A model for gas distribution in coals of the Lower Hunter, Sydney Basin

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Abstract

Gas content and gas composition in the Permian coals of the Lower Hunter, Sydney Basin, show evidence of distinct layering that can be attributed to the tectonic history of the coal measures and the effects of meteoric waters. Essentially, coals closest to the surface are more likely to contain methane of biogenic origin, and are more likely to be undersaturated than those at depth. In addition, a mixed gas zone of methane and CO_2 occurs below the biogenic methane zone and above a deeper thermogenic methane layer. Domains saturated with CO_2 may be explained in terms of magmatic activity, palaeostress fields and structural boundaries. This model is supported by compositional data and isotope analysis. The model explains this variability in terms of burial history, tectonism and groundwater flow paths. The implications of these findings are relevant to an understanding of coal seam gas character in the Hunter Coalfield and for the broader Sydney Basin. The model provides a framework for explaining variability in gas content, composition, saturation and permeability, and has a bearing upon coal seam gas exploration and production strategies.

Keywords: Sydney Basin, Hunter Coalfield, coal seam gas, biogenic methane, magmatic CO_2

Introduction

The Sydney Basin has a long history of underground coal mining. Coal seam gas has also played a significant role mainly because of safety concerns, and the impost for fast, economic extraction of coal. Major Sydney Basin mine disasters associated with coal seam gas include those at Mount Kembla, 1902, Bellbird, 1923, and more recently, Appin, 1979. Modern mining has controlled the risks associated with coal seam gas mainly by the imposition of gas management techniques that come at a considerable cost. However, these techniques have resulted in an improved understanding of coal seam gas science, and have proved outstandingly successful in managing the gas risk associated with coal mining. There has been no gas related fatalities in Sydney Basin underground mining since 1994.

A more recent development has been the growth of the Australian coal seam methane (CSM) industry, which has emerged from being no more than a promising concept in 2000 to become a viable new energy sector. In Queensland, approximately 82% of the gas supplied is now derived from CSM. The figure is 23% for the entire eastern Australian gas market (Baker, pers. com. RLMS 2008). In NSW and Queensland, the CSM industry is tipped to grow significantly over the next 25 years, echoing patterns already experienced in the USA. The proposed development of gas to liquids plants in Queensland is likely to ramp up the production of CSM in eastern Australia.

In NSW, production occurs in the Sydney Basin in the Camden area, and there are significant exploration efforts underway in the Hunter region. Coal mining also remains as a vitally important contributor to the national economy. An understanding of the distribution of gas within the coal measures helps with both the extraction of coal and the generation of CSM.

Coal mining companies are also well aware of their long-term corporate responsibilities to manage greenhouse emissions associated with mining activities. This paper is a direct result of that awareness, and uses data from a study undertaken in the Lower Hunter Valley of NSW for a major coal mining company (see Hennings et al 2007; also see Fig. 1, the 'Lower Hunter Coal Seam Gas Area').

Geological characteristics of Lower Hunter Valley coals

The major resources of Australian coal and coal seam gas are largely contained in the Late Palaeozoic sequences of the Bowen, Sydney, Galilee and Gunnedah basins; and the Mesozoic sequences of the Surat and Clarence-Moreton basins. Estimates of the CSM resources contained in the Bowen, Sydney and Gunnedah basins are very large—Australia's potential CSM gas resources have been estimated by APPEA to be as high as 250 Tcf (see also Brown et al. 1996). Australia's CSM resources compare favourably to the established producing basins of the USA, as well as Australia's more conventional gas fields—according to APPEA, conventional gas reserves stand at 144 Tcf. The proximity of CSM resources to Australia's eastern seaboard market is an added attraction.

In the Lower Hunter Valley, the coal producers generally mine coal from the Late Permian Whittingham Coal Measures. These are broadly time equivalents to the Newcastle and Tomago Coal Measures in the northern Sydney Basin, the Illawarra Coal Measures in the southern Sydney Basin, the Black Jack Formation in the Gunnedah Basin, and the Moranbah Coal Measures in the Bowen Basin. In our study area, mine data shows that the coals of the Lower Hunter Valley are high volatile bituminous in rank with vitrinite reflectance (Romax) values ranging from 0.7% to 1.0%.

