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Coal

world-class energy reserves without limits

G. R. Holdgate.

16.1 Introduction

Black coal has supplied some of Victoria’s early energy needs as a fuel for locomotive use and power generation. After 1921, with the setting up of the State Electricity Commission of Victoria (SECV) and its favoured use of brown coal, the need for black coal declined and the last underground black coal mine closed down in the 1960s. This mining was always difficult, with thinness of seams, depth of mining, extensive faulting, gas risk and small overall reserves all being factors against continuing the exploitation.

All the black coal production came from Gippsland’s Narracan Block, from Lower Cretaceous Strzelecki Group rocks. The principal mines were at Wonthaggi, Korumburra, Jumbunna, Outtrim, Kilsunda, Woolamai and Coalville, with minor production also recorded from Berry’s Creek (Mardan), Boolarra, Rintoul Creek and Cape Patterson (Fig. 16.1). Between 1864 and 1970, total coal production amounted to nearly 23 million tonnes (Knight, 1976).

Brown coal deposits accumulated at some time in most of the Victorian Tertiary basins, with major concentrations in the Gippsland, Port Phillip, Torquay and Murray basins (Fig. 16.2). Only the Otway Basin appears to be generally poor in coal-bearing strata. Presently, large-scale opencut mining of these deposits only occurs in the Gippsland Basin’s Latrobe Valley, where current production averages over 40 million tonnes per year from three mines, to supply most of Victoria’s electricity requirements. Smaller-scale brown coal production of less than 1 million tonnes per year occurs at Anglesea (Torquay Basin) and at Bacchus Marsh (Port Phillip Basin). Historically, other small-scale production has been undertaken at Lal Lal (Ballan Graben), Wensleydale/Deans Marsh/Benwerrin (Otway Basin) and Gelliondale (south Gippsland Basin).

The brown coal deposits of the Latrobe Valley are the largest of their type in the world. As Herman (1922) stated “brown coal in Victoria is like a huge fortune in chancery”. Whether any further future developments occur depends very much on satisfying greenhouse gas emission standards, because there are currently no limits to the economically winnable reserves, at least for many hundreds of years to come.

16.2 Structural history and coal-measure deposition

Following the breakup of Gondwana, a series of extensional rift basins developed during the Late Jurassic in the west and then progressed eastwards (Larson, 1975; Wessell et al., 1977; Shaw, 1978; Larson et al., 1979; Canè & Mutter, 1982). The early structural history of the Cretaceous rift sequences had a fundamental influence on their contained black coal deposits. The rifting cut normal to the dominant meridional structural grain of the older Palaeozoic rock systems. Some of these trends persisted through the Strzelecki Group cover as a series of basin-separating N–S-orientated basement highs, some of which became the focus for black coal deposition and mining.

Continental breakup was diachronous, with the more easterly basins being affected by two sequential events—the Australia–Antarctic separation in the mid-Cretaceous (100 Ma) (Canè & Mutter, 1982) and the Australia/Lord Howe Rise separation in the Late Cretaceous (80 Ma) (Shaw, 1978). Breakup also produced some of the basin-heating events that influenced Strzelecki Group coal rank. Major basin-forming detachment surfaces have also been proposed by Willcox et al. (1992) for the development of the Gippsland Basin. Basin-infill proceeded by southeast foundering and slip along the detachment surface into the opening Tasman Sea to the east and SSE slip into the Southern Ocean.

The earliest structural events in the Gippsland Basin were the development of half-grabens and burial of older basement ridges in the Neocomian — Early Aptian (Constantine, 1992). Later mid-Cretaceous structures and uplift produced a major unconformity in all southern margin basins, demarcating the rift-type of sedimentary style (Strzelecki Group) from the drift-type of sedimentary sequences (Latrobe Group style). This uplift was accompanied by a major thermal event, as seen by the re-setting of sedimentary apatite fission tracks in the Early Cretaceous rift sequences (Singleton et al., 1980; Duddy & Green, 1992). This timing also appears to coincide with the changes in stress regime associated with the Southern Ocean opening and the Tasman Sea rifting (Smith, 1982). Major erosion following uplift stripped considerable thicknesses of Strzelecki Group sediments off the major highs. It was on and adjacent to these structures that many of the black coal deposits that had been deposited in the early history of the rifting have been found.
Faulting and folding trends within the black coal mines and nearby outcrops are multi-directional and variable and may have controlled coal deposition (Constantine, 1992). Four stages of fault development are recognised and were detailed by Willcox et al. (1992). These are:

2. A mid-Cretaceous, often dyke-intruded, NW–SE fault trend, due to NE–SW extension (see also Edwards, 1934).
3. A N–S strike trend that offsets the two earlier trends and is possibly Late Cretaceous in age.
4. NW–SE and NE–SW, respectively, low and high angle reverse fault sets relating to the present NNW–SSE compression, that may have reactivated previous normal faults.

Etheridge et al. (1985) invoked a series of NNE–SSW transfer faults extending from the Southern Ocean over a south-dipping detachment surface to explain the major basin structures by strike slip extension. This model tends to maintain connections between the Early Palaeozoic structural grain and the younger basin geometry, evidence for which can be seen at the shallower western end of the Gippsland Basin (Holdgate & McNicol, 1992). Deep seismic surveys now show that the basin developed as a result of transtension (i.e. oblique extension), by left lateral strike slip in an approximate NW–SE sense (Willcox et al., 1992).

Much of southeastern Australia is now currently under a NNW–SSE compression related to northward movements of the Australian Plate (Barton, 1981). Most of the onshore Gippsland Basin folds trend NNE–SSW, approximately at right angles to this compressional direction.
Fig. 16.2: Brown coal basins of Victoria.
16.3 Black coal

16.3.1 Structural links between basement trends and the onshore Gippsland Basin coalfields.

Early Palaeozoic basement rocks outcrop to the north and west of the Gippsland Basin and are folded into steep N–S-trending folds (Fig. 16.2). Younger Upper Devonian – Lower Carboniferous sediments are more gently folded into the N–S-trending Avon and Mitchell River syncloria. On the southern margins, Palaeozoic outcrops include NNE-trending steep folded metasediments near Corner Inlet and Upper Devonian Wilsons Promontory Granite to the east.

From limited drilling evidence the basement trends continue under the Strzelecki Group and, in particular, beneath the Lakes Entrance Platform. South of here, the greatly thickened sedimentary rocks of the Strzelecki Group largely preclude first-hand knowledge of basement types, except as inliers along sub-Strzelecki Group basement highs, e.g. at Boolarra (Ferguson, 1917). However a number of bores and wells have intersected Palaeozoic basement rocks consistent with the adjacent outcrops along strike. They include Lower Devonian Walhalla Group and Wilson Creek Shales intersected beneath Tertiary and/or thin Strzelecki Group in a number of coal bores in the Yallourn–Morwell and Yinnar areas (from SECV bore data), and in the Moe Basin (Bolger, 1982a). The Yinnar occurrences appear to comprise one of two important NNE-trending basement highs which outcrop or subcrop beneath the Strzelecki Group and which reflect the earlier Palaeozoic structural grain. In conjunction with gravity high data, they provide evidence for two shallow basement ridges crossing under the Gippsland Basin, trending NNE and connecting the Southern Platform to the Lakes Entrance Platform (Fig. 16.3). A cross-section (A–A’) across the Tyers and Wonthaggi basement ridges is shown on Fig. 16.4 (Holdgate, 1996). All the known black coal deposits are located along or adjacent to these two ridges.

**The Tyers Basement Ridge.**

Evidence for this important structural ridge includes bore intersections of Walhalla – Jordan River groups in the Yallourn and Morwell opencut areas, near Yinnar, and basement outcrops near Boolarra (Ferguson, 1917). South of the Boolarra basement outcrops, at least two gravity highs (Fig. 16.3) appear to link the outcrops to the fault-bounded Turtons Creek and Foster North basement outcrops in the South Gippsland Highlands. These appear to be northerly continuations of the South Platform basement outcrops at Corner Inlet. The Tyers Basement Ridge divides the Balook Block of the Gippsland Basin from the Narracan Block of western Gippsland, and provides the loci for the shallow black coal occurrences at Boolarra, Coalville and Foster (Figs. 16.1, 16.3, 16.4).

Fig. 16.3: Gravity map of Gippsland showing major structures in basement and basement ridges beneath the Strzelecki Group (after Holdgate, 1996). Cross-section line A–A’ shown on Fig. 16.4.
Fig. 16.4: Cross-section (A-A' on Fig. 16.3) showing generalised stratigraphy and structure for the Strzelecki Group and known iso-reflectance contours.
The Wonthaggi Basement Ridge.

A similar NNE-trending basement high beneath the Narracan Block (the Wonthaggi Basement Ridge — Holdgate, 1996) was first identified by Edwards et al. (1944) from subsurface black coal exploration data. Underground black coal workings along this high trend include Cape Patterson, Wonthaggi, Outtrim, Jumbunna and Korumburra. The Wonthaggi Basement Ridge is broadly delineated by gravity highs (Fig. 16.3) trending NNE from Cape Patterson to Korumburra, the latter being the most northerly coalfield along this trend (Fig. 16.1). Within the Strzelecki Group along this trend, most coal seams occur a few hundred metres stratigraphically above basement.

