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The influence of petrological properties and burial history on coal seam methane reservoir characterisation, Sydney Basin, Australia

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Abstract

Gas content of coals continuously change throughout their burial histories as a result of the changing state of equilibrium of the coal–gas system caused by variations in P–T conditions and coal rank. To fully evaluate the prospectivity of a coalbed methane resource, numerous coal properties, burial history, P–T conditions, hydrology and the likelihood of secondary biogenic gas generation need to be considered with respect to gas sorption capacity, gas contents and permeability.

Previous studies have given differing interpretations on relationships between rank and maceral composition with sorption capacity. The maximum gas storing capacities for Sydney Basin coals is inversely related to rank up to medium volatile bituminous, but a coked, contact metamorphosed coal has an elevated capacity. Comparison of sorption capacities of coals having similar ranks and variable maceral group composition, indicate that rank has a dominating effect over any effects of organic matter type.

For the Sydney Basin coals, the in-situ gas contents, on average, increase with depth up to about 600 m and with further increases in depth to 900 m, the gas contents tend to plateau or even decrease. Such a trend probably is consistent with the combined effects of pressure and temperature on the gas sorption capacity during the geological history. R-mode cluster analyses of the coal and gas properties yield a positive correlation between gas contents and inertinite abundance. This is related to undersaturation of the vitrinite-rich coals, possibly due to higher permeability and consequent leakage of more gas from vitrinite-rich coals than from inertinite-rich coals.

Although a large amount of methane and other hydrocarbon gases would have been generated in the Sydney Basin at maximum burial during the Early Cretaceous, a large proportion of the gas might not have been sorbed within the coal due to limited gas sorption capacities and enhanced diffusivity at high temperatures. Upon uplift, gas that migrated from deeper in the sequence or from shallower biological activity may have been sorbed into the coals. Without secondary gas replenishment however, many of these coals remain significantly undersaturated.

The areas that contain considerable amounts of secondary biogenic gas are highly prospective for coalbed methane production partly because of the higher gas contents, but also because of the higher permeability, which is required for access of the microbes and nutrients in meteoric waters.

To fully evaluate prospectivity of coalbed methane resources, numerous coal properties, burial history, geologic setting and the likelihood of secondary biogenic gas generation need to be considered with respect to gas sorption capacity, gas contents and permeability.

Keywords: Coal seam gas; Coal bed methane; Sydney Basin; Adsorption isotherms; Biogenic gas; Petrology

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1. Introduction

Coal seam methane is a rapidly growing industry in Australia and becoming an important energy source along the eastern seaboard. Bituminous coals of the Sydney Basin contain a large resource of methane (CH_4) which is located in close proximity to the largest gas market in Australia. The economic production of CH_4 from Sydney Basin coals is challenging because of low permeabilities, high stress and variable gas saturation levels. Therefore, a thorough understanding of the factors that affect variations in these properties is critical for efficiently delineating 'sweet spots' for commercial methane production.

Numerous factors influence gas reservoir properties of coal seams and a holistic approach is required to fully understand the most important controls. Even within a single basin, different influences may predominate in different areas, depending upon coal composition, coal rank, geological structure, igneous activity, stress fields, basin hydrodynamics, burial and thermal histories. With respect to geologic setting, the purpose of the present study is to investigate,

- the major influences on gas storage capacity of Sydney Basin coals and
- the effects of coal properties, together with burial history, on saturation levels and in-situ gas contents.

1.1. Geologic setting

The Sydney Basin (Fig. 1) is a retro-arc, foreland basin with the sedimentary sequence deposited during the Late Carboniferous to Early Triassic on Devonian and Ordovician basement rocks. The majority of the coals targeted for coal bed methane (CBM) production were deposited in the Late Permian, primarily in fluvio-deltaic environments. The Sydney Basin sequence also contains numerous Permian to Tertiary igneous intrusions. Radiometric dating and other stratigraphic studies indicate that igneous activity occurred throughout the geological history of the basin, with peak activity at about 250, 180 and 50 million years ago (Embleton et al., 1985; Facer and Carr, 1979).

Most of the Sydney Basin has been under a net north-east to north–south compressive stress regime since the Late Cretaceous. This deformation has caused anisotropies that are represented by superposition of compressive structures on previous tensional or trans-tensional lineaments. The resultant anisotropy affects CBM production, particularly in the southern Sydney Basin. In most cases, orientation of the previous structures is orthogonal to the present maximum stress direction.

Sydney Basin coals range in rank from high volatile bituminous to low volatile bituminous with mean maximum vitrinite reflectance (VR) values ranging from about 0.7% to 1.9%. Thermal history modelling indicates that these ranks were attained as a result of high paleo-heat flux (75 to 100 mW m^{-2}) and 2.5 to 4 km burial during the Early Cretaceous (Faiz and Hutton, 1993). Subsequently, the basin cooled due to rapid uplift during the Late Cretaceous and Tertiary.

1.2. Coal seam gas in the Sydney Basin

Coal seam gas generally comprises CH_4 with subordinate amounts of CO_2, C_2H_6, higher hydrocarbons (C_{2+}) and N_2. However, in some parts of the Sydney Basin, the coals contain over 90% CO_2 and up to 12% C_2H_6 (Smith et al., 1985; Faiz and Hutton, 1995; Smith and Pallasser, 1996; Faiz et al., 2003).

Gas in Sydney Basin coals has been derived from multiple sources, including,

- thermogenic CH_4 and higher hydrocarbons formed during deep burial during the Jurassic and Early Cretaceous (Faiz and Hutton, 1997),
- secondary biogenic CH_4 formed since Late Cretaceous uplift (Smith and Pallasser, 1996; Faiz et al., 2003), and
- CO_2 derived mostly from intermittent igneous activity between the Permian and Tertiary (Smith et al., 1985; Faiz and Hutton, 1995).

1.3. Gas storage in coal

Porosity and pore size distribution in coal have a major impact on its internal surface area and gas storage capacity. Coal contains pores ranging in size from >50 nm (macro-pores) to <2 nm (micro-pores) in diameter, depending on coal composition and rank. Bituminous coals are dominated by micro-pores, whereas lower rank coals are likely to contain higher volumes of larger pores. In general, the total open porosity and internal surface area of coal decreases with increases in rank from high volatile bituminous (VR ~ 0.7%) to medium volatile bituminous (VR ~ 1.4%) and with further increases in rank they increase (Moffat and Weale, 1955; Mahajan and Walker, 1978; Janowsky, 1984). Several studies have demonstrated that vitrinite contains higher volumes of micro-pores than inertinite at a given rank (e.g. Thomas and Damberger, 1976; Harris and Yust, 1979; Unsworth et al., 1989; Faiz, 1993).

Gas in coal is stored primarily as molecules physically *adsorbed* on micro-pore surfaces due to dispersion (van der Waals) forces, short range repulsive forces, and in the case of polar molecules, electrostatic forces (Brauneur

