

MACQUARIE UNIVERSITY

HIGHER DEGREE THESIS (PhD)

AUTHOR'S CONSENT

This is to certify that I, ... *M. M. Hawlader* ...
being a candidate for the degree of Doctor of Philosophy am aware of
the policy of the University relating to the retention and use of higher
degree theses as contained in the University's PhD Regulations generally,
and in particular, Regulation 21(2).

In the light of this policy and the provisions of the above Regulations,
I agree to allow a copy of my thesis to be deposited in the University
Library for consultation, loan and photocopying forthwith.

P. J. Long
.....
Signature of Witness

M. M. Hawlader
.....
Signature of Candidate

Dated this *31 March* ... day of ... 198*9*

The Academic Senate on 28 November 1989 resolved that the candidate
had satisfied requirements for admission to this degree. This thesis represents
a major part of the prescribed program of study.

D033634

OE
471
-15
-S25
-H39
copy 1

PETROLOGY, DIAGENESIS, AND RESERVOIR POTENTIAL OF THE SURAT BASIN
SANDSTONES WITH SPECIAL REFERENCE TO HYDROCARBON EXPLORATION

by

Hanif M. Hawlader, M.Sc (Hons) (*Moscow*)

School of Earth Sciences

Macquarie University

A thesis submitted to Macquarie University in fulfilment of the
requirements for the degree of Doctor of Philosophy.

1989

CERTIFICATE OF ORIGINALITY

I hereby certify that the work in this thesis is original, except where acknowledged in the customary manner, and has not been submitted for a higher degree to any other University or Institution.

H. M. Hawlader

H. M. Hawlader

March, 1989.

CONTENTS

	Page
ABSTRACT	xviii
ACKNOWLEDGEMENTS	xxi
CHAPTER 1 INTRODUCTION	1
OBJECTIVES AND METHODOLOGY	2
GEOLOGIC SETTING	7
STRATIGRAPHY	8
PETROLEUM EXPLORATION HISTORY	8
HYDROCARBON OCCURRENCE	10
REFERENCES	11
CHAPTER 2 PETROLOGY AND PROVENANCE OF THE SURAT BASIN SANDSTONES	14
ABSTRACT	15
INTRODUCTION	15
FACTORS AFFECTING SANDSTONE COMPOSITION	16
The effect of depositional environment	17
Diagenetic alterations	18
GRAINSIZE - COMPOSITION RELATIONSHIPS AND THE POINT-COUNTING METHOD	19
DETRITAL GRAIN-TYPES	20
The types of rock-fragments	24
The types of feldspar	27
SEDIMENT COMPOSITION AND PROVENANCE	33
Existing concepts on sediment provenance in the Surat Basin	33
Mineralogy and classification of the Surat Basin sandstones	38
Provenance fingerprints from framework-grain composition	38

	Page
Evidence from facies relationships	47
Possible sources of the volcanic rock-fragments in the quartzose facies	50
Upsequence and lateral petrographic trends	55
SEDIMENTARY AND PETROLOGIC CYCLES WITH RESPECT TO PROVENANCE	59
DISCUSSION	63
REFERENCES	67
 CHAPTER 3 DIAGNOSIS AND THE GEOLOGIC EVOLUTION OF POROSITY AND PERMEABILITY OF THE SURAT BASIN SANDSTONES	 71
ABSTRACT	72
INTRODUCTION	73
FACTORS AFFECTING THE GEOLOGIC EVOLUTION OF POROSITY	76
Burial depth	76
Temperature	79
Geologic age	82
Depositional environment	83
Detrital mineralogy	84
Sediment texture	84
THE EFFECT OF TEMPERATURE ON RESERVOIR QUALITY: AN ALTERNATIVE APPROACH	86
DIAGENETIC PROCESSES	92
The relative importance of compaction and cementation	92
Dissolution and cementation	98
DIAGENETIC MINERALS	99
Silica cement	103

