Coal seam gas distribution and hydrodynamics of the Sydney Basin, NSW, Australia

A. BURRA*, J. S. ESTERLE AND S. D. GOLDING

School of Earth Sciences, University of Queensland, Queensland 4072, Australia.

This paper reviews various coal seam gas (CSG) models that have been developed for the Sydney Basin, and provides an alternative interpretation for gas composition layering and deep-seated CO₂ origins. Open file CSG wells, supplemented by mine-scale information, were used to examine trends in gas content and composition at locations from the margin to the centre of the basin. Regionally available hydrochemistry data and interpretations of hydrodynamics were incorporated with conventional petroleum well data on porosity and permeability. The synthesised gas and groundwater model presented in this paper suggests that meteoric water flow under hydrostatic pressure transports methanogenic consortia into the subsurface and that water chemistry evolves during migration from calcium-rich freshwaters in inland recharge areas towards sodium-rich brackish water down-gradient and with depth. Groundwater chemistry changes result in the dissolution and precipitation of minerals as well as affecting the behaviour of dissolved gases such as CO₂. Mixing of carbonate-rich waters with waters of significantly different chemistries at depth causes the liberation of CO₂ gas from the solution that is adsorbed into the coal matrix in hydrodynamically closed terrains. In more open systems, excess CO₂ in the groundwater (carried as bicarbonate) may lead to precipitation of calcite in the host strata. As a result, areas in the central and eastern parts of the basin do not host spatially extensive CO₂ gas accumulations but experience more widespread calcite mineralisation, with gas compositions dominated by hydrocarbons, including wet gases. Basin boundary areas (commonly topographic and/or structural highs) in the northern, western and southern parts of the basin commonly contain CO₂-rich gases at depth. This deep-seated CO₂-rich gas is generally thought to derive from local to continental scale magmatic intrusions, but could also be the product of carbonate dissolution or acetate fermentation.

KEYWORDS: Sydney Basin, coal seam gas, gas origin, hydrodynamics, hydrochemistry, CO₂, carbonates.

INTRODUCTION

Understanding the origins of coal seam gas (CSG) and the controls on gas distribution in a basin allow for the development of predictive models for resource exploration and production forecasting and optimisation. Controls on gas accumulation have been attributed to various parameters, ranging from coal properties (e.g. Levine 1993; Beamish & Crosdale 1998; Laxminaranaya & Crosdale 1999) to the effect of large-scale geological and hydrodynamic settings (e.g. Ayers & Kaiser 1992; Ellard et al. 1992; Scott et al. 1994; Scott 2002; Pashin 2007). In particular, coal rank and type, as well as burial history, have been correlated with thermogenic CSG generation (and storage) potential of coal reservoirs. Biogenic gas accumulations are strongly influenced by the geological and hydrodynamic setting of the region including the potential to flush the system and/or introduce methanogenic consortia (e.g. Rice & Claypool 1981; Whiticar & Faber 1986; Whiticar et al. 1986; Creedy 1988; Ayers & Kaiser 1992; Rice 1993; Boreham et al. 1998; Bustin & Clarkson 1998; Scott 2002; Faiz et al. 2003). High gas saturation levels at shallow depths in coal seams mainly result from the presence of secondary biogenic gas that replaces thermogenic gas lost as a result of basin uplift (Faiz et al. 2003; Golding et al. 2013).

The extensive coal mining and gas exploration history of the Sydney Basin, NSW, allows for the relatively detailed assessment of gas distribution and origin on a local (e.g. Smith et al. 1982; Williams 1991; Creech 1992; Bocking & Weber 1993; Faiz & Hutton 1995) to regional scale (e.g. Faiz 1993; Smith & Pallaser 1996; Faiz et al. 2003; Thomson et al. 2006, 2014; Pinetown 2010, 2014). Basin-wide studies targeting commercial CSG deposits or investigating potential CO₂ sequestration reservoirs have also contributed to the understanding of the basin (e.g. Scott & Hamilton 2006; Blevin et al. 2007).

In addition to gas content, gas composition and, in particular, CO₂ distributions have been investigated. CO₂ is a diluent and potentially corrosive gas for commercial production, and increases outburst risk in
underground coal mines. In the Sydney Basin, high CO₂ levels have been linked to local and regional magmatism (Smith et al. 1982; Faiz et al. 2003), but in many parts of the basin, igneous intrusions are not associated with CO₂-rich CSG (e.g. Creech 1992; Bocking & Weber 1993; Gurba & Weber 2001). This paper presents an alternative explanation for the distribution of deep, CO₂-rich seam gas in these areas through the integration of hydrogeochemical trends at a basin scale.

BACKGROUND

Geological setting

The Sydney Basin is a Permian–Triassic sedimentary basin located on the eastern seaboard of Australia that has been divided into four main regions: the Newcastle, Hunter, Western and Southern Coalfields (Coalfield Geology Council of NSW). For the current study, the basin is divided into five regions closely corresponding to these coalfield divisions, but intended to align more closely to the gas distribution characteristics discussed in this paper (Figure 1). The northern area (N) encompasses the majority of the Hunter Coalfield; the western area (W) corresponds to the Western Coalfield. The southern area (S) covers most of the Southern Coalfield, except for the far northern parts of that district; these are included in the central region (C), together with the southern parts of the Hunter Coalfield. The eastern area (E) covers the Newcastle Coalfield but extends as far south as the Central Coast and Sydney (Figure 1).

The basin hosts a series of Permian coal-bearing sequences formed in a range of fluvial environments, separated by a number of significant marine transgressions between the main formations (Figure 2).

The key coal-bearing sections discussed in this paper belong to the Singleton Supergroup—in particular, the Newcastle and Wittingham Coal Measures—and the equivalent Illawarra Coal Measures. Sedimentary units below this sequence are chiefly of marine and volcanic origin, while the overlying strata consist of Triassic units of fluvial origin. These (and other) sediments covered the coal-bearing sequence regionally at the time of maximum burial, with the coal measures reaching depths of approximately 2–3 km in the early Cretaceous (Faiz et al. 2007a; Jaworska et al. 2010). Cenozoic volcanic rocks overlie the Triassic sequence in the northern and western parts of the basin.

Coal rank in the basin is bituminous, with vitrinite reflectances ranging from 0.5 to >1.40% Ro, although values as high as 2.0% have been reported locally in the basin (Bocking & Weber 1980). In general, the coals in the northern areas of the basin are lower in rank for the same depths than are those in the southern regions (Scott & Hamilton 2006; Faiz et al. 2007a; Jaworska et al. 2010); the latter having experienced deeper burial prior to uplift (Faiz et al. 2007a). In the central region, vitrinite reflectance can reach up to 1.0% at depths of around 500–

Figure 1 (Left) Location map of the Sydney Basin, NSW. Regions discussed in this study are referred to as northern (N), central (C), western (W), eastern (E) and southern (S) as shown by the circled areas. (Right) Location of cross-section discussed in this study indicating boreholes used in gas characteristics interpretation.
800 m, which is comparable with the coal rank in the southern areas. However, when considering similar coal seam sequences (e.g. Newcastle Coal Measures), vitrinite reflectance can range from around 0.5–0.6% in the Upper Hunter region, 0.8–0.9% in the central Sydney Basin, and approach 1.1–1.2% (and up to 2.0%; Faiz et al. 2007a, b) in the southern Illawarra region.

Extensive Late Cretaceous intrusive igneous activity that was associated with a time of rapid uplift in the basin (Veevers 2000 in Healy et al. 2005; Faiz et al. 2007a), emplaced widespread sills and dykes (e.g. Warbooke 1981 in Creech 1992; and OZCHRON data presented by Healy et al. 2005). Uplift as part of the Tasman Rift continued into and levelled off in the Cenozoic, when volcanic activity again became wide spread, particularly in the northwestern and western parts of the region. This latter period of igneous activity resulted in further emplacement of dykes and diatremes, chiefly in the western, southern and eastern parts of the basin (e.g. Facer & Carr 1979). Sydney Basin sediments have experienced limited uplift since the Cenozoic (Faiz et al. 2007a, figure 10); however, the eastern seaboard of Australia is currently undergoing a renewed compressional regime (Veevers 2000; Hillis & Reynolds 2003; Healy et al. 2005).

The Sydney Basin sediments experienced significant syndepositional tectonism; this has amplified various sedimentary features, such as thickening of coal seams and syndepositional faulting, leading to differential subsidence rates observed in the sediments in the vicinity of major structural features such as regional faults and monoclines, particularly near basin margin locations. The main tectonic influence during the Permian–Triassic was the ENE–WSW compression associated with the Hunter–Bowen Orogeny that resulted in a northerly or northwesterly strike orientation for many large-scale features in the Sydney Basin (Figure 3; Healy et al. 2005; Blevin et al. 2007). Of particular relevance for gas distribution in the region is a number of large and spatially extensive monoclines near the basin edges (e.g. Mt Thorley, Lapstone and Nepean (and associated) monoclines; Figure 3). These have a significant impact on hydrodynamics (e.g. Pashin 2007), as meteoric recharge occurs around the up-dip margins of the basin that widens as the beds plunge and thicken east-southeasterly beneath the sea.

The other key structural orientation in the basin is the northeasterly trend of normal faults and dykes. The latter, probably associated with development of the Tasman Rift period during the Late Cretaceous, may have infilled pre-existing fault structures (e.g. Healy et al. 2005). These large-scale faults and dykes serve to compartmentalise the basin locally. A summary of key sedimentary and structural events in the Sydney Basin is shown in Table 1.
The structural development and compartmentalisation of the basin affected the evolution of the hydrogeological flow regimes at various times during its history, up to the present time. In turn, the hydrogeological development likely influenced the origin and distribution of gas, particularly biogenic gas, in the basin (Smith et al. 1992; Faiz et al. 2003; Thomson et al. 2008).

