica and ferruginous constituencies of these sediments are evidence that deep weathering occurred earlier in the source region probably during the Late Miocene and persisted during the Pliocene. Deep weathering is also consistent with a low and gentle landscape of the Mount Lofty Ranges.

These facts led Fenner (1930) to suggest that there were two periods of landscape peneplanation in the Mount Lofty Ranges and that the latest one occurred during the Late Tertiary. Sprigg (1945, p. 299) criticised Fenner's "double peneplanation" arguing that the landscape on which laterisation occurred was old from the birth, while admitting that the peneplanation occurred almost certainly post-Miocene and pre-Glacial. Thus the neutral term of 'landscape relaxation' would reconcile both Fenner's and Sprigg's hypotheses of the gently undulating and deeply weathered Late Tertiary landscape.

A further reduction of stream competence is associated with the Early Pleistocene Point Ellen Formation and Burnham Limestone in the St. Vincent Basin, and with the Bungunnia Limestone in the Western Murray Basin (Werrikooian Stage, Ch. 4). This is possibly related to the reduction of rainfall associated with climatic change toward a cooler and drier mode, however it almost certainly did not imply the increase of landscape energy. Therefore there was a delay in the uplift of the Mount Lofty Ranges probably until the Mid-Pleistocene.

6.4.4 Vigorous Erosion (Mid-Pleistocene to Recent)

The Late Tertiary landscape was subject to an exceptionally moist climate specifically during the Middle Miocene identified as the climatic optimum (McGowran et al., 1997). This leads to the suggestion that sedimentary transport rate had to be at a high or probably highest level at that time. However in reality the highest rate of fluvial sedimentary supply is obviously associated with the Middle and Late Pleistocene (eg. Hindmarsh Clay and Pooraka Formation of the St. Vincent Basin) when, in contrast, a drying climatic trend took

place. It seems unlikely that climatic factors alone could significantly contribute to increased Pleistocene stream competence as the major climatic change from wet and warm mode to cooler and drier condition occurred some time during the Pliocene and a similar to present day environment was already established at the end of the Pliocene (eg. Macphail, 1997). However carbonate type of sedimentation continued during the Early Pleistocene in the St. Vincent and Western Murray Basins. Therefore an increased landscape erosion and sediment transport must be attributed to an increase in landscape energy due to higher topography and channel gradients. This is associated with significant Pleistocene uplift of the Ranges in general, and its western portion in particular.

The most active vertical erosion in the study region was confined to marginal areas associated with active faults, along which the main Pleistocene uplift occurred, and where it is probably still occurring at present. The nick-point on the longitudinal channel profile of the River Torrens, for example, shows that the most active stream erosion has not moved significantly into the Ranges since the uplift has occurred along the Eden-Burnside Fault (Fig. 6-2). Thus the pre-Pleistocene landscape morphology including river systems was preserved in interior parts of the Ranges, while the marginal areas exhibited geomorphological activity at an increased rate. The appearance of debris flows in the Pleistocene succession near both western and eastern margins of the Mount Lofty Ranges clearly distinguishes the high and differentiated Pleistocene landscape from the low and subdued Tertiary landscape of the Ranges.

The youthful and well-dissected slopes of the Ranges with gorges and a number of waterfalls are further geomorphological evidence for major and young uplift of this source area. The coarse deposits such as the Hindmarsh Clay and Pooraka Formation often containing gravels, cobbles and pebbles are clearly the sedimentary response to an active landscape dissection during the last million years. The dramatic change of stream profiles occurred along the earlier established Tertiary boundary faults such as the Eden-Burnside, Para, Clarendon and Willunga on the western side of the Ranges. Similarly, the most active stream erosion during the late Pleistocene is associated with major Tertiary faults such as the Milendella, Palmer, Bremer, Encounter and possibly some others on the eastern side of the Ranges. All of these faults formed prominent fault-scarps during the Pleistocene and some of them significantly affected river systems such as those in the Adelaide and Monarto areas mentioned previously.

Thus the general uplift of the Mount Lofty Ranges mainly occurred along the established Tertiary faults on the borders with flanking the St. Vincent and Western Murray Basins. Such uplift produced the most dramatic landscape modifications in these marginal areas during the Middle and Late Pleistocene and continuing up to the present. Thus this uplift with vigorous stream erosion of the marginal areas of the Mount Lofty Ranges was the major cause of differentiated and dissected landscape along the boundary faults. In contrast, the interior parts of the Ranges still preserve a subdued Tertiary landscape with little active erosion.

Chapter 7

SYNTHESIS & CONCLUSIONS

7.1 Introduction

The long-lasting problem of the nature and evolution of the Mount Lofty Ranges was outlined at the beginning of 20th century by Benson (1911). While the co-existence of a mature gently undulating landscape and deeply dissected and young landscape was recognised long ago (Fenner, 1930; Hossfeld, 1935; Sprigg, 1945), the nature of neotectonic structure and its relationship with these landscapes remained highly speculative up to the present. In order to explain the co-existence of mature and young landscapes a hypothesis of two stages of uplift and peneplanation was born (Fenner, 1930). The first uplift was attributed to differentiation of old peneplain (pre-Middle Eocene Palaeoplain in this thesis), while the second stage of uplift was defined as the most pronounced Pleistocene Kosciusko Uplift that differentiated younger Pliocene to early Pleistocene peneplain (Fenner, 1930).

Neither compressional nor extensional stresses were identified as the major tectonic causes of the Tertiary Mount Lofty Ranges and its flanking and intramontane basins by the initial hypothesis, while Sprigg (1945, p.287) wrote: "The fracture pattern, small hade of the block faults and the tilting of the separate blocks are typical of tensional stress". All later studies made some adjustments and modifications but generally accepted such a two stage uplift of the Mount Lofty Ranges. Neither of these studies took into consideration the topographical position of high pre-Middle Eocene Palaeoplain, and without further neotectonic considerations the Tertiary compressional uplift of the Ranges has become a traditional model.

However this thesis, using the global sea-level curve, identifies that the old Palaeoplain was topographically high enough (>250m above PSL) to generate Tertiary palaeodrainage and thus initiate landscape evolution within proto-Mount Lofty Ranges due to subsidence of the St. Vincent and Western Murray Basin and W-SW tilting of this interbasin source region even without uplift. The crustal extension and segmentation affected study region during the Middle Eocene-Middle Miocene that was attributed to the Palaeoplain differentiation (Ch. 5). However the major uplift of the Mount Lofty Ranges occurred after the Late Miocene-earliest Pleistocene landscape relaxation (Ch. 6). This chapter synthesises the neotectonic evolution

of the Mount Lofty Ranges and flanking basins assembling together the geological, geomorphological and tectonic data into the three stage model.

7.2 Three Stage Neotectonic Model

The three principal neotectonic stages identified in this study are associated with specific neotectonic regimes and styles of crustal movements that imprinted the neotectonic structure of the Mount Lofty Ranges and its flanking basins. These stages are:

- Neotectonic Stage I (Middle Eocene to Middle Miocene) associated with crustal extension;
- Neotectonic Stage II (Middle Miocene to earliest Pleistocene) identified here as a transitional tectonic regime;
- Neotectonic Stage III (Pleistocene to Present) associated with dominant crustal compression.

7.2.1 Neotectonic Stage I: Crustal Extension and Segmentation (~43Ma to ~14Ma)

Analysis of the lithostratigraphic units and palaeoreconstructions within the study region (Ch. 4) show that the commencement of a new period of sedimentation occurred at ~43Ma after a prolonged period of weathering and denudation (>200Ma). The formation of sedimentary accommodation space of the St. Vincent and Western Murray Basins was clearly due to basin subsidence. This subsidence differentiated an extensive, topographically high, deeply weathered and gently undulating Palaeoplain (Ch. 3) into sedimentary basins and the interbasin source region of the proto-Mount Lofty Ranges (ie. a large remnant of the Palaeoplain that remained above the subsiding basins). Such differentiation is interpreted here as a result of crustal extension and segmentation (second order). Further crustal segmentation (third order) resulted in the division of these basins into embayments and the formation of asymmetric block structure within the proto-Mount Lofty Ranges (Ch. 5). The formation of intramontane sedimentary basins including Barossa, Meadows-Myponga and Hindmarsh Tiers Basins was also a result of intermediate crustal extension. A strain transfer zone and a number of attendant strain accommodation zones formed the primary neotectonic setting in the study area (Fig. 1-2).

The Middle Eocene was a crucial time associated with the general establishment of the primary regional structures such as the St. Vincent and Western Murray Basins flanking the proto-Mount Lofty Ranges. The Middle Eocene crustal extension resulted in subsidence of

these basins that partitioned the high-standing Palaeoplain into areas of active sedimentary accommodation space and the relatively stable interbasin source region. However even these basin areas initially remained above the Middle Eocene sea-level (~220m above PSL) as the fluviolacustrine North Maslin Sand and Clinton Formation of the St. Vincent Basin, and the lower part of the Olney Formation of the Western Murray Basin indicate (Johannian Stage, Ch. 4). A number of high-angle normal faults with attendant down-to-basin subsiding blocks (strain accommodation zones) were established on the eastern and western margins of the Ranges. This explains the location of major Middle Eocene depocentres (including lignite and coal) to the edges of the flanking basins, the so-called fault-angle depressions.

A regional low-angle W-SW tilting apparently affected the interbasin source region that later became the Mount Lofty Ranges. Such tilting resulted in the formation of a wide and gentle western slope, while relatively narrow and steep eastern slope was formed mainly as a result of the Western Murray Basin differential subsidence along the boundary normal faults. The asymmetric shape of this interbasin region of the proto-Mount Lofty Ranges was formed thus due to gentle tilting and basin subsidence. The pattern of most river-systems flowing to the St. Vincent Basin from this source region is consistent with this tilting and thus clearly associated with such neotectonic development. The location of the regional watershed along the topographically higher eastern edge of the Ranges is also consistent with such asymmetric type of structure though complicated by local block movements.

The Late Eocene structural development in the study region was associated with continuing crustal extension that increased subsidence of flanking basins with the formation of additional sedimentary accommodation space, specifically near the major boundary faults. Substantial basin subsidence together with regional southern tilting of the southern Australian continental margin caused the first marine transgression into inland St. Vincent and Western Murray Basins (Aldingan Stage, Ch. 4). Basin subsidence and regional tilting were absolutely essential because of the general trend of sea-level fall since the Palaeocene (Figs 4-1; 4-2). The tectonic formation of the sedimentary accommodation space and marine transgression resulted in accumulation of the South Maslin Sand and the Tortachilla Limestone in the St. Vincent Basin, and marine upper Olney Formation and Buccleuch Beds in the Western Murray Basin.

Several factor have been taken into account in calculating the neotectonic effect on the study

region. The major factors are: 1. The initial altitude of the pre-Middle Eocene Palaeoplain that stood ~250-300m above PSL; 2. That the Late Eocene sea-level was ~100m lower than it was during the Middle Eocene; and 3. Despite the general trend of sea-level fall, about 100m of sediments accumulated in flanking basins. These together accounted for >300m of basin subsidence that must have created such sedimentary accommodation space since the initial crustal segmentation took place in this region. An average of 40m/Ma rate of subsidence was calculated for the St. Vincent Basin (Fig. 4-2).

There is no indication of any uplift of the interbasin region of the proto-Mount Lofty Ranges during the Middle and Late Eocene. In contrast, a rapid reduction of terrigenous input in the sedimentary successions indicates that streams substantially lost competence in the Late Eocene in comparison to their activity during the Middle Eocene. This probably resulted from further lowering of the Palaeoplain landscape in the interbasin source region due to continuing S-SW tilting.

An intensive fluvial supply into the Barossa Basin (north part of the study region) from the high Palaeoplain probably also began in the Middle-Late Eocene as the age of basement Tertiary units indicates (eg. Alley, 1995a). Therefore the northern part of the source region (north of the transfer zone, Fig. 1-2) was probably more resilient to the tilting but affected by crustal extension. The subsidence of the Barossa Basin was able to provide sedimentary accommodation space, but insufficient to allow marine transgression into this basin. A substantially increased thickness of Tertiary sediments toward the Stockwell Fault bounding the Barossa Basin on the east (Figs 5-6; 5-7) indicates that down-to-basin block movements along this normal fault generated extra sedimentary accommodation space near the fault. Such a model of accommodation space formation (Fig. 4-6) is consistent throughout the entire study region.

Similar down-to-basin block movements along the Willunga, Clarendon, Eden-Burnside and Para Faults controlled Middle and Late Eocene sedimentation in the St. Vincent Basin. In the SW part of the Murray Basin the Buccleuch Embayment was formed apparently also due to subsidence, because the marine transgression occurred during a general sea-level fall. The western margin of this embayment is clearly associated with the Encounter Fault (Brown & Stephenson, 1991). Down-to-basin block movements along this fault resulted in the formation of the sedimentary accommodation space of the SW part of the Murray Basin and

also accounted to the formation of relatively steep eastern slope of the mount Lofty Ranges. The northern extension of this fault more likely terminates within the Transfer Zone (Fig. 1-2). Inferred strain transfer zone terminates a number of non-aligned faults within the study and neighbouring regions (Fig. 5-8). The fault termination within the transfer zone is consistent with structural characteristics of the Tertiary extensional setting of the study region (Ch. 5). The abundance of quartz and ferruginous sandy sediments was associated with deep regolith inherited from the Palaeoplain. The embryonic drainage systems were attributed here to the first stage of landscape evolution of the Mount Lofty Ranges (Drainage Initiation, Ch. 6).

The Oligocene was associated with a new pulse of crustal extension that resulted in further segmentation of basins and the interbasin proto-Mount Lofty Ranges. While the second order of crustal segmentation accentuated the general basin subsidence, the third order of crustal segmentation affected the southern Mount Lofty Ranges during the Early Janjukian Stage (Late Oligocene) and resulted in the establishment of the intramontane Meadows-Myponga and Hindmarsh Tiers Basins (Fig. 5-4). Downward block movements along the Meadows Fault and an unnamed fault along the eastern slope of the Sellicks Hill Range probably formed a graben-like structure within the previously erosional source region (eg. Fig. 5-3C). A large southern part of this structure was flooded by the Late Oligocene marine inundation that occurred despite a significantly lower sea-level (~100 m) than during the preceding stages (Fig. 4-1). The marine invasion occupied not only the Myponga and Hindmarsh Tiers Basin but also left marine and marginal-marine sediments in the Kwitpo area near Meadows (Alley & Lindsay, 1995).

