



Background Paper on New South Wales Geology

**With a Focus on Basins Containing
Coal Seam Gas Resources**

for

Office of the NSW Chief Scientist and Engineer

by

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Date of Issue: 28 August 2013

Our Reference: J083550

CONTENTS

	Page
1. AIMS OF THE BACKGROUND PAPER	1
1.1. SIGNIFICANCE OF AUSTRALIAN CSG RESOURCES AND PRODUCTION	1
1.2. DISCLOSURE	2
2. GEOLOGY AND EVALUATION OF COAL AND COAL SEAM GAS RESOURCES.....	3
2.1. NATURE AND ORIGIN OF COAL.....	3
2.2. CHEMICAL AND PHYSICAL PROPERTIES OF COAL	4
2.3. PETROGRAPHIC PROPERTIES OF COAL.....	4
2.4. GEOLOGICAL FEATURES OF COAL SEAMS	6
2.5. NATURE AND ORIGIN OF GAS IN COAL SEAMS	8
2.6. GAS CONTENT DETERMINATION	10
2.7. SORPTION ISOTHERMS AND GAS HOLDING CAPACITY	11
2.8. METHANE SATURATION	12
2.9. COAL SEAM PERMEABILITY	12
2.10. ENHANCEMENT OF SEAM PERMEABILITY.....	14
2.11. GEOLOGICAL ASSESSMENT OF CSG DEPOSITS	14
2.12. DATA COMPILATION AND RESOURCE ASSESSMENT	16
3. AN INTRODUCTION TO HYDROGEOLOGY	18
3.1. AQUIFERS AND ROCK POROSITY	18
3.2. REGIONAL STRESS FIELDS AND FRACTURE NETWORKS.....	19
3.3. HYDRAULIC CONDUCTIVITY AND PERMEABILITY.....	21
3.4. RELATIVE AND TIME-VARYING PERMEABILITY	23
3.5. SUBSIDENCE	24
4. GEOLOGY OF NSW COAL BASINS.....	26
4.1. NATURE AND ORIGIN OF SEDIMENTARY BASINS	26
4.2. COAL-BEARING SEDIMENTARY BASINS IN NEW SOUTH WALES	26
4.3. ENERGY RESOURCES OF NSW BASINS	28
4.3.1. Coal Resources	28

4.3.2. Conventional Petroleum Resources	29
5. SYDNEY BASIN.....	31
5.1. STRATIGRAPHY OF THE NORTHERN SYDNEY BASIN	32
5.1.1. Early Permian Marine and Coal-bearing Strata	32
5.1.2. Late Permian Coal-bearing Units, Newcastle Coalfield	32
5.1.3. Late Permian Coal-bearing Units, Hunter Coalfield	33
5.1.4. Triassic Strata.....	34
5.2. STRATIGRAPHY OF THE SOUTHERN AND WESTERN SYDNEY BASIN	34
5.2.1. Early Permian Marine and Coal-bearing Strata	34
5.2.2. Late Permian Coal-bearing Units.....	35
5.2.3. Triassic Strata.....	35
5.2.4. Igneous Intrusions and Lava Flows	37
5.3. STRUCTURE OF THE SYDNEY BASIN	37
5.4. COAL SEAM GAS IN THE SYDNEY BASIN	38
5.4.1. Southern Coalfield	39
5.4.2. Hunter and Newcastle Coalfields.....	40
5.5. HYDROGEOLOGY OF THE SYDNEY BASIN	41
5.5.1. Water Sharing Plans.....	44
6. GUNNEDAH, BOWEN AND SURAT BASINS.....	45
6.1. GUNNEDAH BASIN	45
6.1.1. Permian Volcanics, Marine and Coal-Bearing Strata.....	46
6.1.2. Triassic Strata.....	48
6.1.3. Igneous Intrusions	49
6.2. BOWEN BASIN	50
6.3. SURAT BASIN.....	51
6.4. COAL SEAM GAS IN THE GUNNEDAH BASIN	52
6.5. HYDROGEOLOGY OF THE GUNNEDAH, BOWEN AND SURAT BASINS.....	52
6.5.1. Water Sharing Plans.....	53
7. GLOUCESTER BASIN.....	55
7.1. STRATIGRAPHY AND STRUCTURE	55
7.2. COAL SEAM GAS	57
7.3. HYDROGEOLOGY	58

8. CLARENCE-MORETON BASIN	60
8.1. STRATIGRAPHY.....	62
8.2. COAL SEAM GAS	64
8.3. HYDROGEOLOGY	66
8.3.1. Water Sharing Plans.....	67
9. CONCLUDING COMMENTS	68
REFERENCES	69

APPENDIX I: Hydrogeological Modelling of CSG Impacts

APPENDIX II: NSW Water Sharing Plans

1. Aims of the Background Paper

This document is a background paper prepared for the Office of the NSW Chief Scientist and Engineer (OCSE), providing information and a discussion about the geological characteristics and history of NSW, with a focus on coal seam gas (CSG) resources, as part of a wider-ranging series of reports commissioned by that Office. The overall aim of the work is to define relevant geological concepts and topics, as well as to describe geological issues related to CSG formation and location in New South Wales.

After a general introduction outlining the significance of Australian CSG resources, the first part of the paper provides information on the nature and properties of coal, the processes of coal seam gas formation, and basic information on hydrogeology and groundwater assessment. This is followed by an overview of the geological history and characteristics of the sedimentary basins in NSW known to contain CSG resources, including the nature and distribution of coal seams, CSG resources and CSG-related aquifers within those basins. A list of references is also included, as a guide to sources of additional information on particular aspects if required.

Coverage of several topics peripheral to the main purpose of the paper is limited, partly to retain the focus on CSG geology and partly because of a paucity of information on those topics relevant to the study areas in the public domain. These include the possible extent of shale gas resources, processes for underground gasification of coal seams, geological storage of CO₂ in coal (which can be carried out in conjunction with methane production), and the hydrogeochemistry of groundwaters in coal seams and associated strata. More in-depth coverage of some topics, such as hydrogeological modelling of CSG impacts and an outline of NSW water sharing plans, is provided in appendices attached to the main document.

1.1. Significance of Australian CSG Resources and Production

The commercial production of CSG in Australia commenced in 1996. Since then CSG production has ramped up significantly, particularly in the last five years, to become an integral part of the upstream gas industry in eastern Australia. The major growth in both CSG reserves and production has been in the Bowen and Surat Basins of Queensland. However, an important reserve base has been built up in New South Wales in the Clarence-Moreton, Gloucester, Gunnedah and Sydney Basins. A summary of recent developments in these basins, and also in the CSG areas of Queensland and other states, is provided by Baker and Slater (2008) and Geoscience Australia and BREE (2012).

According to Geoscience Australia and BREE (2012), the economic demonstrated resources (EDR; equivalent to proved and probable or 2P reserves; see Section 2.11) of CSG in Australia (as at January 2012) are 35,905 petajoules (PJ). This represents about 24 per cent of the total EDR of natural gas in Australia. A further 65,529 PJ of sub-economic demonstrated resources of CSG are also indicated. Queensland has 33,001 PJ or 92% of the reserves, with the remaining 2,904 PJ occurring in New South Wales.

Australia's annual CSG production has increased from 1 PJ in 1996 to 240 PJ in 2010-11, with the latter representing around 10% of Australia's total natural gas production. Some 97% of the 2010-11 production (234 PJ) was from Queensland, and only 3% (6 PJ) was drawn from the Sydney Basin in NSW. Australia's primary gas consumption has increased from 74 PJ in 1970-71 to 1371 PJ in 2009-10, representing an average growth rate of 7.8% per year. Gas accounted for 23 per cent of Australia's primary energy consumption in 2009-10, providing the third-largest input after coal and oil.

The Australian domestic gas market consists of three distinct regional markets: the Eastern market (Qld, NSW, ACT, Vic, SA, Tas), the Western market (WA) and the Northern market (NT). These markets are geographically isolated from each other, making transmission and distribution of gas between markets uneconomic at present (Geoscience Australia and BREE, 2012). As a result, all gas production is either consumed within each market or exported as LNG. The Eastern market is the largest consumer of natural gas in Australia, accounting for around 56 per cent of Australia's gas consumption in 2009-10. It is also the only region in which CSG supplements conventional gas supplies. Since 1970-71 the Eastern market has consumed all of the gas produced in its region, although from 2014-15 gas exports as LNG are expected to commence from Queensland.

Australia is presently ranked fourth among the world's LNG exporters (Leather et al., 2013). However, based on projects currently under construction, Australia is destined to become the second largest LNG exporter worldwide by 2015, and could rival Qatar for the position of the world's largest LNG exporter by 2018. Much of this growth would be from conventional gas sources, but exports of liquefied CSG would contribute to the process.

1.2. Disclosure

The authors of this background paper have had the following associations with the coal seam gas industry in New South Wales:

Professor Colin Ward has undertaken consultant work for Metgasco in 2009 on the potential mineability of the coal in that company's CSG holding in the Clarence - Moreton Basin. The report is understood to have been used by company in an application for changes to its well completion requirements. Specific data disclosed by Metgasco for preparation of that report has not been used in the compilation of this background paper.

Through the University of New South Wales, Professor Ward also provided analytical services to Metgasco in 2008 to identify the clays and other minerals in coals and associated rocks from the company's exploration area. He has provided similar analytical services for many years to other organisations concerned with coal mining, preparation and utilisation outside the CSG industry.

Professor Ward acted as technical reviewer of a background paper on CSG impacts prepared by the Sydney Catchment Authority in 2013. Specific data disclosed by the Authority for that review have not been used in the preparation of the present background paper.

Associate Professor Bryce Kelly has written popular press articles on CSG for "The Conversation" and "Australian Geographic". He has recently been awarded a research grant by the Cotton Research and Development Corporation to investigate the uncertainty associated with predicting the long term impact of CSG production on groundwater resources.

2. Geology and Evaluation of Coal and Coal Seam Gas Resources

2.1. Nature and Origin of Coal

Coal is a carbonaceous sedimentary rock, composed essentially of preserved and lithified plant debris. The initial sediment formed by this process is peat, which is typically formed in a swampy sedimentary environment. The peat is modified in both texture and composition by long-term exposure to elevated temperatures and pressures as it and the associated strata are buried, often to great depths, over long periods of geological time.

The properties of a particular coal depend on the interplay of three independent geological variables that reflect its depositional and post-depositional history (Ward, 1984; Taylor et al., 1998; ISO, 2005):

- The nature of the plant debris in the original peat accumulation. This is expressed by the mixture of different types of organic particles or *macerals* in the coal, and represents a parameter referred to as the *coal type*. The mixture of macerals in a particular coal in turn reflects the nature of the plant community in the original peat-forming environment and the degree of preservation or degradation of the different components before burial.
- The extent to which the plant debris in the original peat has been altered by prolonged exposure to elevated temperatures and pressures with burial. The series of changes that occur during this process (Figure 2.1) are referred to as organic maturation or rank advance, and the *rank* of a particular coal is an indication of the extent to which the organic matter has been modified during its burial history.
- The extent to which the organic matter in the coal is free from dilution by admixed mineral and inorganic material. This represents the *grade* of the coal and, for practical purposes, is inversely related to the percentage of non-combustible ash remaining after the coal is burned.

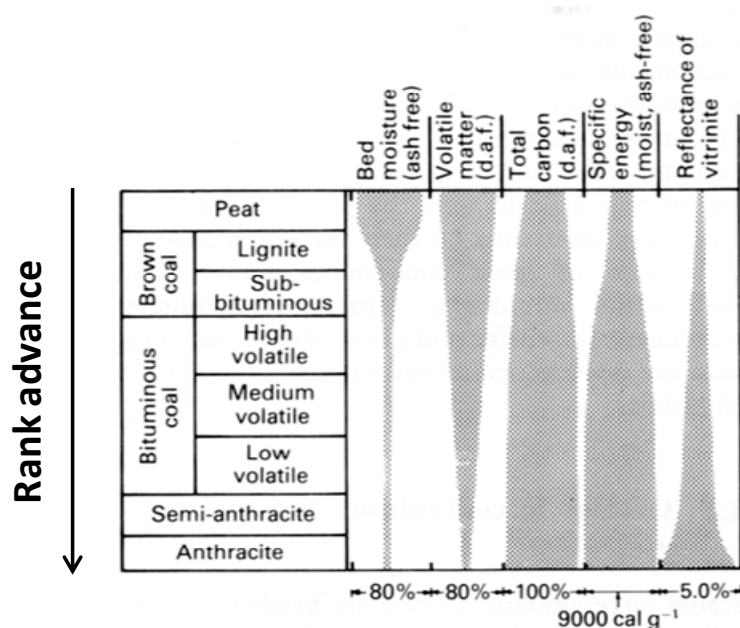


Figure 2.1: Variation in key coal properties with rank advance (after Ward, 1984).

2.2. Chemical and Physical Properties of Coal

A number of different properties may be determined when characterising coal for particular purposes (e.g. Ward, 1984; Thomas, 2002), including combustion and coking applications. The tests and properties that are most relevant to CSG accumulation and extraction include the following:

Moisture content: The proportion of water occurring in the coal and lost from the coal with exposure to the atmosphere (air-drying) or by heating the coal in an inert atmosphere to 100°C. The water may occur in the micro-pores of the coal (inherent moisture), infill fractures in subsurface coal beds, or coat the surfaces of crushed mined-coal products. The proportion of inherent moisture is very high in lower-rank coals, but decreases as the micro-porosity changes with rank advance (Figure 2.1).

Volatile matter: The proportion of volatile components (excluding moisture) released from the coal by heating to high temperatures (e.g. 900°C) in the absence of oxygen. In most cases this represents material released by thermal decomposition (carbonisation) of the organic matter, but may include some components released from heating of the minerals also present. The proportion of volatile matter released from the organic components, recalculated to allow for dilution by moisture and ash (i.e. expressed on a dry ash-free or daf basis), decreases as the rank of the coal increases (Figure 2.1).

Ash yield: The proportion of material remaining as a non-combustible residue after the coal is burnt. This represents the non-volatile remnants of the mineral matter in the coal, including any layers of non-coal rock that may be incorporated within the sample or seam section analysed. The ash yield reflects the coal grade; although the percentage may be allowed for in assessing the properties of the organic matter, the proportion of ash is not related to the rank of the coal concerned.

Fixed carbon: This represents the proportion of material in the organic matter that is not volatile at high temperatures, and is determined by subtracting the total of the moisture, volatile matter and ash percentages for the coal from 100%. If moisture and ash are removed by calculation, the proportion of fixed carbon expressed to a dry ash-free basis therefore increases as the volatile matter decreases and the rank of the coal increases.

Sulphur content: Sulphur may occur in the organic compounds of the coal (organic sulphur), in pyrite and other admixed sulphide minerals (pyritic sulphur), or in sulphate form (sulphate sulphur), with the latter including minerals (e.g. products of pyrite oxidation) and ions in the coal's pore water. Most NSW coals are relatively low in sulphur, with the sulphur being mainly in organic form.

Coal density: The density of a coal depends mainly on the proportion of admixed mineral material, and thus on the ash yield. The organic matter itself typically has a density of around 1.4 g/cm³, but with admixed mineral matter most coals have higher density values. The density of coal in the ground is also affected by the proportion of moisture held within the fracture network (Preston and Sanders, 1993); this may need to be taken into account when assessing in-situ tonnages and coal or CSG resources.

2.3. Petrographic Properties of Coal

The individual particles of organic matter in coal are referred to as macerals. Three groups of macerals are recognised (Taylor et al., 1998; Standards Australia, 1998):

Vitrinite: Particles of well-preserved plant tissue, typically with a relatively homogeneous microscopic structure due to impregnation by organic gels during peat formation.

Liptinite: Small particles of waxy plant components, such as leaf cuticles, spore coatings and algae. Hydrocarbon residues produced during rank advance may also form liptinite components.

Inertinite: Carbon-rich particles with a typically granular structure. These mainly represent plant tissue that was partly burnt or degraded during peat accumulation.

The relative proportions of these maceral groups, or the different macerals within those groups, may be determined by microscopic analysis (maceral analysis). Vitrinite and inertinite are typically the most abundant components and, with some exceptions, liptinite makes up only a minor proportion of the organic matter. Vitrinite-rich bituminous coals typically have a bright lustre in hand specimen (bright coals) while inertinite-rich coals typically have a dull lustre (dull coals).

Vitrinite reflectance: The reflectance of the vitrinite macerals in polished sections of coal increases as the rank of the coal increases (Figure 2.1), and hence is commonly used as an indicator of coal rank (Taylor et al., 1998; ISO, 2005).

Since most coals are dominated by vitrinite and inertinite components, a combination of the percentage of vitrinite macerals, representing the coal type, and the optical reflectance of the vitrinite, indicating the coal rank, can be used to provide a petrographic classification of coal (ISO, 2005). These parameters may vary independently of each other (Figure 2.2); they also provide a geological basis for understanding why different coals have different chemical and technological properties (Ward, 1984; Taylor et al., 1998). Specific energy, for example, increases with rank as measured by vitrinite reflectance (Figure 2.1), and shows only minor variation with coal type. Coking properties depend on a more complex combination of rank and type parameters.

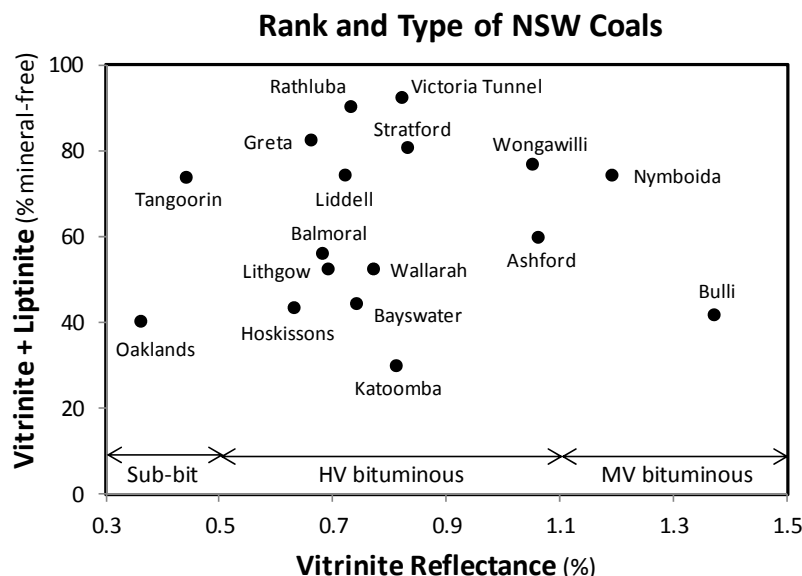


Figure 2.2: Typical petrographic properties (rank and type) for some New South Wales coal seams (Joint Coal Board and ACARP data).

2.4. Geological Features of Coal Seams

Individual seams of coal may display a wide range of features, derived from both the depositional environment of the original peat bed and the post-depositional history of the coal-bearing sedimentary basin. Features that may impact on coal seam gas include:

Coal plies and non-coal bands: Coal seams may contain subsections or plies of different lithological character, due to variations in coal type and/or grade through the vertical section. Individual seams may, for example, include discrete intervals of bright, vitrinite-rich coal, dull, inertinite-rich coal, mineral-rich or stony coal, and layers of claystone and other non-coal sedimentary materials. Thin layers of non-coal sediment within the seam, sometimes representing horizons of contemporaneous volcanic ash (tuff), may also be referred to as bands or partings.

Splits in coal seams: A split is a feature formed by a wedge-shaped unit of non-coal strata, up to several metres or tens of metres in thickness, which separates the seam into two separate coal beds (Figure 2.3). In some cases the plies of coal split off one seam may join the overlying or underlying seam, forming a zig-zag type of split pattern.

Washout structures: Washouts are linear features along which the top, or in some cases the whole coal seam is replaced by sandstone or other non-coal sedimentary rock. They represent erosion of the peat and deposition of non-coal sediment in the eroded channel during or shortly after peat accumulation, before the seam is further buried by overlying strata.

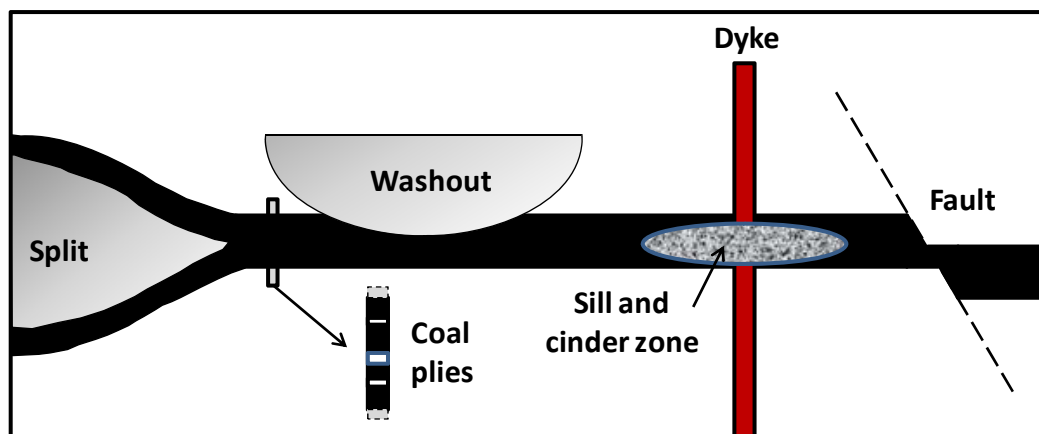


Figure 2.3: Schematic cross section illustrating a split, a washout, individual plies, an igneous intrusion (dyke, sill and cinder zone) and a fault in a coal seam.

Igneous intrusions and their effects: Molten igneous rock (magma) may be injected through fissures and other openings in subsurface sedimentary strata, and crystallise on cooling to form igneous intrusions within the basin sequence. Sheet-like bodies that are discordant to or cut across the layers of sedimentary strata are referred to as dykes (Figure 2.3), while those that are concordant with or parallel to the beds of the host sequence are referred to as sills.

Heat from the magma may affect the strata in contact with the intrusion. Although the impact on most sedimentary strata is relatively limited, when igneous intrusions are in contact with coal these heat effects may be quite significant. The high heat flow may drive off volatile matter from the coal and locally increase the rank of the coal around the intrusion. This may have implications for seam gas generation (discussed separately below).

The magma may also heat the coal under conditions similar to coke production, creating space as the volatile matter is driven off and allowing the magma to replace all or part of the coal bed with igneous material. Dykes, for example, may widen out to form sills when they pass through a coal seam. The igneous material in and around the seam may be heavily altered by volatile matter driven off from the intruded coal, forming a soft, clay-rich substance sometimes referred to as white trap. In some cases the coal may be transformed to a natural coke by the heating process, with the pores of this natural coke, or cindered coal, being heavily impregnated with mineral matter.

Faults and fault displacements: Faults are fractures or zones of fractures in rock strata across which significant displacement has occurred. They include normal faults, where the hanging wall is downthrown relative to the footwall (Figure 2.4), reverse faults, where the hanging wall is upthrown relative to the footwall, and wrench, strike-slip or transcurrent faults, where the blocks on each side of the fault plane have moved laterally but do not show any significant vertical displacement.

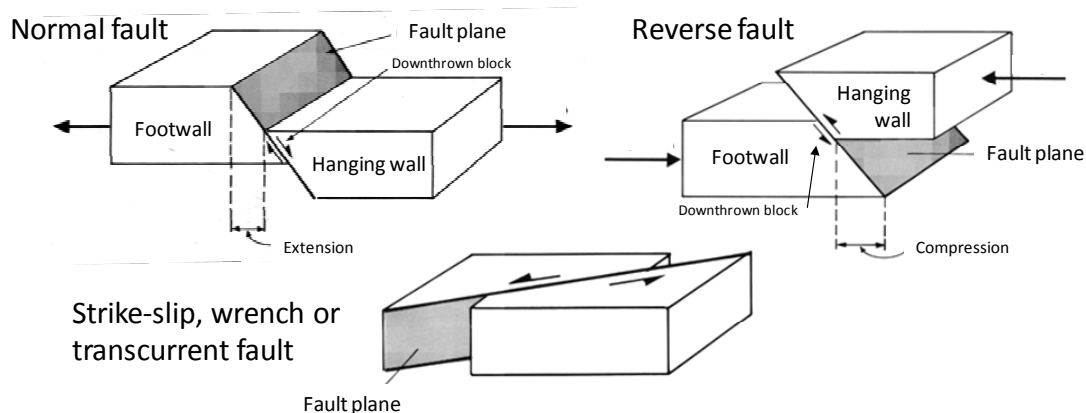


Figure 2.4: Block diagrams showing different fault types

Depending on the magnitude of the displacement involved, individual faults may interrupt the continuity of a coal seam, requiring development for mining or for CSG extraction to be laid out in separate blocks bounded by the fault planes. The rock in and around individual fault planes may also be more heavily fractured or more mineralised than elsewhere in the area, and as a result may have different permeability characteristics. Depending on the nature of the fault plane and the nature of the beds juxtaposed by the displacement, individual faults may act either as seals or as conduits to fluid flow (see discussion below and in Appendix I).

Cleat and joint patterns: Cleats are close-spaced sets of parallel fractures, typically perpendicular or near-perpendicular to bedding, which cut through the different types of coal material (lithotypes) in a coal seam (Figure 2.5). They are similar to the sets of joints commonly found in non-coal rocks, except that they are much more closely spaced and are occur only in the coal material (Pattison et al., 1996).

Although more complex systems may be developed, one set of cleats is commonly made up of individually more persistent fractures, and is referred to as the face cleat (Laubach et al., 1998). The other set, typically at right angles to the face cleat, is made up of less persistent fractures that often terminate on the face cleat planes; this is referred to as the butt cleat. Because coal itself is relatively impermeable, the cleat fractures provide the main network for flow of gases and liquids through the coal bed.

The spacing of cleat fractures within a coal seam depends in part on the nature of the individual plies or seam sub-sections, coal types and maceral bands involved (Dawson and

Esterle, 2010). Cleat fractures are closer together (i.e. have shorter spacings) in bright, vitrinite-rich coals than in dull (inertinite-rich) or stony coals. Individual layers of vitrinite material (vitrain bands) in bituminous coal may contain very close-spaced cleats, forming a micro-cleat network surrounded by material with wider-spaced cleat patterns.

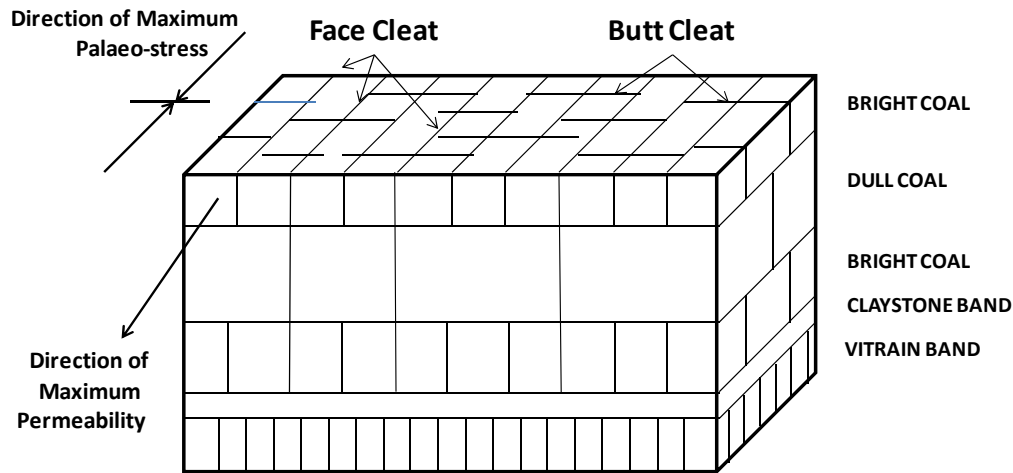


Figure 2.5: Schematic diagram showing face cleat and butt cleat in a coal seam.

The individual cleat fractures may be open, or they may be filled with minerals precipitated from solutions that permeated at different times through the coal seam. These may affect the permeability of the fracture network, and hence the migration of CSG components. A range of minerals may be involved, including carbonates, sulphides, quartz and different types of clay minerals (e.g. Faraj et al, 1996; Dawson et al., 2012). Bitumen residues and similar materials derived from hydrocarbon generation with rank advance may also occur in cleat fractures (Taylor et al., 1998).

2.5. Nature and Origin of Gas in Coal Seams

Coal seam gas (CSG) is gas that is held in subsurface coal seams. Unlike the gas in conventional hydrocarbon reservoirs, the gas is mainly adsorbed on to the surfaces of the micro-pores in the coal's organic matter (macerals). Although these micro-pores are very small, the total surface area of micro-pores per unit mass of coal can be quite large (e.g. 115 square metres per gram of coal, Moore, 2012), and hence a large amount of gas can be held in this way. Additional gas may be held under pressure (like conventional gas) in fractures and macro-pores of the coal, and some may be dissolved in the pore water within the coal seam.

The principal gases held in coal seams are methane (CH_4) and carbon dioxide (CO_2), with the methane being of economic significance as an energy source. Mixtures of both gases may be present, along with other gases such as hydrogen sulphide (H_2S), nitrogen (N_2) and heavier hydrocarbons such as ethane (C_2H_6). Terms such as coal-bed methane (CBM) or coal-seam natural gas (CSNG) tend to focus only on the methane component.

Methane, CO_2 and related gases in coal are generated by one of three possible mechanisms (Moore, 2012):

- **Thermogenic** processes, where the gas is released as part of the chemical changes in the organic matter (macerals) associated with rank advance.

- **Biogenic** processes, where methane is produced by the interaction of micro-organisms in the pore water of the coal with some of the organic components.
- **Magmatic** activity, representing gases generated by processes associated with intrusion of igneous rocks into the coal seam.

