Regional coal seam gas distribution and burial history of the Hunter Coalfield, Sydney Basin

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Basin modelling has been used to improve understanding of the origin and temporal evolution of coal seam gas in the Hunter Coalfield of the Sydney Basin. Burial history models were produced based on data from seven boreholes located in the southern, eastern, central and western areas of the coalfield. Mean random vitrinite reflectance ($R_{v,r}$) data, derived from measurements of mean maximum reflectance ($R_{v,max}$), were used for calibration of the models. A qualitative sensitivity analysis of one model shows that varying the paleoheat flow has a greater influence on calculated $R_{v,r}$ than varying the eroded overburden thickness.

The differences between the constructed models are significant enough to provide plausible explanations for regional gas distribution in the Hunter Coalfield. Coals in the south of the coalfield appear to have the greatest potential for thermogenic gas generation. Modelling has shown that areas that have low gas contents and decreased permeability have been uplifted more, and buried less, compared with areas that have high gas contents. Burial history modelling shows noticeable variations in the extent of burial and uplift, and, consequently, in thermal maturities and potential for thermogenic gas generation; together with the assessment of other coal and gas property data, it appears that present-day gas contents may partially reflect coal ranks and adsorption capacities, with late-stage biogenic gas generation replenishing CH$_4$ volumes that were lost following uplift during the Late Cretaceous.

KEYWORDS: burial history, thermal maturity, Hunter Coalfield, Sydney Basin, coal seam gas, reservoir properties.

INTRODUCTION

Modelling of burial and thermal maturity histories of sedimentary basins has been used to study the evolution of gases from coals (Hildenbrand et al. 2006; Faiz et al. 2007a; Zhang et al. 2008), providing an improved understanding of gas distribution for the purposes of CH$_4$ production from coal seams and estimation of greenhouse gas (GHG) emissions from coal mining. The coal seams of eastern Australia contain significant volumes of gas generated through thermogenic, biogenic and magmatic processes, and gas generation was either directly or indirectly influenced by the burial histories of the sedimentary basins.

Numerous researchers have investigated the origin and composition of gases in eastern Australian coals. Boreham et al. (1998) suggested that thermogenic methane (CH$_4$) and heavier hydrocarbons in the Bowen Basin were produced at two stages during coal maturation, and Smith (1999) concluded that the wet thermogenic gases initially generated in the Sydney and Bowen Basins during deep burial were lost as a result of uplift and erosion, and were almost completely replaced by dry biogenic CH$_4$ and magmatic carbon dioxide (CO$_2$). Smith et al. (1992), Smith (1999) and Ahmed & Smith (2001) attributed the origin of most of the CH$_4$ in eastern Australian basins to the microbial reduction of CO$_2$.

Studies by Smith (1999), Faiz & Hutton (1995), and Faiz et al. (1999, 2006, 2007a, b), focussed on the Southern Coalfield of the Sydney Basin, suggest that most of the CH$_4$ and higher hydrocarbons in that area were formed during the Late Jurassic to Middle Cretaceous at burial depths of $\sim$2 to $\sim$4 km. This was followed by rapid uplift during the Late Cretaceous and early Cenozoic, during which some of the CH$_4$ and higher hydrocarbons were expelled, although they could also have been consumed through microbial processes. CO$_2$ was introduced by periodic igneous activity between the Permian and the Cenozoic (Baker et al. 1995). At depths shallower than 600 m, the seam gases are essentially depleted in C$_2$ (Faiz et al. 1999). Following on from Smith (1999), it has been suggested that some of the lost gas was later replaced by secondary biogenic gas formed as a result of uplift and erosion, bringing the coal into contact with meteoric waters (Faiz et al. 2006).

For the Hunter Coalfield in particular, studies by Craig (2005), Esterle et al. (2006), Thomson et al. (2008) and Pinetown (2010, 2013) have all made valuable contributions to understanding gas distribution. It has been found that factors controlling the origin, migration and
accumulation of coal seam gas (CSG) may vary from one region to the next within the coalfield, as Faiz et al. (2007a) also acknowledge for the Southern Coalfield, and that certain properties have overriding influences on the CSG distribution in a particular region. The present study builds on previous research by conducting an assessment of burial histories to elucidate the overarching geological controls on CSG distribution in the Hunter Coalfield, as well as the implications for CH4 production from coal seams and for estimation of GHG emissions from coal mining.

GEOLOGICAL SETTING AND TECTONIC EVOLUTION OF THE SYDNEY BASIN

The Permian–Triassic Sydney Basin, located in eastern Australia, is up to ~350 km long and ~200 km wide, and extends offshore to the edge of the continental shelf (Tadros 1995). The basin is bounded by older Paleozoic, mainly metamorphic and granitic rocks of the Lachlan Fold Belt to the south and west, and the New England Fold Belt to the northeast. A series of tectonic events led to the formation of the basin; a comprehensive reconstruction of the tectonic development in NSW is presented in great detail by Johnson (1989), Scheibner (1999), Veevers (2000), Woodfull et al. (2004) and Blevin et al. (2007). These events are summarised, based on Tadros (1995) and Scheibner (1999), and illustrated in Figure 1. The Sydney Basin is divided into four main coalfields based on structural and geographic boundaries. The stratigraphic horizons across the western, southern and central regions have been well correlated, with the bulk of the coal deposits hosted by the Illawarra Coal Measures. In the north, the Hunter and Newcastle Coalfields host three coal measure sequences. The detailed stratigraphic column for the Hunter Coalfield in Figure 2 shows the Newcastle, Wittingham and Greta Coal Measures, which were deposited by four major episodes of deltaic to fluvial deposition, separated by three marine transgressive events. Detailed information on the depositional environments of the Sydney Basin and Hunter Coalfield can be found in Basden (1969), Hamilton (1984), Beckett (1988), Agnew et al. (1995), Sniffin & Beckett (1995), Boyd & Leckie (2000), Scheibner (1999), Veevers (2000) and Van Heeswijck (2001).