Calculation of the tectonic subsidence in the interior parts of the southern Mount Lofty Ranges such as in the Myponga Basin, demonstrates that relatively rapid subsidence affected this region sometime in the early Late Oligocene. The average rate of subsidence increased rapidly from ~6m/Ma (attributed to the tilting) to ~85m/Ma (attributed to a new pulse of crustal segmentation and subsidence) at about the Early and Late Oligocene boundary (Fig. 4-9). The formation of the intramontane Meadows-Myponga graben is attributed to creation of sedimentary accommodation space for marginal-marine and fluviolacustrine sediments in this area. The general trend of subsidence of the Myponga Basin indicates that, after this short pulse of extension and segmentation, the rate of subsidence was significantly reduced at the end of Oligocene and later (Fig. 4-9). However continuing marine and marginal-marine

sedimentation in this and Hindmarsh Tiers Basins indicates that there was a prolonged period of accommodation space formation (>10Ma). This apparently related to both relatively high sea-level stands and subtle subsidence since the latest Oligocene.

The record of dominantly carbonate and only very minor and fine-grained terrigenous sediments in the flanking and intramontane basins strongly suggest that only subdued drainage systems have produced such sediments (stage of subdued erosion in landscape evolution, Ch. 6). Thus there is no evidence of any uplift of the Mount Lofty Ranges that could be associated with a significant dissection of its landscape. A brief episode of deposition of the Oligocene Compton Conglomerate in the SW part of the Murray Basin (Buccleuch Embayment) resulted from a marine inundation into the deeply weathered and gently undulating landscape of the southern Ranges and Fleurieu Peninsula. Marine erosion accounted for the stripping of a deep regolith and Permian fluvioglacials that formed the Compton Conglomerate. Strong marine flows over the southern part of the Ranges delivered the sediment eastward into the Buccleuch Embayment (Fig. 4-14B). Thus, in contrast to the traditional point of view concerning the uplift of the Mount Lofty Ranges, this thesis demonstrates that the subsidence of flanking and intramontane basins and low-angle regional tilting were the major regional tectonic process affecting the study region during the Mid-Tertiary.

The Early and Middle Miocene were associated with predominantly carbonate sedimentation in shallow marine and marginal-marine environments that recorded continuing basin subsidence in both the St. Vincent and Western Murray Basins, as well as in the intramontane Meadows-Myponga and Hindmarsh Tiers Basins (Ch. 4). However subsidence slowed down to ~4m/Ma in all these basins during this time-interval (Figs 4-2; 4-9). Increased thickness of Miocene sediments toward the major faults such as Willunga, Clarendon, Eden-Burnside and Para indicate that these normal faults remained active, and together with local low-angle tilting of hanging-wall block, controlled the sedimentation. The model of down-to-basin block movements along the active normal faults bounding sedimentary embayments (Fig. 4-6) was consistent throughout the study region during this time interval also.

Gentle subsidence and regional W-SW tilting in combination with relatively high sea-level provided sufficient accommodation space to keep predominantly marine carbonate sedimentation in all these basins, excluding the Barossa Basin where fluviolacustrine

sedimentation continually occurred. This, together with very limited terrigenous supply from the Mount Lofty Ranges indicates that actual uplift of this interbasin region had not yet occurred. Therefore the landscape of the source area continued to be subdued with preservation of some elements of the Palaeoplain such as planation surfaces and deep regolith along the major watershed. Significant parts of the southern Ranges and Fleurieu Peninsula affected by subsidence were probably submerged under marine waters for some time during the high sea-level stands. This would explain a uniform planation surface developed on the Sellicks Hill Range attributed here to marine abrasion (Fig. 4-12). The combined effect of the Late Oligocene-Miocene subsidence and marine erosion is consistent with the post-Late Tertiary regolith age on the summit surface of the Fleurieu Peninsula (Bird & Chivas, 1989).

The total subsidence during the extensional stage is estimated at about 600-700m in the St. Vincent Basin; ~ 400-500m in the Western Murray Basin; and ~300-400m in the intramontane basin areas of the Mount Lofty Ranges. These calculations take into account a combined thickness of Middle Eocene-Middle Miocene sediments and the initial topographic position of the pre-Middle Eocene Palaeoplain (~250-300m above PSL). Widely spaced strain accommodation zones associated with high-angle normal faults indicate that the study region was affected by low to moderate crustal extension during the Middle Eocene to Middle Miocene (by analogy with the Basin and Range province of western North America, eg. Stewart, 1998).

Further reduction in the rate of subsidence associated with decreased crustal extension, in combination with a substantial sea-level fall at the end of the latest Middle Miocene resulted in termination of sedimentation in all basins within the study region. This is attributed here to a change in the tectonic regime from dominantly extensional to transitional.

7.2.2 Neotectonic Stage II: Transitional Regime (~12Ma to ~1Ma)

The Late Miocene geological record is very limited because of the sedimentary interregnum in all the basins of the study area. This sedimentary hiatus is attributed to the combination of substantial reduction of tectonic activity with dramatic sea-level drop. The total sea-level fall between the Middle Miocene climatic optimum (~15Ma) and the lowest sea-level stand is over 200m according to the recalculated eustatic sea-level curve (Fig. 4-1). This inevitably resulted in the termination of main sedimentation in both flanking and also in the intramontane basins, but also probably over a large upper part of the southern Australian

continental shelf. A number of Late Miocene unconformities and hiatuses in the shelf sedimentary succession (Li et al., 2004) are consistent with this dramatic sea-level fall.

Minor 1-5° southward tilting of the Middle Eocene to Middle Miocene sedimentary package is widely recognised beneath the Miocene/Pliocene unconformity in the St. Vincent Basin. Johnson & Baldvin (1996) who studied many examples of shelf developments around the world stated that 1-5° of the continental slope or shelf is sufficient to remove fine-grained sediments by marine bed-load erosion, normally resulting in widespread low-angle unconformities. Following this model and taking into account 1-5° of angular unconformity attributed to the same degree of southern tilting, the basin-wide marine bed-load erosion is proposed in this thesis to explain the erosional part of the Miocene/Pliocene unconformity during the Late Miocene marine retreats (Ch. 4). Thus instead of uplift of the basin sedimentary surface as a cause for the unconformity, the combination of a low-angle southern tilting with sea-level fluctuations provides a delicate control, and a better explanation, for the widespread low-angle Miocene/Pliocene unconformity.

As there is no record of any other deformations in the study region during the Late Miocene and it appears that substantial reduction of the extensional stress release occurred during this time, but no compression had yet occurred. Thus this relatively steady tectonic regime, between the Middle Eocene-Middle Miocene extensional and the Pleistocene compressional regimes, is referred to here as a "transitional tectonic regime". Such a tectonic regime correlated with a sedimentary interregnum strongly suggests that only very minor sediments were supplied which were removed from the basins by marine erosion. This corresponds to a relatively stable but a low-lying and gently undulating landscape of the Mount Lofty Ranges. This type of landscape was attributed to a new phase of peneplanation (Fenner, 1930), while the landscape erosion to the base-level had never occurred. Remnants of palaeodrainage and some elements of the pre-Middle Eocene Palaeoplain, such as a deep regolith on the major watershed are still present in the interior parts of the Ranges. Therefore this thesis (Ch. 6) proposed a geomorphological stage of landscape relaxation that is corresponded with a relatively stable tectonic regime and also with very minor landscape erosion.

The Pliocene marine transgression into the St. Vincent Western Murray Basins flanking the Mount Lofty Ranges is clearly associated with rapid sea-level rise at about 5Ma ago (Cheltenhamian Stage, Ch. 4). While ~100m of sea-level rise (Fig. 4-1) provides a wide

access to these basins, the preservation of marginal-marine deposits in the St. Vincent Basin occurred only in local depocentres such as close to the Para Fault west of Adelaide (Dry Creek Sand). The preservation of generally fine-grained sediments in the flanking basins attributed here to subtle basin subsidence due to a new but minor pulse of crustal extension resulted in the formation of the Pliocene sedimentary accommodation space. The local down-to-basin block movements along normal faults (such as along the Para Fault) probably continually accompanied the general basin subsidence in a similar way to that which occurred during the Mid-Tertiary.

There is no indication of the Mount Lofty Ranges uplift in addition to the possible tectonic rebound of up to ~100m that prevented the Pliocene marine inundation entering the intramontane Myponga and Hindmarsh Tiers Basins. In other words the exposed sedimentary surface of these intramontane basins must have been higher than high stands of the Pliocene sea-level (Fig. 4-9). However, if the scenario of the Late Miocene marine bed-load erosion took place, then the flanking basin sedimentary surface would have been depressed to about PSL during the Late Miocene (Michelian Stage, Ch. 4). This would also be sufficient to protect intramontane basins from the Early Pliocene marine invasion. Thus the extent of possible tectonic rebound of the Ranges would have been even less than 100m during the transitional stage. Meanwhile, the transitional tectonic regime suggests that both extensional and compressional stress releases were possible and thus, in either case, minor up-warping of the southern Mount Lofty Ranges, or subsidence of flanking basin prevented the central part of the Ranges from the new marine inundation.

Surprisingly, the Late Pliocene marine transgression into the St. Vincent Basin (Hallett Cove Sandstone) was more widespread than during the Early Pliocene, while sea-level was lower (Kalimnan Stage, Ch. 4; Fig. 4-1). This may indicate that some new accommodation space in this basin was created by general basin subsidence. A new assumption on the formation of Lake Bungunnia (Ch. 5) also suggests that a possible new pulse of low-magnitude crustal extension resulted in creation of sedimentary accommodation space during the Late Pliocene (Blanchetown Clay) in the Western Murray Basin due to down-to-basin block movements along the Morgan Fault. However the change of the marginal-marine type of sedimentation (Loxton Sand) to predominantly fluvial Parilla Sand in the SW part of this basin (Firman, 1972) indicates that the Western Murray Basin was subsided less and thus was more resilient to crustal extension than the St. Vincent Basin. However there was some notable landscape

modification in the southern Mount Lofty Ranges associated with the Finniss River that cut through the initial major watershed. This resulted in capture of a large area in the intramontane Meadows-Myponga Basin and in relocation of the major watershed from the eastern portion of the Mount Lofty Ranges (Bull Creek Range) to the Sellicks Hill Range on the western side of the Ranges. This landscape modification perhaps started some time earlier but the Finniss River capture most probably occurred in the Late Tertiary after the marine withdraw from the Meadows-Myponga Basin.

The dominant fine-grained lithology of Pliocene units in both basins flanking the Mount Lofty Ranges once again indicates that the gently undulating landscape of this interbasin source region persisted during the Late Tertiary. A large amount of silica and ferruginous material in the Pliocene sedimentary succession of the St. Vincent Basin and on the exposed surfaces of the Western Murray Basin (Karoonda surface) is consistent with deep weathering and thus with a low and gently undulating landscape drained by low competence subdued river systems.

The Early Pleistocene is typically associated with a carbonate type of sedimentation with only a very minor and fine-grained terrigenous supply in both St. Vincent and Western Murray Basins flanking the Mount Lofty Ranges (beginning of the Werrikooian Stage, Ch. 4). The sedimentary environments, lithological characteristics and thickness of the Burnham Limestone and Point Ellen Formation of the St. Vincent Basin and the Coomandook Formation, Blanchetown Clay and Bungunnia Limestone of the Western Murray Basin would only have been correlated with a relatively stable tectonic regime. There is still no evidence of any significant uplift of the Ranges that could affect a low and generally subdued landscape of this source region. Such landscape is probably corresponded with the pre-Pleistocene 'newer or second peneplain" proposed by Fenner (1930). If one takes into account the age of those Early Pleistocene carbonate units (derived much later than Fenner's proposal) than it is most probably that the geomorphological stage of landscape relaxation (Ch. 6) would certainly be extended to the Early Pleistocene. Therefore a relatively stable transitional tectonic regime continued during the Early Pleistocene.

7.2.3 Neotectonic Stage III: Crustal Compression (~1Ma to Present)

The Pleistocene uplift of the Mount Lofty Ranges is the most recognisable event in the geological history of the study region. This event is also known as the 'Kosciusko Uplift' (eg. Fenner, 1927, 1930; Sprigg, 1945). There is a dramatic change of the lithology from dominantly carbonate to predominantly fluvial in the sedimentary succession near the western portion of the Ranges after the accumulation of the Burnham Limestone and its equivalent Point Ellen Formation dated at ~1.2Ma (Belperio, 1995). However in the Western Murray Basin a real lithological change is clearly associated with appearance of the Pooraka Formation (various alluvial deposits including gravel, pebbles and cobbles) immediately after the cessation of Lake Bungunnia dated as ~ 0.6-0.5Ma (Brown & Stephenson, 1991). This indicates that the western portion of the Mount Lofty Ranges was probably uplifted earlier than the eastern side of the Ranges.

The lithology of the Pleistocene Hindmarsh Clay and Pooraka Formation in the St. Vincent Basin, as well as the Pooraka and Coonambidgal Formations in the Western Murray Basin containing cobbles and boulders (Werrikooian Stage, Ch. 4) is clear evidence of the highest stream competence within the Mount Lofty Ranges. The Pleistocene deposition occurred at the highest rate for the whole Cainozoic history. These together with widespread slope debris (almost absent during preceding stages) along the eastern and western edges of the Ranges is clear evidence of the substantial Pleistocene uplift of the Mount lofty ranges, specifically along the active faults forming the prominent fault-scarps.

The uplift immediately resulted in increased stream gradients with subsequent and corresponding sedimentary response. The young and well-dissected landscape, with a number of gorges and waterfalls is prominent on both marginal sides of the Ranges. However the most active erosion occurred in the western portion in association with uplift along the Eden-Burnside Fault that also formed the topographically highest area of Mt. Lofty (724m above PSL).

The western portion of the Ranges was an integral part of the gently undulating slope tilted W-SW during the Tertiary, and persisted up to the earliest Pleistocene with an appropriate subdued drainage development. The major regional watershed was formed on the topographically highest area in the eastern part of the Ranges due to such tilting, and in response to headward stream erosion (Ch. 6). The major watershed still maintains its original

eastern position up to the present, except in the southern part of the Ranges where it migrated westward due to capture by the Finniss River. However at present, the western portion of the Ranges forms topographically the highest area in the study region that is even higher than the major watershed. Such a significant Pleistocene uplift of the western parts of the Ranges is referred to here as an 'uplift front'.