Thermogenic gas generation is generally thought to commence when the rank of the coal reaches a level corresponding to a vitrinite reflectance value of around 0.5 to 0.6%, within the high volatile bituminous range. Methane generation by thermogenic processes peaks in the medium volatile bituminous range, when the vitrinite reflectance reaches a little over 1.0%, and decreases at higher rank levels (Taylor et al., 1998). Since coal rank is determined by a combination of depth of burial, geothermal gradient and geological time, thermogenic methane generation is usually associated with coal seams that have been buried in the deeper parts of sedimentary basins (Figure 2.6). Such gas may, however, migrate within the seam or between seams, and also to shallower parts of the coal basin (Scott, 2002).

Biogenic gas, by contrast, is generated at relatively shallow depths, with the micro-organisms being introduced in association with recharge of the groundwater system (Flores, 2008; Moore, 2012). Gas generation by microbial processes may take place in coal of any rank, including coals below the rank level associated with thermogenic generation.

Magmatic gas may represent gases such as CO₂ introduced with the igneous material, or it may represent gases generated by carbonisation and coking of the intruded coal material. The high heat flow associated with such igneous bodies may also generate additional thermogenic gas from the coal seam (e.g. Gurba and Weber, 2001a).

The gases produced by these processes may be distinguished from each other by the ratios of particular carbon and hydrogen isotopes (Whiticar, 1996). Gases derived from all of these processes may be present in a single deposit, due to generation in different areas and/or migration of gases within or between coal seams. For example, biogenic gas may dominate at shallow depths and on the basin margins while thermogenic gas may dominate in the deeper-lying coal beds and the more central parts of the basin (Scott, 2002).

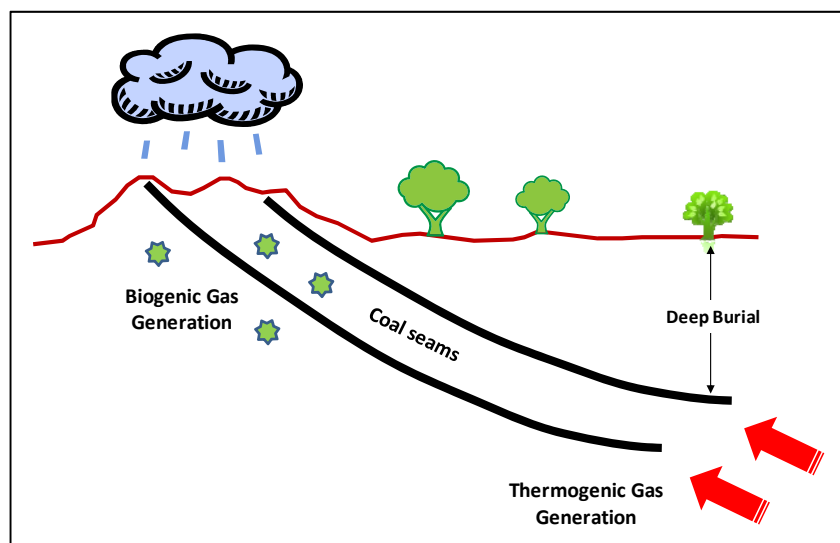


Figure 2.6: Schematic cross section showing generation of thermogenic and biogenic gases in a coal-bearing sedimentary basin.

In addition to methane formed in coal seams, methane can be formed by the action of thermogenic or biogenic processes on dispersed organic matter in other sedimentary rocks. Indeed, this is the main process associated with generation of natural gas in conventional hydrocarbon deposits. Such gas can migrate through the pores of the overlying strata, either as free gas or dissolved in the groundwater, and accumulate in natural trap settings. Gas from such sources may also accumulate in the head space of boreholes or seep into tunnels and other openings, even if a coal seam is not involved.

Methane may also form by different types of biogenic activity in accumulations of organic matter (peat) in modern-day swampy environments. Such gas can escape to the ground surface, or to the surface of the water overlying the peat deposit, and is sometimes seen bubbling in lakes and stream beds as part of the natural set of near-surface geological processes.

Small quantities of hydrogen sulphide (H_2S) have been found in coal bearing sequences in several different countries, particularly in association with high-sulphur coals (Ko Ko and Ward, 1996). However, the occurrence of this gas in Australia is comparatively rare. Several occurrences of H_2S have been reported in coal mining operations in the northern Bowen Basin of Queensland (Ko Ko and Ward, 1996), possibly generated by near-surface microbiological activity. The gas is a safety concern in underground mining, and if present must be maintained below acceptable levels in the mine ventilation system.

Small concentrations of radon have been reported in fugitive gases around some of the wells in a CSG development area in southern Queensland (Tait et al., 2013). Although concentrations are still within normal atmospheric levels, these are suggested to represent increased emissions related to features such as well heads and pipelines, together with more diffuse natural soil sources. The small but measureable radioactivity associated with radon emissions at the ground surface has also been used in the northern Sydney Basin to locate areas where coal has been affected by in-situ combustion (mine fires) in underground workings beneath (Xue et al., 2008).

2.6. Gas Content Determination

Measurement of the gas content of subsurface coals is generally based on extracting a coal sample, enclosing that sample in a sealed container and measuring the volume of the gas evolved. A number of different procedures have been developed based on this broad principle, and these are discussed further by Diamond and Schatzel (1998), Clarkson and Bustin (2011) and Seidle (2011).

In the Australian Standard procedure (Standards Australia, 1999), the coal seam is sampled by coring, and the core placed with minimum delay into a canister to measure the amount of gas desorbed. The amount of gas desorbed from the coal into the canister is measured volumetrically, for example by displacement of water in an inverted measuring cylinder.

The rate of gas desorption during the process is monitored, and the data from the early stages extrapolated to estimate the amount of gas (**lost gas = Q_1**) that would have escaped from the core between the time it was drilled and the time it was placed in the canister. The total quantity of gas evolved into the canister over the period between placement in the canister and cessation of desorption is also measured (**desorbed gas = Q_2**). This step may take up to several months to complete. Subsamples of the core are then taken from the canister and crushed in a sealed mill, allowing the quantity of gas retained in the coal after desorption but released from the coal by crushing (**residual gas = Q_3**) also to be measured.

As an alternative to the above procedure, a “quick crush” technique, also described by Standards Australia (1999), may be used to measure the seam gas content when more rapid

results are required (e.g. in mining assessments). This is similar to the slow desorption technique described above, but proceeds from estimation of lost gas to determination of residual gas without the longer-term desorption process in between.

The total (measured) gas content of the coal is determined by adding the lost gas, desorbed gas and residual gas components together (i.e. $Q_m = Q_1 + Q_2 + Q_3$). The results are usually expressed in cubic metres of gas (at 20°C and one atmosphere pressure) per tonne of coal (as-sampled), although other units, such as cubic centimetres per gram (cc/g) or standard cubic feet per ton (SCF/ton) may also be used (Scott and Hamilton, 2006; Moore, 2012).

In some cases the results may be recalculated to a dry or a dry, ash-free (daf) basis, to allow for the dilution effect of the mineral matter and moisture in the coal as sampled. While this may be useful in identifying trends and relationships, consistency in reporting basis between the coal seam properties (thickness, density, tonnage) and the gas content is necessary when the data are used in resource assessments.

Many factors may affect the results obtained by such measurements, including leakage of gas from the system, solution of CO₂ in water, and temperature and barometric pressure effects (Standards Australia, 1999). Variations may be encountered in data obtained from otherwise similar coals by different laboratories, and these may impact on the consistency of resource assessments.

2.7. Sorption Isotherms and Gas Holding Capacity

The extent to which a particular coal may adsorb a particular gas, such as methane, depends in part on the properties of the coal and in part on the temperature and the gas pressure involved. For a given temperature, the gas adsorption capacity of a particular coal generally increases with the gas pressure following a hyperbolic relationship (the Langmuir isotherm; Figure 2.7). The same coal may have different sorption capacities for different gases; for example the sorption capacity of a given coal for CO₂ is significantly higher than that of methane under otherwise equivalent conditions. A gas for which the coal has a low sorption capacity may also be replaced by a gas for which the coal has a higher sorption capacity; for example methane adsorbed on an in-situ coal seam may be replaced by naturally or artificially-introduced CO₂.

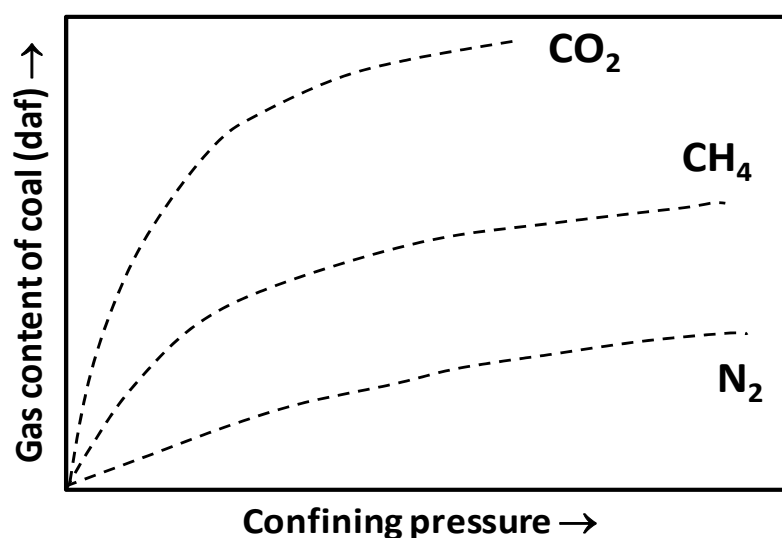


Figure 2.7: Schematic isotherm plots showing sorption of different gases by the same coal at different confining pressures

Determination of the sorption characteristics for a particular coal is based on placing a known mass of crushed coal in a sample chamber with the gas under test, and measuring the response of the coal at a constant temperature to different gas pressures (Crosdale et al., 1998; Saghafi et al., 2007; Seidle, 2011). The response may be measured by adding a fixed volume of gas and monitoring the pressure drop (volumetric method) or by measuring changes in the weight of the coal as it is saturated with gas at increasing gas pressures (gravimetric method).

The relationship between adsorbed gas content and gas pressure, derived from the resulting data points, typically flattens out close to a particular gas content, indicating a value that represents the (maximum) sorptive or gas-holding capacity of the coal tested. Similar curves can be obtained by testing the same coal with several different gases (e.g. CO₂, N₂, H₂S), by testing with the same gas and coal at a number of different temperatures, or by testing of different coals with the same gas under the same conditions, to evaluate the influence of the variables involved (e.g. Faiz et al. 2007; Moore, 2012).

2.8. Methane Saturation

Sorption isotherms indicate the maximum amount of a particular gas that a given coal can hold, while gas content determinations for the same coal indicate the amount of gas actually held by the coal under field conditions. The methane saturation of a particular coal is represented by the total gas content ($Q_1 + Q_2 + Q_3$) of the field sample divided (as a percentage) by the sorptive capacity of the same coal for methane under equivalent (subsurface or reservoir) temperature and pressure conditions (Moore, 2012). It represents the amount of methane actually held, as a percentage of the total methane the coal could possibly hold under the same temperature and pressure conditions.

Coal seams under field conditions are not necessarily fully saturated with methane. This may, for example, be because insufficient gas was generated to saturate the coal, or because some of the gas has escaped from the seam by leakage during its geological history (Moore, 2012). Methane might also be displaced from the coal by other gases such as carbon dioxide, for which coal typically has a higher sorptive capacity. The level of saturation may be lower in the near-surface part of the section, due to either leakage or incomplete gas generation, but tend to increase with depth (e.g. Odins and Bocking, 1994).

2.9. Coal Seam Permeability

In addition to the overall gas content, the economic viability of CSG deposits depends on the capacity for recovery of the gas at acceptable rates and with acceptable environmental impacts. The rate of gas recovery in turn depends on the permeability of the coal seam (see Section 3.3) under the prevailing subsurface confining pressure (or stress) conditions. The gases adsorbed on to coals in the subsurface are kept in place by the confining pressure of the groundwater surrounding the coal seam. A reduction in water pressure, whether natural or artificially-induced, will allow the gas to desorb and to flow towards a well, mine face or outcrop, depending on the geological framework involved.

Two different steps are involved in desorption and flow of gas in coal seams. The first is diffusion of the gas through the micropores of the organic matter, a process based on Fick's Law, and the second is flow of the gas through the macropores and fracture spaces of the coal, a process that generally follows Darcy's Law (Seidle, 2011). The cleat fractures are typically several orders of magnitude more permeable than the coal matrix, and thus usually provide the main overall control on fluid movement. The permeability of the seam in such cases depends mainly on the orientation, spacing, width, infilling and geometric relationships of the cleat and other fractures in the different parts of the bed (Scott, 2002; Moore, 2012).

Although the cleat fractures provide the main flow path, the rate-limiting step for gas flow is diffusion from the organic matter to reach the cleat fracture system. This is particularly significant in cases where the cleat fractures are widely spaced; although the fractures themselves may be open and permeable, the overall flow from the seam is limited by the rate at which the gas can escape from the coal matrix components.

Withdrawal of water from the coal to facilitate desorption also takes place mainly through the network of cleat fractures. Reduction in the pressure of water in the cleat network as a result of this process may allow the coal surfaces on each side of the individual fractures to converge, thus reducing the width (or aperture) of the fracture openings and reducing the overall seam permeability. The magnitude and orientation of the subsurface stress pattern, in relation to the cleat network, may also play a part in the response to fluid withdrawal.

On the other hand, the total volume of the organic material or coal matrix may decrease as the gas desorbs from the coal, a process described as matrix shrinkage (Levine, 1996). This allows the width of the individual cleat fractures to expand, and thus may act to increase the permeability of the coal as gas is progressively produced. The extent of matrix shrinkage varies from coal to coal, and an understanding of the balance between pore pressure reduction and matrix shrinkage effects is important in evaluating short- and long-term changes in permeability at particular extraction sites (e.g. Gray, 1987; Connell et al., 2010; Seidle, 2011; Mazumder et al., 2012).

Three different approaches may be taken to evaluating permeability and permeability changes for a coal seam: laboratory testing, where the permeability of coal samples is directly measured in a controlled experimental setting (Gash, 1991); a field-test approach, where formation permeability is measured by drill-stem or similar testing of boreholes through the coal seam (Kabir et al., 2011); and a theoretical modelling approach, based on fracture width and spacing using the principles of rock mechanics (Seidle, 2011).

Determination of coal seam permeability for CSG evaluation is generally carried out using down-hole techniques, based on monitoring changes in water flow and/or pressure as the reservoir is injected with fluid or is drawn down and allowed to recover (Moore, 2012). A number of different test procedures may be used, including open-hole drill stem tests, cased-hole water injection tests, open-hole production tests, multi-well interference tests, and post-cavitation production and shut-in tests (Mavor and Robinson, 1993; Taco et al., 2012). Matching of mathematical models to parameters from the production history of producing wells may also provide permeability data (Zuber et al., 1987).

Permeability data from laboratory tests may be influenced by changes in coal properties due to removal of the material from the high confining pressures and possibly elevated temperatures prevailing in the subsurface. Such techniques are also inherently applied only to a small sample of the total reservoir bed. Measurements based on the in-situ coal are thus regarded as providing more reliable indications of subsurface flow properties. Different types of in-situ testing may nevertheless yield different results, even for the same reservoir and in the same drill hole (Moore, 2012; Taco et al., 2012), and combining data from several different test procedures may be of value in providing more representative and reliable results.

Coal permeability tends to decrease with depth in subsurface strata. This may be due to increases in confining pressure with depth, but may also be due to factors such as variation in coal rank and type, and the presence of mineralisation or other infillings in the cleat fracture network. Shear zones and other tectonic deformations may increase permeability in some cases but be associated with decreased permeability in others (Wold and Jeffrey, 1999; Moore, 2012).

2.10. Enhancement of Seam Permeability

The fractures in coal and other rocks that facilitate fluid flow are planes of weaknesses that develop in response to tensile failure (opening), sliding (induced shear stress along the plane), or tearing (two faces of the fracture twisting away from each other) (Daneshy 2003). The permeability of a coal seam may be increased for methane production by hydraulic fracturing. This involves forcing water under pressure into a sealed-off section of a borehole and using the water pressure to enhance the available flow paths. When the hydraulic fracturing fluid is injected into the fracture network the pressure will rise until it causes instability and extension of favourably-oriented fractures (Daneshy 2003). The fracture will then propagate along the path of least resistance, which depends on the local stress field and the strength of the material at the tip of the fracture. This increases the permeability of the strata in the zone affected by the fracturing process. Solid particles such as sand may be introduced with the fracturing fluid, to prop the fractures open after the fluid pressure is withdrawn; chemicals may also be added to reduce the surface tension, prevent clogging, and enhance the mobility of the gases.

The capacity to predict the pathway of hydraulic fracture development is limited, due to the heterogeneity of both the matrix materials and the in-situ fracture network. Fracture initiation and propagation mechanisms, including relevant numerical relationships, are comprehensively discussed by Daneshy (2003), Zhang et al. (2011) and Bunger (2013).

Weber (1994) describes a study in which hydraulic fracturing tests were carried out at depths of around 250 m in an area of the northern Sydney Basin that was subsequently mined for coal. Exposure of the fractured zone by mining showed the development of near-vertical fractures approximately 10 mm wide, extending up to 50 m lengthways within the seam parallel to the face cleat pattern. The fractures extended from roof to floor of the seam, but did not grow into the roof or floor strata. Jeffrey et al. (1997) also describe the use of hydraulic fracturing and horizontal drilling for gas drainage in a mining situation.

A comprehensive discussion of hydraulic fracturing in relation to CSG development is given in a separate report for the Office of the Chief Scientist and Engineer by Jeffrey (2012). Hydraulic fracturing and other stimulation technologies (horizontal drilling, gas injection, chemical leaching) are also discussed by Brown et al. (1996).

2.11. Geological Assessment of CSG Deposits

Exploration for and evaluation of coal seam gas deposits is different in many ways to exploration for conventional oil and gas deposits. Geological evaluation of CSG deposits is an extension of the methodology used in coal exploration (Ward, 1984; Standards Australia, 1993; Thomas, 2002; Moore, 2012), and includes:

- a) Measurement and mapping of the coal seam or seams (thickness, structure, overall quality, rank, maceral percentages, mineral contaminants etc.) and hence determining the volume (or mass) of coal making up the CSG reservoir;
- b) Determining the coal's gas content and the gas composition, and also the gas holding capacity and gas saturation, and mapping the distribution of these variables within each seam, ultimately leading to estimation of the volume of gas in place;
- c) Evaluating the permeability of the coal beds containing the gas resources, including factors, such as in-situ stress and/or cleat anisotropy, that may affect seam permeability,

as well as the possible need for permeability enhancement processes (e.g. hydraulic fracturing) to allow the gas to be recovered at economically-acceptable rates;

- d) Evaluation of the groundwater system associated with the coal, including the impact of groundwater withdrawal on the surrounding surface and subsurface environment.

Although additional properties such as gas content and permeability are also taken into account, initial geological evaluation of the CSG reservoir (coal thickness, distribution and quality) is based on similar techniques to those used in evaluation of coal resources for mining operations (Standards Australia, 1993). Depending on the site geology these may include:

- Geological mapping based on outcropping strata, aerial photographs and/or remotely-sensed imagery; evaluation of basin or field structure, and possibly the location of igneous bodies, using ground-based or airborne measurement of gravity, radiometric, magnetic and electro-magnetic fields (Brown et al., 1996);
- Geological investigation of subsurface structure using seismic reflection techniques. Energy input for such studies may be based on explosive charges or mechanical vibration systems (Thomas, 2002), depending in part on the resolution required. As well as traditional two-dimensional (2D) traverses, three-dimensional (3D) surveys, based on intersecting grids of 2D traverses, may also be carried out to improve the understanding of subsurface structural features;
- Drilling of boreholes (cored or non-cored) to determine subsurface geology; description of subsurface strata based on lithologic properties (lithologic logging; Ward et al., 1986; Larkin and Green, 2012); recovery of coal samples (cores) for determination of gas content and gas-holding characteristics (see above); recovery of rock samples (cores) for geomechanical testing;
- Geophysical logging of boreholes (cored or non-cored) to further evaluate the nature and properties of the subsurface coal and non-coal strata. A wide range of down-hole tools have been developed for this purpose, mainly in the petroleum industry (Rider, 1996; Monier-Williams et al., 2009), but not all of these have been adapted for the small-diameter holes used in coal exploration. The principal techniques used for coal and CSG studies are listed in Table 2.1.

The holes used for coal seam evaluation, or additional specially-drilled holes, may also be used to test in-situ properties of the down-hole strata, including the permeability of the coal seam (see above), to evaluate subsurface stress patterns, to measure the elevation and fluctuations of the standing water level, to identify and evaluate water-bearing strata (aquifers; see Section 3.3) within the sequence, and to obtain samples of the groundwater from different horizons for chemical analysis. In more advanced stages of the project patterns of boreholes may be drilled to evaluate permeability, water and gas flow characteristics on a larger (in-situ) scale.

Table 2.1: Down-hole geophysical logs used in CSG exploration (compiled from Ward, 1984; Thomas, 2002; Monier-Williams et al., 2009 and other sources)

Type of Log	Properties Measured	Notes and Typical Application
Gamma-ray	Natural gamma ray emission from rock strata	Evaluation of clay mineral (illite) abundance based on emissions from potassium and other elements.
Spectral gamma	Natural emissions from particular elements	Evaluation of element sources of natural gamma emissions (K, U, Th) and relation of those to lithology.
Density	Backscattering or gamma rays from an adjacent down-hole source	Measurement of rock density and coal seam identification. Carbon in (low-density) coals gives a high level of backscatter; Si, Al and other elements in rocks give low backscatter. Response may thus also indicate coal quality (ash percentage).
Neutron	Response to neutrons introduced from adjacent down-hole source	Evaluation of rock porosity based on neutron capture by hydrogen in pore water (or hydrocarbons). Other possible applications based on H content of coal.
Caliper (single and multiple-arm)	Diameter of borehole	Indicates sections where borehole walls have caved. Used to compensate for caving in density log evaluations. Multiple-arm calliper logs can be used to measure the dip angle and direction of inclined caved zones due to structural features.
Temperature	Temperature of fluid in borehole	Can also be used to identify aquifer horizons from temperature differences in the fluid column. If there is no fluid input from the strata around the borehole, the temperature of the fluid column will reflect the local geothermal gradient.
Sonic velocity or travel-time	Velocity of sound waves through different strata	Used to interpret depths in seismic reflection profiles, and to interpret rock porosity; velocity is also related to rock strength and geomechanical properties.
Self-potential or spontaneous potential	Natural electric currents generated by flow of ions in strata and drilling fluid	Reflects contrast in salinity between bore fluid and rock pore water. Used for identification of lithology, especially of sandstones with saline pore water.
Resistivity, electric and electro-magnetic (induction)	Resistance of the strata to electric currents generated from the sonde	Resistivity of rock strata depends mainly on salinity of pore water, with saline waters being most conductive. Many different types of logs are used, with different down-hole and measurement technologies.
Borehole orientation	Angle and direction of borehole with depth	Used to monitor accidental or planned hole deviations, and to compute 3D position of down-hole features.
Dip-meter	Inclination of thin layers with contrasting resistivity around the hole	Resistivity fluctuations in a radial array of down-hole electrodes are processed to give dip direction and angle of individual beds intersected. Used to interpret gross geological structure, and also detailed rock features.
Borehole imaging (down-hole scanner)	Optical, acoustic or micro-resistivity image of borehole walls	Provides an “unwrapped” image of the inside surface of the hole. Used to evaluate geometry of bedding and/or fracture patterns in different subsurface strata.

2.12. Data Compilation and Resource Assessment

Information from drilling and other geological studies is typically integrated using comprehensive geological database and modelling systems. These are well-established in the coal mining industry, where they are used to store, evaluate and display different types of geological information (including three-dimensional geometric models), evaluate resources and reserves, and develop complex mine plans and production schedules (e.g. Thomas, 2002; Baafi and Li, 2009). A similar approach is also used in the (conventional) oil and gas industry. An expanded discussion of 3D geological modelling and flow simulations is provided in Appendix I.

Moore (2012) and Geoscience Australia and BREE (2012) describe three levels of economic certainty (commerciality) for gas and other petroleum resources, based on a classification developed by the Society of Petroleum Engineers. From least to most certain these are: Prospective Resources, Contingent Resources, and Reserves (Figure 2.8). Different levels

of data are required for material reported in each category. In order to achieve certification at the Reserves level, for example, commercial flow rates must be demonstrated.

Three different levels based on geological certainty (proved, probable and possible) are used within the Reserves category:

Proved Reserves (1P) are those quantities, which, by analysis of geoscience and engineering data, can be estimated with reasonable certainty to be commercially recoverable, from a given date forward, from known reservoirs and under defined economic conditions, operating methods, and government regulations. If deterministic methods are used, the term reasonable certainty is intended to express a high degree of confidence that the quantities will be recovered. If probabilistic methods are used, there should be at least a 90% probability that the quantities actually recovered will equal or exceed the estimate.

Probable Reserves are those additional Reserves which analysis of geosciences and engineering data indicate are less likely to be recovered than Proved Reserves but more certain to be recovered than Possible Reserves. It is equally likely that actual remaining quantities recovered will be greater than or less than the sum of the estimated **Proved plus Probable Reserves (2P)**. In this context, when probabilistic methods are used, there should be at least a 50% probability that the actual quantities recovered will equal or exceed the 2P estimate.

Possible Reserves are those additional reserves which analysis of geoscience and engineering data suggest are less likely to be recoverable than Probable Reserves. The total quantities ultimately recovered from the project have a low probability to exceed the sum of **Proved plus Probable plus Possible Reserves (3P)**, which is equivalent to the high estimate scenario. In this context, when probabilistic methods are used, there should be at least a 10% probability that the actual quantities recovered will equal or exceed the 3P estimate.

Contingent Resources are those quantities estimated to be potentially recoverable from known accumulations, but the relevant project(s) are not yet considered mature enough for commercial development due to one or more contingencies. Contingent Resources may include, for example, projects for which there are currently no viable markets, where commercial recovery is dependent on technology under development, or where evaluation of the accumulation is insufficient to clearly assess commerciality.

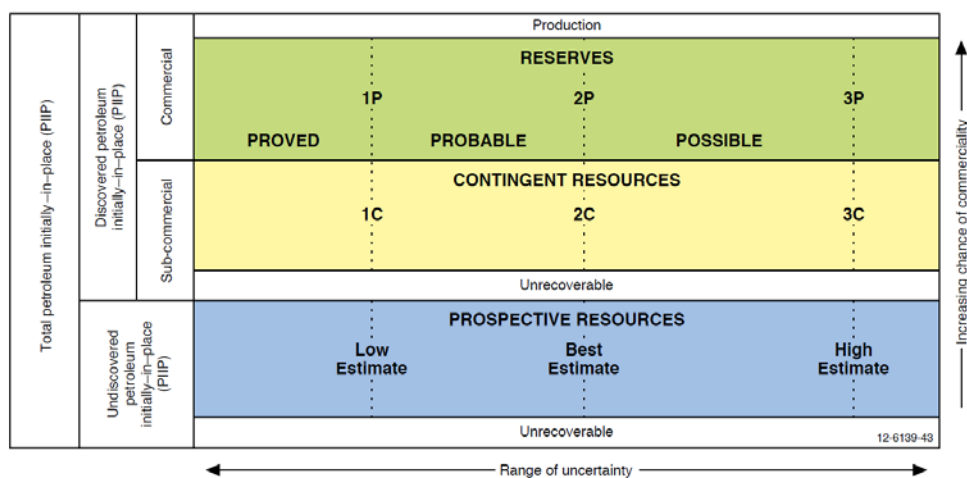


Figure 2.8: Terminology used for resource classification, based on the Petroleum Resources Management System of the Society of Petroleum Engineers (Geoscience Australia and BREE, 2012).

3. An Introduction to Hydrogeology

The hydrogeology of the Earth has been extensively studied for over 100 years. There are now many excellent textbooks that present comprehensive overviews of groundwater fundamentals (Fetter, 2000; Schwartz and Zhang, 2002; Bear 2007; Fitts 2013). Below is a brief discussion of the important properties of aquifers, but the reader is encouraged to refer to one of the cited textbooks for a detailed discussion.

3.1. Aquifers and Rock Porosity

Aquifers are generally considered to be geologic units that contain and can transmit water at rates fast enough to yield useable quantities of water (Bear, 2007). There are two types of unit that may be described as confining units. An aquitard is a unit of low permeability, which can store and transmit water between aquifers. An aquiclude is a unit with an extremely low capacity to transmit water.

If a water table occurs within an aquifer it is called an unconfined aquifer; this is also called a phreatic aquifer. If the complete unit is saturated, and the unit is bounded by aquitards, it is called a confined aquifer (Figure 3.1). At some locations the pressure in a confined aquifer is large enough to force groundwater up the borehole (also called a well or bore) to the point that the water freely flows at the ground surface. Such confined aquifers are called flowing artesian aquifers.