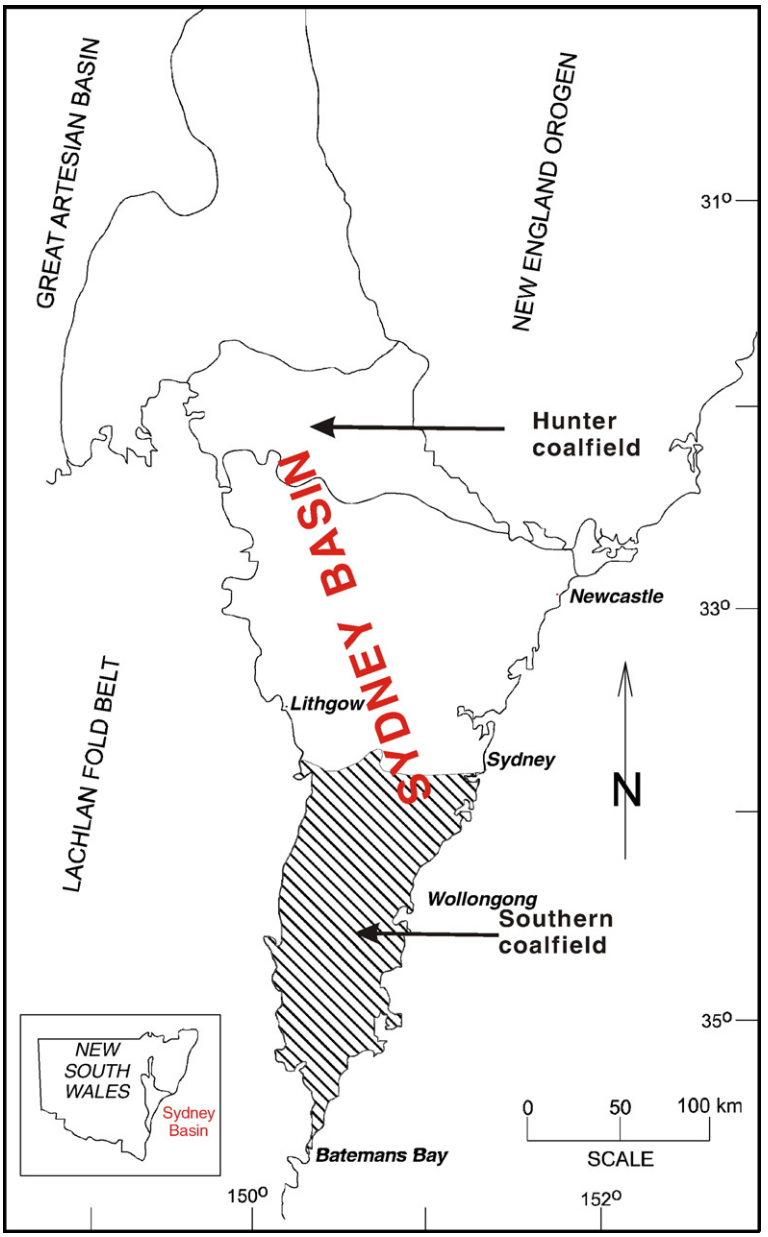

Fig. 1. Location of the Southern and Hunter Coalfields, Sydney Basin, New South Wales, Australia.

et al., 1940; Gregg and Sing, 1967, 1982). It has been postulated that at high pressures, considerable amounts of gas (particularly CO_2) may also be *absorbed* into the coal by penetrating its molecular structure (Reucroft and Patel, 1986; Hsieh and Duda, 1987). The relative proportions of *adsorbed* and *absorbed* gas in coal, are unknown and therefore the collective term 'sorption' can be used to encompass the two modes of gas retention (McBain, 1932). In addition to sorbed gas, lesser amounts of gas can be stored as 'free-gas' in macro-pores and fractures in coal, and as dissolved gas in pore waters within coal seams.

The amount of gas sorbed in coal is primarily related to internal surface area, pressure and temperature. For a given coal, the gas sorption capacity generally increases with increases in pressure, following a hyperbolic relationship. For the pressure range investigated in the present study, isotherms generally follow the 'Type I' isotherm defined in the classification of Braunauer et al. (1940). This type of isotherm is commonly observed for

microporous solids such as coal and activated carbon, and it is assumed that a monolayer of gas is adsorbed on the pore surfaces (Brauneur et al., 1940). Gas sorption is an exothermic process and therefore once equilibrium is reached at a given pressure the sorption capacity decreases with increase in temperature (Gregg and Sing, 1982; Ettinger and Serpinsky, 1991).

The sorption capacity of coal also varies with gas composition, according to their physical and chemical properties; for example, a bituminous coal of the Sydney Basin can store about 1.5 to 2 times more CO_2 than CH_4 at a given set of P–T conditions (Lama, 1988; Faiz et al., 1992), and this ratio can be >10 for sub-bituminous and brown coals. The small size of CO_2 molecules as compared with CH_4 molecules, has been identified to be the primary factor for the higher capacity for CO_2 sorption in coal by Ciu et al. (2004). However, the higher CO_2 sorption capacity may also be related to the strong polarity of CO_2 (presence of a permanent quadrupole), and the electrostatic forces may be a significant contributor to gas sorption (Gregg and Sing, 1967 and 1982). Low rank coals, which contain high amounts of moisture as well as numerous hydroxyl and carboxyl groups, are more ionic than higher rank coals and therefore, the contribution from electrostatic forces to CO_2 sorption is likely to be greatest for low rank coals. Furthermore, in low rank coals that contain very high moisture contents (e.g. brown coal) CO_2 may also be stored in solution especially at high pressures.

2. Samples and methods

2.1. Sampling

For this study, a series of coal core samples were obtained from CBM exploration boreholes as well as gas drainage boreholes in underground coal mines in the Southern and Hunter Coalfields of the Sydney Basin. In-situ gas content and coal characteristics were analysed for 61 samples and gas sorption capacities were determined for 18 samples (Table 1).

2.2. In-situ gas contents

In-situ gas contents were determined using the 'direct method', in accordance with Standards Association of Australia (1999) by Earth Data Limited, a commercial laboratory. After gas content testing, the coal cores were split in half, parallel to their long axes, and subsequently crushed, to obtain representative samples of each gas desorption canister. These representative samples were used for coal composition, rank and gas sorption analyses.

2.3. Gas sorption analyses

Sorption isotherms of the coal samples were analysed using a gravimetric method developed at CSIRO, which involves measurements of the increase in weight of the coal as a result of gas sorption. For these measurements,

Table 1
Coal characteristics and Langmuir volumes for the Sydney Basin coal samples analysed for CH_4 sorption

Sample #	VR %	V_L	Vitrinite %	Inertinite %	Liptinite %	Minerals %	IM %	Ash %	VM %
GLBa	1.3	19.41	54.3	37.2	<0.1	8.5	1.4	30.4	16.1
GLBT	1.33	23.32	50.7	44.8	<0.1	4.5	0.8	12.7	20.4
GLBB	1.35	24.13	29.9	63.5	<0.1	6.6	0.8	11.4	19.4
KPBT	1.13	29.45	20.8	73.0	0.7	5.5	0.6	5.3	26.8
KPBB	1.14	29.79	27.4	68.8	0.7	3.1	0.8	7.2	24.6
WGBT	1.22	28.61	47.6	49.5	0.5	2.4	0.6	7.3	26.5
WGBB	1.24	28.67	63.5	27.6	0.1	8.8	0.7	9.1	25.2
PNWood	0.81	27.91	37.1	56.2	3.8	2.9	2.0	7.3	31.3
PnWark	0.83	28.21	33.8	45.9	3.8	16.5	1.8	11.6	32.6
PNMt	0.8	24.73	53.2	17.8	1.2	27.8	1.8	25.8	26.2
KNWood	0.86	34.32	37.2	57.1	3.5	2.2	2.0	4.0	32.8
KNAr	0.84	31.32	61.8	27.3	2.5	8.4	1.8	6.8	27.2
KNPi	0.97	30.89	40.4	47.3	1.2	10.6	1.5	13.7	27.4
KNVa	0.99	32.40	69.4	24.3	1.6	4.7	1.5	6.5	29.4
METRO1431	1.39	22.26	66.0	28.0	<0.1	7.0	0.4	12.2	21.0
METROMP3	11.20	26.92	65.6	18.5	<0.1	15.8	4.0	21.4	11.9
THGB1	1.04	24.65	79.8	15.3	2.5	2.3	1.2	6.6	33.0
THGWS05	0.99	28.25	44.5	49.2	1.3	5.0	1.2	9.1	25.7

VR % — mean maximum reflectance of vitrinite.
IM % — inherent moisture.
VM % — volatile matter.
V_L — Langmuir volume for CH_4 sorption (cm^3/g).

a sample is exposed to gas pressures between 0 and 5000 kPa, at constant temperature. The data presented in the current study were measured between 27 °C and 33 °C using about 300 g of sample having a median grain diameter of 50 μm.

For the pressure range used in the present study, a mono-layer gas adsorption mechanism is assumed and modelled by a Langmuir equation (Greg and Sing, 1982). The volume of sorbed gas and corresponding pressure are fitted to an equation of the form,

$$C = \frac{V_L \cdot p}{P_L + p} \quad (1)$$

where C is the gas volume adsorbed (cm^3/g), p is gas pressure (kPa), and V_L and P_L are 'experimental coefficients'. Coefficient V_L represents the theoretical maximum gas capacity of the coal and is termed the Langmuir volume. Coefficient P_L is the Langmuir pressure which represents the gas pressure at which coal sorbs a volume of gas equal to half of its maximum capacity.

