2009

Geological Setting of Australasian Coal Deposits

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Publication Details
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Abstract
Coal was discovered in Australia in 1791 by William Bryant, a convict, near the mouth of the Hunter River at Newcastle, New South Wales (NSW). Later discoveries were made along the Brisbane River and near Ipswich in the 1820s. Mining commenced in Australia in 1799, also in NSW. The earliest scientific input to coal exploration was when Sir Joseph Banks, in 1799, introduced drilling equipment to Australia (Bryan, 1990a). Since then, production of coal has occurred in all states with the exception of the Northern Territory. In NSW, Queensland and Western Australia the mined coal is predominantly of bituminous rank, whereas in South Australia, Tasmania and Victoria the coal is sub-bituminous or brown in rank. NSW and Queensland have the largest resources of bituminous coal with the bulk of the production coming from NSW prior to the development of the extensive Bowen Basin coal deposits in Queensland. Queensland is now the largest producer of coal in Australia. The majority of Australia's brown coal reserves are located and mined in Victoria with most used for electricity generation.

Keywords
coal, deposits, geological, australasian, setting

Disciplines
Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

This book chapter is available at Research Online: http://ro.uow.edu.au/scipapers/733
INTRODUCTION

Coal was discovered in Australia in 1791 by William Bryant, a convict, near the mouth of the Hunter River at Newcastle, New South Wales (NSW). Later discoveries were made along the Brisbane River and near Ipswich in the 1820s. Mining commenced in Australia in 1799, also in NSW. The earliest scientific input to coal exploration was when Sir Joseph Banks, in 1799, introduced drilling equipment to Australia (Bryan, 1990a). Since then, production of coal has occurred in all states with the exception of the Northern Territory. In NSW, Queensland and Western Australia the mined coal is predominantly of bituminous rank, whereas in South Australia, Tasmania and Victoria the coal is sub-bituminous or brown in rank. NSW and Queensland have the largest resources of bituminous coal with the bulk of the production coming from NSW prior to the development of the extensive Bowen Basin coal deposits in Queensland. Queensland is now the largest producer of coal in Australia.

The majority of Australia's brown coal reserves are located and mined in Victoria with most used for electricity generation.

Although European and North American coals were deposited during the Carboniferous, virtually no economic coal was deposited in the Gondwanaland palaeocontinent, the predecessor of the Australian, African, Antarctic, Indian and South American continents. Non-economic Carboniferous coal has been described by Staines (1975). Minor occurrences have been identified in all states but are of little extent, thin or of high ash. The bulk of Australian coal accumulated during the Permian and Tertiary periods. Triassic coal is less abundant but does have economic significance in the southern and eastern states, particularly Queensland, South Australia and Tasmania.

The Australian Bureau of Statistics (2007) gives Australia's total estimated bituminous coal resources as 39.2 gigatonne which is approximately five per cent of the world total and the sixth largest in the world. Australia’s brown coal resources were given as 37.4 gigatonne, the largest in the world and 24 per cent of the world total. The majority of Australia’s resources of metallurgical coking and bituminous thermal coal occurs in the Permian deposits of the Sydney and Bowen Basins of NSW and Queensland. Figure 1 shows the distribution of Australian coals. Table 1 shows estimated sub-bituminous and bituminous identified in situ coal resources subdivided by States. Table 2 gives the production figures for 2004. Australia was the fourth largest bituminous coal producer in the world in 2004-05 and the world’s fifth largest brown coal producer.

Coal production in the 1950s was approximately 20 Mt, mostly for domestic use (Bryan, 1990a). Bituminous coal is now Australia’s largest commodity export, with a value of approximately $A24.5 billion in 2005-06 – an increase of 43 per cent over 2004-05. In 2005-06 bituminous coal accounted for 19 per cent of Australia’s total commodity exports.

An excellent summary of the geology of most Australian coal deposits, including seam descriptions, structure and coal quality, was given in Traves and King (1975) with a more up to date review in Ward et al (1995). Harrington et al (1989) gave a detailed analysis of the Permian coals of eastern Australia.

### TABLE 1 - Identified in situ black coal resources (2006) (from Australian Coal Association, 2006)

<table>
<thead>
<tr>
<th>State</th>
<th>Underground Mt</th>
<th>Open pit Mt</th>
<th>Total Mt</th>
</tr>
</thead>
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<tr>
<td>New South Wales</td>
<td>19 530</td>
<td>14 530</td>
<td>34 110</td>
</tr>
<tr>
<td>Queensland</td>
<td>20 080</td>
<td>17 300</td>
<td>29 380</td>
</tr>
<tr>
<td>South Australia</td>
<td>2 450</td>
<td>3 100</td>
<td>5 550</td>
</tr>
<tr>
<td>Western Australia</td>
<td>890</td>
<td>1 300</td>
<td>2 190</td>
</tr>
<tr>
<td>Tasmania</td>
<td>500</td>
<td>20</td>
<td>520</td>
</tr>
<tr>
<td>Total Australia</td>
<td>35 450</td>
<td>36 300</td>
<td>71 750</td>
</tr>
</tbody>
</table>
### TABLE 2 - Production of black coal Australia, 2003-2004

<table>
<thead>
<tr>
<th>Mining method/State</th>
<th>Raw coal Mt</th>
<th></th>
<th></th>
<th>Saleable coal Mt</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2003</td>
<td>2004</td>
<td>2005</td>
<td>2003</td>
<td>2004</td>
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<tr>
<td>Underground</td>
<td>80.9</td>
<td>81.5</td>
<td>89.2</td>
<td>65.8</td>
<td>65.1</td>
</tr>
<tr>
<td>Open pit</td>
<td>271.3</td>
<td>296.3</td>
<td>309.6</td>
<td>213.3</td>
<td>231.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>352.1</strong></td>
<td><strong>377.8</strong></td>
<td><strong>398.9</strong></td>
<td><strong>279.0</strong></td>
<td><strong>296.7</strong></td>
</tr>
<tr>
<td>New South Wales</td>
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<td>152.3</td>
<td>158.9</td>
<td>113.3</td>
<td>117.2</td>
</tr>
<tr>
<td>Queensland</td>
<td>197.8</td>
<td>215.2</td>
<td>229.3</td>
<td>156.1</td>
<td>169.4</td>
</tr>
<tr>
<td>South Australia</td>
<td>3.2</td>
<td>3.5</td>
<td>3.6</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Western Australia</td>
<td>6.0</td>
<td>6.3</td>
<td>6.4</td>
<td>6.0</td>
<td>6.3</td>
</tr>
<tr>
<td>Tasmania</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total Australia</strong></td>
<td><strong>352.1</strong></td>
<td><strong>377.8</strong></td>
<td><strong>398.9</strong></td>
<td><strong>279.0</strong></td>
<td><strong>296.7</strong></td>
</tr>
</tbody>
</table>

**FIG 1** - Bituminous coal deposits in Australia (adapted from Harrington, 1989)
NEW SOUTH WALES
BITUMINOUS COAL

In NSW, several basins contain significant deposits of bituminous coal, with the largest and most economically important being the Sydney Basin. Excellent outcrop of near-surface deposits, convenient to shipping facilities, such as at Wollongong and Newcastle, assured the early development of a coal industry in the Sydney Basin which for many years was the major bituminous coal producer in Australia.

The Sydney Basin is a large sedimentary basin located on the east coast of Australia and is part of the larger Sydney-Gunnedah Basin (Figure 2) which in turn is part of the much larger contiguous Sydney-Gunnedah-Bowen Basin that extends from coastal southern NSW to central Queensland. The Sydney Basin is separated from the Gunnedah Basin by the Mt Corricudgy Anticline (Herbert and Helby, 1980). The northern boundary of the Sydney Basin is faulted against the New England Fold Belt (also called the New England Orogen) by the Hunter-Mooki Thrust (Blayden, 2003) but to the west and south the basin sequence onlaps the basement of granitoid and metasedimentary units. The basin extends eastwards offshore under the marine cover of the Australian continental margin.

![FIG 2 - The Sydney-Gunnedah Basin and its recognised coalfields (redrawn from NSW Department of Primary Industries, 2007)](image)

Detailed geology of the Sydney Basin was given in Mayne et al (1974) and Herbert and Helby (1980). However, in the last two decades, a significant volume of new and revised interpretations have been given covering stratigraphy, structure tectonism and evolution. Early theories on the origin of the Sydney Basin suggested that the basin was formed during a short rifting phase in the Late Carboniferous-Early Permian and evolved as a foredeep to the New England Fold Belt. In a major revision of the geology of NSW, Scheibner (1996; 1998) discussed the structural elements, framework and evolution of the Sydney Basin which was described as one of three sub-basins in the composite Sydney-Bowen Basin. Scheibner's proposed tectonic model, based partly on the work of Murray (1990), had an initial igneous rifting phase followed by a crustal thinning phase terminating in a loading phase when sediments were deposited in the basin. Diesell (1992) described the Sydney Basin as a 'structural depression of retroarc status'. Alder et al (1998) proposed that the basin formed from east-west compression as a result of foreland loading from the Lord Howe Rise to the east of NSW and a ridge comprising the Gerringong Volcanics in the south.

Sediments in the Sydney Basin date from Early Permian, possibly Late Carboniferous, to Triassic with Quaternary alluvium overlying the earlier units in erosional valleys and along coastal plains. Two periods of coal deposition occurred during the Permian. In the Early Permian, the Greta Coal Measures were deposited in the northern section of the basin whereas in the southern part of the basin the Clyde River Coal Measures was deposited. In the Late Permian more widespread coal measures development occurred with the Newcastle and Tomago Coal Measures, and the Singleton Super Group deposited in the north and the Illawarra Coal Measures deposited in the south and west.

Although the coal measures sequences are cut by faults, with only a few exceptions, the Sydney Basin has been only mildly deformed. Seam dips are mostly sub-horizontal with up to 5 to 10° due to local structures.

Historical reviews of the coal geology of NSW including exploration, stratigraphy and historical aspects in the exploration in each coalfield, were given by Rose (1976) and McElroy and Rose (1990).

The National Energy Research Development and Demonstration Program (NERDDP) funded a comprehensive study of the Permian coals of eastern Australia (NERDDP, 1989). This study covered all aspects of the Permian coals including coal in the smaller and less well known basins, as well as the more important Bowen and Sydney basin coals. It contains important information on the properties of the Permian coals as well.

The NSW Department of Primary Industries (2007) provides summaries of the NSW coal industry including coalfields, mines and statistics.
The Southern Coalfield

The Southern Coalfield is the southern portion of the Sydney Basin, covering an area south of Sydney almost to Batemans Bay and bounded approximately by the towns of Campbelltown and Mittagong in the west, and Wollongong and Helensburg in the east. The coalfield contains the economically important Illawarra Coal Measures, which is Permian in age (Sherwin and Holmes, 1986).

The first comprehensive published work on the Illawarra Coal Measures of the Southern Coalfield was by Harper (1915) with a detailed descriptive geology given by Wilson (1975). More recent studies of the Southern Coalfield included Hutton et al (1990a; 1990b; 1990c), Armstrong et al (1995), Bamberry, Hutton and Jones (1995), Hutton and Bamberry (1999) and Moffitt (2000). However, the principal sources of data pertaining to economic geology remain colliery workings and boreholes, and departmental drilling programs such as reported in Bunn (1972).

Stratigraphy

The stratigraphy of the Southern Coalfield was revised by Hutton and Bamberry (1999) after extensive field work and the examination of borehole logs and core. This stratigraphy (Figure 3) was subsequently ratified by the Coalfield Geology Council of NSW (Moffitt, 2000). hill, Kirby and Cozens (2003) recommended minor amendments but these have yet to be ratified.

The basal unit, the Shoalhaven Group lies unconformably on a basement of igneous and metamorphosed sedimentary rocks and consists mostly of sandstones with intercalated beds of shale or mudstone which were deposited mostly in a marine or marine-influenced environment with some fluvial deposits such as the Nowra Sandstone. The top of the Shoalhaven Group comprises interbedded calc-alkaline basalts (latite) and marine sandstone and tuffaceous sandstone. The stratigraphy of the latite units was given by Carr (1983).

At the southern end of the Southern Coalfield, the Clyde River Coal Measures and Yarrunga Coal Measures contain localised and probably discontinuous coal seams some of which are very thin and referable to boghead coals or torbanite. Tye, Fielding and Jones (1996) placed the Clyde Coal Measures in the basal Sydney Basin unit, the Talaterang Group, and the Yarrunga Coal Measures in the younger Shoalhaven Group. There is little possibility of economic seams being found in either coal measures.

The Illawarra Coal Measures consist of lithic sandstone formations with subordinate formations of fine sediments and coal. The coal measures appear above sea level 20 km north of Wollongong and traverse the escarpment of the Illawarra Range. Near Wollongong the full sequence is exposed. The outcrop continues southward for about 40 km, and then turns westward to follow generally the northern side of the valleys of the Shoalhaven River system. The maximum thickness of the Illawarra Coal Measures is approximately 520 m in the northern part of the coalfield.

The Triassic deposits consist of non-coal-bearing lithic and quartz sandstone, shale and mudstone. The formation immediately above the Illawarra Coal Measures is the Coalcliff Sandstone, a lithic sandstone often with a basal shale member, which is part of the Narrabeen Group. Above the Narrabeen Group is the Hawkesbury Sandstone and above it, in the northern part of the coalfield, the Wianamatta Shale.

![Stratigraphy of the Illawarra Coal Measures](image-url)
The Illawarra Coal Measures has been divided into two subgroups, the basal Cumberland Group which contains the Pheasants Nest Formation and the Erins Vale Formation (with the laterally equivalent Kulnura Marine Tongue); the Pheasants Nest Formation contains the uneconomic, discontinuous Unanderra and Figtree seams.

**Structure**

The regional structure of the Southern Coalfield is a broad syncline forming the southern closure of the Sydney Basin. Additional synclinal and anticlinal structures trending north-west were superimposed on the main structure. In general, seams dip up to 5° but dips of less than 2° are the norm. Faulting is not intense and is often associated with folding. Major faulting with a displacement of up to 90 m trends north-westerly. En echelon faulting with a displacement up to 15 m trends north-easterly.

Post-Triassic and Tertiary sills and dykes intruded the coalfield particularly in the eastern and southern margins of the coal measures. Intrusions are doleritic in nature becoming somewhat syenitic to the west. Volcanic plugs and breccia diatremes are known but do not have an effect in currently mined areas.

Several authors have divided the Southern Coalfield into structural units, for example, Bembrick *et al.* (1973) and Brakel (1989a). More recently, Scheibner (1996) stated that the major structural units were bounded by major magnetic lineaments with the dominant structural unit in the Southern Coalfield a linear north-north-east–south-south-west trending structure comprising several large faults including the Lapstone Monocline-Fault System, the Nepean Fault Zone, the Oakdale Fault System and the Bargo Fault. The largest fault throws are in the order of 100 m and many faults have fracture zones up to 100 m wide (Armstrong *et al.*, 1995). Herbert (1989) had earlier stated the faults were a series of subparallel high angle *en echelon* reverse faults formed by compression and wrenching during the late Triassic. Rixon and Shepherd (1989) and Loe *et al.* (1992) also stated that most faults were reverse faults. Bowman and Mullard (1986) previously stated that the majority of faults were normal faults with strike-slip and high-angle reverse faults known to exist.

The dominant feature, Lapstone Monocline-Nepean Fault Zone, also called the Lapstone Structural Complex by Bragam and Pedram (1990) and Moffitt (2000), extends from north of the Blue Mountains to as far south as Tahmoor Colliery where it is manifested as a series of faults. Loe *et al.* (1992) stated the Nepean Fault Zone and associated monocline are found in the eastern part of Tahmoor Colliery. They described the faults as high angle faults with relatively small displacements and generally associated with drag folding.

The Southern Coalfield contains a series of open meridional anticlines and synclines (Moffitt, 2000) with the central and regionally extensive Camden Syncline significant. Dips of the limbs are generally less than 2° but dips of 5° have been noted. The Woronora Ridge is a series of north-west-south-east trending anticlines and synclines with north-westerly/north-easterly plunges.

Structural features that also might impinge upon gas accumulation and migration include four prominent sets of joints, with axes striking 005°, 055°, 105° and 155° (Moffitt, 2000). The joints are essentially parallel or normal to the principal axes of the folds (Lohe *et al.*, 1992).

Several structural domes are found in the central and southern part of the coalfield (Moffitt, 2000). The majority of the domes are thought to be related to intrusions, especially the Mittagong and Nattai domes (both near the town of Mittagong). These intrusions are composed of syenite, diorite or gabbro and vary in geometry from large intrusive complexes (hundreds of metres in width), with related sills, to small, near-vertical dykes (Moffitt, 2000).

Lohe *et al.* (1992) gave a detailed review of mine-scale structures in the Southern Coalfield.

**Coal seams**

The economic coals seams in the Southern Coalfield are all in the Sydney Subgroup of the Illawarra Coal Measures.

**The Bulli Seam**

The Bulli Seam is stratigraphically the top seam in the Illawarra Coal Measures and subcrops over all but the southern margin of the Southern Coalfield and represents the majority of the coal reserves. Seam thickness is generally 2 to 3 m in all but the northern part of the coalfield where it attains a thickness of 5 m. The Bulli Seam is composed of interbanded dull and bright coal plies with minor siderite and claystone interbands. The seam is medium ash (8-9 per cent in the east, increasing westward), medium volatile matter (21.5 to 27.5 per cent, air dry) with a low sulphur content. Vitrinite content ranges from 30 to 55 per cent with inerinite high by world standards (~50 per cent). Bulli coal is used mostly as a coking coal with coking properties varying from weak to strong. The Bulli Seam has been correlated with the Katoomba Seam of the Western Coalfield.

**The Balgowie Seam**

The Balgowie Seam is 5 to 30 m below the Bulli Seam and has only limited potential due to a seam thickness generally of 1.5 to 2 m, maximum of 3.5 per cent, with high ash, and a preference by companies to mine the Bulli or Worongawilli Seams. This seam has been mined to a limited extent in the past but is not being mined at present. The greatest potential for mining is in the Camden-Campbelltown area where it thickens; there is no economic potential south of Lake Woronora (Moffitt, 2000).

**The Worongawilli Seam**

The Worongawilli Seam is the thickest and most widespread seam in the Southern Coalfield. It is 30 to 60 m below the Balgowie Seam. The full geological section varies from 6 to 15 m with a maximum of 18 m in the Campbelltown area (Moffitt, 2000). The Worongawilli Seam is split into
an upper and lower section by the ~1 m Farmborough Heights Claystone (derived from air fall tuff) which is also known as the Sandstone Band, Nolan Band and Three-foot Band. The working section generally consists of the basal 3 m. The part above the working roof consists of uneconomic high ash coal plies and claystone bands (many derived from volcanic ash). The seam maintains its character over most of the coalfield, but it develops an economic section only in the southern portion of the coalfield. The working section consists of bright coal plies with disseminated mineral matter, interspersed with stone bands. The seam contains 60 to 80 per cent vitrinite, mineral matter free (mmf), and is a valuable addition to a coking coal blend. Wongawilli coal is used for cement manufacture at Berrima. The Wongawilli Seam has been correlated with the Middle River Seam of the Western Coalfield and both have similar geophysical log attributes.

