



*The Australian National University*

The Library

reference

GPO Box 4, Canberra, ACT 2601  
Telegrams & cables NATUNIV Canberra  
Telex AA 62694 NATUNI  
Telephone 062-49 5111

USE OF THESES

This microfiche is supplied for purposes of private study and research only. Passages from the thesis may not be copied or closely paraphrased without the written consent of the author.



PETROLOGY, GEOCHEMISTRY  
AND  
TECTONIC SETTING  
OF  
SOME FLYSCH DEPOSITS

by

MUKUL RAJ BHATIA

Thesis submitted for the degree of  
DOCTOR OF PHILOSOPHY

at the

AUSTRALIAN NATIONAL UNIVERSITY

December, 1981

Unless otherwise acknowledged, all data and interpretations in this thesis are my own.

MR Bhatia

M. R. BHATIA

## ACKNOWLEDGEMENTS

I wish to thank Dr. K.A.W. Crook for his supervision and guidance throughout this project and for many helpful discussions.

I am grateful to Dr. B.W. Chappell for his guidance in the geochemical analysis and for writing innumerable computer programs. Dr. S.R. Taylor provided the facilities to carry out the rare earth element determinations in his laboratory. His suggestions and advice on various aspects of this study are gratefully acknowledged. I am also thankful to Dr. J. Veizer for helpful discussions.

I thank Drs. R. Cas, F. Von Vanderberg and J. Fawckner for their help in organizing the field work in various basins.

Expert instruction and assistance were given by R. Freeman and J. Wasik (chemical analysis), J.H. Pennington (X-ray diffraction), P. Oswald-Sealey and M. Shelley (spark source). I am thankful to P. Winer and K. Handel for their help in computing.

I am grateful to my colleagues D. Hough, S. McLennan, D. Walker and M. Alam for their suggestions and help.

This study was carried out while I held an Australian National University Research Scholarship and I am grateful to Dr. K.S.W. Campbell and Dr. M.J. Rickard for providing the necessary facilities.

I wish to express appreciation to Mrs Denese McCann for typing the various drafts with great skill.

I take great pleasure in acknowledging the forbearance, encouragement, and enormous help in tabulation and proof reading given by Florence. Finally, I am indebted to my parents for their understanding and inspiration.

## ABSTRACT

The Paleozoic flysch sequences of eastern Australia show large variations in their mineralogical and geochemical compositions. On the basis of detrital mineralogy, the following five graywacke suites are recognized: Tamworth, Hill End, Hodgkinson, Bendigo and Cookman. The graywackes exhibit increasing maturity from the Tamworth to Cookman suites, characterised by an increase in quartz content and a decrease in lithic and feldspar grains. The graywacke suites are derived from dominantly andesitic, dacitic, crystalline, meta-sedimentary and sedimentary source rocks, respectively. The associated mudrocks are also characterized by variations in abundances of phyllosilicates and tectosilicates (feldspar and quartz). Three broad groups of mudrocks are recognized: tectonic type (Tamworth suite); phyllo-tectonic type (Hill End and Hodgkinson suites); and phyllic type (Bendigo and Cookman suites).

With the increase in mineralogical maturity, increasing geochemical differentiation is observed in the sedimentary suites, in the form of enrichment of Si and Zr in graywackes, and enrichment of large cations (K, Rb, Ba), Al-group (Al, Ga) and ferromagnesian elements (Cr, Ni, Zn) in mudrocks, and loss of small cations (Ca, Na, Sr) in solution. A close similarity is observed between the Th, U, Nb, La/Y, Zr, Sc/Ni, Ni/Co, La/Yb and rare earth element characteristics of graywacke suites and orogenic andesites from various tectonic settings. On this basis, the Tamworth suite is assigned to an oceanic island arc; the Hill End suite to a continental island arc; and the Hodgkinson suite to an Andean type tectonic setting. The Bendigo and Cookman suite graywackes are characterised by their highly quartzose nature and highly fractionated chemistry, suggesting their recycled nature and possibly a passive margin type of tectonic setting.

The major element geochemistry of arenites can be used to infer the provenance type and tectonic setting of sedimentary basins. In general, there is a progressive decrease in total Fe as  $Fe_2O_3+MgO;TiO_2; Al_2O_3/SiO_2$  and an increase in  $K_2O/Na_2O$  and  $Al_2O_3/(CaO+Na_2O)$  in arenites as the tectonic setting changes from oceanic island arc to continental island arc to Andean type to passive margins.

The trace element characteristics of sedimentary rocks show excellent signatures of provenance types and tectonic settings. The most useful elements are those which are relatively immobile, fractionate only in the clastics and have low residence times in sea water, e.g., Th, U, Nb, Zr, REE, Y, Sc and Co. Optimum discrimination of oceanic island arc, continental island arc, Andean type and passive margin tectonic settings is achieved by La-Th; Ti/Zr-La/Sc; La/Y-Sc/Cr; La-Th-Sc; Th-Sc-Zr/10; Th-Co-Zr/10; and Rb-V-Zr plots, for arenites. The trace elements in mudrocks also show characteristics of the tectonic setting and the most discriminating parameters are Th, Nb, U, Nb/Y, Th/U, Zr/Th and La/Sc.