16.3.2 Stratigraphy

The Strzelecki Group is subdivided into five units: the Tyers Conglomerate (Phillip, 1958); Rintoul’s Creek Sandstone (Bolger & Carey, 1983a); Rhyll Arkose (Edwards & Baker, 1943) and the Wonthaggi Formation and the San Remo Member (Constantine, 1992; Tosolini et al., 1999) (Fig. 16.5).

The Tyers Conglomerate, Rintoul’s Creek Sandstone and Rhyll Arkose occur within the Late Berriasian — Barremian D. speciosus spore–pollen Zone. Respectively, they comprise pebble–cobbles metasedimentary conglomerates, fine to medium-grained quartzose sands, mudstones and minor coals, and micaceous carbonaceous mudstones and granite-derived grits and conglomerates. Each unit may exceed 100 m in thickness depending on structural location (Constantine, 1992).

The Wonthaggi Formation ( Aptian—Albian) unconformably overlies these units and spans the P. notensis to P. pannosus spore–pollen Zone. It may exceed 2750 m in thickness and is dominated by epiclastic volcanic sandstone and mudstone. In its lower beds, it includes the Wonthaggi coal measures interval, consisting of carbonaceous shales, mudstones and thin coal seams — the total interval may be up to about 100 m thick. The San Remo Member in the P. notensis spore–pollen Zone includes Palaeozoic-derived granite and metasedimentary grit intermixed with volcaniclastic sand. Some informal unit subdivisions of the Wonthaggi Group are distinguished on the basis of dominant lithologies in deep wells in the onshore Gippsland Basin (Fig. 16.4). Fission track dating indicates contemporaneous volcanism was the source of the volcanic detritus. Palaeocurrent data from the Wonthaggi and Eumella formations indicate a strong NW-transport direction in both the Gippsland and Orway basins, suggesting that the two basins were connected across the Mornington High during this time. Inliers of Strzelecki Group on the Mornington High attest to this connection (McHaffie, 1974; Mallet & Holdgate, 1985).

16.3.3 Coalfield geology

Wonthaggi Coalfield

Coal was first discovered at Wonthaggi in 1888. Company and State-run underground mining was developed from 1909 to supply steam railway locomotive fuels. The cumulative production was 17.1 Mt up until the last mine closures in 1968. Remaining resources of coal are thought to approximate 6.8 Mt from seams 0.4–1.7 m thick. Mining difficulties and gas explosions were not uncommon throughout the life of the mines and today tourism has replaced the economic benefits from coal production.

The Wonthaggi Coalfield comprises two basins — the Kirrak and Dudley basins, respectively to the east and west of a central basement ridge beneath Wonthaggi town (Figs. 16.1, 16.6). In the larger Dudley Basin, up to eight separate coal seams occur over a stratigraphic interval of some 300 m, but only three seams appear to have been worked to any degree. The uppermost or ‘Top Seam’ is up to 3 m thick and the lower or ‘Bottom Seam’, some 75 to 105 m below, was usually split into two, each about 1.25 m thick (Knight, 1970). In the Kirrak Basin, two similar main seams are separated by 150 m of sediment — the ‘Bottom Seam’ is up to 2.2 m thick but a poorly developed ‘Top Seam’ is less than 1 m thick. A cross-section through the Dudley Basin is shown on Fig. 16.6.

Fig. 16.5: Stratigraphy of the Strzelecki Group (from Constantine & Holdgate, 1993).

In the Dudley Basin, strata dip up to 20° to the south, with lesser dips to the east and west in the Kirrak Basin. Faulting produced strata throws which are often greater than 30 m and maybe up to 200 m. Contemporaneous soft-sediment deformation and other syn-sedimentary structures have produced ‘floor rolls’, ‘wants’ and ‘wash-out’ structures detailed by Edwards et al. (1944), and Knight (1970). Dolerite dykes intrude some of the strata and cinder zones extend up to 1 m on each side of the intrusions (Barker, 1998).

Kilcunda/Woolamai Coalfield

Beginning at coal outcrops along the coast between San Remo and Kilcunda (near the town of Woolamai) mines were developed from underground shafts and drives. Early mining got going in the 1840s, but larger scale operations at the Victorian and Kilcunda mines did not begin until 1910 and continued through to 1953. Some half million tonnes were produced. Smaller scale production of 50 000 tonnes was obtained from Woolamai between 1952–1966. The seams were less than 1 m thick and thinned down dip (Brown, 1948).

Jumbunna/Outtrim Coalfield

These coalfields are located on the Narracan Block in hilly country west of the Powlett River Plains and 5 km north of basement outcrops at Kongwak — part of the Wonthaggi Basement Ridge. Wonthaggi Formation strata dip NW at 25–35° and coal seams up to 1.8 m thick occur within a sandstone and carbonaceous shale sequence. Coal seams 0.9–1.6 m thick were worked at Jumbunna between 1894 and 1929 and at Outtrim between 1894 and 1946 (Knight, 1972). Mining generally followed the northerly dipping seams to a depth of 300 m when operations became uneconomic (Brown, 1948). Sporadic mining continued up until 1962 by which time 3 Mt had been recovered from the area.
Fig. 16.6: Cross-sections through the Dudley and Korumburra coalfields (from Constantine & Holdgate, 1993). See Fig. 16.1 for section line A–B. Note the section lines are datummed from the ‘Top Seam’.
Korumburra Coalfield

This coalfield, located 6 km north of Jumbunna, probably worked the same group of seams further north along the Wonthaggi Basement Ridge. Up to five seams, covering a stratigraphic interval of 180 m, dip northwest. In 1893, shafts and adits were commenced at outcrops of the seams. Up to the mine closures in 1962 some 2 Mt was produced, mainly from the ‘Top’ and ‘Main’ Seams, with lesser amounts from the ‘Middle’ and ‘Deep’ Seams. The remaining resources are estimated to be 1.63 Mt (Knight, 1975a) although, as for Wonthaggi, tourism based on the coal mining era probably holds the greater economic potential. A cross-section through the Korumburra Coalfield (Fig. 16.6) shows a similar stratigraphy to that of Wonthaggi.

Coalville Coalfield

Outcrops of coal at the northern end of the Narracan Block, such as at Coalville, occur in proximity to the Tyers Basement Ridge. Shafts and adits extracted up to 62 700 tonnes from seams up to 0.7 m thick between 1884 and 1897 (Kenny, 1948a; Knight, 1975a). Approximately 100 000 tonnes of reserves may remain.

Mirboo North and adjacent areas

Steep-dipping coal seams up to 1.5 m thick were worked from outcrops and underground shafts in the Mandal area near Mirboo North and also at Yimmer South and Jorolangu Junction. The last two are located in close proximity to basement outcrops and form part of the black coal resources along the Tyers Basement Ridge.

Other occurrences in Gippsland

The site of the first Victorian discovery of coal, in 1825, is 1.6 km NW of Cape Paterson, and some 7 km south of Wonthaggi, on the southern part of the Wonthaggi Basement Ridge. Coal seams up to 0.5 m thick outcrop along the coastal platform and were worked from shallow shafts sunk behind the nearby sand-dune cliffs. Four seams occur within an interval of 11 m and interbed within a carbonaceous mudstone sequence. Basaltic dykes intrude parts of the section. Many well-preserved silicified tree trunks occur within the mudstones. Other coal occurrences, at Foster (Thomas, 1951) and Welshpool (Kitson, 1902), have been described.

Subsurface occurrences of Strzelecki Group coal seams in deep oil wells in the onshore part of the Gippsland Basin have been noted during the exploration for hydrocarbons. Gas shows directly associated with these coal seams were first recorded in the Loy Yang-1A well (Capital Energy, 1995) and indicate some potential exists for coal-bed methane production and/or hydrocarbon generation into adjacent reservoir sandstones. Gas and oil shows in the Strzelecki Group have fewer and thinner coal seams with lower rank and higher moisture content than for Gippsland's Strzelecki Group.

16.3.4 Coal quality, rank and reflectance

The black coals of the Strzelecki Group are mainly high-volatile bituminous coals, with 5–10% moisture (air-dried), 30–35% volatile matter and 6–12% ash (see Table 16.1). The gross specific energy is 26–28 MJ/kg (Knight, 1975a; Ward, 1995). Measured vitrinite reflectance on outcrops of coal and associated strata vary between 0.50 and 0.67% Rv (Cook, 1981; Constantine & Holdgate, 1993). With deeper burial, reflectances in the Wonthaggi coal measure strata may exceed 0.9% Rv (Paton, 1982; Capital Energy, 1995; Barker, 1995, personal communication) (see Fig. 16.4).

16.3.5 Black coals of the Torquay and Otway basins

Lower Cretaceous sediments of the Otway Group outcrop at the eastern end of the Otway Basin as the Otway Ranges High and in the central northern part of the basin as the Merino High (Fig 16.2). These sediments are similar in age, composition and depositional setting to the Strzelecki Group in Gippsland but, in general, the outcrops appear to be of the younger, more sandstone-prone lithologies that are often coal-poor. Black coal outcrops have been recorded in both areas but no significant workings have been carried out to date.