**The Tongarra Seam**

The Tongarra Seam is 70 to 80 m below the Wongawilli Seam and consists of interbanded dull and bright coal usually with one or two claystone interbeds. Although recognised throughout the coalfield, the seam is only economic south of Wollongong (approximately 3 m thick) where it was mined at Huntley Colliery as a feed component for power generation. The seam is medium to high in ash yield with medium volatile matter and sulphur content.

**Other seams**

Apart from the above economic seams which occur in the top half of the Illawarra Coal Measures, the Sydney Subgroup also contains the Cape Horn, Hargrave, Woronora, American Creek and Woonna seams. The Woonna Seam was mined in the past, mostly from exploratory adits that have been opened within it. It is discontinuous and has numerous claystone layers where it is exposed on the coast and these indicate its economic potential is minimal. The Woonna Seam has been correlated with the Lithgow Seam of the Western Coalfield.

High ash yield, minimal seam thickness, thin coal intervals, discontinuous lateral extent or a combination of these, render all the lower seams commercially unacceptable (Wilson, 1975).

**Oil shale**

Oil shale was mined during the 1870s in a local development within the American Creek Seam. In the 30 years to 1911 mining and refining of oil shale was carried out at Joadja, west of Mittagong (Knapsman, 1988).

**Resources**

Moffitt (2000) gave a detailed summary of the coal quality of the economic seams and reviewed the resources of the Southern Coalfield (Table 3).

NSW Department of Primary Industries (2005) stated that the Southern Coalfield produced 10.4 Mt of coal in 2003-04 which was a decrease of 0.8 Mt on the previous year. Total colliery reserves in 2003-04 were given as 808.8 Mt. Methane drainage is an important facet of Southern Coalfield mining with some mines having gas contents >10 m³/t and as high as 14 m³/t. The Southern Coalfield contains significant resources of coal seam methane which has only been looked at seriously in the past decade. Brown et al (1996) stated that the Southern Coalfield contains in the order of 752 Bm³ of methane.

**The Newcastle Coalfield**

Newcastle the main centre and port of the Newcastle Coalfield is located on the northeastern margin of the Sydney Basin. The coalfield that occupies an area 30 by 60 km along the coast has been a long time producer of coal for both the domestic and export markets. Detailed geology of the Newcastle Coalfield was given in Herbert and Helby (1980), including a detailed analysis of the palaeoenvironments. Brakel (1989b) and Agnew et al (1995) gave more recent updates on the geology. The stratigraphic nomenclature of the Newcastle Coal Measures was detailed by MacKenzie and Britten (1969) and subsequently modified by the Standing Committee on Coalfield Geology of NSW (1975). Ives et al (1999) undertook major revisions which were subsequently ratified by the Coalfield Geology Council of NSW.

**Stratigraphy**

The Permian sequence in the Newcastle Coalfield comprises three coal measures. The basal coal measures is the Early Permian Greta Coal Measures which is overlain by the Late Permian Tomago Coal Measures; the topmost coal-bearing unit is the Late Permian Newcastle Coal Measures. Above the coal sequence is the non-coal-bearing Narrabene Group of Triassic age. The coal

<table>
<thead>
<tr>
<th>Table 3 - Coal Resources of the Southern Coalfield (from Moffitt, 2000)</th>
<th>Coking coal (Mt)</th>
<th>Export thermal coal (Mt)</th>
<th>Domestic thermal coal (Mt)</th>
<th>Cement manufacture (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulli</td>
<td>1140</td>
<td>530</td>
<td>510</td>
<td>800</td>
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<tr>
<td>Balgownie</td>
<td>765</td>
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<td>Wongawilli</td>
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<td>320</td>
<td>450</td>
<td>1600</td>
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<td>Tongarra</td>
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<td>160</td>
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<td>1255</td>
<td>1095</td>
<td>2560</td>
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</table>
measures outcrops in the north of the field. All three consist of numerous seams with interseam conglomerate, sandstone and finer grained sedimentary rocks. Detailed descriptions of the units in the three coal measures were given in Hawley and Brunton (1995).

The Newcastle Coal Measures is generally richest in the eastern part of the area but thins appreciably towards the west where the thinning is accompanied by convergence of the seams. The sequence is dominantly fluvial and has a maximum thickness of 450 m. The topmost workable seam in the sequence is the Warrah seam and the lowest is the Borehole seam, two of a total sequence of 14 main seams and several minor seams. Thickness, physical conditions and quality for individual seams vary, but generally the top seams are sources of thermal coal and the lower seams supply high volatile coking coal.

The stratigraphy of the Newcastle Coal Measures, as defined by Ives et al. (1999), recognises the Warrah Sandstone as the basal unit with four coal-bearing formations, the Lambton (oldest), Adamstown, Boolaroo and Moon Island Formations, separated by the three significant tuffaceous formations, Nobbys Tuff (the oldest), Warners Bay Tuff and Awaba Tuff.

Underlying the Newcastle Coal Measures is the Tomago Coal Measures, also of Late Permian age, which stratigraphically overlies the marine Maitland Group. The Tomago Coal Measures thickens from approximately 60 m in the west where it outcrops at Maitland to 1200 m in the east. The basal unit is the marine Maitland Group (1200 m thick) and above this Brown and Preston (1985) divided the sequence into three subgroups: the Wallis Creek, Four Mile Creek and Hexham Subgroups. Blayden (1971) recognised an unconformity within the Wallis Subgroup. A significant laterally extensive marine incursion, the Kulnura Marine Tongue (which extends into and has been recognised in drill core in the Southern Coalfield), occurs near the top of the Wallis Greek Subgroup.

The Greta Coal Measures, is the basal coal measures in the Newcastle Coalfield and in the Newcastle district is at a depth in excess of 1000 m.

Doleritic dykes are common in the Newcastle Coal Measures, but do not constitute an insurmountable mining problem.

Structure

The Newcastle Coalfield is separated from the New England Fold Belt by the Hunter Thrust, referred to as the Hunter Thrust System by Lohe et al. (1992), which is a thrust fault with a throw of 1 to 2 km and with the thrust plane at an angle of 5 to 10°.

The coalfield is characterised by a number of broadly north-south to north-west to south-east trending gentle folds (Lohe et al., 1992). The dominant structural features of the Newcastle Coalfield are the Macquarie Syncline, a shallow syncline gently plunging to the south, and the Lochinvar Anticline. Both plunge at 1 to 2° with the limbs dipping at 3 to 4°. Folding about east-west axes resulted in the formation of shallow dome and basin structures within the north-south trending synclinal and anticlinal structures. Normal faults, with displacements usually less than 6 m, but up to 15 m, are dominant. Most faults strike in a similar direction to that of the dykes, approximately north-west, but in some areas north trending faults occur. Thrust faults and bedding plane shearing have been recognised but are generally less important than the normal faults (Lohe et al., 1992).

The Lochinvar Anticline acted as a barrier between the Newcastle and Hunter Coalfields (Lohe et al., 1992) during the Late Permian and its western edge is taken as the boundary between the two coalfields.

Lohe et al. (1992) gave a detailed review of mine-scale structures in the Newcastle Coalfield.

Coal seams

The Warrah Seam

The top seam of the Newcastle Coal Measures is the Warrah Seam, which is one of the most important sources of thermal coal of the Newcastle district. The Warrah Seam is developed from the outcrop south of Swansea to Munmorah, and extends as far west as Vales Point and possibly as far north as Wangi Wangi to the west of and under Lake Macquarie. The working section varies from 2 to 2.5 m and is generally free of claystone layers.

The Great Northern Seam

The Great Northern Seam, which is lower than the Warrah Seam, is also an important source of thermal coal in the area. Conglomerate forms the immediate roof of the seam in a large part of the area where the seam has been investigated. There are three main centres of development, one in the Teralba and Awaba areas in the west, the second a central area around Belmont and Wangi, and the third a south-easterly zone extending south from Catherine Hill Bay and Vales Point. Seam thickness in these areas varies between 1.5 and 3.5 m. A fourth, as yet undeveloped area, lies to the south and south-west of Lake Macquarie extending to Gosford. In this area seam thickness ranges up to 7 m when converted with the overlying Wallarah Seam at Vales Point. The Great Northern Seam has been the major source of supply to thermal power stations in the Newcastle district.

The Fassifern Seam

The Fassifern Seam occurs below the Great Northern Seam and is separated from it by a thickness, ranging from less than 5 m to more than 20 m, of mudstone with some sandstone and conglomerate occurring where the interval is thickest. The Fassifern Seam has a thickness of 6 to 7 m. It generally has a characteristic seam profile and contains several claystone bands approximately 0.01 to 0.10 m thick which are persistent and can be used as marker horizons in the areas of major development. The ash yield of the whole seam is of the order of 35 to 40 per cent because of the inclusion of numerous stone
bands or very high ash coal plies. Where mined, selection of the best section, from the lower-ash middle part of the seam, has varied according to mining method and quality desired. Most mined sections involve leaving roof and floor coal. The Fassifern Seam is a major source of supply to local thermal power stations.

**The Victoria Tunnel Seam**

The Victoria Tunnel Seam crops out in the northern part of the district. It has been extensively mined and prospected on the eastern side of Lake Macquarie and is generally regarded as the topmost coking coal seam in the Newcastle Coal Measures.

It is characteristically banded with seam thickness varying between 2.0 and 3.5 m. While not presently worked this seam with 68 per cent vitrinite has the highest vitrinite content of the local coals and, as such, was successfully blended with coal of low vitrinite content.

**The Nobbys Seam**

The Nobbys Seam lies some 10 to 15 m below the Victoria Tunnel Seam. It is generally in the order of 1 m thick and has been worked to a minor degree in the Newcastle city area.

**The Dudley Seam**

The Dudley Seam lies below the Nobbys Seam. It combines with the Nobbys and the underlying Yard and Borehole seams to form various seam combinations. Although it has limited extent as a separate entity, the reserves as part of a combined seam are extensive.

The Dudley Seam is generally bright with vitrinite content of up to 64 per cent. Ash yield of the seam generally varies from 20 to about 30 per cent. Volatile matter (dmnf) is approximately 37 per cent. When washed, the coal yields a relatively low ash fraction of medium to high swelling coal which is used for blending for metallurgical coke production. Where the seam combines with the underlying Yard Seam the combined section varies in thickness from 3.0 to 3.7 m. Ash yield ranges from 18 to 30 per cent.

**The Young Wallsend Seam**

The Young Wallsend Seam is a combination of the Dudley and Nobbys seams is generally worked to the Stockton Borehole Parting. This worked section is about 2.3 m thick and contains between 18 and 30 per cent ash. The duller coal associated with the Nobbys Seam section decreases the overall vitrinite content to 60 per cent compared with 64 per cent for the Dudley Seam. The Young Wallsend Seam has been extensively mined in the north-western part of the district. With the addition of the underlying Yard Seam the Young Wallsend/Yard Seam is increased in thickness to about 4.0 m and ash yield is decreased to approximately 22 per cent.

**The West Borehole Seam**

This is a combination of the Young Wallsend/Yard and the underlying Borehole seams, it decreases in thickness westerly from about 6 m at the line of convergence to less than 3.5 m. Quality is similar to that of the component sections but decreases to the south-west and west with deterioration mainly in the upper sections of the seam.

**The Yard Seam**

The Yard Seam lies below the Dudley Seam. It was the first seam mined under the city of Newcastle, but is not presently mined as a separate entity. By itself the seam has limited reserves but, in combinations with the overlying Dudley and Nobbys seams and the underlying Borehole Seam, contains large reserves of low ash coking coal.

West from Swansea the seam converges with the overlying Dudley Seam and further west with the Nobbys Seam and then the Borehole Seam to form the Young Wallsend/Yard and West Borehole seams. Over the area of economic development the seam retains a consistent thickness of approximately 1.5 m, where present, both as a separate entity and in combination with other seams. Coal quality is also consistent within the areas of economic development. The ash varies from 9.0 to 14.0 per cent and volatile matter (dmnf) is about 38.5 per cent. The coal is mainly bright and the washed coal has a vitrinite content of approximately 67 per cent. The Crucible Swelling (CS) No is generally 7.5. The seam is a significant source of low ash coking coal. Future mining in the seam will be mainly in areas of combination with either the Dudley or Young Wallsend seams.

**The Borehole Seam**

The Borehole Seam has been widely mined and explored adjacent to the outcrop and southward around Lake Macquarie. Further to the south most of the prospecting holes have been restricted to the upper seams in the measures because the information available suggests that the lower seams are thin and subeconomic.

Along the coast south from Newcastle the working section varies between 1.5 and 2.4 m and thins westerly accompanied by an ash yield increase from 12 to 30 per cent. West of a zone of deterioration the seam regains its working section and thicken north-westerly to about 2.5 m. Ash yield of the working section varies from 12 to 25 per cent.

In the western area the seam combines with the overlying Yard, Dudley and Nobbys seams to form the West Borehole Seam. The washed fraction is low ash coal with a vitrinite content of about 60 per cent. As such, the seam has been the basis of low ash coking coal blend for local metallurgical coke or for export.

**Minor seams**

Coal occurs on five main horizons between the Fassifern and Victoria Tunnel seams. Seam thickness is generally less than 1.5 m and does not exceed 2 m. All these seams contain several claystone layers, often of considerable thickness and this, together with the general lack of thickness of the seams and normally high ash yield of the coal, as mined, makes none very attractive as a source of thermal or coking coal. Exploitation of these seams has been confined to very small areas of workings, none of which is operating at present.
Reserves
Total reserves in the Newcastle Coalfield are estimated at 6800 Mt. Restrictions apply to extraction under residential areas and under tidal waters, as well as in the proximity of other seams.

Resources
Agnew et al (1995) reported that the Newcastle Coalfield contains an in situ resource of 10 700 Mt of coal, of which 4200 Mt is probably sterilised by other land use patterns such as towns, national parks and vital infrastructure. In 2003-04 raw coal production was 17.4 Mt, the same as in the previous year (Department of Primary Industries, 2007), with saleable production of 12.98 Mt. Total reserves were listed at 1597.75 Mt. The coalfield is divided into four production areas – the western area near Cessnock, the northern area near Maitland, the central area near Teralba and the southern area near Wyong – with the southern and central areas the main producers. The central area produces a low ash, medium fluidity soft coking coal for export as well as a medium ash thermal coal for both export and domestic use. The southern area produces medium to low ash thermal coal for domestic power stations with some exported.

In 2003-04, 11 collieries operated with four proposals considered (Department of Primary Industries, 2007).

The Maitland-Cessnock-Greta Coal District of the Newcastle Coalfield
The Maitland-Cessnock-Greta Coal District is a historically recognised coal mining district and is an arbitrarily defined area that includes all the coal to workable depth from the outcrop of the Greta Coal Measures in the vicinity of the townships of Maitland, Cessnock and Greta. Mining development has been carried out throughout the district from the outcrop of the coal seams to depths of 400 m. Since mining first commenced near Greta in 1868 all the areas suitable for mining have been committed to colliery holdings or mining leases. From the inception of mining in the district, most of the readily won coal has been extracted down to a depth of 300 m.

Geology
The dominating structural feature of the district is the Lochinvar Anticline around the flanks of which the Greta Coal Measures crop out. Other important structural features include major faults which limit the extent of accessible Greta coal towards the western boundary of the district, and several other major faults that have displaced the crop of the coal measures towards the north of the district. The Greta Measures comprise a relatively thin group of the order of 100 m thick overlain by up to 1350 m of marine sediments of the Maitland Group and underlain by up to 2000 m of marine sediments of the Dalwood Group. The coals of the Greta Coal Measures are typified by complex splitting and marked variation in thickness. Worked seams included the Greta and Homeville Seams together with their various splits.

Greta Seam
The Greta Seam has its maximum development near Cessnock, where it is up to 10 m thick; it thins southward to less than 3 m. The upper part of the Greta Seam is generally high in sulphur so extraction has been limited to a selected subsection of the order of 6 m thick.

In the north-west of the District, near Rothbury, a middle split of the Greta Seam dipping from 20 to 60° is the main worked section. In parts of this area the middle and bottom splits join to yield 12 m of total coal thickness, but generally the worked thickness of the seam is from 2 to 3 m. The Lower Greta Seam splits from the Greta Seam towards the south-east. The workings of the Lower Greta Seam are continuous with those in the Greta Seam west of the split. The seam thins steadily down dip from almost 8 m at the split to 2.5 m where its full thickness was worked beneath 300 to 400 m of cover.

Homeville Seam
The Homeville Seam comprises a bed of coal up to 8 m thick, which from its outcrop near Kurri Kurri occurs as an elongated tongue extending towards the south. The southerly extent of this tongue is not known. It is separated from the overlying Greta Seam by a predominantly conglomeratic bed up to 30 m thick. This bed lies within the Kurri Kurri Conglomerate which includes both the Upper and Lower Homeville seams and the Homeville Seam itself.

Quality and marketability
The coals from the Greta Coal Measures vary only slightly in their rank. They are all high volatile, low ash coals, having a high vitrinite content ranging from 60 to 70 per cent. Coals from the Greta Coal Measures were once marketed widely within Australia for general industrial use, locomotive fuel and the manufacture of town gas. The domestic market for these coals has diminished, the bulk of the coal is currently sold to Japan for use in the gas and chemical industries. Market requirements almost invariably necessitate selective mining and some form of coal preparation. The coals are not normally used for coking but do exhibit some useful coking properties within the limitation of their low rank and high sulphur content. Reserves of the order of 221 Mt of in situ coal have been estimated to occur to depths of up to 600 m.

Hunter Coalfield
The Hunter Coalfield shown in Figure 2 lies west of the Newcastle Coalfield and east of the Western Coalfield, with northern and southern boundaries defined by geographic features and the western margin by the adjoining Western Coalfield. It occupies an area of 2100 km² towards the north-eastern margin of the Sydney Basin and is centred nominally over the catchment of the Hunter River. The coalfield extends for approximately 50 km north-west from Cessnock to Muswellbrook and a further 120 km north to Murrurundi. The geology was described by Brakel (1989a) and Sniffin and Beckett (1995).
Stratigraphy

The stratigraphic nomenclature for the Hunter Coalfield has been described for at least a century but the terminology adopted for the Permian sequence has long been greyed by the lack of a regional approach. As a consequence local or parochial terminology has commonly been used for areas as small as a single colliery and thus correlation across the coalfield has been difficult at best. Conventionally, the stratigraphy has been divided into, youngest to oldest, the Singleton Super-Group, comprising the Wollombi and Wittingham Coal Measures; the Maitland Group, comprising the Mulbring Siltstone and Branxton Formation; the Greta Coal Measures, and the Dalwood Group comprising Fairley, Rutherford, Allandale and Lochinvar Formations. Historically the lower or Greta Coal Measures have been worked near Muswellbrook since the middle of the 19th century and the Upper Coal Measures, now known as the Singleton Super-Group, were worked near Singleton around the turn of the century.