METHODS

Data collection and processing

Publicly available data were collated from five well completion reports (wells Knight-1, Pinegrove-1, Elecom Hunter Llanillo (EHL-1), Elecom Hunter Randwick Park-1 (EHRP-1) and Wybong-1) sourced through the NSW Department of Trade and Investment’s Digital Imaging of Geological System (DIGS) database. Additional data were obtained for two coal exploration boreholes from a

Figure 1 Tectonic timeline diagram for the Sydney Basin compiled based on Tadros (1995) and Scheibner (1999).
coal mining company operating in the Hunter Coalfield (boreholes DH219 and DH225). The data and information from these reports were used for burial history modelling.

Coal petrological analyses

Coal petrological analyses for samples from boreholes DH219 and DH225 were performed at the CSIRO organic
petrology laboratory in North Ryde. Petrographic blocks were prepared according to Australian Standard 2856.1 (2000). Maceral composition analyses and mean maximum vitrinite reflectance ($R_{\text{v,max}}$) measurements were carried out according to Australian Standard 2856.2 (1998) and Australian Standard 2856.3 (2000), respectively. Maceral composition analyses and $R_{\text{v,max}}$ measurements were carried out on polished particulate blocks using a Carl Zeiss reflected light microscope fitted with a 40× magnification oil immersion objective, and capable of operating in fluorescence mode.

**Burial history modelling**

Burial history models were constructed using Schlumberger PetroMod version 11 petroleum systems modelling software. Data from seven boreholes were selected for modelling purposes, based on the completeness and availability of lithological and geophysical temperature logs, and $R_{\text{v,max}}$ data. In the present study, one-dimensional burial history models were constructed for boreholes Knight-1, Pinegrove-1, DH219, DH225, EHL-1, EHR-1, and Wybong-1. Boreholes Knight-1 and Pinegrove-1 are located south of the Hunter River Cross Fault; boreholes DH219 and DH225 were drilled northwest of Singleton in the Glenneys Creek area; boreholes EHL-1 and EHR-1 are located in the central region of the coalfield, between the Muswellbrook Anticline and the Mount Ogilvie Fault; Wybong-1 is located west of the Mount Ogilvie Fault. Formation lithology and thickness data from each borehole were used as the main inputs for each model. $R_{\text{v,max}}$ data were converted to mean random vitrinite reflectance ($R_{\text{v,r}}$) based on the relationship between $R_{\text{v,max}}$ and $R_{\text{v,r}}$ presented by Ting (1978), and used for calibrating the modelled thermal maturities. Present-day heat flow was calculated using temperature data from geophysical temperature logs and thermal conductivities calculated for each formation, on the basis of default values according to lithology, in PetroMod. These data were used in Fourier’s equation for heat transfer by conduction (Carslaw & Jaeger 1948),

$$q = \frac{k \times \Delta T}{l}$$

where $q$ is heat flux, expressed as W/m², $k$ is thermal conductivity, expressed as W/m/K, $\Delta T$ is the difference between the surface (taken at 10 m below ground surface) and bottom hole temperatures, expressed in °C, and $l$ is the thickness (m) of each formation. Although thermal conductivity varies with temperature, for simplicity the thermal conductivity of each formation as calculated by PetroMod was selected for the mean temperature in each borehole. The present-day heat flow was then calculated by multiplying $q$ by 1000 and expressed as mW/m². One of the key boundary conditions, namely, sediment–water interface temperature throughout geological time, was taken from Welte et al. (1997), for the paleolatitude of the basin (as indicated by Veevers 2000) at each time interval. The paleowater depth was maintained at 0 m for all time intervals in each model since insufficient paleobathymetric information was available. Simulations were run with a maximum cell thickness of 100 m and over a maximum time step duration of 1 Ma.

Since the sedimentary sequence is best preserved in the west of the coalfield, the model for Wybong-1 was constructed first, and data from that borehole were used to fill in for missing sequences when constructing models for other boreholes. A crucial matter for consideration when reconstructing the eroded sections of a basin, particularly in the Hunter Coalfield where most of the Triassic and some of the upper Permian sediments have been eroded, is the likely thickness of the eroded section. Bragnan (1983) placed doubt on the existence of a thick (in excess of 1 km) sedimentary sequence eroded from the Sydney Basin. Faiz & Hutton (1993), however, showed that to achieve observed thermal maturity profiles such as those in the southern Sydney Basin, rapid uplift and erosion of at least 1.5 km of post-Permian sediments must have taken place. Hence, to be consistent with the amount of erosion determined by Faiz & Hutton (1993), the maximum possible formation thicknesses were used for the Narrabeen Group (800 m), the Hawkesbury Sandstone (250 m) and the Wianamatta Group (300 m), along with varying thicknesses of Upper Triassic and possible Jurassic sediments, which could have been eroded as well. To assign ages for depositional periods, ages suggested by Metcalfe et al. (2011) from dating of tuffs throughout the Sydney Basin were used as control points for the upper Permian sediments, along with relative dates proposed by Herbert (1980) for the Triassic sediments. The lengths of erosional periods were based on the thickness of strata assumed to have been eroded at constant rates, and adjusted to suit the vitrinite reflectance data used for calibration.