Otway Ranges

The structure and stratigraphy of the Otway Ranges is complex, with the lower beds being poorly exposed. Coal outcrops occur in the Apollo Bay area (Murray, 1886) and at Devils Elbow, 10 km to the north. The seams are thin and are mostly less than 0.4 m thick. They also outcrop in out-cuts sections NW of Apollo Bay on the Benwerrin Road. Reflectance values indicate that an increase in rank occurs towards the crest of the Otway Ranges High and very high anthracite ranks (>5.0% Rv) have been recorded for coal and carbonaceous sediments in the Olangolah-1 well on the crest of the Otway Ranges High (Cook, 1982). Similar high ranks exist along the Paraparap High between the Otway Ranges and the Barrabool Hills (Holdgate et al., 2001a). The higher ranks were thought to be a result of original large burial depths with subsequent exhumation by uplift (Cooper & Hill, 1997), although higher heat flows and volcanic intrusions may also play a part (Holdgate et al., 2001a).

Merino High

Outcrops of Otway Group sediments occur over an extensive area in the Merino-Casterton-Coleraine districts of western Victoria. Outcrops and bore intersections of coal seams up to 0.6 m thick have been recorded (Douglas et al., 1988) but appear to contain higher ash contents than in Gippsland (see Table 16.2). Rochow (1971) recorded a number of coal seams averaging 0.8 m thick in deep wells south of the Merino High. No workings of these seams are known and in general the Otway Group in the Merino area appears to have fewer and thinner coal seams with lower rank and higher moisture content than for Gippsland's Strzelecki Group.

Table 16.1. Indicative quality of Strzelecki Group coals in the Gippsland Basin (from Knight, 1975a; Ward, 1995).

<table>
<thead>
<tr>
<th>LOCALITY</th>
<th>Moisture %</th>
<th>V.M. %</th>
<th>F.C. %</th>
<th>Ash %</th>
<th>GCV MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dudley Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top seam</td>
<td>9.1</td>
<td>30.6</td>
<td>47.9</td>
<td>12.4</td>
<td>26.0</td>
</tr>
<tr>
<td>Bottn seam</td>
<td>8.06</td>
<td>32.12</td>
<td>52.8</td>
<td>7.02</td>
<td>28.2</td>
</tr>
<tr>
<td>20 shaft top</td>
<td>10.7</td>
<td>32.7</td>
<td>50.0</td>
<td>6.4</td>
<td>27.49</td>
</tr>
<tr>
<td>20 shaft bot.</td>
<td>6.3</td>
<td>35.0</td>
<td>47.7</td>
<td>11.0</td>
<td>27.5</td>
</tr>
<tr>
<td>McBride top</td>
<td>8.34</td>
<td>30.13</td>
<td>52.15</td>
<td>9.34</td>
<td>27.4</td>
</tr>
<tr>
<td>McBride bot.</td>
<td>5.93</td>
<td>31.83</td>
<td>50.95</td>
<td>11.3</td>
<td>27.7</td>
</tr>
<tr>
<td>9&amp;10 shaft</td>
<td>7.84</td>
<td>30.32</td>
<td>55.08</td>
<td>6.76</td>
<td>28.5</td>
</tr>
<tr>
<td>West top</td>
<td>9.8</td>
<td>34.4</td>
<td>49.4</td>
<td>6.4</td>
<td>27.6</td>
</tr>
<tr>
<td>West bot.</td>
<td>7.2</td>
<td>35.4</td>
<td>48.1</td>
<td>9.3</td>
<td>27.7</td>
</tr>
<tr>
<td>Kirrk Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East area</td>
<td>9.4</td>
<td>32.3</td>
<td>50.0</td>
<td>8.3</td>
<td>27.5</td>
</tr>
<tr>
<td>18 shaft</td>
<td>9.5</td>
<td>34.9</td>
<td>47.2</td>
<td>8.4</td>
<td>27.6</td>
</tr>
<tr>
<td>Kirrk area</td>
<td>11.0</td>
<td>31.9</td>
<td>49.7</td>
<td>7.4</td>
<td>27.7</td>
</tr>
<tr>
<td>Other Basins</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jumbunna</td>
<td>5.0</td>
<td>27.2</td>
<td>62.9</td>
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<tr>
<td>Boolarra</td>
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<td>35.21</td>
<td>52.25</td>
<td>6.97</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

Note: V.M. =volatile matter; F.C. =fixed carbon; GCV =gross calorific value; top = top seam; bot. = bottom seam; for all localities see Fig. 16.1.

Table 16.2. Analyses of coal samples from the Merino area (after Douglas et al., 1988).

<table>
<thead>
<tr>
<th>BORE</th>
<th>DEPTH</th>
<th>Moisture %</th>
<th>Vol. matter</th>
<th>Fixed carbon</th>
<th>Ash %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merino-3</td>
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<td>17.85</td>
<td>32.68</td>
<td>29.65</td>
<td>19.90</td>
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<tr>
<td>Merino-4</td>
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<td>27.88</td>
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<tr>
<td>Munthum-3</td>
<td>11m</td>
<td>16.60</td>
<td>25.40</td>
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</tr>
</tbody>
</table>
16.4 Brown Coal

16.4.1 Gippsland Basin

Introduction

Of the ten Cretaceous–Tertiary basins across southeastern Australia, the Gippsland Basin occupies the premier position with regard to the scale and size of its contained brown coal and petroleum energy resources. Within the onshore margins of the basin occurs the largest Australian accumulation of Tertiary brown coal, where total in situ coal reserves of over 100,000 million tonnes have been defined by extensive drilling (Gloe, 1975). In addition, over four times this quantity of brown coal is classified as inferred resources within the whole of the onshore area (Holdgate, 1984). Up to five major coal seams are defined within the Tertiary Yallourn, Morwell and Traralgon formations, with individual seam thicknesses often exceeding 100 m (Fig. 16.7). Where some of these seams occur in vertical stratigraphic superposition, they can form over 400 m of continuous low ash coal (as shown in SECV drilling records).

A succession of marine limestones and marls (the Seaspray Group) accumulated as a facies equivalent to the Yallourn and Morwell formations. These sediments cover most of the near-coastal part of the onshore basin and extend offshore. A transitional sand facies (the Balook Formation) forms the boundary between the mostly nonmarine coals and interseam sediments, and the marine carbonates. Only the older coal seams of the Traralgon Formation pass beneath the Seaspray Group and occur over most of the onshore area (Fig. 16.8).

History of coal exploration

Early investigations for coal began in the vicinity of outcrops of coal, such as in the Latrobe River. Drilling investigations spread out from these areas. By the end of the 1950s most of the brown coal deposits in the Latrobe Valley had been delineated. Discovery of new fields outside the Latrobe Valley Depression, such as Gormandale, Stradbroke, Alberton, Moe, Yarragon and Longford, resulted from the use in combination of remote (geophysical) techniques and facies models, followed up by drilling (Fig. 16.2).

Today, the Victorian brown coal bore database (established by the SECV) contains a record for all brown coal exploration in Victoria and includes the results for over 20,000 bores. Most of this drilling is concentrated in and around the present-day open cuts or prospective fields. For regional studies there are about 200 key and/or better-sampled bores in the rest of Gippsland. In addition there are several hundreds of bores in the Anglesea and Bacchus Marsh areas where other brown coal opencut mines exist (Torquay and Port Phillip Basins).

Brown coal exploration methods

Drilling methods varied between diamond drilling, percussion methods and some rotary methods, with the best results obtained with the rotary and percussion techniques. Exploration drilling in new field areas was begun using a 1–2 km spacing, but this was often closed up in problem areas. Depth of drilling varied with the depth to the base-of-coal and usually ranged between 100 and 500 m. Deeper drilling required in the synclines where Tertiary sediment thickness may be up to 800 m was principally carried out for regional groundwater and stratigraphic purposes. Proving drilling on a grid basis of 400 m or less was undertaken in defined coalfields. Over 140,000 coal sample analyses from many hundreds of bores are available from the former SECV database.

From the 1960s through the 1980s, a number of additional fields were discovered beyond the Latrobe Valley by the SECV and the Mines Department, using a combination of methods followed up by drilling.

Facies models

The advent of coal depositional models provided a spur to examine areas not considered worthy of exploration before. These included the recognition that some of the coal measures in Gippsland had formed originally as back-barrier peat deposits behind coastal barrier systems. Consequently the mapping of the major Tertiary barrier systems and their marine equivalents was useful in identifying likely zones where coal deposits could be found on the landward side of the sand barriers. A classic case for this combination of techniques was used in the discovery of the Alberton coalfield in South Gippsland, where 2000 million tonnes of economic coal was later defined by drilling (Holdgate, 1982).

In other areas of Victoria and interstate, a facies model evolved whereby brown coal deposits would preferentially accumulate in buried palaeovalleys developed on basement rock. These often underlie the modern drainage systems, particularly to the north of the main dividing range or in the drier coastal basins of southern Australia. Successes using this model were achieved by CRA in the Murray Basin near Kerang, Torrumbarry and Echuca (Preston, 1995).

Geophysical methods

The use of gravity surveys to define and augment the SECV drilling results in the Latrobe Valley commenced in the late 1950s (Neumann, 1974). The surveys showed a close correspondence between gravity highs and Latrobe Valley structural highs. Consequently areas likely to contain shallow deposits of coal coincided with gravity high areas. In the converse situation, gravity lows were found to correspond to synclinal structures where the coal was buried to sub-economic depths. Where a gravity low was developed on a major structural high then it was possible that a thick shallow coal basin was present. One example where a coal basin was first defined using gravity occurred in the Gormandale area (Neumann & Lonsdale, 1973). Follow-up drilling established the Gormandale Coalfield, where 2100 million tonnes of economic coal is defined (George, 1965; Gloe, 1980). Gravity surveys helped to identify the Alberton, Moe and Longford Coalfields outside the Latrobe Valley Depression. Gravity residual mapping in the case of Alberton was also found to be useful to define the subtle structuring in this area.