Clay minerals	110
<i>Kaolinite</i>	110
<u>The mode of fluid flow and crystallographic habits of kaolinite</u>	111
<i>Smectite</i>	115
<i>Chlorite</i>	117
Zeolites	123
TYPES OF POROSITY	123
Identification of secondary porosity	128
Microporosity	131
<i>An empirical algorithm to estimate microporosity</i>	132
CORE POROSITY AND THIN-SECTION POROSITY RELATIONSHIPS	135
POROSITY - PERMEABILITY RELATIONSHIPS	137
SECONDARY POROSITY: IMPORTANCE AND POSSIBLE MECHANISMS OF FORMATION	140
Importance of secondary porosity in the Surat Basin succession	140
Secondary porosity in other basins	147
Mechanisms of secondary porosity development	147
Secondary porosity development controlled by burial depth in the Surat Basin	149
The role of kerogen type on levels of thermal maturity	151
The effect of kerogen type on secondary porosity development	156
The role of meteoric flushing	158
PARAGENETIC SEQUENCE	161
CONCLUSIONS	161
REFERENCES	163

	Page
CHAPTER 4 RESERVOIR PROPERTIES OF SOME SURAT BASIN SANDSTONES AS A FUNCTION OF DIAGENETIC CLAY-MINERAL ASSEMBLAGE: IMPLICATIONS FOR HYDROCARBON EXPLORATION AND EXPLOITATION	171
ABSTRACT	172
INTRODUCTION	172
DIAGENETIC CLAYS AND POROSITY - PERMEABILITY RELATIONSHIPS	176
EFFECT OF DIAGENETIC CLAYS ON PORE-SIZE DISTRIBUTION OF CLASTIC RESERVOIRS	186
RELATIVE PERMEABILITY AND WATER SATURATION	193
FORMATION DAMAGE AND RESERVOIR MANAGEMENT	197
RESPONSE OF GEOPHYSICAL WELL LOGS AS A FUNCTION OF AUTHIGENIC CLAYS	198
HEIGHT OF THE OIL-COLUMN	200
DIAGENETIC-PERMEABILITY TRAPS	203
TILTED OIL/WATER CONTACT	205
CONCLUSIONS	205
REFERENCES	207
CHAPTER 5 DIAGENESIS AND RESERVOIR POTENTIAL OF VOLCANOGENIC SANDSTONES - CRETACEOUS OF THE SURAT BASIN	210
ABSTRACT	211
INTRODUCTION	211
AUTHIGENIC MINERALS	212
THE ROLE OF TEMPERATURE AND/OR PORE-FLUID CHEMISTRY ON AUTHIGENIC MINERAL SPECIES	215
POROSITY AND PERMEABILITY	218
MECHANISMS OF SECONDARY POROSITY DEVELOPMENT: A CONCEPTUAL APPROACH	220
THE EFFECT OF POROSITY TYPES ON PERMEABILITY AND OTHER PETROPHYSICAL PARAMETERS	223
DISCUSSION	226
REFERENCES	227

	Page
CHAPTER 6 MULTIPLE LINEAR REGRESSION - A QUANTITATIVE APPROACH TO THE STUDY OF SANDSTONE POROSITY	230
INTRODUCTION	231
THE ILL-EFFECTS OF MULTICOLLINEARITY ON REGRESSION ANALYSIS	234
METHOD OF VARIABLE SELECTION	235
THE RELATIVE IMPORTANCE OF PREDICTOR VARIABLES	236
THE OUTCOME AND INTERPRETATION OF THE ANALYSIS	238
REFERENCES	242
 CHAPTER 7 FACTOR ANALYSIS OF PETROGRAPHIC AND PETROPHYSICAL DATA	 245
INTRODUCTION	246
CHOICE OF VARIABLES AND DATA CONSIDERATIONS	248
MULTICOLLINEARITY AND ILL-CONDITIONED CORRELATION MATRIX	250
AN OVERVIEW OF THE CORRELATION MATRIX AND THE METHOD OF FACTOR EXTRACTION	254
THE NUMBER OF IMPORTANT FACTORS	258
FACTOR ROTATION	261
THE GEOLOGICAL MEANING OF THE FACTORS	265
REFERENCES	266
 CHAPTER 8 A REVIEW OF THE HYDROCARBON POTENTIAL OF SOME SOURCE ROCKS WITH SPECIAL REFERENCE TO THE SURAT BASIN: IMPLICATIONS FOR PETROLEUM EXPLORATION	 268
ABSTRACT	269
INTRODUCTION	269
THE TYPES OF ORGANIC MATTER AND THEIR HYDROCARBON GENERATION POTENTIAL	272
Oil potential of liptinite	272
<i>Response of resinites and suberinites to thermal stress</i>	279