2.4. Coal petrology, proximate and elemental analyses

Vitrinite reflectance measurements were made using a Zeiss microscope with a 40× oil immersion objective and an interference filter having a passband peak of 546 nm; they were carried out in accordance with the procedures of Standards Association of Australia (2000b). Using plane polarised light, the maximum reflectances of 50 vitrinite particles were measured on each sample and the averages of these values are reported as 'mean maximum vitrinite reflectance' (VR).

Maceral analyses of the samples were made using a point counter in accordance with the Standards Association of Australia (1998). The minimum number of points counted was 500 and the amounts of organic and mineral components determined from point-counting are given as volume percent.

A commercial laboratory conducted proximate analyses according to Standards Association of Australia (2000a) and elemental analyses according to Standards Association of Australia (1997).

3. Results and discussion

3.1. Methane sorption capacity

The Langmuir volumes (V_L) for CH_4 sorption for the 18 samples studied range from about 19 m^3/t to 34 m^3/t (Table 1) and the CH_4 sorption isotherms vary considerably on an as received basis (Fig. 2). The rank of all except one of these coals range from high volatile bituminous to medium volatile bituminous and VR values range from about 0.8% to about 1.4%. These samples mainly consist of vitrinite and inertinite with <5% liptinite. The other sample has been contact metamorphosed by an igneous intrusion and has a vitrinite reflectance of about 11%.

As shown in Fig. 3, the CH_4 sorption capacities of the samples analysed show a moderate to weak inverse relationship with the ash yield. This type of relationship is well documented for other coals (e.g. Schwarzer and Byrer, 1983; Mavor et al., 1990; Laxminarayan and Crosdale, 1999). The negative correlation between gas sorption capacity and ash yield is consistent with gas being primarily stored within the organic matter, in which porosity is dominated by micro-pores. Minerals in coal generally contain larger pores and consequently have lower internal surface areas (Faiz et al., 1992). In order to investigate relationships between organic matter characteristics and CH_4 sorption capacity, the V_L values are normalised to a dry ash-free basis.

3.1.1. Influence of coal rank

Previous work has indicated a variety of relationships between gas sorption capacity and coal rank. Some studies indicated that, in the high volatile bituminous to anthracite rank range, CH_4 sorption capacity and porosity decrease with rank to a broad minimum at the medium volatile bituminous stage, followed by increases with increases in rank (e.g. Moffat and Weale, 1955; Ettinger et al., 1966; Schwarzer and Byrer, 1983). For example, based on 94 North American samples, Schwarzer and Byrer (1983) showed that the sorption capacity is at a minimum for coals having C contents between 83% and 88%. In contrast, Kim (1977) postulated that the CH_4 sorption capacity of coal continuously increases with increases in rank from sub bituminous to anthracite.

For the coals analysed in the present study, the V_L values have a negative correlation with VR in the rank range of high volatile to medium volatile bituminous, but the V_L for the contact metamorphosed coal deviates from this trend by having a high sorption capacity (Fig. 4). These results are therefore consistent with the previous studies that indicated a broad minimum in sorption capacity and porosity at intermediate ranks.

The cause for this broad minimum is not well understood. On the basis of X-ray scattering studies, Hirsch (1954) suggested that coal has a 'liquid-type structure' at medium volatile bituminous ranks and contains minimal open porosity at a C content of 89%. Moffat and Weale (1955) suggested that the low CH_4 sorption capacity of these coals is due to the low open porosity related to the highly regular, preferentially oriented lamellar structure. Another plausible explanation for the decreased CH_4

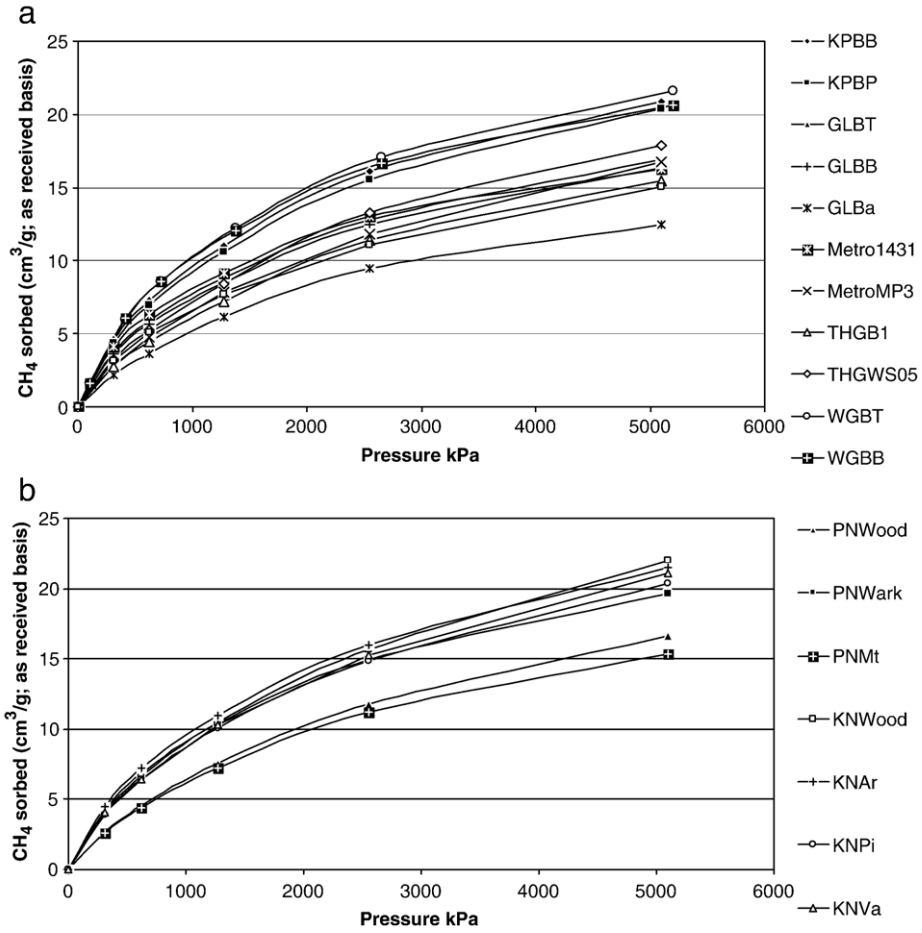

Fig. 2. (a) Sorption isotherms for coals from the Southern Coalfield, Sydney Basin, determined using the gravimetric method. (b) Sorption isotherms for coals from the Hunter Coalfield, Sydney Basin, determined using the gravimetric method.

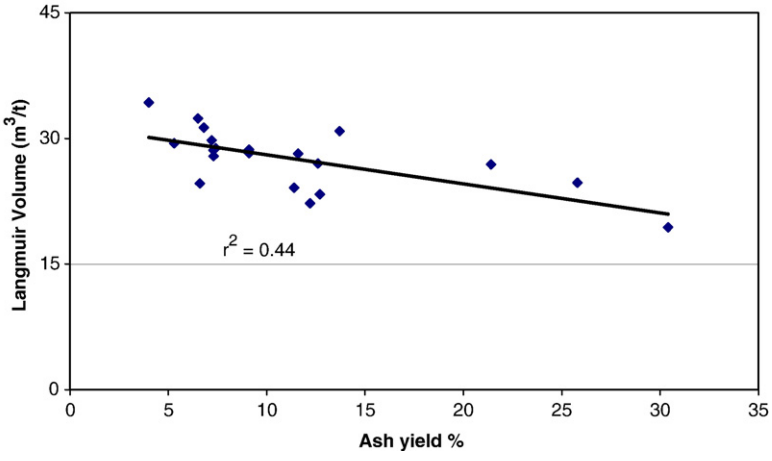

Fig. 3. Relationship between ash yield and Langmuir volume for the Sydney Basin coals.