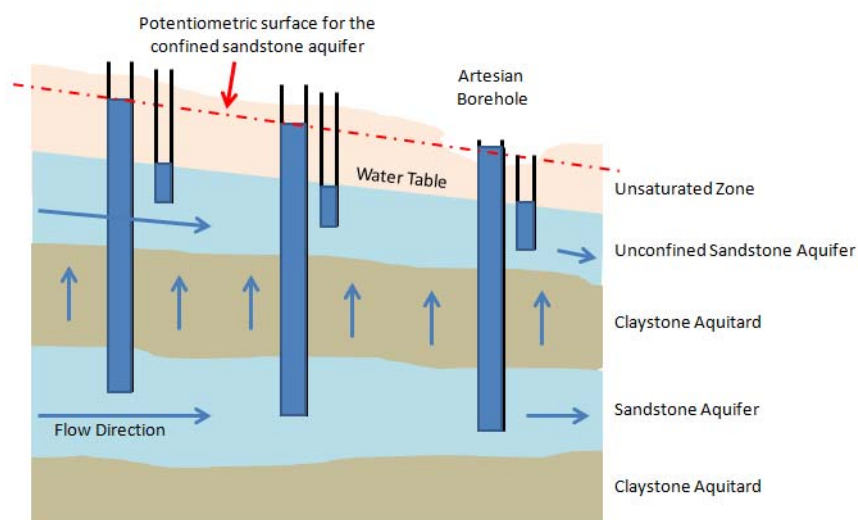


Figure 3.1: Schematic of aquifer types, and the measured groundwater level recorded in monitoring boreholes (adapted from Fitts, 2013).

Sandstone, shale and claystone units form from the accumulation of grains that are cemented together (this is commonly called porous media). The grains are irregular in shape and when packed together pore spaces remain. In porous media water and gas migrate via connected pore networks. For a unit volume of rock the porosity is defined as the volume of voids divided by the total unit volume. Due to cementation between the grains, some of the pores may be sealed off (no water or gas can enter or leave the enclosed void). Because of this, hydrogeologists commonly refer to the effective porosity, defined as the fraction of interconnected voids that are involved in the transmission of fluids.

Rocks near the surface of the Earth are usually fractured. Fracturing of the rocks is caused by regional stress fields and unloading in the near surface. The spacing between the fractures ranges from centimetres to tens of metres. For sedimentary rocks, the pore space

is called the primary porosity and the fracture space the secondary porosity. Groundwater flow is often dominated by flow through the fracture network and along bedding planes.

3.2. Regional Stress Fields and Fracture Networks

Stress is defined as force per unit area. In the near surface of the Earth the vertical stress is predominantly a function of the weight of the rock and water above a given layer. This is commonly called the overburden pressure. In consolidated rock strata horizontal stress is due to a number of factors including, but not limited to, local geological structures, local faulting, and forces at tectonic plate boundaries.

Australia is generally considered to be in a predominantly compressive state (Lambeck et al. 1984). The orientation of the stress fields is highly variable throughout Australia, but at a local scale they have a consistent orientation (Hillis and Reynolds, 2003). The Bowen Basin has a strong north-northeast to south-southwest maximum horizontal stress orientation, which is likely due to dominating plate boundary forces (Hillis and Reynolds, 2003). In the Sydney Basin the maximum horizontal stress field is scattered (Reynolds et al., 2003), and the horizontal stresses are much higher than the vertical stresses (Pells, 2011). The maximum stress orientation is due to a number of superimposing forces associated with plate boundaries, density contrasts, local faults, local geological structures, and continental margin effects. This has implications for predicting the migration of hydraulically-induced fractures in the Sydney Basin.

Fractures induced by hydraulic fracturing predominantly initiate in the orientation of the minimum principal stress (Hillis et al., 1999). Fracture growth depends on the in-situ stress fields and rock strength. After initiation the fractures continue to grow until the stress at the fracture tip is lower than the critical stress-intensity of the rock being fractured (Davies et al., 2012). The fracture initiation pressure (p_b) is a function of the minimum horizontal stress (σ_h), maximum horizontal stress (σ_H), pore pressure (p_p) and the rock tensile strength (σ_t). For a vertical well:

$$p_b = 3\sigma_h - \sigma_H - p_p + \sigma_t.$$

All rocks have a considerable range of values for tensile strength (pressure at point of tensile failure). For a comprehensive discussion on fracture initiation pressures for horizontal and inclined boreholes refer to Huang et al. (2012), Hou et al. (2013) and Feng and Shi (2013). Tensile strength depends on many properties of the rock including, but not limited to, laminations, micro-cracks, type of pore cement, grain packing, and grain size (Hobbs, 1964). In general coal has a lower tensile strength compared to shale and sandstone (refer to Figure 10b, page 140 of Lockner, 1995), but this can vary depending on the geological setting. Thus fracturing will be induced in coal at a lower initiation pressure compared to the surrounding shales and sandstones.

Hydraulic fracturing predominantly enlarges pre-existing fractures (US-EPA, 2004). The formation of new fractures may also be a result of hydraulic fracturing, but they are far fewer in number compared to the natural fractures (US-EPA, 2004). Thus knowledge of the pre-existing fracture network is important for understanding the success and impact of coal seam gas production.

The legacy of the regional stress fields (both extension and compression phases), and also unloading as the rocks get closer to the ground surface, is that all sedimentary rocks have fracture networks. All sedimentary rocks will therefore transmit water to some degree (although some poorly, as will be discussed below).

There are few comprehensive surveys, in the public domain literature, of fracture networks for the basins being reviewed in this document. One detailed study is that by Memarian and Fergusson (2007). They mapped in detail the fracture network in the rocks of coastal rock platforms and adjoining cliffs between Wollongong and Coalcliff, on the south coast of New South Wales. These rocks are part of the late Permian Illawarra Coal Measures and overlying Early Triassic Narrabeen Group (see Section 5.2).

De Castro et al. (2009) collated the results of defect measurements inferred from visual imaging (borehole camera) in over 70 boreholes within the Hawkesbury Sandstone (Figure 3.2). The defects included fractures, bedding planes, and cross-bedding discontinuities. These results clearly highlight the potential for tortuous pathways of connectivity over considerable depth intervals, especially given that the defects spacing ranged from 0.01 to 10 m.

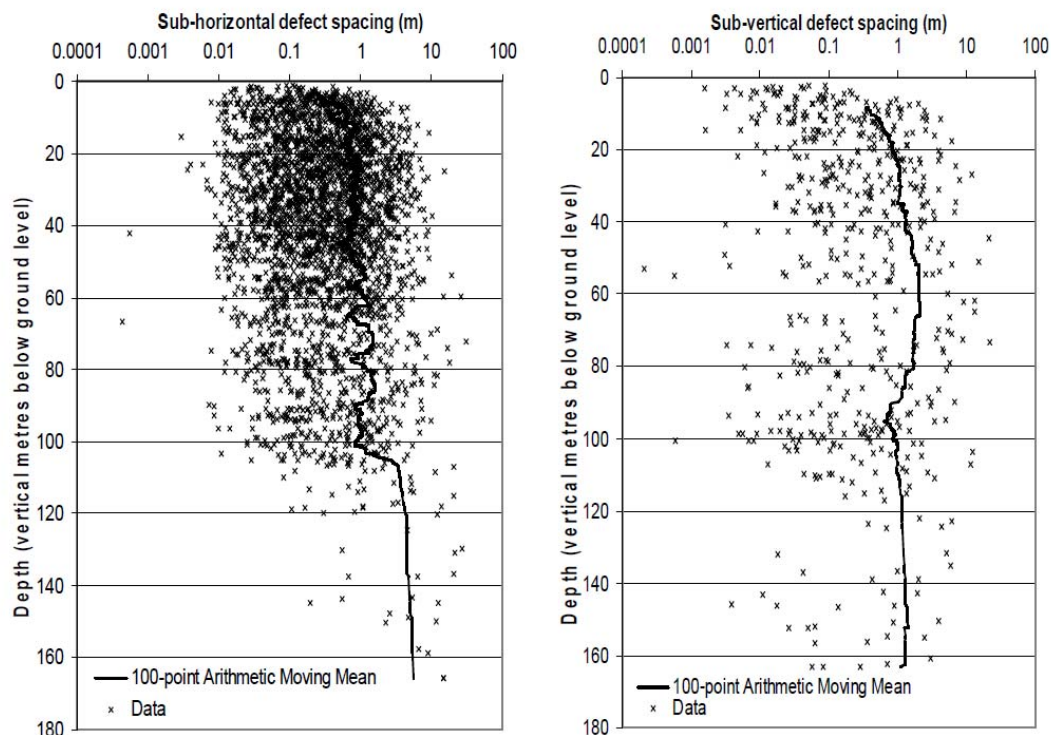


Figure 3.2: Fractures and bedding plane joints (defects) in the Hawkesbury Sandstone (De Castro et al., 2009; used with permission).

Each basin will have fractures and faults with different orientations and spacing, but all the sedimentary rocks throughout NSW will be fractured to some degree. Considerable work is required to understand if fracture networks would allow the movement of groundwater from the coal measures to adjacent aquifers in association with CSG development.

The presence of fractures makes it difficult to predict how rocks that overlie and underlie the coal measures will be affected by hydraulic fracturing, and it is commonly accepted that fracture propagation behaviour cannot be precisely predicted in detail (Davies et al., 2012). There is a tendency for fractures to occur in clusters, which can result in hydraulically connected “pipes” that may extend vertically for hundreds of metres. Davies et al. (2012) analysed 1170 pipes (all internationally available data sets of both natural and hydraulically stimulated fracture networks). The largest naturally occurring vertically connected pipe recorded is 1106 m, but there is only a 10% probability of a natural pipe extending greater than 550 m. Based on micro-seismic measurements the maximum upwards propagation recorded in the Marcellus Shale (USA) is 536 m, but 80% of the recorded events have an

upwards propagation of less than 200 m. The results of Davies et al. (2012) are for conventional and shale gas production, and if hydraulic fracturing is used for CSG production the pressures used to hydraulically stimulate the coal seams are likely to be less.

The authors could not locate any public domain data sets in NSW to perform a similar analysis. The work by Davies et al. (2012) further demonstrates the value of micro-seismic monitoring for providing field based information on potential connectivity between the zones of production and overlying strata.

It is critical to appreciate the important role that fracture networks play in transferring water and pressure through the Earth. Although different geological formations will have different fracture densities and orientations, provided the fractures in each formation intersect there is at least some potential for fluid and pressure transmission via the fractures.

3.3. Hydraulic Conductivity and Permeability

The hydraulic conductivity (K) is the specific discharge per unit hydraulic gradient (Bear, 2007). Its value depends on both the matrix (grain/pore size distribution, grain/pore shape, tortuosity, specific surface, and porosity (θ)) and fluid properties (density (ρ) and viscosity (μ)). The groundwater community uses the term hydraulic conductivity, while the oil and gas sector use a related term called intrinsic permeability (k). Hydraulic conductivity is related to intrinsic permeability, commonly just called permeability, via:

$$K = \frac{k\rho g}{\mu},$$

where g is gravity. Typical values of hydraulic conductivity and permeability for a range of geological materials are presented in Figure 3.3. This figure highlights that, where claystone or shale layers are not fractured or faulted, there will be little or no transfer of fluids between underlying and overlying layers.

It is well established that the larger the representative elementary volume of the Earth being measured, the greater the hydraulic conductivity (Person et al., 1996; Renard et al., 2006). Measurements of the hydraulic conductivity of rock cores from boreholes cannot be easily up-scaled to the values that can be used in flow simulations with cell sizes of 100 m or greater (Burns et al., 2010). The effect of the scale of the measurement on the measured hydraulic conductivity is highlighted in Figure 3.4.

As a general rule, permeability decreases with depth. This is highlighted in Figure 3.5 for the collated Hawkesbury Sandstone and Narrabeen Group permeability values derived from packer tests in the Sydney Basin (Tammetta and Hawkes, 2009). The reduction observed with depth is due to the increasing vertical and horizontal stresses, which reduce the aperture size of the fractures and bedding plane defects.

Faults can be either conduits of fluid movement or barriers. The permeability of the material in the fault zones depends on the burial and strain history (Jolley et al., 2007). Although often represented as a plane, faults are typically zones of deformed rock with a complex internal structure and three-dimensional geometry (Wibberley et al., 2008). For faults to act as seals the coal measures must be juxtaposed against sealing lithologies across the fault, or coal measure to coal measure juxtapositions at the fault-zone must be characterised by sealing fault-rock with a high capillary threshold pressure, and the stress conditions on the fault must not promote flow up the fault plane (Wibberley et al., 2008).

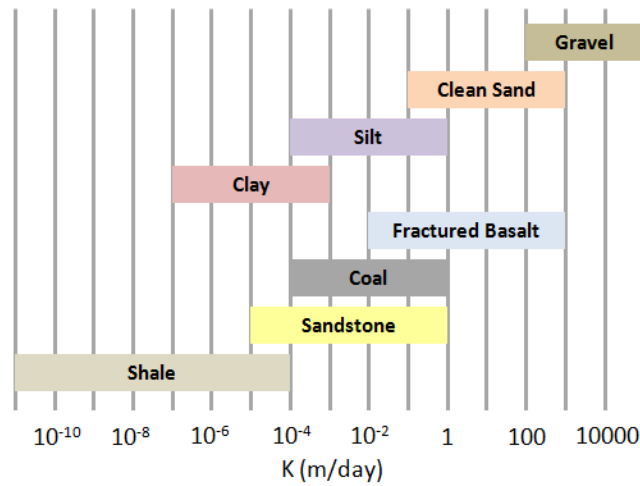


Figure 3.3: The range of values for hydraulic conductivity and permeability for a variety of geological materials (modified from Fitts, 2013).

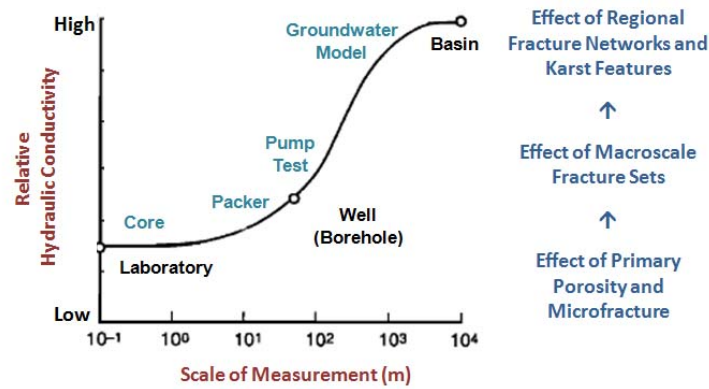


Figure 3.4: Schematic of the effect of scale of measurement on hydraulic conductivity of earth materials (adapted from Person et al., 1996).

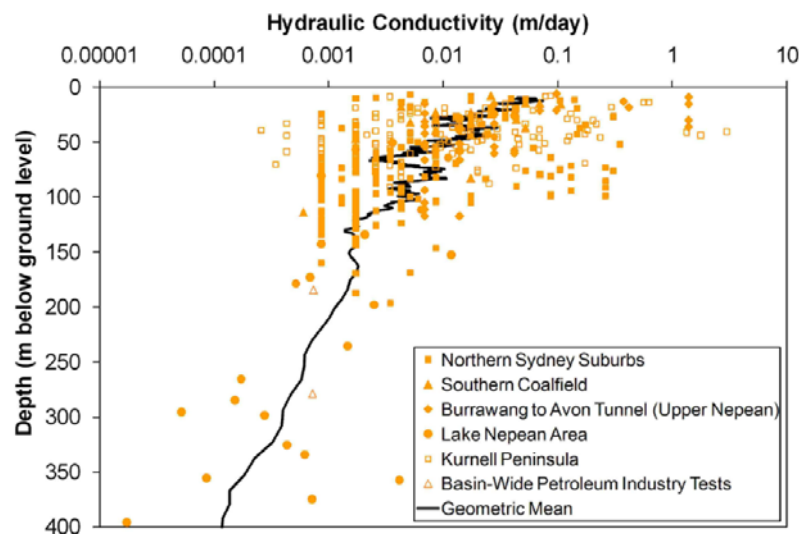


Figure 3.5: Calculated hydraulic conductivity from packer tests within the Hawkesbury Sandstone and Narrabeen Group (Tammetta and Hawkes, 2009; used with permission).

3.4. Relative and Time-varying Permeability

The presence of two or more fluids (e.g. water and gas) reduces the permeability of each fluid compared to a porous medium that only contains one fluid. For example, gas inhibits the flow of water by reducing the interconnected pore volume. If a rock is 100% saturated with water the relative permeability (k_{rw}) equals 1.0. As the pore water is displaced by gas, k_{rw} decreases, while the relative permeability of the gas (k_{rg}) increases. This relationship is highlighted in Figure 3.5. In some geological materials it is not possible to remove all the water or gas (Bear, 2007). For example there may be a layer of water bound to the surface of the grains. This is indicated by the dashed vertical lines in Figure 3.5.

Relative permeability needs to be taken into consideration when modelling the migration of gas and water through the host rock surrounding a coal seam. There are many software applications that have this capability.

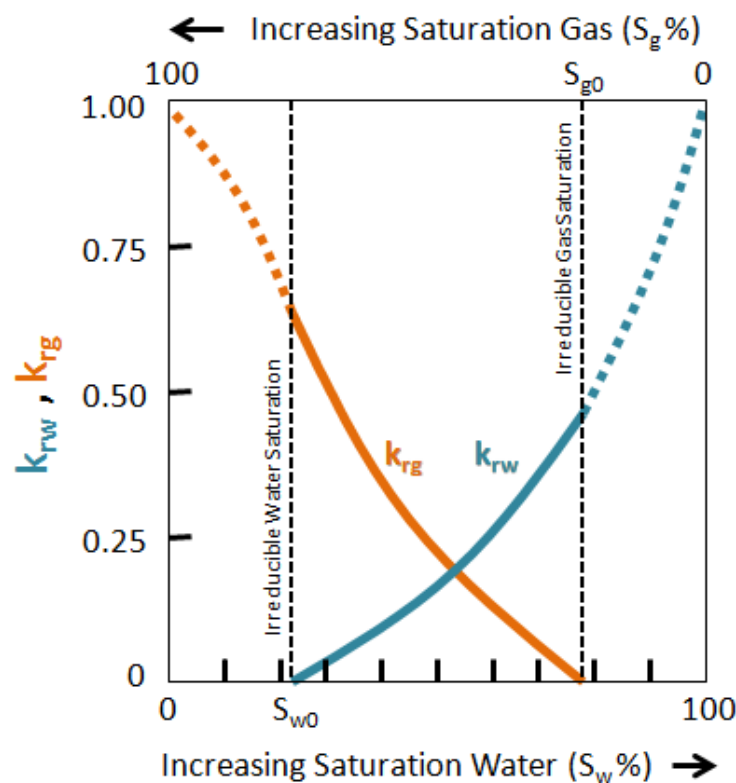


Figure 3.5. Schematic relative permeability curves for a porous rock containing water and gas (adapted from Bear, 2007).

In the initial stage of methane extraction from coal the permeability of the coal increases as the process of gas desorption causes the coal matrix to shrink (Morad, 2012; Chen et al., 2013; Liu and Harpalani, 2013). As the reservoir pore fluid pressure declines over the lifetime of production, the matrix compresses and reduces the cleat aperture width, which reduces the permeability. The relative proportion of gas and water flowing through the interconnected cleats and pores changes over time, thus the relative permeability of each phase varies with time. These coupled processes affect the flow rates of gas and methane in the production well (Figure 3.6). They are described in more detail by Chen et al. (2010) and Morad (2012). A number of dynamic stress, strain and permeability models have been developed to predict production induced changes in coal permeability. These models are reviewed by Chen et al. (2010), Connell et al. (2010), Chen et al. (2013) and Liu and Harpalani (2013).

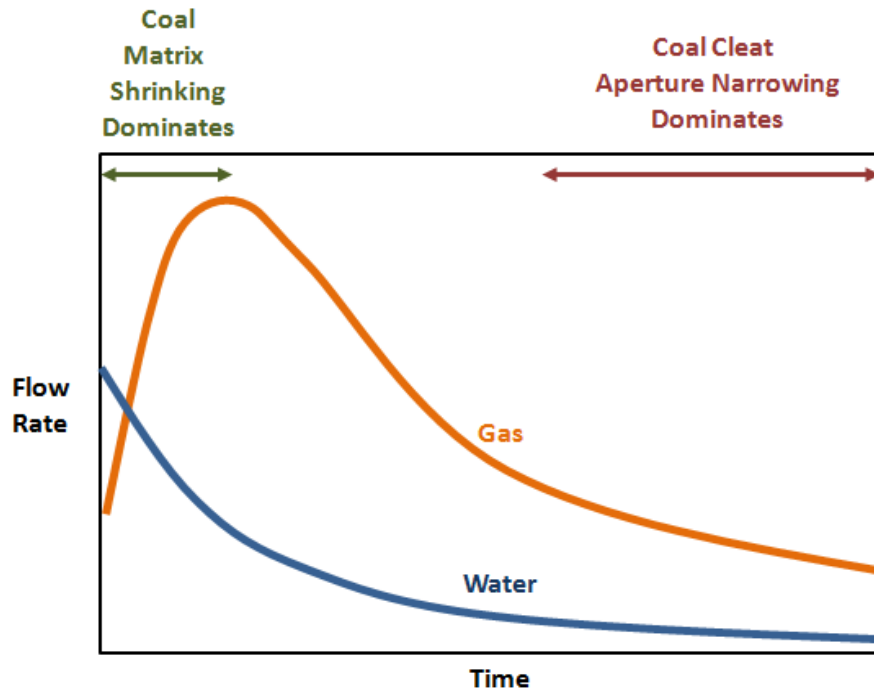


Figure 3.6: Coal bed methane well production life cycle for water and gas flow rates (adapted from Chen et al., 2010).

3.5. Subsidence

In some places where there has been extensive extraction of groundwater, oil or gas subsidence has been observed at the ground surface. Well known examples include the Groningen gas field in the Netherlands (Fokker and Orlic, 2006), the San Joaquin Valley in California, caused by extracting groundwater for irrigation, and Mexico City, caused by extracting water for urban and industrial use (Bear, 1979). Subsidence has already occurred in portions of NSW alluvial aquifers used of irrigation, for example in the lower Namoi (Ross and Jeffery, 1990).

A reduction in pore water pressure due to pumping results in deformation of the sediment matrix. Prior to any groundwater or gas extraction from the rocks, at all depths in the Earth the total load of the sediment, rock and water above a given layer within the Earth are balanced by the grain matrix stress (effective stress) and pore fluid pressure. When the water and gas are extracted via the production well, there is a reduction in the pore fluid pressure, and there is an increase in the load borne by the grain matrix. The increase in load causes the sedimentary matrix to compress, which can cause subsidence, fissures, or faulting (Fitts, 2013). The grains can be considered incompressible, thus the compression results from a reduction in the void spaces. Each sedimentary material compresses a different amount for a given change in effective stress (Table 3.1).

Table 3.1: Representative values of compressibility (Fitts 2013).

Sedimentary Material	Compressibility (m^2 / N)
Soft Clay	3×10^{-7} to 2×10^{-6}
Stiff Clay	7×10^{-8} to 3×10^{-7}
Loose Sand	5×10^{-8} to 1×10^{-7}
Dense Sand	5×10^{-9} to 2×10^{-8}
Fractured Rock	3×10^{-10} to 7×10^{-9}

The rate at which water is withdrawn or expelled from an Earth material depends on its hydraulic conductivity. For sands and gravels compression is rapid. However for clays, silts, shales and claystones there is a noticeable time lag between changes in the stress and corresponding drainage. This time dependent drainage and compaction is called consolidation (Fitts, 2013). The consolidation of the sedimentary material can result in the expulsion of water, which results in an increase in extracted water along with the gas (Ransom, 2010).

Subsidence caused by coal seam gas production is unique to each location. To date in NSW the scale of coal seam gas production is small compared to Queensland and other CSG-producing areas around the world (there are 95 coal seam gas producing boreholes in the Camden field; AGL, 2013b). Any subsidence associated with this small extent of production is unlikely to be detectable. In the Powder River Basin, Wyoming, USA, there are over 20,000 boreholes producing gas (Swindell, 2007). Under those circumstances Grigg et al. (2012) measured up to 6 cm of subsidence associated with a decade of coal seam gas production in the region of highest gas production in the Powder River Basin. Subsidence of this order of magnitude can alter near surface flow paths, and the gradient of the water table (Budhu and Adiyaman, 2013).

4. Geology of NSW Coal Basins

4.1. Nature and Origin of Sedimentary Basins

A sedimentary basin is an area of the Earth's crust in which subsidence in conjunction with deposition has allowed accumulation of sediments to a significantly greater thickness than the sediments of the same age in the surrounding areas. The subsidence is generally driven by tectonic processes, although the weight of the accumulating sediment pressing on the underlying basement may also play a part.

A number of different sedimentary basin types can be identified, depending mainly on their relation to the different processes of plate tectonics (e.g. Miall, 1984; Reading, 1986; Boggs, 2011). Only a few of these types, however, are represented in the coal-bearing sedimentary basins of New South Wales.

Intracratonic basins: Broad but relatively shallow areas of subsidence within an area of otherwise stable crustal material (or craton).

Rift basins: Long, narrow areas of often substantial subsidence developed over down-faulted blocks or rifts in the basement material. These typically form in association with crustal extension by tectonic processes.

Foreland basins: Linear areas of subsidence developed between a newly-emergent compressed orogenic zone on one side and a stable block of continental crust (or craton) on the other. These are typically formed on otherwise stable continental crust by loading by thrust sheets driven toward the continental interior as a result of compression and crustal shortening in a subduction zone.

4.2. Coal-bearing Sedimentary Basins in New South Wales

Over 60% of the land area in New South Wales is covered by sedimentary basins (Figure 4.1). From the perspective of coal and coal seam gas resources the most important of these basins are:

- The Sydney-Gunnedah-Bowen Basin system, of Permian to Triassic age;
- The Gloucester Basin, also of Permian age;
- The Clarence-Moreton Basin, of Triassic to Cretaceous age.

Other basins that contain potential coal and coal seam gas resources include the Oaklands Basin, with low-rank Permian coal, and the Surat and Eromanga Basins, containing Jurassic to Cretaceous strata including some coal seams. A small wedge-shaped body of Permian coal-bearing strata also occurs at Ashford, within the New England Fold Belt.

The Sydney-Gunnedah Bowen Basin is a north-south oriented belt of Permian and Triassic strata extending over 1,700 km from near Batemans Bay on the south coast of NSW to a point near Collinsville in northern Queensland. The basin originally developed as a rift basin with extensional tectonics in the early Permian, but became a foreland basin later in the Permian, due to thrusting from the orogen of the New England Fold Belt and associated tectonic features in the east against the older and more stable craton of the Lachlan Fold Belt in the west (Tadros, 1993, 1995a; Mallett et al., 1995).

The NSW portion of this basin complex contains up to 9,000 metres of sedimentary and volcanic strata, ranging in age from Early Permian to Middle Triassic. These beds are separated from the New England Fold Belt on the eastern side by a series of major thrust

faults (Hunter and Mooki Thrusts), and rest with an angular unconformity on the Lachlan Fold Belt along the western side. The overall sequence is thicker in the eastern part of the basin than in the west (Tadros, 1995a), reflecting greater subsidence associated with loading of the basement from overthrust of the orogenic block on the eastern side.

Because they are parts of a continuous geological feature, the boundaries between the Sydney, Gunnedah and Bowen Basins are essentially arbitrary. Although some authors (e.g. Tadros, 1993, 1995a) regard the Mount Coricudgy Anticline, NW of Muswellbrook, as marking the boundary between the Sydney Basin and the Gunnedah Basin, other studies, such as Stewart and Alder (1995) and Brown et al. (1996), have taken the line of the Liverpool Range, which is made up of Tertiary basalts covering the Permo-Triassic strata, to represent the boundary between the Sydney and Gunnedah Basins. An anticlinal feature north of Narrabri, the Moree High (Tadros, 1995a), is generally taken as the boundary between the Gunnedah and the Bowen Basins.

For convenience in describing their coal (and CSG) geology, the Sydney and Gunnedah Basins have been divided by the Coalfield Geology Council of NSW into a number of different coalfield areas (Figure 4.2). These are the Newcastle Coalfield, covering the area mainly between Lake Macquarie and Cessnock, the Hunter Coalfield, covering mainly the Singleton-Muswellbrook area, the Southern Coalfield, covering the area from the Illawarra to the Southern Highlands and the Burratorang Valley, the Western Coalfield, essentially covering the area between Lithgow and Ulan, and the Gunnedah Coalfield, covering the area north of the Liverpool Range.

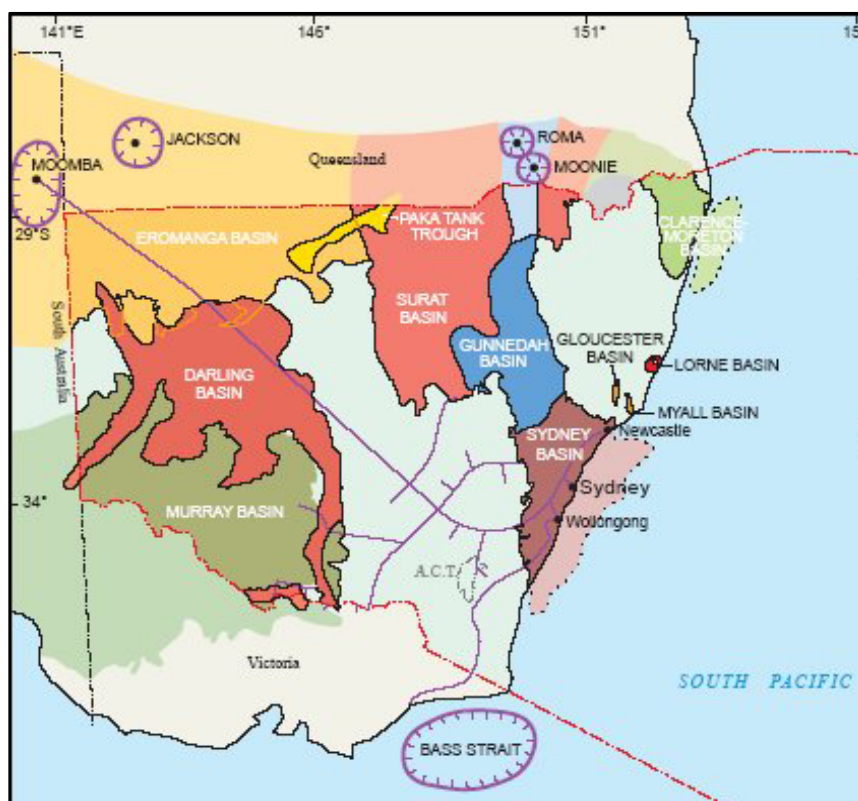


Figure 4.1: Location of sedimentary basins in New South Wales (Geological Survey of NSW, <http://www.resources.nsw.gov.au/resources/petroleum/map> accessed 20/06/2013). Producing petroleum fields (outside NSW) are circled; gas pipelines are also shown.