Hydrogeology and dynamics

Geological and geographical settings exert a strong control on the hydrological development of a region. At its simplest, the topographic relief (and climate) will determine the surface and near-surface flow regimes, as well as the extent of water recharge and discharge areas. When hydrogeology and hydrodynamics are discussed in relation to CSG distributions (e.g. Ayers & Kaiser 1992; Scott et al. 1994; Scott 2002; Scott & Hamilton 2006; Pashin 2007; Song et al. 2012), it is in the context of near-surface flow characteristics related to topographic relief and seam outcrop (e.g. Scott & Hamilton 2006) or of barriers to water movement from faulting or similar structural features (e.g. Lamnarre 2003; Pashin 2007). Surface water influxes are usually referred to as meteoric recharge and are inferred to penetrate a basin from the coal (and strata) outcrops near the edge of basins or along fracture sets penetrating the subsurface (e.g. Pashin 2007; McLean et al. 2010b).

In addition to the meteoric or near-surface gravity-controlled hydrostatic flow, there is deep, pressure-driven upward flow of formation water (e.g. Magara 1978; Kreitler 1989; Bethke & Marshak 1990; Bjorlykke 1993; Gurevich et al. 1994; Brassington & Taylor 2012). The former originates from young and fresh surface waters that seep into the basin moving deeper into the strata assisted by gravity or ‘free-flow.’ Such waters migrate as deep as the pore pressure regime (and other factors such as fluid density and chemistry) allows and occur as a function of the hydrostatic pressure gradient in the region. Hydrostatic gradient is generally considered to be a linear increase in pressure with depth. Deep saline formation waters, however, migrate upward (e.g. towards lower pressures) by one or more of a number of mechanisms such as compaction (and resulting pressure differentials), geochemical changes such as salinity changes and osmosis, and the cracking of hydrocarbons (Kreitler 1989; Bjorlykke 1993; Gurevich et al. 1994; Gurevich & Chilingarian 1997). Where the two flow regimes converge, a mixed water ‘transitional’ regime prevails, and rapid changes in water chemistries develop, as documented from a fresh/saline water interaction in northwest England by Brassington & Taylor (2012).

The flow regimes are widely documented in the hydrogeology and petroleum geology literature, but discussions are typically related to young and subsiding sedimentary basins such as those in the Gulf of Mexico (e.g. Kreitler 1989). In these settings, increasing compaction of sediments provides a strong upward flow towards shallower horizons, where the saline waters meet free convection flows that penetrate to surprisingly deep horizons of around 2–3 km (e.g. Fertl & Chilingarian 1989; Aref 1998). Where compaction rates are higher than the rates at which pore fluids can be expelled, overpressure can develop, which, upon further burial, may provide future drive to upward formation fluid migration (e.g. Magara 1978; Gurevich & Chilingarian 1997). Conversely, in older and uplifting sedimentary basins, such as the Sydney Basin, decompaction (e.g. ‘rebound’) considerations would be of more overriding importance, both in terms of porosity and in terms of fracture frequency and aperture in the upper (hydrostatic) sequence (e.g. permeability).

The location or extent of hydrostatic and geopressured zones is commonly interpreted from porosity assessments using downhole (wireline) geophysical tools such as sonic, neutron, density and resistivity (e.g. Magara 1978; Fertl & Chilingarian 1989; Aminzadeh 2002). The boundary between the two regions is determined by analysing where the decrease in porosity with depth stabilises and becomes significantly reduced or constant, usually at around 5–10% porosity. In the Sydney Basin, actual porosity measurements (compiled by Blevin et al. 2007) allow the accurate identification of this horizon at approximately 1000–1200 m depth (Figure 4). Borecore (horizontal) permeability data (Blevin et al. 2007) also indicate that a significant flow barrier region exists at approximately 800–1000 m depth; and in a large area such as the Sydney Basin, it is reasonable to expect the horizon to vary between these depth ranges in different areas. The significance of this is that it is possible for methanogen-bearing meteoric recharge to penetrate...
subsurface horizons down to approximately 800–1000 m depth in the basin.

**Hydrochemistry**

**HYDROCHEMICAL FACIES IN GROUNDWATER**

Typical hydrochemical facies in a sedimentary basin develop from inland (or elevated) freshwater recharge areas towards coastal (or low-lying) discharge areas through gradually decreasing calcite saturation and increasing sodium bicarbonate and chloride components (Back et al. 1993; Postma et al. 2008). Back et al. (1993) discuss a series of major cation exchanges during groundwater evolution, with significant changes to the system occurring in the presence of dissolved CO₂ and bicarbonate. An increase in CO₂ concentration in the water leads to increased solubility of carbonate minerals

---

**Table 1** Summary of key Sydney Basin structural and sedimentary events (after Healy et al. 2005; Blevin et al. 2007; and additional sources listed in the Appendix).

| Age          | Stress direction | Event                                      | Feature/effect                                                                 | Source                                      |
|--------------|------------------|--------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------|
| Upper Neogene|                  | Australian and Indonesian plates converging| Blue Mountains uplifted                                                       | Hillis & Reynolds 2003; Healy et al. 2005  |
| Cenozoic     |                  | Volcanic activity                          | Diatremes and dykes emplaced (western/southern/eastern regions)               | Healy et al. 2005; Blevin et al. 2007       |
|              |                  | Basin uplift ceased                         | Erosion                                                                       | Faiz et al. 2007a                          |
| Upper Cretaceous|                | Tasman Rift                                | Rapid uplift of Sydney Basin sediments                                        | Faiz et al. 2007a; Veevers 2000 in Healy et al. 2005 |
| Lower Cretaceous|               | Maximum burial of Sydney Bastin            | Approx 2–3 km depth                                                          | Faiz et al. 2007a                          |
| Jurassic      |                  | Igneous intrusions                          | Dykes and sills emplaced (particularly western and northern districts)        |                                             |
| Triassic      |                  | Fluvial/subtidal deposition                 | Narrabeen Group including Hawkesbury Sandstone                               | Blevin et al. 2007; McCabe 2008            |
| Upper Permian|                  | Fluvial deposition with widespread volcanic tuffs | Newcastle/Illawarra Coal Measures                                              | Creech 2002                                 |
|              |                  | Marine transgression                        | Waratah Sandstone                                                             |                                             |
|              |                  | Fluvial deposition                          | Wittingham Coal Measures (Jerrys Plains subgroup)—sediments sourced from New England Fold Belt (from north) and Lachlan Fold Belt (from west) | Fielding et al. 2001                        |
|              |                  | Marine transgression                        | Archerfield Sandstone/Kulnurra Marine Tongue                                  | Fielding et al. 2001                        |
|              |                  | Fluvial deposition                          | Wittingham Coal Measures (Jerrys Plains subgroup)—sediments sourced from New England Fold Belt (from north) and Lachlan Fold Belt (from west) |                                             |
| Middle Permian|                  | Marine transgression                        | Branxton Formation and Mulbring Siltstone                                    |                                             |
| Lower Permian|                  | Hunter–Bowen Orogeny begins                 | Compressional phase                                                           | Collins 1991 in Tamplin 1993               |
|              |                  | Subsidence and continental shelf setting    | Greta Coal Measures                                                            | Herbert 1980 in Tamplin 1993               |
|              |                  | Volcanic activity                           | Gyarran Volcanics/Dalwood Group                                               |                                             |
| Upper Carboniferous|          | Volcanic arc extensions                     | Ayr Volcanic Rift–Sydney Basin sediment constraint                            | Harrington et al. 1984 in Tamplin 1993     |
The CO$_2$ can originate from coal maturation, oxidation and magmatic activity, dissolution of carbonate minerals through groundwater interactions with country rock and methanogenesis.

Kellett et al. (1989) mapped the hydrogeological provinces in the Upper and Central Hunter Valley areas of the northern Sydney Basin and demonstrated a close relationship between geochemistry and geology (lithology) that provided a fingerprint for water origins and migration pathways. In general, waters sourced from regions with Cenozoic basalt and Triassic fluvial sedimentary strata are rich in calcium and bicarbonate (HCO$_3^-$) and see the dissolution and precipitation of carbonates and alumino-silicates, respectively. In contrast, formation waters in Permian coal-bearing strata are dominated by Na, Cl and Mg ions, with precipitation of carbonates and oxidation of sulfides and coals. More recent work in the Lower Hunter Valley (McLean et al. 2010a, b; Holmes & Ross 2011) tracked variation in water geochemistry with depth as well as region (or source area). Water in the shallow alluvial horizons in the Lower Hunter region (where surface rocks are Permian coal measures) are dominated by Na–Mg–Cl and Na–Cl–HCO$_3^-$ ions, whereas waters in deeper strata (~200 m depth) are richer in Na–Cl–HCO$_3^-$ and Na–HCO$_3^-$–Cl. Hawkes & Ross (2008) also confirmed abundant bicarbonate levels and increasing alkalinity along the flow path in the Hawkesbury Sandstone aquifer.

Figure 5 depicts a simplified section of the Sydney Basin superimposed with a hypothetical hydrochemical facies series (based on that discussed by Back et al. 1993) and the respective locations of the groundwater studies discussed above. Facies changes with distance from the recharge area along the flow path, as well as with depth of cover in the subsurface, are accompanied by similar water chemistry evolution (Figure 5). In general, bicarbonate is primarily removed from the water by the precipitation of calcite or by discharge of bicarbonate-rich groundwater from the system (Runnells 1993). Widespread secondary calcite mineralisation (commonly perpendicular to the principal dawsonite mineralisation in the cleats and fractures in the central Sydney Basin; e.g. Staub 1995) would indicate that this bicarbonate reduction process has occurred.