Selecting appropriate paleoheat flows to achieve observed thermal maturities is as important as the relevant overburden thicknesses. Paleoheat flow determinations can vary significantly, depending on the input data and interpretations presented by different researchers. Paleoheat flows were adjusted back in time from the present-day heat flows, and following each simulation, the models were calibrated against the $R_{\text{v,r}}$ data. Adjustments can be made to accommodate possible influences on geothermal gradients, such as the rifting of the Tasman Sea in the case of the eastern Sydney Basin, but these should be made with caution and were not used in the present study. Faiz & Hutton (1993) proposed paleoheat flows of between 70 and 110 mW/m², leading to geothermal gradients ranging between 35 and 50°C/km for the southern Sydney Basin, and suggested that such conditions were probably associated with the rifting event. With regard to influences on geothermal gradients from basement igneous rocks, Facer et al. (1979) concluded that heat generation in the basement has potentially had a long-term influence on coal rank in the southern and western Illawarra Coal Measures. Present-day heat flows for various boreholes in the southern Sydney Basin are generally about 70 mW/m² and up to ~85 mW/m², with one data point of 50 mW/m² recorded for the Scone area of the northern Sydney Basin (Munroe et al. 1975). More recent studies by Odins et al. (1985) have discovered elevated local geothermal gradients of up to ~70°C/km in the Hunter Coalfield, which they attribute to the
presence of basement granites. Furthermore, by compiling a database on crustal temperatures for the Australian continent, Chopra & Holdgate (2005) identified the elevated crustal temperature in the northern region of the Sydney Basin as a potential future ‘hot dry rock’ target. Anomalous geothermal gradients in the central region of the Hunter Coalfield are also supported by findings from geothermal studies by the NSW Department of Trade and Investment (Jaworska 2011), and these observations are further supported by Danis et al. (2012) who conducted numerical modelling of the geothermal state of the Sydney Basin.

Following on from these observations, present-day heat flows calculated as part of the present study vary between 60 and 121 mW/m², with geothermal gradients ranging from 20 to 57°C/km, assuming a surface temperature of 21°C. Hence, in initially assigning paleoheat flows for models presented here, present-day heat flows were extrapolated back in time. To achieve observed maturity profiles, however, paleoheat flows between ca 280 Ma and the period of maximum depth of burial (Early to Middle Cretaceous) varied between 52 and 63 mW/m². It is likely that localised elevated present-day heat flows could be due to the presence of basement granites (Odins et al. 1995), and possibly even the rifting event (Faiz & Hutton 1993), but these possible influences are not reflected in the observed maturity profiles. The main model inputs and borehole geothermal properties are given in the Supplementary Papers (Tables A1–A7) with the boundary conditions set for each model, as shown in Tables 1 and 2.

To establish the inputs to which the models are most sensitive, an exploratory sensitivity analysis was carried out. Since the PetroMod software modules used for assessing sensitivity, risk and uncertainty were unavailable for use during this study, a qualitative analysis was conducted. The main model inputs selected for the analysis were eroded overburden thickness (m) and paleoheat flow (mW/m²), as these parameters appeared to have the greatest influence on the agreement between calculated and measured vitrinite reflectance. The analysis was conducted for borehole Knight-1. Using the settings for model parameters, which provided the best fit between calculated and measured vitrinite reflectance as the ‘correct’ model, the individual modelling inputs were varied between 10 and 50% while keeping the remaining modelling inputs constant.

### RESULTS AND DISCUSSION

#### Sensitivity analysis of modelling results

The influence of varying modelling inputs was assessed by comparing changes in the calculated compared with the measured vitrinite reflectance profiles; results are summarised in Table 3. In all cases, the greatest influence on calculated Ru, is paleoheat flow, as opposed to eroded overburden thickness. For instance, at ~415 m

| Time (Ma) | Paleolatitude (°) | Sediment–water interface temperature (°C) | Knight-1 | Pinegrove-1 | DH219 | DH225 | EHL-1 | EHRP-1 | Wybong-1 |
|-----------|-------------------|------------------------------------------|--------|---------|------|------|------|--------|---------|
| 0         | 30                | 19                                       | 99     | 99      | 60   | 86   | 120  | 109    | 109     |
| 10        | 37                | 19                                       | 95     | 95      | 60   | 80   | 110  | 105    | 105     |
| 20        | 45                | 20                                       | 90     | 90      | 60   | 75   | 110  | 100    | 100     |
| 30        | 50                | 18                                       | 85     | 85      | 60   | 75   | 105  | 95     | 95      |
| 40        | 50                | 21                                       | 80     | 80      | 60   | 70   | 100  | 90     | 90      |
| 50        | 55                | 22                                       | 75     | 75      | 60   | 70   | 95   | 85     | 85      |
| 60        | 60                | 19                                       | 70     | 70      | 58   | 65   | 90   | 80     | 80      |
| 70        | 60                | 19                                       | 70     | 70      | 58   | 65   | 85   | 75     | 75      |
| 80        | 65                | 21                                       | 65     | 65      | 56   | 60   | 80   | 75     | 75      |
| 90        | 65                | 22                                       | 65     | 65      | 56   | 58   | 75   | 70     | 70      |
| 100       | 70                | 22                                       | 63     | 60      | 54   | 56   | 70   | 70     | 70      |
| 110       | 70                | 22                                       | 63     | 60      | 54   | 54   | 65   | 65     | 65      |
| 120       | 70                | 21                                       | 63     | 58      | 52   | 54   | 60   | 60     | 62      |
| 130       | 70                | 20                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 140       | 70                | 19                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 150       | 75                | 18                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 160       | 70                | 18                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 170       | 65                | 18                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 180       | 60                | 18                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 190       | 60                | 18                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 200       | 65                | 17                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 210       | 70                | 16                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 220       | 75                | 17                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 230       | 80                | 15                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 240       | 85                | 10                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 250       | 70                | 15                                       | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 260       | 70                | 7                                        | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 270       | 70                | 5                                        | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
| 280       | 70                | 5                                        | 63     | 56      | 52   | 54   | 58   | 58     | 61      |
Table 2: Borehole geothermal properties for all boreholes.