The Blakefield, Glen Munro, and Woodlands Hill seams are all major coal seams in the Lower Hunter area, and part of the Whittingham Coal Measures; a division of the Jerry's Plains Subgroup. The Jerry's Plains Subgroup represents a complete

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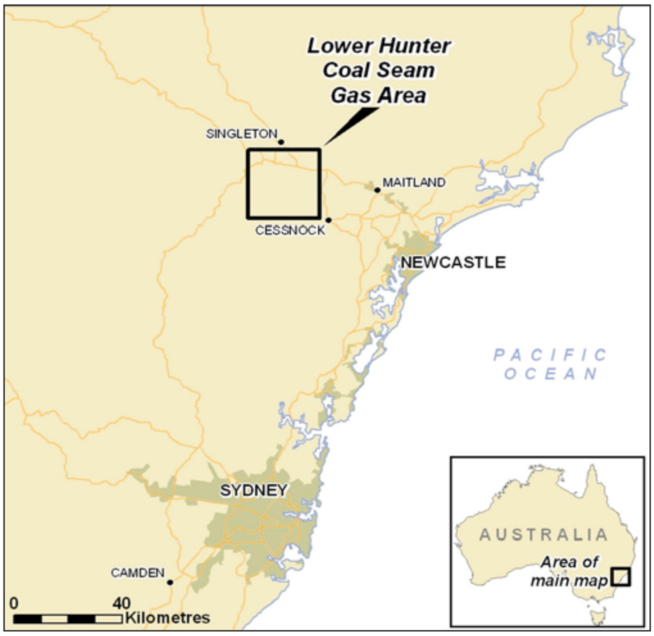

Figure 1. Location of the study area in the Lower Hunter Coalfield, Sydney Basin.

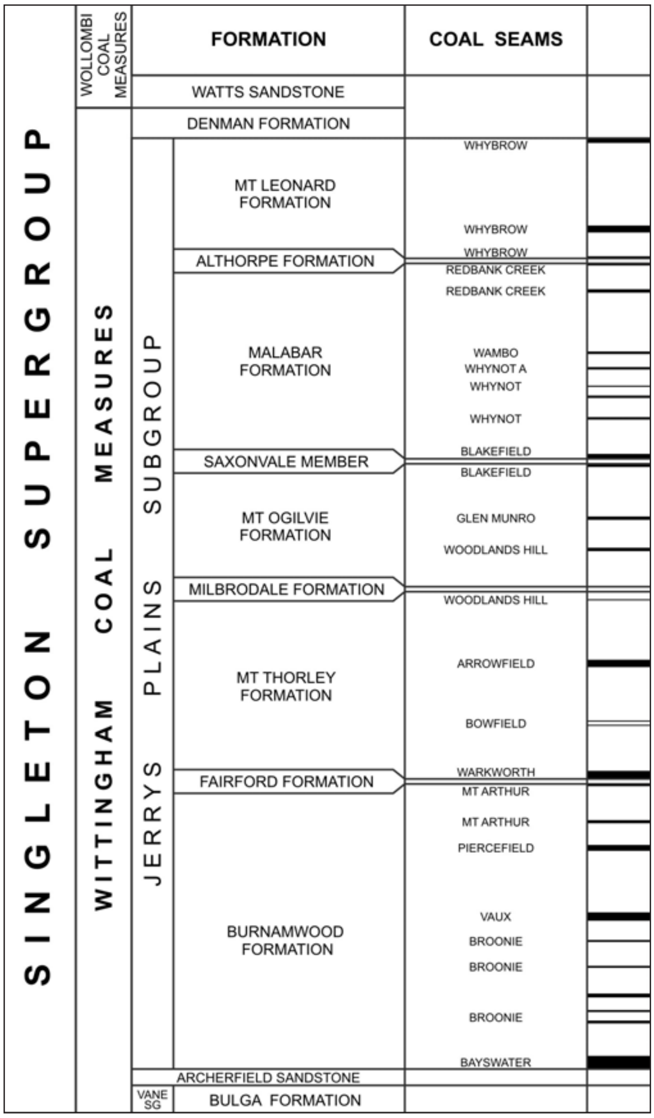

Figure 2. Stratigraphy of the Whittingham Coal Measures in the Lower Hunter (modified from Standing Committee on Coalfield Geology 1986).

cycle of terrestrial coal measure sedimentation up to 800 m thick. Interseam lithologies are typically lithic sandstones, shale and conglomerate, with siltstone, carbonaceous claystone and tuff also occurring throughout the sequence (Fig. 2).