	Page
<i>Geochemical characteristics of oil derived from liptinite-rich source rocks</i>	281
Hydrocarbon potential of vitrinite and inertinite	282
HYDROCARBON POTENTIAL OF COAL	285
Type of hydrocarbons - oil or gas	286
PRINCIPAL ZONE OF GAS FORMATION	288
LIMITATIONS AND SHORTCOMINGS OF SOME COMMON PETROLOGIC/ORGANIC GEOCHEMICAL PARAMETERS	290
Use of Ro as a maturation indicator - a reappraisal	291
Elemental composition	291
Laboratory pyrolysis of source rocks	292
HYDROCARBON GENERATION FROM A MULTICOMPONENT SYSTEM	293
BOUNDARIES OF THE OIL WINDOW	295
POTENTIAL SOURCE ROCKS OF THE SURAT BASIN HYDROCARBONS	295
Macerals of the Evergreen Formation	296
Oil-prone source rocks of the Walloon Coal Measures	300
DISCUSSION	301
CONCLUSIONS	303
REFERENCES	304
 CHAPTER 9 COMPARATIVE HYDROCARBON GEOLOGY OF TWO MESOZOIC CIRCUM-PACIFIC FORELAND BASINS AS A FUNCTION OF SEDIMENT PROVENANCE: SURAT BASIN, EASTERN AUSTRALIA AND WESTERN CANADA BASIN	 310
ABSTRACT	311
INTRODUCTION	312
SURAT BASIN	313
Geologic history	313
Sediment composition, provenance, and depositional environments	318

	Page
Hydrocarbon reservoirs and source rocks	319
<i>Cyclicity and global sea-level stand</i>	321
<i>Clay minerals</i>	322
<i>Hydrocarbon traps</i>	323
WESTERN CANADA BASIN	323
Geologic history	326
Sediment composition and depositional environments	329
Provenance	334
Reservoir characteristics and hydrocarbon occurrence	337
<i>Clay minerals</i>	341
DISCUSSION	342
CONCLUSIONS	347
REFERENCES	348

APPENDICES

	Page
Appendix 1.1. Thin-section point-count format for provenance and porosity characteristics of the Surat Basin sandstones.	353
Appendix 1.2. Operational thin-section criteria for discrimination between some lithic grain-types of intergradational petrographic character.	359
Appendix 1.3. Amounts of mono and polycrystalline quartz, volcanic, sedimentary and metamorphic rock-fragments in the Surat Basin sandstones.	383
Appendix 1.4. Amounts of alkali feldspar based on point-counting of stained thin-sections.	393
Appendix 1.5. Petrographic modal analyses and porosity-permeability data.	395
Appendix 1.6. Electron microprobe analyses of zoned and twinned plagioclase feldspars.	410
Appendix 1.7. Electron microprobe analyses of untwinned altered feldspars.	415
Appendix 1.8.1. Detailed petrographic modal analyses data.	421
Appendix 1.8.2. Detailed mica and heavy mineral content.	431
Appendix 1.8.3. Total volcanic component of the Surat Basin sandstones.	442
Appendix 1.9. Detailed thin-section porosity categories.	447
Appendix 1.10.1. Petrographic modal analyses of the Surat Basin sandstones recalculated to QFR and LVLsLm components.	462
Appendix 1.10.2. QFR triangular plots of sandstones in different formations in the Surat Basin.	472
Appendix 1.11. Methodology employed in the report.	485
Appendix 1.12. Upsequence and lateral petrographic trends in some Surat Basin sandstones.	490
Appendix 1.13. Petrographic correlation charts through GSQ stratigraphic wells based on detrital megaquartz content (Appendix 1.13.1), total volcanic content (Appendix 1.13.2), and detrital megaquartz and total volcanic content together (Appendix 1.13.3).] In back pocket
Appendix 1.14. Reconnaissance palaeocurrent data from surface outcrops of some Surat Basin formations.	