| Borehole geothermal properties | Knight-1 | Pinegrove-1 | DH219 | DH225 | EHL-1 | EHRP-1 | Wybong-1 |
|-------------------------------|-----------|-------------|-------|-------|-------|--------|----------|
| Total depth (m)               | 748       | 511         | 499   | 535   | 766   | 700    | 763      |
| Elevation (m)                 | 97        | 99          | 94    | 102   | 170   | 154    | 150      |
| Temperature at 10 m below surface (°C) | 21       | 21          | 21    | 21    | 21    | 21     | 21       |
| Temperature at 748 m (°C)     | 54        | 44          | 34    | 38    | 65    | 56     | 58       |
| Temperature difference (°C)   | 33        | 23          | 13    | 17    | 44    | 35     | 37       |
| Mean temperature (°C)         | 38        | 33          | 28    | 30    | 43    | 39     | 40       |
| Geothermal gradient (°C/100 m) | 44        | 45          | 26    | 32    | 57    | 50     | 48       |
| Thermal conductivity (k) of all lithological units (W/m K) at mean temperature (W/m K) | 2.25 | 2.21 | 2.32 | 2.71 | 2.11 | 2.19 | 2.25 |
| Heat flux (q; W/m²)           | 0.0995    | 0.0993      | 0.0604 | 0.0861 | 0.1209 | 0.1097 | 0.1090 |
| Present-day heat flow (mW/m²) | 99.46     | 99.30       | 60.55 | 98.07 | 120.91 | 109.66 | 109.05 |

Burial history models for different areas of the Hunter Coalfield

The thermal maturity profiles predicted by PetroMod were based on the simple kinetic model of vitrinite reflectance published by Sweeney & Burnham (1990). The predicted thermal maturity profiles are plotted in Figure 3(a-g), alongside the publicly sourced measured vitrinite reflectance data (boreholes Knight-1, Pinegrove-1, EHL-1, EHRP-1, and Wybong-1) and vitrinite reflectance measurements conducted specifically for the present study (boreholes DH219 and DH225). Predicted thermal maturity profiles were calibrated against the measured vitrinite reflectance data for all models. A high level of agreement can be observed between the predicted thermal maturity profiles and the measured vitrinite reflectance data for each model from the plots in Figure 3. A possible reason for some of the $R_{cr}$ values in the upper part of the section being below the calibrated maturity profile in Figure 3a could be related to variations in vitrinite chemistry (vitrinite reflectance suppression), whereas excursions from the calibrated maturity profile between 250 and 350 m depth in Figure 3e may be the result of igneous intrusions in the vicinity, although none were recorded in the lithological log between those depths.

The burial history models produced for the seven boreholes are shown in Figure 4(a-g). Overlain on these models are the generally accepted zones for immature rocks, rocks mature for oil generation and rocks mature for gas generation, based on the kinetic model for petroleum formation for ‘Type III’ organic matter published by Burnham (1989).

Models for Knight-1 and Pinegrove-1 (Figure 4a, b) show similar histories, depicting deep burial in excess of 3.3 km in the Late Jurassic to Middle Cretaceous, uplift towards the end of the late Permian, and further rapid uplift with subsequent erosion during the Late Cretaceous to early Cenozoic. In addition to the preservation of most of the Wittingham Coal Measures sediments and some of the lower Newcastle Coal Measures sediments, all rocks of the Wittingham Coal Measures are predicted to have maturity for gas generation (Figure 4a, b). In contrast, models produced for boreholes DH219 and DH225 (Figure 4c, d) show that a thinner section of Triassic and Jurassic sediments has been deposited; thicknesses between 1550 and 1850 m (Figure 4c, d), contrast with ~2450 m (Figure 4a, b), with a maximum depth of burial between ~1.8 and 3.1 km. Furthermore, based on the overlying zones for petroleum generation, almost all of these rocks appear to be immature for oil and gas generation, excepting the lowermost strata of the Foybrook Formation (Figure 4c).

Table 3: Results of the qualitative sensitivity analysis conducted for Knight-1.

|                  | 50% | 10% | -10% | -50% |
|------------------|-----|-----|------|------|
| Heat flow        | 1.90| 1.02| 0.76 | 0.48 |
| Eroded overburden thickness | 1.46| 0.96| 0.80 | 0.57 |

Values shown are for variations from the initial value of 0.82% $R_{cr} \sim 415$ m depth.
of burial and is further supported by a slightly thinner section (~2140 m) of Triassic and Jurassic sediment that has been eroded. The lowermost strata of the Wittingham Coal Measures (lower Jerrys Plains and Vane Subgroups) are predicted to have maturities suitable for oil and gas generation (Figure 4g).

