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

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NOTE

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CHAPTER 6. COAL SEAM GASES IN THE ILLAWARRA

COAL MEASURES

6.1 DATA ACQUISITION

Four hundred and eleven records (composite values) of gas data for coal seams in the Illawarra Coal Measures, determined by various coal and petroleum exploration companies, were available for this study. The localities of these data points is shown in Figure 6.1. The data used for this study were measured according to the ‘Direct Method’ of gas content determination (details were given in Diamond and Levine, 1981; Standards Association of Australia, 1991). This technique involves coring the coal seam and placing the sample in a canister to measure the volume of gas desorbed at atmospheric pressure. Three components (Fig. 6.2) are measured - ‘lost gas (Q₁)’, ‘measurable gas (Q₂)’ and ‘residual gas (Q₃)’. The total in-situ gas content of the sample is obtained from the total of Q₁, Q₂ and Q₃.

Lost gas is the volume of gas lost from the sample, during the period of time from its removal from the in-situ position and its enclosure in the desorption canister and consequent measurement of Q₂. Measurable gas (Q₂) is the volume of gas desorbed from the coal sample while enclosed in the canister at atmospheric pressure. After the measurable volume of gas desorbed becomes negligible, the sample (usually in the form of three sub-samples) is pulverised in a gas tight container at atmospheric pressure to measure the residual gas content (Q₃). These measured values are usually converted to
Figure 6.1 Locations of seam gas data.
Figure 6.2 Example of a desorption curves for the Wongawilli seam, TNC 6.
standard temperature and pressure conditions (that is 0°C and 101.1 kPa).

Composition of the gas desorbed is determined by taking the average of a several sub-samples (at least 3 sub-samples are recommended by the Standards Association of Australia, 1991) at various stages of desorption. Gas compositions are usually reported on an air free basis, which eliminates the effect of air contamination. Some data on the gas composition of the non-coaly intervals are also available for this study. A detailed list of the coal seam gas content and composition data used in this study are given in Appendix 3 and a summary of the gas composition of different coal seams is shown in Table 6.1.

The main aims of this chapter is to evaluate the gas contents and compositions of the coal seams and to describe stratigraphic and spatial variations of both. Detailed evaluation of the geological controls will be presented in the Chapter 7.

6.2 SEAM GAS COMPOSITION

The two main gases in the coal seams of the Illawarra Coal Measures are methane and carbon dioxide. Ethane and nitrogen occur as subsidiary amounts and trace amounts of other hydrocarbons, argon, helium and hydrogen are found. For more than 85% of the data, the N_2 content is less than 15% and the mean value for all data is approximately 7% (Fig. 6.3). The anomalously high N_2 values appear to be erroneous and they are believed to have been caused by severe air contamination especially from leaking canisters (Hargraves, pers. comm.). In addition, because some of the oxygen may have reacted
Table 6.1 A summary of gas composition in the major coal seams based on surface borehole data

<table>
<thead>
<tr>
<th>Seam</th>
<th>Samples</th>
<th>CH4%</th>
<th>CO2%</th>
<th>C2H6%</th>
<th>N2%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulli</td>
<td>132</td>
<td>0.4 - 100</td>
<td>0.0 - 99.5</td>
<td>0.0 - 7.5</td>
<td>0.2 - 79.7</td>
</tr>
<tr>
<td>Balgownie</td>
<td>111</td>
<td>0.9 - 99.0</td>
<td>0.0 - 99.1</td>
<td>0.0 - 7.5</td>
<td>0.0 - 79.3</td>
</tr>
<tr>
<td>Cape Horn</td>
<td>31</td>
<td>0.0 - 97.0</td>
<td>0.0 - 97.0</td>
<td>0.0 - 6.0</td>
<td>0.5 - 22.1</td>
</tr>
<tr>
<td>Wongawilli</td>
<td>81</td>
<td>0.5 - 100</td>
<td>0.5 - 98.7</td>
<td>0.0 - 9.5</td>
<td>0.3 - 62.6</td>
</tr>
<tr>
<td>Tongarra</td>
<td>22</td>
<td>3.2 - 96.5</td>
<td>0.3 - 96.5</td>
<td>0.0 - 10.0</td>
<td>0.3 - 12.5</td>
</tr>
</tbody>
</table>