There is evidence of post Mid-Pleistocene reverse fault motions on both sides of the Ranges associated with the Willunga Fault (Sellicks Beach, St. Vincent Basin) and Milendella Fault near Cambrai in the NW Murray Basin (May & Bourman, 1984; Bourman & Lindsay, 1989; Sandiford, 2003). In both locations the old basement rocks are thrust over the Mid-Pleistocene sequence with relatively steep fault planes dipping toward the core of the Mount Lofty Ranges (Ch. 5). Thus Pleistocene compressional stress release along these reverse faults is beyond doubt. In addition, in some areas, such as near Port Adelaide, the originally subsided blocks are dragged up, resulting in the increased thickness of the Late Pleistocene Glanville Formation toward the basin (eg. Belperio & Rice, 1989). Gentle basin-ward tilting of this Formation was also observed within the Normanville Embayment of the St. Vincent Basin (Bourman et al., 1999). Thus basin-ward tilting and increased thickness of late Pleistocene sediments is opposite to that which occurred in the Early and Mid-Tertiary (Fig. 5-14). This, together with clear reverse fault motion along the boundary faults indicates that a compressional regime was dominant during most of the Late Pleistocene.

The most dramatic Pleistocene tectonic and geomorphological development occurred along faults which were active during the Tertiary. However the Tertiary development of these faults was associated with crustal extension and most of them acted as normal faults with down-to-basin block movements and gentle tilting of hanging-wall blocks toward these faults (Fig. 5-14). This indicates that Tertiary active faults served as crustal weakness zones, along which the major uplift of the Mount Lofty Ranges occurred during the Pleistocene compressional tectonic regime. It seems that most of the Tertiary normal faults, specifically those bounding sedimentary embayments, were formed as master faults with a single relatively steep fault plane dipping basin-ward. In contrast, the Pleistocene active faults are often bifurcate and split such as the Eden-Burnside Fault, for example. Thus rather than a master fault, a few or perhaps several sub-parallel fault planes formed active fault zones which were active during the Pleistocene.

7.3 Conclusion

In conclusion it is important to note that the three stage neotectonic model provides an original and unified solution to the nature and evolution of the Mount Lofty Ranges and its flanking and intramontane basins. This model is consistent with all observed facts of the neotectonic setting (Ch. 5), landscape evolution (Ch. 6) and sedimentary patterns and sea-level trends of the flanking St. Vincent and Western Murray Basin (Ch. 4). It presents a new interpretation of the neotectonic structure in the study area and provides a new benchmark for further advances in knowledge based on modern multidisciplinary data.

The following chart summarises correlations of neotectonic, sedimentary and landscape evolution events within the Mount Lofty Ranges, flanking St. Vincent and Western Murray Basins and intramontane Meadows-Myponga, Hindmarsh Tiers and Barossa Basins. These events are plotted against the global eustatic curve used as a valuable reference to the altitude of regional landscape and some characteristics of the sedimentary environments.

Ma	Eustatic curve (100 0(m) -100)	Stages	Tectonics: Events	Sedimentation	Landscape
0–5 Pliocene (Plei: HOL, E, M; Late; Early)		Compressional	Major uplift of the Mount Lofty Ranges. Pleistocene upward block movements along both eastern and western margins of the Ranges resulted in the formation of pronunsed fault-scarp zones. Steep thrusts over Mid-Pleistocene deposits along Willunga Fault dipping eastward and Milindella Fault dipping westward toward the core of the Ranges testify to classical uplift associated with basement compression (see model Fig. 5-14). Late Pleistocene to Holocene basin-ward tlting of hanging-wall blocks recorded by increased thickness of sediments. Western portion of the Ranges identified as a the uplift front with the maximum elevation.	Coarse terrigenous deposition including gravel, pebbles and cobble-size clasts formed widespread fans along both eastern and western edges of the Mount Lofty Ranges. The Middle and Late Pleistocene deposition of the Hindmarsh Clay and Pooraka Formations occurred at the highest rate in compare to the Tertiary and earlier Pleistocene. These deposits often intercalated with slope debris along fault-scarp zone and fluvial sands and swamp clays basinward. Minor marginal-marine sedimentation occurred. Increased thicknesses of both fluvial and marine sediments toward the basin are observed.	Fault-scarps, vigorous slope erosion and deep stream incision with V-shape valleys and a number of waterfalls and gorges formed prominent youthful landscape on the margins of the Mount Lofty Ranges. Mature landscape with wide shallow valleys, well-developed soils and regolith on gentle slopes and summit surfaces is still preserved from headward stream erosion in interior parts of the Ranges. Significant palaeodrainage modification in the Adelaide area and SW Murray Basin associated with Late Pleistocene-Holocene block uplifts along the Para and Bremer Faults.
5–10 Miocene (Late)		Transitional	Tectonic stabilisation resulted in reduction of subsidence in all flanking and intramontane basins. Continuing regional low-angle tilting in the St. Vincent and Western Murray Basins in combination with fluctuating sea-level resulted in the Miocene/Pliocene erosional, stratigraphic and low-angle (1-5°..) unconformity. Possible minor uplift (up to 100m) of the southern Ranges protected intramontane basins from Pliocene marine inundation. A new pulse of extension resulted mainly in a low-magnitude subsidence of flanking basins that accompanied by local down-to-basin block movements along the active faults during the Pliocene-Early Pleistocene.	Mainly a non-deposition/erosional period. Minor fluvial input by sedimentary starved streams from the Mount Lofty Ranges removed from the basins by several marine oscillations. Basin-wide uniform marine bed-load erosion identified as the major cause of prolonged lithostratigraphic hiatus and the Miocene/Pliocene unconformity. Pliocene-Early Pleistocene predominantly shallow-marine sedimentation associated with relatively high sea-levels accompanied by local basin subsidence due to a new pulse of crustal extension.	Topographically low, subdued and gently undulating landscape of the Mount Lofty Ranges inherited from preceding stages. Asymmetric shape of the Ranges drained by incompetent and sedimentary starving streams.
10–15 Miocene (Middle)					
15–20 Miocene (Early)					
20–25 Oligocene (Late)		Extensional	Crustal extension and segmentation resulted in the differential subsidence of the St. Vincent and Western Murray Basins. The Mount Lofty Ranges formed as an interbasin remnant of the pre-Middle Eocene Palaeoplain stood ~250-300m above PSL. Further extension resulted in basin segmentation into embayments and formation of the intramontane Meadows-Myponga and Hindmarsh Tiers Basins and Barossa Basins. Normal faults with down-to-basin kinematics accompanied by a low-angle tilting of hanging-wall blocks resulted in increased thickness of sediments toward the active boundary faults without fold deformation of soft Tertiary sediments. Fundamental attributes of the extensional tectonic setting including Tertiary Transfer Zone (TTZ), a number of strain accommodation zones associated with non-aligned system of normal faults, transfer zone fault terminations, regional low-angle S-SW tilting, down-to-basin block movement with some rotation of hanging-wall blocks toward the fault planes are all recognised within the study region. An assimetric block-structure of the Ranges alongated in the SSW to NNE direction with a low western side and higher eastern and generally plunging southward developed as a result of the extensional stress release.	Early fluvial discharge followed by shallow marginal-marine sedimentation occurred in the flanking St. Vincent and Western Murray Basins and later in intramontane Meadows-Myponga and Hindmarsh Tiers Basins despite the general downward trend of sea-levels. Increased thickness of sediments toward the normal faults bounding embayments. Continuing increase of carbonate marine sedimentation in flanking basins from Middle Eocene to Middle Miocene with only minor terrigenous input from the Mount Lofty Ranges. Carbonate sedimentation also prevailed in these intramontane basins for more than 10Ma while a fluviolacustrine sedimentation was sustained in the intramontane Barossa Basin.	Development of subdued river systems due to flanking basin subsidence and S-SW tilting of the interbasin region of the proto-Mount Lofty Ranges. Major watershed formed along the highest eastern edge of the Palaeoplain remnant. Wide and gentle western slope resulted from low-angle tilting, while narrow and relatively steep eastern slope formed mainly due to differential subsidence of the Western Murray Basin along active boundary faults. Low-relief fault-scarps developed along the sinsedimentary normal faults bounding St. Vincent Basin embayments. Gently undulating landscape with deep regolith cover inherited from the pre-Middle Eocene Palaeoplain generally preserved in the interior parts of the Ranges, except in the south where landscape temporarily submerged under the high sea-level. River captures developed on both eastern and western sides of the Ranges.
25–30 Oligocene (Early)					
30–35 Eocene (Late)					
35–40 Eocene (Middle)		Quasi-equilibrium	Tectonic quiescence	Non-deposition, deep weathering and denudation. Deep chemical weathering up to kaolinitic stage. Tens of metres of weathering profile were formed on the pre-Tertiary basement with minimum regolith redistribution on the pre-Middle Eocene Palaeoplain.	Gently undulating and deeply weathered Palaeoplain landscape standing ~250-300m above the present sea-level formed as a result of long-term (>200Ma) of erosion and denudation before the Middle Eocene neotectonic movements affected this region.
40–45					
	200 100 0 (m)				

SUMMARY CHART: Correlation of neotectonic events with sedimentation and landscape evolution in the study region of the Mount Lofty Ranges and flanking St. Vincent and Murray Basins. Global Eustatic Curve (after Haq et al., 1987 recalculated by Li et al., 2004). Colour is associated with neotectonic regime: brown - Quasi-equilibrium; green - Extensional; yellow - Transitional and orange - Compressional.

Ma	Eustatic curve (100 0(m) -100)	Stages	Tectonics: Events	Sedimentation	Landscape
0 – 5		Compressional	Major uplift of the Mount Lofty Ranges. Pleistocene upward block movements along both eastern and western margins of the Ranges resulted in the formation of pronunsed fault-scarp zones. Steep thrusts over Mid-Pleistocene deposits along Willunga Fault dipping eastward and Milindella Fault dipping westward toward the core of the Ranges testify to classical uplift associated with basement compression (see model Fig. 5-14). Late Pleistocene to Holocene basin-ward tlting of hanging-wall blocks recorded by increased thickness of sediments. Western portion of the Ranges identified as a the uplift front with the maximum elevation.	Coarse terrigenous deposition including gravel, pebbles and cobble-size clasts formed widespread fans along both eastern and western edges of the Mount Lofty Ranges. The Middle and Late Pleistocene deposition of the Hindmarsh Clay and Pooraka Formations occurred at the highest rate in compare to the Tertiary and earlier Pleistocene. These deposits often intercalated with slope debris along fault-scarp zone and fluvial sands and swamp clays basinward. Minor marginal-marine sedimentation occurred. Increased thicknesses of both fluvial and marine sediments toward the basin are observed.	Fault-scarps, vigorous slope erosion and deep stream incision with V-shape valleys and a number of waterfalls and gorges formed prominent youthful landscape on the margins of the Mount Lofty Ranges. Mature landscape with wide shallow valleys, well-developed soils and regolith on gentle slopes and summit surfaces is still preserved from headward stream erosion in interior parts of the Ranges. Significant palaeodrainage modification in the Adelaide area and SW Murray Basin associated with Late Pleistocene-Holocene block uplifts along the Para and Bremer Faults.
5 – 15		Transitional	Tectonic stabilisation resulted in reduction of subsidence in all flanking and intramontane basins. Continuing regional low-angle tilting in the St. Vincent and Western Murray Basins in combination with fluctuating sea-level resulted in the Miocene/Pliocene erosional, stratigraphic and low-angle (1-5°..) unconformity. Possible minor uplift (up to 100m) of the southern Ranges protected intramontane basins from Pliocene marine inundation. A new pulse of extension resulted mainly in a low-magnitude subsidence of flanking basins that accompanied by local down-to-basin block movements along the active faults during the Pliocene-Early Pleistocene.	Mainly a non-deposition/erosional period. Minor fluvial input by sedimentary starved streams from the Mount Lofty Ranges removed from the basins by several marine oscillations. Basin-wide uniform marine bed-load erosion identified as the major cause of prolonged lithostratigraphic hiatus and the Miocene/Pliocene unconformity. Pliocene-Early Pleistocene predominantly shallow-marine sedimentation associated with relatively high sea-levels accompanied by local basin subsidence due to a new pulse of crustal extension.	Topographically low, subdued and gently undulating landscape of the Mount Lofty Ranges inherited from preceding stages. Asymmetric shape of the Ranges drained by incompetent and sedimentary starving streams.
15 – 40		Extensional	Crustal extension and segmentation resulted in the differential subsidence of the St. Vincent and Western Murray Basins. The Mount Lofty Ranges formed as an interbasin remnant of the pre-Middle Eocene Palaeoplain stood ~250-300m above PSL. Further extension resulted in basin segmentation into embayments and formation of the intramontane Meadows-Myponga and Hindmarsh Tiers Basins and Barossa Basins. Normal faults with down-to-basin kinematics accompanied by a low-angle tilting of hanging-wall blocks resulted in increased thickness of sediments toward the active boundary faults without fold deformation of soft Tertiary sediments. Fundamental attributes of the extensional tectonic setting including Tertiary Transfer Zone (TTZ), a number of strain accommodation zones associated with non-aligned system of normal faults, transfer zone fault terminations, regional low-angle S-SW tilting, down-to-basin block movement with some rotation of hanging-wall blocks toward the fault planes are all recognised within the study region. An assimetric block-structure of the Ranges alongated in the SSW to NNE direction with a low western side and higher eastern and generally plunging southward developed as a result of the extensional stress release.	Early fluvial discharge followed by shallow marginal-marine sedimentation occurred in the flanking St. Vincent and Western Murray Basins and later in intramontane Meadows-Myponga and Hindmarsh Tiers Basins despite the general downward trend of sea-levels. Increased thickness of sediments toward the normal faults bounding embayments. Continuing increase of carbonate marine sedimentation in flanking basins from Middle Eocene to Middle Miocene with only minor terrigenous input from the Mount Lofty Ranges. Carbonate sedimentation also prevailed in these intramontane basins for more than 10Ma while a fluviolacustrine sedimentation was sustained in the intramontane Barossa Basin.	Development of subdued river systems due to flanking basin subsidence and S-SW tilting of the interbasin region of the proto-Mount Lofty Ranges. Major watershed formed along the highest eastern edge of the Palaeoplain remnant. Wide and gentle western slope resulted from low-angle tilting, while narrow and relatively steep eastern slope formed mainly due to differential subsidence of the Western Murray Basin along active boundary faults. Low-relief fault-scarps developed along the sinsedimentary normal faults bounding St. Vincent Basin embayments. Gently undulating landscape with deep regolith cover inherited from the pre-Middle Eocene Palaeoplain generally preserved in the interior parts of the Ranges, except in the south where landscape temporarily submerged under the high sea-level. River captures developed on both eastern and western sides of the Ranges.
40 – 45		Quasi-equilibrium	Tectonic quiescence	Non-deposition, deep weathering and denudation. Deep chemical weathering up to kaolinitic stage. Tens of metres of weathering profile were formed on the pre-Tertiary basement with minimum regolith redistribution on the pre-Middle Eocene Palaeoplain.	Gently undulating and deeply weathered Palaeoplain landscape standing ~250-300m above the present sea-level formed as a result of long-term (>200Ma) of erosion and denudation before the Middle Eocene neotectonic movements affected this region.