Figure 4.2: Location of coalfield areas in the Sydney and Gunnedah Basins (Coalfield Geology Council of NSW: <http://www.resources.nsw.gov.au/resources/coal/coalfields> accessed 20/06/2013)

4.3. Energy Resources of NSW Basins

4.3.1 Coal Resources

The economic demonstrated resources (EDR) of higher-rank (black) coal in Australia, covering the range from sub-bituminous coal to semi-anthracite, are estimated at 39,200 Mt (Geoscience Australia and ABARE, 2010). These are assessed as having a total energy content of 883,400 PJ. However, only 13,400 Mt of the Australian total EDR is regarded as “reserves”, based on the standards set by the Joint Ore Reserves Committee (JORC).

Approximately 40% of the EDR are located in New South Wales, mostly within the Sydney and Gunnedah Basins. Estimates by the NSW Department of Trade and Investment (2011) indicate that the recoverable coal reserves and/or resources in the state exceed 12,000 Mt (Table 4.1). These are contained within 62 operating mines and colliery holdings, and areas covered by more than 30 major development proposals.

The principal coal resources in NSW are of bituminous rank, with almost all occurring in the different coalfield areas of the Sydney-Gunnedah Basin (Table 3.1). Over 50% of the state’s

total reserves and/or resources occur in the Hunter Coalfield. A significant resource of sub-bituminous coal has also been identified in the Oaklands Basin, near Jerilderie, but this has not yet been developed. The bituminous resources range from medium- to high-ash, low-sulphur coals that are used for domestic power generation and cement manufacture to low- to medium-ash, high-energy, export-quality thermal coals. Low-volatile, hard coking coals and low-ash, higher-volatile semi-soft coking coals are also mined for both export and domestic markets. Summaries of coal quality and mining infrastructure are given by ACARP (2010) and the NSW Department of Trade and Investment (2011).

Table 4.1: Coal resources and production in NSW (NSW Department of Trade and Investment, 2011)

Coalfield	Reserves and/or in-situ Resources	Raw Coal Production (2008-2009)	Saleable Coal Production (2008-2009)
Hunter	6,832.5	116.85	81.74
Newcastle	463.9	17.57	15.10
Southern	541.5	12.70	10.27
Western	1,769.6	27.32	24.79
Gunnedah	1,270.9	4.99	4.80
Gloucester	45.3	2.56	1.74
Oaklands	1,280.0		
Total	12,203.7	181.99	138.44

Total raw coal production for NSW in 2009-10 was 188.79 Mt, of which 145.37 Mt was saleable. Of the raw production, 62.80 Mt was from underground mines and 125.99 Mt from open-cut mines. Usage by domestic (NSW) power stations was 28.54 Mt, with a further 4.55 Mt being used by the domestic iron and steel industry and 0.94 Mt for other purposes. A total of 81.08 Mt of thermal coal and 28.83 Mt of metallurgical (coking) coal was exported.

Both the coal resources and the rates of coal production are dynamic figures, depending for example on the results of continuing exploration, advances in mining and utilisation technology, availability of markets and transport infrastructure, and possibly changes in regulatory environments. The life of NSW coal resources is therefore difficult to estimate, but dividing the currently known reserves by the current raw production rate is probably inappropriate in such a dynamic setting. Taking into account possible future additions to recoverable reserves, combined with projected changes in production rates, a recent modelling study by Mohr et al. (2011) has suggested that NSW coal production may peak between 2070 and 2080, with production then being much higher than it is at present.

4.3.2. Conventional Petroleum Resources

Petroleum embraces both liquid and gaseous hydrocarbons, as well as natural accumulations of solid hydrocarbon materials such as tar sands. The hydrocarbons that make up “conventional” petroleum resources are generated from (often dispersed) organic matter in a source rock by processes such as thermal maturation (equivalent to rank advance), migrate from the source rock through the pores and/or fractures of overlying strata, and build up in the pores of a reservoir rock under favourable geometric conditions (a trap structure) behind an impermeable natural barrier or seal. The body of hydrocarbons generated from a particular pod of source rock, and accumulated in associated reservoirs and traps, is described as a petroleum system (Geoscience Australia and BREE, 2012).

Although some potential exists, exploration activities to date have shown that New South Wales has very limited conventional hydrocarbon resources. The potential for such accumulations in the different sedimentary basins of the state is reviewed by Stewart and Alder (1995), with more complete data on the Gunnedah Basin given by Hamilton et al. (1993) and on the Clarence-Moreton Basin by Ingram and Robinson (1996).

Small quantities of oil have been reported in the Gunnedah and Bowen Basins, for example in Permian strata of the Willaroo-1 well near the Queensland border (Anon, 2010). No commercial accumulations, however, have so far been identified.

In addition to coal seam gas, which is discussed separately elsewhere in this background paper, small deposits of conventional natural gas have been identified in the Gunnedah and Clarence-Moreton Basins. These include the Wilga Park and Coonarah deposits in the Gunnedah Basin SW of Narrabri (Hamilton et al., 1993; Stewart and Alder, 1995; Pratt, 1998). Significant thicknesses of gas-bearing sandstone are also reported in the central part of the Clarence-Moreton Basin (Ingram and Robinson, 1996; Metgasco, 2012).

5. Sydney Basin

The Sydney Basin extends for approximately 350 km north-south and an average of 60 km east-west, from near Batemans Bay on the South Coast to near Port Stephens north of Newcastle, westward through the Burrigorang Valley, Lithgow and Ulan, and then north-east to Muswellbrook in the Upper Hunter Valley. It occupies an area of approximately 44,000 km² onshore, centred on the city of Sydney, and an additional 5,000 km² between the coastline and the outer edge of the continental shelf (Stewart and Alder, 1995). The broad structural framework of the basin and details of its tectonic evolution are summarised in an overview of its petroleum reservoir characteristics by Blevin et al. (2007).

Within this area the stratigraphic sequence varies from region to region (Figure 5.1), partly because of the pattern of sedimentation and partly because of breaks in continuity of access for mapping of the different areas involved. In broad terms the lower part of the sequence is mainly represented by sedimentary strata deposited in a series of marine environments, partly influenced by glacial conditions. Some volcanic rocks also occur in different parts of this succession. The marine strata are interbedded, especially in north of the basin, with locally-developed coal-bearing sequences of Early Permian age, and those coal measures are in turn overlain by additional marine deposits.

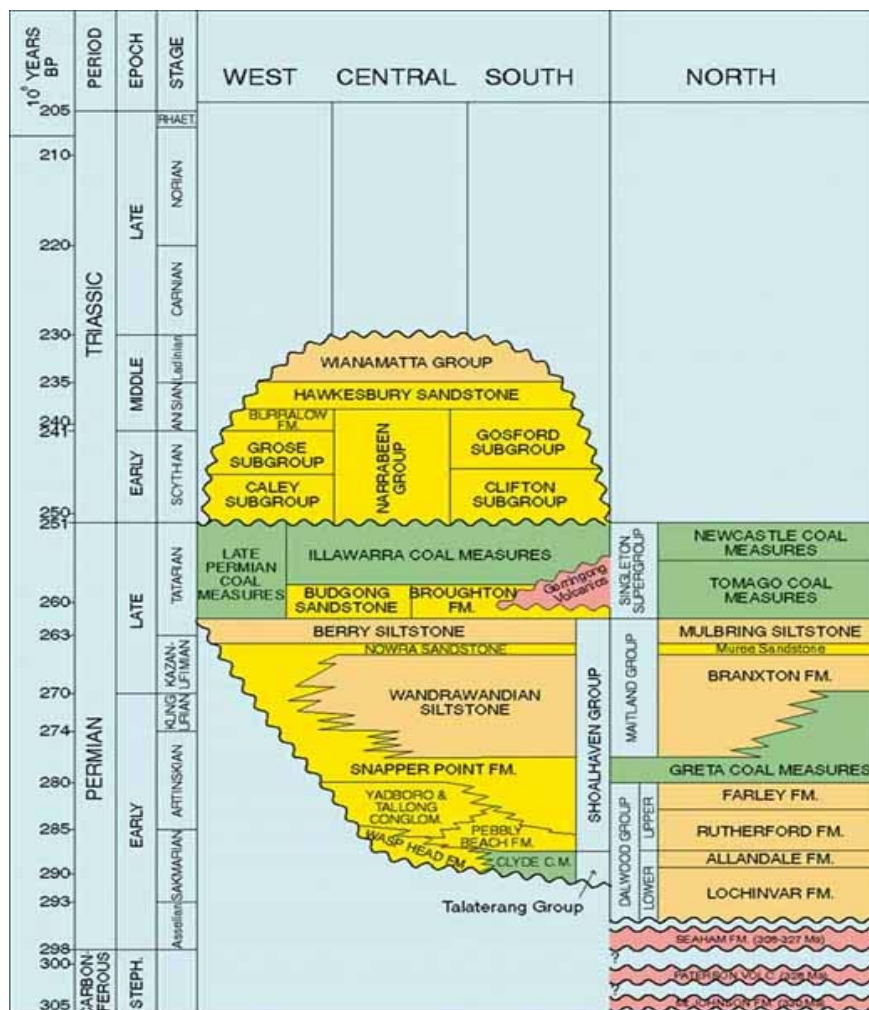


Figure 5.1: Broad-scale stratigraphy of the Sydney Basin (NSW Trade and Investment: <http://www.resources.nsw.gov.au/geological/overview/regional/sedimentary-basins/sydbasin> accessed 23/05/2013) Key: FM = Formation; CM = Coal Measures

Extensive coal-bearing sequences of Late Permian age overlie these marine strata, formed in more terrestrial environments and covering the whole of the basin. These have different stratigraphic names in different areas, and are discussed more fully below. As might be expected, these units contain the most significant coal and coal seam gas resources.

Above the Late Permian coal measures is a succession of terrestrial strata, referred to throughout the basin as the Narrabeen Group, the Hawkesbury Sandstone and the Wianamatta Group. These are regarded for convenience as being of Early to Middle Triassic age, although some of the lower beds in the sequence may in fact have been deposited during the latter part of the Permian Period. The Permo-Triassic sedimentary succession is intruded in places by igneous bodies, ranging from Jurassic and Cretaceous to Tertiary in age, and overlain in places by unconsolidated Tertiary to Quaternary river deposits and coastal sediments.

5.1. Stratigraphy of the Northern Sydney Basin

5.1.1. Early Permian Marine and Coal-bearing Strata

The lowermost beds in the northern part of the basin are a sequence of mainly marine sediments referred to as the Dalwood Group. This unit is further subdivided into the Lochinvar, Allandale, Rutherford and Farley Formations. In the area around Muswellbrook, however, the stratigraphically-equivalent interval is mainly made up of basaltic material and is referred to as the Gyarran Volcanics.

Overlying the Dalwood Group is the Early Permian coal-bearing sequence of the Greta Coal Measures. This unit is exposed on the flanks of two major anticlinal structures, the Lochinvar Anticline near Cessnock and the Muswellbrook Anticline in the Muswellbrook area. It also occurs in the Cranky Corner Basin, a small outlier of Permian strata within the New England Fold Belt north of the Hunter Thrust. The sequence is subdivided into different formations in each of these areas (Basden, 1969; Hamilton, 1986; van Heeswijk, 2001), with the principal coal beds being the Greta seam in the Cessnock-Maitland district, the Balmoral seam on the Muswellbrook Anticline and the Tanguorin seam in the Cranky Corner Basin. The Greta Coal Measures also occur in the subsurface throughout much of the Hunter Coalfield; however, they generally lie at depths greater than 600 m, and geological information on the sequence in that area is limited.

The Greta Coal Measures are overlain in the Hunter and Newcastle Coalfields by the Maitland Group, a succession of mainly shaly strata formed under marine conditions. Three different formations are included in this sequence, the Branxton Formation at the base, the Muree Sandstone in the middle and the Mulbring Siltstone at the top.

5.1.2. Late Permian Coal-bearing Units, Newcastle Coalfield

Above the Maitland Group is an extensive succession of Late Permian coal-bearing sediments, formed mainly by alluvial fans, deltas and river systems flowing into the basin from the New England Fold Belt, combined at different times with input of sediment from contemporaneous volcanic activity (Diessel, 1992; Agnew et al., 1995; Sniffin and Beckett, 1995). In the Newcastle Coalfield this sequence is divided into two major rock units, the Tomago Coal Measures in the lower part of the succession and the Newcastle Coal Measures in the upper part.

The Tomago Coal Measures are a total of around 600 m in thickness where they are exposed in the area south-east of Maitland and >1,200 m thick in the subsurface, beneath unconsolidated Quaternary sediments, in the area north of the Hunter River around Williamtown (Agnew et al., 1995). The sequence consists of mainly of sandstones, shales

and coal seams, and represents a transition between the marine environments that formed the Maitland Group and the more dominant terrestrial environments that formed the overlying Newcastle Coal Measures (Agnew et al., 1995). It is divided into three units, the Wallis Creek Subgroup at the base, the Four Mile Creek Subgroup in the middle and the Hexham Subgroup at the top (Hawley and Brunton, 1995). A marine interval referred to as the Kulnura Marine Tongue also occurs within the succession in the southern part of the coalfield.

The Four Mile Creek Subgroup is the main coal-bearing interval, and includes the Big Ben, Donaldsons and Buttai seams. The Rathluba seam, another locally important coal bed, occurs within the Wallis Creek Subgroup. A shaly unit, the Dempsey Formation, occurs near the top of the unit within the Hexham Subgroup.

The Newcastle Coal Measures are exposed along the coast between Newcastle and Catherine Hill Bay, and extend under Lake Macquarie towards the west. The basal formation of the unit is the Waratah Sandstone, which forms a marker bed to separate the Newcastle Coal Measures from the underlying Tomago sequence. Above the Waratah Sandstone the Newcastle Coal Measures are divided into four sub-groups, with the Lambton Subgroup at the base, the Adamstown and Boolaroo Subgroups in the middle and the Moon Island Beach Subgroup at the top of the succession (Agnew et al., 1995; Hawley and Brunton, 1995). As well as sandstones, shales, coal beds and tuff horizons, several thick conglomerate units occur in the Newcastle Coal Measures, especially within the upper part of the sequence.

Coal seams are more abundant and economically significant in the Newcastle Coal Measures than in the underlying Tomago Coal Measures. The most important seams from a mining perspective occur in the Lambton Subgroup (e.g. Borehole, Yard, Dudley and Victoria Tunnel seams) and the Moon Island Beach Subgroup (e.g. Fassifern, Great Northern and Wallarah seams). The coals in the Lambton Subgroup tend to be vitrinite-rich and are commonly mined as coking coals, whereas the coals in the Moon Island Beach Subgroup tend to be inertinite-rich and are used mainly for combustion purposes (Warbrooke, 1987; Diessel, 1992).

5.1.3. Late Permian Coal-bearing Units, Hunter Coalfield

The equivalent succession in the Hunter Coalfield was originally divided into a lower portion referred to as the Wittingham Coal Measures and an upper portion referred to as the Wollombi Coal Measures (e.g. Beckett, 1988; Sniffin and Beckett, 1995). The two units together were also referred to as the Singleton Supergroup. However, more recent correlations (Creech, 2002) have shown that the Wollombi Coal Measures are stratigraphically equivalent to the Newcastle Coal Measures, and the term Newcastle Coal Measures is now used to describe this part of the section in the Hunter Coalfield, as well as in the Newcastle area. The Wittingham Coal Measures contain the bulk of the coal resources; the Newcastle Coal Measures in the Hunter Coalfield contain seams that are mostly of more limited economic significance.

The lower part of the Wittingham Coal Measures is a sandstone-rich interval referred to as the Saltwater Creek Formation. This is overlain by the Vane Subgroup, the Archerfield Sandstone and the Jerrys Plains Subgroup, with a shaly interval referred to as the Denman Formation at the top of the Wittingham succession. The lower part of the Vane Subgroup, the Foybrook Formation, contains up to six economically-important coal seams (e.g. Liddell, Arties and Pikes Gully seams), interbedded with siltstone, lithic sandstone and conglomerate (Sniffin and Beckett, 1995). The upper part of the Vane Subgroup, the Bulga Formation, consists mainly of burrowed siltstones, which grade upwards to the widespread massive beds of the overlying Archerfield Sandstone.

The Jerrys Plains Subgroup is an interval of lithic sandstones, shales and conglomerates, with several extensive claystone (tuff) horizons and numerous coal seams. The coals include the thick, extensive and inertinite-rich Bayswater seam near the base of the succession, as well as the Vaux, Piercefield, Mount Arthur, Arrowfield, Glen Munro, Blakefield and Whybrow seams. These and the other seams in the Wittingham Coal Measures are mined, mainly from open-cut operations, in the area between Singleton and Muswellbrook, and extending south towards Warkworth and Broke.

The base of the Newcastle (formerly Wollombi) Coal Measures in the Hunter Coalfield is the Watts Sandstone, which is overlain by a sequence, subdivided into four subgroups, with numerous thin coal seams (Sniffin and Beckett, 1995). Recent studies, however, have shown that several of the upper seams from the Newcastle Coalfield continue into this part of the basin (Creech, 2002), with mineable coal resources being present, for example, in the Anvil Hill area west of Muswellbrook.

5.1.4. *Triassic Strata*

The Triassic strata that overlie the Late Permian coal measures in the northern Sydney Basin are mainly represented by a thick sequence of Narrabeen Group strata, overlain in the south by the Hawkesbury Sandstone. These units crop out in the elevated plateau areas south of the Hunter Valley, and extend to the Central Coast area around Gosford and Wyong.

In the south of the Newcastle Coalfield the lowermost unit of the Narrabeen Group is the Dooralong Shale (Uren, 1974, 1980; Hawley and Brunton, 1995), with up to 200 m of interbedded siltstone and claystone, and fine to coarse grained sandstone. This is overlain by, and partly time-equivalent to, the Munmorah Conglomerate, up to 140 m thick, which consists mainly of sandstone, pebbly sandstone and conglomerate, with minor siltstone and claystone. The Munmorah Conglomerate is in turn overlain by the Tuggerah Formation, a sequence up to 280 m thick made up of medium to coarse sandstone with interbedded shaly sediments, and then by the Patonga Claystone, a red-brown sequence of siltstone and claystone up to 167 m in thickness.

The top of the Narrabeen Group in the Central Coast area is the Terrigal Formation, which consists of interbedded fine to medium grained sandstone and siltstone with minor claystone (McDonnell, 1980; Hawley and Brunton, 1995). This is overlain, in topographically high areas of the coalfield, by the quartzose sandstones and minor siltstones of the Hawkesbury Sandstone (Standard, 1969), the outcrop of which extends further south towards Sydney.

Details of the Triassic stratigraphy in the Hunter Coalfield are poorly known. However, the Mt Murwin No 1 petroleum well, located in elevated country some 40 km SW of Singleton, encountered more than 750 m of Triassic strata above the Late Permian (Newcastle) coal measures. Except for the topmost 80 m, which was correlated with the Hawkesbury Sandstone, most of this was sandstone and conglomerate, with red-brown shale beds up to 15 m thick, ascribed to the Narrabeen Group (Stuntz and Wright, 1963).

5.2. Stratigraphy of the Southern and Western Sydney Basin

5.2.1. *Early Permian Marine and Coal-bearing Strata*

The lowermost strata in the southern part of the Sydney Basin, immediately overlying the basement rocks, are a complex of marine and coal-bearing units referred to as the Talaterang Group (Tye et al., 1996; Moffitt, 2000). These beds include the shoreline and marine shelf sediments of the Wasp Head and overlying Pebbly Beach Formations (Figure

5.1), the mainly fluvial Yadboro and Tallong Conglomerates, and the locally developed coal-bearing sediments of the Clyde Coal Measures and the Yarrunga Coal Measures.

Overlying that sequence is a more extensive succession of marine strata referred to as the Shoalhaven Group, which extends throughout both the Southern and Western Coalfields. In the Southern Coalfield this includes sandy beds of the Snapper Point Formation and the Nowra Sandstone, and shaly sequences of the Wandrawandian and Berry Siltstones. At the top of the Shoalhaven Group, exposed in the area around Gerringong and Kiama, is an interbedded sequence of marine sandstones and basaltic (latite) lava flows, stratigraphically identified as the Broughton Formation (Moffitt, 2000), but also known as the Gerringong Volcanics (Carr, 1983).

In the Western Coalfield the lower part of the Shoalhaven Group is represented by a pebbly interval, previously referred to as the Megalong Conglomerate (Goldbery, 1969) but more recently correlated with the Snapper Point Formation (Yoo et al., 1995). This is then overlain by the Berry Siltstone.

5.2.2. Late Permian Coal-bearing Units

The Late Permian coal-bearing strata of the Southern and Western Coalfields are identified as the Illawarra Coal Measures. Different stratigraphic subdivisions, however, are applied in each of these two coalfield areas. The Illawarra Coal Measures also extend under the city of Sydney itself. They are broadly equivalent to the Tomago and Newcastle Coal Measures of the Newcastle Coalfield, and to the Wittingham and Newcastle (or Wollombi) Coal Measures in the Hunter Coalfield (Yoo et al., 1995).

The strata making up the Illawarra Coal Measures are sandstone, siltstone, claystone and coal, with minor tuffaceous and conglomeratic material. The unit reaches a maximum thickness of around 520 m in the northern part of the Southern Coalfield (Hutton and Wootton, 2009), but thins to less than 100 m near Yerrinbool in the southwest (Bunny, 1972). The lower part of the sequence in the Southern Coalfield, the Cumberland Subgroup, is partly marine and relatively coal-barren, and includes several thin basaltic lava flows (Carr, 1983; Moffitt, 2000).

Overlying this section is the main coal-bearing interval, the Sydney Subgroup. Detailed subdivisions of this interval are given by Armstrong et al. (1995), Moffitt (2000) and Hutton and Wootton (2009). Four significant coal seams are recognised, the Tongarra, Wongawilli, Balgownie and Bulli seams, along with several other named coal beds. These are mined from underground operations in the eastern and southwestern parts of the coalfield, and also contain significant coal seam gas resources.

In the Western Coalfield the Illawarra Coal Measures are subdivided into four main intervals: the Nile Subgroup, the Cullen Bullen Subgroup, the Charbon Subgroup and the Wallerawang Subgroup (Bembrick, 1983). The unit ranges in thickness from 50 m near Ulan to approximately 900 m at Wisemans Ferry (Yoo et al., 1995). The main coal seams are the Lithgow, Lidsdale and Ulan seams near the base of the unit and the Katoomba seam near the top. Other coal beds of more local economic potential are the Irondale and Middle River seams, in the middle to upper parts of the succession. Prominent beds of coarse-grained sedimentary rock, the Marrangaroo and Blackmans Flat Conglomerates, occur respectively below the Lithgow and Lidsdale seams.

5.2.3. Triassic Strata

The Triassic strata overlying the Illawarra Coal Measures are represented, in ascending order, by the Narrabeen Group, the Hawkesbury Sandstone and the Wianamatta Group. The

lower two units are exposed along the Illawarra Escarpment and the adjacent Woronora Plateau, as well as in the cliffs and plateaux of the Burragorang Valley, the Blue Mountains and the Lithgow-Ulan area. The Wianamatta Group is mainly exposed between the Picton area and the Cumberland Plain in the western part of Sydney.

The Narrabeen Group contains a wide range of sedimentary rock types, including conglomerates, lithic and quartzose sandstones, and red-brown, green and light to dark grey shales, siltstones and claystones. These were derived from areas with different geology to the north, east and west of the basin, and deposited by an evolving series of alluvial fans, rivers and deltaic systems during the early Triassic Period (Ward, 1972; Herbert, 1997). A summary of the different units within the sequence, and also an indication of the correlations between those units, is given in Figure 5.2.

Southern Coalfield	Western Coalfield		Newcastle Coalfield
Newport Formation	Burralow Formation		Terrigal Formation
Garie Formation	Grose Subgroup	Banks Wall Sandstone	
Bald Hill Claystone			
Bulgo Sandstone		Patonga Claystone	
		Mt York Claystone	Tuggerah Formation
Stanwell Park Claystone		Burra-Moko Head Sandstone	Munmorah Conglomerate
Scarborough Sandstone			
Wombarra Shale	Caley Formation		
Coal Cliff Sandstone			

Figure 5.2: Indicative correlation of Narrabeen Group strata in the Sydney Basin (after Ward, 1972, Hawley and Brunton, 1995, Yoo et al., 1995)

In the eastern part of the Southern Coalfield the Narrabeen Group is dominated by lithic sandstone sequences (Coal Cliff, Scarborough and Bulgo Sandstones), interbedded with shale and claystone units. These include the Stanwell Park Claystone, the Bald Hill Claystone and the Garie Formation, which have a distinctive low-quartz mineralogy and were probably derived from a source east of the present coastline (Ward, 1972). The Stanwell Park Claystone, however, becomes interbedded with sandy material and loses its identity in the subsurface near Campbelltown (Bunny, 1972), and the Scarborough and Bulgo Sandstones merge to form a more continuous succession. The sandstones also become more quartzose towards the west, due to blending of sediment from different sources as these units were deposited (Ward, 1972).

In the Western Coalfield the Narrabeen Group is dominated by the cliff-forming quartzose sandstones of the Grose Subgroup (Burra-Moko Head and Banks Wall Sandstones, plus the Mt York Claystone). This succession is underlain by a shaly interval, the Caley Formation, which is broadly equivalent to the Coal Cliff Sandstone and Wombarra Shale of the coastal area. A horizon within the Banks Wall Sandstone, the Wentworth Falls Claystone Member (Goldbery and Holland, 1973), has a similar composition to the Bald Hill Claystone and Garie Formation, and aids in the correlation of the sequence.

The Narrabeen Group reaches a thickness of more than 600 m under the city of Sydney (Emerson and Branagan, 2011), and the upper units, the Bald Hill Claystone and Newport Formation, are exposed in the Northern Beaches area. The Bald Hill Claystone thins out further to the north, and the Newport Formation and upper Bulgo Sandstone merge to become the Terrigal Formation in the southern part of the Newcastle Coalfield.

The Hawkesbury Sandstone is an extensive unit made up mainly of quartzose sandstones that underlies the city of Sydney and is exposed over much of the Woronora Plateau area. It appears to have been deposited mainly by a large-scale braided river system flowing from southwest to northeast across the basin (Standard, 1969; Conaghan, 1980; Rust and Jones, 1987; Miall and Jones, 2003). The unit has been informally divided into three separate intervals by Lee (2000), a lower sequence dominated by medium to coarse sandstones with relatively high porosity and permeability, a middle sequence of clayey sandstones, siltstones and shales with lower porosity and permeability, and an upper sequence of medium to coarse sandstones similar to the lower sequence.

The Wianamatta Group, at the top of the Triassic sequence, is a shaly succession that crops out over the central part of the Sydney Basin. It is separated from the Hawkesbury Sandstone by an interbedded sequence of sandstones and shales referred to as the Mittagong Formation (Herbert, 1979; Moffitt, 2000). The basal part of the unit is the Ashfield Shale, which consists mainly of dark grey sideritic siltstone and is typically 45 to 60 m thick. This is overlain by a persistent quartz-lithic sandstone unit, the Minchinbury Sandstone, which is typically around 6 m in thickness, and then by a thick but more locally distributed succession of claystones, siltstones and sandstones, with minor carbonaceous intervals towards the base, referred to as the Bringelly Shale (Herbert, 1979).

5.2.4. *Igneous Intrusions and Lava Flows*

Igneous intrusive bodies of various sizes occur within the Sydney Basin, especially in the southern part (Moffitt, 2000). These include intrusions of syenite and related material of Jurassic age at Mt Gibraltar, Mount Jellore and Mount Flora near Mittagong, a gabbro/dolerite at Sutton Forest, and a thick syenite sill intruding the Wongawilli coal seam at Mount Alexander. A basaltic intrusion, also of Jurassic age, occurs at Prospect in the western part of Sydney.

Basalt flows of early Tertiary (Palaeogene) age overlie the Triassic strata in a number of places, especially around Robertson and Berrima in the Southern Highlands. Dykes and sills, also thought to be of Tertiary age, cut the sedimentary strata in many places (Rickwood, 1985), and are encountered in some cases within coal seams during mining operations. Pipe-like intrusive bodies (diatremes) filled with volcanic breccia also occur at many localities within the basin (Crawford et al., 1980).

5.3. Structure of the Sydney Basin

The strata on the western side of the Sydney Basin dip gently towards the east, while those on the northern side of the basin dip gently towards the south-west. The lowest-lying part of the basin, both structurally and topographically, is in the area west of Sydney itself (the Cumberland Basin); this is surrounded by the structurally and topographically higher areas of the Woronora, Blue Mountains and Hornsby Plateaux.

Several major structures, generally oriented N-S, cut across the basin (Figure 5.3). These include the Lapstone Monocline and Kurradjong Fault in the west and the Lochinvar and Kulnura Anticlines, plus the Lake Macquarie Syncline, in the north-east. Some of these were active during deposition of the Permo-Triassic strata (Blevin et al., 2007), and some may represent reactivation during the Tertiary of older basement structures (Stewart and Alder, 1995). A series of anticline and synclinal structures also occurs within the Hunter Coalfield, west of the Lochinvar Anticline (Beckett, 1998).