Table 6.2 A summary of desorbable gas content in the major coal seams based on surface borehole data

<table>
<thead>
<tr>
<th>Seam</th>
<th>Samples</th>
<th>Qd (m3/t)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td>Bulli</td>
<td>94</td>
<td>0.3 - 18.1</td>
<td>8.8</td>
</tr>
<tr>
<td>Balgownie</td>
<td>90</td>
<td>0.3 - 19.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Cape Horn</td>
<td>27</td>
<td>1.6 - 9.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Wongawilll</td>
<td>65</td>
<td>0.2 - 12.7</td>
<td>6.3</td>
</tr>
<tr>
<td>Tongarra</td>
<td>19</td>
<td>3.7 - 11.4</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Figure 6.3 Histogram showing the distribution of measured N₂ proportion in coal seam gases.
with the freshly exposed coal or the metal surface it is not possible to accurately estimate the volume of excess $N_2$ that was initially derived from air (Creedy and Prichard, 1983; Smith and Gould, 1985). Accordingly, in cases of severe oxidation, the estimated $N_2$ values may be very high and, consequently, when the proportion of $N_2$ is very high (> 15%) the gas composition data may be unreliable.

As the two dominant gas components of the coal seams of the study area are $CH_4$ and $CO_2$ most of the detailed discussion here will be directed towards the variations of these two gases, especially the $CO_2$:CH$_4$ ratio.

6.2.1. Occurrence of $CH_4$ and $CO_2$ in coal seams

Histograms showing the distribution of the $CO_2$:CH$_4$ ratio for different coal seams in the Illawarra Coal Measures are presented in Figure 6.4. These histograms clearly indicate that all the seams show a wide range of gas mixtures varying from virtually pure $CH_4$ to pure $CO_2$. However, more cases with dominantly $CO_2$ are found in the Bulli and Balgownie seams than in the stratigraphically lower Wongawilli seam.

The stratigraphic variations in the $CO_2$:CH$_4$ ratios exhibit several trends (Fig. 6.5):

- (a) either a gradual or rapid decrease in the $CO_2$ content with increasing depth;
- (b) quadratic change with increasing depth;
- (c) slight increase in $CO_2$ content with increasing depth; and
- (d) approximately constant gas compositions with depth.

The dominant trend is trend (a) where the proportion $CO_2$ in seam gas decreases with
Figure 6.4  Frequency distributions showing the proportion of CO₂ in seam gas.
Figure 6.5  Stratigraphic variations in the CO₂:CH₄ ratios for selected deep holes.
depth. Trend (c) is rare; not one example showing a rapid increase in the proportion of CO₂ with depth was observed. In most regions the proportion of CO₂ decreases with increasing depth, irrespective of the absolute CO₂ content. Accordingly, the CO₂ content of the coal seams occurring within the Eckersley Formation (for example, Balgownie and Cape Horn seams) and the overlying Bulli seam are generally higher than the stratigraphically lower seams such as the Wongawilli and Tongarra seams.

Spatial distribution of the seam gas composition is complicated and shows wide variations, both locally and regionally. Contoured maps showing the lateral variations in the CO₂:CH₄ ratios for Bulli, Balgownie and Wongawilli seams were constructed by employing an inverse distance squared gridding method (Figs. 6.6 to 6.8). These maps indicate that CH₄ is the dominant seam gas component in a belt running N-S along the central part of the study area. On either side of this belt the percentage of CO₂ is higher and the variations in gas composition show a more complicated pattern. This general pattern is shown by all of the seams. However, as shown before, in any particular area the percentage of CO₂ generally decreases as follows; Bulli seam > Balgownie seam > Cape Horn seam > Wongawilli seam. Greater spatial variability is shown by the stratigraphically higher Bulli and Balgownie seams relative to the deeper Wongawilli seam which generally has a lower CO₂ content.