A determined effort has been made to unravel the idiosyncrasies of the coalfield nomenclature by the Coalfield Geology Council of New South Wales and its predecessor the Standing Committee on Coalfield Geology of NSW (1975), Standing Committee on Coalfield Geology of New South Wales (1986), Rogis (1992), Sniffin and Beckett (1995), Beckett (1999) and Beckett et al (1999). Whilst the group terminology has remained, the details have changed considerably.

Structure

Lohe et al (1992) placed the Hunter Coalfield in the north-eastern subdivision of the Sydney Basin which Bonbrick et al (1973) called the Hunter Valley Dome Belt. Regional geology and in some mines, mine geology is influenced by the Hunter Thrust including the influence of several large scale thrust faults which Lohe et al (1992) interpreted as splays off the Hunter Thrust. The Aberdeen Thrust, a probable extension of the Hunter Thrust is also a major structural feature.

Approximately north-south trending anticlines or domes, synclines (such as the Bayswater Syncline, Lochinvar Anticline, Muswellbrook Anticline, and Camberwell Syncline), meridional faults and monoclines also affect the regional and local geology.


Greta Coal Measures

The Greta Coal Measures underlies a sequence of marine rocks up to 1300 m thick known as the Maitland Group. They occur at depths mostly in excess of 600 m and are commercially significant only in a few isolated places where they approach the surface near major anticlines. In the Balmoral area, immediately south-west from Muswellbrook, the Greta Coal Measures crop out along the crest of the Muswellbrook Antcline.

Rogis (1992) and Beckett et al (1999) revised many of the stratigraphic units of the Greta Coal Measures and attempted correlations across the parts of the coalfield. Seam names were defined for two separate areas, the Skeletar area north of Muswellbrook and the Savoy area, south of Muswellbrook (Figure 4). In the Muswellbrook area the Greta Coal Measures is more than 200 m thick but to the south near the Lochinvar Antcline it thins to approximately 60 m.

Dawson (2006) and Dawson, Coxhead and McMinn (2006) reviewed the geology of coal-bearing sequences in the Werrie Basin near Werrie Creek and in the Willow Tree area. Although both areas are within the limits of the southern Gunnedah Basin, the authors placed the coals in the Greta Coal Measures.

Singleton Super-Group

This is the name given to the strata formerly called the Singleton Coal Measures by Robinson (1969). The Super-Group has been subdivided into the Wollombi and Wittingham Coal Measures, the latter being of far greater economic importance than the Greta Coal Measures previously discussed. The coalmeasures crop out between upthrust older rocks east of, and along, the Hunter Thrust Fault and prominent scarps of younger Triassic rocks to the west. Within this area of outcrop the Singleton Super-Group dips regionally west to south-west towards the centre of the Sydney Basin, although superimposed upon the regional dip are a series of gentle folds. This folding is manifest through important localised structures. These structures also controlled the disposition of the seams and the location of the outcropping coal.

![FIG 4 - Defined seams for the Skeletar and Savoy area, Hunter Coalfield (redrawn from Beckett et al, 1999)](image-url)
The maximum thickness of the Singleton Super-Group is of the order of 1450 m although it wedges out completely along the southern extension of the Lochinvar Anticline.

**Wittingham Coal Measures**

The Wittingham Coal Measures was generally divided in two parts, an upper Jerrys Plains Subgroup which is of economic interest in the western and southern parts of the Upper Hunter Valley and the Vane Subgroup which includes the Foybrook Formation in the eastern and northern parts. The Foybrook Formation coal seams were given different nomenclature on the western side of the Muswellbrook anticline to the traditional mining area on the eastern side, the Liddell-Singleton area.

Rogis (1992) redefined the boundaries of the units within the Wittingham Coal and demonstrated the limits of regional coal seam correlations. Beckett (1999) reviewed the nomenclature in the Hunter Coalfield. Rogis placed the Saltwater Creek Formation at the base of the coal measures and separated the lower coal-bearing Vane Subgroup (comprising the Foybrook Formation and the younger Bulga Formation) from the upper coal-bearing Jerrys Plains Subgroup with the Archerfield Sandstone. The Denman Formation was placed above the Jerrys Plains Subgroup. The Jerrys Plains Subgroup contains the following coal-bearing formations: Burmanwood (the oldest), Mount Thorley (separated from the latter by the Fairford Formation), Mt Ogilvie, Malabar and Mount Leonard (separated from the latter by the Althorpe Formation).

**Wollombi Coal Measures**

The Wollombi Coal Measures refers to the upper coal bearing sequence of the Singleton Super-Group. Sniffin and Beckett (1995) and Beckett (1999) reviewed the terminology. The coal measures is divided into four Subgroups: Apple Tree Flat (the oldest), Horseshow Creek, Doyles Creek and Glen Galfic, with coal seams in the four subgroups.

In 2000 the Coalfield Geology Council of NSW set a working party to address issues relating to the Wollombi Coal Measures. With the use of geophysical logs and detailed analysis of drill core, the working party correlated individual tuffs and working seams that had previously been named separately in the Newcastle Coal Measures and the Wollombi Coal Measures, across the northern part of the Sydney Basin. The interpretations were further substantiated by seam profiles, particularly the tuffaceous layers. Many authors from as early as David (1907), Booker (1954), Britten (1972, 1975) and more recently, Stevenson (1997; 1999), Kramer, Weatherall and Offler (2001) recognised the Wollombi Coal Measures of the Hunter Coalfield and the Newcastle Coal Measures of the Newcastle Coalfield as equivalent. Consequently, the Coalfield Geology Council of NSW supported changes suggested by Creech (2000) and resolved that:

1. the Wollombi Coal Measures nomenclature be replaced by the Newcastle Coal Measures nomenclature;
2. Amoco Whyborn DDH1 be adopted as the reference bore for the Newcastle Coal Measures in the Hunter Coalfield;
3. the base of the Newcastle Coal Measures in the Hunter Valley be taken as the top of the Watts Sandstone; and
4. the Singleton Super-Group in the Hunter Valley be comprised of the Newcastle Coal Measures, Watts Sandstone and the Wittingham Coal Measures.

**Resources**

Initially, the only significant exploitation of the Greta Coal Measures in the area was open pit extraction in the Balmoral Seam, which ranges up to 12 m in thickness. In more recent years, both the Greta and Wittingham Coal Measures, especially the Foybrook Formation seams and the Jerrys Plains Subgroup Seams, are major commercial producers (Sniffin and Beckett, 1995). The Greta Coal Measures is less than 600 m thick in some parts of the coalfield and thus mining generally is restricted to the shallower parts of the seams which are associated with structures such as the Muswellbrook Anticline.

Many of the seams, such as the Foybrook seams, are split by claystone or sandstone intervals and some seams are intruded. Small-scale faulting also disrupts the seam continuity.

Sniffin and Beckett (1995) summarised the coal quality of the Hunter Coalfield. They regarded the seams in the Jerrys Plains Subgroup as having the greatest potential, partly because they are thicker, partly for their better quality but also because of the shallow nature of the seams. They stated that coal quality varies significantly throughout the Hunter Coalfield because of the large number of seams and complex lateral variation and seam splitting. They also divided the Hunter Coalfield into three 'economic' regions with the following products:

1. the northern area which mines the Greta Coal Measures seams (at least six seams mined); low-medium ash, medium volatile thermal and a semi-soft coking coal are produced for the export market and a medium to high ash, volatile thermal coal for domestic use;
2. a central area where up to ten of the seams of the Foybrook Formation occur in the sequence; thermal coal for export and domestic markets, and commercial blends of low ash, volatile high fluidity coking coals are produced for export; and
3. a southern area where the seams of the Jerrys Plain Subgroup are mined.

Sniffin and Beckett (1995) estimated that the Hunter Coalfield contains 61 000 Mt of in situ coal. It is also the largest producer of coal in NSW. The Department of Primary Industries (2007) gave production figures for the Hunter Coalfield as 103 Mt of raw coal with 76.51 Mt saleable. Total reserves were given as 4047.70 Mt. Twenty collieries were operating with nine proposals being considered.
The Western Coalfield

Coal was first discovered in the Western Coalfield (Figure 2) in 1824 and continuous production commenced in 1868 (Bembrick, 1983). Until the early 1970s, both exploration and mining were small scale, commencing from the outcrop adjacent to existing transport routes such as at Lithgow. Under shallow cover, western collieries experienced excellent mining conditions in the past. More recent operations have been mining away from outcrop, under deeper cover, and have encountered some roof instability problems. In an easterly direction from the edge of the coalfield, cover increases gradually to over 300 m and near the western boundary of the Wollemi National Park increases rapidly to over 500 m. Seam gas has not been a mining problem in the past. Rugged topography and proximity to the Park will contribute to making exploitation of the deeper coal difficult. Six coal seams are recognised in the Illawarra Coal Measures, which thicken from 57 m on the western margin to more than 220 m (Morris, 1975). Coal seam stratigraphy varies towards the east down-dip but remains incompletely resolved at present.

Yoo, Norman and McDonald (1995) gave a detailed review of the Western Coalfield geology.

Structure

The Western Coalfield lies along the northwestern margin of the Sydney Basin and historically was centred on the regional town of Lithgow. The eastern boundary is the Southern Coalfield and the eastern boundary the Hunter Coalfield. Seams dip 1 or 2° in an easterly direction except along the margin of the coalfield where dips can reach 10°. Hutton and Feldman (1996) showed there is a strong correlation between basement palaeotopography and seam thickness, dip angle and direction, and coal quality.

Lohe et al (1992) stated that the dominant structures are broadly meridional trending regional-scale monoclines such as the Mt Tomah Monocline and the Lapstone Monocline complex. The latter structure comprises a meridional monocline and a series of subparallel large faults with throws up to 200 m. Small scale faults of generally less than 5 m throw and trending in a north-south direction have an effect in some localised areas. Igneous intrusions are present only in the centre and north-east of the coalfield with intrusions during the Jurassic and early to mid Tertiary.

Lohe et al (1992) gave a detailed review of mine-scale structures in the Western Coalfield.

Stratigraphy

The stratigraphy of the Western Coalfield was set up by Bembrick (1983) and subsequent revisions were given by Yoo, Norman and McDonald (1995) with the most recent by Yoo, Tadros and Bayly (2001) (Figure 5) including unit definitions and seam descriptions. The latter authors also gave descriptions of the seams (Figure 6).

The coal-bearing sequence in the Western Coalfield is the Illawarra Coal Measures which overlies the marine-influenced Shoalhaven Group although correlation of the latter unit with its coastal stratigraphy is difficult because of a lack of deep drill holes between the two. Overlying the coal measures is the Narrabeen group comprising a quartzo-lithic fluviatile sequence. Because of the lateral extent of the Western Coalfield, correlation and terminology between the southern part of the coalfield and the northern part is difficult.

In the southern part of the coalfield, the Illawarra Coal Measures is subdivided into four subgroups, the Nile, Cullen Bullen, Charbon and Wallerawang Subgroups, with best seam development in the top three subgroups.
(a) lower part of the Illawarra Coal Measures

(b) middle part of the Illawarra Coal Measures

FIG 6 - Recognised seams in the Western Coalfield (redrawn from Yoo, Tadros and Bayly, 2001)
Seams

Katoomba Seam

The Katoomba Seam varies from zero to approximately 6 m in thickness and in general is free of claystone layers. The seam is present in the southern and eastern parts of the coalfield but north and east of Lithgow it has been eroded by the overlying Narrabeen Group. Best development of the seam is near Newnes Junction, some distance from outcrop. The seam is correlated with the Bulli Seam of the Southern Coalfield. Typical analysis of the Katoomba Seam, given by Yoo, Tadros and Bayly (2001) is 11 to 23 per cent ash (air dried), volatile matter 28.9 per cent. CSN of Morris (1975) gave a 1 to 1.5. The Katoomba Seam represents a considerable reserve, particularly to the south and the south-east where mining activity started (Robinson and Shields, 1975) and can be expected to increase.

Middle River Seam

The Middle River Seam is a high ash, high vitrinite workable seam up to 4.0 m thick within the 15 to 25 m thick Middle River Coal Member of the Farmers Creek Formation. It is generally uneconomic but shows some potential north of Newnes Junction. Raw ash ranges from 18 to 35 per cent. The Middle River Seam has been correlated with the Wongawilli Seam in the Southern Coalfield.

Moolarben Seam

This is a thin but persistent seam with no apparent economic potential. It is generally less than 1 m thick but reaches more than 3 m in the Ulan area.

Irondale Seam

The Irondale Seam was referred to as the Wolgan Seam in the Wolgan area where it attains its best development of over 2 m. Characteristically, the Irondale Seam is about 1 m thick with a claystone layer near the middle of the seam. The Irondale Seam is the only seam in the Western Coalfield with significant coking properties and high fluidity. A washed product with typical analysis Ash, 10.8 per cent, VM 35.7 per cent, CSN 7½ (Morris, 1975) may be obtained from this seam in the Wolgan area although at relatively low yield.

Ulan Seam

The Ulan Seam is 14 m thick seam and is divided into an upper and lower section by a 0.3 m tuffaceous claystone. In the northern part of the coalfield, the lower section of the Ulan Seam is mined by open pit methods and an 11 to 13 per cent raw ash coal (air dried) is produced.

Lidsdale Seam

This seam was regarded as a split from the lower Lithgow Seam because of its similar properties to the latter. The seam consists of dull coal and carbonaceous shale and occurs only on the western margin of the coalfield (Bembrick, 1983). Sections up to 2 m thick have been mined in several small open pit operations in the Lidsdale area. Yoo et al (2001) recognised an upper rider of the Lidsdale Seam.

Lithgow Seam

The Lithgow Seam varies from 1 m to over 7 m in thickness but where mined, the section taken is 2 to 4 m at the base of the seam. The seam is best developed in the Lithgow-Ben Bullen area but is also worked further north at Kandos. The Ulan Seam in the northern end of the Western Coalfield is correlated with the Lithgow Seam. The Lithgow Seam provides the bulk of the production in the southern part of the coalfield where it is a low vitrinite, medium volatile steaming coal with an in situ ash content of 10 to 25 per cent.

Oil Shale Seams

Considerable quantities of oil shale have been mined in the Western Coalfield in the past, notably in the Glen Davis-Newnes area. Further north, other small deposits are known such as Barrigan. The oil shale is usually in association with thin laterally discontinuous coal seams.

Resources

Yoo, Tadros and Bayly (2001) gave the following unallocated domestic thermal coal resources:

<table>
<thead>
<tr>
<th>Seam</th>
<th>Resource (x10^6 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Katoomba</td>
<td>60</td>
</tr>
<tr>
<td>Middle River</td>
<td>150</td>
</tr>
<tr>
<td>Moolarben</td>
<td>20</td>
</tr>
<tr>
<td>Lidsdale</td>
<td>300</td>
</tr>
<tr>
<td>Lithgow</td>
<td>550</td>
</tr>
<tr>
<td>Ulan - North Ulan area</td>
<td>900</td>
</tr>
<tr>
<td>South Ulan area</td>
<td>170</td>
</tr>
<tr>
<td>Other areas</td>
<td>400</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2630</strong></td>
</tr>
</tbody>
</table>

The Department of Primary Industries (2007) gave production figures for the Western Coalfield as 15.39 Mt of raw coal of which 13.47 Mt was salable. Total reserves were given as 1562.62 Mt. Nine collieries were operating with seven proposals being considered. Western Coalfield salable products are a medium to high ash thermal coal for the domestic (>20 per cent ash) and export (<20 per cent ash) markets.

The Gunnedah Coalfield

Mining operations commenced south of Gunnedah in 1890 with the opening of the Centenary Colliery and Black Jack Colliery. Traditionally, production from this coalfield was tied to the supply of steam coal to the local rail system. Production declined with the conversion from steam to diesel locomotion. In the 1980s the Department of Mineral Resources undertook a major review of the...
Private interests in recent times have been directed towards supplying the export market.

The Gunnedah Basin is a north-west extension of the Sydney Basin and is separated from the latter by the Mt Corricudgy Anticline. The basin extends from the Liverpool Ranges near Murrurundi in the south, to Moree in the north. The eastern boundary is the Mooki Fault System which is a northerly extension of the Hunter Thrust. Scheibner (1996) stated the basin reflects the tectonic style imparted during deformation, with the result that the basin is divided by longitudinal and crosscutting basement ridges into several sub-basins including the Maules Creek and Mullaley sub-basins (Figure 7), which are separated by the Boggabri Ridge. Models for the development of the Gunnedah Basin were given by Scheibner (1993).

The Mullaley Sub-basin is separated from the Gilgandra Sub-basin by the Rocky Glen High. The northern edge of the basin is defined by the Moree High which separated the Gunnedah Basin from the southern part of the Bowen Basin.


Stratigraphy

The stratigraphy of the Gunnedah Basin which is comprised of the Maules Creek and Mullaley sub-basins was described by Tadros (1993; 1995b) following a detailed Department of Minerals Resources drilling program. The stratigraphy was updated by Tadros (1999) and was ratified by the Coalfield Geology Council of NSW.

Tadros (1999) divided the Permian sequence into three groups: the basal Bellata Group overlain by the Millie Group and the younger Black Jack Group. The Black Jack Group, formerly called the Black Jack Coal Measures, was divided into three subgroups; the basal Brothers, Coogal and upper Nea subgroups; with the main coal-bearing intervals in the Coogal Subgroup.

Maules Creek Sub-basin

Tadros (1999) recognised 25 correlatable seams between 1.5 and 3 m thick, although some are extensively split, in the Maules Creek Sub-basin. The seams are thickest near the Boggabri Ridge. Maceral analyses for various coal samples from the Maules Creek Sub-basin show vitrinite content ranges from 50 to 60 per cent in the upper seams and higher, up to 80 per cent, in the lower seams. Vitrinite reflectance ranges from 0.5 to 0.9 per cent. Coal quality varies but the coal is typically very low ash, high volatile content and low sulphur and could be used as either thermal or coking coals depending on preparation.

The seams are in the Early Permian Maules Creek Formation and are equivalent to Greta Coal Measures seams.

Mullaley Sub-basin

The Mullaley Sub-basin contains two coal-bearing sequences, the Maules Creek Formation and the Black Jack Group (Tadros, 1999). In the Maules Creek Formation, the seams are best developed south of Gunnedah and thin eastwards towards the Mooki Fault System. The seam with the greatest potential is the Brown Seam, at depths of 150 to 500 m, which has a low to medium ash and a specific energy of 34 to 35 MJ/kg. A working section of 4 m with 8 to 11 per cent ash has been identified (Tadros, 1999).