Ma: 0, 5, 10, 15, 20, 25, 30, 35, 40, 45

Pleistocene: HOL, Plei; Pliocene: M, E, Late, Early; Miocene: Late, Middle, Early; Oligocene: Late, Early; Eocene: Late, Middle

Eustatic curve: 100 0(m) -100; 200 100 0 (m)

SUMMARY CHART: Correlation of neotectonic events with sedimentation and landscape evolution in the study region of the Mount Lofty Ranges and flanking St. Vincent and Murray Basins. Global Eustatic Curve (after Haq et al., 1987 recalculated by Li et al., 2004). Colour is associated with neotectonic regime: brown - Quasi-equilibrium; green - Extensional; yellow - Transitional and orange - Compressional.

References

REFERENCES

Abele, C., Kenley, P.R., Holdgate, G. & Ripper, D., 1976, Tertiary of the Otway Basin. *In:* Douglas, J.G. & Ferguson, J.A (eds), Geology of Victoria, *Geological Society of Australia, Special Publication,* 5:198-229.

Abele, C., Kenley, P.R., Holdgate, G. & Ripper, D., 1988, Tertiary, Otway Basin. *In:* Douglas, J.G. & Ferguson, J.A. (eds), Geology of Victoria. *Victorian Division of the Geological Society of Australia, Special Publication,* 272-303.

Alley, N.F., 1973, Landsurface development in the Mid North of South Australia. *Royal Society of South Australia. Transactions,* 97:1-17.

Alley, N.F., 1977, Age and origin of laterite and silcrete duricrusts and their relationship to episodic tectonism in the Mid North of South Australia. *Geological Society of Australia, Journal,* 24:107-116.

Alley, N.F., 1995, Late Palaeozoic. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:63-65.

Alley, N.F., 1995a, Barossa Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:173-175.

Alley, N.F. & Bourman, R.P., 1995, Troubridge Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:65-70.

Alley, N.F. & Bourman, R.P., 1984, Sedimentology and origin of late Palaeozoic glacigene deposits at Cape Jervis, South Australia. *Royal Society of South Australia, Transactions,* 108:63-75.

Alley, N.F. & Lindsay, J.M., 1995, Meadows Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:199.

Alley, N.F. & Lindsay, J.M., 1995a, Pirie Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:176-178.

Aitchison, G.D., Sprigg, R.C. & Cochrane, G.W., 1954, The soils and geology of Adelaide and suburbs. *South Australia, Geological Survey, Bulletin,* 32:89p.

Archer, M., Hand, S.J. & Godthelp, H., 1994, Patterns in the history Australia's marsupials and inferences about habitats. *In:* Hill, R.S. (ed), *History of the Australian Vegetation: Cretaceous to Recent.* Cambridge University Press, Cambridge, 80-103.

Archer, M., Hand, S.J. & Godthelp, H., 1996, Tertiary environmental and biotic change in Australia. *In:* Vrba, E (ed), Environmental Change and Evolution. New Haven, Yale University Press, 77-90.

Axen, G.J., 1998, The Caliente-Enterprise zone, southeastern Nevada and southwestern Utah. *In:* Faulds, J.E. & Stewart, J.H. (eds), Accommodation Zones and transfer Zones: The Regional Segmentation of the Basin and Range Province. *Geological Society of America, Special Paper,* 323:181-194.

Barnard, P.D.W., 1973, Mesozoic floras. *Special Papers in Palaeontology,* 12:175-188.

Barron, E.J., 1983, A warm equable Cretaceous: the nature of problem. *Earth Science Review,* 19:305-338.

Belperio, A.P., 1985a, Quaternary geology of the Sandy Point and Outer Harbor-St Kilda areas, Gulf St. Vincent. *South Australia, Geological Survey. Quarterly Geological Notes,* 96:2-6.

Belperio, A.P., 1985b, The Quaternary stratigraphy between St Kilda and Outer Harbor with special reference to excavation conditions in Barker Inlet. *South Australia. Department of Mines and Energy. Report Book,* 85/2 (unpublished)

Belperio, A.P., 1988a, Gawler map sheet. *South Australia, Geological Survey. Geological Atlas 1:50 000 Series, sheet* 6628-IV

Belperio, A.P., 1988b, Vincent map sheet. *South Australia, Geological Survey. Geological Atlas 1:50 000 Series, sheet* 6528-I

Belperio, A.P., 1995, Quaternary. *In:* Drexel, J. F. & Preiss, W.V. (eds) The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:219-241.

Belperio, A.P. & Bateman, J., 1986, Cainozoic stratigraphy and structure of the Gawler and Vincent 1:50000 map sheet areas. *South Australia, Department of Mines and Energy. Report Book,* 86/49 (unpublished).

Belperio, A.P. & Bluck, R.G., 1990, Coastal palaeogeography and heavy mineral sand exploration targets in the western Murray Basin, South Australia. *Australian Institute of Mining and Metallurgy, Proceedings,* 295:5-10.

Belperio, A.P. & Murray-Wallace, C.V., 1984 Comment – Wardang Island: A refuge for Marginopora vertebralis? *Royal Society of South Australia, Transactions,* 108:227-228.

Belperio, A. P. & Rice, R.L., 1989 Stratigraphic investigation of the Gillman development Site, Port Adelaide Estuary. *South Australia, Department of Mines and Energy. Report Book,* 89/462 (unpublished).

Belperio, A.P., Hails, J.R. & Gostin, V.A., 1983, A review of Holocene sea-levels in South Australia. *In:* Hopley, D. (ed), Australian sea-levels in the last 15,000 years: a review. *James Cook University of North Queensland, Department of Geography. Monograph Series,* 3:37-47.

Belperio, A.P., Hails, J.R., Gostin, V.A. & Polach, H.A., 1984, Stratigraphy of carbonate banks and Holocene sea-level of northern Spencer Gulf. *Marine Geology,* 61:297-313.

Benbow, M.C., Alley, N.F., Callen, R.A. & Greenwood, D.R., 1995, Geological History and Palaeoclimate. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin*, 54:208-217.

Benson, W.N., 1911, Note descriptive of a stereogram of the Mt Lofty Ranges, South Australia. *Royal Society of South Australia, Transactions,* 35:108-111.

Berger, W. H., 1982, Deep-sea stratigraphy: Cenozoic climate steps and the search for chemo-climatic feedback. *In:* Einsele, G. & Seilacher, A. (eds), *Cyclic and Events Stratification.* Berlin, Springer-Verlag, 121-157.

Berger, W.H., Vincent, E. & Thierstein, H.R., 1981, The deep-sea record: major steps in Cenozoic ocean evolution. *In*: Warme, J.E., Douglas, R.G. & Winterer, E.L. (eds), The Deep Sea Drilling Project: a decade of progress. *SEPM, Tulsa, Special Publication,* 32:489-504.

Berggren, W.A., Kent, D.V. & Couvering, J.A., 1985, The Neogene: Part 2. Neogene geochronology and chronostratigraphy. *In:* Snelling, N.K. (ed), The chronology of the geological record. *Geological Society of London, Memoir,* 10:211-260.

Bird, M.I. & Chivas, A.R., 1989, Stable isotope geochronology of the Australian regolith. *Geochimica et Cosmochimica Acta,* 53:3239-32-56.

Black, L.P., Ferguson, J. & Gray, P.T., 1993, A Jurassic U-Pb zircon age for a South Australian kimberlitic rock. *South Australia, Geological Survey. Quaterly Geological Notes,* 125:2-5.

Blackburn, G., Bond, R.D. & Clark, A.R.P., 1965, Soil development associated with stranded beach ridges in southeast South Australia. *CSIRO, Australia, Soil publications,* 22.

Blackburn, G., Bond, R.D. & Clark, A.R.P., 1965, Soil development in relation to stranded beach ridges of County Lowan, Victoria. *CSIRO, Australia, Soil publications*, 24.

Boeuf, M.G. & Doust, H., 1975, Structure and development of the southern margin of Australia. *APEA Journal*, 15:33-43.

Bosworth, W., 1985, Geometry of propagating continental rifts. *Nature*, 316:625-627.

Bourman, R.P., 1973, Geomorphic evolution of southeastern Fleurieu Peninsula. *The University of Adelaide, M.A. thesis* (unpublished).

Bourman, R.P., 1989, Investigation of ferricretes and weathered zones in parts of the southern and southeastern Australia: A reassessment of the laterite concept. *The University of Adelaide, Ph.D thesis* (unpublished).

Bourman, R.P., 1987, A review of controversial issues related to the Late Palaeozoic glaciation of southern South Australia. *In:* Gardiner, V. (ed), International geomorphology 1986; *Proceedings of the First International Conference on Geomorphology; Part II.* John Willey and Sons Ltd., 725-742

Bourman, R.P., 1993a, Perennial problems in the study of laterite: a review. *Australian Journal of Earth Sciences,* 40:345-358.

Bourman, R.P., 1993b, Models of ferricrete genesis: evidence south-eastern Australia. *Zeitschrift fur Geomorphologie,* 37:77-101.

Bourman, R.P. & Lindsay, J.M., 1973, Implications of Fossiliferous Eocene Marine Sediments Underlying Part of the Waitpinga Drainage Basin, Fleurieu Peninsula, South Australia. *Search,* 4:77.

Bourman, R.P. & Lindsay, J.M., 1989, Timing, extent and character of late Cainozoic faulting on the eastern margin of the Mt Lofty Ranges, South Australia. *Royal Society of South Australia, Transactions,* 113:63-67.

Bourman, R.P., Belperio, A.P., Murray-Wallace, C.V. & Cann, J.H., 1999, A last interglacial embayment fill at Normanville, South Australia, and its neotectonic implications. *Royal Society of South Australia, Transactions,* 123:1-15.

Bowen, R.L., 1969, Late Palaeozoic glaciation, eastern Australia. *In*: Amos, A.J. (ed). *Gondwana Stratigraphy*. IUGS Symposium, Buenos Aires, 1967. UNESCO Publication, pp.601-611.

Bowler, J.M., 1980, Quaternary chronology and palaeohydrology in the evolution of mallee landscape. *In:* Storrier, R.R. & Stannard, M..E. (eds), *Aeolian landscape in the semi-arid zone of southeastern Australia.* Australian Soil Science Society, Riverina Branch, Wagga Wagga, pp.17-36.

Bowler, J.M., 1982, Aridity in the late Tertiary and Quaternary of Australia. *In:* Barker, W.R. & Greenslade, P.J.M. (eds.), *Evolution of the flora and fauna of arid Australia.* Peacock Publications, Adelaide, pp.35-45.

Brock, E.J., 1964, The denudation chronology of the Fleurieu Peninsula. *The University of Adelaide MA thesis* (unpublished).

Brown, C.M., 1983, Discussion: a Cainozoic history of Australia's Southeast Highlands. *Geological Society of Australia, Journal,* 30:483-486.

Brown, C.M., 1985, Murray Basin, southeastern Australia: stratigraphy and resource potential – a synopsis. *Bureau of Mineral Resources, Australia, Report* 264, 24p.

Brown, C.M., 1989, Structural and stratigraphic framework of groundwater occurrence and surface discharge in the Murray Basin, southeastern Australia. *BMR Journal of Australian Geology and Geophysics,* 11:127-146.

Brown, C.M. & Stephenson, A.E., 1991, Geology of the Murray Basin, Southeastern Australia. *BMR Bulletin,* 235:430p.

Callen, R.A., Sheard, M. J., Benbow, M.C & Belperio, A.P., 1995, Alluvial Fans and Piedmont Slope Deposits. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:241-243.

Campana, B., 1955 The geology of the Gawler Military Sheet. *South Australia, Geological Survey. Report of Investigation,* 4.

Campana, B. & Wilson, R.B., 1954, The geology of the Jervis and Yankalilla Military Sheets. *South Australia, Geological Survey, Report of Investigation,* 3.

Cann, J.H. & Gostin, V.A., 1985, Coastal sedimentary facies and foraminiferal biofacies of the St. Kilda Formation at Port Gawler, South Australia. *Royal Society of South Australia, Transactions,* 109:121-142.

Cann, J.H., Belperio, A.P., Gostin, V.A. & Murray-Wallace, C.V., 1988, Sea-level history, 30000 to 45000yr B.P., inferred from benthic foraminifera, Gulf St Vincent, South Australia. *Quaternary Research,* 29:153-175.

Carter, R.M., Abbott, S.T. & Naish, T.R., 1999, Plio-Pleistocene cyclothems from Wanganui Basin, New Zealand; type locality for an astrochronologic time-scale, or template for recognizing ancient glacio-eustasy? *In:* Shackleton, N.J., McCave, I.N. & Weedon, G.P. (eds), Astronomical (Milankovitch) calibration of the geological time-scale. *Royal Society of London, Philosophical Transactions,* 357:1861-1872.

Chaproniere, G.C.H., 1975, Palaeoecology of Oligo-Miocene larger Foraminiferida, Australia. *Alcheringa,* 1:37-58.

Christophel, C.D., 1994, The Early Tertiary macrofloras of continental Australia. *In:* Hill, R.S. (ed.), *History of the Australian Vegetation: Cretaceous to Recent.* Cambridge University Press, Cambridge.