The earliest seismic surveys to assist coal exploration in the late 1950s proved difficult to interpret, due to the absorption of the seismic frequencies within the upper coal seams. Subsequently, despite various refinements to the seismic techniques and processing, the methods were never found to be particularly useful, although some success was claimed by Esso during the exploration of the Yarragon Coalfield (Fraser, 1983). Frequency absorption by coal seams remains one of the major problems in the petroleum exploration in Gippsland (Beresford & Dunne, 1996). However, definition of the top-most seam is guaranteed. Further areas of the Gippsland Basin may contain shallow economic brown coals that could be identified where good seismic coverage exists.

For borehole geophysical logging for brown coal, the ideal tool is the gamma-neutron combination log which readily discriminates between coal, clay and sand. The density tool also provides a valuable backup particularly where higher ash content coal may not be easily distinguishable from sand by the gamma log.
Stratigraphy

The main coal-bearing sequences in the onshore Gippsland Basin are, in stratigraphic order, the Traralgon Formation, the Morwell Formation and the Yallourn Formation (Fig. 16.8). A more detailed description of these Tertiary sequences and other non-coal bearing units for the Gippsland Basin is given in Chapter 10.

Traralgon Formation

This is the oldest Tertiary Formation that includes useful economic accumulations of brown coal and was first described by Gloe (1960) with amendments by Hocking (1972). It is dated by the Nothofagidites asperus and Lower Proteacidites tuberculatus spore–pollen Zones as being Middle Eocene to Early Oligocene (Partridge, 1971). It is widespread throughout the onshore Gippsland Basin, with the exception of the Lakes Entrance Platform, and is known to extend offshore (Holdgate et al., 2000b) (Figs. 16.9, 16.10).

This formation consists of interbedded gravels, sands, clays and major coal seams. The coarser-grained sands and gravels predominate towards the base, coals and clays in the middle, and sands, clays and minor coals near the top. Stratigraphic correlation of these coal seams is shown on the detailed cross-sections in the onshore Gippsland Basin (Fig. 16.9). Where the formation subcrops below the Pliocene Haunted Hill Formation along the basin margins, or where it is not overlain by Morwell and Yallourn Formations, economically winnable coal seams can be found. Such areas include all the major coalfields along the Baragwanath Anticline (Gormandale, Willung, Holeys Plains, Coolungoolun, Longford Dome, Stradbroke, Boodyarn and Won Wron) and also on the Loy Yang and Gelliondale Domes (Fig. 16.2). Here, uplift along the Baragwanath Anticline block has brought the deeper coal seams near-to-surface. Coals of the Traralgon Formation are also known to occur at Alberton, where they underlie the Miocene Alberton Coal Measures (Fig. 16.10). Calculated economically recoverable reserve figures for these fields are given in Table 16.3. However despite a large economic reserve totalling 10 Gt, no Traralgon Formation coal has ever been mined.

Across the uplifted Baragwanath Anticline, the Traralgon Formation coal seams are subdivided into the main Traralgon 1 (T1) and Traralgon 2 (T2) seams, separated by an interbedded clay and coarse sand interval (isopach thicknesses of the T1 and T2 seams are shown throughout Gippsland on Figs. 16.10a,b). In the deeper areas of the Lake Wellington and Seapspray depressions, the T1 and T2 seams further subdivide and split into subseams. At the coast they mainly show a facies change into thick sandstones of the Dutson Sandstone Member (Fig 16.10c). The T1 seam at Gormandale, Flynnns Creek Syncline and Stradbroke can be over 100 m thick. Further east, at Holey Plains, Coolungoolun and Longford Dome, the seams are reduced to about 40 m each. At Gormandale, George (1965)
Fig. 16.9: Cross-sections through the Latrobe Valley coal measures. (see Fig. 16.2 for locations of A–A’ and B–B’).
Fig. 16.10: Isopach maps of (a) T2 coal seam; (b) T1 coal seam; (c) Dutson Sand Member (after Holdgate et al., 2000).
Kerang deposits 19,599
Murray Basin 221,400
Gippsland deep (e) 243,900
Anglesea 390
B. Marsh-Altona 15,110

deeper burial or folding, moistures below 50% can be found.

The lowest moisture content (average 55%) of any Gippsland Basin coals, but with minor coal seams.

Known as the Honeysuckle Hill Gravels (Gloe, 1975) underlie the coal west to the Traralgon Syncline. Thick gravel sequences (up to 200 m) (Holdgate, 2000b). In the Latrobe Valley Depression a number of seams aggregate up to 150 m of coal in places (Fig. 16.10), but little is known of their quality. Here, the overlying limestone cover varies between 300 and 700 m in thickness. The only fully cored section in which the coal was analysed is from Wulla Wullock-7 bore, where the seams between 500 and 700 m averaged 47% moisture. A few samples analysed from deeper oil wells indicate similar coal qualities with respect to ash yield but, as is to be expected, they are higher in rank, i.e. bed moisture content may be as low as 30%. This resource is estimated to exceed all other combined resources of brown coal in Gippsland, but its thick limestone cover would preclude economic development other than for possible coal-bed-methane.

The Dutson Sand Member lies between the T1 coal seams and the offshore marine Gurnard Formation in a depocentre along the near-coastal onshore part of the basin (Fig. 16.10c). The Dutson Sand Member consists of two to three massive sand bodies. These are coaly, with a series of coal seams up to 5 m thick at the top, and can total 200 m in thickness. Coal seams of possible equivalent age include the T+ seam in the Gormandale Syncline (George, 1965) and the upper T1 coal seam beds at Loy Yang (A. Partridge, personal communication, 1994).

The Morwell Formation was first described by Thomas & Baragwanath (1949) and amended by Hocking (1972). It consists of a complex unit of thick coal seams and lesser clays and sands that disconformably overlie the Traralgon Formation in the Latrobe Valley Depression. The Morwell Formation, together with the similar-aged Alberton Formation in the Yarram area, are confined to that part of the onshore Gippsland Basin west of the sand barriers (Balook Formation) which mark the predominant maximum point of marine transgression for the Seaspray Group (Figs. 16.8, 16.9 and 16.11). The Morwell Formation extends across the Latrobe Valley Depression and grades into the Thorpdale Volcanics in the Moe Swamp Basin and on the Narracan Block (Fig. 16.9). The Lower, Middle and Upper Proteacidites tuberculatus spore–pollen Zones show the Morwell Formation was first described by Thomas & Baragwanath (1949) and amended by Hocking (1972). It consists of a complex unit of thick coal seams and lesser clays and sands that disconformably overlie the Traralgon Formation in the Latrobe Valley Depression. The Morwell Formation, together with the similar-aged Alberton Formation in the Yarram area, are confined to that part of the onshore Gippsland Basin west of the sand barriers (Balook Formation) which mark the predominant maximum point of marine transgression for the Seaspray Group (Figs. 16.8, 16.9 and 16.11). The Morwell Formation extends across the Latrobe Valley Depression and grades into the Thorpdale Volcanics in the Moe Swamp Basin and on the Narracan Block (Fig. 16.9). The Lower, Middle and Upper Proteacidites tuberculatus spore–pollen Zones show the Morwell and Alberton Formations are Oligocene and Early Miocene (Partridge,
Fig. 16.11: Isopach maps of coal seams in the Latrobe Valley: (a) M2; (b) M1B; (c) M1A. (contour interval in metres).
1971). These ages are broadly confirmed by radiometric dating of interbedded Thorpdale Volcanics (Wellman, 1974).

The oldest Morwell 2 seam has a maximum thickness of 140 m in the area between Maryvale and Glengarry, but is usually overlain by younger coal-poor Morwell Formation units and the Yallourn Formation (Figs. 16.9, 16.11a). However, at shallow subcrop along the Latrobe Monocline, it was mined in the past at Yallourn North and Extension Opencut Mines (Fig. 16.11a). The seam in this area is also known as the Latrobe Seam because it includes a limited component of the Morwell 1B seam (Fig. 16.9). Elsewhere there is intense separation between the Morwell 1B and Morwell 2 seams so that the term Latrobe Seam has only local significance.

The Morwell 2 seam thins to the south and west where it is replaced by sediments and volcanics. At Morwell it has reduced to 40 m in thickness. On the Loy Yang Dome (Fig. 16.11a), a second area of thickening of the total coal seam interval occurs and three splits of the Morwell 2 seam are known as the Morwell 2A, 2B and 2C seams (Fig. 16.8). Here they aggregate over 80 m of coal. In 1982, opencut development commenced at Loy Yang at the subcrop of the Morwell 2A and Morwell 2B seams and now exposes a cross-section extending for over 1 km N–S and 2 km E–W. The Morwell 2 seams extend as far as Gormandale and Rosedale, east of which they grade into Balook Formation sands of the Seaspray Group.

The Morwell 1B seam conformably overlies the Morwell 2 seam, usually with an interseam separation of clay and minor sand varying between 2 and 30 m (Fig. 16.8). The Morwell 1B has wider extent and overall greater thickness than any other seam in the Latrobe Valley Depression, covering some 650 km² mostly to the south of the Latrobe River (Fig. 16.11b). In the Loy Yang Dome area, between Traralgon Creek and the Rosedale Monocline, the seam reaches a maximum thickness of between 100 and 120 m where it is mined in the Loy Yang Opencut. Other major depocentres for this seam occur between Yinnar and Morwell and at Flynn Railway area (Fig. 16.11b). East of Rosedale, the M1B seam grades into the barrier sands of the Balook Formation; north of the Latrobe River into clays and minor sands and west of the Yallourn Monocline into interbedded sediments, lavas and tuff of the Thorpdale Volcanics.