The Lapstone Monocline extends southwards along the western side of the Southern Coalfield (Armstrong et al., 1995), with the Camden Syncline developed along its eastern side. East of this syncline the strata in the Illawarra area dip gently towards the NNW, and

are intersected by number of NW-SE oriented synclines, anticlines and faults that cut across the basin (Figure 5.3) in the area between Camden and Wollongong.

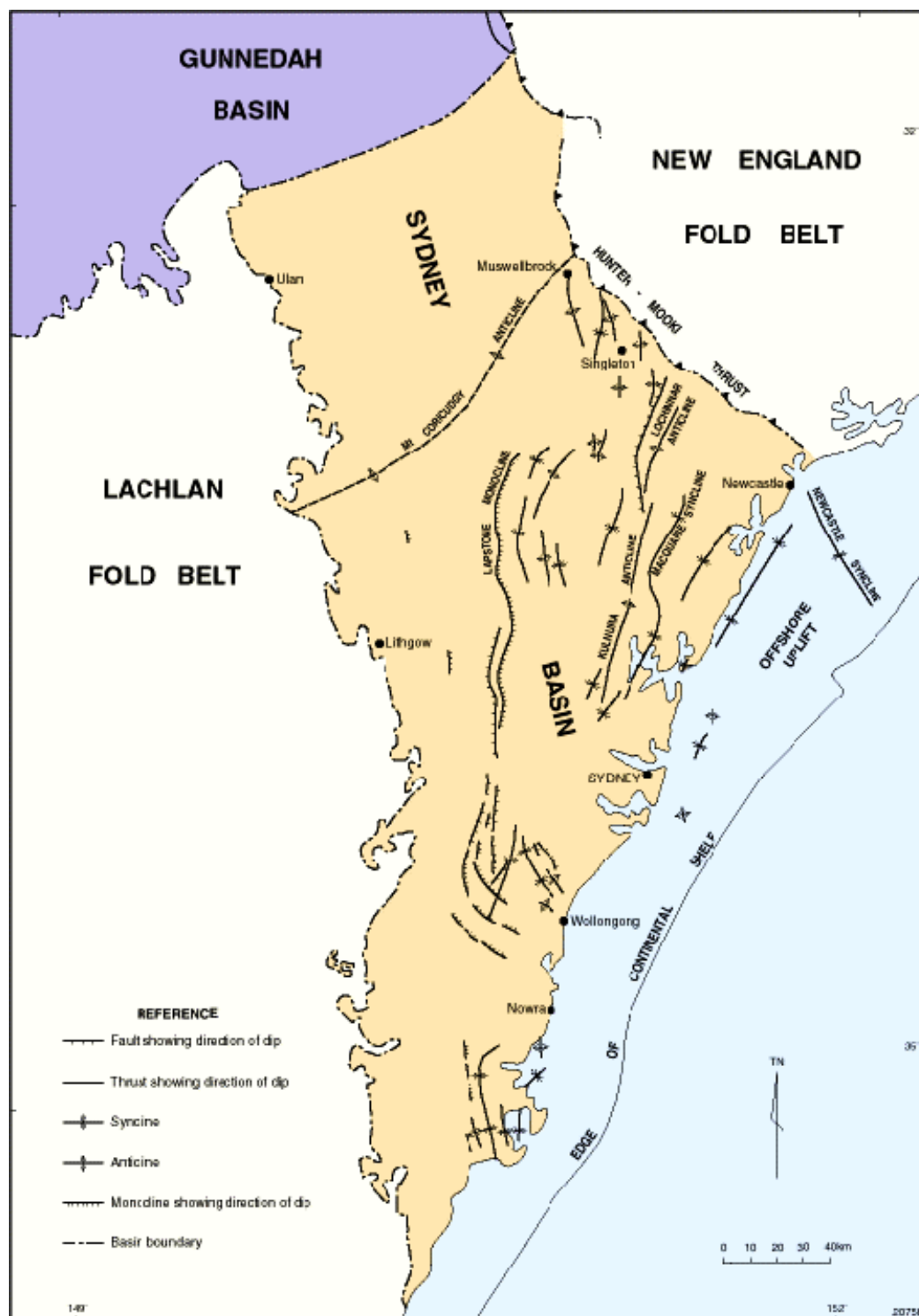


Figure 5.3: Major structural features of the Sydney Basin (Stewart and Alder, 1995).

5.4. Coal Seam Gas in the Sydney Basin

A review of the CSG potential in the Sydney-Gunnedah Basin was compiled in two separate reports for the NSW Department of Trade and Investment by Scott and Hamilton (2006, 2008). These studies have integrated data on coal distribution, basin structure, rank trends,

hydrogeology, gas content and gas composition to identify those parts of the two basins in which economic accumulations of methane are likely to be found. They extend previous reviews of basin-wide CSG potential by Stewart and Alder (1995) and Brown et al. (1996), which nevertheless also provide useful sources of information.

Nett coal thickness is greatest in the northern part of the Sydney Basin (Hunter, Newcastle and southern Gunnedah Coalfields) and decreases towards the south and west (Scott and Hamilton, 2006). The coals occur in both the Early Permian (Greta) and Late Permian coal-bearing sequences. As indicated by Stewart and Alder (1995) and Brown et al. (1996), the vitrinite reflectance in the coals in the Sydney Basin ranges from around 0.7% in the northern parts of the Hunter and Newcastle Coalfields to more than 1.3% in the Southern Coalfield north of Wollongong. The coals over most of the basin thus appear to have reached the threshold for thermogenic gas generation (Scott and Hamilton, 2006).

Gas contents of Sydney Basin coals range from <1 to around 21 m³/t (dry, ash-free) (Scott and Hamilton, 2006; Faiz et al., 2007; Pinetown, 2013). These values are erroneously referred to as grams per cubic centimetre (g/cc) rather than cubic centimetres per gram (cc/g, equivalent to m³/t) by Scott and Hamilton (2006, 2008). As noted above, values in relation to the in-situ (as sampled) coal will be lower than the daf gas contents. Gas contents tend to increase with depth, although the pattern is complex and several different trends appear to be involved in different parts of the basin.

The gases in Sydney Basin coals are generally dominated by methane with subordinate proportions of CO₂, higher hydrocarbons (e.g. ethane, C₂H₆) and nitrogen, but in some areas the coals may contain over 90% CO₂ and up to 12% C₂H₆ (Faiz et al., 2007; Pinetown, 2013). Isotopic studies suggest that a combination of thermogenic, biogenic and magmatic sources have contributed to the different gases in the coal seams (Faiz et al., 2007; Scott and Hamilton, 2006, 2008; Pinetown, 2013).

Face cleats are generally perpendicular to present-day compressive stress directions (Scott and Hamilton, 2006) and the cleat fractures are often mineralised, suggesting that seam permeability may be low. Pinetown (2013) indicates that, while areas of high permeability (>5 mD) exist in different parts of the Hunter Coalfield, permeability decreases with depth and is often less than 1 mD.

Figure 5.4 shows the areas within the Sydney-Gunnedah Basin indicated by Scott and Hamilton (2006, 2008) as having greatest potential for accumulation of CSG resources, based on the generic factors identified in earlier work by Scott (2002). The areas identified within the Sydney Basin are discussed below; those within the Gunnedah Basin are discussed separately in Section 6.4 of this background paper.

5.4.1. Southern Coalfield

The Southern Coalfield (Areas A and B in Figure 5.4 left) is regarded by Scott and Hamilton (2006) as the most prospective for CSG in the Sydney Basin. Nett coal thickness is 10-25 m, the coal rank has reached the main stage of thermogenic gas generation, and there is also potential for biogenic generation with high rainfall and meteoric water influx. However, although gas contents are high, CO₂ is present in places and permeabilities tend to be low. Additional discussion of CSG in this area is given by Faiz et al. (2007) and references cited therein.

CSG has been extracted since 2001 from the AGL Camden Gas Project (AGL, 2013b), which currently includes 95 producing gas wells. Current reserves, including the proposed northern expansion area, are cited by the NSW Department of Trade and Investment (2012) at 148 PJ 2P and 195 PJ 3P.

Gases are also extracted from the underground coal mines in the Southern Coalfield to reduce the risk of outbursts and also possibly explosions in the mining operations (Hanes et al., 2009). Much of the gas extracted is used for power production (97 MW) from generating units at the Appin and Tower mine sites.

5.4.2. Hunter and Newcastle Coalfields

The areas down-dip of mining activities in the Hunter and Newcastle Coalfields, and also the extreme north of the Western Coalfield (Areas C to F in Figure 5.4 left and C and D in Figure 5.4 right) are identified by Scott and Hamilton (2006, 2008) as being prospective for CSG development. Although vitrinite reflectance in these areas is only around 0.7% in near-surface strata, it increases steadily to over 1% at depths of around 700 m (Pinetown, 2013), indicating the possibility of thermogenic gas generation from the deeper parts of the basin.

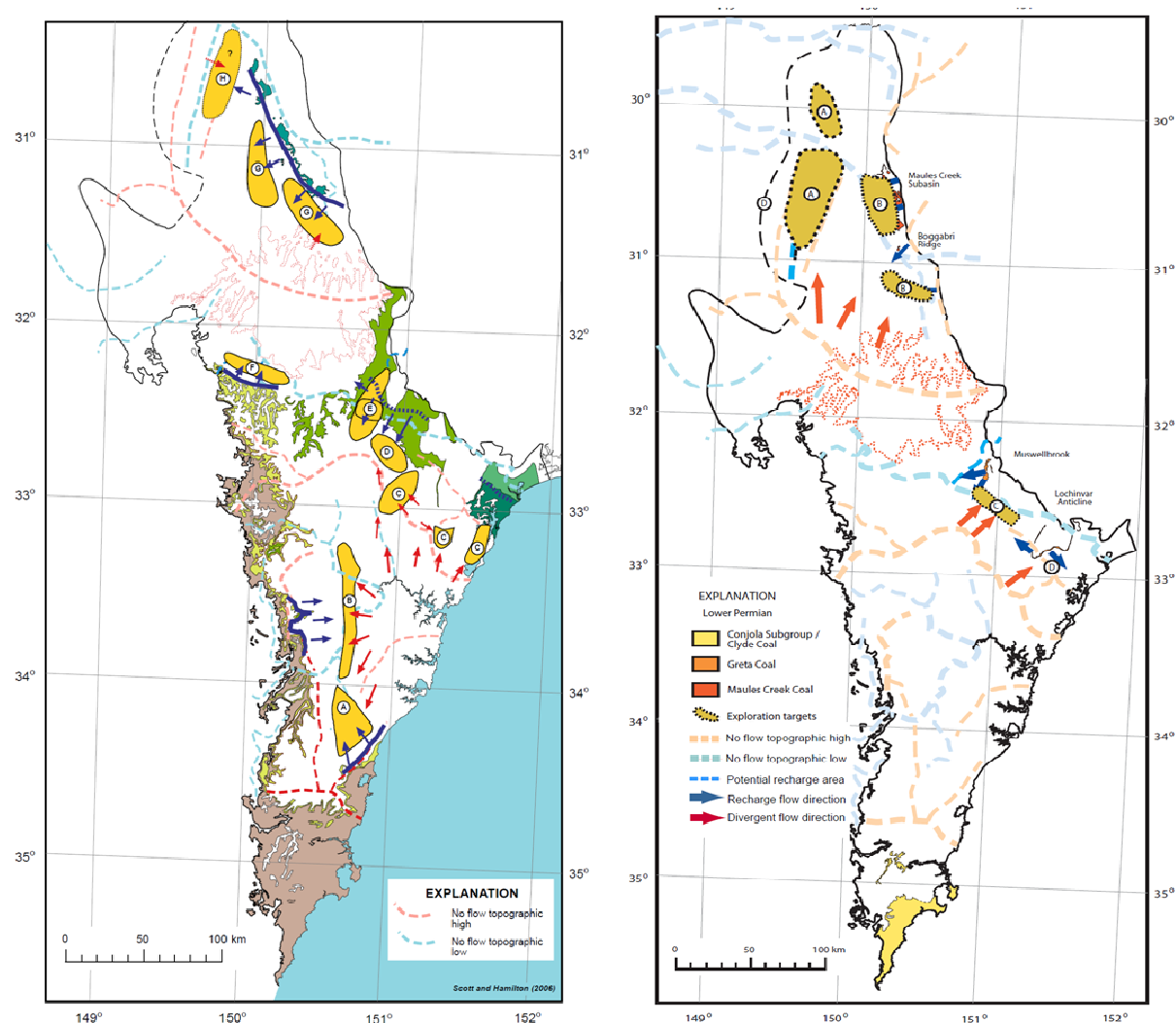


Figure 5.4: Prospective areas for CSG exploration (yellow) within the Late Permian (left) and Early Permian (right) coal measures of the Sydney and Gunnedah Basins, based on modelling by Scott and Hamilton (2006, 2008).

Five separate coal seam gas ‘compartments’ have been identified in the Hunter Coalfield by Pinetown (2013), based on a combination of structural features, gas content and gas composition data. Gas composition varies between predominantly CH₄ and predominantly CO₂, depending in part on the compartment involved. At least some of the CO₂ is probably of

magmatic origin, introduced with igneous intrusions, but the present-day gas distribution may also be related to migration through geological structures and dissolution in groundwater.

Nett coal thickness is up to 80 m, with more than 20 separate seams being recognised in some areas. Average coal permeability at depths between 300 and 800 m is around 1.5 mD, but may be an order of magnitude lower at depths greater than 800 m.

The principal CSG exploration activity in the Hunter Coalfield is the AGL Hunter Gas Project, which is currently focused on an area to the south of Singleton. An initial reserves estimate, announced in October 2010, indicates a total of 142 PJ 2P and 271 PJ 3P (NSW Department of Trade and Investment, 2012). Other activities include exploration by Santos and Dart Energy in the area between Murrurundi and Gulgong, where an aggregate of over 70 m of coal is indicated. Dart Energy is also exploring for CSG in the Tomago Coal Measures of the Fullerton Cove area, in the northern part of the Newcastle Coalfield.

5.5. Hydrogeology of the Sydney Basin

Throughout the Sydney Basin there are numerous boreholes in the unconfined alluvial sediments and upper portions of the porous rocks that supply water for stock, and also small scale irrigation of crops, vegetables and orchards. South-west of Sydney the Triassic sandstones that overlie the Bald Hill Claystone (Figures 5.1 and 5.2) have been investigated as a temporary supplement to Sydney's water supply (SCA, 2005). To the north of Sydney, groundwater is extracted and bottled for domestic markets. The Tomago Tomaree Stockton Coastal Sands groundwater is used for urban water supply by the Hunter Water Corporation (SOC, 2010). The porous rock unconfined aquifers contribute to stream base flow and water supplies in the greater metropolitan region. Some aquifers, like the Botany Sands aquifer, are important water supplies for industry.

Within the Sydney Basin there are many topographic settings, variations in stratigraphy, isolated dykes and faults, and variations in stress. When local information is available it should override any of the generalisations that are discussed below. The Sydney Basin is dominated by porous rocks that are fractured, and pumping yield from these rocks is generally low. However, recent groundwater investigations by the Sydney Catchment Authority near Kangaloon and Leonay have located portions of the porous Triassic sandstones that yielded between 5 to 40 L/s per bore.

There has been extensive testing of the rock strata in the Sydney Basin associated with coal mining, dam construction, numerous tunnels (including the extensive measurements associated with the Deep Ocean Outfall Tunnels), construction of underground car parks and many other civil projects. As a result there is a vast amount of data on the hydraulic and geomechanical properties of the strata. This has not all been collated in public documents, but most major geoengineering consulting companies that operate in the Sydney region maintain their own databases (for example see Blevin et al., 2007; Tammetta and Hawkes, 2009; Pells, 1993). A limited summary is presented in Table 5.1. It is apparent in the table that the claystones have very low vertical hydraulic conductivity. Although it is not reflected in the ranges of hydraulic conductivity values presented in Table 5.1, it is generally accepted that groundwater flow in the Triassic rocks is greater in the horizontal direction, because of enhanced flow along the bedding plane joints, than vertically through the fracture network (McNally and Evans, 2007). No similar collations of hydraulic conductivity measurements, however, have been done for the Hunter and Newcastle Coalfields.

Variability in groundwater age also highlights the need for local investigations. For example, Ziegler and Middleton (2011) report that water entering the Illawarra Coal Measures in a mine located 255 m beneath Cordeaux Dam is modern (less than 50 years old), while AGL (2013a) report an age of greater than 30,000 years for groundwater at depth within the

Triassic sandstones of the Camden district. The presence of such old water nevertheless still indicates a degree of connectivity. Water dates of up to tens of thousands of years old are consistent with the expected millennial transfer rates through low permeability porous and fractured rocks. With respect to water movement, defining something as connected or disconnected thus depends on the time scale being considered.

At most locations the claystones that overlie the coal measures throughout the Sydney Basin are reported to act as a hydraulic barrier to the vertical movement of fluid between the coal measures at depth and the aquifers within porous sandstones (e.g. AGL, 2013a). This is a topic of considerable debate (Pells and Pells, 2012). Faster fluid connectivity between the rocks above and below a claystone will occur in the presence of permeable fault zones, where there is enough throw (vertical offset across the fault) such that the claystone is juxtaposed with sandstone across the fault plane, where fracture networks are dense enough to form vertically connecting pipes, or where dykes occur (the mapping of these is very difficult, as was recently highlighted by the Lane Cove Tunnel collapse). The probability of the occurrence of dykes is very low. Faulting is more common, and within the claystone formations can have throws ranging from centimetres to many metres, as shown in Figure 5.5. There are a limited number of multi-year groundwater hydrograph records that support the case that the claystones act as a hydraulic barrier between the depressurised coal measures (in this case due to longwall coal mining) and the unconfined Triassic porous rock (Merrick, 2009). Excluding zones immediately above a longwall panel, given that the vertical leakage is low through all strata, it may require decades for the depressurisation at depth to impact on the near surface groundwater levels. However, multi-decadal records, required to comprehensively understand the vertical movement of groundwater, could not be located for this study.

Table 5.1: Hydrogeological properties of the Sydney Basin overlying the Illawarra Coal Measures in the southern region (adapted from SCA 2012 and AGL 2013a).

Geological Period	Stratigraphic Unit	Maximum Thickness (m) <small>Geoscience Australia</small>	Type of Hydro geological Unit	Hydraulic Conductivity [Horizontal] (m/day)	Hydraulic Conductivity [Vertical] (m/day)
Quaternary/Neogene	Alluvial	< 20	Unconfined Unconsolidated Sediments	1-10	1-10
Triassic	Wianamatta Group	80	Locally variable: Unconfined or Perched Porous Rock	1×10^{-2} to 1×10^{-1}	0.05
	Hawkesbury Sandstone/	290	Unconfined and Semi-Confined Porous Rock	9×10^{-4} to 70	6×10^{-4} to 0.05
	Newport Formation	49	Unconfined and Semi-Confined Porous Rock	1×10^{-4} to 1×10^{-1}	?
	Garie Formation	8	Unconfined and Semi-Confined Porous Rock	?	?
	Bald Hill Claystone	20	Aquitard	1×10^{-5} to 4×10^{-4}	2×10^{-6}
	Bulgo Sandstone	100	Leaky Confined Porous Rock	6×10^{-4} to 1.0	1×10^{-4}
	Stanwell Park Claystone	?	Aquitard	1×10^{-5} to 4×10^{-4}	6×10^{-6}
	Scarborough Sandstone	?	Leaky Confined Porous Rock	8×10^{-5} to 1×10^{-1}	5×10^{-3}
	Wombarra Claystone	30	Aquitard	1×10^{-4} to 3×10^{-4}	6×10^{-6}
	Coal Cliff Sandstone	?	Leaky Confined Porous Rock	5×10^{-5} to 2×10^{-4}	5×10^{-4}
Permian	Illawarra Coal Measures	150	Leaky Confined Porous Rock	5×10^{-5} to 1×10^{-2}	3×10^{-2}

Note: In some places due to longwall mining, the strata beneath the claystones are now unconfined.



Figure 5.5: Faults in individual claystone beds in sandstone units of the Grose Subgroup, western Sydney Basin (Photograph by Comunian and Kelly 2012).

The Southern Coalfield underlies many of Sydney's water supply catchments. For this reason it is important to understand the extent of hydraulic connectivity between the coal measures and the unconfined aquifers that contribute to Sydney's water requirements.

Subsidence impacts due to longwall mining on near surface water bodies and hanging swamps are still being debated (McNally and Evans, 2007; Pells and Pells, 2012). This highlights the difficulty of assessing and predicting subsidence impact. At the level of CSG production proposed in the Camden region it is unlikely that there will be discernible subsidence impacts on near surface streams and hanging swamps. However, this should be validated with a coupled hydraulic and geomechanical calculation/model. The Camden subsidence review report by MSEC (2007) presents no site-recorded stress measurements, quantified depressurisation estimates based on actual or projected extracted groundwater volumes, or site-related calculations to justify its conclusions.

In the Hunter Coalfield groundwater flow paths have already been significantly affected by agriculture and the extensive coal mining activities within the region. Future assessments of the impact of CSG developments within that region would have to examine the cumulative impact of all groundwater users.

Throughout the Hunter Coalfield there have been numerous environmental impact studies on mining impacts on groundwater systems. However, the hydrological and geomechanical data from these reports have not been coordinated in a publicly available form. Data from those past studies would assist with mapping groundwater flow paths and connectivity between strata. Groundwater in the Hunter region was recently reviewed by SKM (2010). There are two main groundwater systems in the Hunter region, the shallow alluvial aquifers associated with rivers and streams throughout the region, and the porous rocks. The rivers within the region have a significant contribution from groundwater discharge. The shallow alluvial aquifers are hydraulically connected to the porous rocks within the Permian sandstones, shales and coal measures strata at the boundary between the alluvium and the bedrock. What is not well characterised is the extent of hydraulic connectivity between the near surface porous rocks and the coal measures.

In the Broke CSG exploration region of the Hunter Coalfield all groundwater recharge to the alluvial sediments and porous rocks is from rainfall infiltration. The alluvial aquifers have a maximum thickness of 12 m, and the water table is less than 3 m below the ground surface (McLean et al., 2010). Groundwater contributes to stream baseflow throughout the region. Underlying the alluvium are the porous rocks of the Newcastle and Wollombi Coal Measures. The hydraulic conductivity values for the conglomerates, sandstones, shales and claystone units that overlie and are interbedded with the coal seams are likely to be within

the ranges presented in Figure 3.3 (see Section 3 above). In the immediate regions of CSG exploration little is known about the vertical hydraulic connections. A short 12 day pumping test has been undertaken to examine connectivity between the coal measures 323 metres below ground level and the overlying units (McLean et al., 2010). Such a short-term test is not necessarily sufficient to evaluate vertical connectivity in the porous rocks under evaluation. The groundwater ages of 22,000 to 33,000 years reported in McLean et al. (2010) for the Blakefield seam 323 metres below ground level are consistent with the millennial rates of fluid movement expected in porous rocks at these depths. This old water has been transported to the Blakefield seam under natural hydraulic gradients. CSG production will alter the gradients, but the rate of movement through the fracture network should remain low.

There has been coal and CSG exploration in the Fullerton Cove – Williamstown area, beneath the Tomago Tomaree Stockton Groundwater Source. The sands are approximately 90 m thick and provide a significant water supply for the region. The unconsolidated aquifer sands sit unconformably on top of the interbedded mudstones, siltstones and coals of the Tomago Coal Measures. No measurements of the hydrogeological properties of the rocks, or any assessment of the hydraulic connectivity between the coals and the overlying water supply aquifer, appear to have been published.

5.5.1 Water Sharing Plans

Groundwater Sharing Plans that fall within the boundaries of the Sydney Basin are: Kulnura Mangrove Mountain Groundwater Source, Tomago Tomaree Stockton Groundwater Source, and the Greater Metropolitan Region Groundwater Sources (GMRGS). The GMRGS is further sub-divided into the following water resources: Botany Sands, Cocks River Fractured Rock, Goulburn Fractured Rock, Hawkesbury Alluvium, Maroota Tertiary Sands, Metropolitan Coastal Sands, Sydney Basin Blue Mountains, Sydney Basin Central, Sydney Basin Cocks River, Sydney Basin Nepean, Sydney Basin North, Sydney Basin Richmond, and Sydney Basin South.

River and Alluvial Water Sharing Plans that fall within the Sydney Catchment Boundary include: Central Coast Unregulated Water Source, Greater Metropolitan Region Unregulated River Water Source, Hunter Regulated River Water Source, Hunter Unregulated and Alluvial Water Sources, Jiliby Jiliby Creek Water Source, Kangaroo River Water Source, Karuah River Water Source, Ourimbah Creek Water Source, Paterson Regulated River Water Source, and the Wybong Creek Water Source.

Details on the above listed Water Sharing Plans are available from the NSW Office of Water (<http://www.water.nsw.gov.au/Water-management/Water-sharing/default.aspx>).

6. Gunnedah, Bowen and Surat Basins

The Gunnedah Basin and the southernmost portion of the Bowen Basin represent the northern part of the Sydney-Gunnedah-Bowen Basin system within New South Wales. These basins are separated from each other and from the Sydney Basin only by arbitrary boundaries, but because those subdivisions are accompanied by changes in stratigraphic nomenclature each basin is discussed separately. Both basins are also overlain by sediments of the more widely distributed Surat Basin, the geology of which is also covered in this discussion.

Extensional tectonics in the Early Permian gave rise to rapid subsidence in the Gunnedah and Bowen Basins (Korsch and Totterdell, 2009; Stuart-Smith et al., 2010). This was replaced by a period of slower subsidence due to passive thermal processes, after which, at the start of the Late Permian, compressional foreland basin tectonics developed with subsidence driven by loading from the converging New England Fold Belt. Sedimentation ceased with peneplanation (erosion almost to base level) in the Late Triassic, after which more widespread subsidence resumed at the start of the Jurassic along with deposition of the overlying Surat Basin succession.

The Gunnedah Basin and the NSW portion of the Bowen Basin contain more than 1,200 m of marine and non-marine Permian and Triassic sedimentary rock strata, which form part of an essentially continuous depositional system from the Sydney Basin in the south to the Queensland portion of the Bowen Basin in the north. These strata rest with an angular unconformity on the basement rocks of the Lachlan Fold Belt on the western side of the basin, and have a faulted contact along the Mooki Thrust against the orogenic complex of the New England Fold Belt to the east. The boundary between the Gunnedah and Sydney Basins is taken by some authors (e.g. Tadros, 1993, 1995a,b; Gurba et al., 2009) as the Mount Coricudgy Anticline, and by others (e.g. Stewart and Alder, 1995; Brown et al., 1996) at the line of the Liverpool Range. The boundary between the Gunnedah and Bowen Basins is taken by most authors as the Moree High.

North of the Liverpool Range the Permian and Triassic strata are unconformably overlain by Jurassic volcanic and sedimentary rocks of the Surat Basin, which is itself a sub-basin of the Great Artesian Basin (Tadros, 1993). The Permian and Triassic beds crop out along a NNW-trending zone from south of Quirindi to north of Narrabri, with the Surat Basin covering the sequence to the west (Figure 6.1). To the east of this zone the Permo-Triassic sequence is largely eroded, or is overlain by a thick accumulation of Quaternary sediments.

6.1. Gunnedah Basin

A number of structural subdivisions have been identified in the Gunnedah Basin (Figure 6.2), based on subsurface geologic studies. These include two north-south trending anticlinal structures, the Boggabri Ridge to the east and the Rocky Glen Ridge to the west. The Maules Creek Sub-basin is a narrow N-S oriented trough located between the Boggabri Ridge and the New England Fold Belt. The Mullaley Sub-basin, located between the Boggabri Ridge and the Rocky Glen Ridge, is a wider trough, and is divided into a series of smaller troughs and associated features, including the Bando, Bohena and Bellata Troughs and the associated Narrabri High and Walla Walla Ridge. In addition, the Pilliga, Baradine, Tooraweenaa and Gilgandra Troughs lie west of the Rocky Glen Ridge (Stuart-Smith et al., 2010).

The stratigraphic units recognised in the Gunnedah Basin are summarised in Figure 6.3. As with the Sydney Basin, the beds range from Early Permian to Middle Triassic in age. The

units are summarised briefly below; additional information is included in more extensive compilations by Tadros (1993, 1995b) and Pratt (1998).

6.1.1. Permian Volcanics, Marine and Coal-Bearing Strata

Volcanic sequences of contrasting characteristics occur at the base of the sequence. The Boggabri Volcanics, exposed on the Boggabri Ridge, are represented by over 775 m of rhyolitic to dacitic lava flows, interbedded with trachytes, andesites, ash-flow tuffs and shales. Similar acid volcanics also occur in the subsurface along the Rocky Glen Ridge, on the western side of the basin. The Werrie Basalt, represented by up to 1,500 m of basaltic lavas with intervening palaeosols (fossil soils) and local thin coals, makes up the basal part of the sequence throughout the remainder of the basin. The top of the Boggabri Volcanics and Werrie Basalt appears to have been weathered and eroded (Leitch and Skilbeck, 1991), prior to deposition of the overlying sedimentary beds.