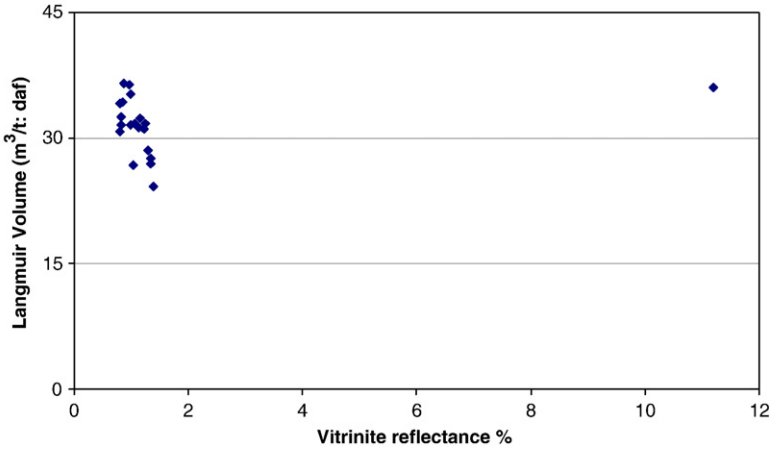

Fig. 4. Relationship between Langmuir volume (dry ash-free basis) and vitrinite reflectance.

sorption capacity for high volatile A to medium volatile bituminous stages is that micro-pores are occupied by heavy hydrocarbon molecules generated as a by-product of coalification (Levine, 1992a,b and 1993). Supporting this argument, Levine (1993) showed that gas sorption capacity varies according to the amount of heavy hydrocarbons occluded in the micro-pores of coals of similar rank. However, further studies are required to fully understand causes for the decreased gas sorption capacity at intermediate ranks.

3.1.2. Influence of maceral composition

Because of inherent differences in the origins of various macerals and consequent variations in their physical and chemical properties, gas sorption capacities are expected to vary with maceral composition. However, in this study comparisons of isotherms for coals having similar VR values (Fig. 5a–c) indicate that CH_4 sorption capacities do not systematically vary between vitrinite and inertinite-rich coals when compared on an ash-free basis.

Previous studies investigating the influence of maceral group composition on gas sorption capacity have shown contradictory results. Ettinger et al. (1966) found that fusinite sorbs more gas than vitrinite in low rank coals, whereas, differences are minimal for high rank coals. Consistent with the findings of the present study, the work of Schwarzer and Byrer (1983), Faiz et al. (1992) and Krooss et al. (2002) showed no systematic differences between gas sorption capacities of vitrinite and inertinite-rich coals. In contrast, several other workers have demonstrated that vitrinite-rich coals sorb more gas than inertinite-rich coals (e.g. Creedy, 1988; Lamberson and Bustin, 1992; Crossdale and Beamish, 1993; Levine et al., 1993; Mastalerz et al., 2004). Furthermore, Lamberson and Bustin (1992) suggested that differences in maceral composition can have a comparable or overriding effect on sorption capacity relative to variations in rank. However, Fig. 4 and the isotherms shown in Fig. 5 indicate that for the Sydney Basin coals studied, rank (as indicated by VR) is the major influence on sorption capacity.

Some of the differences in these findings may be due to variations in maceral compositions (as opposed to maceral group composition). For example, Permian coals of the Sydney Basin are generally richer in inertinite than Carboniferous, northern hemisphere coals and this inertinite comprises more, low-reflecting semifusinite and less fusinite than for the northern hemisphere coals. Fusinite contents of the Sydney Basin coals studied are generally <8% and therefore its influence on overall sorption capacity is likely to be minimal. Gas sorption capacity of much of the semifusinite in Sydney Basin coals may be comparable to vitrinite, such that no significant difference in gas sorption capacity is observable between the vitrinite and inertinite-rich coals, at a given rank. Liptinite is a minor constituent (<5%) of the Sydney Basin coals and therefore the influence of its variations is also likely to be minimal.

3.2. Coal seam gas contents

For the 61 coal samples measured in the present study, gas contents range from about 5 to 20 m^3 of gas/tonne of coal (m^3/t; as received basis). The gas contents, on average increase with increases in depth from ~200 m to 600 m and with further increases in depth to ~900 m the gas contents have a larger scatter and on average, appear to plateau or decrease (Fig. 6). Faiz et al. (1999) found that gas contents for other areas within the Sydney Basin are, on average, lower at depths between 800 and 1200 m than those at about 500–700 m, giving a similar relationship as found in the present study.

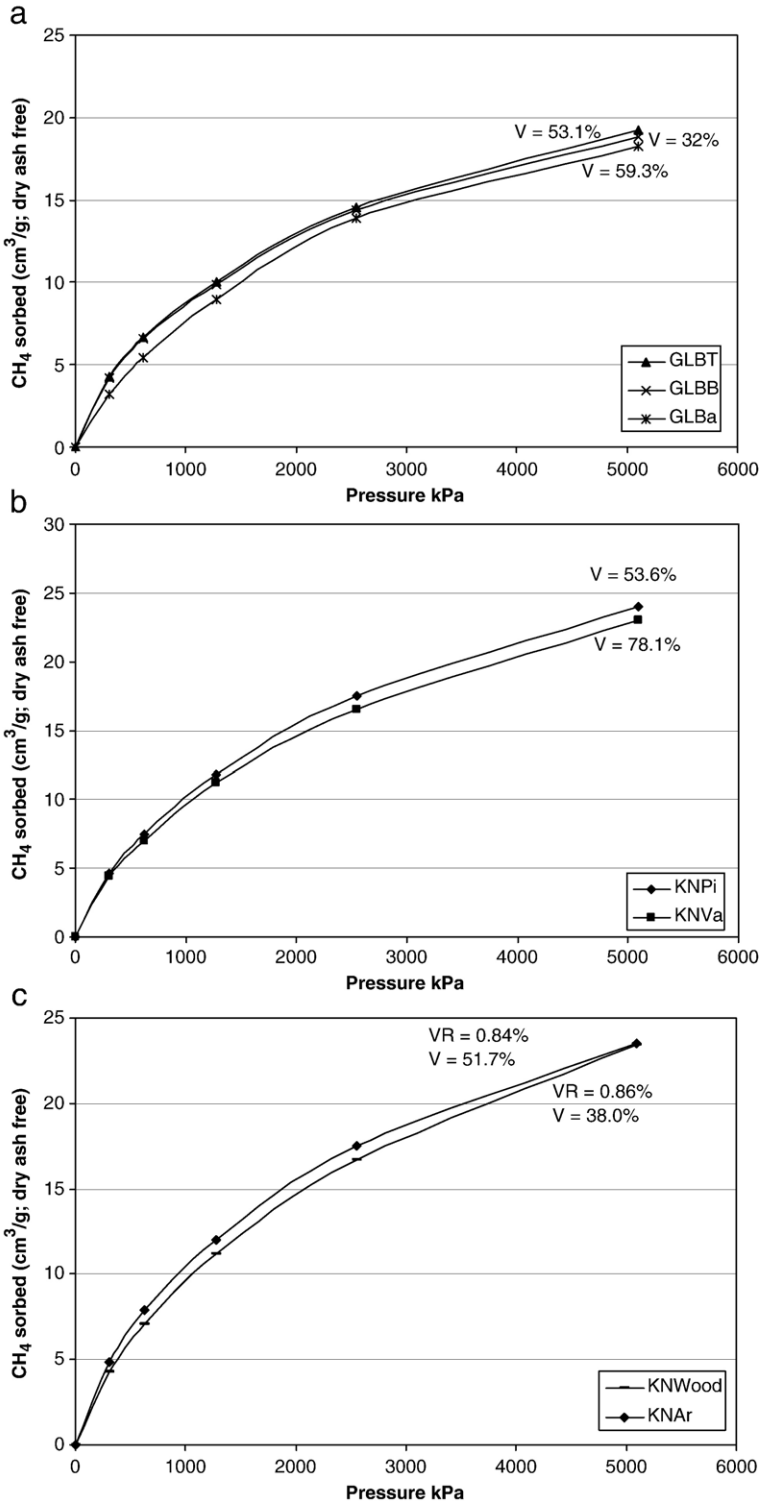

Fig. 5. (a) Sorption isotherms for coals having VR values ranging from 1.3% to 1.35%. (b) Sorption isotherms for coals having VR values ranging from 0.97% to 0.99%. (c). Sorption isotherms for coals having VR values ranging from 0.84% to 0.86%.