The Morwell 1B and overlying Morwell 1A seams combine in the Morwell–Driffield area as the Morwell 1 seam which is up to 165 m thick (Fig. 16.8) and is currently being mined in the Morwell Opencut. On the western flank of the Loy Yang Dome, the Morwell 1A, 1B and 2 seams all combine, producing up to 230 m of continuous low ash coal, some areas of which are currently included in the Loy Yang Open Cut area. The Morwell 1A seam, where it is mined at Morwell (as part of the Morwell 1 seam) and at Loy Yang, is up to 80 m thick (Fig. 16.11c). Elsewhere, the extent and thickness are reduced when compared to the Morwell 1B seam, with most of the reduction being equivalent sequences of interbedded clays, ligneous clays and minor thin coal bands (e.g. in the Traralgon Syncline and the Yallourn to Glengarry area). East of Rosedale, the Morwell 1A seam grades laterally into Seaspray Group barrier sands of the Balook Formation (Fig. 16.11c). Sections of the Morwell Formation with large economic reserves that have not yet been allocated to any mine development include the Flynn, Flynn’s Creek, Rosedale and Yinnar coal fields (Table 16.3 and Fig. 16.11).

**Alberton Coal Measures**

The Alberton Coal Measures, defined by Thompson & Walker (1982) (Fig. 16.3), are in South Gippsland. They are not directly connected to the Morwell Formation in the Latrobe Valley due to uplift and erosion on the intervening Baragwanath Anticline. However, they occur within the same *Proteacidites tuberculatus* spore–pollen Zone (Archer, 1982). The Alberton Coal Measures also grade eastwards into an equivalent barrier sand sequence (Balook Formation) which strikes northwards across the centre of the Seaspray and Alberton depressions (Fig. 16.3) and marks the furthest inland extent of the Seaspray Group. Remnants of this barrier sequence preserved on the Baragwanath Anticline are also down-faulted within the Gormandale Syncline and Merrimans Creek Syncline (Thompson, 1979; Holdgate, 1980). These remnants suggest that a continuous barrier sequence to the Morwell and Alberton Formations once extended for 150 km between Port Albert in the south and Bairnsdale in the north (Fig. 16.3). Table 16.4 shows the interpreted relationships between the Latrobe Valley and Alberton Coal measures, based on palynological ages of Partridge (1971, 1978) and Archer (1982).

Coal deposits at Alberton contain an upper A seam (55 m thick) which is separated from a lower B seam (15 m thick) by a 12 m clay split (Holdgate, 1982) (Fig. 16.12). To the southwest, the A seam extends at least as far as the Gelliondale Dome where it has been described as the Alberton Seam (Greer & Smith, 1982). The B seam locally joins with an older Traralgon Formation C seam and, as shown on Fig. 16.12, may be included within parts of the Gelliondale A and B coal seams on the Gelliondale Dome (Greer & Smith, 1982). To the west and north of Yarram, the Alberton Coal Measures remain to be fully defined. In these areas, where not eroded, the coal measures grade laterally into sands and clays of the Bodman Creek Formation (Thompson & Walker, 1982).
Yallourn Formation

The Yallourn Formation was first defined by Thomas & Baragwanath (1949) and later amended by Hocking (1972). The youngest coal-bearing formation in the Latrobe Valley, it consists mainly of the Yallourn Coal Seam and is dated as Middle Miocene by the spore–pollen Triporopollenites bellus Zone (Partridge, 1971). In a similar manner to the Morwell Formation which it conformably overlies, the Yallourn Formation grades laterally eastwards into barrier sands as Middle Miocene by the spore–pollen Triporopollenites bellus Zone and are therefore of the same age as the Yallourn seam (Fraser, 1983; Holdgate, 1985). The Yallourn Formation in the Traralgon and Latrobe Synclines includes up to 200 m of clay above the coal seam (the post-Yallourn Seam clays of Gloe, 1967). This non-coaly unit has now been designated as the separate Hazelwood Formation (Holdgate, 1996)

Younger Pliocene units including the Haunted Hill Formation

Although these units are not coal-bearing, they are important as the principal overburden material to the coal reserves. Consequently their geological study and mechanical properties have received considerable attention.

All sediments that post-date the period of Late Miocene folding are non-coal-bearing (Dickinson et al., 2001). On structural highs they truncate the older coal-bearing formations with angular unconformity (Figs. 16.3, 16.8). In the Latrobe Valley Depression, Pliocene sandy clays, sands and gravels are referred to as the Haunted Hill Formation (Bolger, 1984). This formation comprises the major overburden material in the current opencut mines. Holocene alluvial sediments and peat swamps in creek beds also overlie the coal measures. At Morwell and Loy Yang opencuts, the Pliocene to Holocene sediments infill fire holes in the Morwell coal seams where burning has created depressions in the top-of-coal surface up to 50 m deep. Granulation and aluminium enrichment in the coal seams also occurs within a 1–2 m weathered zone below the unconformity (Bolger, 1985).

At Alberton and Gelliondale, marine Pliocene units correlated with the Jemmys Point Formation are also present above the Late Miocene unconformity, as are beds of the Boidale Formation in the Lake Wellington Depression.

Balook Formation

The Balook Formation is up to 500 m thick. It forms a predominantly medium to fine-grained sand succession, with minor coals and clays, which intervenes between the Latrobe Valley Group to the west and the Seaspray Group to the east (Fig. 16.8).

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**Table 16.4: Relationships of coal seams between Latrobe Valley and Alberton/Gelliondale.**

<table>
<thead>
<tr>
<th>Latrobe Valley Seams</th>
<th>Alberton Seams</th>
<th>Gelliondale Seams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yallourn</td>
<td>(Holdgate, 1982)</td>
<td>(Glover &amp; Smith, 1982)</td>
</tr>
<tr>
<td>Morwell M1A</td>
<td>Alberton A</td>
<td>Gelliondale/Gelliondale A</td>
</tr>
<tr>
<td>Morwell M1B</td>
<td>Alberton B</td>
<td>Gelliondale/Gelliondale B</td>
</tr>
<tr>
<td>Morwell M2</td>
<td>Alberton C</td>
<td>Gelliondale B</td>
</tr>
<tr>
<td>Traralgon</td>
<td>Alberton C &amp; D</td>
<td></td>
</tr>
</tbody>
</table>

---

**Fig. 16.13:** Isopach map of the Yallourn seam (contour interval in metres). (from Holdgate, 1985).
The Balook Sand was originally described as a composite barrier sand of long-standing but limited lateral extent (Thompson, 1980). It was subsequently modified by Holdgate (1996) to include all the transgressive sand beds in the Latrobe Valley Coal Measures. These can extend up to 30 km to the west of the Balook Formation – Seaspray Group interface. The sand beds are up to 20 m thick and form most of the major formation, intraformational and sequence boundaries in the Morwell and Yallourn formations (Holdgate et al., 1995; Fig. 16.9).

Coal quality

The coal qualities for the principal coalfields in the Latrobe Valley, derived from averaged figures from many thousands of bore analysis, are summarised in Table 16.5.

Ash mineral matter and inorganic constituents

Definitions of ash type

Ash yield in Latrobe Valley-type brown coals is defined as the products remaining after combustion in an oven heated to 815°C. Although a typical Latrobe Valley ash-in-coal is usually below 4% (dry basis), they can have deleterious effects on boiler performance, boiler fouling and chimney emission. Two groupings were distinguished by Kiss & King (1977, 1979). ‘Ash minerals’ include particulate material (e.g. SiO₂ from quartz, Al₂O₃ from clays) and ‘ash inorganics’ include Na, Mg and Ca present as ions and as salts of carboxylate groups, are still seen primarily to be present as cations.

In the open cut areas, mineral matter is randomly distributed without layer or depth dependency, except near interseams (Hibbert et al., 1983; Kiss et al., 1983; Brockway & Borsaru, 1985). Minerals include quartz (SiO₂) and a variety of clays, mostly kaolinite, with minor illite, montmorillonite and muscovite. Pyrite and marcasite can be present, but few carbonates except traces of siderite have been detected. In contrast, the vertical distribution pattern of the inorganic ash generally shows post-depositional migration by ion diffusion through the coal structure (Kiss et al., 1985). Most of the salts are believed derived from the aquifers underlying the seams, dissolved in waters which have migrated upwards through the coal, driven by high potentiometric aquifer pressures. An example is the correlation between areas of salty coal in the Loy Yang – Flynn fields and the inland limits of the underlying relatively higher salinity M1B aquifer (Webster, 1981).

The upward diffusion profile for sodium (and for chloride) through the upper part of the M1B and lower M1A seams at Loy Yang (Fig. 16.14) shows little apparent effect from the layer-dependent lithotypes or marine influence zones. This type of profile is typical in most of the Latrobe Valley with a gradual upward increase in sodium above the M2 seams (Webster, 1981, 1984). Magnesium (Fig. 16.14) to a lesser extent also follows this upward increase. Iron and (acid extractable) aluminium on the other hand generally increase close to interseams. Higher iron content coals occur northeast of Yallourn and in the Yinnar area and appear to relate to proximity of lacustrinal clay facies in these areas. No relationship has been found between ash constituents and brown coal lithotypes, although ash percentages generally slightly increase going from dark to light lithotypes (George & Mackay, 1991).