Role of burial history in the temporal evolution of coal seam gas in the Hunter Coalfield

Through understanding the burial history of the Southern Coalfield of the Sydney Basin, Faiz & Hutton (1993) and Faiz et al. (2006) provided plausible explanations for the temporal evolution of CH4 and CO2 in the Southern Coalfield.
In a similar fashion, burial history models produced in the present study can be used to better understand the CSG in the Hunter Coalfield. Observations based on burial history models were made in the context of the regional assessment of CSG distribution conducted by Pinetown (2010, 2013), who identified five CSG 'compartments' on the basis of geology and gas content and composition trends: 'high gas content area' (south), 'CH₄-rich area' (east), 'low gas content area' (central), 'intermediate gas content area' (west), and 'CO₂-rich area' (north) (Figure 5). A summary of the key characteristics of the CSG in these areas is provided in Table 4.

Pinetown (2010, 2013) showed that, south of the Hunter River Cross Fault, the 'high gas content area' hosts coals with the highest average gas contents (≈9 m³/t), adsorption capacities (Langmuir Volume; Vₐ) for CH₄ (≈23 m³/t on average), permeabilities (between 1.0 and 100.0 mD) and mean maximum vitrinite reflectances (0.56 to 1.15% Rᵥ,max) in the Hunter Coalfield. Burial history modelling for boreholes Knight-1 and Pinegrove-1 (Figure 4a, b) has shown that these traits could be partially due to limited uplift and erosion compared with the eastern, central and western areas. Consequently, the loss of thermogenic gas generally
associated with major basin uplift and erosion in other CSG areas (e.g. Faiz et al. 1999; Scott 2002) appears to have been slightly less in this area than for the other areas in the coalfield. Furthermore, the effects of uplift (temperature) and deep burial (pressure) on the adsorption capacity of gas, as demonstrated by Scott (2002), Hildenbrand et al. (2006) and Bustin & Bustin (2008), in comparison with the other Hunter Coalfield areas, may also have resulted in these coals having the greatest adsorption capacities for gas.

The origin and distribution of the major CSG components (CH₄ and CO₂) as described by Pinetown (2010, 2013) in the ‘high gas content area’ could have been indirectly affected by the basin’s burial and tectonic history. The deepest gases analysed in this area consist predominantly of CH₄. Isotopic signatures are interpreted to suggest biogenic sources of CH₄, even as deep as ~700 m (Pinetown 2010, 2013). The generation of biogenic CH₄ at such depths is not uncommon (Whiticar 1994; Faiz et al. 2006). There is also substantial evidence for the

![Figure 4](image-url)  
**Figure 4** Burial history diagrams based on modelled data for (a) Knight-1, (b) Pinegrove-1, (c) DH219-1, (d) DH225-1, (e) EHL-1, (f) EHRP-1 and (g) Wybong-1 showing hydrocarbon zones based on the Burnham (1989) kinetic model for petroleum formation.
widespread injection of igneous CO₂ into eastern Australian coal measure sequences (Baker et al. 1995), much of which was associated with the break-up of Gondwana (Figure 1). Isotopic values for CO₂ for this area, discussed by Pinetown (2010, 2013), are interpreted to suggest magmatic as well as residual biogenic sources. Studies by Scott (2002) on the hydrogeological factors affecting gas content distribution in the Powder River Basin, and by Pashin (2007) on the hydrodynamics of the Black Warrior Basin, have shown that the generation of biogenic gas is closely associated with the flow of meteoric water; and the hydrogeology of coal-bearing formations is influenced by the flow properties of the sediments within the sequence. A study on the connectivity of shallow (alluvial) and deep (coal formation) aquifers in the southern area of the Hunter Coalfield by Bryant et al. (2010) concluded that there is no connectivity between the shallow and deep aquifers, and that meteoric water recharge of the deep aquifers occurs where they outcrop. Together with the presence of numerous coal seam outcrops, this provides support for meteoric water recharge required to sustain biogenic gas generation in the area.

The flow of meteoric water within coal seams is influenced by the seam permeability. Coal permeability in the 'high gas content area' is greater than anywhere else in the coalfield (Pinetown 2010, 2013). According to Su et al. (2001) and Scott (2002), tectonic stresses greatly influence generation of the cleat and fracture systems in coal, which in turn affect the coal permeability.
Figure 4 (Continued).
Furthermore, the coals of the Jerrys Plains Subgroup are predominantly vitrinite-rich (Pinetown 2010, 2013). Based on findings by Clarkson & Bustin (1997), the greater permeabilities in this area could be the result of well-developed cleat and fracture systems associated with these bright (vitrinite-rich) coals. At present, a compressional stress regime persists in eastern Australia (Lambeck et al. 1984; Zhao & Muller 2001; Memarian & Fergusson 2007). Fracture and cleat systems developed in these bright coals during coal formation and subsequent extensional events may have aided paleometeoric water migration, but present-day compressional stresses could have closed the fractures, blocking pathways for water flow and thus also impeding gas release.

Burial history models for boreholes DH219 and DH225, located in the ‘CH₄-rich area’ (Pinetown 2010, 2013) and shown in Figure 4(c, d), are consistent with a shallower depth of burial than in the other areas. Thrusting near the New England Fold Belt during the Middle Triassic, followed by rapid uplift and erosion during the Late Cretaceous to early Cenozoic (Figure 1), has resulted in, first, much of the coal measures being deformed and eroded (Figure 4c, d; Sniffin & Beckett 1995) and, second, significant volumes of thermogenic gas escaping along numerous large-scale fault and fold structures in the area, similar to observations made by Smith (1999). Adsorption capacities (Lammuir Volume; V_L) are slightly lower than in the ‘high gas content area’ (Pinetown 2010, 2013), and it is likely that the effects of a shallower depth of burial (Figure 4c, d) and/or more rapid uplift (between 100 and 90 Ma; Figure 4c, d) have led to slightly lower rank and therefore reduced adsorption capacities (after Hildenbrand et al. 2006; Bustin & Bustin 2008).