In this hydrochemical facies development process, total dissolved solids (TDS—a proxy used for salinity) increase with depth and down-gradient towards the coast. Salinity is an important factor (together with temperature and pressure) for gas solubility, with increasing salinities impeding both methane and CO$_2$ solubility (e.g. Morton et al. 1981; Chang et al. 1998, Duan & Sun 2003; Hangx 2005; Brassington & Taylor 2012). With increasing salinity and decreasing acidity of waters in sedimentary basins with depth, solubility factors are important for the development of gas layering in some regions.

Sydney Basin gas models

Mapping of gas distribution in the Sydney Basin began in the 1970s and 1980s by underground coal-mining
companies testing for gas concentrations, to mitigate the risk of outburst for safer mining practices. Information from these pockets of locally well-sampled areas was supplemented by data from regional conventional and CSG exploration. Early models looked mostly at thermogenic processes. Subsequently, carbon isotope analysis of CSGs by Smith et al. (1992) suggested that some of the gases in the Sydney Basin and elsewhere on the eastern seaboard of Australia may be of biogenic origin. Gas in the southern Sydney Basin is dominated by thermogenic methane with minor biogenic accumulations along outcrop areas (Figure 6; Faiz 1993). Local accumulations of CO₂ were also identified on anticlines and faults in the vicinity of igneous intrusions (Faiz 1993; Faiz & Hutton 1995; Faiz et al. 2003). CO₂ gas was principally interpreted as having migrated up dip from an igneous source and then trapped against impermeable layers on structural highs, a conventional gas migration and trapping mechanism (Faiz 1993), although the potential for carbonate dissolution and reprecipitation was also considered (Faiz et al. 2007b).

More widespread occurrences of CO₂ were reported from the Hunter Coalfield (e.g. Pinetown et al. 2008; Thomson et al. 2008; Pinetown 2010, 2014; Figure 6). Thomson et al. (2006) observed that CO₂ concentrations in the Lower Hunter Coalfield were located in a consistent and continuous layer between the biogenic and thermogenic methane layers identified by Faiz (1993). They proposed that this deep, high-gas-content CO₂ layer may have originated from regional Cenozoic volcanic activity and was transported into the subsurface by meteoric influx (as opposed to magmatic intrusions; Faiz 1993). It was also noted that the various gas layers in the subsurface cross-cut the regional dip of the strata.

Elsewhere, the spatial extents of different gas trends identified in the northern Sydney Basin region (Figure 6) were investigated against structural domains delineated by Glenn & Beckett (1997), Pinetown et al. (2008) and Pinetown (2010). These studies did not find a strong correlation between geological regions and gas accumulations in those areas, although other research has shown that structural features can affect local gas distributions. Examples of locally higher-stress areas, such as thrust faults and syncline axes, have been observed to have gas content levels up to 50% higher than neighbouring areas (Burra & Esterle 2012).

Gas accumulations in the Sydney Basin have been inferred to be affected by the hydrogeology of the region (Scott & Hamilton 2006), particularly in the context of likely flow regimes, similar to those observed in various geological settings in the USA (Scott 2002). Topographic highs and lows, identified as areas of near-surface ‘divergent’ and ‘convergent’ flows, respectively, provide important constraints for hydrodynamic trapping (or otherwise) of CSG accumulations (Scott & Hamilton 2006).

The significance of thermal history and coal rank for gas saturation and gas content has also been investigated (e.g. Faiz et al. 1992, 2007a; Laxminaranaya & Crosdale 1999), and in some areas was found to be important factors in determining gas quantities located in coals. However, in a regional context, the lower-rank coals in the northern and central parts of the basin host some of the highest gas contents in the basin (e.g. Thomson et al. 2008; Pinetown 2010), whereas the higher-rank coals of the southern district hold generally more moderate concentrations of CSGs.

Overall, gas distribution in the Sydney Basin is variable in both the extent and types of gas accumulations present. It is apparent that both geological and hydrogeological factors exert strong influences on the development of the observed in situ CSG distributions.

**DATASET AND METHODOLOGY**

The models for water and gas presented above provide a foundation to explore variability in gas distribution and compositional layering in the Sydney Basin. A CSG data
set was collated from publicly available information and private coal and CSG companies’ databases (Figure 1). Public data sets were obtained from the NSW Department of Trade and Investment’s MinView and DIGS databases, as well as published literature. Private CSG databases were made available from a number of regions, including the Hunter, Western, Newcastle and Southern Coalfields. The data set includes gas content, composition, isotope and coal quality analyses. Additionally, wireline geophysics, regional mapping and geological interpretation were sourced from a number of coal mines in the northern and southern Sydney Basin. These, in combination with maps and reports published by the NSW Department of Trade and Investment, were used to understand the geological setting. A list of maps and reports utilised in this process is provided in the Appendix.

The borehole dataset of ~100 boreholes and over 2000 gas samples, ranging in depths of from ~10 m to ~1300 m, were analysed for common trends with depth, including gas content (presented on a raw, or as-received, basis in this paper) and composition (air-free basis) parameters. From this analysis, a number of regional gas domains were identified and further reviewed in the context of local and regional geological features and basin development, and existing gas models.

Gas distributions were then compared with published data on the regional hydrology and hydrochemistry, with particular emphasis on groundwater type, geochemical zonation and dissolved gas trends, and then transposed
Figure 7  Gas content and CO₂ composition trends with depth in the Sydney Basin. Part A (far left) depicts total gas contents for the Permian coal-bearing strata sequence in the basin. Part B (left) shows the same chart, zoomed into the shallower horizons of the basin for clarity. Part C (right) highlights the widespread occurrence of CO₂ gas in the vertical profile, making up varying percentages of total gas content. Part D (far right) illustrates CO₂ gas volumes with depth. Parts C and D also show that while CO₂ may make up to 100% of a gas sample, the overall gas volume of this gas in the sequence may be minor. The 'boomerang' CO₂ trend in Part D strongly mirrors the same trend found in the total gas content trend in part A, but at a different depth horizon.
onto gas-distribution model to test for relationships between these apparently different but inherently connected processes. A similar method was followed for the investigation of porosity, permeability and isotope data sets, in particular in the context of considering the extent of biogenic recharge into the system, as well as examining the origins of CO2 gas in the basin.

RESULTS

Gas content and composition trends

Gas content data collated as part of the project ranged from 0.01 to 31.62 m³/t (raw, as received basis), with gases ranging in composition from near 100% CH₄ to near 100% CO₂ or N₂ (air-free basis). Overall, gas contents initially increase with depth but then decrease with depth below approximately 800 m (Figure 7a). However, owing to the basin geometry, different regions of the basin host varying thicknesses of coal-bearing strata and this overall ‘boomerang’ trend with depth is not always fully perceivable at all locations. Figure 8 shows the typical gas trends within the basin to illustrate the variations between the types of gas profiles with depth that are intercepted.

In general, gas content is usually very low, less than 1–2 m³/t, near the surface and down to depths of 100–200 m with gas compositions high in N₂ and CO₂ (Figure 7a, b). Below this zone, gas contents increase gradually to various levels depending on the area, usually reaching ~8+ m³/t (raw), and in some cases, over 20 m³/t (raw). The dominant gas type in this zone is CH₄, and it has a variable thickness ranging from ~100 m to over 800 m. In some areas, this methane layer is underlain by a CO₂-rich horizon in which the CO₂ concentration ranges from 10% to near 100% of the total gas, and covers overall strata thicknesses from ~50 m to over 300 m (Figure 7c, d). Gas contents in this zone are usually quite elevated (up to ~20 m³/t), but in some instances, total gas contents decline part way through this particular gas compositional zone (e.g. Figure 8, Borehole C). Deep boreholes penetrating the CO₂ layer reach another deeper methane-rich zone that is in places accompanied by higher hydrocarbons such as ethane and propane (Figure 9), forming up to 10% of the gas content in some locales (with reports of up to 12% in the south; Faiz & Hendry 2006). However, both the depths at which they appear and the accompanying gas types are not always consistent (Figures 8, 9) with variable gas contents in this deepest layer; declining in some areas and levelling out in others (Figures 7, 8, Boreholes D and G, respectively). The latter trend is chiefly limited to the southern Sydney Basin regions, while the former is observed in the northern and central areas.

Gas-content trends can also vary between the different areas, but there is an overall pattern to these trends when viewed in the context of basin geometry. In the northern part of the basin, the coal seams outcrop and, in many areas, the younger part of the sequence has been eroded, leaving only the lower (older) part of the Wittingham Coal Measures intact. In contrast, in the southern and central parts of the basin, the youngest coal sequence (the Newcastle/Illawarra Coal Measures) is located at deeper horizons in the majority of the area, below approximately 500 m in depth, under the thick Triassic sediments of the Narrabeen Group (Figure 10). The Newcastle Coal Measures outcrop along some areas of the coast line—notably, near the Newcastle and Illawarra regions. In the typical profiles (Figure 8), gas contents initially increase with depth up to a ‘peak’ within a borehole, before declining in the deeper parts. The occurrence of ‘peak’ gas contents is mapped across the basin (Figure 10) and appears to delineate a particular horizon across the region that is not depth or elevation related (ranging from 500 to ~1000 m in depth) and is not associated with any particular coal seam in the sequence (as per the discussion in the previous paragraph and in reports by Creech 1994). This peak gas-content horizon is also not related to any particular gas type or compositional layer (Figure 6), and it cross-cuts stratigraphy in the area (Thomson et al. 2008). As a result, it appears to reflect a phenomenon that post-dates the development of most of the geological features of the basin.