6.2.2 C₂H₆ and Longer Chain Hydrocarbons.

Ethane (C₂H₆) is a relatively minor component in seam gases and accounts for less than 10.5% of the total gas content. In most cases it occurs in trace amounts only (Table 6.1). Longer chain hydrocarbons (C₂+) also occur ranging from trace amount to 1.3%. These
Figure 6.6 Contour map showing the proportion of CO₂ in the Bulli seam.
Figure 6.7 Contour map showing the proportion of CO$_2$ in the Balgownie seam.
Figure 6.8 Contour map showing the proportion of CO$_2$ in the Wongawilli seam.
values are consistent with those found in seam gases of other parts of the world such as in Britain (Creedy, 1985), U.S.A. (Rightmire et al., 1984), Germany (Kneuper and Hükel, 1972) and Poland (Kotabra, 1990).

The spatial variations in the percentage of C₂H₆% in the Bulli seam, shown in Figure 6.9, indicate that relatively higher proportions of this gas occur towards the north with the highest amounts found in the north central part (in boreholes NP1, NP2, NP3 and BL8). The high concentration of C₂H₆ coincides with the dominance of CH₄ in the seam gas (that is low in CO₂; see Figures 6.6 and 6.9), a pattern generally shown by all seams.

6.3 **IN-SITU GAS CONTENT**

*In-situ* coal seam gas content data used in this study are those measured on coal cores from surface exploration boreholes employing the Direct Method for gas content determination. Although some data from mine samples and in-seam boreholes are also available they were not used because those values are likely to have been affected by mining activity and may not represent the true *in-situ* gas content.

**Lost Gas**

As discussed in the introductory section of this chapter, the total gas content of a coal sample comprises three components, Q₁, Q₂ and Q₃. It has been empirically established that when the sampling delay is small the volume of lost gas (Q₁) may be estimated from the relationship which is based on the Airey's equation (Airey, 1968; Creedy, 1985):
Figure 6.9 Distribution of ethane in the Bulli seam gas.
\[ Q_s = \frac{Q_0 t_k^{1/2}}{t_k^{1/2}} - Q_1 \] ...... (6.1)

where,  
\[ \begin{align*}
    t & \quad \text{time} \\
    Q_s & \quad \text{cumulative measured quantity of gas evolved in the canister} \\
    Q_0 & \quad \text{initial gas content} \\
    t_k & \quad \text{time constant (also see chapter 4)}
\end{align*} \]

\( Q_1 \) is represented by the intercept of the plot \( Q_s \) and \( t^{1/2} \) (Fig. 6.2). For the estimate of \( Q_1 \) to be accurate, the \( t \) (sampling delay) should be small as possible; according to Creedy (1985), \( t \) should be less than 15 hours for equation 6.1 to estimate \( Q_1 \) accurately. For majority of the data used in this study, \( t \) is less than 1 hour and therefore, the relative error in the estimation of the value of \( Q_1 \) is small.

For the data set used in this study, the value of \( Q_1 \) ranges from 1\% to 40\% of the total gas content. The value of \( Q_1 \) contains the greatest relative error of the three stages of measurements, as it is based on extrapolation. Creedy (1985), who worked on some British coals, pointed out that when the value of \( Q_1 \) exceeds 40\% of the total measured gas content, the extrapolation is too large and the resulting values of \( Q_1 \) are possibly erroneous. In the data set used for this study such unacceptably high \( Q_1 \) values were not encountered.

**Desorbable Gas**

With regard to coal mining, the desorbable gas \((Q_1 + Q_2)\) is the most significant component of seam gas measurements. Furthermore, the desorbable gas content marks the upper
lim. for the economical production of gas from coal seams.