Although burial history models for the ‘low gas content area,’ as shown for boreholes EHL-1 and EHRP-1 in Figure 4(e, f), are similar to those for the ‘high gas content area’ (Figure 4a, b), gas contents are particularly low (average ~4 m³/t; see Pinetown 2010, 2013). The ‘low gas content area,’ similar to the ‘CH₄-rich area’ (Pinetown 2010, 2013), has experienced a period of increased rapid uplift (as shown by the steeper burial history profiles between 100 and 90 Ma; Figure 4e, f). As most of the strata of the Jerrys Plains Subgroup have been preserved in this area and have maturities for significant gas generation similar to those in the south, it was expected that similar gas distributions would apply as observed in the south. It appears, however, that the coals in the central area have not reached maturity levels as high as those in the south, with Rᵥ,max values ranging from 0.72 to 1.00%. A possible reason could be that paleoheat flows for boreholes in the central area are lower (modelled as...
Table 4  Summary of the key characteristics of the CSG in the areas of the Hunter Coalfield studied.

| Key characteristics            | Geology                                                                 | Gas content                                                                 | Gas composition                                                                 | Other properties                                                                 | Possible influences                                                                 |
|-------------------------------|-------------------------------------------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| High-gas content area         | • Mainly ‘unfolded’ strata, gently dipping towards southwest             | • ~0.5 to ~21.9 m³/t, with average of ~9.0 m³/t                              | • Mainly CH₄ to ~400 m                                                        | • Highest adsorption capacity for CH₄ (average of ~20.6 m³/t)                     | • Limited uplift and erosion, and deeper burial resulting in less lost gas           |
|                               | • Variable seam thickness and frequent seam splitting                    | • 1.9 m³/t increase per ~100 m to ~300 m depth                              | • High (~80%) CO₂ between ~400 and ~700 m then increasing CH₄                 | • Greatest permeability range and values                                           | • Possible CO₂ injection from deep seated igneous intrusions                        |
|                               | • Large basaltic sill and dyke present                                  | • Maximum between ~700 m and ~800 m                                        | • CH₄ biogenic, especially at shallow depth; magmatic and residual biogenic CO₂ | • Highest Rₘₚ (~0.56 to ~1.15%)                                                   | • Dipping strata could assist with meteoric recharge; thus gas volumes replenished through biogenic activity |
|                               |                                                                          | • Highest in coalfield                                                       |                                                                                  |                                                                                  |                                                                                    |
| CH₄-rich area                 | • Extensive uplift and erosion resulting in less gas                    | • ~0.5 to ~20.4 m³/t, with average of ~3.0 m³/t                              | • CH₄ increasing from ~200 m and remains dominant CSG component into Greta Coal Measures, which could be thermogenic | • Similar adsorption capacity for CH₄ as high gas content area but not as high    | • Fold structures could assist with meteoric recharge and influence meteoric water flow directions |
|                               | • owing to large-scale fold structures and faults parallel to Hunter-Mooki Thrust Fault | • 1.4 m³/t increase per ~100 m to ~400 m depth                              |                                                                                  | (average of ~21.5 m³/t)                                                        | • Could also act as conduits for lost gas, particularly CO₂                           |
|                               | • Mainly strata of Vane Subgroup                                       | • Maximum deeper than ~1000 m in Greta Coal Measures                         |                                                                                  | • High adsorption capacity for CO₂ (average of ~59.0 m³/t)                       | • Lack of CO₂ also possibly owing to significant biogenic activity or limited igneous CO₂ injections |
|                               | • Several igneous dykes                                                | • CH₄ increasing from ~200 m and remains dominant CSG component into Greta Coal Measures, which could be thermogenic |                                                                                  |                                                                                  |                                                                                    |
| Low-gas content area          | • Presence of some major faults and mild fold structures                | • ~0.5 to ~19.7 m³/t, with average of ~3.9 m³/t                              | • CH₄ increasing from ~150 m to ~400 m depth                                  | • Similar adsorption capacity for CH₄ as high gas content area but not as high    | • Substantial gas volumes possibly lost as a result of uplift                        |
|                               | • Significant uplift and erosion of Jerrys Plains Subgroup              | • 0.5 m³/t increase per ~100 m to ~550 m depth                              | • High (~80%) CO₂ between ~900 m and ~700 m                                   | • Lower adsorption capacity and possibly other coal properties affecting lack of gas retention |
|                               | • Several igneous dykes                                                | • Maximum between ~400 m and ~600 m                                        | • Mainly biogenic CH₄ and possible mixed sources                               | • Permeability > 1 mD                                                            | • Faults could have sealing effect                                                 |
|                               |                                                                          | • Unexpectedly low gas                                                       | • Magmatic and heavily enriched CO₂                                            | • Lower Rₘₚ compared with south (~0.72 to ~1.00%)                                 | • Evidence for CO₂ from intrusions and for reduction to biogenic CH₄                |
| Intermediate-gas content area | • Relatively flat/monoclinal strata                                    | • ~0.5 to ~9.3 m³/t, with average of ~3.5 m³/t                              | • CH₄ increasing from ~150 m to ~400 m depth                                  | • Simlar adsorption capacity for CH₄ as high gas content area but not as high     | • Loss of thermogenic gas along Mount Ogilvie Fault zone                            |
|                               | • Limited structural features and igneous intrusions                    | • 1.1 m³/t increase per ~100 to ~650 m depth                                | • Wide scatter but CH₄ close to surface                                        | • Adsorption capacity for CH₄ similar to low gas content area (average of ~20.6 m³/t) | • Limited structural influence                                                      |
|                               |                                                                          | • Mixed gas conditions between ~400 and ~800 m                              |                                                                                  |                                                                                  |                                                                                    |

(continued)
58 mW/m² up to the maximum depth of burial) than for the southern area (modelled as 63 and 56 mW/m² up to the maximum depth of burial).