Similar to the peak gas trends, the overall gas compositional layers appear to be consistent across many

Figure 8 Vertical profiles showing gas content and composition trends across the Sydney Basin. ‘Top’ and ‘base’ of coal measure horizons are indicated to differentiate between boreholes or locations that did not host any coals at the drilled horizons from boreholes that did not penetrate or sample the full sequence of coal seams in situ at the specific locations. Note the change in gas content scales.
Figure 8 (Continued)
Figure 8 (Continued)
areas—both in extent and in sequence of occurrence within the vertical profile. Figure 11 shows a schematic diagram of the ‘full’ gas compositional profile that is observed in some parts of the Sydney Basin where the coal-bearing strata thickness is sufficiently large (e.g. some areas around the northern-central region boundary of the basin). In other areas of the basin, only parts of this sequence are present, for example, where only the lowermost coal seams of the Jerrys Plains Subgroup remain at shallow depths, or where the Newcastle/Illawarra Coal Measures lie under the thick Triassic sediments in the south. The gas layer boundaries generally exhibit a gradational shift from one zone to another; although the shallower switch from near-100% nitrogen to near-100% methane is most commonly an abrupt change (e.g. Figure 8, Boreholes A and B).

A conceptual distribution for gas compositional layering through the basin, particularly in the deep, high-gas-content CO₂-rich areas, is presented in Figure 12. The deep CO₂-rich layer between the shallow and deep methane zones is visualised as a ‘plume’ that extends tens of kilometres along strike in the basin from north to southeast. Boreholes intersecting this plume at various locales report varying CO₂ concentrations with depth, depending on which part of the section (in Figure 11) they intercept. Detailed borehole data are not available in the western part of the basin, but it is expected that a similar high CO₂ plume would extend from the Western Coalfield (Lapstone Monocline) towards the central part of the basin. High CO₂ contents reported in the borehole at location F in Figure 8, as well as other regional boreholes such as Turnermans 1 and Goulburn River 1 in the northwestern part of the basin, support this prediction. The approximate extent of the deep CO₂-rich layer as derived from borehole, mine site and geological mapping data is presented in Figure 13.

Figure 14 provides more detail on the compositional layering trends. In this borehole from the central Sydney Basin (Figure 8, location C), the shallow methane layer overlies a deeper and increasingly CO₂-rich section. The gas content peaks at a depth between 400 and 600 m, whereas the percentage of methane in the CSG gradually declines over the same interval. The CO₂ trend, on the other hand, shows a gradual increase in concentration, peaking immediately below the highest gas content window. This is a significant observation because it is commonly assumed in the field that the ‘excess’ CO₂ in the system represents an additional gas volume on top of ‘constant’ methane levels. Furthermore, the peak gas content coincides with declining CH₄ and increasing CO₂ levels. Consequently, if the CO₂ were the cause of the peak gas conditions, this is not evident in this area where the highest CO₂ concentrations of 80% of the gas volume occur at 650 m depth—about 100 m below the peak gas contents.

Figure 14 also presents a good example of the relative location of other gases that occur at depth in the Sydney Basin. Ethane and some higher hydrocarbons commonly
Carbon isotope trends and gas origins

Carbon isotope values for CSG in the region show a large range, with $\delta^{13}C$ from CH$_4$ recording $-70$ to $-30\%_{\text{o}}$, while $\delta^{13}C$ from CO$_2$ ranges from $-20$ to $-20\%_{\text{o}}$. There is an overall enrichment in $^{13}C$ with depth for both principal gas types (Figure 15).

The carbon isotope values from both gases range widely but are within the previously reported ranges (Smith & Pallaser 1996; Faiz et al. 2003; Golding et al. 2013). Instead of discrete ranges of isotope values for either principal gas type (i.e. CH$_4$ and CO$_2$), it appears that carbon isotopes gradually shift from more negative values at shallower depths towards more positive values at deeper horizons. This is consistent with descriptions of methanogenesis and accumulation of $^{13}C$-enriched residual CO$_2$ discussed by Rice & Claypool (1981) and Aref (1998). Figure 15 shows that the carbon isotope values of CSGs in the Sydney Basin are related to depth of cover (or presumably, the extent of meteoric recharge and levels of degradation; e.g. Bates et al. 2011) rather than any particular origin type that would be traditionally assigned for the relevant value ranges. Nevertheless, biogenic alteration of in situ gases appears to be less below approximately 800 m depth, where isotope values for the two principal gases stabilise in the thermogenic gas zone. Above this horizon (i.e. between 400 and 800 m), a mixed origin methane layer persists, with most $\delta^{13}C$ values from methane between $-65$ and $-50\%_{\text{o}}$.

Carbon isotope values for CO$_2$ depict a similarly altered trend in the shallow horizons down to 200–400 m depth, with values ranging from $-25$ to $-10\%_{\text{o}}$, likely as a result of near-surface interactions (e.g. atmospheric and soil gas) and other organic alterations such as coal oxidation (e.g. Smith et al. 1982). While depths of 200–400 m are very deep in the subsurface for such near-surface interactions, in areas of steeply dipping strata (e.g. in the vicinity of monoclines) ‘deep’ sample points can be relatively close to the seam surface outcrop along the bedding and be affected by fresh meteoric recharge (e.g. Pashin 2007; McLean et al. 2010b). At intermediate levels, carbon isotope values of CO$_2$ centre around 0%o and may reflect microbial gas production and utilisation of CO$_2$. This is supported by the apparent coupling of the methane and CO$_2$ gas isotopes in this zone. However, these

**Figure 9** Percentage of ethane composition in coal seam gas plotted against depth in the eastern and northern part of the basin. Note the significantly different depths of occurrence that are not related to any particular coal seam or stratigraphic horizon. In the northern part of the basin, which hosts the thickest Permian coal-bearing sequence, some boreholes show an initial increase in ethane concentration at depth, followed by a decrease in this gas to the basal coal seam/s (Boreholes 1–3).
Figure 10 Schematic cross-section of typical gas content trends across the Sydney Basin. Position of peak gas content is indicated by the dashed line. Location of section line is shown in Figure 1, and boreholes located along the section are indicated with black vertical lines. WAP, Wappinguy 1; BH1, Borehole 1 (Burra 2010, figure 4); BAH/LL, Big Adder Hill/Llanillo 1; PG, Pinegrove 1, WDM, Windermere 4; MPC, Monkey Place 4; PC, Paynes Crossing 1; BC, Boomerang Creek 1; JIL, Jilliby 1/2; CHB, Catherine Hill Bay 1.

Figure 11 Variation in gas composition with depth in the north to central parts of the Sydney Basin. Grey columns indicate relative sections intersected by boreholes shown in Figure 9.
The highest concentrations of CO₂ gases coincide with the highest concentrations of CO₂ gases (Figures 7, 15), suggesting a possible additional external source such as magmatism and/or the dissolution of carbonates. It is not possible to exclude an ultimate magmatic source for the CO₂ residual from methanogenesis; however, the positive trending isotope values provide support for the overall importance of microbial activity in this region (Smith et al. 1982; Boreham et al. 2001).

Isotope data for ethane are limited and show thermogenic origins. The carbon isotope values appear unaffected by secondary (or other) alteration, even at shallower depths, and this is consistent with previous observations that ethane is ‘relatively resistant to biodegradation’ (Katz 2011).

DISCUSSION

Basin geometry and hydrodynamics

The hydrodynamics of a sedimentary basin are controlled by many parameters, particularly those relating to features forming barriers to, or facilitating enhanced flow along, the aquifer path (Scott 2002; Pashin 2007). Areas characterised by highlands and escarpments in the basin experience higher levels of rainfall and recharge conditions than lower regions (e.g. Scott & Hamilton 2006; Hawkes & Ross 2008; Mackie 2009). This serves as an underlying framework for a hydrogeological flow regime that appears to be closely related to the Sydney Basin gas regime.

In recharge areas, meteoric water moves along the bedding plane as well as percolating down the sequence through vertical fractures (McLean et al. 2010b).
mechanisms are particularly effective in basin margin areas, where the steeply dipping strata and increased fracturing associated with folding (e.g. the monoclines) are favourably positioned for enhancing such flow (Pashin 2007).

A hydrogeological model from the Black Warrior Basin of the USA (which is a coal-bearing foreland basin analogous to the Sydney Basin) illustrates this process, where overturned folds at the southeastern margin of the basin allow more extensive meteoric infiltration into deeper horizons (Pashin 2007). In such a setting, meteoric influx along the bedding planes can be more laterally extensive in the shallower horizons, while the deeper layers can be accessed via vertical fracturing, affecting a larger spatial footprint. Hydrochemical sampling and modelling in the Hunter Valley (McLean et al. 2010b; Holmes & Ross 2011) demonstrate that this pattern of infiltration is operating in the vicinity of the Mt Thorley Monocline. It is possible that this style of infiltration pattern is also at play in the southern Sydney Basin, which is bounded by a number of monoclines draping off surrounding highlands and escarpments to the west, the south and the coastal area in the east.

Hydrochemical influences on gas layering

Overprinting the hydrostatic flow regime is the hydrochemical facies evolution from freshwater to brackish and brine waters along the flow path from recharge to discharge areas (Figure 5). This flow path progresses from recharge areas experiencing freshwater influx (e.g. rainwater) with waters high in calcium, magnesium and other mixed ions, particularly when interacting with igneous country rocks in these regions (e.g. Kellett et al. 1989; Golab 2003; Mackie 2009).