The bulk oceanic island arc sedimentary composition is similar to the composition of the total crust, whereas the average Andean type-passive margin sedimentary composition is comparable to the upper continental crustal composition. The continental island arc sedimentary composition is intermediate. The change from oceanic island arc to continental island arc to Andean type and passive margin sedimentary compositions is similar to the change in the average compositions of sedimentary rocks from Archean through Proterozoic to Phanerozoic. This suggests a gradual mafic to felsic transition in crustal composition through geological time.

## TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	i
ABSTRACT	ii
TABLE OF CONTENTS	iv
LIST OF FIGURES	xii
LIST OF TABLES	xx
CHAPTER 1 INTRODUCTION	1
1.1 Sedimentation and Tectonics	1
1.2 Sedimentary Composition and New Global Tectonics	1
1.3 Sedimentary Rocks and Crustal Evolution	2
1.4 Aim and Scope of the Present Investigation	4
1.5 Terminology	5
1.6 Samples and Analytical Techniques	7
CHAPTER 2 GEOLOGICAL SETTING OF THE SEDIMENTARY BASINS	8
2.1 Introduction	8
2.2 Tamworth Trough	8
2.2.1 General Geology	8
2.2.2 Paleogeography	14
2.3 Hill End Trough	16
2.3.1 General Geology	16
2.3.2 Paleogeography	19
2.4 Bendigo Trough	21
2.4.1 General Geology	21
2.4.2 Paleogeography	21
2.5 Hodgkinson Basin	24
2.5.1 General Geology	24
2.5.2 Paleogeography	26
CHAPTER 3 DETRITAL AND DIAGENETIC CHARACTERISTICS OF GRAYWACKES	29
3.1 Introduction	29
3.2 Grain Parameters	29

3.3	Detrital Characteristics of Graywackes	31
3.3.1	Tamworth Trough	31
3.3.2	Hill End Trough	31
3.3.3	Hodgkinson Formation	33
3.3.4	Bendigo Trough	33
3.4	Graywacke Suites	34
3.4.1	Petrofacies and Suites	34
3.4.2	Modal Comparison	34
3.4.3	Maturity and Provenance Indices	37
3.5	Parameter Associations	39
3.6	Grain Size and Modal Composition	43
3.7	Diagenesis of the Tamworth Trough Graywackes	45
3.7.1	Diagenetic Features	45
3.7.1a	Authigenic Cement	46
3.7.1b	Compaction Features	46
3.7.1c	Replacement Features	46
3.7.2	Diagenetic Sequence	46
3.7.3	Albitisation of Ca-plagioclase	47
3.7.4	Burial Metamorphic Facies in the Tamworth Trough	50
3.8	Diagenesis of the Hill End Trough Graywackes	51
3.8.1	Diagenetic Features	51
3.8.2	Regional Metamorphism of the Hill End Trough Sequence	53
3.9	Diagenesis of the Bendigo Trough Graywackes	53
3.10	Diagenesis of the Hodgkinson Formation Graywackes	54
3.10.1	Diagenetic Features	54
3.10.1a	Authigenic Cement and Replacement Features	54
3.10.1b	Compaction Features	54
3.10.2	Diagenetic and Metamorphic Facies in the Hodgkinson Basin	54
CHAPTER 4	GRAYWACKE SUITES AND THEIR PETROGENESIS	55
4.1	Introduction	55
4.2	Principal Component Analysis	55
4.3	Discriminant Function Analysis	59
4.4	Cluster Analysis	64



4.5	Petrogenesis : Source Rocks and Provenance	66
4.5.1	Tamworth Suite	66
4.5.2	Hill End Suite	67
4.5.3	Hodgkinson Suite	68
4.5.4	Bendigo Suite	70
4.5.5	Cookman Suite	73
CHAPTER 5	PETROLOGY AND CLASSIFICATION OF MUDROCKS	75
5.1	Introduction	75
5.2	Mineralogy of Mudrocks	75
5.2.1	Framework Silicates, Iron Oxide and Carbonates	75
5.2.2	Phyllosilicates	77
5.3	Mudrock Suites	77
5.3.1	Semi-Quantitative Mineralogy	77
5.3.2	Cluster Analysis	82
5.4	Mudrock Texture	82
5.5	Petrogenesis of Mudrocks	84
5.6	Classification of Mudrocks	86
5.6.1	Introduction	86
5.6.2	Existing Classifications	86
5.6.3	Proposed Classification of Flysch Mudrocks	89
CHAPTER 6	GEOCHEMISTRY OF FLYSCH SEDIMENTARY ROCKS	93
6.1	Introduction	93
6.2	Major Element Geochemistry	93
6.3	Trace Element Geochemistry	98
6.3.1	Ba-Rb-Sr-Pb	98
6.3.2	Ferromagnesian Elements	100
6.3.3	Th-U-Zr-Nb	103
6.3.4	Rare Earth Elements	103
6.4	Petrochemistry	106
6.4.1	Graywackes	106
6.4.2	Mudrocks	108
6.5	Geochemical Differentiation of Graywacke Suites	112
6.5.1	Chemical Maturity Indices	112
6.5.2	Discriminant Function Analysis	112
6.6	Geochemical Differentiation of Mudrock Suites	116
6.6.1	Geochemical Maturity Indices	116

