Thermal history and geological controls on the distribution of coal seam gases in the southern Sydney Basin, Australia

Mohinudeen Mohamed Faiz
University of Wollongong

UNIVERSITY OF WOLLONGONG
COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced, communicated or distributed in any form or by any means without the prior written permission of the copyright owner.

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.
THERMAL HISTORY AND GEOLOGICAL CONTROLS ON THE DISTRIBUTION OF COAL SEAM GASES IN THE SOUTHERN SYDNEY BASIN, AUSTRALIA.

A thesis submitted in (partial) fulfillment of the requirements for award of the degree of

DOCTOR OF PHILOSOPHY

from

THE UNIVERSITY OF WOLLONGONG

by

MOHINUDEEN MOHAMED FAIZ

(B.Sc. (Hons), University of Peradeniya, Sri Lanka)

Department of Geology

1993
The contents of this thesis are the results of original research by the author and material contained herein has not been submitted to any other university or similar institution for a higher degree.

M.M. Faiz
ABSTRACT

Coal seams of the southern Sydney Basin contain large volumes of gas, mainly methane (CH₄) and carbon dioxide (CO₂) with subordinate volumes of longer chain hydrocarbons (C₅₀) and nitrogen (N₂). Data from exploration boreholes, underground mines and laboratory sorption-desorption tests are used to investigate the composition and distribution of gases in the coal seams. The influences of thermal history, coal composition, rank, geological structure, stratigraphy and igneous activity are evaluated.

The coals of the Late Permian Illawarra Coal Measures attained ranks of up to medium- and low volatile bituminous coals as a result of high palaeo-heat flows (up to 2.5 HFU) and deep burial (up to 2500 m) in the Cretaceous. During the interval between Early Triassic and Middle Jurassic, large volumes of CO₂ and H₂O and subsidiary amounts of hydrocarbons were generated by coalification. The major phase of CH₄ and other hydrocarbon generation occurred between the Middle Jurassic and Late Cretaceous at burial depths between 1.5 km and 2.5 km.

The gas retention and emission characteristics of coals are primarily dependent on pore-size distribution. The Permian coals studied composed of mostly vitrinite and inertinite and the porosity of these coals is dominated by micro- and meso-pores (<50 nm). Pores associated with the mineral matter are mainly macro-pores (>50 nm) hence the presence of mineral matter in coal relatively decreases its micro-porosity.

The gas sorption in coals mainly occurs in the micro-pores and increases with fixed carbon content, vitrinite reflectance and content but decreases with increasing mineral matter, volatile matter and moisture content. The CO₂ sorption capacity of coal is between two to three times higher than that for CH₄. Coal also desorbs CO₂ at a significantly higher rate than CH₄. For a given gas, the desorption rates are related to the abundance of macro-pores and fractures and accordingly increases with mineral matter and vitrinite content. Hence the residual gas content decreases with the increasing CO₂, mineral matter and vitrinite content.

CH₄ and longer chain hydrocarbons presently occurring within the Illawarra Coal Measures were generated during coalification, whereas most of the CO₂ was introduced into the sequence in association with the periodic igneous activity since the Middle Jurassic. Most of the CO₂ generated during the early stages of coalification have been expelled from the coal measures. The variations in the gas composition are mainly related to structural features and depth; the volume of CO₂ increases towards structural highs with highest concentration occurring in anticlines and near some faults. Structural lows contain dominantly CH₄ but local pockets of CO₂ sometimes occur adjacent to faults and dykes. Furthermore, in majority of the boreholes, the volume of CO₂ increases with decreasing depth. These variations are mainly related to the migration and solubility properties of CO₂.

The quantity of ethane and longer chain hydrocarbons occurring at depths less than 500 m is very small (<0.1%) but increases with depth. It is postulated that this trend is related to the ready expulsion of most of the early-formed longer chain hydrocarbons from shallow depths and the subsequent invasion by later-formed CH₄.