Adsorption capacities in the central area are also comparable with those in the ‘CH₄-rich area’ (see Pinetown 2010, 2013) and suggest that, in accordance with observations by Bustin & Bustin (2008), the rapid uplift (temperature) may also have resulted in lower adsorption capacities for the central Hunter coals. A potential explanation for such low gas contents is that thermogenic gases were lost during uplift, and CH₄ concentrations were replenished by the generation of late-stage biogenic gases as observed by other researchers (Smith 1999; Kotarba 2001; Scott 2002; Faiz et al. 2006; Pashin 2007). Although gas contents differ significantly from those measured in the south, the gas composition trends in the central area follow a similar pattern, i.e. high concentrations of CO₂ between depths of ~600 and ~800 m, predominantly CH₄ between ~400 and ~600 m, increasing CO₂ concentrations at depths shallower than 200 m, and isotopic signatures indicating mainly biogenic sources for the CH₄ in all samples (see Pinetown 2010, 2013). Furthermore, isotopic signatures for CO₂ suggest magmatic and residual biogenic origins (Pinetown 2010, 2013) within the depth ranges studied. However, in accordance with findings by Su et al. (2001) for coals of western North China and by Solano-Acosta et al. (2007) for coals of Pennsylvania, it is likely that the permeabilities in this area of generally <1 mD (Pinetown 2010, 2013) have resulted in restricted meteoric water recharge, which in turn has inhibited the generation of significant volumes of biogenic CH₄.

As observed from the burial history model in Figure 4g, coals to the west of the Mount Ogilvie Fault were buried less and uplifted more than those in the south (Figure 4a, b). Most coal seams do not outcrop since, according to Glen & Beckett (1997), the footwall strata of the Mount Ogilvie Fault, which covers most of the area, are horizontal. Gas contents are significantly lower than in the south, and, based on limited and scattered data, the CSG appears to be a mixture of CH₄ and CO₂ between ~400 and ~800 m, primarily CH₄ between ~200 and ~400 m, and have surprisingly high CH₄ concentrations along with CO₂ at depths shallower than 200 m (Pinetown 2010, 2013). Without isotopic data available for this area, interpretations regarding the origin of the gases require further substantiation. The possible explanation for the gas distribution in this area is a loss of thermogenic gas via the Mount Ogilvie Fault, and restricted meteoric water recharge for biogenic gas production owing to limited cross-formational water exchange between shallow and deep aquifers, and to low permeabilities (Pinetown 2010, 2013).

Although suitable borehole data were not available to produce burial history models for the northern Hunter Coalfield, it is suggested that this area may have a similar burial history to that of the central area. Observations by Pinetown (2010, 2013) show that gas contents in the north are on average greater than in the eastern, western and central areas, and that the gas contains significantly higher CO₂ concentrations. In the absence of isotopic, adsorption isotherm, permeability and maturity data, the most reasonable explanation for the
discussed by Pinetown (2010, 2013), CSG reservoirs in the Hunter Coalfield. In addition, based on the findings combined to influence the potential for gas reservoirs in excess of CH4 production is reservoir permeability (for content, a crucial parameter that determines the success of CH4 production is reservoir permeability (for discussions, see Nolde & Spears 1998; Scott 2002). The coals in the Hunter Coalfield host significant volumes of gas, although low permeability, as well as low saturations in some areas, may have rendered many areas of the coalfield unfavourable for economic CH4 extraction. Options for developing these resources include directional and multilateral wells, as well as hydraulic fracturing.

Of the areas of the coalfield studied here, burial history modelling results show that the south has the greatest potential for thermogenic gas generation; given its high gas content and enhanced permeability compared with other areas of the coalfield, this area is also likely to have the greatest potential for CH4 production. Given its vast potential coal resources, this area could host economically viable gas volumes. Although the presence of considerable concentrations of CO2 at intermediate (~500 m) depths is unattractive, further research is required to establish the areal extent of the CO2 in the southern region of the Hunter Coalfield. The areal extent of igneous intrusions could be incorporated into burial history models, where data are available, to provide insights into the effects of intrusions on thermal maturity and gas characteristics. There is limited evidence to indicate the influence of fault and fold structures on coal permeability in the Hunter Coalfield, although it is likely that the geometry of the strata may have assisted with biogenic gas generation. Geometric factors account for a significant proportion of the CH4 produced from many other CSG reservoirs, such as those in the Bowen Basin (Kinnon et al. 2010).

The northern area of the coalfield is considered to have the least potential for CH4 production owing to its high CO2 concentrations, although the extent of this anomaly requires further evaluation. Because of its potential coal resources and intermediate gas contents, the area west of the Mount Ogilvie Fault could also be considered as a potential target area, although the low coal permeability could be a challenge for economic gas extraction. Similar factors could also pose a problem in the central part of the coalfield, where gas contents and permeabilities are low. Detailed evaluation is required to assess gas extraction potential from large-scale structures in the central and eastern areas of the coalfield.