Histograms showing the distribution of desorbable gas contents for the major seams are presented in Figure 6.10. Desorbable gas contents in the coal seams of the Illawarra Coal Measures vary from less than 1 m$^3$/t up to 20 m$^3$/t ($m^3/t = cm^3/g$; Table 6.1 and Fig 6.10) although values of up to 23 m$^3$/t have been reported from individual plies in the Bulli and Balgownie seams (for example, WER 3). Desorbable gas content of Bulli and Balgownie seams varies from less than 1 m$^3$/t up to 20 m$^3$/t, with average values of 9 m$^3$/t and 8 m$^3$/t, respectively. The average gas content of the other stratigraphically lower seams are relatively low with mean values of 5 m$^3$/t, 6.5 m$^3$/t and 7.5 m$^3$/t for Cape Horn, Wongawilli and Tongarra seams, respectively. These differences in gas contents between the upper and lower seams give a bimodal distribution in the histogram (Fig 6.11a) indicating the presence of two populations - Population P1 corresponding to the lower seams that have low gas contents and population P2 corresponding to the Bulli and Balgownie seams which have higher gas contents.

Lower gas contents in the deeper seams are mostly attributed to the occurrence of high volumes of mineral matter and lower CO$_2$ contents. In addition, as discussed in Chapter 3 these lower seams have a different maceral composition to the upper seam; the lower seams are rich in vitrinite relative to the Bulli and Balgownie seams which may also be influencing the differences in gas contents.

The spatial variations in desorbable gas contents for the three main seams, Bulli, Balgownie and Wongawilli seams, are shown as contour maps in Figures 6.11 to 6.13.
Figure 6.10  Frequency distributions of the desorbable gas content for the major seams.
Figure 6.11 Contour map showing the desorbable gas content of the Bulli seam.
Figure 6.12 Contour map showing the desorbable gas content of the Balgownie seam.
Figure 6.13 Contour map showing the desorbable gas content of the Wongawilli seam.
These maps were constructed using an inverse distance squared gridding method. Construction of such maps for other seams was not feasible due to the paucity of data.

Spatially, all the coal seams show substantial variability throughout the study area. Generally, however, higher desorbable gas contents are found towards the central part whereas very low gas contents (<4 m³/t) occur towards the south. These variations in relation to the gas composition and geology will be evaluated in Chapter 7.

Residual Gas

Residual gas represents gas that is entrapped within the coal matrix after long periods of desorption at ambient temperature and pressure conditions. This residual gas may not be released from the coal during mining or economical gas production and hence it is of less practical significance. Therefore, for majority of the data available for this study the residual gas content has not been measured.

For coals of the Illawarra Coal Measures, the residual gas content ($Q_3$) varies from zero to 4.1 m³/t with a mean value of 0.88 m³/t (Fig. 6.14). For the majority of data, the value of $Q_3$ is less than 2 m³/t. Proportionally, $Q_3$ varies from less than 1% to approximately 60% of the total gas content. As indicated in Figure 6.14 for more than 80% of the data presented, the percentage of $Q_3$ is less than 15% with a mean of 12.7%.

The volume of residual gas in coal is primarily controlled by the desorption and diffusion rates (Diamond and Levine, 1981) and hence it is significantly dependant on whether sufficient time was allowed for all the desorbable gas ($Q_1+Q_2$) to be desorbed or not.
Figure 6.14 Distribution of residual gas content in coal seams of the Illawarra Coal Measures.
The very high $Q_3$ values could be attributed to the fact that insufficient time was allowed for complete desorption to occur, probably because of technical difficulties.