6.6.2	Discriminant Function Analysis	116
6.7	Bulk Compositions of Sedimentary and Common Igneous Rocks	121
6.8	Geochemical Comparison of Average Sedimentary Suite and Source Rock Compositions	123
6.8.1	Tamworth Suite	124
6.8.2	Hill End Suite	127
6.8.3	Hodgkinson Suite	130
6.8.4	Bendigo Suite	130
6.8.5	Cookman Suite	133
6.9	Migration and Redistribution of Elements	137
CHAPTER 7	TECTONIC SETTING DISCRIMINATION USING GEOCHEMICAL CHARACTERISTICS OF SEDIMENTARY ROCKS	141
7.1	Introduction	141
7.2	Tectonic Classification of Flysch Basins	142
7.3	Tectonic Settings of Sedimentary Basins of Eastern Australia	143
7.3.1	Tamworth Trough	143
7.3.2	Hill End Trough	147
7.3.3	Hodgkinson Basin	148
7.3.4	Bendigo Trough	148
7.4	Tectonic Control on Geochemical Variables	149
7.4.1	Source Rocks	150
7.4.2	Relief	153
7.4.3	Weathering	153
7.4.4	Physical Processes	154
7.4.5	Diagenesis	155
7.5	Tectonic Setting Discrimination Using Mineral Composition	155
7.5.1	Arenites	155
7.5.2	Mudrocks	161
7.6	Residence Time of Elements	164
7.7	Tectonic Setting Discrimination Using Major Element Geochemistry of Arenites	166
7.7.1	Geochemical Parameters	166
7.7.2	Discriminant Function Analysis	174

7.8	Tectonic Setting Discrimination Using Major Element Geochemistry of Mudrocks	178
7.9	Tectonic Setting Discrimination Using Trace Element Geochemistry of Arenites	184
7.9.1	Introduction	184
7.9.2	La-Th	186
7.9.3	La-Th-Sc	189
7.9.4	Th-Zr	189
7.9.5	V-Sc	191
7.9.6	Ti/Zr-La/Sc	191
7.9.7	La/Y-Sc/Cr	191
7.9.8	Th-Sc-Zr and Th-Co-Zr	193
7.9.9	Rb-V-Zr	196
7.9.10	Summary	196
7.10	Tectonic Setting Discrimination Using Trace Element Geochemistry of Mudrocks	199
7.10.1	Introduction	199
7.10.2	Th-Sc-Zr	199
7.10.3	La-Th	202
7.10.4	Nb-Zr/Th	202
7.10.5	Th-Nb/Y	202
7.10.6	La/Sc-Nb/Y	204
7.10.7	Nb-Th/U	204
7.10.8	Summary	204
7.11	Robertson Bay Group : Composition and Tectonic Setting	209
CHAPTER 8	RARE EARTH ELEMENT GEOCHEMISTRY AND TECTONIC SETTING OF SEDIMENTARY ROCKS	212
8.1	Introduction	213
8.2	REE Parameters	213
8.3	REE Patterns and Source Rocks	217
8.3.1	Tamworth Suite	217
8.3.2	Hill End Suite	226
8.3.3	Hodgkinson Suite	226
8.3.4	Bendigo and Cookman Suites	229
8.4	REE Parameters and Compositional Characteristics	229
8.4.1	Grain Size	229
8.4.2	Detrital Mineralogy	229

8.4.3	Clay Mineralogy	232
8.4.4	Chemical Maturity	232
8.5	Tectonic Settings and REE Characteristics	235
8.5.1	Tamworth Suite	235
8.5.2	Hill End Suite	238
8.5.3	Hodgkinson Suite	238
8.5.4	Bendigo and Cookman Suites	241
8.5.5	Tectonic Setting Discrimination	241
8.6	Rare Earth Elements in Tektites and Sedimentary Rocks	244
CHAPTER 9	GEOCHEMICAL EVOLUTION OF SEDIMENTARY ROCKS AND CRUSTAL GROWTH	245
9.1	Introduction	245
9.1.1	Upper Continental Crust	245
9.1.2	Total Crust	245
9.1.3	Aim	246
9.2	Tectonic Model of Geochemical Differentiation of Sedimentary Rocks	246
9.3	Average Compositions of Sedimentary Basins	252
9.3.1	Procedure	255
9.3.2	Oceanic Island Arc Basin	256
9.3.3	Continental Island Arc Basin	256
9.3.4	Andean Type Basin	256
9.3.5	Passive Margin Type Basins	261
9.4	Sedimentary Rock and Crustal Compositions	261
9.5	Archean Sedimentary Rocks : Geochemical Composition and Constraints on Provenance	267
9.5.1	Introduction	267
9.5.2	Major Element Geochemistry	271
9.5.3	Trace Element Geochemistry	271
9.5.3a	Ba-Rb-Sr-Pb	271
9.5.3b	La-Th-Sc	272
9.5.3c	Th-Sc-Zr	272
9.5.3d	Th-U	272
9.5.3e	Zr-Hf-Nb	275
9.5.3f	Cr-Ni	275
9.5.3g	Rare Earth Elements	276
9.5.4	Provenance	276