Appendix 2.1. Electron microprobe analyses of cockscomb skeletal feldspars.	499
Appendix 2.2. Energy dispersiver X-ray (EDX) diffractograms of some authigenic mineral species.	502
Appendix 2.3. X-ray diffractograms of less than 2 um fractions of some selected samples of the Surat Basin sandstones.	508
Appendix 2.4. Electron microprobe analyses of authigenic zeolites.	519
Appendix 2.5.1. Hisogram of secondary porosity index (SPI) distribution in the Surat Basin sandstones.	524
Appendix 2.5.2. A west-east cross-section of the Surat Basin showing the principal zones of secondary porosity development.	526
Appendix 2.6. Electron microprobe analyses of authigenic kaolinite.	528
Appendix 2.7. Core porosity - permeability relationships of different formations.	534
Appendix 2.8. Vitrinite reflectance - depth relationship in the Surat Basin.	541
Appendix 3.1. Glossary of text mnemonics and mathematical symbols used in Chapter 4.	547
Appendix 4.1. Correlation matrix and relevant multiple regression statistics for different formations and subset of samples.	550
Appendix 5.1. Correlation matrix, anti-image correlation (AIC) matrix, unrotated and rotated varimax and oblimin factor pattern/structure matrices of different formations and subset of samples.	560

LIST OF FIGURES: CHAPTERS 1-9

	Page
Figure 1.1. Location (A) and major structural elements (B) of the Surat Basin.	3
Figure 1.2. Generalised stratigraphic column and the distribution of hydrocarbons and aquifers in the Surat Basin.	9
Figure 2.1. Thin-section photomicrographs showing the composition and detrital grain-types of some Surat Basin sandstones.	25
Figure 2.2. Schematic diagrams showing a single-cycle evolution of a foreland basin and the resulting basin-fill pattern.	36
Figure 2.3. Average QFR detrital composition of the Surat Basin sandstones on a formation basis.	39
Figure 2.4A-C. Means and one standard deviation of the Lower Jurassic (A), Middle and Upper Jurassic (B), and Lower Cretaceous sandstones (C) of the Surat Basin.	40
Figure 2.5A. Average rock-fragment composition of the Surat Basin sandstones on a %LvLsLm plot.	43
Figure 2.5B-C. Means and envelopes of one standard deviation of Surat Basin sandstones on %LvLsLm plot.	44
Figure 2.6. Time-space diagram of the Surat and Maryborough Basins (section AA' in Figure 9.1) showing the distribution of preserved petrofacies and lacunae.	48
Figure 2.7. Generalized stratigraphy of the Eromanga and Surat Basins showing the distribution of different petrofacies and occurrence of hydrocarbons.	49
Figure 2.8. Schematic time-space cross-section (B) of a retro-arc foreland basin (A) showing the distribution of gross petrofacies and sediment-transport directions within a single petrologic cycle.	56
Figure 2.9. Stratigraphic distribution of mean and one standard deviation of the detrital quartz content (%QFR) for each formation in the Surat Basin succession.	60
Figure 2.10. Average K-feldspar to total feldspar (K/Ft), and common (plutonic) quartz to total megaquartz (Qc/Q) ratios in sandstones of each formation of the Surat Basin succession.	61
Figure 2.11. Stratigraphic distribution of the mean and one standard deviation of the volcanic rock-fragment content (Lv, as %LvLsLm) (A), and total volcanic component, Lvt (B), in the Surat Basin sandstones.	62

Figure 2.12. Geologic setting of the Surat-Eromanga Basins with interpreted areas of sediment input.	64
Figure 2.13. Speculative Jurassic-Cretaceous palaeogeographies of eastern Australia.	65
Figure 3.1. A general classification of diagenetic processes.	74
Figure 3.2. Distribution of overburden pressure as a function of pore-fluid pressure and grain-to-grain pressure.	75
Figure 3.3. Core porosity - depth relationship of the Surat Basin sandstones (all formations) superimposed on vitrinite reflectance.	77
Figure 3.4. Depth - porosity relationship of sandstones with different mineralogic compositions.	80
Figure 3.5. Thin-section porosity as a function of detrital quartz content in the Hutton Sandstone.	85
Figure 3.6. Relationship between the occurrence of secondary dissolution porosity and grainsize of the Surat Basin sandstones.	87
Figure 3.7. Relationship between geothermal gradient and sandstone porosity.	89
Figure 3.8. Schematic diagram showing the geologic evolution of porosity in sandstones with contrasting detrital composition.	91
Figure 3.9. Thin-section photomicrographs illustrating ductile deformation of soft framework grains.	93
Figure 3.10. Plot of minus-cement porosity against total diagenetic cement of the Surat Basin sandstones (all formations).	95
Figure 3.11. Plot of minus-cement porosity against total diagenetic cement for the Evergreen Formation and Hutton Sandstone.	96
Figure 3.12. Thin-section and SEM photomicrographs showing varieties of skeletal feldspar (A-D) and carbonate cement (E-G).	100
Figure 3.13. Thin-section and SEM photomicrographs illustrating various aspects of silica cementation.	105
Figure 3.14. Thin-section and SEM photomicrographs of different types of authigenic kaolinite.	112
Figure 3.15. X-ray diffractograms of authigenic nontronite.	116