Regional distribution of ash constituents

Relative ash constituents (out of 100% ash) by seam, for each of the main coal field areas in the Latrobe Valley is shown in Table 16.6, derived from Gloe (1980). A synopsis of these data is presented in the section on chronology of palaeoenvironment change. There is a progressive increase in mineral ash content with geological age for the main Latrobe Valley coalfields, as shown by the ratios of mineral ash to inorganic ash (Table 16.7).

Lithotype and palaeodepositional environment

Brown coal lithotype

In the Latrobe Valley, brown coal lithotype refers to banding visible in air-dried coal, usually seen where moisture losses of about 2–5% occur in the top few centimetres of the open cut faces. The layering effect is characterised by variations in colour, texture, gelification and shrinkage weathering patterns. Individual layers may be sharply bounded or

### Table 16.5: Properties of Latrobe Valley coals (after Gloe, 1980)

<table>
<thead>
<tr>
<th>AREA</th>
<th>SEAM</th>
<th>MOIST %</th>
<th>ASH %</th>
<th>VOL %</th>
<th>C %</th>
<th>H %</th>
<th>NWSE</th>
<th>GDSE</th>
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<td>4.8</td>
<td>6.3</td>
<td>26.6</td>
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<tr>
<td></td>
<td>M1</td>
<td>61.3</td>
<td>2.3</td>
<td>51.1</td>
<td>67.4</td>
<td>4.8</td>
<td>8.2</td>
<td>26.7</td>
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<tr>
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<td>Yallourn</td>
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<td>2.6</td>
<td>51.6</td>
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Note: Moist = Moisture, Vol = Volatiles, C = Carbon, H = Hydrogen, NWSE = net wet specific energy (MJ/kg), GDSE = gross dry specific energy (MJ/kg), db = dry basis.
gradational and are 0.2–5.0 m thick. These layering effects are thought to indicate changes in the original depositional environment, especially water table changes, brought about by differing palaeobotanical communities, climatic changes and/or adjacent sea level changes. Lithotype is difficult to observe in the normal wet-coal state but it can be logged in bore core if the core is laid out to dry for several months (Fig. 16.15).

Various classifications exist for brown coal lithotype based on the degree of preference for colour or texture. In the Latrobe Valley, Edwards (1947) recognised a 3-fold subdivision — earthy coal, lignitic coal and pollen coal. Subsequently, George (1975) proposed a 5-fold subdivision, dividing earthy into light and medium light and lignitic into medium dark and dark, with pollen coal as the pale lithotype. As yet no internationally uniform system has been evolved.

Characteristics of Latrobe Valley lithotypes
All five of the Latrobe Valley lithotypes have been fully documented by George & Mackay (1991). Each lithotype varies in moisture content, volatile matter, specific energy, specific gravity, hardness and colour index. From dark to light, moisture decreases up to 5%, volatile matter increases from 48% to 63%, specific energy (gross dry basis) increases from 26 to 29 MJ/Kg, specific gravity decreases from 0.91 to 0.70 and hardness decreases in the air-dried state. No apparent ash changes occur with lithotype. With increased rank, the lithotype colour contrasts decrease and the boundary becomes less obvious. Gels become hard and shrink in air-dried coal (George & Mackay, 1991) so gelification is strongly related to lithotype. It is usually seen as part of the biochemical stage of coalification and is thought to occur under low-eH, water-covered conditions (Diedel, 1980). Maximum gelification occurs in the regional dark lithotypes, suggesting their deposition in relatively wetter and anoxic environments (Holdgate, 1996).

Fusinite or charcoal in brown coal is often associated with burning phenomena. It mainly occurs in the medium–dark or dark lithotypes and is particularly prevalent in the Flynn and Rosedale area near the M1A–M1B boundary. The preferential abundance of fusinite in the darker coals has been taken to indicate their depositional environment being drier than the lighter.
lithotypes, but equally the fusinite may be allochthonous in origin, washed in to the more waterlogged areas.

Wood in brown coal varies from microscopic fragments to tree trunks up to 5 m long. It has deleterious effects on boiler ignition due to a higher moisture content and affects the mills grinding coal for briquettes. It occurs chiefly in the medium–light and medium–dark lithotypes and, as mapped in coal-faces and between lithotype bores, often shows preferred stratigraphic layering. Common woods occurring in the Yallourn and Morwell opencuts include species of Araucariaceae, Podocarpaceae and Proteaceae (George et al., 1984; George, 1988). An extensive investigation of wood types and macrofossils as related to lithotype was undertaken by Blackburn (1980, 1981, 1985).

Origin of lithotypes

The origin of brown coal lithotypes in both the Latrobe Valley and other basins remains an intensely debated subject amongst coal workers. Most papers envisage the banding to be a product of water-level fluctuations in the original peat swamp, which in turn controlled the plant communities living at the time. In the current argument, most palynologists and palaeontologists favour the light lithotype as representing the more waterlogged conditions of deposition, while petrologists favour the dark lithotype.

One model for Latrobe Valley coal envisages the light lithotypes representing the deeper-water environment, with the darker lithotypes representing a drier more oxygenated environment (Luly et al., 1980; Sluiter...
Kershaw, 1982; Kershaw & Sluiter, 1982; Kershaw et al., 1991). Plant macrofossil studies by Blackburn (1980, 1985) and interpretations of biochemical data by Verheyen et al. (1984) and Finotella & Johns (1986) also tended to support these views. Anderson & Mackay (1990) suggested that other peat swamp environmental factors such as pH and Eh were more important influences on lithotype than original plant material. These authors favoured greater aerobic decomposition for the lighter lithotype coals and more intensive anaerobic decomposition for the darker lithotypes, i.e. the lighter lithotypes are more weathered and the darker lithotypes are more ‘waterlogged’. Modern examples of such conditions were cited from the raised peats of coastal Indonesia (Anderson, 1964; Anderson & Muller, 1975; Esterle et al., 1992). Comparison of the two different depositional models is illustrated diagrammatically on Fig. 16.16. Sluiter et al. (1995) modified their concepts to invoke the eustatic model of Holdgate et al. (1995), whereby all lithotypes formed under a vegetation cover, but the canopy tended to open out from dense swamp forest, forming the darkest lithotypes, to raised bog forming the lightest lithotypes.

Both concepts put forward for the Latrobe Valley coal seams require either a relative decrease or increase in water table levels or variations in the rates of basin subsidence as the controlling factor for lithotype succession. Recognition of marine dinoflagellates and foraminifera in the clay sediments between the major coal seams suggested a eustatically-controlled origin for coal formation (Holdgate and Sluiter, 1991; Holdgate et al. 1995) linked to lithotype succession.

Table 16.7: Weight average mineral ash to inorganics ratio for the main Latrobe Valley coal seam depocentres.

<table>
<thead>
<tr>
<th>SEAM</th>
<th>Traralgon*</th>
<th>Morwell 2</th>
<th>Morwell 1B</th>
<th>Morwell 1A</th>
<th>Yallourn**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.4:1</td>
<td>1.5:1</td>
<td>0.8:1</td>
<td>0.5:1</td>
<td>0.3:1</td>
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* figure excludes sulphur content brought in by marine influence.

** figure excludes iron content brought in from lateral groundwater diffusion.

Fig. 16.16: Possible peat depositional models for the origin of Latrobe Valley brown coal lithotypes in relation to nearby water depths: (A) after Luly et al., 1980; (B) after Diesell (1992).
Fig. 16.17: Stratigraphic correlation of M1A and M1B coal seams of the Gippsland Basin based on brown coal lithotypes, organic sulphur content, relative abundance of key warmer climate Myrtaceae pollen and upwards-lightening lithotype cycles. See Fig. 16.2 for section locations.
Regional distribution of lithotypes and relationship to marine influence

A cross-section from Yallourn/Morwell in the west to Rosedale in the east provides a regional correlation of brown coal lithotypes across the entire Latrobe Valley for the upper M1B and M1A coal seams (Fig. 16.17). Between-bore correlations are based on regionally correlatable dark lithotype beds (up to 10 m thick). These disconformably overlie light or pale lithotypes (Fig. 16.18). The sharp boundary contact subdivides the lithotype succession into a number of upward-lightening cycles. Coal at the boundary exhibits an increase in organic sulphur, evidence of weathering, minor erosion and differential compaction. Correlatable cycles occur on average every 12-18 m (Mackay et al., 1985; Holdgate, 1992).

Down dip towards the marine boundary near Rosedale, interseam sediment bands occur at these stratigraphic levels and contain marine dinoflagellate species. Each cycle is thought to represent a subseam, with up to five subseams constituting one of the major Latrobe Valley coal seams. Increasing marine influence from the east, where greater bacterial degradation occurred in lower lying coastal areas, appears to have favoured the darker coals. In contrast, the lighter coals are more favoured in the west, where they were more remote from marine influence and where the swamps were more likely to have been elevated and experienced greater weathering. This provides a model for the origin of brown coal lithotypes as shown on Fig. 16.19. Commencement of each coal cycle begins with a thick dark lithotype that can be correlated regionally and is a lateral facies-equivalent of many marine-derived interseam sediment horizons to the east. Medium-dark to medium-light lithotypes make up most of the coal cycle that lightens upward and that is terminated by erosion and weathering, thereby producing some of the pale coal immediately below the boundary. Each cycle represents a parasequence.