9.6	Secular Variations in the Chemical Composition of Sedimentary Rocks	279
9.6.1	General Observations	279
9.6.2	Major Element Geochemistry	280
9.6.2a	Archean Sedimentary Composition	280
9.6.2b	Phanerozoic Sedimentary Composition	283
9.6.2c	Proterozoic Sedimentary Composition	283
9.6.3	Trace Element Geochemistry	286
9.6.4	Epilogue	287
9.7	Evolution of Sedimentary Rocks and Crustal Growth	289
CHAPTER 10 CONCLUSIONS		293
REFERENCES		297
APPENDIX A SAMPLING, PREPARATION AND ANALYTICAL TECHNIQUES		321
A.1	Sampling	321
A.2	Sample Preparation	321
A.3	Geochemical Techniques	321
A.3.1	Major Elements	321
A.3.2	Trace Elements	323
A.3.3	Rare Earth Elements	323
A.4	X-Ray Diffraction Studies	324
A.4.1	Identification of Minerals	324
A.4.2	Semi-Quantitative Estimation of Minerals	324
A.5	Determination of Quartz by Infra-Red Spectroscopy	325
A.6	Grain Size Analysis	326
A.6.1	Graywackes	326
A.6.2	Mudrocks	327
A.7	Modal Analysis	327
A.8	Facies Attributes	329
APPENDIX B LOCATION OF SAMPLES		330
APPENDIX C AN INTRODUCTION TO THE MULTIVARIATE STATISTICAL METHODS		334
C.1	Principal Component Analysis	334
C.2	Discriminant Function Analysis	338

C.3 Cluster Analysis	339
APPENDIX D PETROGRAPHY OF GRAYWACKES	341
D.1 Tamworth Trough	341
D.1.1 Typical Graywackes	341
D.1.2 Crow Mountain Creek Beds	345
D.2 Hill End Trough	346
D.2.1 Turondale, Waterbeach, Merrions Tuff and Cunningham Formations	346
D.2.2 Chesleigh Formation	350
D.2.3 Cookman Formation	353
D.3 Bendigo Trough	355
D.4 Hodgkinson Formation	358
APPENDIX E CHEMICAL COMPOSITION OF PALEOZOIC CLASTIC SEDIMENTARY ROCKS OF EASTERN AUSTRALIA	363
APPENDIX F TRACE-ELEMENT GEOCHEMISTRY AND SEDIMENTARY PROVINCES : A STUDY FROM THE TASMAN GEOSYNCLINE, AUSTRALIA. Chem. Geol., 33, (1981), 115-125 (Jointly with S.R. Taylor).	372

## LIST OF FIGURES

	Page
<u>CHAPTER 1</u>	
1.1 Location Map of Sedimentary Basins of Eastern Australia	6
<u>CHAPTER 2</u>	
2.1 Generalised Distribution of Tectonic Units in Eastern Australia	9
2.2 Generalised Geological Map of the Tamworth Trough	12
2.3 Tectonic Interpretative Map of the New England Fold Belt	15
2.4 Generalised Geological Map of the Hill End Trough and Surrounding Regions	17
2.5 Schematic Paleogeographic Reconstruction of the Hill End Trough - Canberra Magmatic Province During the Silurian-Devonian Times	20
2.6 Generalised Geological Map of the Bendigo Trough and Surrounding Regions	22
2.7 Paleogeographic Map of Southeastern Australia during the Ordovician	23
2.8 Generalised Geological and Structural Map of the Hodgkinson - Broken River Provinces	25
2.9 Paleocurrent Directions in the Hodgkinson Basin	27
<u>CHAPTER 3</u>	
3.1 QFL and QpLvLs Plots Showing the Detrital Characteristics of Various Graywacke Suites	35
3.2 Plot of Maturity Index and Provenance Index for Various Graywacke Suites	38
3.3 Plot of Mean Grain Size Versus Inclusive Graphic Standard Deviation for Graywackes	38
3.4 Plot of Mean Grain Size Versus the Sedimentary Rock Fragment, Volcanic Rock Fragment, Quartz, and Feldspar Percentage in Graywackes	44