The Whittingham Coal Measures were deposited in a retroarc foreland basin during the Late Permian at a time when the Sydney-Bowen Basin complex was undergoing east–west compressional tectonics (see Fielding 1990; Fielding et al. 1990; and Scheibner & Basden 1998). The sediments were largely derived from the north and east, shedding off a contemporaneous high associated with the New England Fold Belt and the already developed Hunter-Mooki Thrust System (Sniffen & Beckett 1995).

Our investigations suggest that palaeocontemporaneous highs such as the Loder Dome found in the Lower Hunter area were probably influential at the time of coal seam deposition. Subsequent burial, rifting and recent compressional tectonics has all influenced the structural character of the area. The seams generally dip to the south and west at less than 5º. Igneous activity occurred at various stages of geological history, particularly during the Jurassic, Late Cretaceous, and Tertiary (Carr & Facer 1980), and is important because it introduced CO_2 to the Sydney Basin. Evidence of igneous activity is present within many of the coals of the Lower Hunter Valley.

Coal seam gas character and depth

In the Lower Hunter, coal seam gas content tends to increase with depth. Conversely, the permeability decreases with depth. These relationships are illustrated in a conceptual sense in Figure 3, which is derived from a range of coal mining data from the Sydney and Bowen basins (see Williams et al. 2000). For a CSM operator, the best coal seam gas contents may be at depth, but the benefits of higher gas content may be counteracted by reduced permeability, and a subsequent increase in extraction costs.

However, the conceptual relationship above varies greatly from site to site. Gas content and permeability can be highly site specific, and is presumably influenced by structure and tectonic history. In Figure 3, the zone to the right of the cross over point

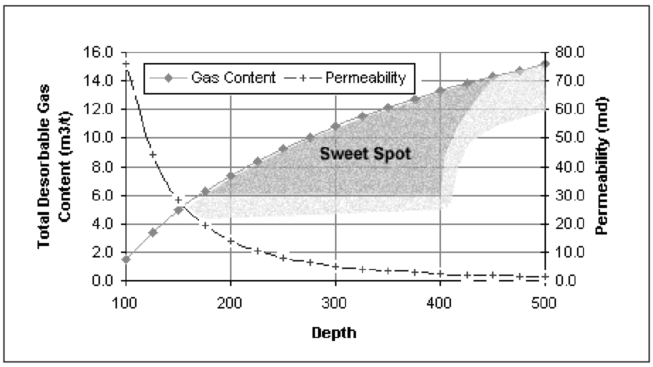

Figure 3. Conceptual relationship between permeability and gas content with depth, using coal mining data from the Sydney Basin (from Thomson & MacDonald 2002; modified from Williams et al. 2000).

marked 'sweet spot' suggests that there is an opportunity to identify moderate permeability coals with moderately high gas contents at quite shallow depths. This observation applies specifically for the Lower Hunter, but has also been observed in other locations in the Sydney-Bowen Basin complex by the authors. It is these zones that have been the target for some of the successful medium radius surface to inseam directional drilling production that has been conducted in Australia.

The maturity of the Lower Hunter Valley coals is generally suitable for methane generation; however, the gas composition can be variable. The same seam may exhibit wide variation in the ratio of methane to CO_2. This is not peculiar to the Lower Hunter. For example, from the authors' observations, some mines working the Bulli Seam in the southern Sydney Basin experience 90% or more CH_4 in some parts of the mine, and 90% CO_2 in other parts. These variations can occur over distances of less than 200 m. The authors are also aware of the same phenomenon elsewhere in the Hunter Valley, for example at the Dartbrook Mine near Scone

In our work, which is concerned with the Lower Hunter, we have observed the following relationship between gas composition and depth:

- Zone 1 – A surface zone extending to a depth of about 150 m, which contains negligible gas. The gas that is present is often CO_2. It is postulated that this CO_2 is not due to magmatic sources but may be due to another process, perhaps the oxidation of coal (see Clayton, 1998).
- Zone 2 – the 'Biogenic Window' (see section on 'Isotopic Evidence' below) containing shallow methane and extending from a depth of approximately 150 m to about 250–350 m. The gas content of this zone is usually from 4–12 m^3/t and increases with depth.
- Zone 3 – A 'Mixed Gas Zone' below Zone 2 and extending to a depth of approximately 600–700 m. The gases in this zone are both methane and CO_2, but mostly CO_2.
- Zone 4 – the 'Thermogenic Zone' of high methane below Zone 3.

This relationship is illustrated by gas composition data (Figs 4, 5) taken from deep boreholes drilled in the Lower Hunter region. Zones 2 and 3 are clearly evident as is the top of Zone 4. The data does not extend deep enough to indicate the bottom of zone 4. Zone 1 is ignored due to extremely low gas contents.

This pattern is repeated in every borehole drilled and sampled for gas composition in the Lower Hunter study area (see further examples, Fig. 6). Early studies did not extend to the same depths, and it is interesting to note that the prior local mining consensus was that "the CO_2 would continue to increase with depth". It is only more recently that deeper boreholes have been drilled and reveal the existence of Zone 4.

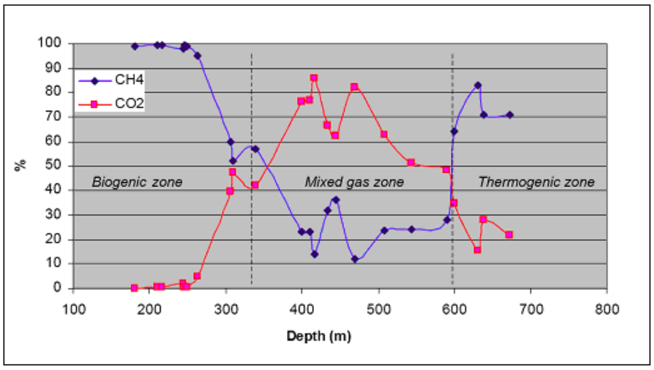

Figure 4. Changes in the gas composition with depth for a deep borehole in the Lower Hunter area.

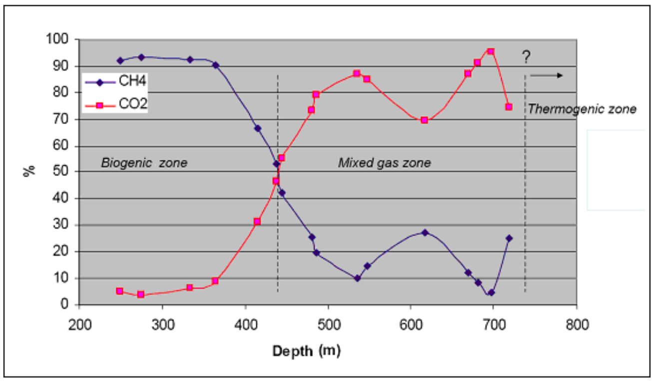

Figure 5. Another example of the changing gas composition with depth. In this case the high methane zone extends to ~370 m, with the mixed gas zone crossover from 430 m. The suggestion of a further zone of high methane occurs around 730 m.

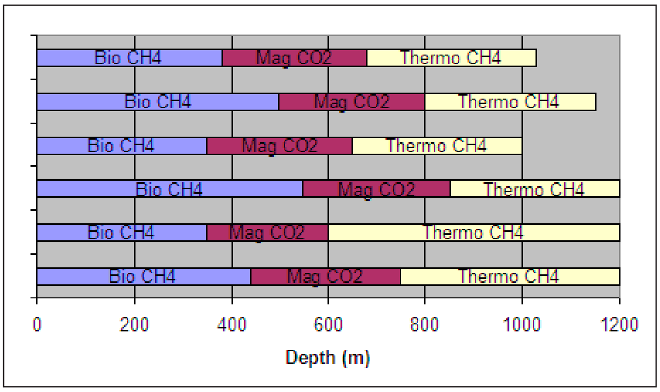

Figure 6. Summary of the gas zones found in six deep boreholes in the Lower Hunter. This general pattern is found throughout the area and appears to be independent of the stratigraphy (note: Zone 1 and Zone 2 are combined in this figure).