Clarke, G.L., 1987, Basement control of cover folding in the Adelaide Geosyncline, South Australia. *Geological Society of Australia, Abstracts,* 19:125.

Clarke, G.L. & Powell, R., 1989 Basement-cover interaction in the Adelaide Fold Belt, South Australia: the development of an arcuate fold belt. *Tectonophysics,* 158:209-226.

Clarke, J.D.A., 1994, Evolution of the Lefroy and Cowan palaeodrainage channels, Western Australia. *Australian Journal of Earth Sciences,* 41:55-68.

Coaldrake, J.E., 1951, The climate, soils and plant ecology of portion of County Buckingham (ninety-mile Plain), *South Australia. CSIRO Australia, Bulletin,* 266.

Cobb, M.A., 1986, Groundwater Resources of the Barossa Valley. *South Australia, Geological Survey, Report of Investigation,* 55.

Coblentz, D.D., Sandiford, M., Richardson, R.M., Zhou, S. & Hillis, R., 1995, The origins of the intraplate stress field in continental Australia. *Earth and Planetary Science Letters,* 133:299-309.

Colletta, B., Le Quellec, P., Letouzey, J. & Moretti, I., 1988, Longitudinal evolution of the Suez rift structure (Egypt). *In:* Le Pichon, X. & Cochran, J.R. (eds), The Gulf of Suez and Red sea rifting. *Tectonophysics,* 153:221-233.

Cook, P.J., Colwell, J.B., Firman, J.B., Lindsay, J.M., Schwebel, D.A. & von der Borch, C.C., 1977, The late Cainozoic sequence of southeast South Australia and Pleistocene sea-level changes. *BMR Journal of Australian Geology and Geophysics,* 2:81-88.

Cooper, B.J., 1979, Eocene to Miocene stratigraphy of the Willunga Embayment. *South Australia, Geological Survey, Report of Investigation,* 50.

Cooper, B.J., 1985, The Cainozoic St Vincent Basin – tectonics, structure, stratigraphy. *In:* Lindsay, J.M. (ed), Stratigraphy, Palaeontology, Malacology: papers in honour of Dr Nell Ludbrook. *South Australia, Department Mines and Energy, Special Publication,* 5:35-49.

Cooper, J.A., Jenkins R.J.F., Compston, W. & Williams, I.S., 1992, Ion-probe zircon dating of mid-Early Cambrian tuff in South Australia. *Geological Society of London, Journal,* 149:185-192.

Cooper, G.T. and Hill, K.C., 1997. Cross-section balancing and thermochronological analysis of the Mesozoic development of the eastern Otway Basin. *APEA Journal,* 37:390-414.

Crespin, I., 1943, The stratigraphy of the Tertiary marine rocks in Gippsland, Victoria. *BMR Australia, Geology & Geophysics Bulletin,* 9:4.

Crespin, I., 1964, Catalogue of fossil type and figured specimens in Tasmania. *BMR Australia, Geology & Geophysics Report,* 69.

Crittenden, M.D., Coney, P.J. & Davis, G.H. (eds), 1980, Cordilleran metamorphic core complexes. *Geological Society of America, Memoir,* 153:490p.

Crocker, R.L., 1946, Post-Miocene climatic and geologic history and its significance in relation to the

References

genesis of major soil types of South Australia. *Council for Scientific and Industrial Research, Australia. Bulletin,* 193.

Crocker, R.L., 1952, Soil genesis and the pedogenic factors. *Quarterly Review of Biology,* 27:139-168.

Daily, B. & Milnes, A.R., 1973, Stratigraphy, structure and metamorphism of the Kanmantoo Group (Cambrian) in its type section east of Tunkalilla Beach, South Australia. *Royal Society of South Australia, Transactions,* 97:213-242.

Daily, B., Twidale, C.R. & Milnes, A.R., 1974, The age of the lateritized summit surface on Kangaroo Island and adjacent regions of South Australia. *Geological society of Australia, Journal,* 21:387-392.

Daily, B., Firman, J.B., Forbes, B.J. & Lindsay, J.M., 1976, Geology. *In:* Twidale, C.R., Tyler, M.J. & Webb, B.P. (eds), Natural History of the Adelaide Region. *Royal Society of South Australia, Occasional Publications*, 1:5-42.

Dalrymple, G.B & Clague, D.A., 1976, Age of the Hawaiian-Emperor bend. *Earth and Planetary Sciences Letters,* 31:313-329.

Dalziel, I.W.D., 1991, Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. *Geology,* 19:598-601.

Davis, G.A. & Burchfiel, B.C., 1973, Garlock fault: An intra-continental transform structure, southern California. *Geological Society of America, Bulletin,* 84:1407-1422.

Deighton, I., Falvey, D.A. & Taylor, D.J., 1976, Depositional environments and geotectonic framework: southern Australian continental margin. *APEA Journal,* 16:25-36.

Dickinson, S.B., 1944, The Leigh Creek Coalfield. *Mining Review, Adelaide,* 80:23-86.

Dickinson, W.R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona. *Geological Society of America, Special Paper,* 264, 106p.

Dickinson, J.A., Wallace, M.W., Holdgate, G.R., Daniels, J., Gallagher, S.J. & Thomas, L., 2001, Neogene tectonics in SE Australia; implications for petroleum systems. *APPEA Journal*, 41:37-52

Dickinson, J.A., Wallace, M.W., Holdgate, G.R., Gallagher, S.J. & Thomas, L., 2002, Origin and timing of the Miocene-Pliocene unconformity in southeast Australia. *Journal of Sedimentary Research,* 72:317-332.

Diessel, C.F.K., 1980, Newcastle and Tomago Coal Measures. *In:* Herbert, C. & Helby, R. (eds.), A guide to the Sydney Basin. *New South Wales, Geological Survey, Bulletin,* 26:101-114.

Drexel J.F. & Preiss W.V. (eds), 1995, *The geology of South Australia.* Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54, 347p.

Dyson, I.A., 1998, Estuarine facies of the North Maslin Sand and South Maslin Sand, Maslin Beach. *MESA Journal,* 11:42-46.

Eberhard, B.A., 1980, Hazelwood Park recreation Reserve, Hydrogeological Investigation: bore completion report. *South Australia, Geological Survey, Report,* 80/136 (unpublished).

Etheridge, M.A., Branson, J.C. & Stuart-Smith, P.G., 1985, Extensional basin-forming structures in Bass Strait and their importance for hydrocarbon exploration. *APEA Journal,* 25:344-361.

Etheridge, M.A., Branson, J.C. & Stuart-Smith, P.G., 1987, The Bass, Gippsland and Otway Basins, southeast Australia: A branched rift system formed by continental extension. *In:* Beaumont, C. & Tankard, A. (eds), Sedimentary basins and basin-forming mechanisms. *Atlantic Geoscience Society, Special Publication*, 5:147-162.

Etheridge, M.A., Symonds, P.A. & Powell, T.G., 1988, Application of the detachment model for continental extension to hydrocarbon exploration in extensional basins. *APEA Journal,* 28:167-187.

Etheridge, M.A., McQueen, H & Lambeck, K., 1991, The role of intraplate stress in the Tertiary and Mesozoic deformation of the Australian continent and its margins: a key factor in petroleum trap formation. *Exploration Geophysics*, 22:123-128.

Fairburn, W. A., 1998, The Willunga Embayment – a stratigraphic revision. *MESA Journal,* 11:35-41.

Fairburn, W. A., 2000, Cainozoic stratigraphy of the Noarlunga Embayment. *MESA Journal,* 18:42-47.

Farrand, M.G., 1995, Mesozoic Igneous Rocks. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin*, 54:148-149.

Falvey, D.A., 1974, The development of continental margins in plate tectonic theory: *APEA Journal,* 14:95-106.

Falvey, D.A. & Mutter, J.C., 1981, Regional plate tectonics and the evolution of Australia's passive continental margins. *BMR Journal of Australian Geology and Geophysics*, 6:1-29.

Faulds, J.E. & Stewart, J.H. (eds), 1998, Accommodation Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province. *Geological Society of America, Special Paper,* 323, 257p.

Faulds, J.E. & Varga, R.J., 1998, The role of accommodation zones and transfer zones ion the regional segmentation of extended terranes. *In:* Faulds, J.E. & Stewart, J.H. (eds), Accommodation

References

Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province. *Geological Society of America, Special Paper,* 323:1-45.

Faulds, J.E., Geissman, J.W. & Mawer, C.K., 1990, Structural development of a major extensional accommodation zone in the Basin and Range Province, northwestern Arizona and southern Nevada: implication for kinematic models of continental extension. *In:* Wernicke, B.P. (ed), Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada. *Geological Society of America, Memoir,* 176:37-76.

Fenner, C., 1927, Adelaide, South Australia: a study in human geography. *Royal Society of South Australia, Transactions,* 51:193-256.

Fenner, C., 1930, The major structural and physiographic features of South Australia. *Royal Society of South Australia, Transactions,* 54:1-36.

Fenner, C., 1931. South Australia-A Geographical Study. Whitcombe and Tombs, Melbourne, 352p/

Ferguson, J., Arculus, R.J. & Joyce, J., 1979, Kimberlite and kimberlitic intrusives of southeastern Australia: a review. *BMR Journal of Australian Geology and Geophysics*, 4:227-241.

Firman, J.B., 1963, Quaternary geological events near Port Adelaide. *South Australia, Geological Survey. Quarterly Geological Notes*, 7.

Firman, J.B., 1965, Late Cainozoic lacustrine in the Murray Basin, South Australia. *South Australia, Geological Survey. Quarterly Geological Notes*, 16:1-2.

Firman, J.B., 1966a, Stratigraphic units of Late Cainozoic age in the St Vincent Basin, South Australia. *South Australia, Geological Survey, Quarterly Geological Notes,* 17:6-9.

Firman, J.B., 1966b, Stratigraphy of the Chowilla area in the Murray Basin. *South Australia, Geological Survey, Quarterly Geological Notes,* 20:3-7.

Firman, J.B., 1967, Stratigraphy of late Cainozoic deposits in South Australia. *Royal Society of South Australia, Transactions,* 91:165-177.

Firman, J.B., 1969, Stratigraphy and landscape relations of soil materials near Adelaide, South Australia. *Royal Society of South Australia, Transactions,* 93:39-54.

Firman, J.B., 1972, Renmark, South Australia – 1:250 000 Geological series. *South Australia, Geological Survey, Explanatory Notes,* SI/54-10.

Firman, J.B., 1973, Regional stratigraphy of surficial deposits in the Murray Basin and Gambier Embayment. *South Australia, Geological Survey, Report of Investigations*, 39.

Firman, J.B., 1976, Limestone at the base of the Pleistocene sequence in South Australia. *South Australia, Geological Survey, Quarterly Geological Notes,* 58:2-5.

Flinders Diamonds Ltd, Prospectus, ASX, 2001, 108p

Flottmann, T. & Cockshell, C.D., 1996, Palaeozoic basins of southern South Australia; new insights into their structural history from regional seismic data. *Australian Journal of Earth Sciences,* 43:45-55.

Flottmann, T., James, P., Rogers, J. & Jonson, T., 1994, Early Palaeozoic foreland thrusting and basin reactivation at the southeastern paleo-Pacific margin of the Australian Precambrian Craton: a reappraisal of the structural evolution of the Southern Adelaide Fold-Thrust Belt. *Tectonophysics,* 234:95-116.

Flottmann, T. & James, P., 1997, Influence of basin architecture on the style of inversion and fold thrust belt tectonics of the southern Adelaide Fold-Thrust Belt, South Australia. *Journal of Structural Geology,* 19:1093-1110.

Frakes, L. & Rich, P.V., 1982, Paleoclimatic setting and paleogeographic links of Australia in the Phanerozoic. *In:* Rich, P.V. & Thompson, E. M. (eds), *The fossil vertebrate record of Australasia.* Monash University Offset Printing Unit. Clayton, Victoria, Australia, 28-52.

Frakes, L.A., Burger, D., Apthorpe, M., Wiseman, J., Dettmann, M.E., Alley, N.F., Flint, R.B., Gravestock, D.I., Ludbrook, N.H., Backhouse, J., Skwarko, S., Scheibnerova, V., Mc Minn, A., Moore, P.S., Bolton, R.B., Douglas, J.G., Christ, R., Wade, M., Molnar, R.E., McGowran, B., Balme, B.E. & Day, R.A., 1987, Australian Cretaceous shorelines, stage by stage. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 59:31-48.

Frakes, L.A., Francis, J.E. & Syktus, J.I., 1992, *Climate Modes of the Phanerozoic: the history of the Earth's climate over the past 600 million years.* Cambridge, Cambridge University Press, 274p.

Frost, E.G & Martin, D.L. (eds.), 1982, *Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada.* San Diego, California, Cordilleran Publishers, 608p.

Fullerton, L.G., Sager, W. W. & Handschumacher, D.W., 1989, Late Jurassic-Early Cretaceous evolution of the eastern Indian Ocean adjacent to Northwest Australia. *Journal of Geophysical Research,* 94:2937-2953.

Furlong, K.P., Sheaffer, S.D. & Malservisi, R., 2001, Thermal-rheological controls on deformation within oceanic transforms. *In:* Holdsworth, R.E., Strachan, R.A., Magloughlin, J.F. & Knipe, R.J. (eds), The nature and tectonic significance of fault zone weakening. *Geological Society of London, Special Publications*, 186:65-83.

Furness, L.J., 1975, The hydrogeology of the Hindmarsh Tiers Basin. *Flinders University (South Australia). B.Sc. (Hons) thesis* (unpublished).

Furness, L.J., Waterhouse, J.D. & Edwards, D.R., 1981, The hydrogeology of the of the Hindmarsh Tiers and Myponga Basins. *South Australia, Geological Survey, Report of Investigations, 53.*

Gaina, C., Muller,,R.D., Royer, J.- Y., Stock, J., Hardebeck, J. & Symonds, P., 1998, The tectonic history of the Tasman Sea: A puzzle with thirteen pieces. *Journal of Geophysical Research,* 103:12413-12433.

Gaina, C., Muller, R.D., Royer, J.- Y., Stock, J. & Symonds, P., 1999, The evolution of the Louisiade triple junction. *Journal of Geophysical Research,* 104:12927-12939.

Gallagher, S.J., Greenwood, D.R., Taylor, D.J., Smith, A.J., Wallace, M.W. & Holdgate, G.R., 2003, The Pliocene climatic and environmental evolution of southeastern Australia: evidence from the marine and terrestrial realm. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 193:349-382.