The Black Jack Group contains several seams that have significant lateral extent, with the Hoskisson and Melville seams having the greatest potential. The Hoskisson Seam varies in thickness from 1 m in the west to 1.2 m in the east. Several intrusions have affected the seam. Hoskisson coal is a low to medium ash, high volatile coal with low sulphur. The Melville Seam is generally 2.5 to 3.5 m thick in the east and thickens towards the west. Although Melville Seam coal is of good quality (Tadros, 1999), splitting of the seam occurs in some of the thicker sections rendering it less prospective for mining. The coal is a low to medium ash coal with 0.6 to 1.2 per cent sulphur.

Outcrop of the Black Jack Group shows evidence of intrusion by numerous basaltic sills. In earlier mining, the Black Jack Seams were mined at Gunnedah and Preston Extended Collieries. The basal 3 m of this 10 m seam is mined to produce a low ash, high volatile coking coal. The roof of the working section is a hard dull coal which is conducive to high productivity except where igneous intrusions have an adverse effect. The Melville Seam was mined by open pit at Gunnedah. In 2004, a 5 m section of the Whitehaven Seam was mined in the Whitehaven Colliery which produced 0.78 Mt of raw coal with 0.64 M saleable (Department of Primary Industries, 2007). Six proposals were being considered.
Resources

Tadros (1999) stated that the Gunnedah Basin contains 28 000 Mt of 'potentially usable' in situ coal or 38 per cent of the total in situ resources of NSW, based on recoverable coal at <500 m depth. Taking into account coal between 500 and 600 m depth and coal under affected areas such as national parks, total reserves are 38 000 Mt. Distance from domestic markets and ports for exporting coal puts the Gunnedah Basin at a disadvantage to the other coalfields of NSW.

Coal resources in the Mullaley Sub-basin north of the Liverpool Ranges is almost entirely within the Black Jack Group which extends over at least 80 per cent of the sub-basin. Tadros (1999) summarised the resources in this sub-basin as:

\[
\text{Inferred resources (Mt)}
\]

<table>
<thead>
<tr>
<th>Area</th>
<th>0-300 m</th>
<th>300-500 m</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breeza area</td>
<td>1800</td>
<td>1500</td>
<td>3300</td>
</tr>
<tr>
<td>Caroona area</td>
<td>4200</td>
<td>5400</td>
<td>9600</td>
</tr>
<tr>
<td>Narrabri area</td>
<td>1300</td>
<td>3100</td>
<td>4400</td>
</tr>
<tr>
<td>West Gunnedah area</td>
<td>3000</td>
<td>5600</td>
<td>8600</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10 300</strong></td>
<td><strong>15 600</strong></td>
<td><strong>25 900</strong></td>
</tr>
</tbody>
</table>

Coal resources in the Maules Creek Sub-basin are mostly within the Maules Creek Formation and are much less than the resources of the Mullaley Sub-basin. Tadros (1999) summarised the resources in this sub-basin as:

\[
\text{Mineable in situ reserves (Mt)}
\]

<table>
<thead>
<tr>
<th>Area</th>
<th>Surface</th>
<th>Underground</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vickery project area</td>
<td>155</td>
<td>155</td>
<td>310</td>
</tr>
<tr>
<td>Maules Creek project area</td>
<td>345</td>
<td>310</td>
<td>655</td>
</tr>
<tr>
<td>Boggabri project area</td>
<td>330</td>
<td>320</td>
<td>650</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>830</strong></td>
<td><strong>785</strong></td>
<td><strong>1615</strong></td>
</tr>
</tbody>
</table>

The Oaklands Basin

The Oaklands-Coorabin Basin, located in the central southern area of NSW, is a Permo-Triassic basin occupying the Ovens Graben, which is concealed by Cenozoic sediments of the eastern Murray Basin. A general geology of the basin was given by O'Brien (1989a) and subsequently revised by Yoo (1995). Coal was discovered early in the 20th century in water bores. Minimal production from several shafts occurred until 1960. Since that time exploration has been conducted by the Department of Mineral Resources.

Detailed stratigraphy was given by Yoo (1995a). Two coal units, the Coreen Creek Coal Member (Loghmore Formation) and the Lane's Shaft Coal Member (Narrow Plain Formation), are found in the Coorabin Coal Measures which occur near the top of the Permian strata. The Permian subcrop covers at least 260 km² (Driver, 1975). The Permian strata (up to 70 m thick), which are often weathered, are overlain by Tertiary water-filled gravels and clays. The coaly units of the Coorabin Coal Measures represent fining upwards units with basal conglomerate and sandstone overlain by point bar sandstone deposited by meandering stream, which in turn is overlain by alluvial plain claystone including peat.

The Coreen Coal Member is a thin discontinuous member which attains a thickness of up to 4.8 m in the northern part of the basin. The Lane's Shaft Member is the dominant coaly unit and is 18 m thick in the Oaklands-Coorabin area. The deposit is a dull coal containing two bands up to 1 m thick. Depth of cover varies from 60 to 350 m.

Yoo (1995a) described the coal as high moisture, low volatile sub-bituminous coal with low vitrinite (16 to 18 per cent), high inertinite (62 to 72 per cent) and liptinite (5 to 9 per cent). Ash content ranges from 13 to 19 per cent with volatile matter 25 to 29 per cent and low sulphur (0.25 per cent) (Yoo, 1995).

Measured in situ resources are 1200 Mt near Oaklands with 3000 Mt inferred in situ resources in the northern part of the graben (Yoo, 1995). Another 10 000 Mt may be present. Open pit in situ resources in the Oaklands area are estimated to be 880 Mt (Yoo, 1995).

Gloucester Basin

This basin is located approximately 80 km north of Newcastle and consists of a small narrow basin about 40 km long and 10 km wide. Small scale mining has been attempted since its discovery in 1855. The Permian Gloucester Coal Measures attain a maximum thickness of 760 m (George, 1975). Exploratory drilling proved economic coal exists in some areas of the basin. The coal is a high swelling coking coal capable of washing to about ten per cent ash. Seam dips of 40° are not unusual. Thinner coal seams in the overlying Craven Coal Measures also display some potential. Brakel (1989c) and Hughes (1995) gave detailed accounts of the geology of the basin.

Although coal was first discovered in the Gloucester basin in the 1850 it was only after exploration was carried out by a number of companies in the 1970s that two potentially commercial open pit mines were defined in the Stratford and Wards River areas in the 1980s. Stratford Colliery commenced production in 1995, exploiting the Avon, Triple, Bowens Road and Marker seams. Production in 2003-04 was 1.1 Mt of medium ash volatile coking and thermal coal. Duralie Mine commenced operations in 2003 and produced 1.3 Mt of coal in 2003-04 from the Weismantel Seam.

Of the more than 50 coal seams that have been identified in the Gloucester Basin only 20 have been named. Most of the seams are part of the Gloucester Coal Measures which have been divided into the upper Craven Subgroup and the lower Avon Subgroup. The main seams are the...
Weismantel Seam (Weismantel Formation) and the Avon, Glenview, Bowens Creek and Clovedale seams. Hughes (1995) provided an overview of the stratigraphy.

Gloucester Basin coal is a medium to high volatile bituminous coal with properties varying across the basin. The Avon and Glenview Seams are the most consistent. The washed product has 15 to 17 per cent ash, 27 to 34 per cent volatile matter and specific energy of 28.4 MJ/kg.

The NSW Department of Primary Industries (2005) gave the estimated recoverable coal reserves of the Gloucester Basin as 20 Mt. Hughes (1995) gave an identified in situ resource of 30 Mt for the Wards River deposit and 72 Mt for the Stratford deposit.

**Ashford Coalfield**

This coalfield is part of a narrow strip of Permian sediments in the Ashford-Inverell area. Coal was discovered in 1884 and since then small-scale mining has taken place periodically. The only economic seam, the Ashford Seam, has been mined by open pit methods for local power generation. Less than 1 Mt has been mined. Not more than 6 Mt of in situ resources were thought to remain (Britten, 1975). The seam is very variable in quality and has structural dips of 20° to 40°. The seam is a medium ash coal that could be considered as a coking coal. However, the small recoverable reserves (2.5 Mt in situ), probable difficult underground mining conditions (seams dip at up to 16°) and remoteness from a market make the coal subeconomical other than a small local market.

Wells (1995a; 1995b) and Flood (1995) summarised the geology, coal properties and resources. Flood stated that the Ashford Seam is part of the Ashford Coal Measures which was deposited in a fluvial environment.

**Other coal basins**

Coal has been identified in other localities in NSW but few have been detailed. Wells (1995a; 1995b) gave a brief description of the coal geology of the Nymboida area, and Goscombe and Coxhead (1995) gave a similar summary of the coal in the Clarence-Moreton Basin. Facer and Foster (2003) compiled a detailed review of the small Cranky Corner Basin which is an isolated outlier approximately 55 km north-west of Newcastle and 8 km north of the Hunter Thrust. Coal was exploited from the Cranky Corner Basin up to 1999.

Of the proven bituminous coal reserves in the State, which presently amount to about 36 000 Mt, Permian coal measures account for about 81 per cent, including virtually all 15.0 Bt of coking coal reserves, and about 68 per cent of non-coking reserves. The distribution of Permian and Mesozoic coal measures in Queensland is shown in Figures 8 and 9 respectively.

A historical review of the coal geology of Queensland up to 1990 was given by Mengel, Baffe and Coffey (1990) including a description of the coals grouped by age, the historical development of exploration and mining in the 19th century, followed by a detailed analysis of the coal exploration and mining from 1900 to 1950, and post 1950, including a review of geophysical techniques. Ward *et al* (1995) provided a review of the geology of Queensland deposits. The Queensland Department of Natural Resources and Water (2007) gives links to Queensland production, resources, mining operations, coal transport and statistics.

**Carboniferous coal**

The oldest known coal-bearing strata in Queensland are the Pascoe River Beds, of Early Carboniferous (Viscian) age, which were deposited at the northern end of the Coen Inlier in the far north of the state (Day *et al*, 1983). The coal is of no economic importance.

**Permian coal**

**Bowen Basin**

The most important of the Permian coal basins in Queensland, in terms of both reserves and production, is the Bowen Basin, which is exposed in a large, triangular-shaped area of Central Queensland, 600 km long and up to 250 km wide (with an outcrop area of 75 000 km²). To the south, the Bowen Basin extends in the subsurface beneath Mesozoic sediments of the Surat Basin and is thought to be contiguous with the Gunnedah and Sydney Basins in NSW. Detailed discussions of the Bowen Basin are given in Brakel (1995), Mallet *et al* (1995) and O’Brien (1996).

Coal was discovered in the Bowen Basin in 1845 with the first commercial production from Blair Athol in 1892, followed by mining in the Bowen Basin in 1904 at Bluff (Brakel, 1995). The distribution of coal measures and location of existing mines and major prospects in the Bowen Basin are shown in Figure 10. The proceedings volumes of the Bowen Basin symposia provide updated information on most aspects of the Bowen Basin every five years (The Geological Society of Australia, 1985; 1990; 1995; 2000; 2005).

**Structure**

Dickens and Malone (1973) divided the Bowen Basin into four major tectonic elements: the Taroom Trough, Collinsville-Comet High, Denison Trough and Springsure Shelf. In a later paper, Hammond (1990) distinguished between a Collinsville Shelf and a Comet Ridge, and
added a Folded Zone and the Nebo Synclinorium, thus recognising seven morphotectonic elements. Murray (1990) provided a detailed reappraisal of the tectonic evolution of the Bowen-Gunnedah-Sydney Basin and identified several significant criteria in the evolution of the basins:

1. the Bowen-Gunnedah-Sydney Basin extends for 1700 km and parallels the entire length of the New England Fold Belt;
2. the Bowen Basin is a retro-arc foreland basin and is associated with the Early Permian Camboon Volcanic Arc along the eastern margin of the basin;
3. the Bowen, Gunnedah and Sydney basins are linked by the long narrow and continuous Meandarra Gravity Ridge which has been attributed to a buried Devonian-Carboniferous magmatic arc;
4. modelling of the Meandarra Gravity Ridge shows it is an anomalously dense body in the upper crust; and
5. the Meandarra Gravity Ridge represents a volcanic rift.

Using the above information, Murray suggested that the Bowen Basin is an extremely complex basin that experienced polyphase subsidence and tectonic history with at least three stages of development: an Early Permian magmatic rift stage followed by a mid Permian sag stage and a final Late Permian-Early Triassic foreland basin stage.

FIG 8 - Distribution of Permian coal-bearing basins in Queensland

FIG 9 - Distribution of Mesozoic coal-bearing basins in Queensland

FIG 10 - Major coal centres and mines in the Bowen Basin (redrawn from Queensland Coal Board, 1993)
Mallet et al (1995) described the Bowen Basin as a composition of first-order NNW-SSE trending platforms or shelves separated by sedimentary troughs. They only recognised two stages in the development of the Bowen Basin: an early crustal extension stage that produced linear half graben structures which became centres for regional crustal sag, followed by a transition to a foreland basin with sedimentation predominantly in the Taroom Trough coincident with magmatic activity along the eastern margin.

**Stratigraphy**

Coal seams in the Bowen Basin exhibit great variations in rank and quality. A broad pattern of rank increase towards the Dawson Tectonic Zone in the east-central part of the Basin has long been recognised, and was used to help define exploration targets during the search for coking coal in the late 1950s and early 1960s (King and Goscombe, 1968). Patterns of rank variation in the Bowen Basin have been described in detail by Beeston (1981). In the east-central part of the basin near the Dawson Tectonic Zone, rank ranges from semi-anthracite to low-volatile bituminous, and deposits tend to exhibit relatively complex structure. Coals in the central part of the basin, on the Comet Ridge and the Collinsville Shelf, are medium to high-volatile bituminous coal, and include the best coking coal. Structural deformation in these deposits is generally relatively mild. A similar gradation in rank and moderation in structural deformation occurs to the north and south of the Dawson Tectonic Zone.

Further south and west, coal rank falls below the coking range and the most significant deposits are of low-ash non-coking coal. These deposits are generally unaffected by major structural complications. The westerly decrease of rank continues across the Springsure Shelf and into the Galilee Basin.

Coal-bearing strata occur at numerous stratigraphic levels throughout the Bowen Basin, but deposits of economic importance are restricted to four age groups (Hawthorne, 1974; Staines and Koppe, 1979). These groups represent regressive depositional phases, and are separated by transgressive sequences in which non-coking-bearing marine sediments predominate.

Unlike the Sydney Basin, the Bowen Basin has not been divided into coalfields. The Bowen Basin contains up to 2300 m of sedimentary rocks in the Denison Trough (southwest) and 3000 m of sedimentary and volcanic rocks in the north-east with the thickest coal-bearing sequences in the Denison Trough. Draper et al (1990) revised the stratigraphy of the basin, arbitrarily dividing the basin into four regions (south-east, south-west, central and northen), each with its own stratigraphic terminology. Mallet et al (1995) summarised the stratigraphy and linked it to the tectonic stages of the basin evolution. Only the two youngest stratigraphic units, the Rewan Formation (youngest) and the Rangal Coal Measures were recognised in all regions.

The stratigraphy given in Mallet et al (1995) recognises four coal groups. The oldest coal group, Group I coal measures, was deposited during the initial extensional rift stage and occurs in the graben-filling Reids Dome beds which extend north along the western margin of the basin. The Reids Dome beds are of highly variable thickness and lithology. In the southern Denison Trough, seams in the Reids Dome beds attain thicknesses in excess of 30 m, but such occurrences are at considerable depth. Further north the seams are thinner but nearer to the surface; shallow reserves of good quality coking and non-coking coal have been delineated in the Capella area. In the Denison Trough a thick marine sequence covers the Reids Dome beds. North of Collinsville, coal in the Crush Creek beds is interbedded with volcanic rocks.

Group II coal measures include several unconnected deposits around the northern and western margins of the basin including the Collinsville Coal Measures (Webb and Crapp, 1960) in the extreme north. The Collinsville Coal Measures are divided into an upper and a lower sequence by the Glendo Sandstone Member which was deposited during a marine transgression. Nine persistent seams are mined in the Collinsville Coal Measures with the coals exhibiting variable properties, continuity and uniformity depending on the environment of deposition.

Other coal measures are found at Rugby, north-north-east of Clermont; and a group of deposits in the Clermont area, including the Blair Athol and Walfang basins, which are structural outliers of the Bowen Basin (Cook and Taylor, 1979). Seams of similar age occur in the Freitag and Aldebaran Sandstone Formations of the Denison Trough in the central western and south-western parts of the Basin, but rarely attain thicknesses sufficient to warrant economic consideration. The Calen Coal Measures, which lie near the coast north of Mackay, are considered to be of similar age (Day et al, 1983).

In the Clermont area, the Blair Athol Coal Measures occur in an 8 by 6 km basin. Maximum seam thickness is found in a central 4.5 km² area. This coal measure has a maximum thickness of 250 m with a lower conglomerate up to 150 m thick. Four major seams, numbered 1 to 4 downwards, occur in the upper part of the sequence with the thickest being the No 3 seam which has an average thickness of 29 m.

Mining had been undertaken at Collinsville and Blair Athol for many years prior to major expansions of both operations in the mid-1980s. Collinsville produces both coking and steaming coal, whereas at Blair Athol the product is a medium volatile, low rank, low ash steaming coal.

Group III coals were deposited on the relatively stable Collinsville Shelf, under conditions which varied from marine-influenced distal deltaic in the German Creek Formation, to dominantly fluvial flood plain environments in the Moranbah Coal Measures (Koppe, 1978). These formations contain major deposits of high grade coking coal, which are mined by open pit and underground operations from Gordonstone near Emerald to Goonyella North in the hinterland of Mackay. Other mines in this group include Oaky Creek, German Creek, Norwich Park, Saraji, Peak Downs, Goonyella and Riverside.
Each of these mines produces high quality coking coal, characterised in general by high fluidity.

Five periods of coal seam development have been identified for Group III coals. In the northern Bowen Basin, the Moranbah Coal Measures are laterally equivalent to the German Creek Coal Measures found in the central part of the basin. The northern Bowen Basin has an aggregate of 20 m of coal in four to five seams in the west, splitting into 20 thin seams in the east. The economically important seams are the Goonyella Lower, Middle and Upper seams with the first two seams 7 to 9 m thick and 7 to 19 m thick respectively.

In the central Bowen Basin, the upper part of the German Creek Formation contains coal with eleven very thin seams being mappable over 100 km. Economically important seams are German Creek, Corvus 1 and 2, Tieri, Aquila and Pleiades seams.

A marine transgression which halted the main phase of deposition of Group III coals in the south did not extend into the northern part of the Basin, and environments conducive to coal accumulation persisted. However, volcanism at this time resulted in major tuff layers. Above the tuff layers, the coal seams are grouped as Group IIIA Coal Measures. Many seams have high ash contents, such as the Fair Hill Formation and Fort Cooper Coal Measures, and such seams are uneconomic despite their considerable thicknesses. Group IIIA seams can attain a thickness of 30 m but clastic and tuffaceous material may comprise up to 80 per cent of the seam.