Isotopic evidence

Methane in coal can be derived from biogenic or thermogenic sources. Evidence for the origin of the methane in a coal seam can be derived from the isotopic composition of the carbon in the methane. This is expressed by the δ (delta) notation relative to a Pee Dee Belemnite (PDB) standard (Craig, 1953). For thermogenic methane, δ13C can be expected to be in the range of about -34‰ to -50‰ (Faiz & Hendry 2006). Biogenic methane is generally isotopically light, with $\delta^{13}C$ values less than about -55‰ (Faiz & Hendry 2006).

For CO_2, the range of $\delta^{13}C$ can be large as it may be derived from multiple sources (Faiz & Hendry 2006). CO_2 derived from thermogenic processes or from the oxidation of coal has negative $\delta^{13}C$ values (around -20‰ to -30‰ would be typical). Magmatic CO_2 is isotopically heavier, and usually has values varying from -5‰ to -10‰ (Faiz & Hendry 2006).

$\delta^{13}C$ values were measured in the Lower Hunter with the following results:

- Zone 1, the near surface zone, has very little gas and was not sampled. Empirically, CO_2 is the most prevalent gas in this zone and the origin is either thermogenic (unlikely explanation), or due to coal oxidation or another process related to near surface exposure (more likely explanation).
- For the biogenic window (Zone 2), $\delta^{13}C$ for CH_4 (16 samples from two boreholes) were measured and had $\delta^{13}C$ values between -53.1‰ and -80.7‰ (Fig. 7). These are within the range considered diagnostic of CH_4 of biogenic origin. The zone is characterised by generally low-moderate gas contents and moderate permeability. Our work has revealed that the coals are significantly undersaturated (up to 30–50%).
- For the mixed gas zone, the isotopic data (16 samples from

two boreholes) reveals that $\delta^{13}C$ for CO_2 is commonly in the range 0‰ to -10‰; this suggests magmatic origins for the CO_2. A few samples (three of 16) may suggest some remnant thermogenic CO_2. It is postulated that the methane contained in the 'mixed gas zone' is likely to be biogenic towards the top of the zone (this is suggested by isotope studies) and thermogenic towards the base (to be confirmed). The gas contents are higher than in Zone 2, but consistent with Figure 3, the permeability declines. This zone also tends to be undersaturated (10–50%) respective to the mixed methane / CO_2 isotherm.

- For Zone 4, we suggest that the methane is dominantly thermogenic methane. It is characterised by higher gas contents and low permeability and tends to be saturated. No isotopic data currently exists for this zone in our Lower Hunter study area, but a thermogenic origin for the methane is inferred based on the observations of Faiz et al. (2003) in the Camden area of the southern Sydney Basin.

The relationship between regional structure and the biogenic window

Our results show that the gas contained within any coal seam is not constant. An individual seam may be close to 100% methane or 100% CO_2 or anywhere between. Furthermore, the compositional layering that is observed with depth is largely independent of the regional geological dip (Fig. 8).

The independence from dip has important implications regarding the timing of the gas emplacement. Our results suggest that the formation of Zones 1, 2 and 3 is a process that post dates the regional tilting event that probably occurred as result of either the Hunter Orogeny (255–250 Ma) or the Bowen Orogeny (mid Triassic) (see Fielding 1990; Fergusson et al. 1990; or Scheibner & Basden, 1998).

The fact that the layering is subparallel to the present day land surface supports the importance of the near surface configuration in governing the distribution of gases in the subsurface. It is certainly not a function of individual seam properties. The proximity to the surface, and the depressurisation associated with erosion and uplift determines the extent of gas loss, and the effect of groundwater migration downwards determines the extent of 'topping up' of biogenic methane gas for any given area.

Subparallel layering also suggests that the primary mechanism for migration of microbe bearing groundwater is via vertical fracture systems and not through the coal seam aquifer itself.