3.5	Descriptive Framework for the Diagenesis of Volcanogenic Graywackes (after Surdam and Boles, 1979) as Observed in the Tamworth Trough Stratigraphic Sequence	48
3.6	Burial Diagenetic History of the Tamworth Trough	49
 <u>CHAPTER 4</u>		
4.1	Plot of Factor Scores for Graywackes, Along Factor I Versus Factor II	58
4.2	Plot of Discriminant Scores Along Discriminant Function I Versus II	62
4.3	Plot of Discriminant Scores Along Discriminant Function I Versus III	63
4.4	Simplified Dendrogram Showing Various Clusters of Graywacke Suites	65
4.5	Plot of Quartz Varieties in the Hodgkinson Suite Graywackes, on the Diagram Proposed by Basu et al. (1975)	69
 <u>CHAPTER 5</u>		
5.1	Plot of Phyllosilicate Versus Quartz + Feldspar Content in Mudrocks	79
5.2	Simplified Dendrogram Showing Various Clusters of Mudrocks	81
5.3	Plot of Estimated Mean Grain Size Versus Quartz + Feldspar, Phyllosilicate, and Sorting Index in Mudrocks	83
5.4	Mineralogical Classification of Mudrocks Based on the Quartz-Feldspar-Phyllosilicate Content	91
5.5	Plot of Mudrock Maturity Index Versus Estimated Mean Grain Size	91
 <u>CHAPTER 6</u>		
6.1	Harker Variation Diagrams of Major Elements in Graywackes	96
6.2	Plot of $\text{SiO}_2$ Versus $\text{Al}_2\text{O}_3$ , Total FeO, $\text{K}_2\text{O}$ , and $\text{Na}_2\text{O}$ in Mudrocks	97



6.3	Variation in the Rb, Sr, Ba and Pb Abundances in Sedimentary Rocks	99
6.4	Plot of Total Fe as FeO Versus Sc, V, Co and Zn for Graywackes	101
6.5	Cr Versus Ni Plot for Mudrocks	102
6.6	Plot of $Al_2O_3$ Versus Ga in Graywackes and Mudrocks	102
6.7	Plot of Th Versus U, Nb and Zr for Graywackes and Mudrocks	104
6.8	Variation in the Rare Earth Element Characteristics of Graywackes and Mudrocks	105
6.9	Diagram showing the Major Loadings of Geochemical, Mineralogical and Textural Variables on Each Factor, in Various Graywacke Suites and in the Total Group	107
6.10	Diagram showing the Major and Minor Loading of Geochemical and Mineralogical Variables in Various Factors in the Total Mudrock Group	109
6.11a	Plot of Mineralogical Maturity Index Versus $Al_2O_3/SiO_2$ , Showing the Discrimination of Various Graywacke Suites	111
6.11b	Plot of $Al_2O_3$ Versus $\log K_2O/Na_2O$ , Showing the Discrimination of Various Graywacke Suites	111
6.12	Plot of Discriminant Scores Along Function I Versus II, to Discriminate the Various Graywacke Suites	115
6.13	Plot of the Mudrock Maturity Index Versus $\log K_2O/Na_2O$ for the Discrimination of Various Mudrock Suites	117
6.14	CaO-Na <sub>2</sub> O-K <sub>2</sub> O Plot to Discriminate the Mudrock Suites	117
6.15	Plot of Discriminant Scores Along Function I Versus II, to Discriminate the Various Mudrock Suites	120
6.16	Plot of $SiO_2$ Versus $Fe_2O_3+FeO+MgO+CaO+Na_2O$ for Graywackes and Mudrocks and Comparison with Common Igneous Rocks (Andesite-Dacite-Granodiorite-Granite)	122
6.17	CaO-Na <sub>2</sub> O-K <sub>2</sub> O Plot for Graywackes.	122
6.18	Comparison of the Compositions of (a,b) : The Average Graywacke and Mudrock of the Tamworth Suite (c,d) : The Average Tamworth Suite and the Average Andesite of Taylor (1979)	126

6.19	Comparison of the Compositions of (a,b) : The Average Graywacke and Mudrock of the Hill End Suite (c,d) : The Average Hill End Suite and the Average Goobarrandra Dacite, N.S.W. (Wyborn et al., 1981)	129
6.20	Comparison of the composition of (a,b) : The Average Graywacke and Mudrock of the Hodgkinson Suite (c,d) : The Average Hodgkinson Suite and the Georgetown Granitoids (Sheraton and Labonne, 1978)	132
6.21	Comparison of the Compositions of (a,b) : The Average Graywacke and Mudrock of the Bendigo Suite (c,d) : The Average Bendigo Suite and the Robertson Bay Group (Harrington et al., 1967; Nathan 1976)	135
6.22	Comparison of the Compositions of (a,b) : The Average Graywacke and Mudrock of the Cookman Suite (c,d) : The Average Cookman and Bendigo Suite	136