Formation waters of certain geochemical compositions have been linked to methanogenesis (Van Voast 2003; Draper & Boreham 2006; Kinnon et al. 2010; Golding et al. 2013; Taulis & Milke 2013), with water compositions from methane-producing wells showing markedly similar characteristics in reported areas [e.g. US (Van Voast 2003), Bowen Basin (Draper & Boreham 2006; Kinnon et al. 2010) and New Zealand (Taulis & Milke 2013)]. The results commonly show minimal Ca and Mg but significant concentrations of Na and HCO₃ (Van Voast 2003; McLean et al. 2010a; Taulis & Milke 2013). In some areas, Cl is prominent as well, but this is often connected to coals in paralic or marine influenced depositional
Figure 15 Carbon isotope values with depth from different coal seam gas types in the Sydney Basin.

Figure 16 Cross-plot of carbon isotope values from methane and CO₂ in the Sydney Basin. Carbon isotope fractionations from 1.06 to 1.09 are characteristic of CO₂ reduction, whereas acetate fermentation results in α values from 1.03 to 1.06 where α_{CO₂–CH₄} = (1000 + δ¹³C–CO₂) / (1000 + δ¹³C–CH₄) (Whiticar et al. 1986; Smith et al. 1992; Golding et al. 2013).
settings (e.g. Van Voast 2003), which also have relatively elevated salinity and TDS. Golding et al. (2013) and Taulis & Milke (2013) have highlighted increased alkalinity levels in such waters as well. Limited water data from the Sydney Basin (McLean et al. 2010a, b; Holmes & Ross 2011) are consistent with these findings, with principally Na and HCO3-dominated waters occurring in regional 2011) are consistent with these findings, with principally Na and HCO3-dominated waters occurring in regional methane production observation wells that show increasing alkalinity, salinity and Cl content with depth.

The chemical evolution of groundwater; resulting in the development of hydrochemical facies (in terms of dominant ions), has the potential to dissolve minerals (such as carbonates) and transport those components further along flow (Back et al. 1993). Salinity or alkalinity changes can instigate precipitation down-gradient (e.g. Runnels 1993) in open systems. Conversely, such changes can potentially result in the liberation of CO2 from the formation water and absorption of this gas on to the coal surface in closed or compartmentalised environments.

**Origin of CSGs in the Sydney Basin**

CSG distribution in the Sydney Basin is complex and reflects original coalification processes as well as hydrogeological processes from the time of coalification to the present. There are two principal CSGs (methane and CO2) with the minor but important accessory gases of nitrogen and ethane. The principal gases and nitrogen occur in shallow and deep strata, but in each condition they are of different origins. Ethane only occurs at depth and is of thermogenic origin (Figure 15).

**METHANE**

Methane was produced through both thermogenic and biogenic processes as evidenced by carbon isotope data (Figure 15). Biogenic methane can be generated through two main pathways—acetate fermentation and CO2 reduction. It is has been widely reported that the principal methanogenic pathway in Australian coal basins is CO2 reduction (e.g. Smith & Pallaser 1996; Faiz et al. 2003); however, carbon isotope fractionation analysis (cf. Whiticar et al. 1986) shows that both of these processes have operated in the Sydney Basin (Figure 16). The significance of this is that, in addition to the methane, the acetate fermentation process also produces CO2, and this has implications for the origin of CO2 accumulations at depth in the basin.

It has further been observed that carbon isotope values in methane commonly exhibit a shift from more negative to more positive values along flow path or with depth. This can be interpreted in a number of ways. Mixing between shallow biogenic and deep thermogenic methane can yield a ‘mixed’ isotopic signature between the two regimes. It can also be considered as an indication of the extent of methanogenesis in the system, evidently associated with groundwater residence time (Bates et al. 2011). Further, isotopic fractionation can also occur as a result of diffusion from depth, but findings by Xia & Tang (2012) indicate that this effect is not likely to be greater than 5%, significantly smaller than

the large shifts of ~40% observed in the Sydney Basin (Figure 15).

**CARBON DIOXIDE**

Previous studies have concluded that CO2 gases in the Sydney Basin coals are primarily of igneous origin (Smith & Pallaser 1996; Faiz et al. 2003). Carbon isotope results in the range of ~7 to ~3‰ are interpreted as representing igneous, magmatic or ‘deep external’ origins (Smith & Pallaser 1996) and support findings by Baker et al. (1995) that continental-scale magmatism resulted in the emplacement of CO2 and dawsonite formation in the Bowen–Gunnedah–Sydney basin system. While this conclusion is widely accepted, isotope data collated in the current study (Figure 15) indicate that the range of δ13C CO2 is much wider than the narrow magmatic-source values and that the overall trend of the CO2 isotope values represents a pattern of δ13C enrichment with depth across the region. In other words, the δ13C CO2 range reported in the Sydney Basin is not likely to be (at least, solely) of magmatic, igneous or volcanic origin (Smith & Pallaser 1996; Faiz et al. 2003; Faiz & Hendry 2006; Thomson et al. 2009). Smith et al. (1992) suggested some other possible CO2 sources in the region, such as oxidation of coals and ‘thermal decomposition of carboxyl groups’; the former process produces isotope values of around ~20‰, while the latter shows values greater than 0‰. Rice (1993) and Boreham et al. (2001) described shifts from more negative to more positive carbon isotope values in CO2 and interpreted them to be due to microbial activity. Such a shift can also be due to interactions with the country rock or groundwater, which can alter the original CO2 carbon isotope compositions (e.g. Hoefs 2009). As a result, the interpretation of CO2 origin from carbon isotope values should be carried out in the context of the hydrogeological and biogeochemical regime (cf. Golding et al. 2013).

In the Sydney Basin, the shallow layers with δ13C around ~20‰ are interpreted to represent CO2 from oxidised coals and other organic sources (e.g. Rice 1993) (Figure 15). The increasing enrichment in δ13C below this layer is indicative of further alteration of carbon isotope values by methanogens, and probably represents both utilisation and production of CO2. The generation of this gas may also be from other sources, such as dissolution of carbonates. In the thermogenic zone, no significant CO2 concentrations occur; however, residual CO2 isotope values consistently report between +5 and +10‰, and are indicative of a more consistent ‘background’ signature, likely to be from the thermal degradation of carbonates (e.g. Smith et al. 1982; Clayton et al. 1990).

**NITROGEN**

Up-gradient, inland areas with coal seams outcropping at the surface that experience freshwater recharge (such as the Hunter Coalfield region) commonly exhibit a number of shallow, very-low-gas-content horizons (<1 m3/t) with very distinct CO2 and N2 concentrations down to ~50 m depth, and near-100% nitrogen concentrations down to depths as great as ~150–200 m. Although
higher nitrogen percentages may be a result of coal oxidation during sampling or testing (e.g. Jin et al. 2010), most shallow samples in the dataset for this paper (Figure 8, locations A and B) were helium flushed, both in the field and in the laboratory during testing, to limit oxidation. Results were also nitrogen corrected, but still consistently reported over 90% nitrogen (i.e. greater than that contained in air at ~78% nitrogen); it is clear that the excess nitrogen originated from sources other than air contamination or sample oxidation.

The shallow nitrogen-rich zones are controlled by the extent of the weathering profile, with the 50 m-thick CO₂ and N₂ layer resulting from the strata occurring within the unsaturated and vadose (partially saturated) ground water zones (e.g. Alley 1993; AWWA 2003) and experiencing some levels of coal oxidation (e.g. Whiticar & Faber 1986). Below the water-table, at the top of the fully water-saturated region, the nitrogen-rich zone persists down to the depth at which the biogenic methane zone abruptly begins.

The nitrogen-rich layer probably represents the zone in the groundwater profile that has experienced denitrification, which is the conversion of nitrates (from weathered layers) to N₂ gas (Korom 1992; Lovley & Chapelle 1995). The N₂ does not have a very high affinity with water (Runnells 1993) and is commonly reduced further as part of the iron and sulfate-reducing processes on the way to CO₂ generation and methanogenesis as part of acetate fermentation (Chapelle et al. 1993; Lovley & Chapelle 1995; Christensen et al. 2000; Brinck et al. 2008).

Total gas contents appear to follow a parabolic trend with depth; gas contents increase to a certain horizon in the subsurface, below which values decrease to the base of the coal-bearing sequence (Figure 7). This trend (which has been reported previously; e.g. Faiz et al. 2007a in Sydney Basin, NSW; Hamilton et al. 2012 in Surat Basin, Qld) is best observed in the central north and central eastern areas that host a near-full sequence of the coal measures. Elsewhere in the Sydney Basin, the parabolic trend is only partially intercepted, resulting in an apparently increasing or decreasing gas content trend with depth (Figure 11).

Acetate fermentation produces small volumes of gas from methanogenesis, particularly at shallow depths where the gases escape or are dissolved and carried away by regional water flows (Rice & Claypool 1981; Schoell 1988; Rice 1993; Flores et al. 2006). This observation from other basins, including the documented typical vertical gas profile at those locations (e.g. Korom 1992, figure 1; Rice 1993; Smith & Pallaser 1996; Faiz et al. 2003; Flores et al. 2006; Brinck et al. 2008, figure 1), is consistent with gas characteristics described from shallow coal seams outcropping in the northern recharge areas of the Sydney Basin (e.g. Figure 8, boreholes A and B).

Gas distribution and layering

Total gas contents appear to follow a parabolic trend with depth; gas contents increase to a certain horizon in the subsurface, below which values decrease to the base of the coal-bearing sequence (Figure 7). This trend (which has been reported previously; e.g. Faiz et al. 2007a in Sydney Basin, NSW; Hamilton et al. 2012 in Surat Basin, Qld) is best observed in the central north and central eastern areas that host a near-full sequence of the coal measures. Elsewhere in the Sydney Basin, the parabolic trend is only partially intercepted, resulting in an apparently increasing or decreasing gas content trend with depth (Figure 11).