Discussion

The gas patterns in the Lower Hunter are unquestionably a response to regional events. It should therefore be possible to extend the model beyond the Lower Hunter to the Sydney Basin more generally. The final aspect of our model relates to the igneous intrusions in the Sydney Basin that have created the CO_2 in the zone of mixed gas, and the more recent effects of groundwater migration that have been responsible for the introduction of microbes, which have converted this CO_2 to methane within the biogenic window.

Faiz et al. (2003) developed a model for the southern Sydney Basin whereby they postulated that the CO_2 was introduced to the coal measures during various phases of igneous activity that have

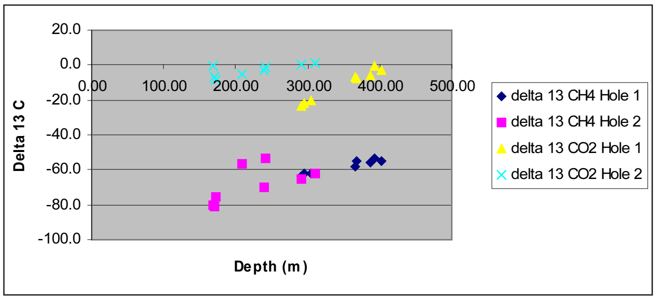

Figure 7. Isotope data for two holes in the Lower Hunter. The $\delta^{13}C$ values for CH_4 strongly support a biogenic origin for the methane at these depths. The $\delta^{13}C$ for CO_2 supports a predominantly magmatic origin for the CO_2.

occurred subsequent to the formation of the coals. At pressures greater than those corresponding to ~800 m depth of burial CO_2 will remain in solution in magmatic waters, but at shallower depths it could come out of solution and be preferentially adsorbed into the coal. We suggest that there it remained, being progressively released as pressures were reduced as a result of gradual uplift and erosion. In the first instance it remained in the coal cleats and fractures. Ultimately it could escape to the surface.

The formation of the biogenic methane requires the existence of biogenic agents. Faiz et al. (2003) suggest that these microbes or nutrients were introduced through the flow of meteoric groundwater, and that they reduced the emerging CO_2 to methane which was then adsorbed back into the coal.

This model is consistent with our results from the Lower Hunter, and so we offer the following underlying interpretation for the development of the gas zones observed in the Lower Hunter (see Scheibner & Basden 1998; and also Faiz et al. 2003 for additional discussions of these geological processes).

1. The Sydney Basin underwent deep burial through the Triassic and Jurassic, up until the mid Cretaceous, and the thermogenic phase of coal seam gas generation occurred. At this time, all of the Sydney Basin coals would have been effectively saturated with thermogenic methane (resulting in Zone 4).
2. At various times through the Late Triassic to Early Jurassic, mid-Cretaceous, and Late Cretaceous to Late Oligocene (Carr & Facer 1980), igneous intrusions occurred as part of the development of the Tasman Sea rift. CO_2 associated with these intrusive events was introduced to the coal measures and was either adsorbed to the coal (Zone 3 equivalent) or remained in solution, depending on whether it was above or below ~800 m depth.
3. Uplift began in the Late Cretaceous to Early Tertiary associated with the rifting of the Tasman Sea. Erosion commenced and thermogenic methane and CO_2 escaped through structural conduits to the surface as a result of depressurisation associated with this erosion. An equivalent to the present day Zone 1 formed near the ground surface. As deeper sediments came closer to the surface, CO_2 was released from solution and was in turn adsorbed to the coal (continued formation of Zone 3), or released at shallower depths (Zone 1). Most structural controls and regional dips were in place by this time. The structural conduits and surface exposures also allowed meteoric waters containing CO_2 reducing microbes to flow into the shallow subsurface and begin to act on any available CO_2 to create biogenic methane, which was adsorbed into coal (the formation of Zone 2 began).
4. Extensive volcanism again occurred in the mid Tertiary (up until late Oligocene) (Carr & Facer 1980) and likely resulted