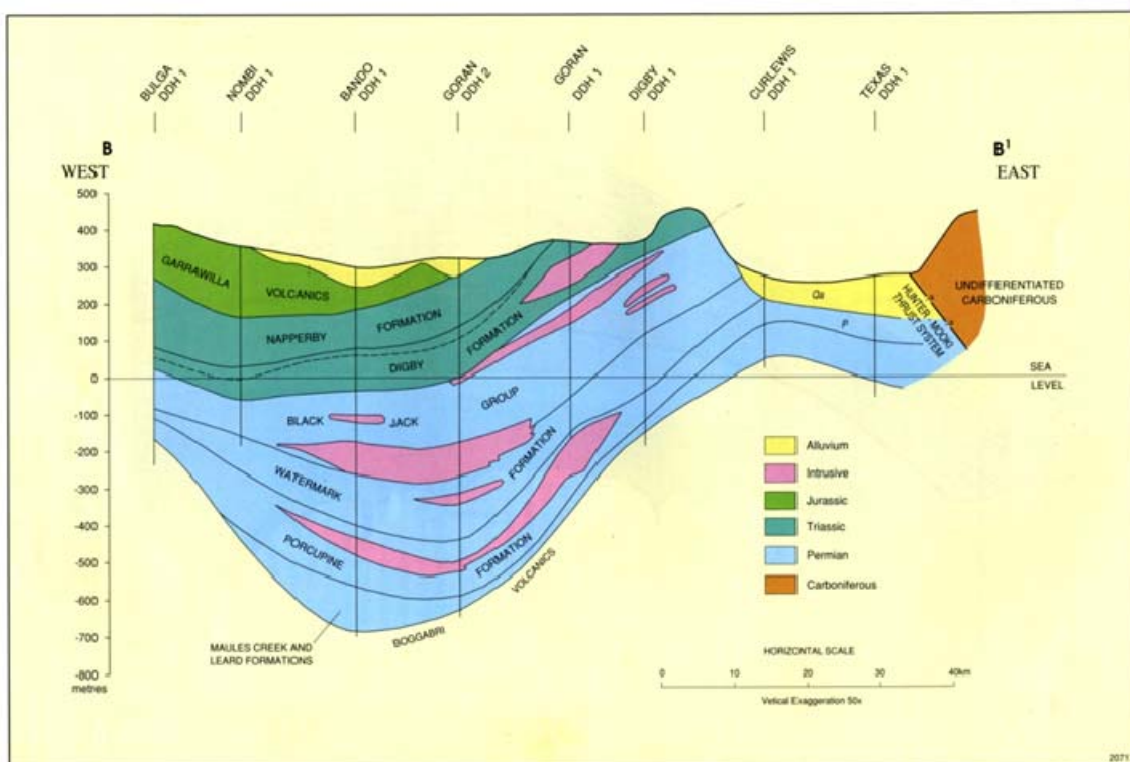


Figure 6.1: Geological cross-section from west to east across the Gunnedah Basin, showing the relation of the Permian and Triassic strata to the Carboniferous rocks of the New England Fold Belt (right) and the overlying Garrawilla Volcanics of the Surat Basin (left) (Stewart and Alder, 1995).

The Bellata Group is an Early Permian sequence of terrestrial sediments, unconformably overlying the basal volcanic materials. One of the units locally developed at the base of this sequence is the Leard Formation, a succession of pelletal kaolinite clayrocks (flint clays), thought to represent weathering of the basaltic substrate (Loughnan, 1975), interbedded with conglomerates, sandstones and siltstones. Another is the Goonbri Formation, which consists mainly of organic-rich siltstone and coaly material grading up to sandstone beds.

The Maules Creek Formation is a coal-bearing sequence that overlies and onlaps these units. It is stratigraphically equivalent to the main coal-bearing unit of the Greta Coal Measures in the Muswellbrook area of the Sydney Basin (Pratt, 1998). The unit is best developed in the Maules Creek Sub-basin, where over 800 m of conglomerate, sandstone, shale and coal are present (Thomson, 1993). Up to 25 coal seams are recognised (Tadros,

1995b), most of which range from 1.5 to 3.5 m in thickness. The thickest is the Braymont seam, which is up to 9 m thick. In the Mullaley Sub-basin the Maules Creek Formation is less than 100 m thick, with quartz-rich sandstone in the north, volcanogenic sedimentary rocks in the central area, and fine-grained sediments with abundant coal in the south-east (Thomson, 1993).

Overlying the Maules Creek Formation is an Early Permian marine sequence made up of the Porcupine and Watermark Formations, stratigraphically correlated with the Maitland Group of the Sydney Basin and collectively referred to as the Millie Group (Tadros, 1995b). The Porcupine Formation generally fines upwards from a muddy or sandy conglomerate at the base to bioturbated muddy sandstones at the top. It is typically 20-60 m in thickness, but in the south is up to 175 m thick. The unit rests on beds of the Maules Creek Formation in the middle part of the Mullaley Sub-basin, but if that unit is not present the Porcupine sediments rest directly on the Werrie Basalt or the Bogabri Volcanics.

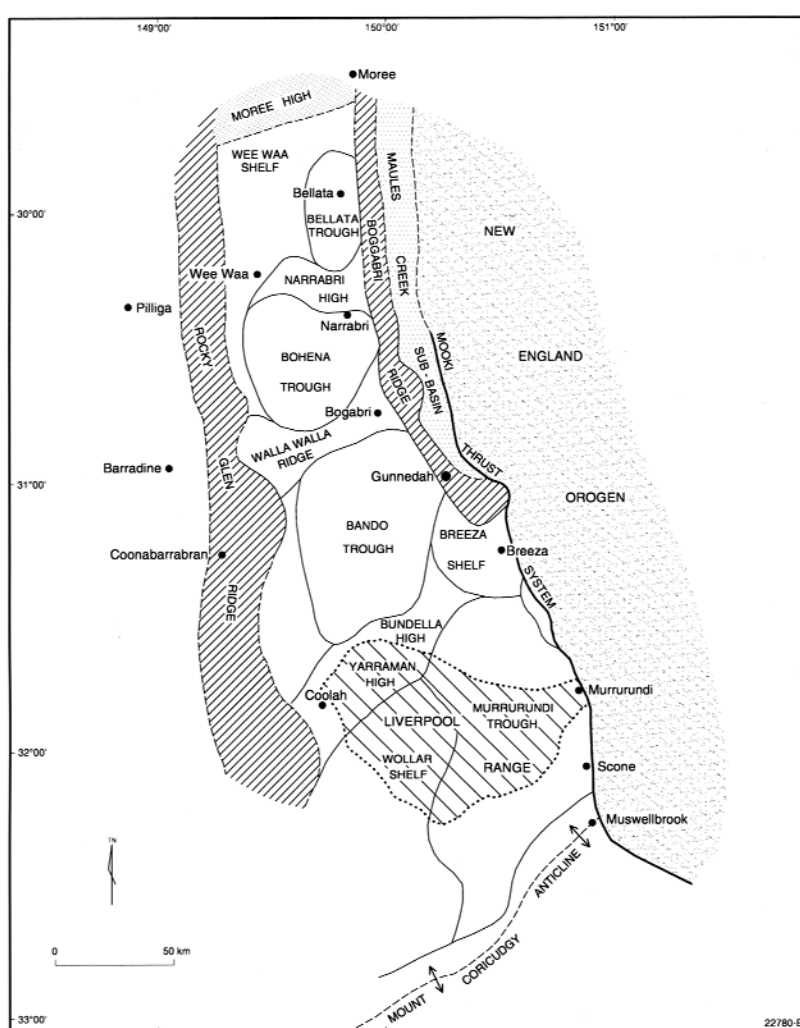


Figure 6.2: Structural subdivisions of the Gunnedah Basin (Pratt, 1998).

The overlying Watermark Formation consists mainly of siltstones, claystones and laminated sandy sediments, with sandstone becoming more abundant towards the top. It is correlated with the Mulbring Siltstone of the northern Sydney Basin (Pratt, 1998). Above the Watermark Formation are the Late Permian coal measures of the Black Jack Group. Formerly known as the Black Jack Formation, this sequence is divided into three subgroups (Figure 6.3) on the basis of detailed borehole studies (Tadros, 1995b).

The lowermost unit of the Brothers Subgroup, the Pamboola Formation, is made up of sandstone, siltstone, claystone and conglomerate, with intercalated coal beds. The most significant coal is the Melvilles seam (Mellvilles Coal Member), which is relatively rich in vitrinite and typically 2.5 to 3.2 m thick. Above the Pamboola Formation in the southern and central parts of the Mullaley Sub-basin is the Arkarula Formation, made up mainly of a burrowed lithic sandstone and thought to represent a shallow marine deposit (Hamilton, 1991). In the northern and western areas of the basin this is replaced by a sequence of more pebbly sandstone and carbonaceous siltstone, the Brigalow Formation, apparently formed under fluvial conditions.

The basal formation of the overlying Coogal Subgroup is the extensive, inertinite-rich Hoskissons Coal. This seam varies from less than 1 m thick in the western part of the basin to more than 12 m in the north and approximately 18 m in the south-east, and is thought to correlate with the Bayswater seam in the Hunter Coalfield of the Sydney Basin. The Hoskissons seam interfingers with and is overlain by the Clare Sandstone in the west, and is overlain by the massive organic-rich mudstone of the Benalabri Formation in the east. Two significant coal seams, the Caroon Coal Member and the Howes Hill Coal Member, occur within the Benalabri Formation. The Breeza Coal Member occurs within the Clare Sandstone in the southern part of the Mullaley Sub-basin.

Triassic	Middle	Deriah Formation				
		Napperby Formation				
	Early	Digby Formation				
Permian	Late	Black Jack Group	Nea Subgroup	Trinkey Formation		
				Wallala Formation		
			Coogal Subgroup	Clare Sandstone	Benalabri Formation	
					Hoskissons Coal	
			Brothers Subgroup	Brigalow Formation	Arkarula Formation	
					Pamboola Formation	
		Millie Group	Watermark Formation			
			Porcupine Formation			
		Early	Bellata Group	Maules Creek Formation		
	Leard and Goonbri Formations					
			Boggabri Volcanics and Werrie Basalt			

Figure 6.3: Schematic stratigraphy of the Gunnedah Basin (after Tadros, 1993, 1995b; Pratt, 1998)

The remainder of the coal-bearing sequence in the Gunnedah Basin is represented by the Nea Subgroup, which is divided into the Wallala and Trinkey Formations. Several coal seams occur within this interval, including the Clift seam and the Doona seam. A total of up to 28 coal seams, covering the interval from the Melvilles seam in the Brothers Subgroup to the Doona seam in the Nea Subgroup, are contained within the Black Jack Group in the Caroon area, 40 km SE of Gunnedah, representing a potentially very significant coal resource (Pratt, 1998).

6.1.2. Triassic Strata

The Triassic strata overlying the Permian sequence in the Gunnedah Basin are represented by three separate rock units: the Digby, Napperby and Deriah Formations (Jian and Ward, 1993; Pratt, 1998). These were deposited, with at least a partial angular unconformity on the Black Jack Group, in alluvial fan, fluvial and lacustrine-delta environments.

The lowermost unit, the Digby Formation, is up to around 200 m in thickness. It contains extensive lithic conglomerates at the base (the Bomera Conglomerate Member) which grade up to lithic and quartzose sandstones (Ulinda Sandstone Member) at the top. The conglomerates are thickest on the eastern side of the basin, and probably represent alluvial fan deposits derived from the New England Fold Belt (Jian and Ward, 1993; 1996). The lithic and quartzose sandstones in the upper part of the sequence were probably deposited by river systems, and were respectively derived from the New England and Lachlan Fold Belts. A basin-wide mudstone horizon, thought to represent an extensive palaeosol, occurs at the top of the sequence. The Digby Formation is stratigraphically equivalent to the lower part of the Narrabeen Group in the Sydney Basin; the palaeosol horizon is thought to be an equivalent of the Bald Hill Claystone and the Wentworth Falls Claystone Member.

The Napperby Formation, which is up to 250 m thick, is made up of three separate sedimentary successions, each coarsening upwards from dark grey shale, often with burrows and sideritic laminae, to interlaminated sandstone and shale and then to cross-stratified or rippled sandstone beds (Jian and Ward, 1993; 1996). These intervals are interpreted as deposits of alluvial fans that prograded from the east into an extensive lacustrine system, with a transition to a fluvial environment near the top of the sequence. The Napperby Formation is only found in the Mullaley Sub-basin; it is probably equivalent to the upper Narrabeen Group, Hawkesbury Sandstone and Ashfield Shale in the Sydney Basin.

The Deriah Formation ranges up to 160 m in thickness (Pratt, 1998), but is disconformably overlain by Jurassic strata of the Surat Basin and is often not present in the sequence due to post-Triassic erosion. The lower part of the unit is dominated by a distinctive green lithic sandstone, and the upper part by off-white lithic sandstone with interbedded mudstone and minor coal beds. The Deriah Formation is found mainly in the northern part of the basin. It is correlated with the Bringelly Shale of the Sydney Basin, and was probably formed by low-sinuosity fluvial systems derived mainly from the New England Fold Belt (Jian and Ward, 1993; 1996).

6.1.3. *Igneous Intrusions*

Igneous intrusions into the Permo-Triassic strata occur over much of the Gunnedah Basin, and in some cases their effects may limit the extent of the basin's coal resources (Tadros, 1993). Most of these intrusions are of Jurassic or Early Cretaceous age (Pratt, 1998), and are probably associated with formation of the Garrawilla Volcanics in the overlying Surat Basin sequence. They include bodies such as the Black Jack Sill and the Ivanhoe Sill SW of Gunnedah (both dated as Jurassic; Pratt, 1998), as well as numerous igneous intrusions encountered in drilling programs. Further information on these materials, including their size and shape, mechanisms of emplacement, and interaction with the coal seams, is given by Martin (1993).

The thickness of individual intrusions encountered in drill core ranges from a few centimetres to more than 120 m. Intrusions appear to be most concentrated in the area SW of Gunnedah (Gurba and Weber, 2001a), where the aggregate thickness of igneous material reaches up to 160 m.

In at least one case these intrusions may be associated with higher gas contents in the adjacent coals, due to additional generation of thermogenic methane from the heat-affected coal beds (Gurba and Weber, 2001a). The coals in the thermal aureoles around the intrusions in this instance were also found to contain characteristic micropores and slits, which may have enhanced the gas adsorption capacity, permeability and desorption characteristics. In addition, the sills may have acted as a seal to the CSG reservoir, during and after the intrusion process.

Similarly, heat from an igneous intrusion into the Napperby Formation in the Bellata area, in the northern Gunnedah Basin, appears to have generated oil that migrated into the Jurassic strata of the overlying Surat Basin (Othman et al., 2001). Intruded coals are also found near several conventional gas occurrences, including the Coonarah Gas Field (Pratt, 1998).

6.2. Bowen Basin

The Permian sequence in the Gunnedah Basin has been partly eroded on the Moree High, located in the Bellata-Moema Zone as shown in Figure 6.4. North of that feature the Permo-Triassic strata have a greater affinity with the Bowen Basin succession in Queensland (Mallett et al., 1995) than with the Gunnedah Basin units.

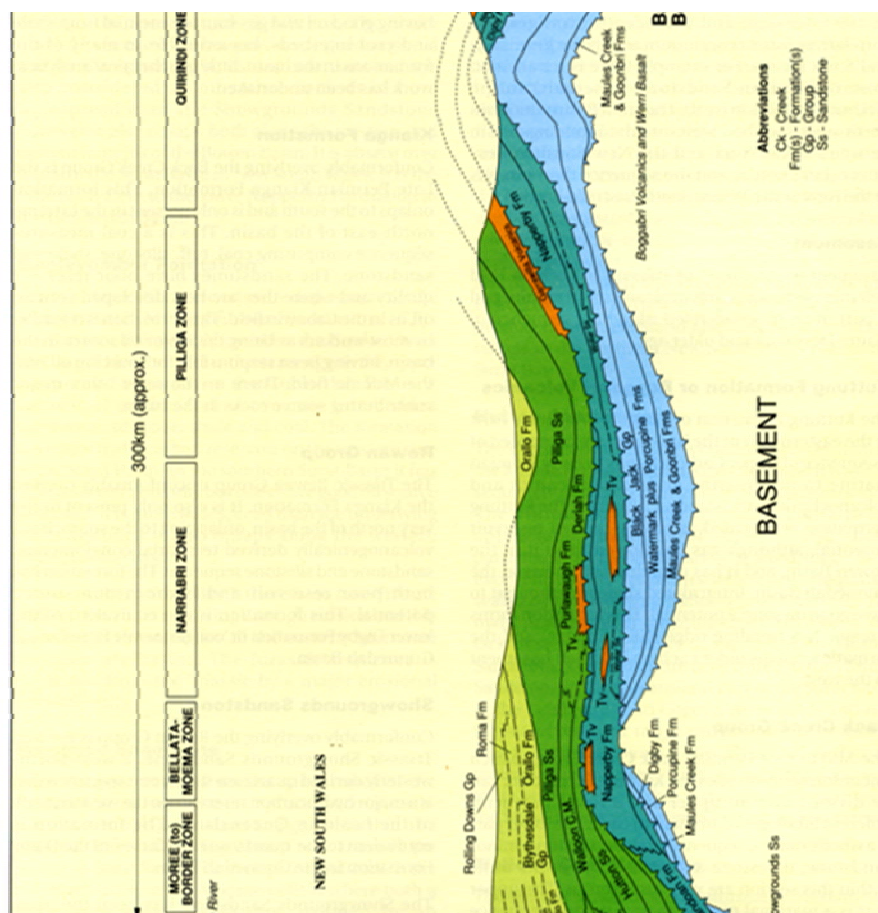


Figure 6.4: North-south cross section through the Bowen (left), Gunnedah (centre-right) and overlying Surat Basins in New South Wales (Stewart and Alder, 1995).

Carbonaceous lacustrine to fluvial sediments up to 100 m thick, of similar age to the Goonbri Formation, occur at the base of the Permian sequence in the NSW portion of the Bowen Basin. These are equivalent in age to the Reids Dome Beds in the Queensland portion of the basin (Totterdell et al., 2009). Where it is present this interval is overlain by a succession of coarse clastic sediments, mudstones and coals, equivalent to the Maules Creek Formation. Where the underlying strata are not present the Maules Creek equivalents rest directly on the basement rocks.

Above this sequence is a succession of shallow marine to fluvio-deltaic sediments up to 300 m thick, equivalent to the Porcupine Formation and the Pamboola and Arkarula Formations

of the lower Black Jack Group. This sequence is identified by Morton et al. (1993) and Othman and Ward (2002) as equivalent to the Back Creek Group in the Queensland portion of the basin, and by Totterdell et al. (2009) as equivalent to the Oxtrack Formation and the upper part of the Alderbaran Sandstone in Queensland.

The Back Creek or Oxtrack equivalents are overlain in some parts of the basin by a coal-bearing terrestrial succession, described by Othman and Ward (1999, 2002) and other authors as an equivalent to the Kiangra Formation and the Baralaba Coal Measures in Queensland. Totterdell et al. (2009), however, suggest that the beds are older, and probably equivalent to underlying Late Permian beds in Queensland. This sequence is not present in many parts of the basin due to Late Permian or Early Triassic erosion (Totterdell et al., 2009); where present it is probably equivalent to the upper part of the Black Jack Group.

Triassic strata equivalent to the Digby Formation and lower Napperby Formation appear to be absent from the NSW portion of the Bowen Basin (Totterdell et al., 2009), probably due to Late Permian to Early Triassic erosion. The Triassic strata in the area north of the Moree High are mainly represented by a sequence of sandstones, shales and thin coal seams. This has characteristics similar to the Middle Triassic Showgrounds Sandstone and Moolayember Formation in the Queensland portion of the basin, rather than to the upper Napperby and Deriah Formations of the Gunnedah Basin sequence.

6.3. Surat Basin

The Jurassic beds of the Surat Basin unconformably overlie the Permo-Triassic sequence of the Gunnedah Basin. Further to the west, however, the Permo-Triassic strata are absent and the Jurassic beds rest directly on the basement materials of the Lachlan Fold Belt.

The lowermost unit of the Surat Basin sequence in the Gunnedah Coalfield is the Garrawilla Volcanics, a sequence of basaltic and intermediate lava flows and volcanic ash (pyroclastic) deposits, mainly of early Jurassic age (Pratt, 1998), up to 180 m in thickness. Some of this material in the north of the basin may, however, be of Late Triassic age. Intrusive bodies (Glenrowan Intrusives and Bulga Complex) also occur within the overall volcanic complex.

The Purlawaugh Formation is a poorly-exposed terrestrial sequence of low-porosity sandstones, siltstones and carbonaceous claystones up to 84 m thick, lying between the Garrawilla Volcanics and the overlying Pilliga Sandstone. Where the Garrawilla Volcanics are not present, this unit rests directly on the Napperby and/or Deriah Formations.

Above these strata are the quartzose sediments of the extensive Pilliga Sandstone. This unit, which is generally between 100 and 250 m thick, represents the main intake beds and aquifer for the artesian groundwater of the Great Artesian Basin. It consists mainly of well-sorted medium to coarse-grained quartz sandstone, with minor mudstone, siltstone and finer sandstone interbeds (Hawke and Bourke, 1984). A basal conglomerate is frequently present, and lenticular conglomerates occur throughout the sequence. The unit is thought to have been formed by north-flowing river systems draining the Palaeozoic basement rocks in the south-west and possibly uplifted sediments of the Sydney Basin in the southeast (Arditto, 1982).

The top of the Surat Basin sequence in the Gunnedah Coalfield is the Orallo Formation, a Late Jurassic to Early Cretaceous sequence of fine to coarse-grained clayey sandstones, interbedded with siltstones and mudstones (Hawke and Bourke, 1984). This was probably deposited by waning river systems with extensive floodplain deposits.

6.4. Coal Seam Gas in the Gunnedah Basin

Several areas are indicated by Scott and Hamilton (2006, 2008) as having potential for CSG resources in the Gunnedah Basin and related parts of the north-western Sydney Basin (sites G and H in Figure 5.4. left, A and B in Figure 5.4. right). Nett coal thicknesses range from 15 to 30 m for the Black Jack Group, with vitrinite reflectance values between 0.6 and 0.9% suggesting that deeper-lying coals in this sequence may have reached the threshold for thermogenic gas production. The principal cleat patterns may, however, be roughly perpendicular to present-day stress patterns, thus reducing permeability. Substantial nett coal thicknesses (5-25 m) also occur in the Early Permian coals of the Bellata Group, and higher rank levels may be expected at depth.

Significant exploration has been carried out for the Narrabri Coal Seam Gas Project (PEL 238) in the Bohena Trough west of Narrabri, including core drilling and seismic surveys, testing of different borehole completion techniques, and pilot gas production. Targets include both the Early Permian Maules Creek Formation, especially the thick Bohena seam, and the Late Permian Black Jack Group, especially the Hoskissons seam (Budd and Edgar, 2008). Initial 2P reserves of 185 PJ and 3P reserves of 1300 PJ were reported by the company in early 2008 (ESG, 2010). Wilga Park Power Station, near Narrabri, with capacity scheduled to increase from 16 to 40 MW, has been using CSG since 2009.

Santos acquired Eastern Star Gas in 2011. The company also has other CSG exploration areas in the Gunnedah Basin, extending north to the State border and west almost to Dubbo. Drilling and seismic studies are also taking place in these areas (NSW Department of Trade and Investment, 2012).

6.5. Hydrogeology of the Gunnedah, Bowen and Surat Basins

The Gunnedah and Bowen Basins and the overlying Surat Basin are all hydraulically connected (there is water transfer and pressure communication), and these basins are also hydraulically connected to the near surface alluvial aquifers. Overlying these basins are the major alluvial aquifers of the Lower Macquarie, Namoi, and Gwydir Catchments. The Namoi alluvial aquifer overlies the Gunnedah and the Surat Basins, the Gwydir alluvial aquifer overlies the Surat and Bowen Basins, and the Macquarie alluvial aquifer overlies the southern extent of the Surat Basin.

There is limited knowledge about where hydraulic connections occur and flow paths between the fractured and porous rocks and the adjacent or overlying alluvial aquifers. Historically in NSW the focus of groundwater monitoring throughout the Gunnedah and Surat Basins has been in the highly productive alluvial aquifers (SWS, 2012). Multi-decadal groundwater levels have been recorded for the porous rock aquifers of the Great Artesian Basin (GAB), but not for the other fractured and porous rocks (SWS, 2012). Knowledge of the hydraulic conductivities of the fractured and porous rocks throughout the Surat, Gunnedah and Bowen Basins is also limited. In SWS (2012) it is reported that borehole hydraulic conductivity measurements are being done as part of exploration and production in the Gunnedah Basin. Welsh (2006) estimated the hydraulic conductivity of the primary GAB aquifers for the majority of the NSW portion of the Surat Basin to be less than 2 m/day. For the main aquifers of the GAB there is a comprehensive summary in CSIRO (2012).

Recharge to both the fracture and porous rock aquifers is from diffuse rainfall recharge. Most of the recharge to the Surat Basin is via the eastern margin where the basin outcrops. This extends from Dubbo in the south and trends north-north-east through the eastern edge of the Pilliga, to the NSW/QLD border, and ends on the eastern side of the Condamine catchment (refer to Figure 2.1, page 12 of CSIRO, 2012). Direct recharge to the Gunnedah

Basin porous rocks occurs where the strata outcrop on the rocky plateaus and hill slopes along the Liverpool Range, and the western margin of the Great Dividing Range. Of importance with respect to the expansion of CSG exploration and production in the Narrabri through Coonamble districts, is that the eastern side of the Coonamble Embayment is one of the highest recharge zones for the GAB. On the east side of the Coonamble Embayment recharge to the GAB is estimated to be as high as 45 mm/year (CSIRO, 2012).

Recharge to the alluvial aquifers is via diffuse (areal) rainfall recharge, mountain front recharge (also called alluvial margin recharge), irrigation deep drainage, leakage from the base of rivers, and flood waters. The Surat Basin is part of the Great Artesian Basin (GAB) and there is a positive pressure from the GAB into the base of the lower Namoi alluvial aquifer (CSIRO, 2007a).

The alluvial aquifers in the Lower Macquarie (CSIRO, 2008), Namoi (CSIRO, 2007a) and Gwydir (CSIRO, 2007b) catchments are some of the most comprehensively monitored and modelled aquifer systems in Australia. This is due to the fact that these alluvial systems support a highly productive and profitable agricultural sector. The Namoi Catchment Water Study is the largest example of a cumulative impact study in Australia. It incorporates agriculture, coal mining, and projected coal seam gas groundwater use (SWS, 2012).

From 1886 until the 1950s more than 3000 freely flowing bores were installed throughout the GAB (GABCC, 1998). This depressurised large portions of the basins, and groundwater head declined. Some boreholes stopped flowing freely. From 1952 until now there has been a highly successful borehole capping program that has partially restored the pressure throughout the GAB (Welsh, 2006). Further details about the NSW portion of the cap and pipe program are provided on the NSW Office on Water web pages (<http://www.water.nsw.gov.au/Water-management/Water-recovery/Cap---Pipe/Cap-and-pipe-bores/default.aspx>). Groundwater head needs to be maintained throughout the GAB to keep the water flowing for agricultural water supplies while eliminating the need for pumps, and to maintain the groundwater dependent ecosystems associated with mound springs (see Figure 2.1, page 12 of CSIRO 2007, and refer to the Groundwater Dependent Ecosystem Atlas <http://www.bom.gov.au/water/groundwater/gde/>). Large scale CSG production from the Surat Basin could depressurise significant portions of GAB, and have the potential to affect water supplies to the mound springs.

Knowledge on the hydrogeology of the NSW portion of the Bowen Basin is very limited. The focus of drilling in this region has been on evaluating the hydrocarbon potential. We are not aware of any hydrogeological investigations that focus on the NSW portion of the Bowen Basin, and which examine the water movement and pressure transfers between the Bowen Basin and the Surat Basin. If there were CSG production from the Bowen Basin coal measures, the siltstones and claystones that overlie the coal measures, but underlie the Surat Basin, would likely act as sealing rocks - especially at these depths.

Before an assessment can be made of any large scale coal seam gas production impacts on the likelihood of subsidence, further work is required to assess the tensile strength, compressibility, hydraulic conductivity, and storativity properties of the rocks within the basins.

6.5.1. Water Sharing Plans

Groundwater Sharing Plans within the Bowen/Surat/Gunnedah Basin boundaries include: Groundwater Sources Overlaying the NSW Great Artesian Basin, NSW Great Artesian Basin Groundwater Sources, Lower Gwydir Groundwater Source, Lower Macquarie Groundwater Sources, Upper and Lower Namoi Groundwater Sources, NSW Murray-Darling Basin

Porous Rock Groundwater Sources, and NSW Murray-Darling Basin Fractured Rock Groundwater.

River and Alluvial Water Sharing Plans within the Bowen/Surat/Gunnedah Basin boundaries include: Barwon-Darling Unregulated and Alluvial; Castlereagh River above Binnaway; Castlereagh (below Binnaway) Unregulated and Alluvial; Gwydir Regulated River; Gwydir Unregulated and Alluvial; Intersecting Streams Unregulated and Alluvial; Macquarie Bogan Unregulated and Alluvial; Macquarie and Cudgegong Regulated Rivers; Namoi Unregulated and Alluvial; NSW Border Rivers Regulated River; NSW Border Rivers Unregulated and Alluvial; Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock; Phillips Creek, Mooki River, Quirindi Creek and Warrah Creek; Rocky Creek, Cobbadah, Upper Horton and Lower Horton; Tenterfield Creek; and Upper Namoi and Lower Namoi Regulated River.

Details on the above listed Water Sharing Plans are available from the NSW Office of Water (<http://www.water.nsw.gov.au/Water-management/Water-sharing/default.aspx>).

7. Gloucester Basin

7.1. Stratigraphy and Structure

The Gloucester Basin is a north-south trending trough approximately 38 km long and 9.5 km wide (Brown et al., 1996), filled with coal-bearing strata of Early to Late Permian age, developed within the New England Fold Belt approximately 80 km north of Newcastle (Figure 7.1). These strata rest on a basement of Devonian and Carboniferous sedimentary and volcanic units. The Permian strata are folded into an overall synclinal pattern and cut by a complex series of normal and reverse faults (Figure 7.2), especially in the south-eastern part of the basin (Hughes, 1995).