Gans, P.B., Mahood, G.A. & Schermer, E., 1989, Synextensional magmatism in the Basin and Range province: A case study in the eastern Great Basin. *Geological Society of America, Special Paper,* 233, 53p.

Gatehouse, C.G., 1995, Polda Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:130-133.

Gibbs, A.D., 1984, Structural evolution of extensional basin margins. *Geological Society of London, Journal,* 141:609-620.

Gill, E.D., 1968, Oxygen isotope palaeotemperature determinations from Victoria, Australia. *Tuatara,* 16:56-61.

Glaessner, M.F., 1953, Some problems of Tertiary geology in South Australia. *Royal Society of New South Wales, Proceedings,* 87:31-45.

Glaessner, M.F & Wide, M., 1958, The St. Vincent Basin. *In:* Glaessner, M.F & Parkin, L.W. (eds), The Geology of South Australia. *Geological Society of Australia, Journal,* 5:115-126.

Goldstein, A., 1959, Cherts and novaculites of Ouachita facies. *In:* Ireland, H.A. (ed), Silica in sediments. *Social and Economic Palaeontologists and Mineralogists, Special Publication,* 7:135-149.

Goode, A.D.T & Williams, G.E., 1980, Posible western outlet for an ancient Murray River in South Australia – Discussion 3. Reply. *Search,* 11:227-230.

Gostin, V.A., Belperio, A.P. & Cann, J.H., 1988, The Holocene non-tropical coastal and shelf carbonate province of southern Australia. *In:* Nelson, C.S. (ed), Non-tropical shelf carbonates; modern and ancient. *Sedimentary Geology,* 60:51-70.

Gravenor, C.P., 1979, The nature of the Late Palaeozoic glaciation in Gondwana as determined from an analysis of garnets and other heavy minerals. *Canadian Journal of Earth Sciences,* 16:1137-1153.

Greenwood, D.R., 1994, Palaeobotanical evidence for Tertiary climates. *In:* Hill, R.S. (ed), *History of Australian vegetation. Cretaceous to Resent.* Cambridge University Press, Cambridge, 44-59.

Hails, J.R., Belperio, A.P. & Gostin, V.A., 1984, Quaternary sea-levels, northern Spencer Gulf, Australia. *Marine Geology,* 61:373-389.

Haq, B.U., Hardenbol, J. & Vail, P.R., 1987, Chronology of fluctuating sea level since the Triassic. *Science,* 235 (4793):1156-1167.

Harris, W.K., 1970, Palynology of Lower Tertiary sediments, southeastern Australia. *The University of Adelaide, M.Sc. thesis* (unpublished).

Harris, W.K., 1980, Palynology of samples from two bores on the eastern margin of the Adelaide Plains Sub-basin, St Vincent Basin. *Western Mining Co., Palynology Report,* 80/3 (unpublished).

Hill, A.J., 1995, Bight and Duntroon Basins. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:133-141.

Hill, K.C., Grey, A., Foster, D.A. & Barrett, R., 1993, An alternative model for the Oligo-Miocene evolution of northern PNG and the Sepik-Ramu Basins. *In:* Carman, G.J. & Carman, Z. (eds), Petroleum Exploration and Development in Papua New Guinea, *Proceedings of the Second PNG Petroleum Convention.* PNG Chamber of Mines & Petroleum, Port Moresby, 241-259.

Hills, E.S., 1975, The Physiography of Victoria. Whitcombe and Tombs, Melbourne.

Hills, E.S., 1961, Morphotectonics and geomorphological sciences with special reference to Australia. *Geological Society of London, Quarterly Journal,* 117:77-89.

Holbrook, J & Schumm, S.A., 1999, Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognising subtle epeirogenic deformation in modern and ancient settings. *Tectonophysics,* 305:287-306.

Holdgate, G.R., Wallace, M., Daniels, J., Gallagher, S.J., Keene, J. & Smith, A.D., 2000, Controls on Seaspray Group sonic velocities in the Gippsland Basin: a multidisciplinary approach to the canyon seismic velocity problem. *APPEA Journal,* 40:295-313.

Hornibrook, N.B., Brazier, R.C. & Strong, C.P., 1989, Manual of New Zealand Permian to Pleistocene Foraminiferal Biostratigraphy. *New Zealand Geological Survey Paleontological Bulletin,* 56:175p.

References

Howchin, W., 1911, Description of a disturbed area of Cainozoic rocks in South Australia, with remarks on its geological significance. *Royal Society of South Australia, Transactions,* 35:47-59.

Howchin,W., 1918, The Geology of South Australia. South Australian Education Department, Adelaide.

Howchin,W., 1933, "The Dead Rivers of South Australia Part II. The Eastern Group". *Royal Society of South Australia, Transactions,* 57:1-41.

Hudson, M.R., Rosenbaum, J.G., Gromme, C.S., Scott, R.B. & Rowley P.D., 1998, Paleomagnetic evidence for counterclockwise rotation in a broad sinistral shear zone, Basin and Range province, southeastern Nevada and southwestern Utah. *In:* Faulds, J.E. & Stewart, J.H. (eds), Accommodation Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province. *Geological Society of America, Special Paper,* 323:149-180.

Huntley, D.J., Hutton, J.T. & Prescott, J.R., 1993, The stranded beach-dune sequence of southeast South Australia: a test of thermoluminescence dating. *Quaternary Science Reviews,* 12:1-20.

INQUA: International Union for Quaternary Research. Commission on Neotectonics, Website: http://www.letras.up.pt/geograf/neotect.html

Jenkins, R.J.F., 1990, The Adelaide fold belt: tectonic reappraisal. *Geological Society of Australia, Special Publication,* 16:396-420.

Jenkins, R.J.F. & Sandiford, M., 1992, Observations on the tectonic evolution of the southern Adelaide Fold Belt. *Tectonophysics*, 214:27-36.

Johns, R.K., 1970 The Leigh Creek coal measures. *South Australia, Mineral Resources Review,* 132:145-154.

Johns, R.K., 1975a, Leigh Creek Coalfield, Boolcunda Basin and Springfield Basin, South Australia. *In:* Traves, D.M., & King, D. (eds), *Economic Geology of Australia and Papua New Guinea, 2, Coal.* Australasian Institute of Mining and Metallurgy, Monograph Series, 6:301-305.

Johns, R.K., 1975b, Tertiary coal in South Australia. *In:* Traves, D.M., & King, D. (eds), *Economic Geology of Australia and Papua New Guinea, 2, Coal.* Australasian Institute of Mining and Metallurgy, Monograph Series, 6:366-371.

Johnson, H.D. & Baldwin, C.T., 1996, Shallow clastic seas. *In:* Reading, H.G. (ed), *Sedimentary Environments: Processes, facies and Stratigraphy.* Blackwell Science, UK, 232-280.

Kemp, E.M., 1978, Tertiary climatic evolution and vegetation history in the Southeast Indian Ocean region. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 24:169-208.

Kennett, J.P & Shackleton, N.J., 1976, Critical development in evolution of deep-sea waters 38 Ma ago: oxygen isotopic evidence from deep-sea sediments. *American Geophysical Union, Eos, Transactions,* 57:256.

Kershaw, A.P., Martin, H.A. & McEven-Mason, J.R.C., 1994, The Neogene – a period of transition. *In:* Hill, R.S. (ed), *History of the Australian Vegetation: Cretaceous to Recent.* Cambridge University Press, Cambridge, 301-327.

King, L., 1976, Planation remnants upon high lands landscape. *Zeits. fur Geomorphologie,* 20:133-148.

Kwitko, G., 1995, Triassic intramontane Basins. *In:* Drexel, J. F. & Preiss, W.V. (eds), *The geology of South Australia.* Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:98-101.

Lange, R.T., 1970, The Maslin Bay flora, South Australia: The assemblage of fossils. *Neues Jahrbuch Geologie und Palaontologie, Monatshefte*, 8:486-490.

Lange, R.T., 1982, Australian Tertiary vegetation, evidence and interpretation. *In:* Smith, J.M.B. (ed), *A history of Australasian vegetation.* McGraw Hill, Sydney, 44-89.

Lawrence, C.R., 1975, Geology, hydrodynamics and hydrochemistry of the southern Murray Basin. *Victoria, Geological Survey, Memoirs*, 30.

Lemon, N., 1988, Diapir Recognition and modelling: with examples from the Late Proterozoic Adelaide Geosyncline, Central Flinders Ranges, South Australia. *The University of Adelaide, PhD thesis* (unpublished).

Lemon, N. & McGowran, B., 1989, Structural development of the Willunga Embayment, St Vincent Basin, South Australia. *The University of Adelaide, NCPGG, Field Guide* (unbublished).

Li, Q., James, N.P. & McGowran, B., 2003, Middle and Late Eocene Great Australian Bight lithobiostratigraphy and stepwise evolution of the southern continental Australian margin. *Australian Journal of Earth Sciences*, 50, 113-128.

Li, Q., Simo, J.A., McGowran, B. & Holbourn, A., 2004, The eustatic and tectonic origin of Neogene unconformities from the Great Australian Bight. *Marine Geology,* 203:57-81.

Liggett, M.A & Childs, J.F., 1977, An application of satellite imagery to mineral exploration. *U.S. Geological Survey Professional Paper*, 1015:253-270.

Lindsay, J.M., 1967, Foraminifera and stratigraphy of the type section of Port Willunga Beds, Aldinga Bay, South Australia. *Royal Society of South Australia, Transactions,* 91:93-110.

Lindsay, J.M., 1969, Cainozoic foraminifera and stratigraphy of the Adelaide Plains Sub-basin, South

Australia. *South Australia, Geological Survey, Bulletin*, 42.

Lindsay, J.M., 1976, Tertiary history of South Australia – the foraminifal record. *In:* 25th *Internatiaonal Geological Congress, Sydney, Abstracts*, 1:329-330.

Lindsay, J.M., 1981, Tertiary stratigraphy and foraminifera of the Adelaide City area, St Vincent Basin, South Australia. *The University of Adelaide, MSc thesis (unpublished).*

Lindsay, J.M., 1985, Aspects of South Australian Tertiary foraminiferal biostratigraphy , with emphasis on studies of *Massilina* and *Subbotina*. *In:* Lindsay, J.M. (ed), Stratigraphy, palaeontology, malacology: papers in honour of Dr Nell Ludbrook. *South Australia, Department of Mines and Energy, Special Publication*, 5:187-231.

Lindsay, J.M. & Alley, N.F., 1995, St Vincent Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:163-172.

Lindsay, J.M. & Bonnett, J.E., 1973, Tertiary stratigraphy of three deep bores in the Waikerie area of the Murray Basin. *South Australia, Geological Survey, Report of Investigations,* 38.

Lindsay, J.M. & Harris, W.K., 1979, Tandanya sand Member (Chinaman Gully Formation) in the Adelaide City area, St Vincent Basin, South Australia. *South Australia, Geological Survey, Quarterly Geological Notes,* 70:2-4.

Lindsay, J.M. & McGowran, B., 1986, Eocene/Oligocene boundary, Adelaide region, South Australia. *In:* Pomerol, C & Premoli-Silva, I. (eds), Terminal Eocene events. *Developments in Palaeontology and Stratigraphy Series,* 9. Elsevier, Amsterdam, 165-173.

Lindsay, J.M. & Williams, A.F., 1977, Oligocene marine transgression at Hartley and Monarto, southwestern margin of the Murray Basin. *South Australia, Geological Survey, Quarterly Geological Notes*, 64:9-16.

Liu, C.S., Curray, J.R. & McDonald, J.M., 1983, New constraints on the tectonic evolution of the eastern Indian Ocean. *Earth and Planetary Science Letters,* 65:331-342.

Love, D.N., Preiss, W.V. & Belperio, A.P., 1995, Seismicity, Neotectonics and Earthquake Risk. *In:* Drexel, J. F. & Preiss, W.V. (eds) The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:268-273.

Ludbrook, N.H., 1957, Permian foraminifera in South Australia. *Australian Journal of Science*, 19:161-162.

Ludbrook, N.H., 1959, A widespread Pliocene molluscan fauna with *Anodontia* in South Australia. *Royal Society of South Australia, Transactions,* 82:219-235.

Ludbrook, N.H., 1960, Chowilla dam site, River Murray. Stratigraphy and micropalaeontology. *South Australia, Department of Mines, Report Book,* 51/121.

Ludbrook, N.H., 1961, Stratigraphy of the Murray Basin in South Australia. *South Australia, Geological Survey, Bulletin,* 36.

Ludbrook, N.H., 1963, Correlation of the Tertiary rocks of South Australia. *Royal Society of South Australia, Transactions,* 87:5-15.

Ludbrook, N.H., 1971, Stratigraphy and correlation of marine sediments in the western part of the Gambier Embayment. *In:* Wopfner, H. & Douglas, J.G. (eds), The Otway Basin of southeastern Australia. *South Australia and Victoria, Geological Survey, Special Bulletin,* 47-66.

Ludbrook, N.H., 1973, Distribution and stratigraphic utility of Cenozoic molluscan faunas in southern Australia. *Tohoku University, Sendai, Japan. Science Reports, 2nd Series (Geology), Special Volume (Hatai Memorial Volume),* 6:241-261.

Ludbrook, N.H., 1976, The Granville Formation at Port Adelaide. *South Australia, Geological Survey, Quarterly Geological Notes,* 57:4-7.

Ludbrook, N.H., 1980, A guide to the geology and mineral resources of South Australia. *South Australia, Department of Mines and Energy, Handbook*, 4.

Ludbrook, N.H., 1983, Molluscan faunas of the Early Pleistocene Point Ellen Formation and Burham Limestone, South Australia. *Royal Society of South Australia, Transactions,* 107:37-49.

Ludbrook, N.H., 1983, Quaternary molluscs of South Australia. *South Australia, Department of Mines and Energy, Handbook*, 9.

Ludbrook, N.H. & Lindsay, J.M., 1969, Tertiary foraminiferal zones in South Australia. *In:* Bronnimann, P. & Renz, H.H. (eds), *Proceedings of the 1st International Conference on Planktonic Microfossils. Geneva, 1967. E.J. Brill, Leiden,* 2:366-374.