Implications for CH4 production in the Hunter Coalfield

A wide range of factors have combined to create one of the world’s most prolific CSG plays, the San Juan Basin (Scott et al. 1994), and similar factors have also combined to influence the potential for gas reservoirs in the Hunter Coalfield. In addition, based on the findings discussed by Pinetown (2010, 2013), CSG reservoirs in the Hunter Coalfield have been compartmentalised in a similar way to the reservoirs of the CBM fields in Alabama (Pashin & Groshong 1998), where faulting has compartmentalised the reservoirs that produced exceptionally high volumes of gas and water, and intensive faulting has enhanced permeability. Apart from gas content, a crucial parameter that determines the success of CH4 production is reservoir permeability (for discussions, see Nolde & Spears 1998; Scott 2002). The coals in the Hunter Coalfield host significant volumes of gas, although low permeability, as well as low saturations in some areas, may have rendered many areas of the coalfield unfavourable for economic CH4 extraction. Options for developing these resources include directional and multilateral wells, as well as hydraulic fracturing.

Implications for fugitive greenhouse gas emissions from open cut coal mines in the coalfield

With more than 75% of Australia’s raw black coal being produced from open cut coal mines (ACA 2011), the issue of fugitive GHG emissions has become a concern for the coal industry. In NSW a significant proportion of the 205 Mt of raw black coal produced between 2010 and 2011 (ACA 2011) was sourced from open cut mines in the Hunter Coalfield. With increasing depths for open cut mining (up to ~250 m in some mines), there is increased potential to release large volumes of greenhouse gases into the atmosphere. In areas with high gas contents and where most of the gas above 300 m depth is CH4, such as in the south, GHG emissions from such mines could contribute substantially to Australia’s annual fugitive emissions from open cut coal mining. CH4 has 23 times the global warming potential of CO2 by mass (IPCC 2001), and with the tonnage of coal produced each year in mines south of the Hunter River Cross Fault, the CO2-equivalent volumes released from these mining activities are likely to be significant.

In the eastern, central and western areas, where gas contents are somewhat lower, fugitive GHG emissions are likely to be less. The CSG in these areas has similar concentrations of CH4 and CO2 within the first ~300 m of the subsurface; however, the majority of the coal mines in the Hunter Coalfield are located in these areas, and given the amounts of coal produced, there may still be potential for significant volumes of CO2 to be released, possibly even more than that released from mining activities in the south. The situation would be very similar in the north, where most of the CSG within the first ~500 m consists of CO2, although mining activities have been limited in that area.

CONCLUSIONS

The burial history of the Sydney Basin has had an overarching control on the temporal evolution of CSG in the Hunter Coalfield. The evolution of CSG in the northern Sydney Basin followed a similar history to that suggested by other researchers for the southern Sydney Basin. However, deformation and thrusting in the north have given rise to some of the coalfield’s complex structural elements that, along with gas content and composition trends, form the basis for delineating coal seam gas ‘compartments’ in the Hunter Coalfield.
Through the use of basin modelling techniques, this study has provided new insights into gas distribution in the coal-bearing strata of the Hunter Coalfield. Burial history models constructed in the present study, with an emphasis on the coal seams, indicate noticeable variations in the extent of burial and uplift, and consequently, in thermal maturity, potential for thermogenic gas generation, and replenishment of lost CH₄ through generation by microbial processes, between the southern, central and northern areas of the coalfield. Differences between the constructed models are significant enough to provide plausible explanations for the regional gas distribution in the Hunter Coalfield.

The burial and uplift of strata affect both coal properties and environmental factors such as temperature and pressure. Although an interplay of these parameters has resulted in present-day gas distribution patterns, a key finding of burial history modelling is that the southern area of the coalfield has greater potential for thermogenic gas generation compared with other areas, which is partially reflected by the high present-day gas contents. Despite the low gas saturation levels, coals in the area of the coalfield have greater potential for thermal generation compared with other areas, which is partially reflected by the high present-day gas contents.

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SUPPLEMENTARY PAPERS

Table A1 Main model inputs for Knight-1.
Table A2 Main model inputs for Pinegrove-1.
Table A3 Main model inputs for DH219.
Table A4 Main model inputs for DH225.
Table A5 Main model inputs for EHL-1.
Table A6 Main model inputs for EHRP-1.
Table A7 Main model inputs for Wybong-1.

REFERENCES

Agnew D., Bocking M., Brown K., Ivins M., Johnson D., Howes M., Prescott B., Rigby R., Wardbrooke P. & Weber C. R. 1995. Sydney Basin – Newcastle Coalfield. In: Ward C. R., Harrington H. J., Mallett C. W. & Beeson J. W. eds. Geology of Australian Coal Basins, Geological Society of Australia Incorporated Coal Group Special Publication 1. Sydney, NSW, pp. 197-212.

Ahmed M. & Smith J. W. 2001. Biogenic methane generation in the degredation of eastern Australia Permian coals. Organic Geochemistry 32, 809-816.

Australian Coal Association (ACA). 2011. The Australian Coal Industry – Coal Production. http://www.australiancoal.com.au/the-
Woodfull C., Munroe S., Griffin S., Buckingham A. & Ham A. 2004. Sydney Basin Regional Structural Framework & Structural Risk Analysis. SRK Report SB601, 92 pp.

Zhang E., Hill R. J., Katz B. J. & Tang Y. 2008. Modeling of gas generation from the Cameo coal zone in the Piceance Basin, Colorado. AAPG Bulletin 92, 1077–1106.

Zhao S. & Muller R. D. 2001. The Tectonic Stress Field in Eastern Australia. Proceedings of the PESA Eastern Australasian Basins Symposium, pp. 61–70. Melbourne, Vic.

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