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

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CHAPTER 8. SUMMARY AND CONCLUSIONS

This study re-constructs the thermal and gas generation history of the southern Sydney Basin on the basis of vitrinite reflectance and identifies the principal factors controlling the variations in the gas distribution within the Illawarra Coal Measures.

A large quantity of seam gas data were obtained from measurements on exploration surface borehole cores. The spread of data permitted the construction of a coalfield-wide gas composition map and a desorbed gas content map for the major coal seams. These maps are first detailed maps, utilising data from working collieries, exploration drill holes and other drill hole data, constructed for the region. Quantitative and qualitative examination of petrographic, stratigraphic and structural controls on the distribution of seam gas trends identified the trends and potential areas for further gas exploration. Together with laboratory experimental results and borehole core desorption rates petrological and physical factors influencing the rate of gas emission from coals was established. These results were then related to outburst-prone conditions during coal mining. Mathematical models utilised for gas emission predictions in coal mines could be significantly improved if these petrological and physical properties are incorporated.

Following is summary of the findings and conclusions pertaining to the aims of this thesis.

1. COAL PETROLOGY AND THERMAL HISTORY

Coal seams of the Illawarra Coal Measures consist mainly of vitrinite and inertinite with minor liptinite. The younger Bulli and Balgownie seams have higher inertinite contents relative to underlying seams. Bulli, Balgownie and Cape Horn seams have low mineral matter with average values of generally less than 10% whereas the lower seams have up to 60%.

Vitrinite reflectance ($R_v$max) values for Bulli and Balgownie coals vary from approximately 1% in the west to over 1.4% toward the northeast; the vertical $R_v$max gradient ranges from 0.44 %/km in the west up to 1.75 %/km towards the northeast.

Thermal modelling indicated that the high maturity level of the Illawarra Coal measures was attained by the combination of both deep burial (up to 2500 m) and high heat flows (up to 2.5 HFU) during the Cretaceous. Since the Late Cretaceous continental rifting along the eastern coast, the sequence was uplifted and up to approximately 2 km of rocks have been eroded.

2. GAS GENERATION HISTORY IN THE SOUTHERN SYDNEY BASIN

On the basis of thermal maturity modelling, three broad stages of gas generation from the Illawarra Coal Measures can be distinguished; they are

Late Permian to Triassic	-	mainly biogenic gas;
Early Triassic to Middle Jurassic	-	mainly CO_2 with subordinate hydrocarbons and CH_4;
Middle Jurassic to Late Cretaceous	-	mainly CH_4 and other hydrocarbons.

Broad calculations indicate that the total volumes of hydrocarbons generated from these coals varied between 5 mg/g of coal in the west up to 65 mg/g of coal towards the northwest.

3. POROSITY, GAS SORPTION AND DESORPTION PROPERTIES OF COAL

In coal porosity mainly comprises meso-pores (< 50 nm) and micro-pores (< 2 nm) with the majority of macro-pores associated with the mineral matter. Micro-porosity of vitrinite is higher than semifusinite and inertodetrinite and increases with coal rank.

Gas sorption in coal is mainly into the micro- and meso-porosity of the coals. Increasing mineral matter content in coal causes a relative decrease in the micro- and meso-porosity and consequently reduces the gas sorption capacity. For the coal samples studied, the gas sorption capacity also increases with increasing vitrinite reflectance and decreases with increasing inherent moisture and volatile matter content. As a result, the net sorption capacity is directly proportional to fixed carbon content of coal.

The experimental results do not show any systematic variation in the gas sorption capacity of coal relative to maceral composition where the coals contain inherent moisture. However, where two coals have identical rank parameters the gas sorption capacity of a vitrinite-rich coal appears to be fractionally higher than the inertinite-rich coal.

At a given set of pressure/temperature conditions, coal can sorb approximately two to three times more CO_2 than CH_4.

Gas desorption rates from coal increases with increasing temperature, pressure and gas content. At a given set of pressure and temperature conditions, the rate of gas desorption from coal is up to 7 times greater for CO_2 than for CH_4. Borehole core desorption data also confirms that coal desorbs CO_2 at a faster rate than CH_4.

Desorption rates are highly dependent on the pore-size distribution in the coal. Rates at which gas desorbs out of coal will increase with the increasing macro-pore volume and therefore increases with increasing mineral matter content. Similarly, because of the higher fracture density in vitrinite-rich coals compared to semifusinite- and inertodetrinite-rich coals, vitrinite-rich coals desorb gas at a relatively faster rate.

4. COAL SEAM GAS DISTRIBUTION IN THE SOUTHERN SYDNEY BASIN

Coal seam gases in the southern Sydney Basin consist dominantly of CH_4 and CO_2 with subordinate amounts of N_2, C_2H_6 and longer chain hydrocarbons. The volume of CH_4 and CO_2 accounts for greater than 90% of the total gas and the relative proportions of these two gases are highly variable.

The variations in the gas composition is mainly related to structure and depth. Laterally high proportions of CH_4 occur in synclinal structures whereas CO_2 increases towards structural highs. High concentrations of CO_2 also occur in association with several faults, for example, Metropolitan Fault and the northern part of Nepean Fault Zone. Analogous to the structural trend, increasing concentrations of CO_2 occur in stratigraphically high levels (both coal seams and adjacent strata) rather than deeper levels.