Macphail, M.K., Alley, N.F., Truswell, E.M. & Sluiter, I.R.K., 1994, Early Tertiary vegetation: evidence from spores and pollen. *In*: Hill, R.S. (ed.), *History of Australian vegetation. Cretaceous to Recent.* Cambridge University Press, Cambridge, 189-261.

Macphail, M.K., 1997, Late Neogene climates in Australia; fossil pollen- and spore-based estimates in retrospect and prospect. *Australian Journal of Botany*, 45:425-464.

Macumber, P.G., 1983 Interaction between groundwater and surface systems in northern Victoria, as reflected by hydrochemistry, hydrodynamics, and geomorphology. *University of Melbourne, Ph.D thesis* (unpublished).

References

Mancktelow, N.S., 1990, The structure of the southern Adelaide Fold Belt, South Australia. *In:* Jago, J.B. & Moore, P.S. (eds), The evolution of a late Precambrian-early Palaeozoic rift complex: The Adelaide Geosyncline. *Geological Society of Australia, Special Publication,* 16:369-395.

Mandl, G., 1988, Mechanics of tectonic faulting; models and basic concepts. : Elsevier Scientific Publication, Amsterdam, Netherlands, 407p.

Marshak, S. & Flottmann, T., 1996, Structure and origin of the Fleurieu and Nackara arcs in the Adelaide fold-thrust belt, South Australia; salient and recess development in the Delamerian Orogen. *Journal of Structural Geology,* 18:891-908.

Martin, H.A., 1977, The Tertiary stratigraphic palynology of the Murray Basin in New South Wales. 1.The Hay_Balranald Wakool districts. *Royal Society of New South Wales, Journal and Proceedings,* 110: 41-47.

Martin, H.A., 1991, Tertiary stratigraphic palynology and palaeoclimate of inland river systems in New South Wales. *In:* De Deckker, P., Williams, M.A.J. & Kershaw , A.P. (eds), The Cainozoic in Australia: A re-appraisal of the evidence. *Geological Society of Australia, Special Publication,* 181-194.

Mathews, R.K. & Poore, R.Z., 1980, Tertiary oxygen isotope record and glacio-eustatic sea-level fluctuations. *Geology,* 8:501-504.

Mawson, D & Sprigg, R.C., 1950, Subdivision of the Adelaide System. *Australian Journal of Science,* 13:69-72.

Maud, R.R., 1972, Geology, geomorphology and soils of central County Hindmarsh (Mount Compas-Milang), South Australia. *CSIRO, Soil Publications*, 29.

May, R.I & Bourman, R.P., 1984, Coastal landslumping in Pleistocene sediments at Sellicks Beach, South Australia. *Royal Society of South Australia, Transactions,* 108:85-94.

McDougal, I. & Wellman, P., 1976, Potassium-argon ages for some Australian Mesozoic igneous rocks. *Geological Society of Australia, Journal,* 23:1-9.

McGowran, B., 1978a, Early Tertiary foraminiferal biostratigraphy in southern Australia: a progressive report. *BMR, Geology and Geophysics. Bulletin,* 192:83-95.

McGowran, B., 1978b; Stratigraphic record of Early tertiary oceanic and continental events in the Indian Ocean region. *Marine Geology,* 26:1-39.

McGowran, B., 1979a, The Tertiary of Australia: foraminiferal overview. *Marine Micropalaeontology,* 4:235-264.

McGowran, B., 1979b, Comments on Early Tertiary tectonism and laterization. *Geological Magazine,* 116:227-230.

McGowran, B., 1986, Cainozoic oceanic and climatic events: the Indo-Pacific foraminiferal biostratigraphic record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 55:247-265.

McGowran, B., 1987, Late Eocene perturbations: foraminiferal biofacies and evolutionary overturn, southern Australia. *Paleoceanography,* 2:715-727.

McGowran, B., 1989, The later Eocene transgressions in southern Australia. *Alcheringa,* 13:45-68.

McGowran, B., 1990, Fifty million years ago. *American Scientist,* 78:30-39.

McGowran, B., 1991, Maastrichtian and early Cainozoic, Southern Australia: planktonic foraminiferal biostratigraphy. *In:* Williams, M.A.J., De Deckker, P. & Kershaw, A.P. (eds), The Cainozoic of the Australian Region. *Geological Society of Australia, Special Publication,* 18:79-98.

McGowran, B., 1991a, Evolution and environment in the Early Palaeogene. *In:* Radhakrishnan, B.P. (ed), The World of Martin F. Glaessner: Bangalore, *Geological Society of India, Memoir, 20:21-53.*

McGowran, B. & Beecroft, A., 1986, Foraminiferal biofacies in silica-rich neritic sediment, Late Eocene, South Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 52:321-345.

McGowran, B & Li, Q., 1994, The Miocene oscillation in southern Australia. *In:* Pledge, N.S. (ed), Australian Vertebrate Evolution, Palaeontology and Systematics. *Records of the South Australian Museum*, 27:197-212.

McGowran, B. & Li, Q., 1996, Ecostratigraphy and sequence biostratigraphy with a neritic foraminiferal examples from the Miocene in southern Australia. *Historical Biology,* 11:137-169.

McGowran, B. & Li, Q., 1998, Cainozoic climatic change and its implication for understanding the Australian regolith. *In:* Eggleton, R.A. (ed), The State of the Regolith. *Geological Society of Australia, Special Publication,* 20:86-103.

McGowran, B. & Li, Q., 2002, Sequence biostratigraphy and evolutionary palaeoecology: Firaminifera in the Cainozoic Era. Association of Australian Palaeontologists , Memoir, 27:167-188.

McGowran, B. & Lindsay, J.M., 1969, A Middle Eocene planktonic foraminiferal assemblage from the Eucla Basin. *South Australia, Geological Survey, Quarterly Geological Notes,* 30:2-10.

McGowran, B., Moss, G.D. & Beecroft, A., 1992, Late Eocene and Early Oligocene in southern Australia: local neritic signals of global oceanic changes. *In:* Prothero, D.R. & Berggren, W.A. (eds), *Eocene-*

Oligocene Climatic and Biotic Evolution. Princeton, Princeton University Press, 178-201.

McGowran, B., Li, Q. & Moss, G.D., 1997, The Cenozoic neritic record in southern Australia. The Biogeohistorical Framework. *In:* James, N.P & Clarke, J.D.A. (eds), Cool-water Carbonates. *Society of Economic Paleontologists and Mineralogists, Special Volume,* 56:185-203.

McGowran, B., Holdgate, G.R., Li, Q. & Gallagher, S.J., 2004, Cenozoic stratigraphic succession in southeastern Australia. *Australian Journal of Earth Sciences,* 51:459-496.

McKenzie, D. & Sclater, J.G., 1971, The evolution of the Indian Ocean since the Late Cretaceous. *Royal Astronomical Society, Journal,* 25:437-528.

Miles, K.R., 1952, Geology and underground water resources of the Adelaide Plains area. *South Australia, Geological Survey Bulletin*, 27.

Milnes, A.R. & Bourman, R.P., 1972, A late Palaeozoic glaciated granite surface at Port Elliott, South Australia. *Royal Society of South Australia, Transactions,* 95:149-155.

Milnes, A.R., Compston, W. & Daily, B., 1977, Pre-to syn-tectonic emplacement of Early Palaeozoic granites in the southeastern South Australia. *Geological Society of Australia, Journal,* 24:87-106.

Milnes, A.R., Cooper, B.J. & Cooper, J.A., 1982, The Jurassic Wisanger Basalt of Kangaroo Island, South Australia. *Royal Society of South Australia, Transactions,* 106:1-13.

Milnes, A.R., Ludbrook, N.H., Lindsay, J.M. & Cooper, B.J., 1983, The succession of Cainozoic marine sediments on Kangaroo Island, South Australia. *Royal Society of South Australia, Transactions*, 107:1-35.

Moores, E.M, 1991, Southwest U.S.-East Antarctic (SWEAT) connection: a hypothesis. *Geological Society of America, Geology,* 19:425-428.

Morley, C.K., 1989, Extension, detachments, and sedimentation in continental rifts (with particular reference to East Africa). *Tectonics,* 8:1175-1192.

Morley, C.K., Nelson, R.A., Patton, T.L. & Munn, S.G., 1990, Transfer zones in the East African Rift System and their relevance to hydrocarbon exploration in rifts. *American Association of Petroleum Geologists, Bulletin,* 74:1234-1253.

Morton, J.G.G., 1995, Otway Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:142-147.

Moustafa, A.R., 1996, Internal structure and deformation of accommodation zone in the northern part of the Suez rift. *Journal of Structural Geology*, 18:93-108.

Muller, R.D., Mihut, D. & Baldwin, S., 1998, A new kinematic model for the formation and evolution of the West and Northwest Australian margin. *In:* Purcell, P.G. & Purcell, R.R. (eds), The sedimentary basins of Western Australia, 2. *Petroleum Exploration Society of Australia, Perth,* 55-72.

Muller, R.D., Gaina, C. & Clark, S., 2000, Seafloor spreading around Australia. In: Veevers, J.J. (ed.), *Billion-year earth history of Australia and heighbours in Gondwanaland.* Macquarie University, GEMOC Press, Sydney, 18-28.

Murray, J.M., 1973, Distribution and ecology of living benthic foraminiferids. Heinemann Educational Book Ltd., London.

Murray-Wallace, C.V. & Belperio, A.P., 1991, The last interglacial shoreline in Australia – a review. *Quaternary Science Reviews,* 10:441-461.

Murray-Wallace, C.V. & Kimber, R.W.L., 1987, Evaluation of the amino acid racemization reaction in studies of Quaternary marine sediments in South Australia. *Australian Journal of Earth Sciences*, 34:279-292.

Murray-Wallace, C.V. & Kimber, R.W.L., 1990, Amino acid racemization dating. *Chemistry in Australia,* 3:68-70.

Murray-Wallace, C.V., Kimber, R.W.L., Belperio, A.P. & Gostin, V.A., 1988, Aminostratigraphy of the last interglacial in southern Australia. *Search,* 19:33-36.

Murray-Wallace, C.V., Belperio, A.P., Picker, K. & Kimber, R.W.L., 1991, Coastal aminostratigraphy of the last interglaciation in southern Australia. *Quaternary Research,* 35:63-71.

Murray-Wallace, C.V., Belperio, A.P., Gostin, V.A. & Cann, J.H., 1993, Amino acid racemization and radiocarbon dating of interstadial marine strata (oxygen isotope stage 3), Gulf St. Vincent, South Australia. *Marine Geology,* 110:83-92.

Namy, J.N., 1974, Early diagenetic chert in the Marble Falls group (Pennsylvanian) of Central Texas. *Journal of Sedimentary Petrology*, 44:1262-1268.

Offler, R. & Fleming, P.D., 1968, A synthesis of folding and metamorphism in the Mt Lofty Ranges, South Australia. *Geological Society of Australia, Journal,* 15:245-266.

O'Drisscoll, E.S.T., Structural corridors in Landsat lineament interpretation. *Mineralium Deposita,* 16:85-101.

Ollier, C & Pain, C., 2000, The origin of mountains. Routledge/Taylor & Francis Group. London, United Kingdom, 345p.

Parkin, L.W., 1953, The Leigh Creek Coalfield. *South Australia, Geological Survey, Bulletin,* 31.

Patton, T.L., Moustafa, A.R., Nelson, R.A. & Abdine, S.A., 1994, Tectonic evolution and structural setting

of the Suez rift. *In:* Landon, S.M. (ed), Interior rift basins. *American Association of Petroleum Geologists, Memoir,* 59:9-55.

Paul, E.G., 1998, The geometry and controls on basement-involved deformation in the Adelaide Fold Belt, South Australia. *The University of Adelaide, PhD thesis* (unpublished).

Peterson, M.N.A. & Von der Borch, C.C., 1965, Chert: modern inorganic deposition in carbonate-precipitating locality. *Science,* 149:1501-1503.

Preiss, W.V. (Compiler), 1987, The Adelaide Geosyncline – late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. *South Australia, Geological Survey, Bulletin,* 53.

Preiss, W.V. (compiler), Belperio, A.P., Cowley, W.M. & Rankin, L.R., 1993, Neoproterozoic. *In:* Drexel, J.F., Preiss, W.V. & Parker, A.J. (eds), The geology of South Australia; Vol. 1, The Precambrian. *South Australia, Geological Survey, Bulletin,* 54:170-203.

Preiss, W.V., 1995, Early and Middle Palaeozoic Orogenesis: Delamerian Orogeny. *In:* Drexel, J. F. & Preiss, W.V. (eds) The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:45-60.

Preiss, W.V., 1997, Revision of lithostratigraphy and structure, and evidence of volcanism in lower Burra Group type sections, Carey Gully-Basket Range area, Mount Lofty Ranges. *MESA Journal,* 7:37-46.

Quilty, P.G., 1977, Cenozoic sedimentation cycles in Western Australia. Geology, 5:336-340.

Reading, H.G. & Levell, B.K., 1996, Controls on the sedimentary rock record. *In:* Reading, H.G. (ed), *Sedimentary Environments: Processes, Facies and stratigraphy.* Blackwell Science, UK, London, 5-36.

Reynolds, M.A., 1953, The Cainozoic succession of Maslin and Aldinga bays, South Australia. *Royal Society of South Australia, Transactions,* 76:114-140.

Rogers, P.A., 1978, Chowilla, South Australia - 1:250 000 Geological Series. *South Australia, Geological Survey, Explanatory Notes*, SI/54-6.

Rogers, P.A., 1980, Pinnaroo, South Australia - 1:250 000 Geological Series. *South Australia, Geological Survey, Explanatory Notes*, SI/54-14.

Rogers, P.A., 1995, Berri Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:127-130.

Rogers, P.A., 1995, Continental sediments of the Murray Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:252-254.

Rogers, P.A., Lindsay, J.M., Alley, N.F., Barnett, S.R., Lablack, K.L & Kwitko, G., 1995, Murray Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:157-162.

Rosendahl; B.R., 1987, Architecture of continental rift with special reference to East Africa. *Annual Review of Earth and Planetary Sciences Letters,* 15:445-504.

Rowett, A.I, 1997. Preliminary Report of palaeodrainage in the St Vincent Basin and Mt Lofty Ranges. *South Australia, Department of Mines and Energy, Report Book,* 97/25 (unpublished).

Royer, J.Y. & Rollet, N., 1997, Plate-tectonic setting of the Tasmanian region. *Australian Journal of Earth Sciences,* 44:543-560.