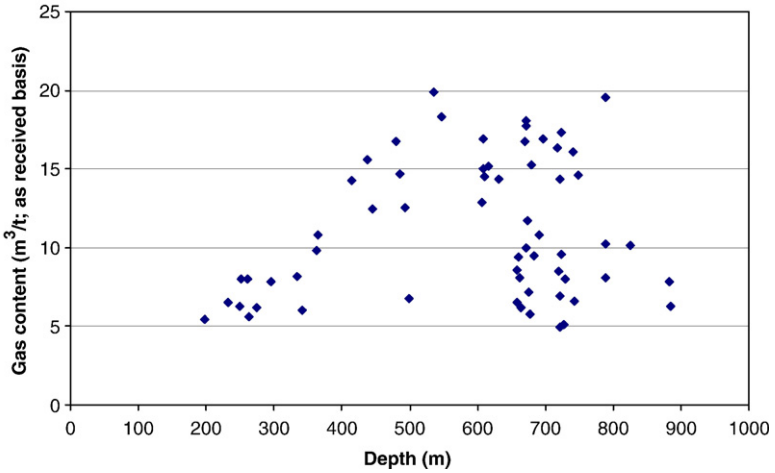

Fig. 6. In-situ gas content and depth for the Southern and Hunter Coalfields of the Sydney Basin.

Similar to the relationship of Langmuir volume with ash yield, the in-situ gas contents have a moderate to weak inverse relationship with ash yield (Fig. 7), indicating the association of coals seam gas with organic constituents.

3.2.1. Multivariate statistical analysis

Because gas contents are related to a variety of coal properties however, multivariate statistical analyses are required to comprehensively investigate the relationships and in the present work, R-mode cluster analysis was employed. This technique arranges variables into a hierarchical classification scheme (dendrogram), such that data in each category resemble each other more than they resemble data in other categories.

A correlation matrix, based on Pearson product moment coefficients, for key coal and coal gas properties is given in Table 2 and the associated cluster analysis dendrogram is given in Fig. 8.

The '*x*-axis' of the dendrogram gives the level of similarity between clusters. As shown in Fig. 8, the data can be divided into several clusters, and gas contents (Q (m^3/t)) are closely grouped with carbon and fixed carbon contents and the inertinite content. Because of the association of gas with organic matter, gas contents are positively correlated with C contents and fixed carbon contents and are negatively correlated with ash yield and mineral content (Table 2). Gas contents are positively correlated with inertinite contents, which is consistent

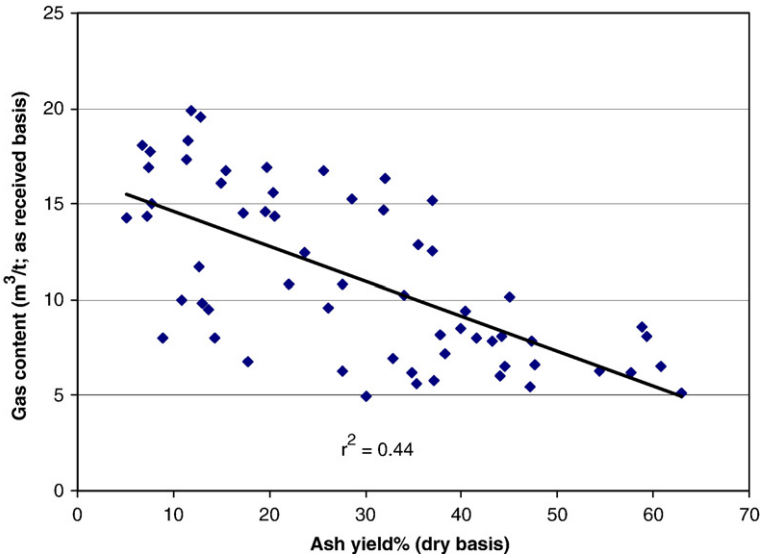

Fig. 7. Relationship between in-situ gas content and ash yield.

Table 2
Pearsons product moment correlation matrix for the various properties of 61 Sydney Basin coals and their gases

	Depth (m)	Q (m^3/t)	IM %	Ash %	VM %	FC %	VR %	C %	CH_4 %	C_2H_6 %	CO_2 %	Vit %	Lip %	In %	MM %
Depth	1.00														
Q (m3/t)	0.21	1.00													
IM %	−0.70	−0.36	1.00												
Ash %	0.10	−0.66	0.33	1.00											
VM %	−0.61	0.38	0.18	−0.77	1.00										
FC %	0.19	0.69	−0.56	−0.94	0.52	1.00									
VR %	0.90	−0.01	−0.60	0.22	−0.71	0.08	1.00								
C %	0.01	0.67	−0.44	−0.99	0.68	0.98	−0.10	1.00							
CH_4 %	0.35	−0.28	−0.36	0.16	−0.46	0.03	0.52	−0.07	1.00						
C_2H_6 %	0.48	−0.13	−0.27	0.19	−0.40	−0.05	0.54	−0.12	0.28	1.00					
CO_2 %	−0.43	0.32	0.38	−0.22	0.54	0.01	−0.61	0.13	−0.91	−0.33	1.00				
Vit %	0.07	0.16	−0.28	−0.42	0.33	0.40	0.02	0.43	0.06	0.05	−0.05	1.00			
Lip %	−0.63	0.17	0.42	−0.29	0.61	0.07	−0.68	0.19	−0.50	−0.32	0.56	−0.22	1.00		
In %	0.03	0.45	−0.14	−0.41	0.20	0.44	−0.02	0.42	0.04	−0.22	−0.05	−0.51	0.33	1.00	
MM %	−0.12	−0.43	0.30	0.58	−0.32	−0.61	−0.01	−0.60	−0.16	0.28	0.14	−0.31	−0.12	−0.51	1.00

Q (m^3/t) — gas content (as received basis); VR — mean maximum reflectance of vitrinite; IM — inherent moisture; Ash — ash yield; VM — volatile matter; FC — fixed carbon; C — Carbon; Vit — vitrinite; Lip — liptinite; In — inertinite; MM — mineral matter.

with the findings of Faiz and Cook (1991) for a suite of coals from the southern Sydney Basin; in this study, the gas contents increased from ~5 to ~10 m^3/t with increases in inertinite contents from ~10 to ~50%. In the present study however, the positive relationship of gas content with inertinite content is weaker. A similar weak positive correlation between desorbed gas amounts and inertinite contents was observed by Levine (1987) for a suite of coals from the United States of America.

For samples from the well WG-1 in the Southern Coalfield, coal seam gas contents have a moderately well defined negative relationship with vitrinite content (Fig. 9). The two samples having the lowest gas contents (<10 m^3/t) contain 80–90% vitrinite whereas the samples with the highest gas contents (>20 m^3/t) contain up to 60% inertinite. According to sorption isotherm analyses, the vitrinite-rich coals are undersaturated with gas in comparison to the inertinite-rich coals and therefore no major

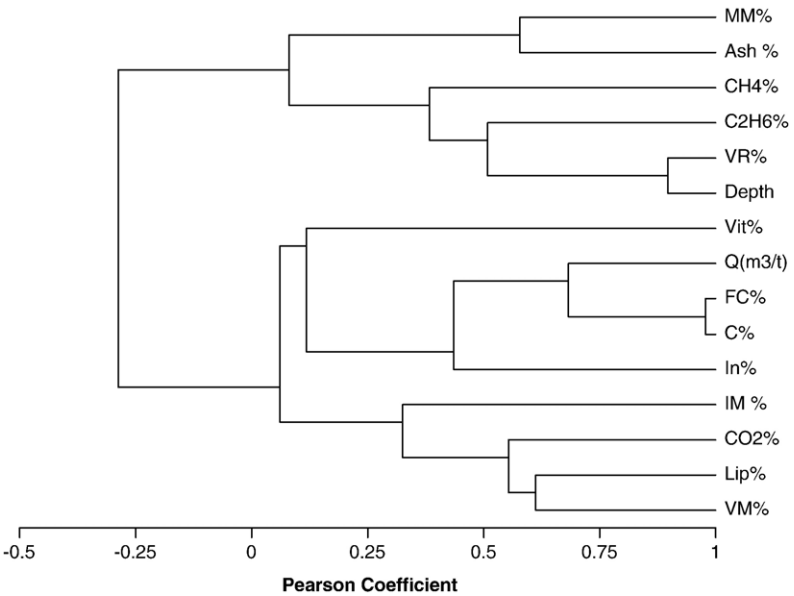

Fig. 8. R-mode cluster analysis dendrogram for the gas and coal properties of 61 samples studied from the Sydney Basin. VR — mean maximum reflectance of vitrinite; IM — inherent moisture; Ash — ash yield; VM — volatile matter; FC — fixed carbon; C — Carbon; Vit — vitrinite; Lip — liptinite; In — inertinite; MM — mineral matter; Q(m^3/t)—gas content (as received basis).