The final phase of coal deposition in the Bowen Basin resulted in the formation of Group IV coals which include the Rangal Coal Measures and its equivalents, the Elphinstone Coal Measures, Baralaba Coal Measures and Bandanna Formation. These units contain the most diverse group of seams in terms of quality, and also are most widely distributed within the basin. Deposition of Group IV coals occurred under fluvial, lacustrine and paludal conditions.

The Group IV Coal Measures varies in thickness from 50 m on the Collinsville Shelf to 300 m in the Taroom Trough.

In the northern Bowen Basin, coal distribution is influenced by faulting and folding within the Nebo Synclinorium. Along the edge of the Collinsville Shelf, the Rangal Coal Measures vary in thickness between 25 and 112 m. Two thick seams, the Vermont and Leichhardt, dominate the sequence north of a zone between the Mackenzie River and Middlemount. To the south-east the seams split.

In the central Bowen Basin, the Rangal Coal Measures are found in the Yarrabee Structural Zone. The continuity and seam nomenclature is not at all clear because of seam splitting. Two main seams are found, with the upper seams thought to be a correlative of the Vermont Seam, in Curragh Colliery. In the Blackwater area, several seams appear to join to form the Mackenzie Seam (Pisces, Orion, Pollux seams), the Mammoth Seam (Aries and Castor seams) and a thin Cancer Seam (Mallet et al., 1995).

In the southern Bowen Basin, the Rangal Coal Measures crop out along the eastern margin of the Minos Syncline. As for the central part of the basin, seam definition is difficult. For example, six seams are recognised at Moura Colliery, in a coal measures thickness of 200 m, but to the north and south the seams split and nine seams can be identified. In the Theodore area the coal measures thickness is 350 m.

Although the quality and rank of Group IV coals vary greatly, they are characterised by a comparatively low reactivies content and low concentrations of sulphur. They are of major economic importance as a source of both coking and non-coking coal.

**Resources**

According to Mallet et al. (1995) no accurate figures can be given for total in situ resources although the resources in mine leases to a depth of 300 m was given as 20 000 Mt. Previously, Brakel (1989d) had given in situ measured and indicated reserves as 23 678 Mt. The Queensland Department of Natural Resources and Water (2007) gave the following resources in Mt, as at 2003 (Table 4). The total represents a decrease of 5000 Mt and this is attributed to a change from the previous published figures because of the way in which the resources were reported which was necessitated by the introduction of the JORC Code.

In 2003-04, Queensland produced 160.1 Mt of saleable coal, an increase of 4.2 per cent over the previous financial year. This production included:

1. coking coal: 89.15 Mt (56 per cent),
2. thermal coal: 70.92 Mt (44 per cent),
3. open-cut: 136.20 Mt (85 per cent), and
4. underground: 23.86 Mt (15 per cent).

---

**TABLE 4 - Summary of Queensland Coal Resources (from Smith, Coffey and Abbott, 2004)**

<table>
<thead>
<tr>
<th>Coal type</th>
<th>Permian (Mt)</th>
<th>Mesozoic (Mt)</th>
<th>Total (Mt)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coking - open pit</td>
<td>4 114</td>
<td>0</td>
<td>4 114</td>
<td>12.6</td>
</tr>
<tr>
<td>Coking - underground</td>
<td>7 079</td>
<td>47</td>
<td>7 126</td>
<td>21.7</td>
</tr>
<tr>
<td>Thermal - open pit</td>
<td>4 905</td>
<td>8 928</td>
<td>13 833</td>
<td>42.3</td>
</tr>
<tr>
<td>Thermal - underground</td>
<td>7 091</td>
<td>565</td>
<td>7 656</td>
<td>23.4</td>
</tr>
<tr>
<td>Total</td>
<td>23 189</td>
<td>9 540</td>
<td>32 729</td>
<td></td>
</tr>
</tbody>
</table>
More than 80 per cent of production was exported, primarily for use in the iron and steel industry, and in power generation. Domestic electricity production consumed most of the remainder. Coal exports represented 30 per cent of Queensland total overseas exports by value. In 2003-04 total value of saleable coal was A$7243 million consisting of A$5397 million (74.5 per cent) for coking coal and A$1846 million (25.5 per cent) for thermal coal.

Of total coal production in Queensland, 85 per cent is produced from the Bowen Basin with the remainder from the Moreton, Tarong, Callide and Surat basins.

**Galilee Basin**

The Galilee Basin (Figure 1) is an intracratonic basin that is filled with Late Carboniferous to Middle Triassic sedimentary rocks. It covers an area of 247,000 km², is contiguous with the Bowen Basin, separated from the latter by the Nenine Ridge and contains large quantities of subhydrous, non-coking coal. Because of the remote geographic location and relatively unfavourable quality, exploration has been comparatively slow. However, reserves in excess of 2.5 Gt have been identified, and unquantified resources are undoubtedly much greater.

The geology of the Galilee Basin was summarised by Wells (1995c), and Scott et al (1995). Scott, Beeton and Carr (1995) stated that the stratigraphy of the Galilee Basin is related to that of both the Bowen and Cooper Basins. Coal is found in the Bandanna Formation, the Colinlea Sandstone and the Betts Creek beds.

The main potential lies in seams correlatable with Group IV coals of the Bowen Basin. In the eastern Galilee Basin, these are represented by correlatives of the Bandanna Formation which contain numerous seams, but are typically covered by thick Cainozoic alluvium which reduces the potential for strip mining (Carr, 1975a). Near the northern margin of the basin, the Betts Creek Beds are of similar age and contain at least two seams, one of which was mined at Oxley Creek, near Pentland. Drilling has shown that the Betts Creek beds in the vicinity of Hughenden contain one seam at least 10 m thick at considerable depth (Gray, 1977; Baife, 1979).

Deep drilling by petroleum companies has identified an older coal-bearing sequence in the Galilee Basin (Gray and Swarbrick, 1975). This unit, known as the Aramac Coal Measures, is correlatable with the Reids Dome Beds of the Bowen Basin, but occurs only at considerable depth, and is not economically significant.

In the eastern part of the basin, the Alpha oil shale deposit lies within the axis of the Glen Avon Syncline, a southwest plunging structure located on the eastern flank of the Permian Galilee Basin. The Glen Avon Syncline separates the Voltiguer Anticline from the Avonmore Anticline. The deposit is part of the Permian Colinlea Sandstone that contains 150 m of cross-bedded sandstone with minor conglomerate, siltstone and mudstone. The sequence has a gentle dip of 2° to 5° to the west.

The upper seam is composed entirely of Cannel Coal oil shale that has a yield as measured by Modified Fischer assay of up to 150 LTOM at zero moisture (LTOM). The lower seam comprises a Cannel Coal oil shale seam with a torbanite lens. Oil yields for the coal are comparable with those of the upper seam but the oil yield of the torbanite is in excess of 600 LTOM where the algal content is high.

The interval above the upper seams consists primarily of cross-bedded and rippled quartzose to lithic sandstone and conglomerate with minor siltstone and claystone. Where the torbanite crops out, the torbanite-coal interval is overlain by 1.1 m of siltstone and fine-grained sandstone which is in turn overlain by channel deposits comprising a basal conglomerate grading upwards into cross-bedded sandstone. Above this is a thin siltstone and claystone bed that is overlain by a 4 m massive sandstone.

The shale oil resources are:

<table>
<thead>
<tr>
<th>Resource</th>
<th>Average oil yield (LTOM)</th>
<th>Oil resource (barrels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper seam</td>
<td>115</td>
<td>22.3 million</td>
</tr>
<tr>
<td>Lower seam</td>
<td>130</td>
<td>60.1 million</td>
</tr>
<tr>
<td>Torbanite</td>
<td>420</td>
<td>7.1 million</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>89.5 million</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Cooper Basin**

The coal resources in the Queensland sector of the Cooper Basin are vast with an estimate of 1000 Gt in situ. However, the seams all lie at depths, far beyond present economic limits. Two main coal-bearing intervals are recognised. In the Early Permian Patchawarra Formation, the average aggregate coal thickness basin wide is of 25 m. Coal is also found in the younger Toolachee Formation which has an aggregate coal thickness basin wide of 9.4 m (Thomson, 1979).

The geology of the Cooper Basin was discussed by Wells and O'Brien (1989) and Beeston (1995).

**Other basins**

Coal has also been described in the Olive River Basin (Wells, 1995d), Calen Basin (Brakel, 1995) and the Laura Basin (Wells, 1995c; Matheson, 1995).

Coal seams in the Laura Basin are located at Mount Mulligan and have been correlated with Group IV coals of the Bowen Basin (Wells, 1995). The coals are within the Little River Coal Measures and Normandy Formation which infill small faulted blocks which lie around the western and southern margins of the Laura Basin (Day et al, 1983).

The coal at Mount Mulligan is high-volatile bituminous and of variable quality. Three separate seams were mined by underground methods, including longwall, between 1914 and 1957, but reserves now appear to be virtually exhausted (Hawthorne, 1975). The seams in the Little River Coal Measures and Normandy Formation are of poor quality, steeply dipping and structurally complex, and have no economic potential (Carr, 1975b).
The stratigraphic correlation of coal-bearing formations in the major Permian basins of Queensland is summarised in Figure 11.

Triassic coal

By contrast with the Permian, the Triassic was a period of relatively limited coal deposition (Figure 12). Minor occurrences in the Moolayembar Formation of the Bowen Basin, and the Esk Trough in southeast Queensland are of middle Triassic age (Day et al., 1983). More significant deposits of late Triassic age occur in isolated intermontane basins in the south-eastern and central coastal areas of the state.

Ipswich Basin

The Ipswich Basin, an intermontane basin, occupies 250 km² southwest of Brisbane and has had a long history of coal mining since 1843. It continues to be a significant producer of thermal coal for domestic power generation, and a small amount is exported.

The seams of economic interest are within the Tivoli and Blackstone Formations, in the Brassal Subgroup of the Ipswich Coal Measures which attain a thickness of 1200 m. More than 20 seams have been worked at various times during the history of the coalfield (Mengel and Carr, 1976). The seams are typically banded with bands tending to be lenticular, and the seams themselves often split and rejoin over relatively short distances. Palynological studies indicate a late Triassic age (de Jersey, 1970a; 1971).

Ipswich coal is mostly a bright coal with a high ash content and is classified as high volatile bituminous coal. A low ash coking fraction can be produced from some of the coal.

Historically, mining in the Ipswich Basin has been by underground methods, almost exclusively bord and pillar. However, present day mining is almost exclusively by open pit methods with production in excess of 2 Mt of coal per annum. Staines, Faulkner and Thornton (1995) gave in situ measured and indicated resources as 575 Mt.

Callide Basin

The Callide Basin is located near Biloela in the central coastal area of Queensland and contains significant coal measures of late Triassic age, correlative with and in part slightly younger than the Ipswich Coal Measures (de Jersey, 1974). Coal was first discovered in Callide Creek in 1890 with coal production commencing in 1945.

The Callide Basin is an intramontane, fault-bounded synclinal basin (Biggs, Burgess and Patrick, 1995) along a north-west trending axis. The oldest unit in the basin is the Muncon Volcanics which are overlain by the Callide Coal Measures. The topmost unit is the Precipice Sandstone. The Callide Coal Measures include four persistent seams which are up to 26 m thick. The seams contain numerous shale and sandstone bands. In some areas, the seams have two or three major splits.

Callide coal is a medium ash, high-volatile, low sulphur coal used domestically for power generation.

Tarong Basin

The Tarong Basin is a small, fault-bounded basin situated about 190 km northwest of Brisbane. The basal unit of the sequence in the basin is the Tarong Beds which comprise sandstone and conglomerate, with several coal seams. The sequence has been palynologically dated as late Triassic and is correlative of the Tivoli Formation of the lower Ipswich Coal Measures, and slightly older than the Callide Coal Measures (de Jersey, 1970b; 1974).

![FIG 11 - Stratigraphic distribution of coal-bearing formations in the major Permian basins of Queensland (redrawn from Queensland Coal Board, 1993)](image-url)
Coal was first discovered in water bores in 1967. The major reserves are contained in the King and Meanda Creek seams which range up to 16 m and 34 m thick respectively. All seams have high raw coal ash contents, ranging from 25 to 45 per cent, and require washing to maintain product specification. The Meanda orebody mine produced 5.3 Mt of coal in 1991-92 for use in the adjoining Tarong power station. Pegram (1995) gave the measured and indicated in situ reserves as 183 Mt.

Jurassic coal

Jurassic coal measures sequences are widely distributed in Queensland, and the reserves identified are second in size and extent only to those of the Permian. However, relatively little mining has taken place in these deposits, due mainly to the superior quality and accessibility of the Permian coal. The geology of several basins was given in Goscombe and Coxhead (1995).

In the Moreton Basin, with by far the most extensive deposits, and the only ones presently of economic importance, lie within the Walloon Coal Measures of Middle Jurassic age (Day et al., 1983).

The seams in the Walloon Coal Measures occur in thick banded intervals where individual coal beds are separated by lenses of carbonaceous shale, mudstone, siltstone and sandstone of varying thickness. The main mining area is the Rosewood-Walloon coalfield near Ipswich where extensive underground mining was carried out in the past, and production, mainly from open pit operations at Ebeneezer and Jeebropilly, produced nearly 2.5 Mt in 1991-92. Underground production also occurred at Oakley, Acland and Tannymorel on the Darling Downs, but these areas are now abandoned. Over the last 25 years very large resources amenable to open pit extraction have been delineated in the Millmerran, Oakley and Macefister areas. Total resources, all amenable to open pit mining, exceed 2.1 Bt.

The Walloon Coal Measures extend across the Kumbarilla Ridge into the Surat Basin, where they crop out in an arcuate zone extending from Warra to Injune. No mining presently occurs in this area, although the Maranoa Colliery near Injune produced coal for 30 years until 1963, and small workings operated at Warra during the period 1914 to 1919 (Swarbrick, 1975). Major deposits have been delineated in the Brigalow, Chinchilla, Wandoan and Taraoom areas, and total resources in the basin exceed 2.6 Bt, all amenable to open pit mining. The coal occurs in two subordinate coal measure intervals, the Teroolin and and Juaindah Coal Measures, separated by approximately 100 m of sandstone (Swarbrick, 1973).

In both the Moreton and Surat basins, coal from the Walloon Coal Measures is very high-volatile, bituminous, low rank and non-coking (Queensland Coal Board, 1978). It is perhydrous, with a high exinite content, and is potentially a good feedstock for the production of synthetic liquid fuels. A significant characteristic of Walloon coals is their low Hardgrove Grindability Index, which ranges from 30 to 55. Recent trials for use in conventional pulsed boilers show that by adopting coarser grinds this problem can be largely overcome because the coal is highly reactive.

In the Eromanga Basin, which is continuous across the Nebine Ridge with the Surat Basin, the Birkhead Formation, is correlative with the Walloon Coal Measures (Swarbrick, 1973). The formation crops out in a belt running from Injune northwest to about as far as latitude 24°S (Gray, 1975). Although seams up to 1.5 m thick have been encountered, they are generally much thinner. No coal from the Birkhead Formation has been mined, and the prospect of identifying workable deposits is relatively poor.

The Mulgildie Basin is a narrow, north-easterly offshoot of the Surat Basin containing lower to middle Jurassic sediments. The uppermost unit in this sequence is the Mulgildie Coal Measures, which are of equivalent age to the Walloon Coal Measures (Day et al., 1983). The Mulgildie Coal Measures contain several banded seams within an interval of approximately 85 m; only one is sufficiently well developed to be of economic interest. Between 1949 and 1966, the seam was extracted by underground methods in the now abandoned Selene Mine (Svenson and Rayment, 1975). Remaining reserves of the coal, which is of similar quality to that in the Surat Basin, are relatively small.

In the eastern part of the Laura Basin, the Dalrymple Sandstone of Middle Jurassic age contains sizeable reserves of coking coal. Company exploration has identified several seams, one of which attains a thickness in excess of 2 m, and averages about 1.6 m. The coal can
be washed to produce a low-ash, high-swelling product with good yield. Sulphur content is relatively high, typically in the range 1.0 to 1.5 per cent total sulphur of which the major part is organic.

**Cretaceous coal**

Although Cretaceous strata are widely distributed in Queensland, few significant Cretaceous coal deposits are known. Thin seams of high-volatile bituminous coal occur in the Burram Coal Measures of the Maryborough Basin (Thornton, 1995) and the Early Cretaceous Styx Coal Measures of the Styx Basin (Day et al., 1983). Both areas have been mined by underground methods in the past, but remaining reserves are very small.

In the Eromanga Basin, the late Cretaceous Winton Formation contains lignitic coal seams, but limited exploration indicates that the potential for significant discoveries is poor.

The stratigraphic distribution and economic significance of Mesozoic Coal Measures are summarised in Figure 13.

Considerable tonnages of low rank, lignitic coal are known to occur in association with oil shale in several small Tertiary basins (such as The Narrows Graben near Gladstone, Duaringa Basin, and Hillsborough Basin near Proserpine) and in the coastal areas of central and southern Queensland (Noon, 1984). These are of interest mainly in the context of synthetic fuel production, the feasibility of which is under continuing investigation.

**VICTORIA**

**Brown coal**

Over 95 per cent of the known brown coal resources of Australia lie within Victoria. The Victorian brown coals comprise an estimated 94.7 per cent of the non-renewable energy resources available within the state (Figure 14).

Nearly all of the Victorian brown coal reserves and production occur in the Latrobe Valley (Figure 15). Extensive seams of 100 m or more in thickness commonly occur beneath less than 20 m of overlying sediments. Such extensive and thick seams, beneath relatively thin overburden, are exceptional. The remainder of the state’s brown coal occurs in the Otway Basin of the Western District where brown coal is produced from open pits at Anglesea and Bacchus Marsh. Other minor deposits occur in the Otway Basin at Altona, Lal Lal, Wensleydale, Benwerrin and Deans Marsh (Figure 15) and have been worked in the past. Tertiary coal deposits have been investigated by private mining companies in the Murray Basin. Summaries of the geology and coal properties in the Gippsland Basin, Murray Basin and Otway Basin are given in Barton et al. (1995), Brown, Preston and Gloe

**FIG 14 - Proportion of Victorian non-renewable energy sources**

Nearly all of the Victorian brown coal reserves and production occur in the Latrobe Valley (Figure 15). Extensive seams of 100 m or more in thickness commonly occur beneath less than 20 m of overlying sediments. Such extensive and thick seams, beneath relatively thin overburden, are exceptional. The remainder of the state’s brown coal occurs in the Otway Basin of the Western District where brown coal is produced from open pits at Anglesea and Bacchus Marsh. Other minor deposits occur in the Otway Basin at Altona, Lal Lal, Wensleydale, Benwerrin and Deans Marsh (Figure 15) and have been worked in the past. Tertiary coal deposits have been investigated by private mining companies in the Murray Basin. Summaries of the geology and coal properties in the Gippsland Basin, Murray Basin and Otway Basin are given in Barton et al. (1995), Brown, Preston and Gloe

**FIG 13 - Stratigraphic distribution of coal-bearing formations in the major Mesozoic basins of Queensland (redrawn from Queensland Coal Board, 1993)**

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Characteristics of brown coal

Brown coal is a soft, earthy, red-brown coal which is composed of partially altered plant debris. The maceral groups comprise plant tissues and woods (humotelinite), spores and cuticles (liptinite) and gelified material (humocollinite) set in a coaly groundmass (humodetrinite).