Figure 3. 16. Thin-section and SEM photomicrographs of authigenic nontronite and chlorite.	118
Figure 3. 17. SEM photomicrographs illustrating various aspects of authigenic smectite (montmorillonite).	120
Figure 3.18. A genetic classification of porosity types in sandstones.	125
Figure 3. 19. Thin-section photomicrographs showing different genetic pore-types.	126
Figure 3.20. SEM photomicrographs showing geometric V-shaped notch- and groove-like features on quartz overgrowth surfaces.	129
Figure 3. 21. Types of porosity in the Hutton Sandstone and Griman Creek Formation superimposed on the QFR compositional triangle.	133
Figure 3. 22. Plot of core porosity against thin-section porosity of the Surat Basin sandstones.	136
Figure 3.23. Plot of measured core porosity against permeability of the Surat Basin sandstones.	138
Figure 3. 24. Plot of measured thin-section porosity against permeability of the Surat Basin sandstones.	139
Figure 3. 25. A log-log plot of thin-section porosity and permeability of the Surat Basin sandstones.	141
Figure 3. 26. Thin-section porosity - depth relationship of the Surat Basin sandstones.	142
Figure 3. 27. Plot of secondary dissolution porosity against depth of the Surat Basin sandstones superimposed on vitrinite reflectance.	143
Figure 3. 28. Plot of secondary porosity index (SPI) of the Surat Basin sandstones against depth.	144
Figure 3.29. Means (asterisks) and bars defined by plus and minus one standard deviation of secondary porosity in different stratigraphic units of the Surat Basin succession.	145
Figure 3.30. Stratigraphic distribution of secondary porosity index (SPI) in the Surat Basin succession.	146
Figure 3. 31. Schematic diagram showing the geologic evolution of sandstone porosity.	148
Figure 3. 32. Schematic diagram showing the zone of maximum secondary porosity development at depth as a function of carboxylic acid concentration.	150

	Page
Figure 3. 33. Permeability - depth relationship of the Surat Basin sandstones superimposed on vitrinite reflectance.	152
Figure 3. 34. Schematic diagram showing the general composition and evolutionary pathways of different types of kerogen as a function of thermal maturation with the concomitant liberation of various functional groups prior to hydrocarbon generation.	154
Figure 3. 35. Amounts of oxygen engaged in various functional groups in different types of immature kerogens.	155
Figure 3.36. Maceral composition of the Evergreen Formation, Surat Basin, and of Permian coals of the underlying Bowen Basin.	157
Figure 3.37. Relative yield of gases from different types of organic matter.	159
Figure 3.38. Inferred paragenetic sequence of diagenetic events in the Surat Basin sandstones.	160
Figure 4.1. Stratigraphic distribution of major diagenetic minerals in the Surat Basin sandstones.	174
Figure 4.2. Schematic diagram illustrating the modes of occurrence of authigenic and allogenic clays.	175
Figure 4.3. SEM photomicrographs showing the different morphology and geometry of distribution of diagenetic clay-minerals.	177
Figure 4.4. Porosity-permeability plots of some Hutton Sandstone samples containing different amounts of authigenic kaolinite.	181
Figure 4.5. SEM photomicrographs showing microporosity within different species of diagenetic minerals.	182
Figure 4.6. Porosity-permeability plots of two formations with comparable texture but characterized by different species of diagenetic minerals.	185
Figure 4.7. SEM photomicrographs of two sandstones of very similar texture but having different type and morphology of diagenetic clays.	187
Figure 4.8. Oil-water relative permeability curves of three sandstones of comparable texture.	189
Figure 4.9. Relationship between specific surface area and cation-exchange capacity (CEC).	190
Figure 4.10. SEM photomicrographs showing the abundance of micropores due to the presence of ubiquitous diagenetic clays.	191