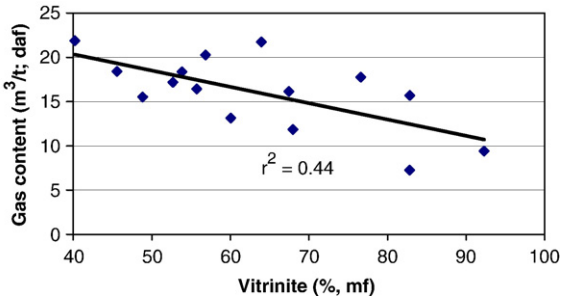

Fig. 9. Relationship of in-situ gas content (dry ash-free basis) and vitrinite content (minerals free basis) for samples from WG-1 well, Southern Coalfield, Sydney Basin.

differences would exist in gas contents if all the coals were fully saturated. A possible cause for the undersaturation is that, the vitrinite-rich (particularly telovitrinite-rich) coals may have lost more gas than the inertinite-rich coals during uplift (Fig. 10), due to their higher fracture permeabilities (Figs. 11 and 12).

3.2.2. *Influence of burial history, temperature and pressure*

Although it is well accepted that the gas sorption capacity of coal decreases with increases in temperature, the nature of this relationship at high pressures >7000 kPa is not well understood. Yang and Saunders (1985) indicated that at about 7000 kPa, the CH_4 sorption capacity of a coal at 102 °C is about 40% of that at 22 °C. Based on isotherms measured at various temperatures, Ettinger et al. (1966) and Kim (1977) proposed empirical equations giving CH_4 sorption capacities for coals at various temperatures. The experiments by Krooss et al. (2002) also suggest that the gas sorption capacity of coal decreases with increasing temperature, however, at high temperatures these effects are likely to be complicated and may be not be readily simulated in the laboratory.

Khorasani and Michelsen (1999) speculated that, despite high temperatures, gas storage capacity of coal at high pressures may be high due to the dominance of absorption over adsorption. If this holds true, some of the deepest coals in the Sydney Basin could contain CH_4 contents of 30–40 m^3/t or higher (i.e. above the Langmuir Volume). As mentioned above, however, data from the present study and Faiz et al. (1999) indicate that coals from depths of >1 km (i.e hydrostatic pressure >10 MPa and temperature >45 °C), have lower gas contents (<15 m^3/t) than those from about 600–700 m (i.e hydrostatic pressure ~6–7 MPa and temperature ~35–40 °C). According to the sorption isotherms, for fully saturated coals, the gas contents increase with increasing hydrostatic pressure to depths of about 600–700 m but with further increases in depth, the increases in temperature could lead to decreased gas contents, which overrides the smaller positive effects from increased pressure.

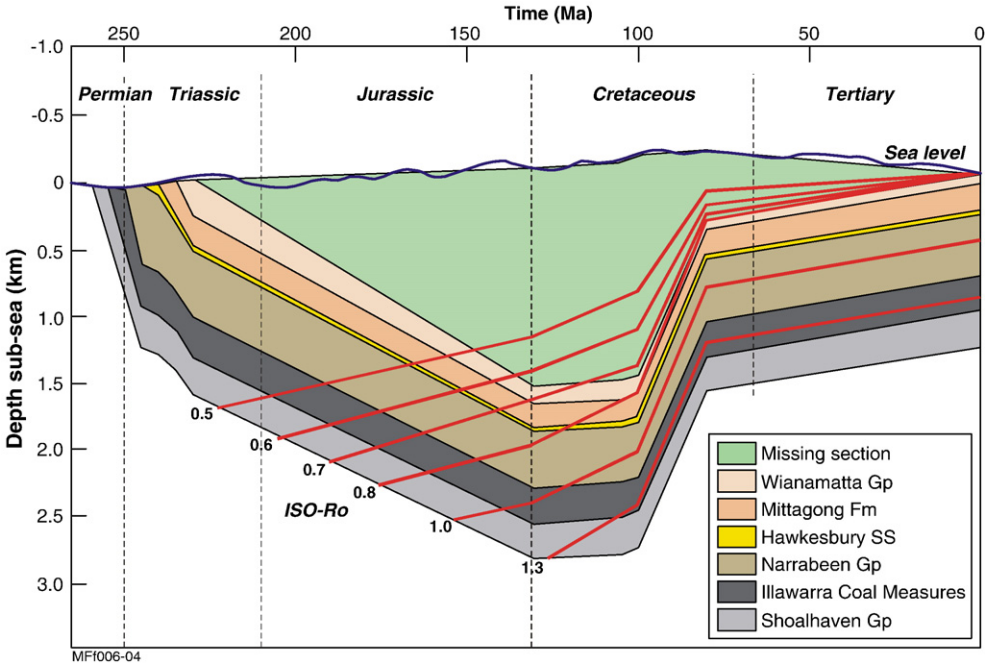

Fig. 10. Burial history re-construction based on a deep well (BL-8) from the Southern Coalfield, Sydney Basin (modified from Faiz, 1993).

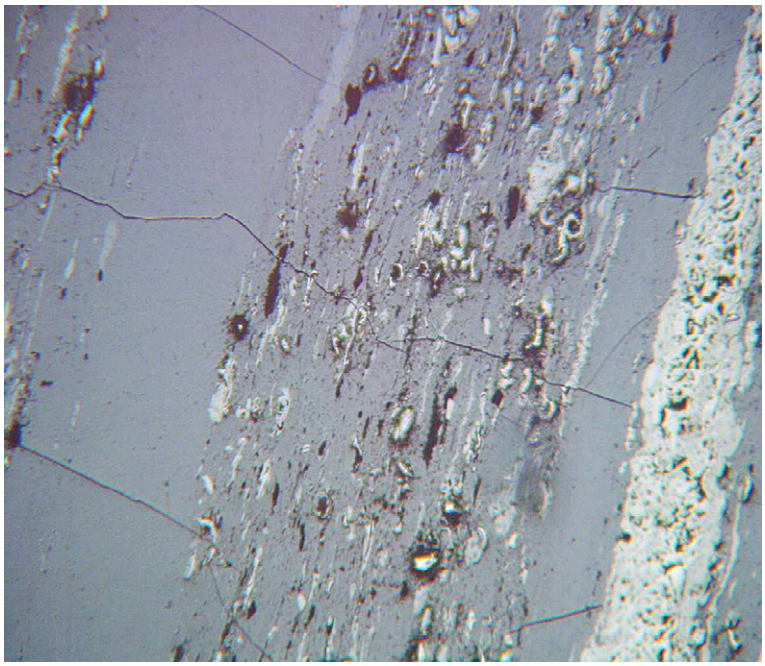

Fig. 11. Photomicrograph showing preferential fracturing in telovitrinite in the Bulli Coal, Southern Coalfield, Sydney Basin. Reflected white light. Field width 0.25 mm.

In addition to the variations in sorption capacity caused by changing temperature and pressure regimes, in-situ gas contents of coals also vary throughout their burial history according to the volumes of gases generated (Scott, 2002). In the southern Sydney Basin, the main phase of thermogenic gas generation occurred during the Early Cretaceous, when the Permian coals were deeply buried and were subjected to temperatures > 120 °C (Fig. 13; also Faiz and Hutton, 1997). Kinetic modelling of gas generation for this area indicates that the cumulative volumes of CH_4 and higher hydrocarbons generated were >50 m^3/t in some locations (Faiz and Hutton, 1997). Comparing these values to the temperature–CH_4 sorption capacity relationship proposed by Kim (1977), shows that a significant amount of CH_4 generated during the Early Cretaceous may have not have been retained within the coal (Fig. 13). If this is the case, the excess gas may have been expelled by diffusion and through the micro-fracture network. High temperatures may also considerably enhance the gas desorption rates due to activated diffusion. Any expulsion through micro-fractures would probably have been more intense in telovitrinite-rich coals, which, as mentioned above, are more prone to micro-fracturing than inertinite-rich coals (Figs. 11 and 12). Gas expulsion may also be high in coals containing high volumes of matrix mineral matter as indicated by their high gas desorption rates measured in laboratory experiments (Faiz et al., 1996). As a result of the post-Cretaceous uplift, the gas sorption capacity of the coals is likely to have increased due to a decrease in temperature and they may have sorbed gas again, where sufficient gas was available. This gas could have originated from deeper strata including coal and carbonaceous shales or from secondary biogenic gas generation.