On a dry weight basis, the coal usually contains <5 per cent ash and commonly <2 per cent. The ash is made up of minerals such as clays, quartz, pyrite-marcasite, siderite and inorganic cations of elements such as Ca, Mg, Na and Fe, which are bonded into the coal mass.

The brown coal represents an early stage of coalification which has progressed to the point where the original cellulose is destroyed, hydrogen, oxygen and moisture are slightly reduced and carbon is slightly increased. The progression of such changes increases the rank of the coal leading ultimately to bituminous and anthracitic coal.

Coalification is brought about by heat and pressure acting on the coal over a long period of time. In the Latrobe Valley, there is still an abnormally high increase in temperature with an increase in depth of approximately 1°C per 15 m; and seams have been buried beneath the Tertiary and the Quaternary sediments subsequent to their formation. The older strata have been more deeply buried and as a consequence of the imposition of greater stress.

FIG 15 - Location of the Latrobe Valley Coalfields burial depths of brown coal


A summary of the discovery, exploration and development of coal mining in Victoria was given by Kenley (1990). Latest information on Victorian coal is given by the Victoria Department of Primary Industries, Minerals and Petroleum (2007).
from overburden weight, greater temperatures at depth and greater time, the older seams have lower moisture contents.

During faulting, coals in the vicinity of faults have been subjected to higher than normal stresses. As a result, rank is consequently increased, for example, at Yallourn North Extension, where Morwell age seams near the Yallourn fault and monocline have a typical moisture content of 52 per cent as opposed to the usual 60 per cent. Aspects of the faulting are discussed below.

The brown coals, although very low in ash, generally less than five per cent on a dry basis, are low grade fuels, which mostly contain more than 50 per cent water. Since it is not generally economic to transport such fuels over long distances, the processing, either by directly burning or by initial reduction of water as in briquetting, is located close to the site of the open pits. Minor variations in water content, coal structure and ash type exert an important influence on the way the coal behaves during burning, briquetting or conversion to oil or gas.

Formation of Latrobe Valley brown coals

Pre-depositional events

Between the formation of the Lower Cretaceous sedimentary rocks 140 million years ago and the start of the brown coal accumulation 50 million years ago, the Palaeozoic and Lower Cretaceous rocks were eroded in the onshore areas of Gippsland. This gap in sediment accumulation coincided with the start of the faulting which established the Latrobe Valley. The faults provided the pathway for lava to rise to the surface and to solidify into the basalts of the Thorpdale Volcanic Suite.

Depositional events

The first sediments to form in the valley were generally river, fluvial, gravels and coarse sands. These oldest sediments were followed by further sequences of fluvial sands and lake, lacustrine, clays. At this time and indeed throughout the Tertiary period, the climate was apparently cool to mild with sufficient water to favour fresh growth. The congenial climate and the presence of well-watered low-lying clay soils allowed forests to become established on the clay soils within the Latrobe Valley. The forests contained ancient representatives of the modern kauri pine, *Agathis sp.* The southern beech or myrtle, *Nothofagus sp.*, grew on the surrounding hills and is only represented in the coal formation by wind blown pollen. *Eucalyptus* is not identified in the coal sequence because it appears that this genus only came into existence after the end of the main coal seam deposition.

The trees and plants of the forests continued to die and regenerate at roughly the same rate as the floor of the valley dropped between the marginal faults. In this way, thick peat accumulations were deposited and, in the course of time, became more deeply buried beneath later coal and sediments (Figure 16). The peat compacted more than the sediments until eventually the forest floor subsided beneath the water level and the peat was replaced by lacustrine clays. New forests then became established elsewhere in the valley, where thick sediments occurred and where subsidence by compaction was less.

Notable exceptions occur at Loy Yang and Morwell where local upward earth movements cancelled out the compaction effect and coal accumulation occurred, with few breaks, over many millions of years. The apparently continuous accumulation resulted in the stacking of seams to a total thickness of up to 300 m.

For long periods of time, the forests grew in pure peat soil formed from the rotting plant remains from the earlier vegetation. Essential nutrients are thought to have been supplied from lateral filtering of water from the lakes around the swamps and from upward-flowing groundwater.

Some of the peat contained more leaf coatings, cuticles, spores and pollen and, after coalification, formed the light-coloured types of coal known as light lithotypes. Other peat contained more dark-coloured gelified plant debris including many wood pieces and formed the dark-lithotype coals. The light lithotypes may have formed under less waterlogged conditions but this is by no means certain as evidence to support this view is not conclusive.

Post-depositional events

After the deposition of the Yallourn Seam, the coal-bearing strata of the Latrobe Group were folded by...
late Tertiary earth movements. Along the margins of the valleys and, in some cases in the central areas as at Morwell, the folding was brought about by movements along faults in the underlying hard rock. The Tertiary strata were draped over these basement faults to produce monoclinic folds. In other areas, such as Loy Yang and Goomandale, the strata are more gently folded into anticlines and synclines.

After the termination of the major earth movements, weathering and erosion, particularly by rivers, cut across the folded surface producing a flat-lying plain which was subsequently covered by the fluvial and lacustrine sediments of the Pliocene-Pleistocene Haunted Hill Gravels.

The complex distribution pattern of the irregularly folded coal seams on the unconformable contact beneath the Haunted Hill Gravels reflects all of the major structural processes leading up to the present-day location of the coal deposits.

**Gippsland Basin**

Tertiary sedimentary deposits, including brown coal seams, are contained in the thick onshore part of the Gippsland Sedimentary Basin. The major deposits of brown coal in this basin are found in the Latrobe Valley, which is a fault-bounded depression extending westward from the Rosedale-Sale area to Yallourn.

The centre of the Latrobe Valley depression occurs near the Latrobe River where up to 700 m of Tertiary-aged sedimentary rocks, known as the Latrobe Valley Group, unconformably overlie lower Cretaceous rocks of the Strzelecki Group.

Within the Latrobe Valley, the Tertiary rocks have been tilted and folded, and widespread erosion has removed large quantities of the rocks from the uplifted areas. As a result, some areas have been left where thick coal seams lie near the surface, whereas in other areas the coal seams have been depressed to considerable depths. Throughout the remainder of the Gippsland Basin most coal seams occur at greater depths than in the Latrobe Valley and are currently uneconomic to mine. The main exceptions to this situation occur in uplifted areas close in to the edges of the Strzelecki Hills, such as at Stradbroke, Won Wron, Alberton and Gelliondale (Figure 15).

The Tertiary sediments in the Latrobe Valley are subdivided into three main formations, each of which contains thick brown coal seams (Figure 17). The lowest and oldest, of Eocene to Early Oligocene age, is the Traralgon Formation which contains the Traralgon Seam, up to 80 m thick interbedded with gravels, sands and clays. Traralgon Formation coal is generally the driest of these. The younger Morwell and Yallourn Formations occur to the west of this old shoreline and progressively thicken, to more than 200 m, towards the western end of the Latrobe Valley.

The sequence contains several seams; the youngest seam is the Yallourn Seam within the Yallourn Formation which is 97 m thick (Department of Primary Industries, 2007). The Morwell Formation contains three seams which coalesce in some areas. Near Morwell open-cut, the Morwell Formation is 150 to 180 m thick but increases to 210 m at Goomandale. Near Morwell there are two seams, the Morwell 2 and Morwell 1B seams, but elsewhere the two coalesce and the seam is known as the La Trobe Seam. In Morwell open-cut, the Morwell 1B and Morwell 1A seams coalesce to form the Morwell 1 Seam.

The coals of the upper formations are generally wetter than the coals in the Traralgon Formation varying between 55 and 65 per cent moisture. Around the edges of the Latrobe Valley, the main coalfields, which contain Morwell and Yallourn Formation coal seams, occur at Yallourn, Yallourn North, Morwell, Driffield, Maryvale, Tyers, Yinnar, Loy Yang, Flynn and Rosedale. Presently, production is solely by the State Electricity Commission from open pits located near Morwell, Yallourn North and Loy Yang (Figure 15).

**Otway Basin, including Torquay and Port Phillip Sub-basins**

In the Otway Basin the Palaeocene to Oligocene age brown coals occur around the north-east part of the Otway Ranges, between Deans Marsh and Anglesea, whilst probable Oligocene to Miocene coals occur in separate localities between Altona and the Bacchus Marsh area. The most significant deposit of the Otway Ranges is at Anglesea where a coal-bearing sequence approximately 140 m thick, called the Eastern View Formation, overlies the Lower Cretaceous rocks and is covered unconformably by terrestrial sands, clays and gravels. The Eastern View Formation, in areas to the east and north of the present Alcoa's Anglesea open pit, is covered by Eocene and Miocene marine deposits. Eight seams more than 3 m
thick have been recognised in the open pit area with the thickest seam reaching 24 to 30 m and occupying a position in the upper part of the sequence. The coal has a moisture content of approximately 45 per cent by weight and an ash content of around four per cent by weight on a dry coal basis. Brown coals between Altona and Bacchus Marsh occur within the predominantly sandy Werribee Formation which rests upon the Silurian basement and is covered over, in much of the area, by Quaternary to Recent volcanic rocks. The Werribee Formation contains many thin coal seams and attains a thickness of nearly 300 m in the centre of the Ballan Graben to the west of Bacchus Marsh. At the Australian Paper Mill Maddingley open pit near Bacchus Marsh production is from a seam approximately 30 m thick containing around 60 per cent by weight of moisture and around five per cent of ash on a dry weight basis.

**Anglesea coalfield**

The Anglesea coalfield is located south of Melbourne near the provincial city of Geelong. The sequence is up to 140 m thick with a 25 to 45 m upper seam and three to six thinner seams, aggregating 30 m, further down the sequence. The seams are near horizontal except at the margins of the coalfield where dips of 2 to 5° have been measured. The coal at Anglesea is a soft brown coal with 44 per cent moisture (<4 per cent ash, dry), high volatile content (48 per cent, dry) and a specific energy of 26.5 MJ/kg (dry); sulphur is high, approximately three per cent in many samples. Anglesea coal is harder and drier than Latrobe Valley coal.

**In situ** resources are estimated to be 160 Mt to a depth of 150 m, with 70 Mt in the upper seam. Annual production (open pit) is approximately 1 Mt per year. Production from the Alcoa Anglesea open pit produces electricity for aluminium smelting.

**Bacchus Marsh Coalfield**

Coal of similar character to the Latrobe Valley coal is found at Bacchus Marsh where it is mined by open pit methods. Resources are estimated to be approximately 1000 Mt with reserves of 25 Mt. Bacchus Marsh coal has 59 per cent moisture, 2.6 per cent ash (dry), 20 per cent volatile matter (dry) and a specific energy of 26 MJ/kg (dry); sulphur contents are 2.8 per cent. Production is 75 000 t annually (open pit) which provides coal for fuel in paper production at the Australian Paper Mill, Maddingley, Bacchus Marsh, and for lignopeat soil additives.

**Murray Basin**

Brown coals of the Murray Basin occur in the terrestrial silts and clays of the Olney Formation within the upper parts of the Palaeocene to early Miocene Renmark Group. The only known seams of significant thickness are at depths of greater than 100 m within fluvial sediments of the ancient Murray and Loddon river valleys. The coal is often high in ash and salt. The Murray Basin resource, of largely non-economic coal, is thought to be 20 000 Mt.

**Brown coal resources and production**

Total known world resources of brown coal are estimated at $5 \times 10^{12}$ t, with approximately four per cent of the total within Australia.

The estimated brown coal resources of Victoria vary considerably with estimates at more than 200 000 Mt of which more than 41 500 Mt could be readily extracted with available technologies and are consequently defined as economic or readily recoverable reserves (Victorian Government, 1984). Glee and Holdgate (1991) stated the total resources to the base of the coal measures in the Latrobe depression were estimated to be 107 847 Mt of which 35 754 Mt were classified as economically winnable.

Approximately 160 000 Mt of Victorian brown coal, which includes approximately 40 000 Mt of readily recoverable reserves, occur within the central and southern Latrobe Valley. Also in the Gippsland Basin, more than 6000 Mt of coal occurs at Gelliondale-Alberton, out of which some 1500 Mt have been defined as readily mineable. More than 50 000 Mt of coal is located in the deeper parts of the Gippsland Basin. Approximately 35 Mt/yr of Latrobe Valley brown coal is dug by the State Electricity Commission at Loy Yang, Morwell, Yallourn and Yallourn North Extension open pits. Most of the coal is used to produce electricity but some 2 Mt is used to produce briquettes and char and about 200 000 t is used directly by the APM Paper Mill at Maryvale. A pilot brown coal to oil plant, using coal produced by the State Electricity Commission, has recently been established at Morwell.

**Bituminous Coal (South Gippsland)**

By Australian standards, the sub-economic or economic 'black' coals of Victoria are meagre in thickness and extent.
and are known to occur only in the Lower Cretaceous of South Gippsland. They were worked by underground mining methods from practically the beginnings of settlement in Victoria to the late 1960s when the major operator, the State Collieries at Wonthaggi, closed as the mining had become uneconomic. Wonthaggi history is closely linked to the era of steam railway for which the coal was mainly sought. When the steam locomotives were replaced by diesel locomotives, the need for black coal declined and most of the mines closed down.

General geology and coal characteristics
The black coals accumulated under cool climatic conditions on flat lying plains in association with the fluvial and lacustrine sediments which spread across all of Southern Victoria during Lower Cretaceous times. The coals occur in the lower parts of the essentially feldspathic sandstone and mudstone sequences comprising the rocks of the Strzelecki Group. Most of the faulting which gave rise to the highlands and valleys of Victoria, including the Latrobe Valley, occurred after the deposition of the black coals.

Major problems associated with the Gippsland workings in general were thinness of seam, prevalence of faulting, steepness of dip and occurrence of stone bands. On the other hand the coal quality is good for steam purposes, comprising mostly banded bituminous coals with usual proximate analyses yielding:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>&lt;10 per cent</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>27.2 to 35.4 per cent</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>47.2 to 62.9 per cent</td>
</tr>
<tr>
<td>Ash</td>
<td>&lt;10 per cent</td>
</tr>
<tr>
<td>Gross specific energy</td>
<td>26.0 to 30.3 MJ/kg</td>
</tr>
</tbody>
</table>

The potential for finding additional economic deposits is probably not great, although large tracts of the Strzelecki Group host rocks remain untested.

Production history
Over ten independent mining areas were established following the discovery of coal outcrops in the Strzelecki Hills during the late 1800s. These outcrops tend to occur along a 70 km north-east trend between the coast at Cape Paterson and Coalville, south of the Latrobe Valley. The main production centres were at Wonthaggi, Korumburra, Jumbunna-Outtrim and Kilcunda-Woolamai.

Drilling in the close vicinity of the known outcrops usually established sufficient reserves for private operations and mining would then commence at the outcrops and continue by drive and shaft extensions.

The largest deposit at Wonthaggi was initially located by a private shaft dug for water in 1908, and in the ensuing years, drilling outlined two coal basins subdivided by faults and separated by a basement ridge under the Wonthaggi township. The larger westerly field, known as the Dudley Basin, contained two workable seams separated by up to 105 m of sediments over an area of about 5 x 3.5 km. The top seam had a thickness up to 3.0 m and the bottom seam, which split into two near the western margin, a thickness of about 1.0 m. The smaller easterly Kirrak Basin contains one main seam up to 2.2 m thick. Up until closure in 1970 approximately 17 Mt were mined from 12 separate pits at Wonthaggi, to a depth of 440 m, primarily by the State Collieries. It is estimated that a total additional amount of approximately 6 Mt were won from the other production centres, about half of which came from the Jumbunna-Outtrim Coalfield.

SOUTH AUSTRALIA

The first discovery of coal in South Australia was a lignite near Fidina in 1885. Coal has subsequently been found throughout the state in sedimentary basins ranging in age from Permian to Tertiary. Most of this coal is of low rank and poor quality. Johns and Wigglewirth (1990) provided a brief history of the discovery of coal in South Australia and also the history of coal exploration. South Australia Minerals (2007) gives an overview of the deposits.

Permian Coal
Substantial resources of sub-bituminous coal have been found in the Arckaringa Basin (Figure 18) in the north of the state and four of the six coal deposits found there have been grouped as the Arckaringa Coalfield (Wintinna, Westfield, East Wintinna and Murloocoppie), with the remaining two called the Phillipson Coalfield and Weedina deposit. The deposits contain many seams which are flat-lying and covered with 30 to 300 m of cover. Details of the coal in the Archaringa Basin have been given by McConochie and Dunster (1995).

Two seams exceed 20 m in thickness. The Phillipson Coalfield, on the southern flank of the Arckaringa Basin, has 11 seams with thicknesses of 1.5 to 9.0 m at depths of 50 m to in excess of 150 m (Wells and O'Brien, 1989b). The coal is high moisture, high volatile, low ash steaming coal.

Coal seams up to 25 m thick have been intersected during petroleum exploration programs in Early Permian sedimentary rocks of the Cooper and Pedirka Basins, at depths ranging from 1300 to 4000 m. The Patchawarra Formation contains one seam in excess of 15 m thick with total coal thickness of the order of 50 m. The Toolahee Formation has a total thickness of 13 m of bituminous coal (Johns, 1975). Both formations are located in excess of 2000 m below the surface. Resources estimated at hundreds of Mt surpaiss all other known deposits in Australia. Details of the coal are given by Beeston (1995).

Triassic Coal
The Triassic Telford Basin, containing the sub-bituminous Leigh Creek deposit (Figure 18), is located in central South Australia approximately 550 km from Adelaide. Coal was discovered at Copley in 1888. Open-cut mining commenced in 1943. Leigh Creek coal is transported to Augusta Power Stations over a 250 km dedicated rail link between Leigh Creek and Port Augusta.
Details of the Leigh Creek coal were given in Springett, Kemeny and Brennan (1995). The coal is found in four small isolated basins; the Telford Basin (or Lobe AB), Copley Basin (or Lobe A) and two lobes of the North Field (lobes C and D), over a 20 km distance. Each of the basins is less than 30 km² in area. The Telford Basin, the largest of the four basins, has dimensions of 7.5 × 4.5 km and contains up to 1000 m of sequence. The sequence is dominated by mudstone which contains organic matter. Some layers associated with the coal were assessed as a lacustrine oil shale in the mid 1980s. Coal is found in three intervals, informally referred to as the Lower Series (containing 65 m of interbedded coal, mudstone and fine grained sandstone), the Main Series (with up to 20 m of coal) and the Upper Series (containing coal, mudstone and siltstone).