In this study no directly predictable relationship between $Q_3$ and either coal rank, type or gas composition was observed. However, stepwise multiple regression analyses (details of the procedure are given in Weisberg, 1985), using the least squares fit method, indicate that the value of $Q_3$ is positively correlated with the volume of inertinite and negatively correlated with the ash yield and the CO$_2$% (equation 6.1). Using Z-scores (standardised residuals) of the variables to normalise for measurement units, gas composition and the maceral composition of the coal exerts the greatest influence on the residual gas content (equation 6.2); residual gas content increases with increasing inertinite content and decreases with increasing CO$_2$ content and ash yield (or mineral matter content) as shown below.

$$Q_3 \text{(m}^3/\text{t}) = 0.867 - 0.0173 \text{CO}_2\% + 0.0223 \text{In}\% - 0.0145 \text{Ash}\% \quad \cdots(6.1)$$

where, $\text{In} = \text{inertinite}$

$Q_3 = \text{residual gas content}$

$N = 49$

$R^2 = 31.7\%$

and,

$$(Z)Q_3 = 0.339 - 0.434 (Z)\text{CO}_2\% + 0.324 (Z)\text{In}\% - 0.718(Z)\text{Ash}\% \quad \cdots(6.2)$$
These observations are consistent with the experimental results (Chapter 5) which indicates that the gas desorption rates are higher for vitrinite- and mineral matter-rich coals, and CO₂-rich gases. Accordingly, at a given time, the residual gas content (gas remaining within the coal) is expected to be small for coals with abundant vitrinite, mineral matter and containing dominantly CO₂. However, it should be noted that the computed multiple regression equation satisfactorily accounts for approximately 32% of the variability and rest of the variability may be caused by other geological factors and technical error. The coals which had a very high residual gas content (> 3 m³/t) showed a large standard residual in the regression equation indicating that factors other than those considered in the regression analyses may also be strongly influencing the residual gas content. Levine (1992b) suggested that the residual gas content is also rank dependent, and the highest values, up to 5 m³/t, have been recorded from high volatile bituminous A coals (approximate vitrinite reflectance range 0.75% and 1.1%) which are within the stage of peak hydrocarbon generation (so called 'oil window'). Levine (1992b) attributed such high residual gas contents to the very low diffusion rates caused by the obstruction of pores by occluded hydrocarbons (especially long chain hydrocarbons).

6.4 GEOSTATISTICAL STUDY OF GAS DISTRIBUTION

Geostatistics is an important statistical tool which is useful for describing the spatial continuity of a spatially distributed data set. The basic difference between geostatistics and classical statistics is that the latter assumes that the samples considered for deducing the unknown population are random and independent. Geostatistics assumes that samples
located at close intervals are better correlated to each other spatially than those located further away. Therefore, the correlation between samples is a decreasing function of distance.

The comparison of adjoining samples is achieved by calculating a semi-variogram (variogram; details in Journel and Huijbretts, 1978). A semi-variogram represents the variability among samples as a function of distance and is defined as the difference between half the mean square of sample values. In addition to spatial correlation, the variogram also provides information on the range of influence of a sample value in a nominated direction.

Variograms can be omnidirectional or multidirectional in any number of specified directions. Four basic types of variogram models are commonly used; these are spherical, exponential, linear and gaussian. An example of a spherical variogram is shown in Figure 6.15 and the three important parameters that can be deduced from a variogram are,

- **range** - represents the maximum range of influence of one sample to another; beyond this distance samples are no longer correlatable and are independent of one another; the range is the distance at which the variogram flattens out and if there is anisotropy in the spatial variations of the sample values, the range in different directions is variable.

- **sill** - is the plateau which the variogram reaches and represent the total variability of the data.
Figure 6.15 Example of a variogram and its parameters.
nugget - is the value of the variogram at a distance zero; nugget effect represents the short term variability of the samples, and in most cases, sampling error can account for the nugget effect.