Figure 4.11. Schematic diagram showing the importance of interstitial diagenetic clays on the length of the oil-column in two adjacent structural traps (A and B).	202
Figure 5.1. Framework grain composition of the Lower Cretaceous sandstones of the Surat Basin.	213
Figure 5.2. Diagenetic mineral assemblages and porosity-permeability of the Lower Cretaceous sandstones of the Surat Basin.	214
Figure 5.3. Thin-section and SEM photomicrographs illustrating the morphology of diagenetic minerals and secondary dissolution porosity in some Lower Cretaceous sandstones of the Surat Basin.	216
Figure 5.4. Plot of thin-section porosity against depth of the Lower Cretaceous sandstones, Surat Basin.	219
Figure 5.5. Plot of secondary porosity index (SPI) against depth, Lower Cretaceous sandstones, Surat Basin.	221
Figure 5.6. Ternary plot of porosity types of the Lower Cretaceous sandstones of the Surat Basin.	225
Figure 7. 1. Plot of principal components (PC)-extracted eigen values (scree plot).	259
Figure 7. 2. Plots of varimax rotated factors.	262
Figure 7. 3. Plots of oblimin rotated factors.	263
Figure 8.1. Location (A) and major structural elements (B) of the Surat Basin.	270
Figure 8.2. Generalised stratigraphic column of the Surat and Bowen Basins showing the occurrence of hydrocarbons and possible source rocks.	271
Figure 8.3. General scheme of kerogen evolution in the van Krevlen diagram.	274
Figure 8.4. Elemental composition of selected plant and coal materials in the van Krevlen diagram.	275
Figure 8.5. Diagram showing the evolution of the land-plants.	276
Figure 8.6. Schematic diagram showing the different stages of organic maturation and generation of hydrocarbons.	287
Figure 8.7. Ternary diagram showing the different types of terrestrially-derived organic matter and their thresholds of liquid hydrocarbon generation	294

Figure 8.8. Basin-wide vitrinite reflectance of the Evergreen Formation.	297
Figure 8.9. Maceral composition of the Evergreen Formation.	298
Figure 8.10. Type of organic matter in the Walloon coals based on Rock-Eval pyrolysis plotted on a modified van Krevlen diagram.	298
Figure 9.1. Regional setting (A) and major structural elements (B) of the Surat Basin.	314
Figure 9.2. Generalised stratigraphic column of the Surat Basin showing the detrital mineralogy, depositional environments, and hydrocarbon source and reservoir potentials.	316
Figure 9.3. SW-NE time-space diagram of the Surat and Maryborough Basins showing the distribution of preserved lithofacies and of lacunae.	317
Figure 9.4. Surat Basin, Eastern Australia (A), and Western Canada Basin (B), drawn at same scale for comparison.	324
Figure 9.5. Schematic transverse cross-sections of the Surat and Western Canada Basins, drawn at same scale for comparison.	325
Figure 9.6. Schematic west - east cross-section showing the tectonic setting of the Western Canada Basin during the Cretaceous.	327
Figure 9.7. Generalised stratigraphic correlation chart of the Lower Cretaceous succession of the Western Canada Basin showing the distribution of major petrofacies and hydrocarbon occurrence.	328
Figure 9.8. Stratigraphic reference areas for Figure 9.7.	331
Figure 9.9. Palaeotectonic setting of North America during the Late Jurassic - Cretaceous time showing the detrital composition of the sandstone suites in QFL and QmFLt diagrams.	333
Figure 9.10. Schematic cross-section of a foreland basin showing the distribution of organic matter type across the foreland and epicratonic basins during a relatively high water table.	346