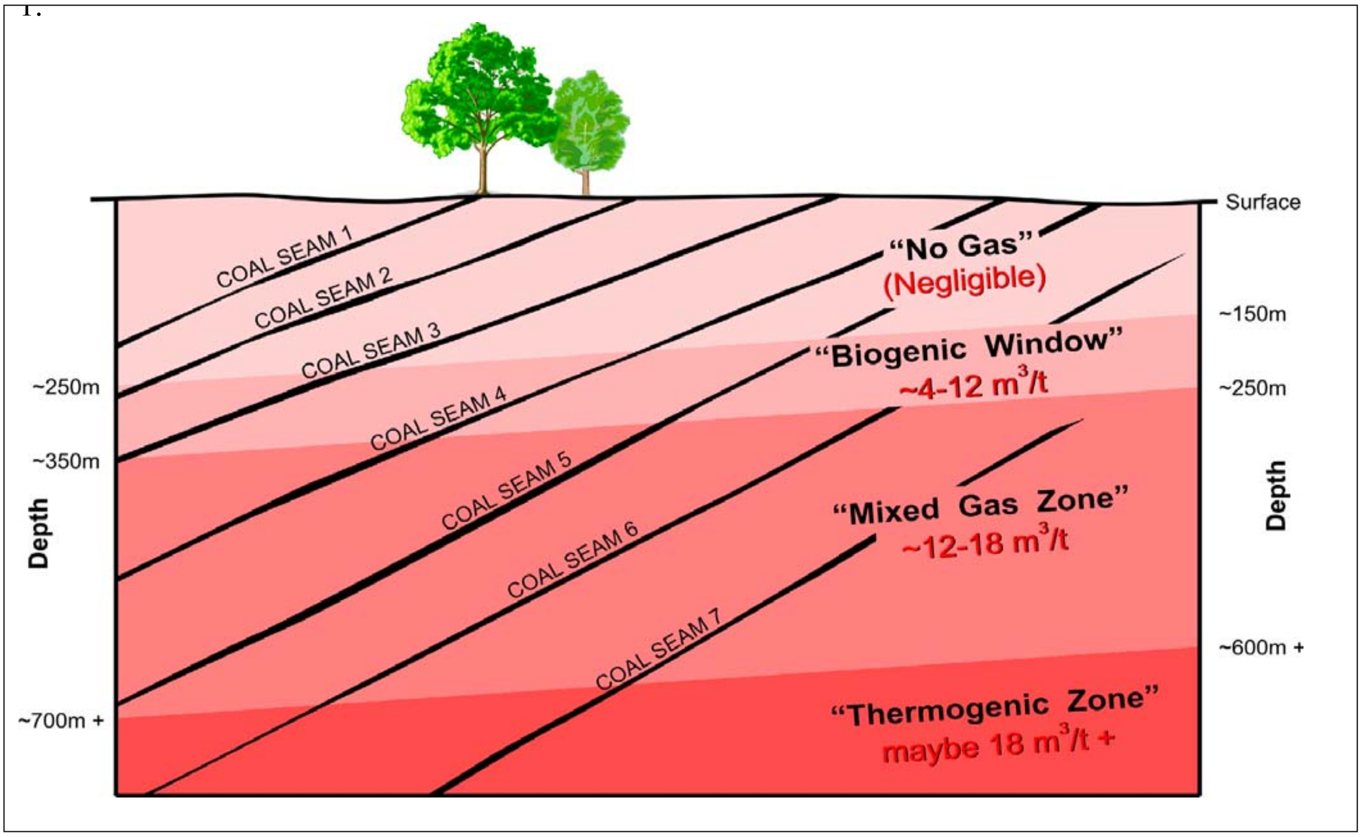

Figure 8. Schematic view of the relationship between the gas zones in the Lower Hunter and the regional dip. The layering is independent of dip and individual seam stratigraphy.

in the further emplacement of CO_2 into Sydney Basin coals. Again, this was either adsorbed into coal or remained in solution, depending on depth. At depths corresponding to a hydrostatic pressure of greater than ~800 m, thermogenic methane remained the dominant coal seam gas (Zone 4).