The total in-situ gas content of coal, measured from core desorption test, varies from <1 m³/t to 20 m³/t. The desorbable gas content at depths shallower than 200 m is negligible but, on average, increases by approximately 4 m³/t per 100 m in increase depth up to 600 m, and thereafter the rate of increases is significantly low. However, at a given depth, individual values can show up to 80% variability depending on gas composition, geological structure, coal composition and rank. Elevated gas contents occur where the gas is dominantly CO₂ whereas anomalously low gas contents occur near highly faulted zones.
CHAPTER 6 · DISTRIBUTION OF COAL SEAM GASES IN THE ILLAWARRA COAL MEASURES

6.1 DATA ACQUISITION

6.2 SEAM GAS COMPOSITION
   6.2.1 Occurrence of CH₄ and CO₂
   6.2.2 C₂H₆ and Longer Chain Hydrocarbons

6.3 IN-SITU CONTENT

6.4 GEOSTATISTICAL STUDY OF GAS DISTRIBUTION

6.5 SUMMARY

CHAPTER 7 · GEOLOGICAL CONTROLS ON THE SEAM GAS DISTRIBUTION

7.1 INTRODUCTION

7.2 GAS SORPTION, EXPULSION AND ACCUMULATION
   7.2.1 Gas Sorption and Expulsion from Coal
   7.2.2 Migration and Entrapment

7.3 DISTRIBUTION OF CH₄ AND CO₂ IN COAL SEAMS
   7.3.1 Petrographic and Stratigraphic Controls
   7.3.2 Spatial Variations and Structural Controls

7.4 DISTRIBUTION OF C₂H₆ AND LONGER CHAIN HYDROCARBONS

7.5 VARIATIONS IN THE CUMULATIVE SEAM GAS CONTENTS
   7.5.1 Influence of Coal Composition, Rank and Depth
   7.5.2 Spatial variations and Effect of Geological Structure

7.6 IMPLICATIONS FOR CH₄ EXPLORATION AND COAL MINING IN THE SOUTHERN SYDNEY BASIN
   7.6.1 Commercial CH₄ Prospects
   7.6.2 Coal Mining

7.7 SUMMARY

CHAPTER 8 · SUMMARY AND CONCLUSIONS

REFERENCES

ACKNOWLEDGMENTS

APPENDICES

1 SUMMARY OF COAL PETROGRAPHIC DATA
2 SORBED GAS VOLUME CALCULATIONS
3 COAL SEAM GAS DATA
LIST OF FIGURES

1.1 Location of the Sydney Basin and its coalfields 2
1.2 Location of the mine leases in the study area 3

2.1 Stratigraphy of the Illawarra Coal Measures, southern Sydney Basin 18
2.2 Structure contours for the base of Bulli seam 28
2.3 Major structures in the study area based on the Bulli seam 29

3.1 Location of bore holes used in the coal petrographic study 32
3.2 Average vitrinite contents of various coal seams 38
3.3 Photomicrographs showing the typical compositions of various coals 40
3.4 Contour map showing the vitrinite content (mf) of the Bulli seam 42
3.5 Contour map showing the vitrinite content (mf) of the Balgownie seam 43
3.6 Contour map showing the vitrinite reflectance of the Bulli seam 46
3.7 Contour map showing the vitrinite reflectance of the Balgownie seam 47
3.8 Contour map showing the vitrinite reflectance of the Cape Horn seam 48
3.9 Depth versus vitrinite reflectance profile for BL8 50
3.10 Depth versus vitrinite reflectance profile for IL55 51
3.11 Depth versus vitrinite reflectance profile for TNC16 52
3.12 Depth versus vitrinite reflectance profile for BL1 53
3.13 Typical heat flows associated with sedimentary basins of various tectonic settings 57
3.14 Heat flow and subsidence curves for BL8 60
3.15 Relationship between measured and calculated vitrinite reflectance values Campbelltown-1 well 69
3.16 Modelled versus observed vitrinite reflectance for BL8 70
3.17 Modelled versus observed vitrinite reflectance for IL55 70
3.18 Modelled versus observed vitrinite reflectance for TNC16 71
3.19 Modelled versus observed vitrinite reflectance for BL1 71
3.20 Geohistory plot for BL8 72
3.21 Geohistory plot for IL55 73
3.22 Geohistory plot for TNC16 74
3.23 Geohistory plot for BL1 75
3.24 Modelled values for palaeoheat flow and thickness of missing sections 76