LIST OF TABLES: CHAPTERS 1-9

	Page
Table 1.1. Name and location of the GSQ stratigraphic test wells with sample distribution on formation basis.	4
Table 2.1. A classification scheme of petrographic grain-types of the Jurassic - Lower Cretaceous sandstones of the Surat Basin.	21
Table 2.2. Average detrital quartz percentage and K-feldspar to total feldspar ratio of some Surat Basin sandstones based on a count of 600 points in each thin-section.	28
Table 2.3. Means of modal analyses (whole-rock %) of the Surat Basin sandstones based on thin-section point-counting.	30
Table 2.4. Mean and one standard deviation of %QFL and %LvLsLm of the Surat Basin sandstones based on a consistent count of 1000 points in each thin-section.	51
Table 3.1. Correlation matrix, its 1-tailed significance, multiple correlation coefficient (R), R^2 and other relevant statistics of the multiple regression analysis on the Hutton Sandstone with microporosity as the dependent variable.	134
Table 4.1. Cation-exchange capacity and specific surface area of some common diagenetic minerals.	196
Table 4.2. Relationship between permeability, pore-throat sorting (PTS) and the minimum height of the oil-column relative to free-water level (FWL), and trap-relief of some actual hydrocarbon reservoirs.	204
Table 6.1. Factors controlling porosity in clastic reservoirs.	233
Table 6.2. Correlation matrix, 1-tailed significance of correlation coefficients, and relevant statistics of the multiple regression analysis. Data represent all formations.	237
Table 6.3. Correlation matrix, 1-tailed significance of correlation coefficients, and relevant statistics of the multiple regression analysis. Data represent samples with less than 5% cement.	239
Table 6.4. Correlation matrix, 1-tailed significance of correlation coefficients, and relevant statistics of the multiple regression analysis. Data represent samples with >50% detrital quartz.	240
Table 7.1. Correlation matrix, KMO MSA, Bartlett's test of sphericity and 1-tailed significance of correlation matrix. Data represent all formations.	249
Table 7.2. Anti-image correlation matrix and the reproduced correlation matrix. Data represent all formations.	251

	Page
Table 7.3. Principal components (PC)-extracted eigen values, factor (loading) matrix and initial and final communalities. Data represent all formations.	253
Table 7.4. Varimax rotated factor matrix and oblimin rotated factor pattern and structure matrices (all formations).	255
Table 8.1. A general classification of sedimentary organic matter.	278
Table 8.2. Main stages of the evolution of sedimentary organic matter.	280
Table 9.1. Detrital composition of the Lower Cretaceous sandstones of the Foothills and the Plains, Western Canada Basin.	336
Table 9.2. Comparison of average porosity and permeability of Lower Cretaceous sandstones in the Deep Basin and the Peace River/Alberta Shelf area.	339
Table 9.3. Occurrence of hydrocarbon in the Athabasca Tar Sands (McMurry Formation and its equivalents) as a function of sandstone mineralogy, texture, clay minerals and depositional environments.	340
Table 9.4. Analogous morphotectonic elements and comparative features of the Surat and Western Canada Basins.	343

PETROLOGY, DIAGENESIS, AND RESERVOIR POTENTIAL OF THE SURAT BASIN
SANDSTONES WITH SPECIAL REFERENCE TO HYDROCARBON EXPLORATION

ABSTRACT

The detrital composition of the Jurassic and Lower Cretaceous Surat Basin sandstones comprises a wide spectrum ranging from quartzarenite through sublitharenite and feldsarenite/lithic feldsarenite to feldspathic litharenite. The sandstones are subdivided into two petrofacies: quartzose having more than 50% QFR detrital quartz, and labile having less than 50% detrital quartz. The results of petrographic modal analyses illustrate the characteristically dual-provenance basin-fill pattern of the succession, namely, an andesitic magmatic arc to the east-northeast and a stable craton consisting of plutono-metamorphic terrains and sedimentary and silicic volcanic rocks in older basins and platforms in the flanking cratonic regions. The labile sandstones are derived from the magmatic arc which intermittently shed volcanogenic detritus into the subsiding foreland basin. Conversely, the quartzose facies received predominantly cratonic input (deposited during waning phases of magmatism in the arc and concomitant gentle rise of the foreland) with some additional sediments from the arc which presumably was dissected to varying degrees during these periods of relative tectonic quiescence. Sandstones of the whole Mesozoic succession in the Surat Basin comprise several petrologic cycles each of which begins with a craton-derived quartzose facies and ends with an arc-derived quartz-poor labile facies. These cycles reflect the episodic tectonic activity of the arc-craton couplet during basin evolution.

A study of the geologic evolution of sandstone reservoir characteristics suggests that compaction and cementation have both reduced primary porosity and permeability to an extent that is dependent on detrital composition and texture. On the other hand, subsequent

dissolution of framework grains and cement have created secondary porosity that is present in varying proportions in sandstones of all mineralogic compositions. Two mechanisms are thought to have been especially important in the development of secondary dissolution porosity in the Surat Basin sandstones: firstly, selective framework-grain and interstitial cement dissolution caused by organic maturation products emanating from intercalated mudrocks prior to the onset of hydrocarbon generation; and secondly, meteoric flushing of the basin consequent upon the inception of its artesian character (i.e., as a geographic component of the Great Artesian Basin) in the Tertiary.