Peak gas contents can be traced across the basin and are interpreted to represent the interface between the hydrostatic and geopressed groundwater flow

Figure 17 Model illustrating the relative extents of different flow regimes and associated coal seam gas characteristics in the Sydney Basin. The base of 'hydrostatic only' flow is represented by the peak gas content horizon (Figure 10), which persists down to the base of the CO₂-rich (and equivalent biogenic methane layer elsewhere) (Figure 12). Below the peak gas horizon, increasing ethane levels mark the top of the geopressed zone, and the overlapping layer hosts mixed gases and flow regimes (including transitioning hydrochemical characteristics).
regimes. In particular, the peak gas horizon is associated with the lower extent of the biogenic methane zone, which is associated with the meteoric influx under the hydrostatic pressure gradient. This places it at the base of the 'hydrostatic only' flow, below which total gas contents decrease.

This horizon is also associated with the appearance of (thermogenic) ethane concentrations within the strata profile; these results, together with the observation that ethane can be associated with most gas types at depth in the basin, mark it as the uppermost limit of the geopressed zone.

Below the 'hydrostatic only' flow section, a mixed, transitional zone prevails, which exhibits the most varied gas compositions in the profile (i.e. the transitional zone concept in Brassington & Taylor 2012). This zone experiences significantly reduced hydrostatic (meteoric) influx while thermogenic gas input increases. A mixed carbon isotopic signature is evident in this region (e.g. Faiz et al. 2003; Faiz & Hendry 2006), and a shift towards more positive methane carbon isotope values (Figure 15) partially represents a decreasing biogenic influence on the system. This is also supported by decreasing porosity and permeability conditions (Figure 4), coupled with an increase in CO₂ gas contents (Figure 7) in areas of carbonate-rich formation waters. Elsewhere (in down-gradient coastal areas), the mixed gas/water zone is dominated by mixed origin methane and thermogenic hydrocarbons. This model is illustrated in Figure 17.

Borehole Windermere 4 in Figure 14 (located in the northern part of the basin) provides an example of the mixed gas zone characteristics at around 600–700 m depth. While isotope data from this borehole are limited, the δ¹³C of the CH₄ is -60.4‰ at 700 m depth. The same sample also contains 35.1% methane, 59.27% CO₂, 3.65% ethane and 1.6% nitrogen. In other words, mostly biogenic methane occurs with deep CO₂ and nitrogen of unknown (but not air-contamination) origin, as evidenced by the trends shown in Figure 14. The pattern exhibited by the increasing ethane concentration curve strongly mirrors that of the CO₂ ~100 m above it and the nitrogen ~50 m below it (Figure 14). This may be a further illustration of hydrochemical transitioning from less saline to more saline conditions changing the relative solubility of gases in the presence of CO₂ (cf. Boreham et al. 2011).

An alternative Sydney Basin gas model

CSG distribution in the Sydney Basin has been mapped and documented at a local level for a number of decades (Faiz 1993; Faiz et al. 2003; Faiz & Hendry 2006; Scott & Hamilton 2006; Thomson et al. 2008; Pinetown et al. 2008; Pinetown 2010, 2014). The models and observations are mostly complementary with a general agreement about the mixed thermogenic and biogenic origins of the methane and the gas generation pathways (including timing of geological events and thermogenesis). Most researchers assign an igneous or magmatic origin to the widespread CO₂ gas found in the basin (Smith & Pallaser 1996; Faiz et al. 2003; Thomson et al. 2008; Pinetown 2014); however, analysis in a hydrogeological context can yield a different interpretation. As detailed by Faiz et al. (2003) and Faiz & Hendry (2006), hydrocarbon generation was initiated as part of the Sydney Basin sediment burial in the Cretaceous. Regional Jurassic magmatism resulted

Figure 18 Model of hydrogeological constraints on various gas compositional layers observed in the Sydney Basin. Extent of the CO₂ plume derived from borehole data, with CO₂ concentrations indicated by colouring and annotation. Blue dashed lines represent generalised hydrochemical facies boundaries (Figure 5) and the black dashed line shows the interpreted hydrostatic-geopressed flow contact. Location of section line is shown in Figure 1, and boreholes located along the section are indicated with black vertical lines. WAP, Wappinguy 1; BH1, Borehole 1 (Burra 2010, figure 4); BA/LL, Big Adder Hill/Llanillo 1; PG, Pinegrove 1; WDM, Windermere 4; MPC, Monkey Place 4; PC, Paynes Crossing 1; BC, Boomerang Creek 1; JIL, Jillicby 1/2; CHB, Catherine Hill Bay 1.
in the deposition of carbonate mineralisation throughout the coal measures (Golab 2003; Healy et al. 2005). Late Cretaceous to Cenozoic uplift and subsequent erosion and meteoric infiltration probably contributed to some level of biogenic methane generation; however, owing to the significant extensional tectonic activity, most of the gases generated would have been released as part of these upheavals. Nevertheless, a regional hydrodynamic environment would have evolved as part of the balancing forces of uplift and erosion, resulting in the development of hydrostatic and geopressured flow conditions in the subsurface. More recent epochs have provided a relatively stable geological and geographical setting for regional hydrochemical evolution. Elevated, inland recharge areas provided meteoric influx into the system that progressed down-gradient and with depth, changing in chemical character with progress through the various lithological and geochemical environments. As part of this development, young, calcium-rich waters (likely originating from Cenozoic volcanic terrains; Kellett et al. 1989) infiltrated carbonate-rich environments, dissolving CO2 and carrying it along the flow path (both laterally and vertically into deeper horizons). With increasingly saline conditions, CO2 was liberated from the groundwaters, either by precipitation of calcite in host rocks (including coals) or by expulsion of gases at depth, where the differential compressional characteristics of the formation water and free gases would have forced the deep CO2 to adsorb on to the coal surfaces. These gases were then held in place by the pressure exerted by the formation water influx (e.g. so-called hydrodynamic trapping; Scott 2002) or geological features (such as faults, dykes, or sedimentary facies boundaries).

Subsequent influx of meteoric waters transported methanogenic consortia into the system that flourished in the increasingly sodium-rich hydrochemical facies along this stage of the flow path. Sodium-rich waters are associated with biogenic methanogenesis because this process increases bicarbonate concentrations in the water; the bicarbonate is in turn either consumed by the methanogens (i.e. excess CO2 in the system) or precipitated as calcite in the host strata. The extent of the methanogen-bearing meteoric water influx is controlled by the porosity and permeability gradients of the region, which, in the Sydney Basin, have been determined to provide favourable conditions down to depths of approximately 800–1000 m (Blevin et al. 2007). At these horizons, the upward flowing geopressured region prohibits further downward penetration of meteoric water.

In this manner, the boundary between the deep thermogenic gas-bearing regions and the shallower CO2-rich or biogenic methane zones, is graduated by the level and extent of mixing of the various waters and their respective chemical compositions. Thermogenic ethane marks the top of the geopressured zone, while peak gas contents developed just above this horizon where the optimum (including hydrochemical) conditions existed for the main gas types in the system. In other words, peak gas occurs just above the horizon where the deep geopressed thermogenic gas-bearing zones of an uplifted basin met with the younger biogenic methane and carbonate CO2-bearing waters under hydrostatic flow.

With the groundwater development process producing more saline conditions in ‘down-gradient’ regions, extensive CO2 gases are no longer present in the system, and as such, the central part of the Southern Coalfield and the eastern part of the Sydney Basin (e.g. Newcastle Coalfield) are dominated by biogenic and thermogenic hydrocarbons, with elevated wet gas contents at depth. Near-surface gas compositional layering characteristics in the far northern recharge areas of the Sydney Basin are indicative of active methanogenesis by acetate fermentation processes, and consistent with groundwater dissolved gas characteristics reported in similar settings (e.g. uplift and recharge) worldwide (e.g. Christensen et al. 2000; Pitkanen & Partamies 2007).

Thus, the overall gas-accumulation process can be represented by an illustration that includes the key elements in this paragenesis, such as flow regimes and boundaries, hydrochemical facies boundaries, and gas compositional layering (Figure 18). The complex interaction between these principal processes operating on a basin-wide scale and the different geological environments encountered in the region can result in the development of locally altered conditions in some areas. However, the underlying framework remains an important aspect of regional gas-distribution trends.

CONCLUSION

CSG distribution in the Sydney Basin has been analysed and existing gas models tested in the context of regional geological, hydrodynamic and hydrochemical regimes. It is concluded that there are a number of gas compositional layers in the subsurface, and that their position is chiefly controlled by groundwater flow and hydrochemical speciation from up-gradient recharge areas to coastal or basin-central (i.e. structurally down-gradient) locales. The gas layer types and locations in the subsurface are related to the openness of the reservoir system in terms of structural and hydrodynamic traps, including proximity to basin edge and basement boundaries, which probably affected stress regimes and pore pressure distributions.

In this manner, the biogenic to thermogenic gas boundary is related to the location of the boundary between the hydrostatic and geopressed flow regimes, with the presence or otherwise of the deep CO2-rich layer between these horizons controlled by groundwater chemistry and flow regimes (including hydrodynamic or hydrochemical trapping). This interface is mappable, by tracing the peak gas content horizon and the depths at which ethane appears in the gas profile.

The effect of hydrochemical conditions in the groundwater under which gas layering developed with depth is thus in agreement with both characteristics of previous gas models: development of gas layering with depth (Faiz & Hendry 2006) and across stratigraphic layering (Thomson et al. 2008). However, the new model provides an alternative origin for CO2 gas layer locations in the subsurface. The main point of difference is that the deep (high gas) CO2 is proposed to have originated from carbonate dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwater dissolution and possibly, acetate fermentation pathway methanogenesis as part of groundwa
chemistry evolution with flow from (principally inland (or ‘highland’) recharge areas towards lowland and then coastal discharge areas. This is in contrast to the established models that interpret the extensive CO2 volumes to have originated chiefly from igneous intrusions (e.g. Smith et al. 1982; Faiz & Hendry 2006; Thomson et al. 2008).