## CHAPTER 7

7.1	Relationship between Attributes of Plate Tectonic Setting and Compositional Variables	151
7.2	QFL and QpLvLs Plots of Arenites and Sands for Tectonic Setting Discrimination	158
7.3	P/F Versus Lv/L, and P/F Versus Quartz Plots for Arenites	159
7.4	Plot of Phyllosilicate Versus the Phyllosilicate/Feldspar Ratio for Mudrock Suites of Eastern Australia	162
7.5	Plot of Log Residence Time in Sea Water Versus Log[Concentration in Sea Water/Concentration in Upper Continental Crust] for Elements	165
7.6	Major Element Tectonic Setting Discrimination Plots for Arenites- Plot of $TiO_2$ , $Al_2O_3/SiO_2$ , $K_2O/Na_2O$ , and $Al_2O_3/(CaO+Na_2O)$ Versus $Fe_2O_3+MgO$ (Total Fe as $Fe_2O_3$ ).	171
7.7	Plot of Discriminant Scores Along Function I Versus II for Various Arenites and Sands	176
7.8	$CaO-Na_2O-K_2O$ Plot of Mudrocks for Tectonic Setting Discrimination	180

7.9	Plot of $K_2O/Na_2O$ Versus $Al_2O_3/(CaO+Na_2O)$ of Mudrocks for Tectonic Setting Discrimination	181
7.10	La-Th Plot of Arenites for Tectonic Setting Discrimination, Based on Data of Eastern Australia	187
7.11	La-Th-Sc Plot of Arenites for Tectonic Setting Discrimination	188
7.12	Th Versus Zr, and Sc Versus V Plots for Various Arenites	190
7.13	La/Sc Versus Ti/Zr, and Sc/Cr Versus La/Y Plots of Arenites for Tectonic Setting Discrimination	192
7.14	Th-Sc-Zr/10 and Th-Co-Zr/10 Plot of Arenites for Tectonic Setting Discrimination	194
7.15	Rb-V-Zr Plot of Arenites for Tectonic Setting Discrimination	195
7.16	Flow Diagram Illustrating the Proposed Method of Characterising the Tectonic Setting of Arenites	197
7.17	Th-Sc-Zr/10 Plot of Mudrocks for Tectonic Setting Discrimination	201
7.18	La Versus Th, and Nb Versus Zr/Th Plots of Mudrocks, for Tectonic Setting Discrimination	203
7.19	Tectonic Setting Discrimination Plots of La/Sc, and Th Versus Nb/Y in Mudrocks	205
7.20	Nb Versus Th/U Plot of Mudrocks Representing Various Tectonic Settings	206
7.21	Flow Diagram Illustrating the Proposed Method of Characterising the Tectonic Setting of Mudrocks	207

## CHAPTER 8

8.1	(a) Rare Earth Element Abundance in Chondrite and Average Shale (PAAS)	215
	(b) Chondrite Normalised Rare Earth Element Pattern of Average Shale (PAAS)	215
8.2	Chondrite Normalised REE Plots of the Baldwin Formation Graywackes, Tamworth Trough	221
8.3	Chondrite and PAAS Normalised REE Plots of the Tamworth Suite Sedimentary Rocks	222
8.4	Chondrite and PAAS normalised REE Plots of the Hill End Suite Sedimentary Rocks (Turondale Formation)	223

8.5	Chondrite and PAAS Normalised REE Plots of the Hill End Suite Sedimentary Rocks (Waterbeach, Merrions Tuff and Cunningham Formation)	224
8.6	Chondrite and PAAS Normalised REE Plots of the Hill End Suite Sedimentary Rocks (Chesleigh Formation)	225
8.7	Chondrite and PAAS Normalised REE Plots of the Hodgkinson Suite Sedimentary Rocks	227
8.8	Chondrite and PAAS normalised REE Plots of the Bendigo and Cookman Suite Sedimentary Rocks	228
8.9	Plot of Mean Grain Size Versus $\Sigma$ REE	230
8.10	Plots of Mineralogical Maturity and Provenance Indices Versus the REE Parameters of Graywackes	231
8.11	Plot of Clay Maturity Index Versus $\Sigma$ REE and Eu/Eu*	233
8.12	Plots of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ Versus REE Parameters for Graywackes and Mudrocks	234
8.13	Comparison of Chondrite Normalised REE Patterns of Various Graywacke Suites and Orogenic Andesites	237
8.14	Th Versus La/Yb Plot of the Tamworth Suite Graywackes	239
8.15	Sc/Ni Versus La/Yb Plot of Average Graywacke Suites	240
8.16	Chondrite and PAAS Normalised Discriminatory Plots for Graywackes of Various Tectonic Settings	243

#### CHAPTER 9

9.1	Plot of $\text{SiO}_2$ Versus $\text{Al}_2\text{O}_3/\text{SiO}_2$ for Graywackes and Mudrocks of Eastern Australia	248
9.2	Plot of $\text{SiO}_2$ - $\text{Al}_2\text{O}_3$ + $\text{K}_2\text{O}$ -Rest, to Show the Geochemical Fractionation in Sedimentary Rocks	249
9.3	Tectonic Model of the Geochemical Evolution of Sedimentary Rocks	251
9.4	Comparison Diagram of Average Oceanic Island Arc and Phanerozoic Sedimentary Compositions	257
9.5	Comparison Diagram of Average Continental Island Arc and Phanerozoic Sedimentary Compositions	258