5. The processes of erosion and isostatic uplift has continued through to the present time, together with the ongoing release of gases, introduction of microbes carried by meteoric waters, and generation of biogenic methane. In the vicinity of the ground surface, oxidation of coals likely leads to the creation of small amounts of CO_2 (Zone 1). A new phase of tectonic compression that commenced about 48 Ma (Veevers 2000) probably blocked some pathways for gas release and water flow, and is likely to have created the current situation whereby the CO_2 reduction is not uniform and allows the development of nearby regions with differing amounts of CO_2 and methane. This is still the situation, and the current compressive stress field presumably has a continuing major impact upon permeability and contemporary groundwater flow.

The variations in gas composition, saturation and permeability in the Lower Hunter can thus be explained by understanding the impact of the processes described above.

Implications for regional coal seam gas exploration and coal mining gas issues

The geological processes that affected the Lower Hunter are not unique; the Sydney-Gunnedah-Bowen Basin complex has generally experienced the same regional tectonic history. It is therefore logical that the findings from this work can be extended to other parts of the Permian coal bearing sequences in eastern Australia. The key findings from this work that are likely to have an impact upon broader coal seam gas exploration strategies include:

1. Given the widespread nature of igneous intrusions along eastern Australia, the presence of a layered sequence of no gas, biogenic gas, mixed gas and deep thermogenic gas is likely to be observed beyond the Lower Hunter. This has important implications that may impact upon the economics of CSM, namely:

a. Shallow biogenic methane is a good target for CSM, with reasonable gas contents (4–12 m^3/t) and moderate to high permeability. The coals, however, are likely to be undersaturated.

b. The existence of mixed gas zones and significant levels of CO_2 will be problematic for some CSM operators. Some of the mixed gas zones are likely to contain more than 90% CO_2.

c. Below the base of the mixed gas zone, it is likely that reserves of deep thermogenic methane exist that are close to saturation. This is generally good news for CSM operators, however, permeability is likely to be very low in these areas.

2. The biogenic window is a potential target for CSM and occurs at relatively shallow depths. However, these targets are likely to be contained within one of the many coal mining leases in the Sydney Basin. The degree of undersaturation may also reduce the economic viability of this zone as a CSM resource in its own right. The integration of coal mining and gas extraction, however, can create the opportunity for the beneficial use of this resource. Furthermore, given the requirements for mine safety and the emerging greenhouse gas implications for coal miners, utilisation of these paired resources will need to be considered by many mining operations.

3. The interplay of tectonic history, magmatism and more recent groundwater flow are likely to be the main drivers behind the compositional variability of the coal seam gases throughout the Sydney-Bowen-Gunnedah Basin. Prospective CSM operators and coal mining companies with gassy seams need to consider the effects of these drivers and integrate this understanding with their approach to coal seam gas exploration and development.

Conclusions

Gas compositional layering with depth has been observed in the Sydney Basin coals of the Lower Hunter: (i) an upper 'negligible gas' zone is underlain by (ii) the 'biogenic window', a gas zone that is methane-rich, which in turn gives way to (iii) a mixed gas zone (CO_2 and methane) and finally at depth, (iv) a fourth zone dominated by methane that is likely to be of thermogenic origin. These observations are based on gas content and composition sampling from a number of boreholes in the Lower Hunter area and are supported by isotopic evidence. It is likely that similar layering is present throughout the Sydney Basin.

The drivers behind this layering in the Lower Hunter are regional tectonic events and the overprint of uplift, erosion and the flow of groundwater. Microbes carried by the groundwater have created relatively shallow zones of biogenic methane depending on groundwater access, past and present.

It is also suggested that variants of this layered model are likely to be pervasive in eastern Australian coal basins. The extent of the 'mixed gas zone' in particular is likely to be a function of depth of burial of the coals at the time of magmatic CO_2 emplacement. Below ~800 m and no CO_2 would be observed, and conversely, above ~800 m may result in significant CO_2 adsorption. In addition, the extent of 'biogenic window' development will be a response to the extent of open fracturing available to allow groundwater flow into the subsurface.

These observations are significant for CSM and coal mining operators in that they provide a model for understanding the distribution of various gases, and variation in saturation and permeability with different depths. This is important for CSM exploration and development strategies, and also for coal mining gas drainage and utilisation practices.

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