ACKNOWLEDGEMENTS

The authors would like to thank Australian Coal Association Research Program (ACARP) (project C21061) for the sponsorship of this research. We would also like to acknowledge and thank J. Sandford of Glencore (formerly Xstrata Coal) for his support throughout the project, as well as C. Holmes (AGL) and M. Creech (SRK) for valuable discussions that contributed to the refinement of this work. We would also like to thank C. Ward, M. Faiz and an anonymous reviewer for very helpful and constructive feedback on the manuscript.

REFERENCES

American Water Works Association (AWWA). 2003. Groundwater: AWWA Manual M21, Third Edition. AWWA, Denver.

Alley W. M. 1993. Establishing a conceptual framework. In: Alley W. M. ed. Regional Ground-Water Quality. pp. 23–60, Van Nostrand Reinhold, New York.

Amendah E., Chilingar G. V. & Robertson J. O. Jr. 2002. Seismic methods of pressure prediction. In: Chilingar G. V. Serebraykov V. A. & Robertson J. O. Jr. eds. Origin and predictions of abnormal pressures, pp. 169–190 Elsevier, Amsterdam.

Aker M. A. M. 1998. Biogenic carbonates: Are they a criterion for underlying hydrocarbon accumulations? An example from the Gulf of Suez regions, Egypt. AAPG Bulletin 82, 356–332.

AREF M. A. M. 1998. Biogenic carbonates: Are they a criterion for underlying hydrocarbon accumulations? An example from the Gulf of Suez regions, Egypt. AAPG Bulletin 82, 356–332.

Baker J. C., Bai G. P., Hamilton P. J., Goldberg S. D. & Kennic J. B. 1995. Continental-scale magmatic carbon dioxide seepage recorded by dawsonite in the Bowen-Gunnedah-Sydney Basin System, Eastern Australia. Journal of Sedimentary Research A65, 522–530.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.

Bates B. L., McIntosh J. C., Lohse K. A. & Brooks P. D. 2011. Influence of groundwater flow paths, residence times and nutrients on the extent of microbial methanogenesis in coal beds: Powder River Basin, USA.
FAIZ M. M. 1993. Thermal history and geological controls on the distribution of coal seam gases in the southern Sydney Basin, Australia. PhD thesis. Department of Geology, University of Wollongong.

FAIZ M. M. & HENDRY P. 2006. Significance of microbial activity in Australian coal bed methane reservoirs—a review. Bulletin of Canadian Petroleum Geology 54, 261–272.

FAIZ M. M., ASIZ N. I., HUTTON A. C. & JONES B. G. 1992. Porosity and gas sorption capacity of some eastern Australian coals in relation to coal rank and composition. Symposium on coalbed methane research and development in Australia, pp. 9–20. James Cook University of North Queensland, Townsville, Queensland, Australia.

FAIZ M. M. & HUTTON A. C. 1995. Geological controls on the distribution of CH₄ and CO₂ in coal seam gas of the Southern Coalfield, NSW, Australia. In: Lam R. D. ed. Proceedings of the International Symposium-cum-workshop on management and control of high gas emissions and outbursts in underground coal mines, pp. 375–383. Wollongong, NSW, Australia.

FAIZ M., SAGHAFI A., SHERWOOD N. & WANG I. 2007a. The influence of petrological properties and burial history on coal seam methane reservoir characterisation, Sydney Basin, Australia. International Journal of Coal Geology 70, 193–208.

FAIZ M. M., SAGHAFI A., BARCLAY S. A., STALKER L., SHERWOOD N. R. & WHITFORD D. J. 2007b. Evaluating geological sequestration of CO₂ in bituminous coals: The southern Sydney Basin, Australia as a natural analogue. International Journal of Greenhouse Gas Control 1, 223–235.

FAIZ M. M., STALKER L., SHERWOOD N., SAGHAFI A., WOLD M., BARCLAY S. A., CHOCHEURY J., BARKER W. & WANG I. 2003. Bio-enhancement of coal bed methane resources in the southern Sydney Basin. APPEA Journal 43, 595–610.

FERTL W. H. & CHILINGARIAN G. V. 1989. Prediction of tectonically caused overpressures by using resistivity and density measurements of associated shales. Journal of Petroleum Science and Engineering 3, 203–208.

FIELDING C. R., SLIMA R., HOLLICOME R. J. & JONES A. T. 2001. A new palaeogeographic synthesis for the Bowen, Gunnedah and Sydney basins of Eastern Australia. In: Hill K. C. & Bernecker T. eds. Eastern Australasian Basins Symposium. A refocussed energy perspective for the future, pp. 269–278. Petroleum Exploration Society of Australia, Special Publication. Melbourne Vic.

FLORES R. M., RICK C. A., STRICKER G. D., WRADEN A. & ELLIS M. S. 2008. Methanogenic pathways of coal-bed gas in the Powder River Basin, United States: the geologic factor. International Journal of Coal Geology 76, 52–75.

GLEN R. A. & BECKETT J. 1997. Structure and tectonics along the inner edge of a foreland basin: the Hunter Coalfield in the northern Sydney Basin, New South Wales. Australian Journal of Earth Sciences 44, 853–877.

GOBLAR A. 2005. The impact of igneous intrusions on coal, coal seam and groundwater composition. PhD Thesis, University of Wollongong, NSW, Australia.

GOLDING S. D., BOOREHAM C. J. & ESTERLE J. S. 2013. Stable isotope geochemistry of coal bed and shale gas and related production processes: a review. International Journal of Coal Geology 120, 24–49.

GURBA L. W. & WEBER C. R. 2001. Effects of igneous intrusions on coal bed methane potential, Gunnedah Basin, Australia. International Journal of Coal Geology 46, 113–131.

GURVICH A. E. & CHILINGARIAN G. V. 1997. Notes on the origin of formation fluid pressure: Well-logging methods aspect. Journal of Petroleum Science and Engineering 17, 321–330.

GURVICH A. E., CHILINGARIAN G. V. & AMINZADEH F. 1994. Origin of fluid pressure distribution and ways of improving pressure prediction methods. Journal of Petroleum Science and Engineering 12, 67–77.

HAMILTON S. K., ESTERLE J. S. & GOLDMAN S. D. 2012. Geological interpretation of gas content trends, Wilcannia Subgroup, eastern Surat Basin, Queensland, Australia. International Journal of Coal Geology 101, 21–35.

HARRINGTON H. J. 2005. Subsurface mineralisation: Rate of CO₂ mineralisation and geomechanical effects on host and seal formations. CATO (CO₂ Capture, Transport & Storage in The Netherlands) Work package WP 4.1. http://wwwvco2.cato.org/publications/publications/subsurface-mineralisation-rate-of-co2-mineralisation-and-geomechanical-effects-on-host-and-seal-formations-a-review-of-relevant-reactions-and-reaction-rate-data-41-24-05-march-2005

HARRINGTON H. J., BRAKER A.T. & HUNT J. W. 1984. Sedimentation and tectonics in the Permian coal basins of eastern Australia. Advances in the study of the Sydney Basin, pp. 10–11. Programme and Abstracts of the 18th Newcastle Symposium. The University of Newcastle, Newcastle, NSW.

HAWKES G. R. & ROSS J. B. 2000. Groundwater resource investigation for Sydney’s water supply reservoir at Leonay: Western Sydney, NSW. IAH News, December, 2008. http://www.connectedwaters.unsw.edu.au/resources/articles/leonay.html

HEALY B., WOODFILL C., MINNOSE S., HAN A., PRENDERGAST L. & HILLSON P. 2005. Sydney Basin regional structural framework and structural risk analysis—October 2005 Update. SRK Project Code: SBA002. SRK Consulting, Sydney.

HERBERT C. 1980. Depositional development of the Sydney Basin. In: Herbert C. & Helley R. A. eds. A guide to the Sydney Basin, pp. 11–52. Geological Survey of New South Wales—Bulletin 26. Sydney NSW.

HILLS R. R. & REYNOLDS S. 2003. In situ stress field of Australia. In: Hills R. R. & Muller R. D. eds. Evolution and dynamics of the Australasian Plate, pp. 43–52. Geological Society of Australia Special Publication 22. Sydney.

HOSNI J. 2009. Stable isotope geochemistry 6th Edition. Springer, Berlin. 285 p.

HOLMES C. & ROSS J. 2011. CSG Reservoirs—The importance of geological setting in understanding hydrogeological regimes. In: Proceedings from the International Association of Hydrogeologists, NSW Branch, NSW IAH Symposium 2011 Hydrogeology in NSW: the challenge of uncertainty, pp. 73–80. 5–6 September, 2011. Sydney.

JAWORSKA J., MANTARING R., ALEXANDER A., TUTT-BRANCO A., GURBA L. & BARBER C. 2010. Recent data from Mumnorah-1 and Vales Point-1 shed new light to the geothermal and petroleum potential of the Sydney Basin. Proceedings of the 37th Symposium on the Geology of the Sydney Basin—Advances in the study of the Sydney Basin. Hunter Valley, NSW, 6–7 May 2010.

JIN H., SCHMIDLMANN A., MASTALERZ M., POPE J. & MOORE T. 2010. Coalbed gas desorption in canisters: Consumption of trapped atmospheric oxygen and implications for measured gas quality. International Journal of Coal Geology 81, 64–72.

KATZ B. J. 2011. Microbial processes and natural gas accumulations. The Open Geology Journal 5, 75–83.