If the absorption capacity of coal is high at very high pressures (e.g. Khorasani and Michelsen, 1999), the volume of gas sorbed in the coals during peak gas generation was likely to be higher than indicated in Fig. 13. However, the effects of high temperature on total gas storage capacities of coals at high pressures are not known

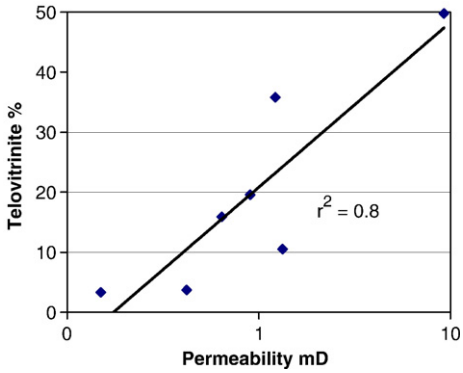

Fig. 12. Relationship between telovitrinite content and 'matrix permeability' for a suite of samples from the Southern Coalfield, Sydney Basin (from Faiz et al., 2002).

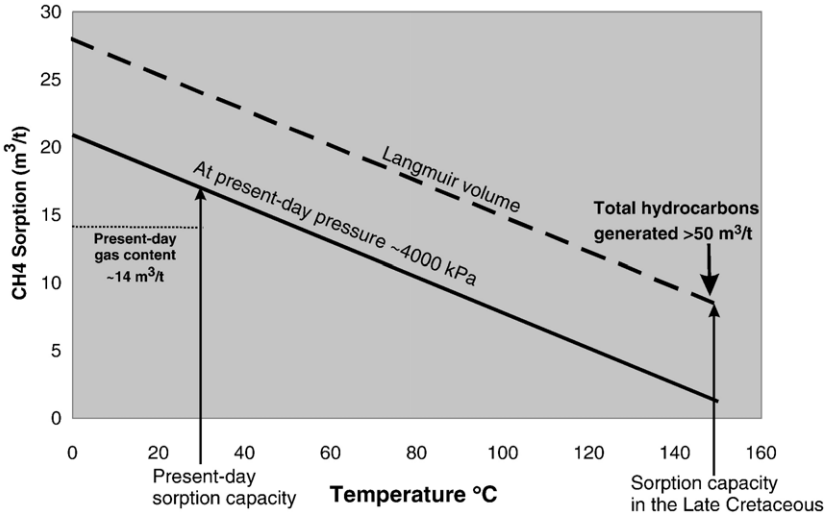

Fig. 13. An example of how the CH_4 sorption capacities may vary in relation to changes in temperature for the coal Metro1431; temperature sorption capacity relationships projected by Kim (1977). Peak gas generation in the basin occurred during the Early Cretaceous at depth ~2.5 km, temperature of ~150 °C and the volume of gas generated was >50 m^3/t (after Faiz, 1993). In this example it is assumed that gas sorption capacity at depth ~2.5 km was equal to the Langmuir volume, however this assumption is uncertain. The present day hydrostatic pressure for the coal seam is ~4000 kPa and the in-situ gas content is ~14 m^3/t.

because these conditions cannot be accurately simulated in the laboratory. In addition, because laboratory experiments are conducted using sealed canisters (closed system) the experiments do not yield a true simulation of gas expulsion during peak generation as has been described by previous workers such as Littke and Leythaeuser (1993).

3.3. Significance of secondary biogenic gas generation

Isotope analyses of numerous gases from Sydney Basin coals (e.g. Smith and Pallasser, 1996) have indicated the presence of considerable amounts of secondary biogenic CH_4 generation since the Late Cretaceous uplift. This gas has originated from microbial alteration of the organic matter and pre-existing gases and is most common in highly permeable parts of the coal seams where microbes and nutrients in meteoric waters can access the coal (Faiz, 2004). In areas where secondary biogenic gas generation has been intense, the coals are highly saturated with CH_4 with respect to its sorption isotherm (Faiz et al., 2003), and in areas where secondary biogenic CH_4 generation has been less intense, coals are often severely undersaturated. The effects of biogenic gas generation can therefore overprint other important influences on gas contents.

In the southern Sydney Basin, the 'high production fairway' is located exclusively in areas where secondary biogenic gas generation has been prevalent (Faiz et al., 2003). Gas production rates in this fairway are an order of magnitude greater than in areas containing primarily thermogenic wet gases.

4. Summary and Conclusions

Numerous factors influence gas reservoir properties of coal seams and a holistic approach is required to fully understand the main controls. Even within a single basin, different influences may predominate in different areas, depending upon coal composition, coal rank, stress fields, basin hydrodynamics and burial and thermal histories.

The gas sorption data for the Sydney Basin coals indicate that the gas primarily resides within the organic matter and therefore consideration of relationships between sorption characteristics and potential controlling factors requires conversion of the data to an ash-free or mineral-free basis. Methane sorption capacity does not show any systematic relationship with the maceral group composition but is strongly related to coal rank. Sorption capacity decreases with rank for the high volatile to medium volatile bituminous coals of the Sydney Basin possibly due to the retention of bitumen and heavy hydrocarbons generated during coalification in the coal micro-pores. The sorption capacity for a contact metamorphosed sample, however, is considerably high possibly due to conversion of the bitumens to gas, followed by expulsion.

In-situ gas contents are directly proportional to inertinite content, which is inconsistent with the relationships found for sorption capacity. This positive correlation is possibly induced by the variability in gas saturation levels for these samples. The inertinite-rich samples tend to have higher gas saturation levels than vitrinite-rich samples probably due to expulsion of gas out of the permeable vitrinite.

Gas contents of coal are not constant during the burial history and they vary as equilibrium within coal–gas system changes as a result of the changes in P–T condition and rank. In the Sydney Basin for example, peak gas generation occurred in the Early Cretaceous when the coals were at maximum burial (2.5 to 4 km), but the sorption capacities were probably low because of the high temperatures (>120 °C). As the coals decreased in temperatures during uplift, sorption capacity increased such that more methane could be sorbed if available. Studies on the Sydney Basin have shown that the most prospective areas are where secondary biogenic methane generation have re-saturated coal seams with methane. In order to form biogenic methane, the coals need enough permeability to allow access of meteoric waters; this permeability adds to their attractiveness for economically producing gas.