Once the variogram parameters have been computed, krigging can be used to estimate a parameter. Krigging is a geostatistical method which is used to estimate the value of an unknown point based on the value of surrounding points. The main aims of the estimator are to establish an unbiased estimate and minimise error variance. The idea of an unbiased estimate is to have a zero error on the expected value so that the estimator predicts the correct value. Ordinary krigging considers two important aspects in estimation problems - distance and clustering. Krigging has the ability to use clustered data optimally and therefore has an advantage over other deterministic estimation methods such as inverse distance squared, polygonal or triangulation methods (Issaks and Srivastava, 1989; Baafl and Kim, 1983). However, this method is most effective for local estimation in an area with closely spaced sample data rather than for a regional-scale data set.

Krigged estimates of gas contents and CO₂% for Bulli and Balgownie seams were conducted on an exploration area covering 150 km², belonging to Kembla Coal and Coke Limited (Iluka-Wedderburn). The technique, if successful will be useful for the prediction of gas content or 'gassiness' of coal seams during future mining. This area was found to be most suitable for this purpose because of the high density of closely-spaced data points.
Table 6.3  Exponential variogram parameters of gas content and composition data, Iluka-Weddleburn area.

<table>
<thead>
<tr>
<th>Seam</th>
<th>Variable</th>
<th>Nugget</th>
<th>Sill</th>
<th>Range</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>maximum</td>
<td>minimum</td>
<td>maximum</td>
</tr>
<tr>
<td>Bulli</td>
<td>CO₂%</td>
<td>11.2(%)²</td>
<td>1580(%)²</td>
<td>3000m</td>
<td>1550m</td>
</tr>
<tr>
<td></td>
<td>gas content</td>
<td>0</td>
<td>9.3(m³/t)²</td>
<td>2800m</td>
<td>2100m</td>
</tr>
<tr>
<td>Balgownie</td>
<td>CO₂%</td>
<td>38.3(%)²</td>
<td>1520(%)²</td>
<td>3100m</td>
<td>1500m</td>
</tr>
<tr>
<td></td>
<td>gas content</td>
<td>0</td>
<td>11.2(m³/t)²</td>
<td>4000m</td>
<td>1200m</td>
</tr>
</tbody>
</table>

Table 6.4  Exponential variogram parameters of the Bulli seam for the entire study area

<table>
<thead>
<tr>
<th>Area</th>
<th>Variable</th>
<th>Nugget</th>
<th>Sill</th>
<th>Range</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>maximum</td>
<td>minimum</td>
<td>maximum</td>
</tr>
<tr>
<td>west</td>
<td>CO₂%</td>
<td>0</td>
<td>1280(%)²</td>
<td>6700m</td>
<td>5100m</td>
</tr>
<tr>
<td>east</td>
<td>CO₂%</td>
<td>0</td>
<td>950(%)²</td>
<td>2500m</td>
<td>2000m</td>
</tr>
<tr>
<td></td>
<td>gas content</td>
<td>0</td>
<td>8.5(m³/t)²</td>
<td>1700m</td>
<td>2100m</td>
</tr>
</tbody>
</table>
An exponential type variogram fits both gas content and composition data for the Bulli and Balgownie seams. Variogram parameters for these data are summarised in Table 6.3 and the contour maps showing the krigged estimates are shown in Figures 6.16 to 6.19. Variograms for the CO$_2$ data of both seams show very similar parameters and show significant geometric anisotropy. The direction of maximum range for both seams are NW-SE (120°), which parallels the major structural trends of the area. This indicates that the CO$_2$ levels in seam gas are most continuous along a NW-SE direction but vary rapidly along a NE-SW (030°) direction. This direction of the maximum range parallels most of the major structures in this region and therefore indications are that the variations in the gas composition may be related to the geological structure.

The desorbable gas content data for the Bulli seam shows less anisotropy whereas those for the Balgownie seam show strong anisotropy with NNW-SSE being the direction of maximum continuity.