Sandiford, M., 2003, Neotectonics of southeastern Australia: linking the Quaternary faulting record with seismicity and in situ stress. *In:* Hillis, R.R & Muller, R.D. (eds), Evolution and Dynamics of the Australian Plate. *Geological Society of Australia Special Publication 22 and Geological Society of America Special Paper,* 372:107-119.

Sandiford, M., 2003a, geomorphic constraits on the Late Neogene tectonics of the Otway Range, Victoria. *Australian Journal of Earth Sciences,* 50:69-80.

Sandiford, M., Fraser, G., Arnold, J., Foden, J. & Farrow, T., 1995, Some causes and consequences of high-temperature, low-pressure metamorphism in the eastern Mt Lofty Ranges, South Australia. *Australian Journal of Earth Sciences*, 42:233-240.

Scott, D.C., 1989, Drilling investigation of Tertiary sand deposits near Freeling. Mount Lofty ranges Review. *South Australia, Department Mines and Energy, Report Book*, 89/25.

Scott Smith, B.H., Danchin, R.V., Harris, J.W. & Stracke, K.J., 1984, Kimberlites near Orroroo, South Australia. *In:* Kornprobst, J. (ed), Kimberlites, 1: Kimberlites and related rocks. Proceedings of the 3rd International Kimberlite Conference. *Development in Petrology Series,* 11A. Elsevier, Amsterdam, 121-142.

Seibold, E. & Berger, W.H., 1993, *The sea floor: an introduction to marine geology.* Springer-Verlag. Berlin, Federal Republic of Germany, 356p.

Selby, J. & Lindsay, J.M., 1982, Engineering geology of the Adelaide city area. *South Australia, Geological Survey, Bulletin,* 51.

Shackleton, N.J., 1984, Oxygen isotope evidence of climatic change. *In:* Benchley, P. (ed.), *Fosils and climate.* John Wiley and Sons, New York, 27-34.

Shackleton, N. J., 1986, Paleogene stable isotope events. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 57:91-102.

Shackleton, N.J. & Kennet, J.P., 1975, Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: oxygen and carbon isotope analysis in DSDP sites 277, 279, and 281. *In: Initial reports of*

the Deep Sea Drilling Project 29. US Government Printing Office, Washington, D.C.

Shackleton, N.J., Hall, M.A. & Pate, D., 1995, Pliocene stable isotope stratigraphy of Site 846. *Proceedings of the Ocean Drilling Program, Scientific Results*, 138:337-355.

Sheard, M.J. & Bowman, G.M., 1987, Definition of the upper boundary of the Hindmarsh Clay, Adelaide Plains Sub-Basin and Adelaide/Golden Grove Embayment. *South Australia, Geological Survey, Quarterly Geological Notes*, 103:9-16.

Sheard, M.J. & Bowman, G.M., 1987, Definition of the Keswick Clay upper boundary of the Hindmarsh Clay, Adelaide Plains Sub-Basin and Adelaide/Golden Grove Embayment. *South Australia, Geological Survey, Quarterly Geological Notes*, 103:4-9.

Sheard, M.J. & Bowman, G.M., 1996 Soils, stratigraphy and engineering geology of near surface materials of the Adelaide Plains. *South Australia, Department of Mines and Energy, Report Book,* 94/9

Scheibner, E., 1999, The Geological Evolution of New South Wales – A Brief Review. *Geological Survey of New South Wales,* 32p.

Singleton, O.P., McDougall, L & Mallett, C.W., 1976, The Pliocene-Pleistocene boundary in southeastern Australia. *Geological Society of Australia, Journal,* 23:299-311.

Singleton, F.A., 1941, The Tertiary geology of Australia. *Royal Society of Victoria, Proceedings,* 53:1-125.

Smith, P.C., Rogers, P.A., Lindsay, J.M., White, M.R. & Kwitko, G., 1995, Gambier Basin. *In:* Drexel, J. F. & Preiss, W.V. (eds), The geology of South Australia. Vol. 2, The Fanerozoic. *South Australia, Geological Survey, Bulletin,* 54:151-157.

Sprigg, R.C., 1942, The geology of the Eden-Moana Fault Block. *Royal Society of South Australia, Transactions,* 66:185-214.

Sprigg, R.C., 1945, Some aspects of the geomorphology of portion of the Mount Lofty Ranges. *Royal Society of South Australia, Transactions,* 69:277-302.

Sprigg, R.C., 1946, Reconnaissance geological survey of portion of the western escarpment of the Mount lofty Ranges. *Royal Society of South Australia, Transactions,* 70:313-347.

Stagg, H.M.J. & Willcox, J.B., 1992, A case for Australia-Antarctica separation in the Neocomian (ca 125 Ma). *Tectonophysics,* 210:21-32.

Stagg, H.M.J., Willcox, J.B., Symonds, P.A., O'Brien, G.W., Colwell, J.B., Hill, Peter J., Lee, C.S., Moore, A.M.G. & Struckmeyer, H.I.M., 1999, Architecture and evolution of the Australian continental margin. *AGSO Journal of Australian Geology and Geophysics*, 17:17-33.

Stephenson, A.E., 1986, Lake Bungannia – A Plio-Pleistocene megalake in southern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 57:137-156.

Stephenson, A.E. & Brown., C.M., 1989, The ancient River Murray. *BMR Journal of Australian Geology and Geophysics,* 11:387-395.

Stewart, J. H., 1998, Regional characteristics, tilt domains, and extensional history of the late Cenozoic Basin and Range Province, western North America. *In:* Faulds, J.E. & Stewart, J.H. (eds), Accommodation Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province. *Geological Society of America, Special Paper,* 323:47-74.

Stuart, W.J., 1969, Stratigraphic and structural development of the St Vincent Basin, South Australia. *The University of Adelaide, PhD thesis* (unpublished).

Thomson, B.P., 1969, Adelaide map sheet. *South Australia, Geological Survey, 1:250 000 Map series,* SI/54

Thomson, B.P. & Horowitz, R.C., 1962, Barker map sheet. *South Australia, Geological Survey, 1:250 000 Map series,* SI/54-13.

Tikku, A.A. & Cande, S.C., 1999, The oldest magnetic anomalies in the Australian-Antarctic basins: are they isochrons? Journal of Geophysical Research, 104:661-677.

Tokarev, V., Sandiford, M. & Gostin, V., 1999, Landscape evolution in the Mount Lofty Ranges: implication for regolith development. *In:* Taylor, G. & Pain, C. (eds), New Approaches to an Old Continent. *Proceedings of Regolith'98, 3rd Australian Regolith Conference, Kalgoorlie, WA, Cooperative Research Centre for Landscape Evolution and Mineral Exploration, Perth*, 127-134.

Tokarev, V. & Gostin, V., (in press), Mount Lofty Ranges, South Australia. *In:* Anand, R. R. & de Broekert P. (eds), *Regolith-Landscape Evolution Across Australia*. CRC LEME.

Truswell, E.M. & Harris, W.K., 1982, The Cainozoic palaeobotanical record in arid Australia: fossil evidence for the origins of an arid-adapted flora. *In:* Barker, W.S. & Greenslade, P.J.M. (eds.), *Evolution of the flora and fauna of arid Australia*. Peacock Publications, Adelaide, 67-76.

Twidale, C.R., 1976, Geomorphological evolution. *In:* Twidale, C.R., Tyler, M.J. & Webb, B.P. (eds), Natural history of the Adelaide Region. *Royal Society of South Australia, Occasional Publications,* 1:43-59.

Twidale, C.R., 1983, Australian laterites and silcretes: ages and significance. *Revue de Geologie et de Geographe Physique*, 24:35-45.

Twidale, C.R., 1991, A model of landscape evolution involving increased and increasing relief amplitude. *Zeitschrift fur Geomorphologie,* 35:85-109.

Twidale, C.R., 1994, Gondwanan (Late Jurassic and Cretaceous) palaeosurfaces of the Australian Craton. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 118:157-186.

Twidale, C.R. & Bourne, J.A., 1975, Geomorphological evolutionof part of the eastern Mount Lofty Ranges, South Australia. *Royal Society of South Australia, Transactions,* 99:197-209.

Twidale, C.R., Lindsay, J.M. & Bourne J.A., 1978, Murray Valley Gorge in South Australia: age and origin. *Royal Society of Victoria, Proceedings,* 90:27-42.

Veevers, J.J. (ed), 2000, *Billion-year earth history of Australia and heighbours in Gondwanaland.* Macquarie University, GEMOC Press, Sydney, 388p.

Veevers, J.J., 2000, Present tectonic state. *In:* Veevers, J.J. (ed), 2000, *Billion-year earth history of Australia and heighbours in Gondwanaland.* Macquarie University, GEMOC Press, Sydney, 61-73.

Veevers, J.J. (ed.), 1984, *Phanerozoic earth history of Australia.* Oxford, Clarendon, 418p.

Veevers, J.J., Jones, J.G. & Powell, C.M.A., 1982, Tectonic framework of Australia's sedimentary basins. *APEA Journal,* 22:283-300.

Veevers, J.J., 1986, Breakup of Australia and Antarctica estimated as Mid-Cretaceous (95 + or - 5 Ma) from magnetic and seismic data at the continental margin. *Earth and Planetary Science Letters,* 77:91-99.

Veevers, J.J. & Evans, P.R., 1975, Late Palaeozoic and Mesozoic history of Australia. *In:* Campbell, K.S.W. (ed), Gondwana geology. *Proceedings of the 3rd Gondwana Symposium,* Canberra, 1973, ANU Press, 579-607.

Veevers, J.J., Stagg, H.M.J. Willcox, J.B. & Davies, H.L., 1990, Pattern of slow seafloor spreading (<4 mm/ year) from breakup (96 Ma) to A20 (44.5 Ma) off the southern margin of Australia. *BMR Journal of Australian Geology and Geophysics,* 11:499-507.

Wade, M., 1958, The morphological and stratigraphical analysis of foraminiferal faunas of the Tertiary basins of South Australia. *The University of Adelaide, PhD thesis* (unpublished).

Ward, W.T., 1966, Geology, geomorphology and soils of the southwestern part of County Adelaide, South Australia. CSIRO Soil Publications, 23.

Watchman, A.L. & Twidale, C.R., 2002, Relative and 'absolute' dating of land surfaces. *Earth Science Reviews,* 58:1-49.

Weisell, J.K. & Hayes, D.E., 1972, Magnetic Anomalies in the Southeast Indian Ocean. *In:* Hayes, D.E. (ed), Antarctic Oceanology 2, The Australian-New Zealand sector. American Geophysical Union, Antarctic Research Series, 19:165-196.

Weisell, J.K. & Hayes, D.E., 1974, The Australian-Antarctic discordance: new results and implications. Journal of Geophysical Research, 79:2579-25-87.

Wernickie, B.P., 1990, Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada. *Geological Society of America, Memoir,* 176, 511p.

Wernicke, B.P. 1992, Cenozoic extensional tectonics of the U.S. Cordillera. *In:* Burchfiel, B.C., Lipman, P.W. & Zoback, M.L. (eds.), *The Cordilleran orogen: Conterminous U.S.* Geological Society of America, The Geology of North America, G-3:553-581.

Willcox, J.B., 1990, Gravity trends as an expression of lithospheric extension on the southern margin of Australia. *Australian Journal of Earth Sciences,* 37:85-91.

Willcox, J.B. & Stagg, H.M.J., 1990, Australia's southern margin; a product of oblique extension. *Tectonophysics,* 173:269-281.

Williams, G, E., 1973, Late Quaternary piedmont sedimentation, soil formation and palaoclimates in arid South Australia. *Zeitschrift fur Geomorphologie,* 17:102-125.

Williams, M.A.J., Dunkerley, D.L., De-Deckker, P., Kershaw, A.P. & Stokes, T.J., 1993, *Quaternary environments.* Edward Arnold. London, United Kingdom, 329p.

Wilson, J.T., 1965, A new class of faults and their bearing on continental drift. Nature, 207:343-347.

Wopfner, H., 1970, Permian palaeogeography and depositional environment of the Arckaringa Basin, South Australia. *In:* Haughton, S.H. (ed), *2nd Gondwana Symposium, Pretora, South Africa, 1970, Proceedings and papers.* Council for Scientific and Industrial Research, 273-291.

Wopfner, H., 1972, Depositional history and tectonics of South Australian sedimentary basins. *Mineral Resources Review, South Australia,* 133:32-50.

Wopfner, H., 1978, Silcretes of northern South Australia and adjacent regions. *In:* Langford-Smith, T (ed), *Silcrete in Australia.* New England University Press, Armidale, NSW, 93-141.

Wopfner, H., 1980, Development of Permian intracratonic basins in Australia. *In:* Cresswell, M.M. & Vella, P. (eds), Gondwana five. *Proceedings of the 5th International Gondwana Symposium,* Wellington, New Zealand, 1980, 365-372.

Yassaghi, A., James, P.R, Flottmann, T. & Winsor, C.N., 2004, P-T conditions and kinematics of shear zones from the southern Adelaide Fold-Thrust Belt, South Australia: insights into the dynamics of a deeply eroded orogenic wedge. Australian Journal of Earth Sciences, 51:301-317.

Yassaghi, A., 1998, Geometry, kinematics, microstructure, strain analysis and P-T conditions of the shear zones and associated ductile thrusts in the southern Mt Lofty Ranges/Adelaide Hills area, South Australia. *The University of Adelaide, Ph.D thesis* (unpublished).

Zachos, J.C., Opdyke, B.N., Jones, C.E., Halliday, A. & Quinn, T.M., 1994, Antarctic glaciation, continental erosion, and early Cenozoic variations in seawater (super 87) Sr/ (super 86) Sr values. *American Geophysical Union, Eos Transactions,* 75:203.

Zoback, M.L., Zoback, M.D., Adams, J., Assumpcao, M., Bell, S., Bergman, E.A., Blumling, P., Brereton, N.R., Denham, D., Ding, J., Fuchs, K., Gay, N., Gregersen, S., Gupta, H.K., Gvishiani, A., Jacob, K., Klein, R., Knoll, P., Magee, M., Mercier, J.L., Muller, B.C., Paquin, C., Rajendran, K., Stephansson, O., Suarez, G., Suter, M., Udias, A., Xu, Z.H. & Zhizhin, M., 1989, Global patterns of tectonic stress. *Nature,* 341:291-298.