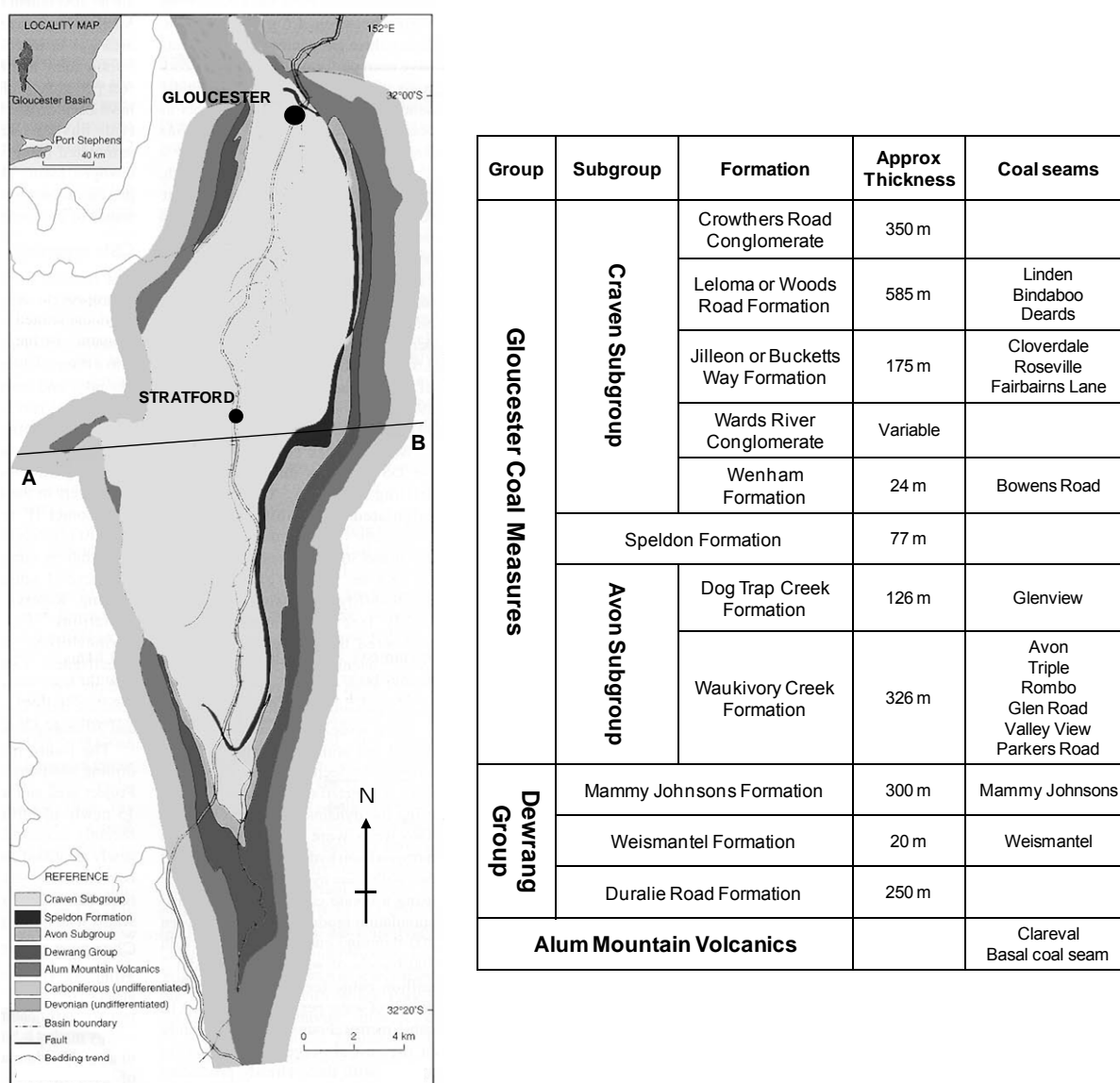


Figure 7.1: Schematic geological map (left) and stratigraphic units (right) of the Gloucester Basin (after Ward et al., 2001; Ogier-Halim, 2010).

The lowermost sequence in the basin is the Early Permian Alum Mountain Volcanics. This unit is about 2,000 m thick, and consists of basaltic and rhyolitic lava flows interbedded with conglomerates, sandstones, mudstones and tuffs, with some coal seams (Ogier-Halim, 2010). It is overlain by a coal-bearing succession of mainly alluvial fan, fluvial and delta-plain sediments (Hughes, 1995), also around 2,000 m in total thickness, which is divided into the

Early Permian Dewrang Group and the Middle to Late Permian Gloucester Coal Measures (Figure 7.1). The Dewrang Group is thought to be equivalent in age to the Maitland Group of the Sydney Basin and the Gloucester Coal Measures equivalent to the Wittingham and Newcastle Coal Measures.

Two significant coal seams occur within the Dewrang Group: the thick (up to 15 m) but relatively high-sulphur Wiesmantel seam (Hughes, 1995) and the more lenticular and often stony coal seam within the Mammy Johnsons Formation (Ogier-Halim, 2010).

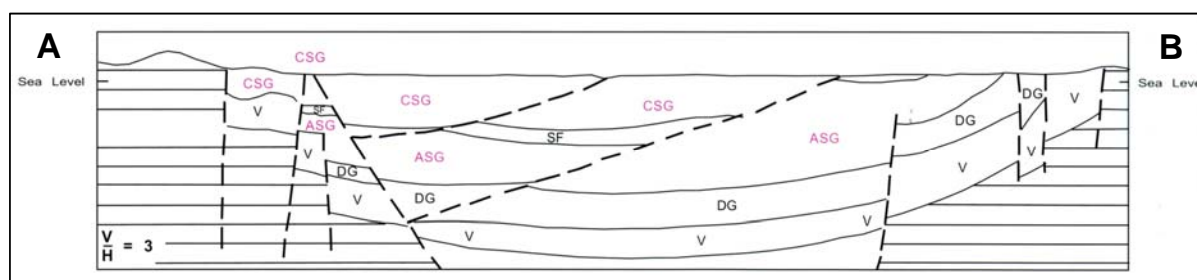


Figure 7.2: Geological cross-section from west to east through the Gloucester Basin, along line A-B in Figure 7.1 (after Brown et al., 1996). V = Alum Mountain Volcanics; DG = Dewrang Group; ASG = Gloucester Subgroup; SF = Speldon Formation; CSG = Craven Subgroup.

The Gloucester Coal Measures is divided into two coal-bearing intervals, the Avon Subgroup at the base and the Craven Subgroup at the top, separated by a coal-barren marine interval referred to as the Speldon Formation. Coal is best developed in the eastern part of the basin (Gurba and Weber, 2001b), with conglomerate more abundant in the western section.

A number of coal seams occur in the Waukivory Creek Formation (Figure 7.1). The most consistent is the Avon seam, which is up to 20 m thick in the Stratford area but thins to less than 5 m in the southern parts of the basin (Hughes, 1995). Many of the major seams are further split into separate sub-sections, identified by suffixes from A at the top (e.g. Avon A seam) to D or E at the bottom. The Glenview seam, in the overlying Dog Trap Creek Formation, reaches up to 3 m thick in the northern part of the basin; like the Wiesmantel seam, the coal has a relatively high sulphur content, due to marine influence associated with deposition of the overlying Speldon Formation (Hughes, 1995).

The Speldon Formation is made up mainly of burrowed marine sandstone and mudstone, with pebbly and conglomeratic beds (Hughes, 1995), and varies from 60 to 100 m in thickness. The overlying Craven Subgroup, which is approximately 1,000 m thick, has been divided into five separate formations, some of which are referred to by different names in different publications.

One of the main coal seams in the Craven Subgroup is the Bowens Road seam, which consists mainly of dull (high-inertinite) coal. This seam is up to 12 m in thickness north of Stratford (Hughes, 1995), but decreases to <1 m thick in other parts of the basin. It is similar in character and age to the Bayswater seam in the Hunter Coalfield of the Sydney Basin and the Hoskissons seam in the Gunnedah Basin.

The Wards River Conglomerate is thickest in the west of the basin, but is significantly reduced in thickness on the eastern side. Indeed, the unit makes up most of the Gloucester Coal Measures succession in the western part of the basin (Hughes, 1995). It consists mainly of conglomerate and lithic sandstone, and was deposited mainly in alluvial fan and braided stream environments.

Several coal seams occur in the Craven Subgroup above the Wards River Conglomerate, including the Roseville and Cloverdale seams in the Jilleon or Bucketts Way Formation and the Deards and Bindaboo seams in the Leloma or Woods Road Formation. Volcanic ash beds up to 14 m in thickness, including one referred to as the Jo Doth Tuff (Member), also occur within the Leloma or Woods Road Formation (Hughes, 1995).

At the top of the Permian succession is another alluvial fan to braided stream sequence, the Crowthers Road Conglomerate. As with the underlying Wards River Conglomerate, this unit is also largely confined to the western part of the basin.

7.2. Coal Seam Gas

Although the coals of the Dewrang Group may also contain gas, the best-known CSG resources in the Gloucester Basin occur in the Gloucester Coal Measures, especially the top 200 m of the Avon Subgroup and the basal 250 m of the Craven Subgroup (Gurba and Weber, 2001b). Most exploration to date has been focussed on a small area east of Stratford, where up to 11 major seams (>2.5 m thick) and numerous minor seams occur in this stratigraphic interval, with an average total coal thickness of 30-60 m (Bilston, 2008).

The seams in this sequence have gas contents of 12-25 m³/t on a dry, ash-free (daf) basis (Bilston, 2008). Because the coals are relatively high in ash, however, in some cases with 30-50% mineral matter (Ward et al., 2001), in-situ (i.e. as-sampled) gas contents will be somewhat lower. Gas content increases significantly with depth; Gurba and Weber (2001b) indicate values of <10 m³/t (daf) for coals shallower than 200 m and 20-25 m³/t at depths of around 600 m. The methane content of the gas varies from 95 to 100%, with up to 5% CO₂ and very minor nitrogen (Gurba and Weber, 2001b). The methane is mainly thermogenic, with minor biogenic gas at shallow depths.

Vitrinite reflectance increases from around 0.8% in coal seams near the ground surface to over 1.4% at depths of around 800 m (Gurba and Weber, 2001b). This appears to confirm the dominantly thermogenic origin indicated for the methane component. Most of the coals are vitrinite-rich (75-90% vitrinite, mineral-free), except for the inertinite-rich Bowens Road seam (30-40% vitrinite). Cleat is well developed in all seams except the Bowens Road; face cleat spacing is 2-8 mm, although the butt cleat pattern is not so well-defined. The cleat is almost wholly free of carbonate or clay mineralisation.

Coal permeability is relatively high at shallow depths (e.g. around 20 mD at 300 m), but decreases rapidly with depth (e.g. 1 mD at 500 m; Gurba and Weber, 2001b). Jointing and fracturing are also present, and even the cleat-free Bowens Road seam is reported to have high permeability values. In-situ stresses in the basin are relatively low (Enever et al., 1999), with the maximum horizontal stress approximately parallel to the basin axis and the N-S strike of the coal beds. Unlike many other NSW basins, the minimum horizontal stress is less than the overburden pressure (Gurba and Weber, 2001b). Reservoir pressure is high, but not abnormally high; Gurba and Weber (2001b) suggest that these may be a reflection of artesian conditions associated with outcrop of the coal seams to the east of the main prospect area.

The NSW Department of Trade and Investment (2012) indicates current 2P (proven and probable) reserves of 669 PJ and 3P (proven, probable and possible) reserves of 832 PJ for the Gloucester Basin area.

7.3. Hydrogeology

From the hydrogeological perspective the Gloucester Basin is complex. The extensive faulting, displacement of strata across the faults, folded and discontinuous lithologies, and lack of any fault seal analysis make it difficult to state with certainty how fluids will migrate and how pressures will be transferred between the coal measures and the overlying strata. However, the east-west geometry (ridge-valley-ridge) and the single north-south axis have a major influence on the regional scale flow paths. The basin has a narrow width (maximum 24 km, Pells, 2012) and there is a steep hydraulic gradient from the ridge line (approximately 400 m) to the valley bottom (approximately 100 m). Under natural conditions the streams are likely to be connected to the water table for the majority of their length. This conceptualisation is supported by the large number of small farm dams that have been placed along the valley bottom spring lines between Craven and Gloucester. A schematic of the valley cross section and expected flow-lines is shown in Figure 7.3. Exactly how the groundwater systems interact with the near surface is poorly understood. It is not known in detail where the streams in the area are gaining, losing or losing-disconnected (SKM, 2012).

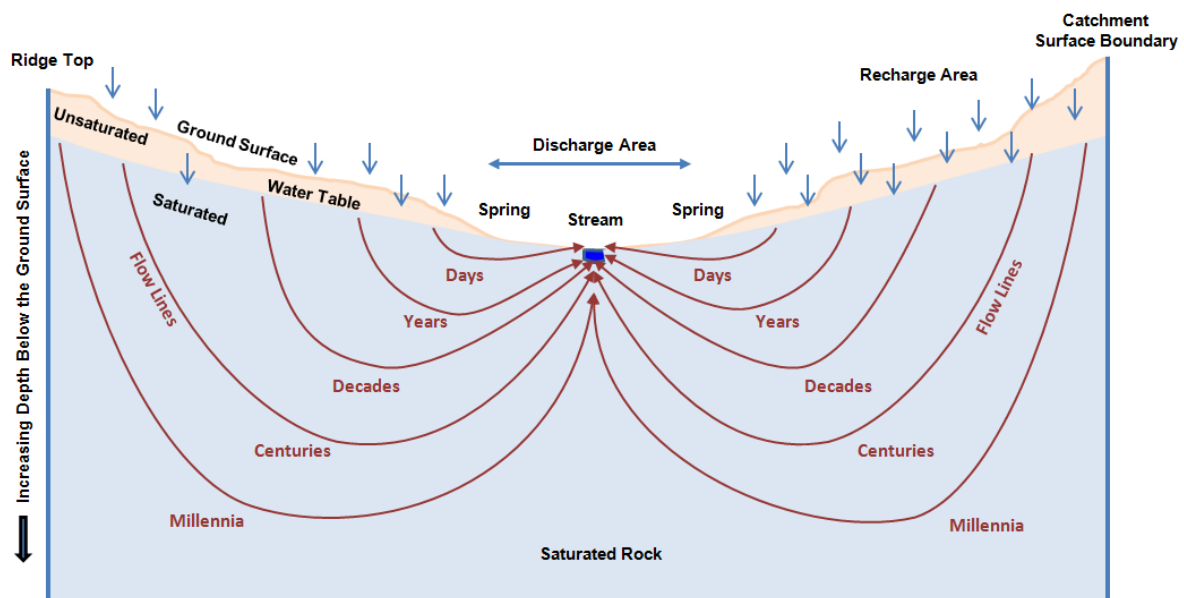


Figure 7.3: Cross section of a valley showing the expected direction and rate of groundwater movement (adapted from Winter et al., 1998; Waller, 2013).

PB (2012) has divided the region near Stratford into four major hydro-stratigraphical divisions:

- Alluvial aquifers, maximum depth 12 m, clays and gravels (3×10^{-1} to 500 m/day);
- Shallow rock aquifers, maximum depth 150 m, but commonly less than 100 m, consisting of fractured interbedded sandstone, siltstone and claystone (1×10^{-2} to 20 m/day);
- Interburden, low hydraulic conductivity interbedded sandstones, siltstones and claystones (2×10^{-6} to 6×10^{-3} m/day); and
- Coal seam water bearing zone (2.3×10^{-3} to 3×10^{-2} m/day).

PB (2012) has dated the age of the groundwater. The residence times indicated by the results presented in PB (2012) are consistent with the conceptualisation presented in Figure 7.3. The Permian coal measures contain water that has been dated to be less than or equal to 22,350 years old, 162-168 m below the ground surface, in strata that are millions of years

old (PB 2012, borehole S4MB03). This indicates that there is some degree of mixing between the near-surface groundwater and the groundwater within the coal measures at depth, and results reported in PB (2012) are consistent with the millennia flow paths known to exist in many basins throughout the world.

There are numerous core permeability and stress measurements results in the borehole completion reports archived in the DIGS database. These data have not been collated and reported in a single public domain document. This information could provide insights on the hydraulic properties of all strata and advance our understanding of connectivity within the Gloucester Basin. SKM (2012, page 29) also provide a listing of reports that contain hydrogeological measurements that could be used to increase the documented variability of hydrogeological properties of the rocks throughout the Gloucester Basin. The majority of the hydraulic conductivity measurements in the borehole completion reports are for core samples. As highlighted in Figure 3.4 (see Section 3), these are not representative of the regional scale permeability.

Within the Gloucester Basin there are few published packer and slug test results (22 and 5 respectively in PB, 2012). Hydraulic conductivities reported from these tests are within the expected ranges for each lithology listed in Figure 3.3 (see Section 3), with the exception of a low interburden sandstone reading.

Extensive seismic surveys have located the major faults in the Gloucester Basin (Grieves and Saunders, 2003; PB, 2012). However, the permeability and heterogeneity of the fault zones have not been studied. Future investigations will quantify the fault seal properties adjacent to coal beds from which the gas will be produced (SKM, 2012). Until they are proven to be sealing faults, it is reasonable to assume that the fault zones would provide pathways of hydraulic connectivity from the coal measures to the near surface. This is supported by the dating of the groundwater by PB (2012), which requires a groundwater flow path from the ground surface to the lower portions of the rock strata. Given the low hydraulic conductivity of the shales, siltstones and claystones that overlie the coal measures, groundwater movement from the ground surface to lower portions of the rock strata is either along the fault zones, through the fracture network, or along bedding plane joints (especially given the steeply dipping strata that outcrop at the ground surface).

For the Gloucester Basin, there are insufficient data on compressibility of the strata in the public domain to quantify potential subsidence impacts. The depressurisation of the coal measures required to produce gas will cause changes in pressure at all depths. This may have an impact on near surface hydraulic gradients (Pells, 2012).

There is no Groundwater Sharing Plan for the region; this reflects the small scale of groundwater extractions. Groundwater is extracted from the alluvial and near surface sandstone units for stock, minor irrigation, domestic, waste disposal, industrial and mining purposes (PB, 2012).

The River and Alluvial Water Sharing Plan that is associated with the Gloucester Basin is titled Lower North Coast Unregulated and Alluvial.

Details on the above listed Water Sharing Plans are available from the NSW Office of Water (<http://www.water.nsw.gov.au/Water-management/Water-sharing/default.aspx>).

8. Clarence-Moreton Basin

The Clarence-Moreton Basin is an elliptical-shaped intracratonic basin in the north-eastern corner of New South Wales, extending further north across the State border into Queensland (Figure 8.1). The NSW portion covers an area of 16,000 km², being more than 200 km N-S and 120 km E-W, and contains 3,000 to 4,000 m of mainly fluvial Triassic, Jurassic and possibly Cretaceous sedimentary strata (Stewart and Alder, 1995). These include three important coal-bearing intervals, the Nymboida and Ipswich Coal Measures (Triassic) and the Walloon Coal Measures (Middle Jurassic), with the latter being of most significance for coal seam gas development.

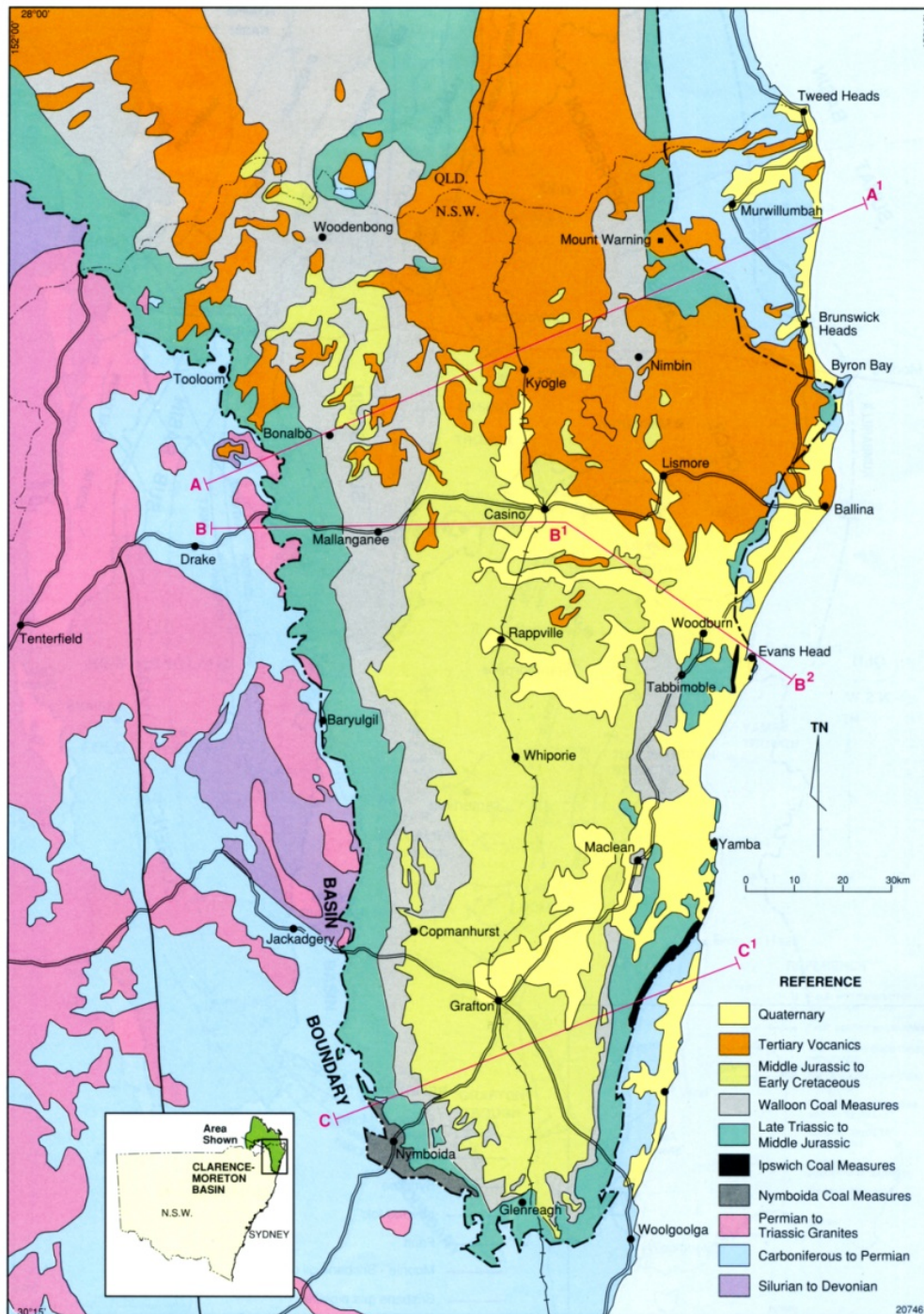


Figure 8.1: Surface geology of the Clarence-Moreton Basin (Stewart and Alder, 1995).

The basin is bounded in the west, south and east by metamorphic rocks and granites of the New England Fold Belt, and appears to have developed in response to movement on fault-bounded blocks in that basement associated with different phases of Permian and Triassic tectonism (Ingram and Robinson, 1996; Sommacal et al., 2008). In the north it is overlain by Tertiary basaltic material from the Mt Warning shield volcano. The Queensland portion of the basin continues north-westwards into the Surat Basin, with the boundary between the two being taken as the Kumberilla Ridge in the Darling Downs area (Goscombe and Coxhead, 1995).

Two sub-basins, the Laidley Sub-basin and the Logan Sub-basin, have been recognised in the New South Wales portion, separated by a structural high made up of the South Moreton Anticline and East Richmond Fault (Figure 8.2). Individual segments within the Logan Sub-basin include the Casino Trough, the Grafton Trough and the Mid-basin High.

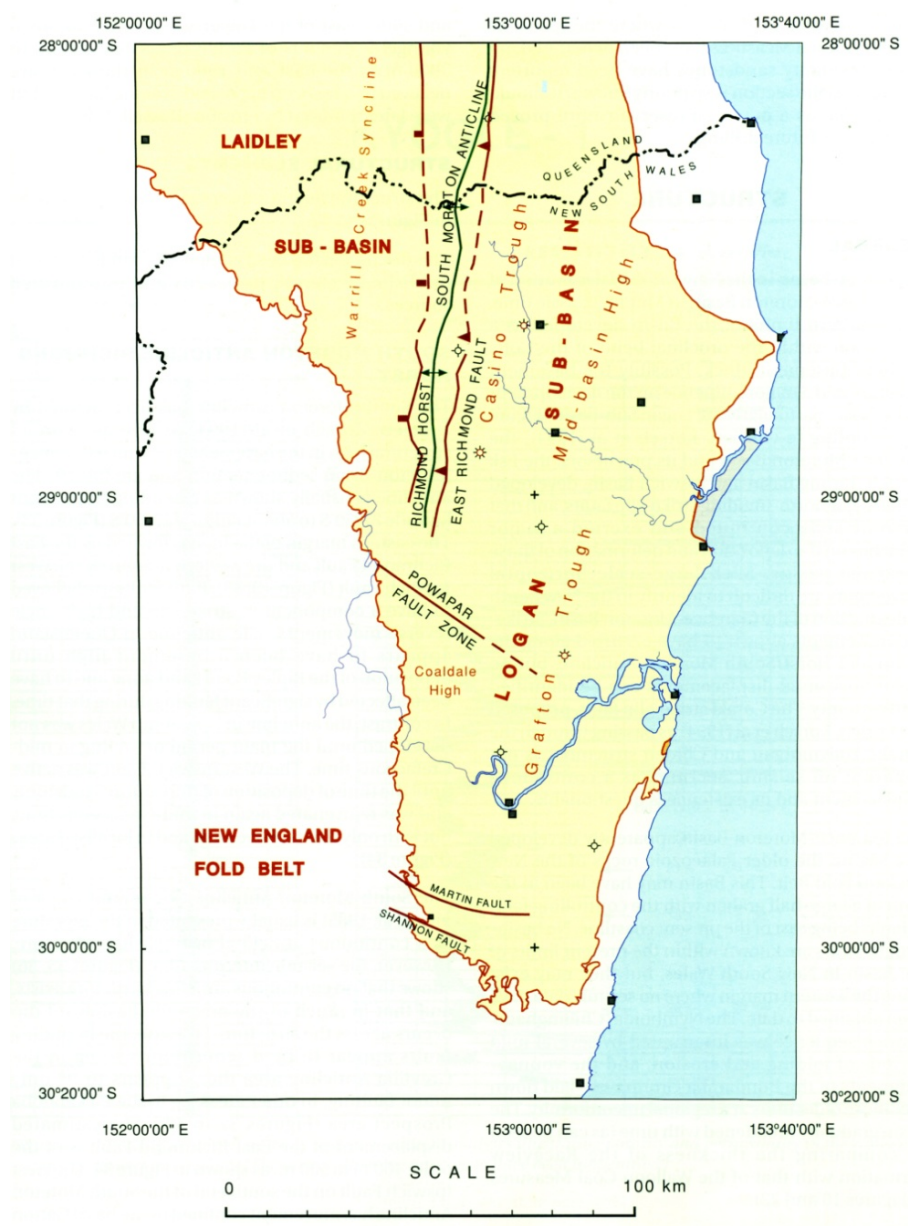


Figure 8.2: Major structural elements in the NSW portion of the Clarence-Moreton Basin (Ingram and Robinson, 1996).

8.1. Stratigraphy

The lowermost unit in the basin is the Middle Triassic Nymboida Coal Measures (Figure 8.3), which is a sequence of sandstone, shale, conglomerate, coal, tuff and basalt found mainly in the south-eastern part of the basin. This unit is of the order of 1,000 m thick (Stewart and Alder, 1995), and may have been formed under foreland basin tectonic conditions (Sommacal et al., 2008). It is exposed in the SW of the basin near Nymboida, where it rests unconformably on the basement rocks. Coal from the unit in that area has been mined for use in local power stations (Wells, 1995).

Other Triassic coal-bearing sequences, identified as the Ipswich, Red Cliff and Evans Head Coal Measures, overlie the Nymboida Coal Measures in different parts of the basin. The Ipswich Coal Measures are also exposed in the Queensland portion of the basin, where the coal has been mined for many years (Hutton and Wootton, 2009). The Red Cliff Coal Measures are of the order of 600 m in thickness, and consist of conglomerate, lithic sandstone, mudstone and coal (Wells, 1995). The Evans Head Coal Measures are about 300 m thick, and rest directly on the basement rock materials. These units may have been formed during a rift phase of basin development (Sommacal et al., 2008).

A thick sequence of Triassic rhyolites and tuffs, referred to as the Chillingham Volcanics, is exposed in the NE of the basin around Murwillumbah. These beds also underlie the Ipswich Coal Measures in the subsurface (Ingram and Robinson, 1996). They are similar to Late Triassic volcanics in the Queensland part of the basin, and thus were probably formed at around the same time as the Ipswich Coal Measures and equivalent successions.