9.6	Comparison Diagram of Average Andean and Phanerozoic Sedimentary Compositions	259
9.7	Comparison Diagram of Average Passive Margin and Phanerozoic Sedimentary Compositions	260
9.8	Comparison Diagram of Average Oceanic Island Arc Sedimentary and Total Crustal Compositions	263
9.9	Comparison of Average Fractionated (Andean and Passive Margin Types) Sedimentary Composition and Upper Continental Crustal Composition	264
9.10	Comparison Diagram of Trace Elements of the Fractionated Sedimentary and Upper Continental Crustal Compositions	265
9.11	Plot of Archean Graywackes on the Major Element Discriminatory Diagrams of Arenites	269
9.12	Plot of Archean Mudrocks on the $\text{CaO-Na}_2\text{O-K}_2\text{O}$ Discriminatory Diagram	270
9.13	La-Th-Sc and Th-Sr-Zr/10 Discriminatory Plots of Archean Samples	274
9.14	Comparison of Chondrite Normalised REE Plots of Archean Sedimentary Averages with Graywackes of Various Tectonic Settings	278
9.15	Comparison Diagram of Average Oceanic Island Arc and Archean Sedimentary Compositions	281
9.16	Comparison Diagram of Average Fractionated and Phanerozoic Sedimentary Compositions	282
9.17	Comparison Diagram of Average Continental Island Arc and Proterozoic Sedimentary Compositions	285
9.18	Secular Trends in the $\text{K}_2\text{O/Na}_2\text{O}$ for Sediments and Basement (after Engel et al. 1975), and $^{87}\text{Sr}/^{86}\text{Sr}$ in Carbonates (from Veizer and Compston, 1976), through Geological Time and Comparison with Variation in the Abundances of La, Th, U and Nb in Clastic Sedimentary Rocks of Various Tectonic Settings	288

#### APPENDIX D

D.1	Photomicrographs of the Representative Graywackes of the Tamworth Trough	343
D.2	Photomicrographs of the Representative Graywackes of the Hill End Suite	348

- |     |                                                                                           |     |
|-----|-------------------------------------------------------------------------------------------|-----|
| D.3 | Photomicrographs of the Representative Graywackes of the Chesleigh and Cookman Formations | 352 |
| D.4 | Photomicrographs of the Representative Graywackes of the Bendigo Trough                   | 357 |
| D.5 | Photomicrographs of the Representative Graywackes of the Hodgkinson Formation             | 361 |

## LIST OF TABLES

CHAPTER 2

- 2.1 Summary of the Characteristics of the Sedimentary Sequences Studied in Detail 10
- 2.2 Stratigraphy of the Tamworth Trough 13

CHAPTER 3

- 3.1 Detrital Grain Parameters 30
- 3.2 Average Modal Composition of Graywackes 32
- 3.3 Framework modes of graywacke suites 36
- 3.4 Correlation Matrix of Mineralogical and Textural Variables in Various Suites and in the Total Group 40
- 3.5 Parameter Associations in Various Graywacke Suites and in the Total Group. 42
- 3.6 Diagenetic Features in the Graywackes of the Hill End Trough Region 52

CHAPTER 4

- 4.1 Factor Loadings for the First Six Factors, after Varimax Rotation 56
- 4.2 Standardised Discriminant Function Coefficients of the Mineralogical Variables and Related Statistics 60
- 4.3 Unstandardised Canonical Discriminant Function Coefficients 61
- 4.4 Comparison of the Actual and Predicted Number of Samples on the Basis of Discriminant Functions in each Graywacke Suite 61

CHAPTER 5

- 5.1 Estimates of the Mineralogical Composition of Mudrock Suites 76
- 5.2 Semi-quantitative Mineralogy, Maturity Index, Estimated Grain Size and Sorting Index of Mudrocks 78
- 5.3 Recent Classifications of Mudrocks 87
- 5.4 Proposed Classification of Flysch Mudrocks and their Modern Analogues (Fine Grained Deep Sea Sediments) 90

CHAPTER 6

6.1	Correlation Matrix of Chemical Elements and Maturity Index in Graywackes	94
6.2	Correlation Matrix of Chemical Elements and Maturity Index in Mudrocks	95
6.3	Standardised Discriminant Function Coefficients and Related Statistics of Graywackes	113
6.4	Unstandardised Discriminant Function Coefficients Used to Calculate Discriminant Scores for Graywackes	114
6.5	Comparison Between the Actual and Predicted Number of Samples in Each Graywacke Suite on the Basis of Discriminant Analysis	114
6.6	Standardised Discriminant Function Coefficients and Related Statistics for Mudrocks	118
6.7	Unstandardised Discriminant Function Coefficients Used to Calculate Discriminant Scores for Mudrocks	119
6.8	Comparison Between the Actual and Predicted Number of Samples in Mudrock Suites, on the Basis of Discriminant Analysis	119
6.9	Compositions of Average Tamworth Suite Sedimentary Rocks and Average Andesites	125
6.10	Compositions of Average Hill End Suite Sedimentary Rocks and Average Source Rocks	128
6.11	Compositions of the Average Hodgkinson Suite Sedimentary Rocks and Average Source Rocks	131
6.12	Compositions of Average Bendigo and Cookman Sedimentary Suites and Source Rocks	134