KEELLEY J. R., WILLIAMS B. G. & WARD J. R. 1989. Hydrogeochemistry of the upper Hunter River valley, New South Wales. Australian Government Publishing Services, Canberra.

KINNON E. C. P., GOLDING S. D., BOOREHAM C. J., BAURLEI K. A. & ESTERLE J. S. 2010. Stable isotope and water quality analysis of coal bed methane production waters and gases from the Bowen basin, Australia. International Journal of Coal Geology 82, 219–231.

KOROM S. F. 1992. Natural denitrification in the saturated zone: A review. Water Resources Research 28, 1657–1668.

KRIETLES C. W. 1989. Hydrogeology of sedimentary basins. Journal of Hydrogeology 106, 29–53.

KROOS B. M., LITTER R., MÜLLER B., FREILINGSDORF J., SCHWOCHAU K. & IM I. E. F. 1995. Generation of nitrogen and methane from sedimentary organic matter: implications on the dynamics of natural gas accumulations. Chemical Geology 126, 291–318.

LAMARRA R. A. 2003. Hydrodynamic and stratigraphic controls for a large coalbed methane accumulation in Ferron coal of east-central Utah. International Journal of Coal Geology 56, 97–100.

LAXMINARA YANAC. & CROSDALE P. 1999. Role of coal type and rank on methane adsorption characteristics of Bowen Basin, Australia coals. International Journal of Coal Geology 40, 309–325.

LEVINE J. R. 1993. Coalification: the evolution of coal as source rock and reservoir rock for oil and gas. In: Law B.E. & Rice D.D. eds. Hydrocarbons from coal: AAPG Studies in Geology 38, pp. 39–77. Tulsa USA.

L约EY D. L. & CHAPPELL F. H. 1995. Deep subsurface microbial processes. American Geophysical Union Reviews of Geophysics 33, 365–381.

MACKIE C. D. 2009. Hydrogeological characterisation of coal measures and overview of impacts of coal mining on groundwater systems in the Upper Hunter Valley of NSW. PhD Thesis, The University of Technology, Sydney.

MACARA K. 1978. Compaction and fluid migration: Practical petroleum geology (Developments in Petroleum Science, 9). Elsevier, Amsterdam, 319 pp.

MACK P. J. 2008. Subtidal origin of the Hawkesbury Sandstone, Middle Triassic, Sydney Basin. (Abstract). PESA Eastern Australasian Basins Symposium III, Sydney NSW 14–17 September, 2008.
Sydney Basin coal seam gas distribution and hydrodynamics

McLean W., Bryant N., Ross J. & Scarff S. 2010a. Isotopic tools for assessing aquifer connectivity during coal seam gas exploration. Groundwater 2010, National Groundwater Conference, 31 October-4 November, 2010, Canberra, Australia. http://www. groundwater2010.com/documents/McLeanWendy.pdf.

McLean W., Scarff S. & Bryant N. 2010b. Broke groundwater investigation and monitoring report—AGL Hunter Gas Project. Parsons Brinckerhoff, Sydney. http://www.agl.com.au/Downloads/Broke%20GW%20Monitoring%20Final%20Report%20V3.3%20%20full%20report%20240310.pdf.

Morton R. A., Posey J. S. & Garrett C. M. Jr. 1981. Salinity of deep formation waters, Texas Gulf Coast—Preliminary results. In: Bebout D. G. & Bachman A. L. eds. Fifth Conference Geopressed—geo thermal energy proceedings. October 13–15, 1981, Louisiana State University, Louisiana, USA.

PASSIN J. C. 2007. Hydrodynamics of coalbed methane reservoirs in the Black Warrior Basin: Key to understanding reservoir performance and environmental issues. Applied Geochemistry 22, 2257–2272.

Pentzke N. 2010. Delineation of coal seam gas domains in the Hunter Coalfield, Sydney Basin. Proceedings of 37th Symposium on the Geology of the Sydney Basin, Hunter Valley NSW, 6–7 May, 2010.

Pentzke N. 2014. Regional coal seam gas distribution and burial history of the Hunter Coalfield, Sydney Basin. Australian Journal of Earth Sciences 61, 409–426. doi:10.1080/08120099.2014.893539.

Pentzke N. L., Faiz M. M., Saghafi A., Stalkee L. & Van Hout J. 2008. Coal seam gas distribution in the Hunter Coalfield, Sydney Basin. PESA Eastern Australasian Basins Symposium III, pp. 399–402. 14–17 September 2008, Sydney NSW.

Petkas H. & Parnythe S. 2007. Origin and implications of dissolved gases in groundwater in Olkiluoto. Posiva Oy, Finland. http://www.posiva.fi/files/341/Posiva2007-04web.pdf.

Postma D., Klokkers C., Soegaard Andersen M., Coenraad De Meio M., T. & Gaar I. 2008. Geochemical modelling of processes controlling baseline compositions of groundwater. In: Edmonds W. M. & Shand P. eds. Natural Groundwater Quality, pp. 71–90. Blackwell Publishing Ltd, Oxford.

Rice D. D. 1983. Composition and origins of coalbed gas. In: Law R. E. & Rice D. D. eds. Hydrocarbons from coal, pp. 159–184. AAPG Studies in Geology #38. Tulsa USA.

Rice D. D. & Claypool G. E. 1981. Generation, accumulation and resource potential of biogenic gas. AAPG Bulletin 65, 5–25.

Rumble D. D. 1993. Inorganic chemical processes and reactions. In: Alley W. M. ed. Regional groundwater quality, pp. 131–154. Van Nostrand Reinhold, New York.

Schoell M. 1988. Multiple origins of methane in the earth. Chemical Geology 71, 1–10.

Scott A. R. 2002. Hydrogeologic factors affecting gas content distribution in coal beds. International Journal of Coal Geology 50, 363–387.

Scott A. R. & Hamilton D. S. 2006. Targeting Sydney–Gunnedah Basin coal seam methane exploration fairways and sweet spots based on a coalbed methane exploration model. Phase I report. NSW Department of Primary Industries Mineral Resources, Maitland, NSW, 48 p.

Scott A. R., Kassis W. R. & Ayers W. B. Jr. 1994. Thermogenic and secondary biogenic gases, San Juan Basin, Colorado and New Mexico—Implications for coalbed gas producibility. AAPG Bulletin 78, 1186–1209.

Smith J. W., Gould K. W. & Rigby D. 1982. The stable isotope geochemistry of Australian coals. Organic Chemistry 3, 111–131.

Smith J. W. & Pallister R. J. 1996. Microbial origin of Australian coalbed methane. AAPG Bulletin 80, 891–907.

Smith J. W., Pallister R. J. & Rigby D. 1992. Mechanism for coalbed methane formation. Symposium on coalbed methane research and development in Australia, pp. 63–73. James Cook University of North Queensland, Townsville, Queensland, Australia.

Song Y., Lu H., Hong P., Qin S., Liu S., Li G. & Zhao M. 2012. Syncline reservoir pooling as a general model for coalbed methane (CBM) accumulations: Mechanisms and case studies. Journal of Petroleum Science and Engineering 88–89, 5–12.

Staeh J. R. 1986. Fracture analysis, diagenesis, and analysis of environments of deposition. Study of the Wollombi Brook No 1 well. Carbon Consultants International, Murphysboro, Illinois, USA. Unpublished. (http://digsopen.minerals.nsw.gov.au/ReportWCR270, 68–240).

Tamplin S. 1993. Palaeo-environmental development of the Wittingham Coal Measures in the Muswellbrook region, NSW. Honours Thesis, University of Newcastle, NSW.

Talies M. & Miles M. 2013. Chemical variability of groundwater samples collected from a coal seam gas exploration well, Maramarua, New Zealand. Water Research 47, 1021–1034.

Thomson S., Hatherly P.,亨宁斯 S. & Sandford J. 2006. A model for gas distribution in coals of the Lower Hunter, Sydney Basin. PESA Eastern Australasian Basins Symposium III, Sydney NSW, 14–17 September 2008.

Thomson S., Thomson D. & Flood P. 2014. Observations on the distribution of coal seam gas in the Sydney Basin and the development of a predictive model. Australian Journal of Earth Sciences 61, 395–407. doi:10.1080/08120099.2014.903860.

Van Voast W. 2003. Geochemical signature of formation waters associated with coalbed methane. AAPG Bulletin 87, 667–676.

Veevers J. J. 2000. Billion-year earth history of Australia and neighbours in Gondwanaland. GEMOC Press, North Ryde, NSW, 388 p.

Warbrick P. R. 1981. Depositional environments of the Upper Tomago and Lower Newcastle Coal Measures, New South Wales. PhD thesis. University of Newcastle.

Whiticar M. J. & Faber E. 1986. Methane oxidation in sediment and water column environments—Isotope evidence. Advances in Organic Chemistry 1985. Organic Geochemistry 10, 759–768.

Whiticar M. J., Faber E. & Scholl M. 1986. Biogenic methane formation in marine and freshwater environments: CO2-reduction vs acetate fermentation—isotopic evidence. Geochimica et Cosmochimica Acta 50, 693–709.

Williams R. J. 1991. Carbon dioxide and methane emission at Tahmoor Colliery. In: Bambery W. J. & Depers A. M. eds. Symposium on gas in Australian coals. University of NSW, 4–5 February 1991. Geological Society of Australia Symposium Proceedings 2, 141–155.

Xia X. & Tang Y. 2012. Isotope fractionation of methane during natural gas flow with coupled diffusion and adsorption/desorption. Geochimica et Cosmochimica Acta 77, 489–503.

Received 5 July 2013; accepted 12 March 2014

SUPPLEMENTARY PAPER

Appendix 1 Reports and documents accessed for borehole data and local geology and gas regime interpretation.