The Telford Seam has been exploited by open pit mining around the northern margin of the basin. The main seam ranges from 6 to 18 m in thickness, averaging 12 m (Johns, 1978). Other multi-seam sequences overlie and underlie the main seam and are separated from it by not less than 10 m of sediments. Moisture content of the Telford Seam is 17 per cent, ash yield 20 per cent and volatile matter 38 per cent. Specific energy is approximately 15 MJ/kg. Known resources in the Telford Basin are estimated to be approximately 500 Mt.

The Copley Basin is a small (2.3 × 1.6 km) basin containing up to 300 m of sequence. The lower part of the sequence comprises 150 m of predominantly mudstone and coal informally known as the ‘Lower Coal Zone’. Seams in the Lower Coal Zone are 1.5 to 6 m thick (Wells, 1984) but contain claystone bands. The upper part of the sequence contains mudstone minor sandstone and coal and is referred to as the Upper Coal Zone”. This unit is 15 to 20 m thick with coal seams generally less than 1 m thick.

In the North Field, Lobe C, a high sulphur, high ash coal ranging from 1.6 to 16 m thick, has been mined by open pit methods. The North Field Lobe D has two main seams of 6 m and 9 m thickness. Lobe D has been completely extracted and Lobe C has few remaining reserves. Mining has ceased in Lobe C due to deteriorating quality. No reserves have been proven in the Copley Basin, Lobe A.

All remaining reserves are contained within the Telford Basin, Lobe B, the majority of which are not amenable to open pit extraction.

**Jurassic**

Sub-bituminous coal occurs in the Pelda Formation of the Porda Basin located on the western flank of the Eyre Peninsula. High ash coal in seams 0.5 to 6 m thick occurs beneath 50 to 150 m of cover.

**Tertiary**

Large resources of lignite high in sulphur, sodium and chlorine are located in the southeast of the state as well as the Eyre Peninsula and the eastern margin of the Nullabor Plain. Exploration was concentrated in the south-east in the St Vincent Basin, Kingston, Anna and Sedan. Considerable resources have been proven at depths of 50 to 100 m below the surface. Development of these resources is hindered by the water-saturated, unconsolidated overburden and interburden. The high water, salt and sulphur content of the lignites probably necessitates some pre-treatment.
The discovery of coal in Western Australia did not come about until 1846 when a German Naturalist, Preiss, reported coal near the Murray River south of Perth and then only after the government offered a free grant of land to the first person to discover coal in Western Australia (Lord and Wilson, 1990). Other finds soon followed.

Western Australia has a number of basins that contain coal but coal is mined only in the Collie Basin. A summary of the geology of the coal basins in Western Australia is given by the Western Australia Geological Survey (1990).

**Perth Basin**

Kristensen (1995) gave a detailed description of the Perth Basin, which extends for at least 1000 km from the Murchison River to the south coast, and its included coals. The Perth Basin is a large basin covering approximately 45,000 km$^2$ onshore and a similar area offshore with up to 15,000 m of Permian and Mesozoic sequence. Coal was discovered in the Perth Basin in 1846 when an outcrop was identified at Irwin River. The Perth Basin has been subdivided into several structural units of which several contain coal.

The Vasse Shelf has the Permian Sue River Coal Measures which is up to 1800 m thick. The typical basal Permian stratigraphic section has eight coal intervals in a sequence of point bar deposits. The lowermost seam is approximately 250 m above the basement. Four seams are considered economic and have been intersected along a strike length of 17 km at depths ranging between 180 and 450 m. The thickest seam, informally named the Osmington Seam, is at least 4 m thick; other seams are up to 2 m thick. In situ resources of the four seams, delineated by drilling with 2 km centres and for seams at least 1 m thick, are estimated to be 200 Mt. Vasse Shelf coal is a thermal coal with raw ash ranging from 7 to 15 per cent and gross specific energy ranging from 28 to 31 MJ/kg (dry basis). Sulphur content is <1 per cent.

The Irwin River Sub-basin contains the Early Permian Irwin River Coal Measures which was deposited in an upper delta progradation into a dominantly marine and paralic sequence. The coal measures is known to extend for at least 40 km with units increasing in thickness towards the south. Nine seams, ranging in thickness from 0.5 to 3 m with an aggregate of 10 m, occur in a stratigraphic interval of 50 m. Ash values are high (13 to 34 per cent) and specific energy values are low (13.7 to 17.8 MJ/kg). A resource of 80 Mt is inferred.

Jurassic coal of potential economic significance is found in the Hill River area.

**Carnarvon Basin**

Hocking (1995) gave a brief description of the Carnarvon Basin and its included coal. The Wooramal Group was deposited in a fluvial to wave dominated deltaic environment. The coal is relatively thin and of sub-bituminous rank. LeBlanc Smith (1990) gave the coal properties as ash contents ranging from 12 to 28 per cent, specific energy from 17 to 28 MJ/kg and sulphur content less than two per cent.

**Canning Basin**

The Canning Basin is an extremely large basin covering an area of 4320,000 km$^2$ onshore with an additional area offshore. The basin contains up to 18,000 m of sediment. Although coal is thought to be widely spread, little detail is known because of the paucity of drilling. Coal has been intersected in paralic sequences such as the Winifred Formation in the southern part of the basin and the Liveringa Group in the Fitzroy Sub-basin. A detailed review of the geology and structure of the basin was given in Yeates et al (1984). A comprehensive coverage of the Canning Basin including papers on exploration, petroleum geology, geochemistry and geophysics is given in Purcell (1984).

**Collie Basin**

The Collie Basin is located 55 km inland from the port of Bunbury and 160 km south of Perth. The Basin consists of two parallel troughs formed by glacial scours of the Pre-Cambrian basement and the subsequent filling by Permian and later sediments. The Collie Basin, 27 km long and 13 km wide with a subcrop area of 224 km$^2$, has been divided into two troughs or asymmetrical lobes separated in the south by an exposed basement structure referred to as the Stockton Ridge. The westerly trough is known as the Cardiff Sub-basin whereas the easterly trough, the Premier Sub-basin, has been subdivided into the Shotts and Muja Sub-basins.

Ashton, Betlinski and Chapman (1995) gave a detailed description of the Collie Basin which is the principal coal mining area in Western Australia. The basal Permian unit is the Stockton Formation (up to 330 m thick in the Cardiff Sub-basin and <40 m thick in the Premier Sub-basin). The latter unit is overlain by the Collie Coal Measures which is divided into three coal-bearing members with barren interbeds. The Permian sequence is overlain by the 5 to 30 m thick Cretaceous Nakina Formation and Tertiary units.

Ashton, Betlinski and Chapman (1995) estimated the in situ resources to be 1000 Mt measured, 700 Mt indicated and 600 Mt inferred. Of this total, extractable open pit resources in seams greater than 1 m thick and with a stripping ratio of 10:1 were estimated to be 500 Mt with 320 Mt of underground resources in seams greater than 2 m thick. Premier Coal (2007a) gave more recent figures stating that the total resources of the Collie Basin...
were 2400 Mt with total open-cut resources of 522 Mt (measured), 102 Mt (indicated) and 99 Mt (inferred) of which recoverable reserves for both companies totalled 399 Mt.

Collie Coal Measures
The Collie Coal Measures is a thick arenaceous sequence composed of felspathic sandstone, interbedded siltstone, shale, mudstone and coal. The oldest unit, the Ewington Member, is the only unit that can be correlated across the sub-basins and ranges in thickness from 48 to 64 m (Ashton, Bethelkis and Chapman 1995). Aggregate thickness of the coal units is 14 m in the Premier Sub-basin and 16 m in the Cardiff Sub-basin.

Above the Ewington Member in the Cardiff Basin is a coaly unit, the Collieburn Member, which is 340 m thick at the type section locality. Numerous seams have a combined thickness of approximately 20 m. Overlying the Collieburn Member is the Cardiff Member which has a type section of 140 m. However, if other coals seam along the western margins of the Cardiff Sub-basin are included in this member, the aggregate of coal is 23 m in a 250 m thick sequence.

Overlying the Ewington Member in the Premier Sub-basin is the Premier Member. This unit is found in the northern and central parts of the basin and has an aggregate of approximately 30 m of coal in 236 m of sequence. In the southern part of the basin the Chicken Creek Member overlie the Ewington Member and has approximately 30 m of coal in a 216 m sequence. The topmost coal-bearing unit in the Premier Sub-basin is the Muja Member which is restricted to the southern part of the basin. An aggregate of 26 m of coal is found in 145 m thick sequence. The Hebe Seam (Figure 19), the thickest coal seam in the Collie Basin, is up to 12 m thick.

Collie coal is of brown coal to sub-bituminous rank (0.3 to 0.5 per cent vitrinite reflectance), with low ash yield (3 to 11 per cent), high moisture (23 to 27 per cent) and a specific energy range of 18 to 22.5 MJ/kg. The composition of the coal varies. Ewington Member coal has the lowest vitrinite contents, of 13 to 41 per cent, with the exception of the Priam Seam which has 60 per cent vitrinite. Vitrinite content in the Premier Coal Measures is higher than in the other members, ranging from 24 to 75 per cent (Wesfarmers Premier Coal Limited, 2004).

Since 1960 only two companies, Premier Coal (formerly Western Collieries), owned by Wesfarmers Coal (Wesfarmers Limited, 2007) and Griffin Coal, operated. Production is now approximately 7 Mt of coal per annum (Premier Coal, 2007b). Historically, production from the Collie field has been directed towards local power generation as well as local industry such as alumina extraction and ilmenite upgrading (Lord, 1975). This continues in 2007, with for example, Griffin Coal producing 2 Mt per annum from its Muja mine for Western Power electricity generation and 1 Mt from its Ewington mine for the alumina, cement and mineral sands industry (Griffin Coal, 2007).

The Premier Mine is set midway between the Collie and Muja power stations with currently defined total coal resources of 360 Mt and coal reserves sufficient to carry the mine beyond 2040 at present production rates. Two pits are in operation (Premier Coal, 2007b). Pit 1 mines four seams of the Premier Coal Measures and will reach a maximum depth of 75 m. Plans for a deep option are under consideration, which may extend the depth to over 200 m. Pit 4 extracts eight seams from the Muja Coal Measures that occurs in a relatively steep synclinal structure where overburden and thicker interburden are bunched. Pit 4 has a life of around eight to nine years and will eventually meet up with the Muja mine, operated by Griffin Coal, and will reach a maximum depth of 200 m.

Premier Coal produces low sulphur (0.3-0.8 per cent), low ash (4-9 per cent) sub-bituminous steaming coal that primarily feeds the Collie, Muja and Kwinana power stations with a much smaller amount of nut product travelling by road to the Iluka Resources mineral sands operation at Capel.

The Muja Seams are mined by Griffin Coal in the Muja Mine, and by Premier Coal in the Premier Mine. In addition, the Premier Seams are mined by Griffin in the Ewington II Mine, and by Premier Coal in parts of the Premier Mine. The Ewington seams are found around...
the edges of the basin and were formerly mined in many of the early open pit and underground workings. The Griffin Coal’s Ewington 1 Mine is planned to open in the Ewington Coal Measures in the near future.

Wilga Basin

The Wilga Basin is a narrow graben structure approximately 14 km long, south of the Collie Basin. Coal is found in several units but little is known of the coals because of the lack of drilling.

TASMANIA

Coal was first recorded in Tasmania by the French explorer Labillardiere in 1793 (Bryan, 1990b). After European settlement in 1803, numerous discoveries of coal were made but successful mining did not occur until 1834 when the colonial government opened a mine at Saltwater River on the Tasmania Peninsula. Coal has been mined in various areas of Tasmania with major deposits of black coal being discovered in the Fingal Valley in 1863. The completion of the railway line to St Marys in 1886 enabled the establishment of larger scale coal mining in the Fingal Valley and this area has provided the majority of Tasmania’s coal since that time. Competition from oil caused a decline in the coal mining industry until more efficient mining and transport methods that were introduced in the mid-1960s allowed steam coal to become competitive. The major consumers of Tasmanian coal are currently a cement plant at Railton and the Norske Skog newsprint mill at Boyer. Mineral Resources Tasmania (2007) provides links to latest coal production figures for Tasmania.

The coal seams of Tasmania are found within the Parmeener Supergroup which is essentially flat-lying and was deposited in a structural basin, called the Tasmania Basin (Figure 20) which covers a large part of central and eastern Tasmania. The rocks range in age from Late Carboniferous to Late Triassic. Structurally, the Tasmania Basin has several small tectonic folds with limbs dipping at 10° or less, and drape folds over bedrock topography (O’Brien, 1989c). The sequence has been intersected by many steeply dipping faults with displacements of less than 100 m. During the Late Cretaceous and Early tertiary, horst and graben structures fragmented and dislocated the coal sequences.

The Parmeener Supergroup (Figure 20) was originally subdivided into four sequences (each composed of several formations) comprising, in stratigraphic order, the Lower Marine, Lower Freshwater, Upper Marine and Upper Freshwater Sequences. (O’Brien, 1989c). Bacon (1995) gave a revised stratigraphy and divided the Parmeener Supergroup into the Lower Parmeener Supergroup, comprising the Lower Marine and Upper Marine Sequences (marine and glacio-marine lutite, marl, minor limestone and a thick basal tilite), which is separated by the Lower Freshwater (all older than Permian) from the Upper Parmeener Supergroup, of fluvial origin, comprising the Upper Freshwater Sequence and an Above Upper Freshwater Sequence (Permo-Triassic age).

The Lower Freshwater Sequence contains Early Permian terrestrial coal-bearing strata represented by the Preolenna and Mersey Coal Measures and their lateral equivalents. The two sequences in the Upper Parmeener Supergroup are separated by a disconformity which represents a late Permian to middle Triassic hiatus between the Upper Freshwater Sequences and the younger Above Upper Freshwater Sequence (Bacon, 1995). The Upper Freshwater Sequence contains the Cygnet and Adventure Bay Coal Measures which contain the economic seams. The Parmeener Supergroups were extensively intruded by dolerite derived from tholeiitic magma during the mid Jurassic with one of the intrusions, the Red Hill granophyre, dated at 170 million years (Bacon, 1995). The dolerite mostly occurs as discordant sills, up to 550 m thick, which form a nearly continuous body. Dykes have been recorded. The dolerite is thought to represent more than 8000 km² of magma.

Early Permian Mersey Coal Measures and Preolenna Coal Measures

The Mersey Coal Measures was deposited as a thin 6 to 50 m sheet of fluvial sands which covered the earlier Permian seafloor and thinned on the highland areas. The coal is thin and discontinuous and was deposited around the margins of the depositional basin. The Mersey Coal Measures was deposited in the central to eastern part of Tasmania with the Preolenna Coal Measures restricted to a small sub-basin in northwestern Tasmania. The coal is not economic.

Early Permian coal is typically low ash (eight to 12 per cent) and relatively high in sulphur (three to five per cent) with pyrite in cleats (Bacon, 1995). Specific energy is 26 to 30 MJ/kg with vitrinite reflectance 0.45 to 0.5 per cent.

Late Permian Cygnet Coal and Adventure Bay Coal Measures

The Cygnet and Adventure Bay Coal Measures were deposited in a fluvial to upper delta plain setting. The dominant lithology is sandstone with minor siltstone interbedded with the sandstone. This coal measures is absent in the northern and eastern parts of the Tasmania basin because of pre-Tertiary erosion and is probably discontinuous elsewhere. The seams are not economic.

Triassic Coal Measures

The discontinuous Late Triassic coal sequences cover much of eastern and southern Tasmania (Noldart, 1975). Triassic coals are found in fining upwards sequences comprising sandstone representing channel deposits and siltstone and coal representing overbank deposits which were deposited on a flood plain with many streams of moderate to low sinuosity and frequently changing direction. Overall the coal measures has a higher proportion of sandstone, indicating classical high sinuosity meandering streams (Bacon, 1995). The economic seams are within the Triassic deposits.

The Preolenna Coalfield is located 20 km southwest of Wynyard and has a maximum thickness of 50 m with the seams 0.2 to 0.6 m thick (Bacon, 1995). Dips are 14 to 25°. Historically mining has been unsuccessful due to the severe faulting and seam thickness.

The Mersey-Don Coalfield is the easterly equivalent of the Preolenna Coalfield and occupies an area between the Mersey and Don Rivers; the sequence is 19 to 29 m thick seams are less than 1 m thick. Twentyone collieries mined the coal intermittently between 1850 and 1962.

Coalfields

Cygnet Coalfield

The Cygnet Coalfield occupies an area near Mt Cygnet and Mt Henley. The sequence is approximately 30 m thick and the seams are <1 m thick. A laterally equivalent sequence crops out on Bruny Island in Adventure Bay. Little mining has been carried out in the coalfield.

The Late Permian coal is similar to the Late Triassic coals whereas the Early Permian coal is quite different, having been formed in a back-barrier environment with paralic influence. This coal is high in sulphur, up to five per cent, low in ash (8 to 12 per cent) with a high specific energy (29 to 30 MJ/kg) although the seams are very thin.

Fingal, Mt Nicholas and Dalmayne Coalfields

Although small scale mining has occurred at many localities where the Triassic coal measures are found, the three main coalfields are the Fingal Coalfield (centred on Fingal Tier), Mt Nicholas Coalfield (in the Nicholas ranges north-east of Fingal Tier) and Dalmayne Coalfield (east of the Fingal Coalfield) which are located in the north-east corner of the state. These coalfields contain the bulk of the Tasmanian coal resources. The Lower Paraean Coal Measures is up to 120 m thick in these coalfields and is controlled by erosion. The Upper Paraean Supergroup which hosts the coal seams, is 350 m thick. Eight coal seams are found in the Fingal Coalfield, designated seams A to H although the upper two seams are very poor quality verging on being carbonaceous shale. The most economic seams are the Duncan (F) seam and the East Fingal (H) Seam which is stratigraphically 30 m below the Duncan Seam. The Blue Seam is mined at Blackwood Colliery on Mt Nicholas and the Merrywood Seam has been mined in an open pit operation southwest of Fingal.

Late Triassic coal is a very dull coal that formed in a dry forest moor environment, with ash 25 to 30 per cent, specific energy 20 to 24 MJ/kg (air dried); vitrinite reflectance is 0.5 to 0.6 per cent although coal affected by the dolerite sills has a much higher rank with vitrinite reflectance up to 3 per cent. Sulphur is much lower than for the Permian coals, approximately 0.5 per cent. Typical maceral analyses give 60 to 70 per cent inertinite, ten per cent vitrinite and five to ten per cent liptinite.

The Duncan Seam comprises 2 to 3 m of dull coal with minor claystone and mudstone interbeds. Raw ash is approximately 30 per cent and the specific energy is 22 to 24 MJ/kg. Vitrinite content in the Duncan Seam is higher than the average, up to 30 per cent. The East Fingal Seam is generally split, with 1 to 2 m of coal with intrascan classic rocks up to 10 m thick. Coal quality is similar to that of the Duncan Seam.

The Cornwall Coal Company is the major supplier of coal mined in Tasmania. The company currently mines black coal from underground and open pit mines near St Marys, from where the product is transported to a whasery at Duncan Siding near Fingal, and from the Duncan Colliery at Fingal. Most of the washed coal is transported by rail to the major consumers in bottom dump hopper wagons.