4.1 General scheme of oil and gas formation as a result of coal maturation 81
4.2 Variations of atomic H/C and O/C ratios with maturation of various macerals 82
4.3 Evolution of different types of volatiles as a result of the maturation of Carboniferous coal of the Ruhr area, Germany 84
4.4 Distribution of activation energies determined for hydrocarbon generation from coal 90
4.5 Distribution of activation energies for the generation of CO₂ from vitrinite 90
4.6 Hydrocarbon and CO₂ generation plot s for BL1 93
4.7 Hydrocarbon and CO₂ generation plot s for BL8 94
4.8 Hydrocarbon and CO₂ generation plot s for IL55 95
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>Hydrocarbon and CO₂ generation plots for TNC16</td>
<td>96</td>
</tr>
<tr>
<td>4.10</td>
<td>Relationship between vitrinite reflectance and the volume of hydrocarbon generated from the coals of the Illawarra Coal Measures</td>
<td>99</td>
</tr>
<tr>
<td>4.11</td>
<td>Map showing the calculated volumes of hydrocarbons generated from coals of the Sydney Subgroup Illawarra Coal Measures</td>
<td>101</td>
</tr>
<tr>
<td>4.12</td>
<td>Genetic classification of methane based on carbon and deuterium concentration in methane</td>
<td>103</td>
</tr>
<tr>
<td>4.13</td>
<td>Relationship between $^{13}$C values of CH₄ and vitrinite reflectance for coal seams of the Illawarra Coal Measures</td>
<td>105</td>
</tr>
<tr>
<td>5.1</td>
<td>Schematic model for the variations in coal structure with rank</td>
<td>113</td>
</tr>
<tr>
<td>5.2</td>
<td>High pressure gravimetric gas sorption-desorption system</td>
<td>121</td>
</tr>
<tr>
<td>5.3</td>
<td>Variation of helium density of coals with carbon content</td>
<td>128</td>
</tr>
<tr>
<td>5.4</td>
<td>Variation of porosity of coals with carbon content</td>
<td>129</td>
</tr>
<tr>
<td>5.5</td>
<td>Pore volume distribution in coal samples determined by mercury intrusion</td>
<td>130</td>
</tr>
<tr>
<td>5.6</td>
<td>Variation of carbon dioxide surface area of coals with carbon content</td>
<td>136</td>
</tr>
<tr>
<td>5.7</td>
<td>Relationship between the volume of macro-pores and the volume of minerals in coal</td>
<td>139</td>
</tr>
<tr>
<td>5.8</td>
<td>SEM photographs showing the association of macro-pores with mineral matter in coal</td>
<td>141</td>
</tr>
<tr>
<td>5.9</td>
<td>X-Y plots showing the relationship between various pore sizes and the pore volume determined by CO₂ adsorption</td>
<td>143</td>
</tr>
<tr>
<td>5.10</td>
<td>Relationship between the volumes of meso- and micro-pores and coal macerals</td>
<td>144</td>
</tr>
<tr>
<td>5.11</td>
<td>CH₄ sorption isotherms at 25°C</td>
<td>148</td>
</tr>
<tr>
<td>5.12</td>
<td>CO₂ sorption isotherms at 25°C</td>
<td>149</td>
</tr>
<tr>
<td>5.13</td>
<td>CH₄, CO₂ and mixed gas sorption isotherms for Bulli Coal</td>
<td>152</td>
</tr>
<tr>
<td>5.14</td>
<td>Sorption isotherms for different partial pressures of (CH₄/CO₂) from Bulli seam</td>
<td>152</td>
</tr>
<tr>
<td>5.15</td>
<td>Product-moment correlation matrix for experimental data</td>
<td>156</td>
</tr>
<tr>
<td>5.16</td>
<td>R-mode cluster analyses dendrogram for the experimental data</td>
<td>157</td>
</tr>
<tr>
<td>5.17</td>
<td>Relationship between the sorption capacity and the ash yield of coal</td>
<td>158</td>
</tr>
<tr>
<td>5.18</td>
<td>Relationship between the sorption capacity and the volume of minerals in coal</td>
<td>158</td>
</tr>
<tr>
<td>5.19</td>
<td>Relationship between the sorption capacity and fixed carbon content</td>
<td>160</td>
</tr>
<tr>
<td>5.20</td>
<td>Relationship between sorption capacity and vitrinite reflectance</td>
<td>161</td>
</tr>
<tr>
<td>5.21</td>
<td>Relationship between the sorption capacity and volatile matter yield</td>
<td>161</td>
</tr>
<tr>
<td>5.22</td>
<td>Relationship between the sorption capacity and volume of telovitrinite</td>
<td>162</td>
</tr>
<tr>
<td>5.23</td>
<td>Relationship between the sorption capacity and volume of detrovitrinite</td>
<td>162</td>
</tr>
<tr>
<td>5.24</td>
<td>Relationship between the sorption capacity and volume of semifusinite</td>
<td>163</td>
</tr>
<tr>
<td>5.25</td>
<td>Relationship between the sorption capacity and volume of fusinite</td>
<td>163</td>
</tr>
<tr>
<td>5.26</td>
<td>Sorption isotherms (dry ash free) for samples MP-1 and MP-2</td>
<td>165</td>
</tr>
<tr>
<td>5.27</td>
<td>CH₄ desorption curves for coal samples</td>
<td>170</td>
</tr>
<tr>
<td>5.28</td>
<td>CO₂ desorption curves for coal samples</td>
<td>174</td>
</tr>
<tr>
<td>5.29</td>
<td>Relationship between the diffusion parameter and temperature for CH₄</td>
<td>184</td>
</tr>
<tr>
<td>5.30</td>
<td>Relationship between the desorption rate and the initial CH₄ pressure</td>
<td>185</td>
</tr>
<tr>
<td>5.31</td>
<td>Relationship between the CH₄ emission rate and the initial gas content</td>
<td>186</td>
</tr>
</tbody>
</table>
5.32 Relationship between the CH$_4$ emission rate and ash yield 186
5.33 Relationship between the CH$_4$ emission rate and the coal macerals 187
5.34 Photomicrograph showing the preferential fracturing 189
properties of vitrinite
5.35 SEM photographs of coals showing the well developed fractures 190
in vitrinite
5.36 Frequency distribution of gas emission rates for the coals 193
from the West Cliff and Tahmoor areas
5.37 Frequency distribution for CH$_4$ and CO$_2$ emission rates 195
5.38 Frequency distribution of the gas emission rates for Bulli and 196
Wongawilli seams