To determine if the method is effective for estimating regional variations, and to identify any structural anisotropy, krigging was also attempted for Bulli seam desorbable gas content and composition over the entire study area. Because the variogram parameters in the Iluka-Wedderburn area indicated that there may be some structural control on the variations in the gas composition, the area was sub-divided into two parts along a north-south axis (273000 Easting) approximating the axis of the Camden Syncline. The reason for this division is that the structures on either side of this syncline show different trends. The western limb of the Camden Syncline shows dominantly of a series of N-S trending eastward dipping monoclines. In contrast, the eastern limb is characterised by a series of
Figure 6.16 Krigged estimates of the proportion of CO₂ in the Bulli seam, Iluka-Wedderburn area.

Figure 6.17 Krigged estimates of the proportion of CO₂ in the Balgownie seam, Iluka-Wedderburn area.
Figure 6.18  Krigged estimates of the desorbable gas content in the Bulli seam, Iluka-Wedderburn area.

Figure 6.19  Krigged estimates of the desorbable gas content in the Balgownie seam, Iluka-Wedderburn area.
NW-SE trending anticlines and synclines.

Again an exponential type variogram was observed to fit the gas composition data and shows a strong geometric anisotropy (Table 6.4). The direction of maximum continuity of data on the western side is approximately N-S and on the eastern side NW-SE. These directions conform with the major structural trends of the respective areas and may be again an indication that the variations in the gas composition are related to the geological structures.

Desorbable gas content data for the Bulli seam was best modelled by a single variogram. In this case, the directions of maximum and minimum continuity of data are ENE-WSW (070°) and NNW-SSE (160°), respectively, but this does not show a strong anisotropy. The direction of minimum continuity approximates the direction in which the depth to coal seam varies rapidly and hence the gas contents are least continuous in this direction.

Although there are some subtle local variations regionally, contour maps constructed using kriged data show similar contour patterns to those constructed using an inverse distance squared gridding method (Figs 6.20 and 6.21). However, as indicated before, kriged estimates may be a useful method to accurately estimate the gas contents and compositions in relatively small areas (for example on a coal mine scale) given that sufficient information is available from prior exploration.
Figure 6.20 Krigged estimates for the proportion of CO₂ in the Bulli seam.
Figure 6.21 Krigged estimates for the desorbable gas content of the Bulli seam.
6.5 SUMMARY

Coal seam gases of the Illawarra Coal Measures consist dominantly of CH\textsubscript{4} and CO\textsubscript{2} with minor amounts of N\textsubscript{2}, C\textsubscript{2}H\textsubscript{6} and long chain hydrocarbons. The amount of CO\textsubscript{2} and CH\textsubscript{4} is highly variable both spatially and stratigraphically. In majority of the boreholes the greatest amount of CO\textsubscript{2} is found in the upper seams with the proportion of CO\textsubscript{2} gradually decreasing with increasing depth. Spatial variations indicate that CH\textsubscript{4} is the dominant seam gas along a central N-S trending belt. On either side of this belt higher proportions of CO\textsubscript{2} are found and the variations show a more complex pattern. Although C\textsubscript{2}H\textsubscript{6} is a relatively minor component an enrichment of this gas is seen towards the north of this central CH\textsubscript{4} rich belt.

The volumes of gas desorbed from coal seams of the Illawarra Coal Measures coal seams ranges from less than 1 m\textsuperscript{3}/t up to 20 m\textsuperscript{3}/t. Higher gas contents are generally found in the upper seams, that is, in the Bulli and Balgownie seams, relative to the underlying seams.

Multiple regression analyses suggest that the residual gas content of the coal (at ambient pressure temperature conditions) is related to the compositions of the coal and gas. Residual gas content increases with increasing inertinite content and decreasing proportions of mineral matter and CO\textsubscript{2} gas.

Variogram analyses of gas composition data indicate a strong geometric anisotropy. The directions of maximum continuity on either side of Camden Syncline closely correspond to
the directions of the major structural features, that is, approximately N-S in the west and NW-SE in the east. This is a probable indication that variations in gas composition are structurally controlled.

Variogram analyses of gas content data indicate considerably less geometric anisotropy. The direction of minimum continuity of gas content data, ENE-WSW, approximates the direction in which depth of cover is most variable.