CHAPTER 7

7.1	Plate Tectonic Classification of Flysch Basins	144
7.2	Geochemical Comparison of Graywackes of Eastern Australia with Andesites from Various Tectonic Settings	146
7.3	Variation in Compositional Variables with the Tectonic Setting of the Sedimentary Basins	152



7.4	Mean Detrital Modes of Arenites and Sands Representing Various Tectonic Settings	157
7.5	Detrital Mineralogical Characteristics of Arenites and Sands from Various Tectonic Settings	160
7.6	Mineralogical Characteristics of Mudrocks of Various Tectonic Settings	163
7.7	Average Chemical Composition of Arenites and Sands of the Oceanic Island Arc Tectonic Setting	167
7.8	Average Chemical Composition of Arenites and Sands of the Continental Island Arc Tectonic Setting	168
7.9	Average Chemical Composition of Arenites and Sands of the Andean Type Tectonic Setting	169
7.10	Average Chemical Composition of Arenites and Sands of the Passive Margin Tectonic Setting	170
7.11	Average Chemical Composition of Arenites of Various Tectonic Settings	173
7.12	Tectonic Setting Classification of Various Arenite Suites on the Basis of Discriminant Analysis	175
7.13	Average Chemical Composition of Mud and Mudrocks from Various Tectonic Settings and Estimates of Average Mudrock Compositions	179
7.14	Average Chemical Composition of Mudrocks of Various Tectonic Settings	183
7.15	Trace Element Characteristics of Arenites from Various Tectonic Settings	185
7.16	Trace Element Parameters of Arenites for Tectonic Setting Discrimination	198
7.17	Trace Element Characteristics of Mudrocks from Various Tectonic Settings	200
7.18	Trace Element Parameters of Mudrocks for Tectonic Setting Discrimination	208
7.19	Geochemical Comparison of Robertson Bay Group Graywackes with Arenites from Various Tectonic Settings	210

CHAPTER 8

8.1	Rare Earth Element Abundance in Chondrites and Post-Archean Average Australian Shale	214
8.2	Rare Earth Element Parameters	214
8.3	Rare Earth Elements, Mineralogical and Geochemical Maturity Indices in the Tamworth Suite Sedimentary Rocks	218
8.4	Rare Earth Elements, Mineralogical and Geochemical Maturity Indices in the Hill End Suite Sedimentary Rocks	219
8.5	Rare Earth Elements, Mineralogical and Geochemical Maturity Indices in the Hodgkinson, Bendigo and Cookman Suite Sedimentary Rocks	220
8.6	Rare Earth Element Comparison of Graywacke Suites with Andesites from Various Tectonic Settings	236
8.7	Most Discriminating Rare Earth Element Characteristics of Tectonic Settings of Sedimentary Basins	242

CHAPTER 9

9.1	Average Major Element Composition of Clastic Sedimentary Rocks of Various Tectonic Settings, and other Crustal Estimates	253
9.2	Average Trace Element Compositions of Clastic Sedimentary Rocks of Various Tectonic Settings, and Crustal Compositions	254
9.3	Average Major Element Compositions of Archean Graywackes and Mudrocks	268
9.4	Comparison of Average Archean Shale with Oceanic Island Arc and Continental Island Arc Mudrocks	273
9.5	Comparison of Rare Earth Element Characteristics of Archean Shales with Oceanic Island Arc and Continental Island Arc Graywackes	277
9.6	Various Averages of Proterozoic Clastic Sedimentary Rocks	284

APPENDIX A

A.1	Summary of Analytical Conditions for X-ray Spectrometry	322
A.2	Simplified Facies Classification Scheme Used in the Present Work and the Arbitrary Units Labelled for Each Facies	328

APPENDIX D

D.1	Modal Composition of Graywackes from the Tamworth Trough	342
D.2	Modal Composition of Graywackes from the Hill End Trough	347
D.3	Modal Composition of Graywackes of the Chesleigh Formation, Hill End Trough	351
D.4	Modal Composition of Graywackes of the Cookman Formation, Hill End Trough	354
D.5	Modal Composition of Graywackes of the Bendigo Trough	356
D.6	Modal Composition of Graywackes of the Hodgkinson Formation	358

APPENDIX E

E.1	Chemical Composition of Graywackes of the Tamworth Trough	364
E.2	Chemical Composition of Mudrocks of the Tamworth Trough	365
E.3	Chemical Composition of Graywackes of the Hill End Suite	366
E.4	Chemical Composition of Mudrocks of the Hill End Suite	368
E.5	Chemical Composition of Graywackes and Mudrock of the Cookman Suite	369
E.6	Chemical Composition of Graywackes and Mudrocks of the Hodgkinson Suite	370
E.7	Chemical Composition of Graywackes and Mudrocks of the Bendigo Suite	371