6.1 Map showing the locations of seam gas data 200
6.2 Example of a desorption curves for the Wongawillli seam, TNC6 201
6.3 Histogram showing the distribution of measured N$_2$ 204
proportion in seam gas
6.4 Frequency distributions showing the proportion of CO$_2$ in seam gas 206
6.5 Stratigraphic variations in the CO$_2$:CH$_4$ ratio for selected deep holes 207
6.6 Contour map showing the proportion of CO$_2$ in the Bulli seam 209
6.7 Contour map showing the proportion of CO$_2$ in the Balgownie seam 210
6.8 Contour map showing the proportion of CO$_2$ in the Wongawillli seam 211
6.9 Distribution of ethane in the Bulli seam gas 213
6.10 Frequency distribution of the desorbable gas content for 216
the major seams
6.11 Contour map showing the desorbable gas content of the Bulli seam 217
6.12 Contour map showing the desorbable gas content of the Balgownie seam 218
6.13 Contour map showing the desorbable gas content of the 219
Wongawillli seam
6.14 Distribution of residual gas content in coal seams 221
6.15 Example of a variogram and its parameters 225
6.16 Krigged estimates of the proportion of CO$_2$ in the Bulli seam, 229
Iluka-Wedderburn area
6.17 Krigged estimates of the proportion of CO$_2$ in the Balgownie seam, 229
Iluka-Wedderburn area
6.18 Krigged estimates of the desorbable gas content in the Bulli seam, 230
Iluka-Wedderburn area
6.19 Krigged estimates of the desorbable gas content in the Balgownie seam, 230
Iluka Wedderburn area
6.20 Krigged estimates for the proportions of CO$_2$ in the Bulli seam 232
6.21 Krigged estimates for the desorbable gas content of the Bulli seam 233