Botanical composition and petrological changes through time

Important differences have been noted in the palaeobotanical components of the Latrobe Valley coal seams. These include:

1. Dominance of sclerophyll component in the Yallourn seam with an increasing importance of fire within the region (Luly et al., 1980; Blackburn, 1980, 1981; Kershaw & Sluiter, 1982).
3. A high percentage of Nothofagus pollen derived from the beech forests in the adjacent highlands.
4. Rainforest-dominant swamp species such as Podocarpaceae and Casuarinaceae, Cunoniaceae, Myrtaceae, Elaeocarpaceae and Proteaceae are usually present (Kershaw et al., 1991).
5. Petrographic data (Kershaw et al., 1991) show an increase in the percentage of coarse plant tissue with decreasing seam age and lithotype.

Fig. 16.18: Brown coal lithotypes, Loy Yang open cut mine, showing the contact between a light lithotype overlain disconformably by a laminated dark lithotype at the 64 m cycle boundary (upper part of the M1B coal seam). Note: pick for scale is 1 m long. Photograph from G. Holdgate.

Fig. 16.19: Idealised sequence across the Latrobe Valley showing three coal upwards-lightening lithotype cycles (parasequences) and two major interseam intervals (from Holdgate, 1996).
Late Middle Eocene (Traralgon 2 Seam phase)
provided most of the sediment source.

time was a faulted palaeovalley. Palaeozoic highlands along the basin margins
thicken into the offshore parts of the basin. The Honeysuckle Hill Gravels
of onshore basin development (Fig. 16.10a). The coal seams of this period
dominantly nonmarine environment that was widespread in the early phase

Paleoclimate profiles
Paleoclimatic interpretations from the botanical and petrological data generally agree that the annual precipitation levels were high (>1500 mm) to maintain the regional rainforest cover (Duigan, 1966; Luly et al., 1980). Sluiter et al. (1995) presented bioclimatic palynoscopy profiles for the Morwell Seams (mainly M1B) indicating mean annual precipitation levels were at least 1500 mm and probably between 2000 and 2200 mm, which is nearly three times the current rainfall for Gippsland (i.e. 850 mm). They also established mean annual temperatures around 19º C (i.e. 4–5º C above the present). Seasonality was probably different from today, with most rain occurring in the summer, giving a mesothermal temperature regime in an evergreen subtropical forest, with a contemporaneous cooler temperate forest (Nothofagus) in the adjacent highlands.

Paleoaltitudes for Gippsland
These varied between 55º S in the Eocene to 45º S for mid-Miocene (Veevers, 1986; Veevers & Eittreim, 1988). The subtropical forest environments in the coal measures are explained by the existence of a wider tropical and subtropical zone at the time — a consequence of an ice-free Antarctica and lack of a circum-polar current (Truswell & Harris, 1982; Bowler, 1982; Berggren & Prothero, 1992). The northward drift of Australia (placing Gippsland into its present latitude of 38º S) required the whole climatic zonation system to significantly change from that of the Eocene to Early Miocene, resulting in climates less favourable to coal seam deposition.

Paleoenvironmental and palaeoclimatic change in the onshore Gippsland Basin
Major coal-forming phases were episodically deposited to form the coal measures of the onshore Gippsland Basin:

Paleocene to late Middle Eocene (Honeysuckle Hill phase)
This period is dominated by fluvial and outwash alluvial fan sequences with minor coals. The succession represents a high-energy, polycyclic, quartzose, dominantly nonmarine environment that was widespread in the early phase of onshore basin development (Fig. 16.10a). The coal seams of this period thicken into the offshore parts of the basin. The Honeysuckle Hill Gravels were located along the east-trending nose of the Balook Block, which at the time was a faulted palaeovalley. Palaeozoic highlands along the basin margins provided most of the sediment source.

Late Middle Eocene (Traralgon 2 Seam phase)
The first major coal seam — the Traralgon 2 Seam — developed in an ENE-trending palaeovalley as an extension of the Balook Block (Fig. 16.10a). North and south boundaries for the T2 Seam are provided by normal faulting along the line of the Rosedale and Foster fault systems (Fig. 16.10a). Relatively fast rates of peat accumulation of the order of 2800 years/m appear to have been maintained over a period estimated at 700 000 years, giving a brown coal seam of up to 60 m thick (Holdgate et al., 2000b). The T2 seam contains a high proportion of mineral compared to inorganic ash, indicating a strong influence from the surrounding fluvial, lacustrine and estuarine environments (Table 16.7). The last became increasingly important nearer the coast where the seam is split by clay and silt interseams derived from the east. Sulphur content is the highest for any seam in Gippsland and reflects the marine influence from the east. LITHOTYPES in the T2 Seam are mainly lighter varieties.

The T2 seam formed during a high stand period of the late Middle Eocene, thought to equilibrate to the sequence cycle TA3.5 (40.5–42.5 million years) of Haq et al. (1988). PALEOALTITUDES for Gippsland at this time were between 55–60º S and palaeotemperatures were warmer than present, as indicated by O18/O16 ratios. Development of the T2 coal swamps suggests a high rate of precipitation. Relative sea-level fall or tectonic uplift at the end of the Middle Eocene caused the upper peat surfaces of the T2 seam to become partly incised. Subaerial wastage caused losses to the coal seam, particularly along the crest of the rising Baragwanath Anticline. This boundary approximates to the Latrobe Unconformity in the offshore Gippsland Basin.

Latest Eocene (Traralgon 1 Seam phase)
Sea levels maintained their lower levels until the latest Eocene, when coastal depositional processes returned to the onshore parts of the basin. The T1 Seam formed as an extensive back-barrier swamp behind a coastal sand barrier system aligned to the present day 90 Mile Beach (Figs. 16.10b & 16.10c). Marine flood events periodically overtopped this barrier and extended the marine faces as estuarine systems back into the peat swamps. Separate coal depocentres also became established for the first time in the Latrobe Valley, each with a slightly differing component of coal types and ash sources. This trend was to continue into the Oligocene–Miocene seams with increasing differentiation. Peat accumulation rates were slightly faster, at 2000 years/m, than for the T2 Seam. Ash inputs to the swamps were primarily minerals from fluvial sediment sources (Table 16.6). Lithotypes were in general similar to the T2 seam, with a small increase in the darker component and an increase in lithotype differentiation (Holdgate et al., 2000b).

Late Traralgon T0 Seams of the slightly younger Upper Nothofagidites aspenn age occur in the Loy Yang area and indicate that Traralgon Formation coals straddle the Eocene–Oligocene boundary. Coal-seam deposition continued into the early parts of the Lower Oligocene. A contemporaneous sand barrier system known as the Dutson Sand Member formed along the near-coastal area of the basin (Fig. 16.10c) and provided a buffer between the coal swamps and the marine Gurnard Formation.

Early Oligocene (Morwell 2 Seam phase)
The increasing differentiation between the Latrobe Valley and the rest of the Gippsland Basin largely began in the Early Oligocene. This can be attributed to the tectonic uplift of the Baragwanath Anticline and adjacent downwarping of the Latrobe Valley Depression, coupled to a high rate of relative coastal onlap at this time. Throughout most parts of the rest of the basin, marine carbonate sedimentation prevailed, with the only other exception being in the Alberton–Gelliondale area in South Gippsland where a smaller depression was localised between the Wilsons Promontory basement high and the easterly dipping Napier High near Yarram (Fig. 16.2). The coal measures of the Oligocene–Miocene period are more localised than the Eocene seams and their total resources are smaller (Table 16.3). However they are more accessible for mining due to their lower ratios of overburden to coal.

The first major coal seam developed was Morwell 2, mainly restricted to the Loy Yang – Gormandale and Maryvale–Glengary (Fig. 16.11a). Up to 150 m of almost continuous coal accumulated at Maryvale–Glenquiry. The Morwell 2 Seam was thicker in the north of the basin due to a small regional tectonic uplift, especially near the Wilsons Promontory basement high. The Duty Sand Member formed along the 90 Mile Beach at this time. Throughout most parts of the rest of the basin, marine carbonate sedimentation prevailed, with the only other exception being in the Alberton–Gelliondale area in South Gippsland where a smaller depression was localised between the Wilsons Promontory basement high and the easterly dipping Napier High near Yarram (Fig. 16.2). The coal measures of the Oligocene–Miocene period are more localised than the Eocene seams and their total resources are smaller (Table 16.3). However they are more accessible for mining due to their lower ratios of overburden to coal.
Earliest Miocene (Morwell 1B Seam phase). Sea-level rise and a high rate of coastal onlap at the beginning of the Miocene caused base levels to rise and coal measures to develop over most of the Latrobe Valley. Earlier transgressive marine carbonate pulses in the Late Oligocene are recorded as the Middle A & B Lakes Entrance Formation (Holdgate & Gallagher, 1997), but are not represented in the nonmarine basinal areas.