Acknowledgements

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Appendix A

Details of various properties of 61 Sydney Basin coals and their gases

Sample No.	Depth (m)	Q (m^3/t)	IM %	Ash %	VM %	FC %	VR %	C %	CH_4 %	C_2H_6 %	CO_2 %	Vit %	Lip %	In %	MM %
1	607.38	12.9	0.9	35.5	21.6	42.0	1.22	51.0	87.5	0.0	12.5	50.7	1.8	36.7	10.6
2	608.35	15.0	0.9	7.7	24.2	67.2	1.22	81.6	87.2	0.0	12.8	54.2	0.7	42.4	10.6
3	609.34	16.9	0.9	7.4	23.6	68.1	1.24	82.3	87.2	0.0	12.8	44.1	0.1	52.6	11.6
4	610.37	14.6	0.8	17.2	22.2	59.8	1.25	72.6	94.9	0.0	5.1	69.4	0.4	20.8	12.6
5	631.53	14.4	1.3	20.5	19.6	58.6	1.29	69.5	86.7	0.0	8.2	47.2	0.1	40.4	13.6
6	658.07	6.5	1.3	60.8	10.2	27.7	1.35	31.5	95.1	1.1	3.7	32.4	0.0	29.1	14.6
7	658.82	8.5	1.8	58.9	10.0	29.3	1.00	32.7	95.3	1.1	3.6	41.5	0.0	23.4	15.6
8	659.76	9.4	1.2	40.4	14.5	43.9	1.35	50.7	94.1	0.6	5.3	50.1	0.0	24.2	16.6
9	663.09	8.1	3.6	59.4	11.5	25.5	1.38	29.1	94.5	0.5	5.0	25.4	0.0	37.8	17.6
10	664.40	6.2	2.7	57.7	12.2	27.4	1.39	31.2	94.1	0.4	5.5	28.9	0.0	30.3	40.8
11	676.40	7.1	1.4	38.3	15.6	44.7	1.38	52.1	95.4	0.0	4.3	43.5	0.0	20.5	36.0
12	677.43	5.8	1.4	37.2	17.0	44.4	1.35	53.5	95.6	0.0	4.4	70.7	0.0	5.9	20.6
13	722.21	5.0	1.2	30.0	16.5	52.3	1.46	61.1	93.0	5.7	0.8	58.3	0.0	12.1	22.6
14	723.26	9.5	1.3	26.2	16.8	55.7	1.45	65.0	93.0	5.5	1.2	46.0	0.0	30.6	23.6
15	721.70	14.4	1.1	7.2	22.5	69.2	1.41	83.9	93.0	5.1	1.4	78.2	0.0	16.2	21.6
16	671.10	10.0	0.9	10.9	22.9	65.3	1.13	77.9	91.7	0.0	8.3	41.0	0.0	48.4	10.6
17	671.81	18.1	1.0	6.8	24.4	67.8	1.13	82.7	91.9	0.0	8.1	62.8	0.6	33.9	11.6
18	672.74	17.8	1.0	7.5	26.4	65.1	1.15	81.3	93.2	0.0	7.3	46.3	0.7	50.1	12.6
19	673.72	11.7	0.9	12.7	22.8	63.6	1.14	76.9	92.3	0.0	7.7	62.8	0.5	30.5	13.6
20	682.86	9.5	1.2	13.6	25.8	59.4	1.15	75.4	90.2	1.1	8.4	53.1	0.5	36.9	14.6
21	691.62	10.8	1.4	27.6	24.4	46.6	1.18	60.6	89.4	2.6	7.2	58.1	0.9	33.0	15.6
22	719.62	8.5	1.0	39.9	18.0	41.1	1.22	49.5	94.7	0.9	3.9	51.4	0.0	18.0	16.6
23	721.54	6.9	1.0	32.8	16.8	49.4	1.22	57.7	94.8	1.1	4.2	55.2	0.0	18.6	17.6
24	727.15	5.1	2.0	63.0	11.1	23.9	1.30	28.0	95.0	0.7	4.1	46.6	0.0	10.2	18.6
25	728.62	8.0	1.8	41.5	17.6	39.1	1.29	47.1	0.0	0.0	0.0	53.0	0.0	31.5	19.6
26	742.46	6.6	1.8	47.6	14.9	35.7	1.33	42.3	92.3	3.9	2.3	46.5	0.0	14.3	20.6
27	788.26	19.6	1.0	12.8	21.5	64.7	1.34	76.7	89.8	8.7	1.2	74.0	0.1	19.8	21.6
28	788.65	8.1	1.6	44.2	14.1	40.1	1.30	46.3	94.9	3.8	1.2	49.3	0.0	5.9	22.6
29	789.63	10.2	1.1	34.0	17.0	47.9	1.33	56.1	95.5	2.9	1.4	72.5	0.0	17.6	23.6
30	723.46	17.4	0.9	11.4	20.6	67.1	1.34	78.4	94.8	0.1	4.7	39.2	0.0	59.3	3.8
31	741.57	16.1	1.0	15.0	21.6	62.4	1.36	74.2	88.1	0.7	8.3	53.3	0.0	36.2	10.5
32	748.74	14.6	1.0	19.6	20.4	59.0	1.37	70.8	91.2	0.1	8.1	62.6	0.0	24.5	12.5
33	825.73	10.1	2.0	45.0	13.7	39.3	1.52	45.8	95.4	1.8	2.5	46.2	0.0	19.6	34.2
34	883.39	7.8	0.8	43.2	12.6	43.4	1.57	49.8	89.8	7.8	0.5	36.5	0.0	26.6	36.9
35	884.70	6.3	1.5	54.4	12.1	32.0	1.57	36.9	88.4	10.3	0.5	37.8	0.0	13.0	49.2
36	363.88	10.8	2.2	22.1	30.0	45.7	0.81	63.1	88.1	0.1	11.9	67.6	1.2	20.0	11.2
37	697.26	16.9	1.7	19.7	24.0	54.6	1.12	67.9	4.6	0.0	95.2	67.7	0.7	10.6	21.0

Appendix A (*continued*)

Sample No.	Depth (m)	Q (m^3/t)	IM %	Ash %	VM %	FC %	VR %	C %	CH_4 %	C_2H_6 %	CO_2 %	Vit %	Lip %	In %	MM %
38	680.41	15.3	1.9	28.6	21.6	47.9	1.12	60.0	8.4	0.0	91.3	55.2	0.3	17.2	27.3
39	669.50	16.8	1.5	25.6	23.5	49.4	1.04	61.4	16.3	0.7	82.8	51.7	1.2	23.8	23.3
40	616.41	15.2	1.6	36.9	20.6	40.9	1.05	51.6	28.3	0.6	71.0	22.7	1.6	33.9	41.8
41	547.38	18.3	2.0	11.5	25.1	61.4	1.03	75.0	14.7	0.0	85.1	41.4	4.0	47.0	7.6
42	415.18	14.3	2.2	5.1	32.1	60.6	0.86	79.5	63.6	0.1	36.3	37.2	3.5	57.1	2.2
43	535.76	19.9	2.0	11.8	27.8	58.4	0.99	74.9	23.3	0.6	75.8	71.7	0.4	16.8	11.1
44	492.68	12.6	2.0	36.9	20.3	40.8	0.99	51.5	29.0	0.9	69.8	25.9	1.3	39.5	33.3
45	486.45	14.7	2.1	31.9	24.2	41.8	0.94	55.4	19.6	1.2	79.0	55.4	1.4	18.2	25.0
46	437.32	15.6	2.6	20.4	24.9	52.1	0.84	65.7	43.5	0.2	56.3	7.0	2.4	86.6	4.0
47	718.51	16.3	1.6	32.0	21.8	44.6	1.13	51.5	14.8	0.4	84.7	54.4	0.9	7.3	37.4
48	480.48	16.8	2.0	15.4	27.6	55.0	0.92	70.6	25.7	0.0	73.1	59.6	1.5	27.5	11.4
49	249.68	6.3	3.0	27.6	24.2	45.2	0.87	58.6	91.9	0.0	5.0	63.8	1.0	11.5	23.7
50	444.36	12.4	2.0	23.7	26.4	47.9	0.84	62.5	52.4	0.1	47.5	52.2	1.9	31.5	14.2
51	275.07	6.2	2.8	34.9	24.6	37.7	0.83	51.4	93.2	0.0	3.6	65.0	0.4	11.7	22.9
52	333.70	8.1	2.2	37.8	22.6	37.4	0.88	48.6	92.5	0.0	6.3	61.7	1.2	16.6	20.5
53	231.33	6.5	2.6	44.6	21.5	31.3	0.80	41.2	55.2	0.1	44.6	34.1	2.4	16.2	47.3
54	296.03	7.8	2.5	47.4	21.6	28.5	0.83	39.2	56.0	0.1	43.8	27.9	0.5	9.4	62.2
55	197.43	5.5	2.8	47.2	21.1	28.9	0.81	38.6	54.4	1.1	44.4	34.2	0.5	13.1	52.2
56	251.92	8.0	2.6	8.9	34.6	53.9	0.78	74.7	37.7	0.0	83.6	79.7	1.5	12.6	6.2
57	261.66	8.0	2.5	14.3	30.5	52.7	0.83	70.4	43.4	0.0	51.4	33.8	3.8	45.9	16.5
58	262.35	5.6	2.4	35.3	25.8	36.5	0.83	49.9	43.4	0.5	56.1	47.8	2.6	15.9	33.7
59	341.02	6.0	2.5	44.1	22.0	31.4	0.84	42.5	41.7	0.7	57.6	45.4	1.6	14.1	38.9
60	362.44	9.8	2.2	13.0	32.2	52.6	0.86	71.3	46.4	0.0	53.3	62.1	1.5	20.8	15.6
61	499.53	6.7	1.9	17.8	30.4	49.9	0.94	67.4	6.4	0.0	85.4	59.5	0.4	10.2	29.9

VR — mean maximum reflectance of vitrinite; IM — inherent moisture; Ash — ash yield; VM — volatile matter; FC — fixed carbon; C — Carbon; Vit — vitrinite; Lip — liptinite; In — inertinite; MM — mineral matter.

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