Production of raw coal in 2005/2006 totalled 635 467 t, with 415 090 t of saleable coal being produced (Mineral Resources Tasmania, 2007).

All Tasmanian coal is non-coking and is used in Tasmania as a thermal coal for raising steam.

Small deposits of brown coal of Tertiary age are found near Rosevale where the in situ resource is estimated to be 118 Mt.
Focal Petroleum Engineering Pty Ltd (2005) briefly mentioned four other insignificant coalfields: Schouten Island Coalfield, now declared a national park; Triabunna Coalfield, midway between Hobart and the north-eastern coalfields; Buckland Coalfield, near Buckland; and Saltwater Coalfield, at the northern end of the Tasman Peninsula. None are likely to be prospective.

Localised development of oil shale up to 2 m thick (late Carboniferous age) is found stratigraphically below the Mersey Coal Measures. The oil shale, termed Tasmanite, is a marine oil shale and was mined in the 1920s and 1930s.

**NEW ZEALAND**

New Zealand is a relatively small coal producer by world standards with all but a small proportion used domestically. New Zealand coal is generally Upper Cretaceous to Mid Tertiary in age and ranges in rank from lignite to semianthracite. Geographically, the New Zealand deposits have been divided into seven geographic regions (Figure 21) with the South Island having greater resources than the North Island (Hower et al., 1995). Newman and Newman (1992) and Sherwood et al. (1992) summarised the tectonic and depositional controls influencing the formation of New Zealand coals.

A summary of the estimated recoverable coal reserves and the percentage extractable by open pit methods is given in Taylor and Kunz (1983) and Ancshorn et al. (1988).

**South Island sub-bituminous and bituminous coals**

Coal of sub-bituminous and bituminous rank in the South Island is for the most part in coal measures of Upper Cretaceous to Upper Eocene in age. The coal was deposited in a transgressive environment directly on Tordesse or other basement rocks that had been deformed and uplifted by the Rangitata Orogeny which occurred approximately eight million years ago. Minor Cretaceous coal occurs in the Collingwood Coalfield (Pakawau Coal Measures) and in small coalfields in Canterbury and Otago (Shag Point Coal Measures). The most important fields with Cretaceous coal are the Greymouth and Pike River Coalfields on the West Coast, and Ohai and Kaitangata Coalfields in Southland and South-East Otago respectively.

Most of the Cretaceous-Lower Tertiary coals in the South Island have all been deformed and compressively folded and faulted. The most intense deformation is in the Westland-Nelson Coal Region where the coal measures are extensively folded and faulted. Deformation is less intense in the Kaitangata, Ohai and Canterbury Coalfields.

**Canterbury coal region**

Coals in this region are of sub-bituminous rank mostly with localised semi-anthracite deposits. The coals were deposited in transgressive fluvial to marginal marine environments. The Canterbury region is a small producer with production of several hundred thousand tonne per annum. The main coalfield is the Mt Somers Coalfield with smaller coalfields such as the Avoca, Acheron and Malvern Hills coalfields.

**Nelson-Westland coal region**

The Nelson-Westland Coal Region extends from the north-west tip of the South Island south and along the western coast. It is the largest producer on the South Island. The rank of the coal is mostly high to medium volatile bituminous coal that is sought after as coking coal. The age of the coal ranges from Cretaceous to Tertiary. Upper Cretaceous coal is confined to tectonic depressions in the basement and show very little or no marine influence.

Coal is found in three stratigraphic intervals (Hower et al., 1995):

1. Miocene Rotokohu Coal Measures which were deposited in basal fluvial to marginal marine environments;
2. Eocene Brunner Coal Measures which were also deposited in basal fluvial to marginal marine environments; and
3. Upper Cretaceous-Palaeocene Paparoa, Pakawau and Tauperikaka Coal Measures which were deposited in fluvial to fluvio-lacustrine intermontane environments, commonly in rift valleys.

The Cretaceous Paparoa Group and the coal measures of the Greymouth and Pike River Coalfields are confined...
to a narrow fault-bounded basin in which peat swamps developed adjacent to a meandering axial river system (Bowman and Newman, 1983). Syndepositional tectonic subsidence allowed exceptionally large thickness, up to 1000 m, of Paparoa Coal Measures to accumulate but the coal measures were followed by a period of tectonic quiescence in which there was almost no sedimentation.

At least six economic coal seams occur in the Paparoa Coal Measures but the seams are discontinuous and lensoidal and are extensively folded and faulted. The rank of the Paparoa coals is variable with the majority being high volatile bituminous coal. Paparoa coal is vitrinite-rich (<30 per cent vitrinite), low in ash (<10 per cent), and low sulphur (0.3 to 1.0 per cent); the high rank coals, a minor proportion of reserves, have exceptionally high Crucible Swelling Indices (9 to 9+ + +).

In the Nelson-Westland Coal Region a major Eocene transgression deposited coal measures in many parts of Nelson and Westland (Quartzose Coal Measures). In the west coast part of the region the Brunner Coal Measures lapped on to basement (Buller Coalfield) and on to Paparoa Coal Measures in the Greytown and Pike River Coalfields. Most of the Eocene coal has some marine influence and variable amounts of sulphur. The Eocene coal seams are thinner and much more extensive than those of the Cretaceous coals. The most economically important of the Eocene coal measures is the Brunner sequence in the Buller Coalfields. Brunner coal has a strong marine influence, a high organic sulphur content (commonly 5 to 7 per cent) and has a notably canneloid appearance which results from its strongly degraded petrographic nature.

The Buller Coalfield contains an estimated 57.5 Mt of recoverable reserves, more than 80 per cent of which are exploitable by open pit methods. The Buller coals range from high volatile bituminous C to medium volatile bituminous; they are notably low in ash (<5 per cent) and high in vitrinite and liptinite (>90 per cent). Buller coals in the prime coking range have exceptionally high Crucible Swelling Indices (9 + + +) and in the Stockton area the coal has excellent washing characteristics and can be washed to produce a coal with less than 0.2 per cent ash.

Other smaller deposits of Eocene low ash, high volatile bituminous coals occur in the Garvey Creek Coalfield (6.8 Mt of recoverable reserves) and in the Reefton Coalfield (6.3 Mt of recoverable reserves). The Garvey Creek coal is high volatile bituminous coal with variable sulphur (mostly <2 per cent). The coal is locally weathered and hence has lost much of its swelling capacity where weathering has occurred. The Reefton Coalfields contain sub-bituminous and high volatile bituminous coals which are generally too low in rank to be used as coking coals and their Swelling Indices are less than three.

Otago coal region

In the Otago Coal Region, the Kaitangata Coalfield is the biggest producer with some additional mining in the Central Otago Coalfield. Total production is approximately 100 000 t/yr. The Kaitangata coal is Upper Cretaceous to Palaeocene in age and is found in fluviolacustrine cyclic sequences with a marginal marine influence near the top. Central Otago coal is found in the Manuherikia Group which is also a fluviolacustrine succession. Total resources are estimated to be 1.086 Bt.

In the Kaitangata Coalfield, the Taratu Coal Measures accumulated initially in a fault angle depression within basement semischists, ultimately filling the depression and spreading out over the eroded basement surface and passing conformably up into marine sediments. The sequence at Kaitangata is 300 m thick and contains up to ten seams although the seams are discontinuous and frequently split. The recoverable reserves in the Kaitangata Coalfield are estimated at 50 Mt with the majority able to be exploited by open pit methods. The Kaitangata coals vary from lignite to sub-bituminous rank and have variable sulphur content (sometimes up to six per cent). Kaitangata coal has a high inertinite content (up to 30 per cent) in comparison with other New Zealand Cretaceous coals where inertinite does not usually exceed five per cent.

Southland coal region

The Southland Coal Region is the second largest coal producing area in New Zealand with the two main coalfields being the Ohai Coalfield and the Main Eastern Southland Coalfield (Hower et al., 1995). The rank of the coals range from brown/ sub-bituminous (Main Eastern Southland Coalfield) to high volatile bituminous (Ohai Coalfield). The latter coal has very low sulphur, low ash and high specific energy making it a well sought-after commodity. The seams in the Ohai Coalfield are Upper Cretaceous in age and are part of the fluviolacustrine Morley Coal Measures which was deposited in a rift basin. This coal measure is overlain by the Eocene Beaumont Coal Measures.

Drilling during petroleum exploration in the offshore Great South basin intersected 2000 m of coal measures with almost 200 coal seams having an aggregate thickness of 500 m (Sherwood et al., 1992). The coal is of high-volatile bituminous rank with sulphur increasing towards the top of the seams.

The Cretaceous Ohai coal was deposited in a similar setting to the Paparoa coals but at Ohai tectonic movements were less regular and a sudden major subsidence produced a second Cretaceous coal-bearing sequence, the Morley Coal Measures which overly the earlier Wairio Coal Measures. Following the deposition of the Morley Coal Measures the Ohai area was uplifted and eroded, during which time much of the Cretaceous sequence was removed. The combined thickness of the coal measures is probably approximately 180 m with the majority of the 51 Mt of reserves in the Ohai Coalfields being in the Morley Coal Measures. The coal has low sulphur (<0.5 per cent), low ash (0.5 per cent) and typically a high vitrinite-liptinite content (>90 per cent).
The Eocene brought a period of renewed tectonic activity, subsidence and further coal measure sedimentation. In the Ohai area, a third period of fluviatile sedimentation deposited the Beaumont Coal Measures on the eroded Motley Coal Measure surface. These younger Eocene coal measures extended out beyond the Ohai region to cover most of west Southland before finally passing up into marine sediments.

**North Island sub-bituminous coal**

The coal resources of the North Island are much smaller when compared to the South Island but production is higher, probably because of the larger population centres. The North Island has been divided geographically into three coal regions.

The North Island Coalfields have a deformational style characterised by faulting and regional tilting. The faulting is usually normal except in Northland where major reverse faulting occurs. The individual coalfields are usually outlined by block faulting or major fault boundaries.

**Northland coal region**

The highest rank North Island coal is in the Northland Coal Region where the rank of the coal is sub-bituminous locally transitional into high-volatile bituminous. Five coalfields have been recognised with the coals of late Eocene age. The Northland Kamo Coal Measures, found at Kawakawa, Hikurangi, Kamo, Avoca (a structural complex area) and Kiripaka, are para-coal measures with medium to high sulphur at the base of the marine Whangarei Group. Infaulted remnants of the coal measures are found in several localities in Northland. The Kamo Coal Measures is rarely more than 20 m thick and usually contains only two workable seams of a few metres thickness. The Northland Coal Region has produced in excess of 8 Mt, but most of the coalfields have now been worked out. Recoverable reserves remaining are estimated to be 2 Mt and an assessment by Isaac (1985) concluded that there is little possibility of finding further exploitable coals in the region. Mining is not undertaken at present; total recovered tonnage was 7.5 Mt (Hower et al, 1995).

**Taranaki coal region**

The Taranaki Coal Region is estimated to contain 130 Mt of recoverable coal, mostly of mainly relatively low ash (<5 per cent) and medium sulphur (2 to 3 per cent) and sub-bituminous rank. The major reserves are in the Mokau (74 Mt) and Waitewhena (28 Mt) coalfields. Total inferred resources for the Taranaki Coal region is 173 Mt.

The Taranaki Coal Region contains exposures of the Eocene coal measures at the base of the Te Kuiti Group but these occur only in the north (Aria Coalfield) and are insignificant. The economically important coal measures are the Miocene Maryville Coal Measures enclosed within the marine Mokau Group. The Taranaki coal is para-coal and has variable sulphur (1 to 5 per cent). The Maryville Coal Measures is characterised by many thin but extensive coal seams usually less than 3 m thick. Coals on the eastern margin of the Taranaki Coal Basin (Mokau Coalfield) are very degraded and liptinitic rich. The western Taranaki coal is less degraded and contains more telinite.

**Waikato coal region**

The Waikato Coal Region contains the major proportion, 507 Mt, of New Zealand's sub-bituminous coal reserves. It is the largest coal-producing region and is currently providing approximately 55 per cent of the annual national total coal production. Most of the recoverable reserves in the Waikato Coal Region are in four coalfields: Maramarua Coalfield (87 Mt of coal of which 45 per cent is amenable to open pit mining); Huntly Coalfield (242 Mt, five per cent open pit); Waikare-Ohinewai Coalfield (78 Mt, 55 per cent open pit); and Kawhia Coalfield (73 Mt). The latter two coalfields have not yet been exploited. Total inferred coal resources are 860 Mt.

The Waikato Coal Measures lie at the base of the Te Kuiti Group and although not thick, usually 30 to 100 m, are extensively developed from South Auckland to Kawhia. The coal measures contain two significant coal seams which are very discontinuous but locally very thick, up to 30 m. The Waikato coal is dominantly low ash (<5 per cent) and of sub-bituminous rank. The lowest rank coal is found in the northern Maramarua Coalfield and the highest rank coal in the now worked-out Glen Massey Coalfield. The Waikato coals, at least as far south as the Rotawaro coalfield, show no evidence of marine influence and are low sulphur (<0.5 per cent). The southern Waikato Coalfields (Glen Massey, Whatawhata and Kawhia coalfields) have a marine influence and contain on average two to three per cent organic sulphur. The coal seams are directly overlain by marine sediments. Waikato coal has high vitrinite contents (>85 per cent), although locally thin canneloid bands with abundant sporinite have been recognised. A particularly notable feature of the Waikato coals is the abundance of resinite, frequently forming fist-sized chunks or concentrated in discontinuous bands in the coal.

**Lignite resources**

Lignite constitutes New Zealand's largest non-renewable energy resource. The full extent of the lignite resources, located in the south of the South Island, was determined by a government-funded exploration program in the late 1970s. Ten major lignite deposits were identified with an estimated in-ground resource totalling 18 Bt. Approximately 6 Bt are currently classed as technically recoverable using large scale open pit mining techniques. The defined lignite resource is over five times greater than New Zealand's previously known reserves of sub-bituminous and bituminous rank coals.

Since the discovery of these deposits, a wide range of investigations has been conducted to better understand the resource and to allow major energy planning decisions to be made.

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The lignite deposits are all mid Tertiary or late Oligocene-Miocene age with the exception of Benhar deposit which is of Late Cretaceous age. In spite of similar age and geographic proximity of the deposits, the character of the deposits varies markedly, reflecting differences in depositional environment, depth of burial and subsequent tectonic history. The deposits can be subdivided broadly into three groups:

1. Six major lignite deposits are present beneath intensively utilised farm land in Eastern Southland. The three located in the northern part, the Mataura, Waimumu and Croydon deposits, have a significantly higher rank than those in the southern part, the Morton Mains, Waimatua and Ashers Waituna deposits. All deposits comprise relatively extensive multiple seams, up to ten in number, which range in thickness from 2 to 20 m and are inter-bedded with weakly consolidated mudstones, sandstones and gravels. Lignite was formed as peat deposits on a relatively extensive prograding fluvi-deltaic plain under stable tectonic conditions. Seams dip gently at 1° to 5° and with the exception of the Croydon and Waimumu deposits, all appear to be structurally simple with no clear evidence for major or widespread faulting.

2. The three Central Otago deposits, Roxburgh, Home Hills and Hawkdun deposits, are more compact comprising complexly split seams up to 90 m thick, with an extent of 5 km or less. Lignite-forming peat was deposited in swamps on the shoreline and in extensive deltas around the margins of a large inland lake during the mid-late Tertiary. Subsequently the region has been dramatically block-faulted which has emplaced and preserved thick lignite-bearing sequences in complex structural settings dominated by reverse faulting. Although these deposits are located in areas of low intensity land use, the distance from population centres and markets is an inhibiting factor.

3. The Benhar deposit, of late Cretaceous age, is situated in South Otago and is overlain by the shallow swamp-fringed Lake Tuakitoto and adjacent farm land. The deposit contains up to eight potentially workable, but complexly split seams ranging from 2 to 40 m in thickness. Of all the lignite deposits, Benhar Seams are the most complex in terms of thickness variation and splitting; they have the highest sulphur content, 2.05 per cent, and also possesses the highest rank. High sulphur arises from the direct influence of marine conditions where peat was originally formed in a coastal plain lagoonal environment. Higher rank results from the subsequent burial history, which at Benhar included a significant marine cover. Although the deposit structure is apparently simple at the Benhar deposit, recent studies have shown that extensive unconsolidated water-saturated Quaternary sediments would pose serious problems for overburden stripping.

Lignite mining and exploration

The existence of lignite in the Southland and Otago Provinces has been known since the time of first European settlement. Today seven open pit mines operate in the region producing a total of about 200 000 t/yr. The largest pits are located near Mataura in eastern Southland where gently dipping lignite seams 6 m to 20 m thick are worked at low overburden ratios, principally using hydraulic backhoe type excavators.

It was not until 1976, when a government funded survey of the region was carried out, that the true size and extent of the lignite deposits were recognised. Using rotary and diamond drilling with geophysical downhole logging and assisted by gravity and seismic reflection surveys, an area of over 7000 km² was probed for shallow lignite bodies containing a minimum resource of 200 Mt.

As a result, 12.5 Mt of potentially open pit mineable lignite was identified, with 10 Mt in ten major deposits widely scattered throughout the region. The three most prospective deposits (Benhar, Hawkdun and Ashers-Waituna) were selected for further study and were subject to geological, geotechnical and mining assessments as well as comprehensive environmental and socioeconomic studies.

Lignite reserves and quality

The technically recoverable reserves figures are derived from preliminary mining feasibility studies. Analysis of the relatively limited amount of core from each deposit shows the lignite has low ash, five to ten per cent, low sulphur, 0.5 per cent except for the Benhar deposit which has two per cent sulphur. Bed moisture varies from 40 per cent in the Benhar deposit to 61 per cent in the Morton Mains deposit with corresponding specific energy values, at bed moisture, ranging from 4.59 to 8.57 MJ/kg.

Future of the lignite resources

Preliminary mining studies, conducted by West German mining consultants, concluded that, using bucket wheel excavators, all but four of the major deposits are capable of producing 1 Mt per annum for 30 years. Lignite quality and process evaluation studies have shown that all deposits contain lignite that is potentially suitable for synthetic fuel (synfuel) feedstock. The most likely alternative use must involve thermal electric power generation when currently available hydro-electric power resources have been fully exploited.

Investigation and assessments to date have defined the basic geological, geotechnical, environmental and socioeconomic parameters of the ten major deposits. However whilst they have shown that all are potentially economic deposits using large-scale, modern mining technology, they have also identified a diverse and complex range of favourable and unfavourable attributes in each case. Energy planners will require more detailed and comprehensive assessments before major decisions concerning the development of this resource can be made with confidence.
ACKNOWLEDGEMENTS

The Chapter Editor acknowledges the contribution of the following persons to the previous volume: P E Baffe, C M Barton, T M Blatch, P F Balger, R G Bowman, J F Doyle and G Sutcliffe.

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