7.1 Schematic model depicting the stages of gas generation, expulsion 240
and resorption
7.2 Some common structural traps for oil and gas accumulation 243
7.3 Relationship between percentage of CO$_2$ in seam gas and 244
vitrinite reflectance
7.4 Relationship between the percentage of CO$_2$ in seam gas and the vitrinite 246
content
7.5 Major geological structures and the variations in CO₂ content of the Bulli seam 247
7.6 Cross-section showing the relationship between geological structure and percentage of CO₂ in coal seam gas 249
7.7 Variations in δ¹³C values of CO₂ with changing CO₂ concentrations in seam gas 250
7.8 Percentage of CO₂ in Bulli seam gas and known major igneous intrusions in the area 252
7.9 Percentage of CO₂ in seam gas and the major structural features of the Bulli seam, West Cliff area. 254
7.10 Hypothetical model depicting the introduction of CO₂ from the Woronora igneous province towards Woronora anticline and Metropolitan Fault 257
7.11 Solubility of CO₂ and variations in the volume of CO₂ coal seam gas with depth 260
7.12 Variations in the volume of long chain hydrocarbons in seam gas and depth 266
7.13 Relationship between the volume of long chain hydrocarbons in seam gas and vitrinite reflectance 268
7.14 Variations in the volume of long chain hydrocarbons in coals and sandstones with depth 270
7.15 Relationship between the in-situ gas contents and ash yield of coals 272
7.16 Relationship between the in-situ gas contents and fixed carbon content of coals 273
7.17 Relationship between the in-situ desorbable gas content and ash yield for BL8 and BL9 274
7.18 Relationship between th in-situ desorbable gas content and fixed carbon content for BL8 and BL9 275
7.19 Relationship between seam gas contents (daf) and vitrinite reflectance 278
7.20 Relationship between seam gas contents (daf) and volume of vitrinite in coal 279
7.21 Relationship between seam gas contents (daf) and depth 280
7.22 Relationship between the desorbable gas content (daf), averaged over 50 m intervals, and depth for coals of the southern Sydney Basin 282
7.23 Variations in the desorbable gas content (daf) of the Bulli seam 284
7.24 Cross-sections showing the variations in the desorbable gas content (daf) with depth and geological structure 286
7.25 Relationship between the desorbable gas content (daf) and depth of Bulli seam, West Cliff area 287
7.26 Desorbable gas content (daf) and major geological structures of the Bulli seam, West Cliff area 290
7.27 Prospective areas for further methane exploration 294
# LIST OF TABLES

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Stratigraphy of the southern Sydney Basin.</td>
<td>16</td>
</tr>
<tr>
<td>3.1</td>
<td>Classification of coal macerals.</td>
<td>35</td>
</tr>
<tr>
<td>3.2</td>
<td>Summary of maceral composition of the major seams.</td>
<td>37</td>
</tr>
<tr>
<td>3.3</td>
<td>Input data used for geohistory modelling.</td>
<td>63</td>
</tr>
<tr>
<td>3.4</td>
<td>Modelled heat flow and thickness of eroded section.</td>
<td>68</td>
</tr>
<tr>
<td>5.1</td>
<td>List of samples used for gas sorption-desorption testing.</td>
<td>118</td>
</tr>
<tr>
<td>5.2</td>
<td>Petrographic and proximate analyses data for the samples tested.</td>
<td>119</td>
</tr>
<tr>
<td>5.3</td>
<td>Densities, pore volumes and porosities of selected coals.</td>
<td>126</td>
</tr>
<tr>
<td>5.4</td>
<td>Densities of the major maceral groups.</td>
<td>126</td>
</tr>
<tr>
<td>5.5</td>
<td>Surface area of coals determined by CO₂ sorption.</td>
<td>127</td>
</tr>
<tr>
<td>5.6</td>
<td>Pore volumes estimated from different methods.</td>
<td>127</td>
</tr>
<tr>
<td>5.7</td>
<td>Volume of methane sorbed on coal samples.</td>
<td>139</td>
</tr>
<tr>
<td>5.8</td>
<td>Volume of carbon dioxide sorbed on coal samples.</td>
<td>139</td>
</tr>
<tr>
<td>5.9</td>
<td>Langmuir constants for the coal samples.</td>
<td>154</td>
</tr>
<tr>
<td>5.10</td>
<td>Diffusion parameters for methane and carbon dioxide.</td>
<td>177</td>
</tr>
<tr>
<td>5.11</td>
<td>Emission constants for methane and carbon dioxide.</td>
<td>181</td>
</tr>
<tr>
<td>5.12</td>
<td>Emission constants for the first hour of desorption.</td>
<td>182</td>
</tr>
<tr>
<td>6.1</td>
<td>Gas composition in the major coal seams.</td>
<td>203</td>
</tr>
<tr>
<td>6.2</td>
<td>Desorbable gas content in the major coal seams.</td>
<td>203</td>
</tr>
<tr>
<td>6.3</td>
<td>Variogram parameters for the Iluka-Wedderburn area.</td>
<td>227</td>
</tr>
<tr>
<td>6.4</td>
<td>Variogram parameters for the study area.</td>
<td>227</td>
</tr>
</tbody>
</table>