Diagenetic clay minerals are present in all stratigraphic units, either as individual species or in preferred species associations, and invariably are found to have reduced porosity and permeability. Their effects on reservoir characteristics are a function of the abundance, mineralogy, crystallographic habits, and geometry of distribution of the clay within the reservoir. Some of the clay minerals are fresh-water- and/or acid-sensitive whereas others are prone to effect a mechanical migration-of-fines problem due to pressure-differential between the formation and the well during drilling, testing and hydrocarbon production. Furthermore, the presence of interstitial clays, whether detrital or authigenic, has drastically increased the proportion of microporosity while at the same time reduced effective (macro-) porosity - information about which phenomena is crucial for reliable estimation of hydrocarbon reserves.

The diagenetic clay minerals in the Surat Basin are found to follow certain stratigraphic and geographic trends: the relatively quartzose sandstones contain mainly kaolinite with some minor smectite, illite-smectite and chlorite whereas formations rich in volcanogenic detritus are characterised by smectite, mixed-layer smectite-illite, and minor kaolinite.

A quantitative study employing multiple regression analysis indicates that the present-day porosity of the Surat Basin sandstones is primarily a function of five variables; in order of decreasing importance they are the diagenetic cement, detrital mineralogy, geologic age, burial depth and depositional environments. The present study also confirmed in a quantitative manner the notion and observations of various workers that: in a retro-arc foreland basin, hydrocarbon reservoirs occur preferentially in the craton-derived mineralogically mature quartzose sandstones; and conversely, petroleum source-rocks preferentially comprise the arc-derived finer-grained lithic/labile volcanogenic rocks that are prone to be 'tight' because of their greater physical and chemical reactivities. A literature survey of the Mesozoic Western Canada Basin indicates a similar pattern of association suggesting that the occurrence of hydrocarbons in retro-arc foreland basins probably follows this general pattern world-wide.

ACKNOWLEDGEMENTS

I wish to thank the successive Heads of the School of Earth Sciences, Professor Blair Hostetler and Assoc. Professor Chris Powell for provision of the facilities of the School for this research. The cooperation of the Geological Survey of Queensland (GSQ) in providing me with core materials from their stratigraphic test wells is greatly acknowledged. I express my sincere thanks to John White and Brian Mackay of the Bureau of Mineral Resources (BMR) staff for access to their facilities and to Paul Duff and Stephen Clarke of the BMR Petrophysical Laboratory at Fyshwick, Canberra, for helping me with the porosity-permeability measurements. I am grateful to Jim Conaghan of Roma and June Beattie of Brisbane who provided hospitality during an orientation field trip in the northern Surat Basin, the Clarence-Moreton Basin, and during sampling of core materials in the GSQ core library at Zillmere, Brisbane.

The late Roland Beaugeais made high-quality thin-sections for petrography and microprobing. Neils Munksgaard assisted with the electron microprobing analyses, and Sue Doyle of the School of Biology helped with the Scanning Electron Microscopy. Assoc. Prof. Ron Vernon allowed me access to his thin-section photographic equipment. Alan Ferguson and Dr. Ervin Slansky of the Geological Survey of NSW assisted with XRD analyses of clay minerals. Dr. Jock Keene of the Dept. of Geology and Geophysics of the University of Sydney helped with EDX analyses. To all these people I express my thanks. Tim Watson and Olga Zackroczynski and other technical and clerical staff of the School of Earth Sciences provided various support, and the staff of the Macquarie University Library, especially the inter-library loans section helped in acquiring numerous publications for my research. Assoc. Prof. John Veevers is thanked for stimulating discussions.

Finally I wish to record me gratitude to Dr. Patrick Conaghan who suggested and supervised the project, for his patient guidance all through my candidature, for meticulously teaching me the petrographic skills, for providing logistic support in various stages of the project and for his guidance during a six-week-long orientation field trip in the northern Surat Basin, southern Bowen Basin, and the Clarence-Moreton Basin in January and February, 1986, and assistance with core inspection and sample collection at the GSQ core library at Zillmere, Brisbane, during this same period.

The financial assistance of Macquarie University in the form of a Postgraduate Research Award and associated grants-in-aid is gratefully acknowledged.