Many of the CO_2 occurrences can be related to igneous intrusions and this is consistent with previously-published hypotheses based on carbon isotope data which suggested that majority of the CO_2 presently occurring in the Illawarra Coal Measures (especially when CO_2 >10%) was sourced from igneous intrusions. Near Woronora and Yerrinbool igneous provinces, CO_2 appears to have migrated, mainly in solution, considerable distances up structure and was entrapped in anticlinal crests, faults or dyke-related barriers. It is postulated that such distant migration probably occurred along the interseam sandstones and along open fractures rather than along the coal seam itself. However, the gas subsequently diffused and sorbed into the adjacent coal seams. During upward migration of CO_2-rich solutions, increasing amounts of CO_2 gas exsolve as a result of the decreasing pressure. A sharp decreases in the CO_2 solubility occurs at depths shallower than 600 m and consequently, CO_2 rises by buoyancy causing increased volumes of CO_2 gas at stratigraphically higher strata.

Lack of age data for these major intrusions does not permit reliable estimates of the timing of the emplacement of CO_2. However, it is postulated that most of the CO_2 that has migrated considerable distances from the source, may have been emplaced after the

Middle Jurassic but before end of peak gas generation in the Late Cretaceous. In other cases where CO_2 was introduced since the Late Cretaceous, migration was restricted over long distances due to reduced permeability and hence probably only occurred adjacent to the igneous source itself. Such localised accumulations of CO_2 may also occur in structural lows, especially adjacent to igneous intrusions and faults.

The proportion of C_2H_6 and longer chain hydrocarbons in coals and adjacent strata decreases with decreasing depth and accordingly laterally increases northwards. At depths shallower than 500 m, the proportion of these gases is very small (generally less than 0.1%) indicating that these long chain hydrocarbons, which were formed during early stages of coalification, may have been readily expelled from the sequence soon after its formation. The following equation incorporating depth and $R_v$max accounts for approximately 84% of the variability in ethane and longer chain hydrocarbons (C_{2+}) in the Illawarra Coal Measures:

$$\%C_{2+} = 0.367 + 0.0176 \text{ Depth (m)} - 7.53 R_v\text{max}$$

The total volume of gas desorbed from *in-situ* coal varies from less than 1 cm^3/t to 20 m^3/t. The residual gas content (gas not desorbed from coal cores at ambient conditions) varies from less than 1 m^3/t up to 4.2 m^3/t which accounts for less than 1% up to 60% of the total gas content; the average value for all data is 12.7%. The residual gas content chiefly depends on the desorption rate and appears to decrease with increasing CO_2, mineral matter and vitrinite content of the coal.

The volume of gas desorbed from coal is directly proportional to the organic content and hence the fixed carbon content of coal. Least squares regression analyses suggest that where the ash yield is 100% the *in-situ* gas content is approximately 0.8 m^3/t, a fairly insignificant value.

When considered on a dry ash free (daf) basis, seam gas content (daf) increases with increasing depth as a result of increasing pressure. At depths of less than 200 m severe degassing has occurred and the desorbable gas content (daf) approaches zero. On average, the desorbable gas contents (daf) increase by approximately 4 m^3/t per 100 m increase in depth, up to approximately 600 m and thereafter the rate of increase is significantly low. However, at a given depth the individual gas content may vary from the average value by up to 80%. Near the Woronora Anticline and the northern part of Nepean Fault Zone, where the gas has a high CO_2 content, anomalously high gas levels are observed in the coal seams. Such elevated gas contents are related to the ability of coal to sorb greater volumes of CO_2 compared to CH_4.

The effect of faulting on seam gas contents appears to be variable. In the West Cliff area coal seams near the Stokes Fault System contain anomalously low gas contents probably because of intense degasification *via* the faults and related fractures. Therefore, the *in situ* gas content at a given location cannot be accurately predicted on the basis of depth, coal composition or rank.

In the southern Sydney Basin, CH_4 volumes suitable for commercial production exist mainly in structural lows. In this context most prospective areas for further CH_4

exploration are the Camden Syncline in the central part and the northern structural low of the southern Sydney Basin. In other structurally higher areas high purity CH_4 may be available only at depths greater than 500 m. However, in such areas CH_4 reserves are small as coals are sparse at deeper levels.

5. FURTHER WORK

The present study has built a strong foundation for further research and the refinement of observations and hypotheses presented.

The distribution of CO_2 gas in relation to the regional structure was one of the major findings of this study. However, to gain a better understanding of the time of its origin and migration reliable data on the ages of the major igneous intrusions is necessary. Furthermore, a systematic study of the depth related variations in the chemical composition of groundwater within basin will be useful for testing the hypothesis relating to the stratigraphic variations in the CO_2 content in seam gas.

Despite that some of the new techniques rapidly determine the gas content of coal by crushing samples, and are therefore considered to be more sophisticated, it is always useful, especially for research purposes, to conduct desorption tests on solid core samples because it is possible to determine realistic desorption rates.

More data near faults is needed so that the role of various fault types on the gas content of coals can be better understood.