? Cretaceous – Late Jurassic	Grafton Formation		
	Kangaroo Creek Sandstone		
Middle Jurassic	Walloon Coal Measures		Maclean Sandstone Member
Early Jurassic	Bundamba Group	Marburg Subgroup	Koukandowie Formation
			Gatton Sandstone
Woogaroo Subgroup		Ripley Road Sandstone	
		Raceview Formation	
		Laytons Range Conglomerate	
EarlyLate Triassic	Ipswich, Red Cliff and Evans Head Coal Measures	Chillingham Volcanics	
Middle Triassic	Nymboida Coal Measures	Basin Creek Formation	
		Bardool Conglomerate	
		Cloughers Creek Formation	
Palaeozoic	Coffs Harbour Beds / Neranleigh-Fernvale Group		

Figure 8.3: Stratigraphic units in the Clarence-Moreton Basin (after Brown et al., 1996)

Unconformably overlying these Triassic coal-bearing and volcanic units is a Late Triassic to Early Jurassic sequence of sandstone, conglomerate, shale and minor coal, up to around 1,200 m thick, referred to as the Bundamba Group. Details of the five different formations recognised within this sequence (Figure 8.3) are given by Ingram and Robinson (1996). Some documents, including the compilation by Stewart and Alder (1995), describe the upper part of the Bundamba Group as the Marburg Formation, rather than the Marburg Subgroup.

The Raceview Formation consists of thinly interbedded shales, sandstones, minor conglomerates and thin coal beds, with a well-cemented coarse-grained unit, the Laytons Range Conglomerate, at the base of the sequence on the flanks of the basin. The Raceview Formation is overlain by a mainly quartz-rich fluvial sandstone sequence referred to as the Ripley Road Sandstone.

The Gatton Sandstone overlaps the underlying formations of the Bundamba Group, and further west may rest directly on the basement rocks (Ingram and Robinson, 1996). Like the Ripley Road sequence, this unit also consists mainly of medium- to coarse-grained, quartz-rich fluvial sandstone, although a finer-grained sandstone unit, the Calamia Member, occurs at the base. The Koukandowie Formation, at the top of the Bundamba Group, consists of fine- to coarse-grained quartz-lithic sandstone, with a variable sequence of sandstone, siltstone and shale (Ma Ma Creek Member) at the base. Another part of the unit, the Heifer Creek Sandstone Member, is regarded by Ingram and Robinson (1995) as a potentially favourable reservoir bed for conventional hydrocarbon (oil and gas) accumulation.

Overlying the Bundamba Group is the extensive sequence of the Middle Jurassic Walloon Coal Measures. This unit crops out around the margins of the NSW portion of the basin, and reaches a maximum thickness of around 600 m in the area of the Casino Trough (Ingram and Robinson, 1996). The Walloon Coal Measures are also found in the Queensland portion of the basin, and extend across the Kumberilla Ridge into the Surat Basin as well (Goscombe and Coxhead, 1995).

In the NSW portion of the basin the Walloon Coal Measures consist of volcanoclastic silty sandstones and shales, interbedded with numerous coal seams. Some of these coals have been mined, for example in the area around Bonalbo in the north-west of the basin. The sequence was deposited by sluggish streams meandering across a wide swampy floodplain, with volcanic ash falls commonly clogging the drainage system (Ingram and Robinson, 1996). A feldspathic sandstone interval, the Maclean Sandstone Member, is present at the top of the formation. Igneous intrusions (sills) are also encountered in parts of the Walloon Coal Measures, possibly associated with localised dome-like features in the basin structure.

High-energy fluvial conditions returned to the Clarence-Moreton Basin in the Late Jurassic, with deposition of the medium- to coarse-grained, quartz-rich Kangaroo Creek Sandstone (Goscombe and Coxhead, 1995). This sequence is overlain by the lithic-quartz sandstones and montmorillonite-bearing mudstones of the Grafton Formation. The latter unit contains plant fossils and traces of coal, and is the youngest formation in the NSW portion of the basin.

A geological cross-section from west to east, through Casino and Evans Head (line B-B in Figure 8.1) is given in Figure 8.4.

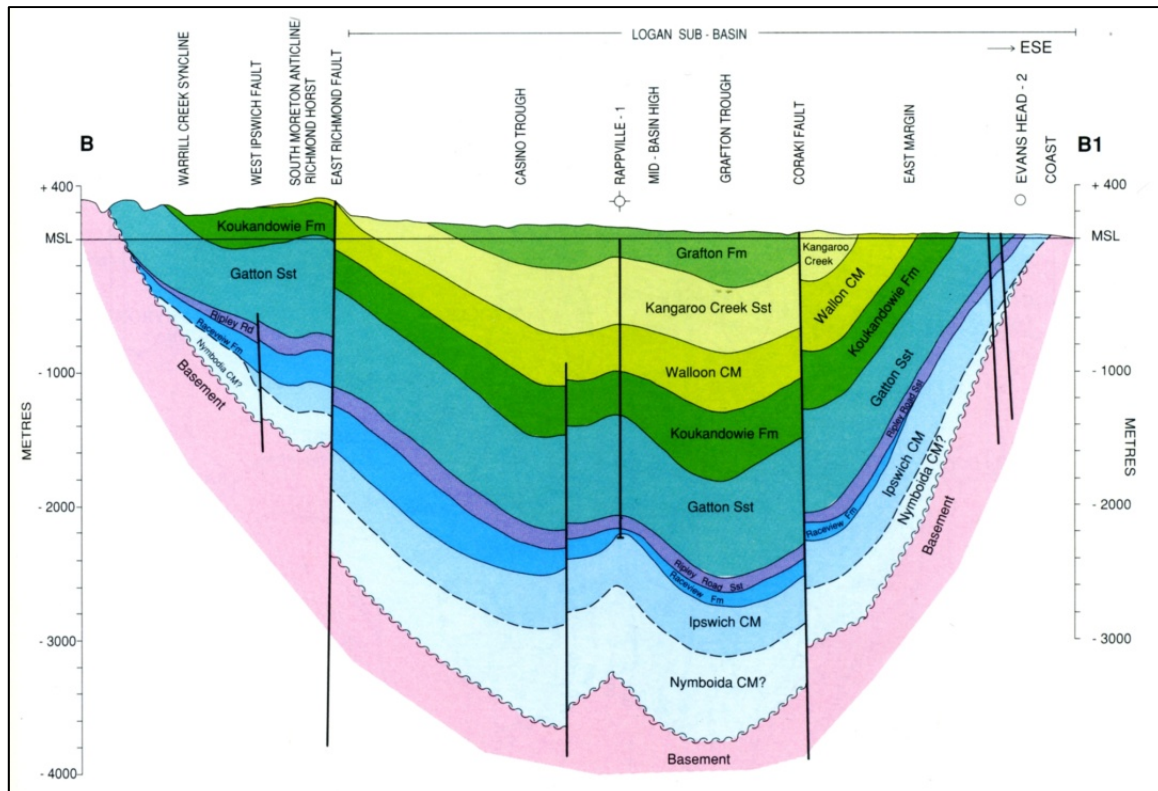


Figure 8.4: Geological cross section through the Clarence-Moreton Basin from Drake through Casino to Evans Head (Ingram and Robinson, 1996).

8.2. Coal Seam Gas

Gas has been noted in the coal seams of the Nymboida Coal Measures (Ingram and Robinson, 1996), including an explosion in underground mine workings in 1956. Vitrinite reflectance levels average 0.95% in the SW part of the basin, and increase to more than 2.5% in the east, making the unit prospective for thermogenic gas generation. However, individual seams appear to persist over distances of <2 km, and because of the relatively steep dip (about 15° at the basin margins) the sequence reaches depths of >1,000 m within about 15 km of the outcrop area (Figure 8.5). Ingram and Robinson (1996) suggest that the Nymboida and Ipswich Coal Measures may have potential for CSG resources in the area between the up-dip edge and the 1,000 m cover line, although no additional exploration appears to have been carried out at this stage.

By contrast, extensive exploration for CSG has been carried out in the Walloon Coal Measures, especially in the area of PEL 13 and PEL 16 near Casino. The Walloon Coal Measures crop out 10 to 30 km inside the basin margins (Figure 8.5), and occur at depths of between 130 and 800 m in the Casino Trough and adjacent areas. Greatest aggregate coal thicknesses occur in the northern part of the Casino Trough (Ingram and Robinson, 1996), with up to 58 m of coal reported in a borehole near Kyogle, together with a nett coal thickness of 20 m in the underlying Koukandowie Formation. Metgasco (2013) has identified 11 seams near Casino, with nett coal thicknesses of between 2 and 9 m.

Vitrinite reflectance for the Walloon Coal Measures ranges from 0.8% on the western side of the basin to more than 1.4% on the eastern side (Ingram and Robinson, 1996). Combined with the variation in net coal thickness, this suggests that the area near Casino (green colour in Figure 8.5) has the greatest potential for CSG resources. The area to the south (blue in Figure 8.5) may also have some potential, with moderate but still significant coal thicknesses and relatively high maturation (rank) levels.

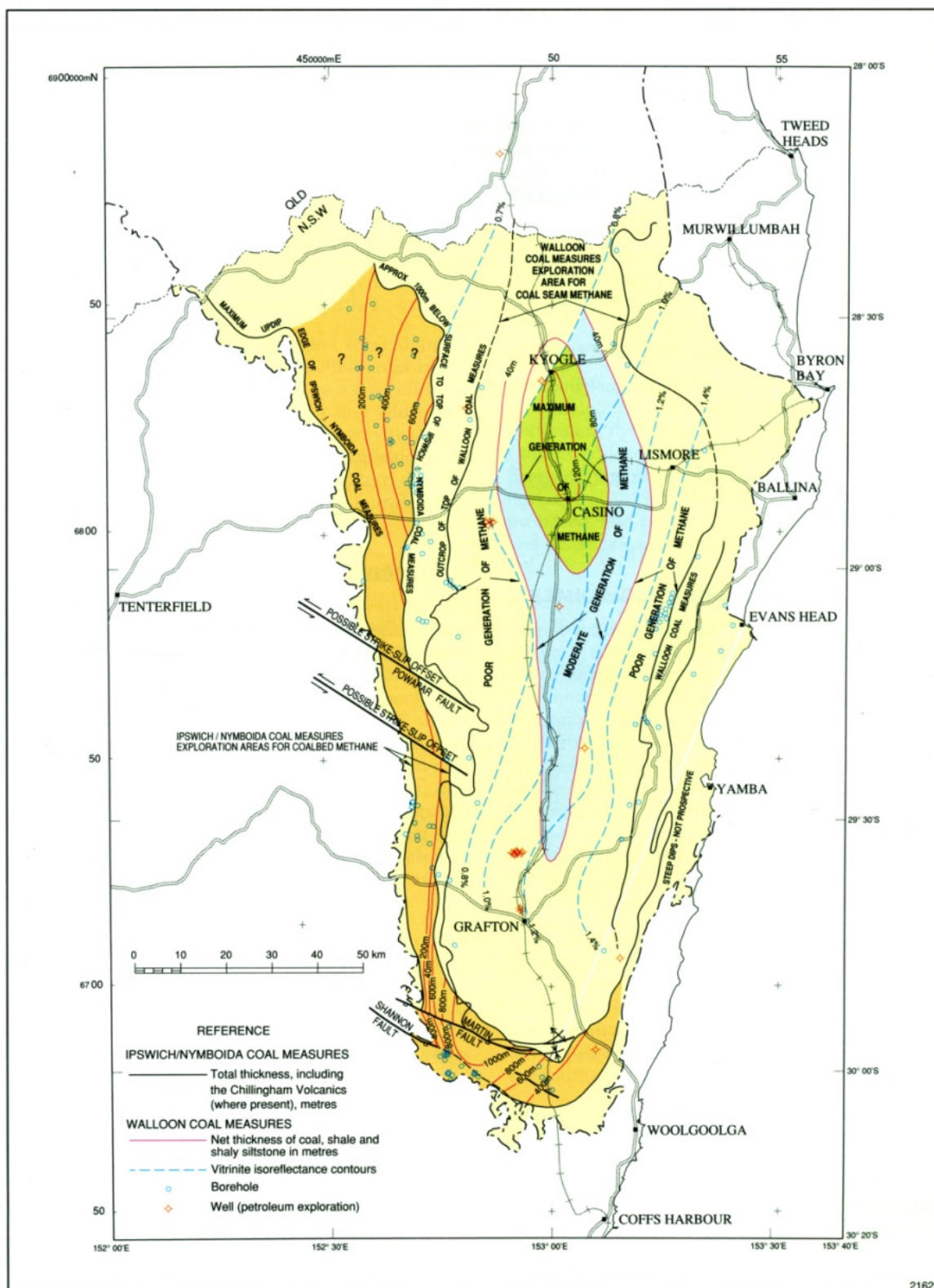


Figure 8.5: Coal seam gas exploration areas in the Clarence-Moreton Basin (Ingram and Robinson, 1996). Colour codes: Orange – favourable depth and structure for Ipswich and Nymboida Coal Measures; Green – Maximum generation from Walloon Coal Measures; Blue – Moderate generation from Walloon Coal Measures.

Metgasco (2013) indicates that the seams in the area of PEL 16 have high gas content, and indeed tend to be oversaturated with gas. Gas composition analysis indicates approximately 98% or more methane and a negligible CO₂ content.

The NSW Department of Trade and Investment (2012) indicates 2P methane reserves of 397 PJ and 3P reserves of 2,239 PJ in PEL 16. A further 13 PJ of 2P reserves and 302 PJ of 3P reserves are indicated for PEL 13. Metgasco (2013) indicates an additional contingent (2C) resource of 2,511 PJ.

8.3. Hydrogeology

Water resources within the Clarence-Moreton have recently been comprehensively reviewed for Rouse Water by PB (2011). The major aquifers are summarised in Table 8.1.

Table 8.1: Summary of the major geological units and their hydrogeological properties (adapted from PB, 2011).

Formation	Geology	Aquifer Type	Typical Thickness (m)	Bore Yield (well)	Water Sharing Plan
Coastal Sands	Unconsolidated sand	Unconfined	15 m	Common Range 0.5 to 6.0 L/s Maximum 34 L/s	No
Estuarine and Fluvial River Alluvium	Unconsolidated sand	Unconfined	25 m	Common Range 0.5 to 2.0 L/s Maximum 15 L/s	Yes
Alstonville Basalt/ North Coast Basalt	Fractured basalt	Unconfined	60 m	Common Range 1 to 15 L/s Maximum 38 L/s	Yes/No
Kangaroo Creek Sandstone	Medium grained sandstone, which is porous and fractured	Semi-Confined	436.5 KE01 Well 434.5 m Riflebird E5 Well	Typically < 1.0 L/s Potential 10 L/s	No
Walloon Coal Measures	Interbedded coals, shales and isolated sand channels.	Semi-Confined Upper most Maclean Sandstone Member is unlikely to be an aquitard. On a local scale floodplain shale and mudstone deposits may act as an aquitard	185.3 m KE01		No
Bundamba Group		Mudstones layers within the Koukandowie Formation would act as aquitards	263.9 m KE01		

The Alstonville Basalt, associated with the Mount Warning Complex, is the most extensively used aquifer in the region. A detailed map of all the boreholes and their respective yields is presented on page 7 of PB (2011). There is potential to increase the extraction of groundwater from the Kangaroo Creek Sandstone.

The region has undergone periods of extension and compression, which have formed an extensive fracture network throughout the basin. The statistics on the fracture network have not been collated. There is the potential for increased vertical hydraulic connectivity along the West Richmond and East Richmond Faults. This depends on the nature of the fault sealing material, and to date this has not been assessed.

Within the Clarence-Moreton Basin there are no continuous claystone or shale layers that would prevent, at a regional scale, the movement of fluid between the Walloon Coal

Measures and the overlying strata. On a local scale, the floodplain deposits in the Maclean Sandstone Member would act as an aquitard between the coals and the Kangaroo Creek Sandstone.

Before an assessment can be made of any large scale coal seam gas production impacts on the likelihood of subsidence, further work is required to assess the tensile strength, compressibility, hydraulic conductivity, and storativity properties of the rocks within the basin, and in particular within the Walloon Coal Measures.

8.3.1. *Water Sharing Plans*

Groundwater Sharing Plan within the Clarence-Moreton Basin boundary: Alstonville Plateau Groundwater Sources:

River and Alluvial Water Sharing Plans within the Clarence-Moreton Basin boundary include: Coopers Creek; Richmond River Area Unregulated, Regulated and Alluvial; Tweed River Area Unregulated and Alluvial; Upper Brunswick River.

Details on the above listed Water Sharing Plans are available from the NSW Office of Water (<http://www.water.nsw.gov.au/Water-management/Water-sharing/default.aspx>).

9. Concluding Comments

Based on the work of numerous geological scientists over more than 100 years there is a very good level of knowledge on the stratigraphy and depositional history of the sedimentary basins in New South Wales. Acquisition of this knowledge has been stimulated for most of the basins under discussion by drilling and associated activities associated with evaluation of coal, hydrocarbon and groundwater resources. The geological structure and tectonic history of the basins is also relatively well understood, at least at the broad, basin-wide scale. However, as has been found in the course of coal mining and civil engineering projects, many smaller-scale structural features, such as individual faults and dykes, may only be identified when excavations and other developments involving the strata are actually carried out.

Despite this general understanding of the stratigraphy and structure, knowledge about on the hydrogeology, and in particular detailed information on the hydraulic connectivity between the coal measures and the overlying aquifers in the basins, is limited. New information is continually being collected from drilling programs, core sampling, in-situ hydraulic conductivity measurements, and geophysical mapping for particular projects, but the results of such studies are mostly project-specific and not readily available in the public domain.

With respect to hydrogeological investigations it is important to note that, until a site is hydraulically stressed by CSG production, it will always be difficult to predict in detail how the region will respond, how well individual faults will seal, and where the preferential flow paths through the fractured rocks are located. It may take years or decades of pumping before some aspects of the hydraulic boundary conditions are fully known.

The purpose of this background paper is to provide a summary of the geology that underpins the occurrence and development of coal seam gas in New South Wales, and also the basic elements of the hydrogeology of the regions with potential for CSG development. Although areas where uncertainty exists are indicated, such as in the extent of hydrogeological data available to assess the likely response of groundwater systems to CSG development, a more extensive review on a site-by-site basis is required before any further comments can be offered at a project or basin-wide scale.

An indication of the factors that might be included in developing a better understanding of the hydrogeological response to CSG development is provided in a review of the techniques available for hydrogeological modelling of CSG impacts, attached as Appendix I to this background paper. A brief summary of NSW Water Sharing Plans, which also need to be integrated with hydrogeological studies for CSG development, is given in Appendix II.

Although not covered in this review, the quality of the groundwater in the coal and other aquifers, including factors such as salinity, major and trace elements, organic components and possibly micro-organisms, also needs to be considered in the context of appropriate baseline data for the site and surrounding region. This has implications for the environmental assessment and water management in CSG projects, including options for water treatment, discharge, re-injection or beneficial use.

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August 21, 2013

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Hydrogeological Modelling of CSG Impacts

The recently updated Australian Groundwater Modelling Guidelines (AGMG, Barnett et al., 2012) should be read in conjunction with this document. The guideline clearly outlines the requirements for groundwater modelling and reporting. This guideline does not focus on coal seam gas. Another drawback to the guideline is that it focuses on calibrating groundwater models where there is a good length of record, which enables the calibration, sensitivity analysis and verifications of model parameter selection. At most locations where CSG developments have been proposed the groundwater records are limited.

There are few published examples of post-audited surface and sub-surface flow models (Karlsen et al., 2012, and references cited therein). A common issue where models performed poorly is that the conceptual geological model had errors.

Below is an introduction to some of the issues that relate to developing a 3D conceptual geological model of CSG production sites and fluid flow simulation models. At most locations where there is active CSG exploration the total volume of the exploration boreholes represents a tiny fraction of the rock mass within the region of interest (commonly less than a fraction of a percent). Ground based geophysical surveys and well-logs assist with improving the coverage of properties measured, but in the case of surface geophysics the vertical resolution of the data is low, and geophysical well-logs only sample a small volume around a well. At any site only a small fraction of the rocks will be sampled and their physical properties measured (porosity, permeability, tensile strength etc). Some important properties will be difficult to measure, such as the tensile stress of the fractures, joints, and faults. This is particularly relevant to the Gloucester region where the geology is moderately complex due to folding and faulting of the strata.

There will be uncertainty in the conceptualisation of the geology, hydrogeology (structure), the data used for calibration (inputs), and the calculated set of calibrated model parameters. Differences in model structure, inputs, and parameter selection results in different fluid flow simulation outcomes. The extent of the uncertainty needs to be quantified so that it can be managed. Conceptualisation of the problem to be modelled (for example, how many hydrostratigraphic layers do you incorporate into the model, and do you need to include faults?) is one of the largest potential sources of uncertainty and is difficult to define. Uncertainty associated with parameter estimation is a more tractable problem. Both structure and parameter uncertainty are topics of considerable debate in the scientific literature (Pappenberger and Beven, 2006; Renard et al., 2010; Clark et al., 2012; Beven et al., 2012; Beven 2013; Yoon et al., 2013). Structure uncertainty is often not examined, because of time and cost constraints. **Best practice will address both parameter and structure uncertainty as part of an environmental impact assessment.** The issue of just how much variability there is in interpreting geological data sets is highlighted in the northern Yucca Flats case study from the USA (Ye et al., 2010). At this site there are 5 different geological models that are consistent with the data available (59 wells, DEM, geophysical surveys and field mapping). The scale of the northern Yucca Flats case study is similar to many CSG projects.

Barnett et al. (2012) do not discuss in detail multiple conceptual models (see page 102 of Barnett et al., 2012). At new coal seam gas development locations, ambiguity in the interpretation of the hydrostratigraphic structure and how that is represented in the flow simulations will have the largest impact on predictions. **It is recommended that multiple models (Rojas et al. 2010; Ye et al., 2010) be used as part of assessing the uncertainty**

in the predictions. Strategies for handling geological uncertainty were recently reviewed by Refsgaard et al. (2012).

Conceptual Geological Models

For most major mine, oil, and gas projects a 3D geological model is built to represent the conceptual understanding of the geological structure (strata tops and fault surfaces) and the distribution of changes in physical properties (porosity, permeability, water quality etc). 3D geological models are built by integrating information from geophysical surveys (e.g. seismic, electrical, gravity and magnetics), geological maps, borehole lithological logs, and borehole geophysical logs.

Hydrogeologists use 3D geological modelling as a framework to:

- represent how many hydrostratigraphic layers they need to incorporate into groundwater flow models;
- approximate the lithology between boreholes, and the distribution of porosity and hydraulic conductivity (permeability);
- map dominant pathways of connectivity;
- map fault planes and fault intersections; and
- represent fracture networks.

The workflow for constructing 3D geological models is comprehensively discussed in Caumon et al. (2009) and De Donatis et al. (2012).

In the context of CSG developments the 3D geological models are also useful for communicating to decision makers and the public the spatial relationships between the coal measures and aquifers. To date in NSW at the proposed CSG development sites no 3D geological models have been constructed that take into account faulting and fracture networks.

There are many companies that have developed software to meet the needs of the geological community that can be used to build 3D geological models in faulted and folded environments.

Geological structural and property models are useful for highlighting data gaps and where new exploration wells should be targeted. **It is recommended that a 3D geological model be constructed at each new CSG exploration and production location.** Ideally an interactive version of the model would be placed on the web. There are many examples from the USA on the internet:

<http://pubs.usgs.gov/sir/2004/5226/>

http://pubs.usgs.gov/dds/dds-033/USGS_3D/ssx_txt/all.htm

https://newsline.llnl.gov/rev02/articles/2009/may/05.22.09-modeling_print.php

Hydrostratigraphy

How the hydrostratigraphy is conceptualised is critical for assessing the impact of CSG production on fluid-flow. The lithostratigraphy does not always align with the hydrostratigraphy. The hydrostratigraphy is determined using a combination of information inputs including piezometers (and their associated groundwater hydrographs), packer, and pumping tests.

It is not realistic, or necessary, to capture all details of the geology in a regional scale fluid-flow simulation. **When a simplified model structure is used to predict the impact of CSG production supporting evidence for the model simplification needs to be provided.** For

example the data must demonstrate that it is reasonable to combine stratigraphic layers into a single hydrostratigraphic layer, or that it is reasonable to assume homogeneous values for a given hydrostratigraphic layer.

Modelling Faults

Hydrostratigraphic layers can be further compartmentalised by faults. Faults are usually mapped in the field, within well-logs, or by undertaking seismic or electrical surveys. Faults are often represented as planes, but it is generally recognised that they are a zone of altered material (Cerveny et al., 2004). Faults can act as seals or be conduits of fluid flow. How a fault influences fluid-flow ultimately has to be measured in the field using pumping tests and production data, but the likely behaviour of a fault can be inferred from micro-structural information, and core analysis (Cerveny et al., 2004). **A fault cannot be ignored in flow simulations, unless it has been demonstrated that the fault:**

- **does not alter the local stress field,**
- **does not act as a hydraulic barrier, and**
- **does not act as a conduit of fluid flow.**

Assigning fault picks between seismic sections and assigning a fault pick from within a well-log to a fault plane is still largely a manual process. There will always be ambiguity in constructing a fault tree (Hoffman and Neave, 2007, Cherpeau, 2010).

It is recommended that where faults are known to exist, a fault analysis be completed.

A comprehensive fault seal analysis will describe the mechanism of fault creation, the fault geometry, lithological juxtaposition, the clay content or the identification of low permeability deformation bands, the internal fault zone architecture, pressure/stress directions, and fault rock geometrical properties (Cerveny et al., 2004).

Fracture Networks

Consideration must be given to the impact of fracture networks. Fracture networks should be mapped in outcrops (Chesnaux, 2009), and in boreholes using a range of geophysical tools: heat pulse, gamma logging, self potential, fluid electrical conductivity, borehole camera inspections, and packer tests, (Morin et al. 1997, Wu and Pollard, 2002). Given enough data on variability of fracture density and geometry (vertical and horizontal extent, aperture, dip and dip azimuth), it is possible to simulate the distribution of fractures throughout each strata, and to assess their influence on fluid-flow (Berkowitz, 2002; Neuman, 2005).

Because it is impossible to construct the actual fracture networks, multiple representations of the fracture network need to be constructed, and these multiple frameworks used to assess the sensitivity of the model outputs to the input fracture network. One of the dominant paradigms for modelling fracture networks is Discrete Fracture Network (DFN) modelling (Cacas, 1990), but there is also active development of Multiple Point Statistics, and Marked Point Processes (Dowd et al., 2007).

DFN models are usually applied in a stochastic workflow, where multiple realisations of the fracture network are used in multiple fluid-flow simulations (Berkowitz, 2002). Because of the computational demands of modelling the movement of fluid flow through a DFN framework, DFN models are usually up-scaled to cells, which have the same equivalent volume averaged hydrogeological properties as the combined fractures and porous media (Quental et al., 2012; Jafari and Babadagli, 2012). Geological structural and property frameworks developed this way are usually used for forward predictions.

Depending on the purpose of the model, the scale of a cell can range from the order of a metre to hundreds of metres. In geological settings where there is no evidence of faulting, dykes or fracture “pipes”, it is not necessary to incorporate the fine geological detail in a flow model to assess the impact of a CSG production impacts. This is the situation in portions of the Sydney Basin. Where the density of fractures is high, they can be represented as patches of high hydraulic conductivity cells.

Modelling fluid flow in faulted and fractured rock is a complex task (Berkowitz, 2002; Neuman, 2005), and there is no universally agreed approach to modelling such environments. This is reflected by the recently established carbon capture and storage multi-model simulation project called Sim-SEQ (Mukhopadhyay et al., 2012a). This project has been set up to compare predictions and model uncertainty. Fifteen groups are using leading flow-simulation packages to assess model uncertainty at a location where CO₂ is being injected into a depleted oil and gas reservoir. A full listing of participating research institutions, commercial software developers, and petroleum companies is listed in Mukhopadhyay et al. (2012a), and preliminary results are presented in Mukhopadhyay et al., (2012b).

The key message from the Sim-SEQ project is that one flow simulation model of a CSG production site will not adequately characterise the uncertainty. **It is recommended at each CSG development location that the impact of fractures on fluid-flow be assessed using multiple models.**

Models Fit for Purpose

Models are simplifications of reality. We cannot expect any CSG fluid-flow model to capture every detail. This does not make them wrong (Bakker, 2013). If a model is well designed it will allow us to gain insights about processes we cannot measure in the field or at a particular point in time or space. There will always be uncertainties in models, but they can be constrained (Beven and Alcock, 2012). In this regard it is important that sufficient effort be put into mapping the stratigraphy, faults, fracture networks, and hydrogeological properties of the strata (from core to field scale).

It is inevitable that simplifications will be made in all geological and fluid-flow models, but the simplifications of the geology and hydrostratigraphy need to be justified. When this is done it needs to be documented how such assumptions will be tested and validated or rejected against appropriate assessment criteria (Beven and Alcock, 2012).

If the scale of the CSG development is to be large, then ideally, fluid-flow modelling should be coupled with geomechanical modelling to enable the best practice assessment of near surface impacts of CSG production at depth (Hobbs et al. 2000; Rutqvist et al., 2002; Connell and Detournay, 2009; Ji et al., 2009).

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Appendix II

NSW Water Sharing Plans

NSW Water Sharing Plans were established to balance over the long-term the water requirements of the environment and users. The Plans are separated into Water Sharing Plans for regulated and unregulated creeks, rivers and alluvial systems, and groundwater plans for deep alluvial, porous rock and fractured rock aquifers. The rules within the plans are structured to share the water to meet the environmental needs of river and aquifers, and civil water requirements for town, rural domestic, stock watering, industry and irrigation farming.

Water Sharing Plans have been gradually implemented throughout New South Wales following the introduction of the *Water Management Act 2000*. Comprehensive details on the plans are available on the Department of Primary Industries Office of Water internet site: <http://www.water.nsw.gov.au/Water-management/Water-sharing/default.aspx>

The NSW Office of Water has outlined how coal seam gas activities must work within the Water Sharing Plans and honour the NSW Aquifer Interference Policy. Comprehensive details are provided at the following internet site: <http://www.water.nsw.gov.au/Water-management/Groundwater/Water-and-coal-seam-gas/Water-and-coal-seam-gas>