A re-establishment of the Balook Formation at the eastern end of the Latrobe Valley Depression followed a widespread transgressive incursion, which saw the deposition of the M1B sand aquifer across much of the depression (Fig. 16.9). This allowed extensive peat-swamp deposition of the first of the large Miocene coal seams—the Morwell 1B Seam. The large extent and thickness of peat developed at this time is most likely a result of the lengthy 2.8 million year duration for the high stand system tract allocated to this seam (sequence cycle TB1.4, 22.0–24.8 million years; Haq et al., 1988). This provides for a relatively slow average depositional rate of 9300 years/m for the 120-m thick seam. However continuous deposition is probably unlikely, considering the seam has five lithotype cycles all possibly separated by time breaks.

The Morwell 1B Seam developed within two distinct depocentres at Loy Yang and Morwell. Ash constituents show a concentric zoning with the ratios of mineral ash to inorganic ash increasing from 0.5:1 to 3.0:1 away from the depocentres (Table 16.6). This reflects the increased input to the swamp margins from sediment sources, the dominant inorganic ions and salt nutrient sources in the central raised bogs, and the easterly influence of marine-sourced sediments. Expansions relative to the Morwell 2 depocentres were related to differential compaction together with prograding during the lengthy TB1.4 sequence cycle. Throughout the rest of the onshore Gippsland Basin there was contemporaneous marine carbonate deposition, as mudstones and marls of the Upper Lakes Entrance Formation and shallower water high-carbonate limestones and dolomites of the Gippsland Limestone.

Mid-Early Miocene (Thorpdale Volcanics phase) Lavas of the Thorpdale Volcanics covered the Narracan, Warragul and western Balook blocks and date within the mid–Early Miocene. Basaltic sills extending from the major eruptive centres locally interbed with the earlier Morwell 2 phase and caused some alteration to the adjacent sediments.

Latest Early Miocene (Morwell 1A Seam phase) Deposition of the Morwell 1A Seam came towards the end of the Early Miocene when sea levels were higher and a rapid rate of coastal onlap occurred. This period represents the beginning of the mid–Miocene climatic optimum period that saw the development of the major M1A and Yallourn brown coal seams. In the Latrobe Valley, the earliest transgressive phase saw the widespread deposition of the M1A sand aquifer, followed by peat–swamp developments over the southern half (Figs. 16.9, 16.11c). The same depocentres as for the M1B Seam at Loy Yang and Morwell were favoured but reduced in area due to expansions of contemporaneous fluvo-lacustrine systems from the north and southwest. Sediment inputs notably influenced the ash constituents on the margins of the swamps. The mineral ash and in particular the iron content in the coal rises progressively towards the major lacustrine depocentres at Toongabbie and Yinnar (Table 16.6).

Limestone and marly marine sediments of the Gippsland Limestone accumulated throughout the rest of the onshore basin under a low productivity, shallow–water environment. Subsequent mid–Miocene sea–level falls caused extensive downcutting and subaerial wastage to some of the upper beds of the M1A coal interval. Areas where complete preservation took place are generally in the synclines, whereas the structurally higher Loy Yang and Morwell anticlines saw substantial erosion of the youngest beds. Offshore, the major mid–Miocene canyoning episodes begin from this time. Carbonate sediments filled the canyons as sea levels rose in the early Middle Miocene.

Early Middle Miocene (Yallourn Seam phase) A warm climate period known as the mid–Miocene climatic optimum saw the relatively high sea levels of the late Early Miocene rapidly return. High water tables developed peat swamps of the Yallourn Seam at the western end of the Latrobe Valley (Fig. 16.13). The high stand systems tract for the sequence cycle TB2.3 (Haq et al., 1988) is favoured here as the correlative time interval, but the seam may also include parts of the following TB2.4 cycle. Accumulation rates for the 100 m or so of Yallourn Seam are the highest for any Gippsland seam at 1800 years/m and are reflected in the abundant wood debris and stumps buried in situ. Thick lacustrine systems returned to the Toongabbie and Yinnar areas and provide higher mineral ash and iron content to the coals of these areas. Other than in these areas, the inorganic ash constituents are greater for Yallourn Seam than for any previous coals and reflect the overall low input of sedimentary detritus into the Latrobe Valley Depression at this time (Table 16.7). This may indicate a lowering of relief in the surrounding hinterlands or a palaeoclimatic shift towards hotter and drier conditions. More components of darker lithotype than in previous seams relate to the increased sclerophyll component of the Yallourn Seam. Together with charcoal evidence for palaeoclimatic drying compared to the Lower Miocene seams, there appears to be an increasing influence of fire in the environment.

Contemporaneous carbonate sediments of the Wuk Wuk Murlar occur throughout the rest of the onshore basin. They were deposited into a high-productivity, upwelling, warmer water (subtropical) environment that characterises the Batesfordian Stage in the Victorian coastal successions. Paleotemperatures were warmer than present, as indicated by $^{18}O/O^{16}O$ ratios, plant species living in the peat swamps and incursions of tropical foraminifera into the adjacent marine environments.

A rapid increase in the $^{18}O$ isotope ratio during the Middle Miocene has been interpreted to be a result of a major growth in the Antarctic ice sheet. This, coupled with the northerly drift of Australia into the mid–latitudes where precipitation is low, saw the end of coal deposition in the Gippsland Basin. No further coaly accumulations after cycles TB2.1–2.4 occur in the Gippsland Basin, which became increasingly subjected to compressional tectonic forces and adjacent development of highland relief.

Middle Miocene to Holocene (the Haunted Hill Formation phase) A series of thinner nonmarine to marine largely clastic deposits characterises this final depositional period of the onshore Gippsland Basin. The number and thickness of these units decrease to the west. In the Latrobe Valley, a period of structural uplift in the Late Miocene was followed by the widespread deposition of outwash coarse clastics of the Haunted Hill Formation.

16.4.5 Other brown coal deposits in Victoria Data on other brown coal deposits in Victoria (Fig. 16.2) are given in Table 16.8. Brown coal reserves for these other basins are given in Table 16.3.

Bacchus Marsh – Altona (Port Phillip Basin) Introduction Coal was first discovered in the Port Phillip Basin at Altona in 1890. It was extracted from below thick basalts, at depths of about 180 m, up until 1919. In 1929, mining commenced on a deposit of brown coal near Bacchus Marsh, 40 km WNW of Melbourne, at the Lucifer, Star, Boxlea and Maddingley No. 1 & 2 opencuts. Drilling results indicate the two coal deposits are linked beneath the basaltic cover of the Werribee Plain (Thomas & Baragwanath, 1950; Prestwich, 1981; Holdgate et al., 2002a). Estimated resources in the entire deposit exceed 15 Mt (Gloe, 1991), making it the second largest deposit after the Latrobe Valley.

Stratigraphy The Tertiary sediments of the Port Phillip Basin are composed of predominantly nonmarine sands, clays and coals of the Werribee Formation (Thomas & Baragwanath, 1950), together with some interbedded basaltic lavas and tuffs of the Older Volcanics. Ages for the Werribee Formation vary between Paleocene and Lower Miocene, depending to some extent on the ages or inferred ages of the interbedded volcanics. For example, in the Melbourne area, K–Ar dates derived from basalts in the Werribee Formation are 20–22 Ma (Bowen, 1974). Recent deeper drilling on the Werribee Plains suggests that, underlying the Werribee Formation, is an older sedimentary sequence that
includes coal measures and is similar to the Yaloak Formation of the adjacent Ballan Graben. Ages of these beds extend the mainly nonmarine sediments of the Parwan Trough down to the Late Cretaceous (Holdgate et al., 2002a). The Werribee Formation is disconformably overlain by Miocene marine carbonate sediments now referred to as the Fyansford Formation of the Torquay Group (Abele et al., 1988). In turn, these carbonates are overlain unconformably by Late Miocene—Early Pliocene Moorabool Viaduct Formation and thick basaltic flows and intercalated sediments of the Pleistocene Newer Volcanics.

Bore log cross-sections through the Ballan Graben and Parwan Trough (Figs. 10.25, 16.20) tie the coal measure successions to marine equivalents of the Fyansford Formation in Port Phillip Bay and on the Nepean Peninsula. The main coal seam (the Maddingley Seam of Thomas & Baragwanath, 1950) occurs at the top of the Werribee Formation and can be over 40 m thick. It is dated within the Protoacidites tuberculatus spore–pollen Zone, mostly within the upper part of this zone (Partridge, 1971; 1997c). It is disconformably overlain by marine sands and clays of the Fyansford Formation, which have been dated as being of late Lower Miocene Longfordian Stage (Parr, 1942; Taylor, 1963). A previously unnamed, 1–6 m thick seam occurs within the Fyansford Formation about 10 m above the Maddingley Seam and is here referred to as the Truganina Seam. At Bacchus Marsh, the Fyansford Formation may be absent in the upper part of the Lower Miocene (Upper P. longus zone; Partridge, 1971; 1997c). It is disconformably overlain by shelly marine clays of the upper Longfordian Stage (Carter 1964; Parr, 1942; Taylor, 1963, Gallagher, personal communication, 1997). Older Volcanics basalts underlaying the seam in the Melbourne area have been radiometrically dated at 20–22 Ma. Therefore the Maddingley Seam is constrained to a time interval that is no older than 20 Ma and an oldest age for Fossil Unit 8 of 16.6 Ma (Haq et al., 1988).

Coal quality and lithotype
The quality of the Maddingley Seam at Bacchus Marsh and Altona, as given by Gloe (1976), is shown in Table 16.8. Organic sulphur content at about 2.7% is relatively high for both mined areas, with sulphur content over 4.5% in the upper and lower 6 m of the seam, with the middle part averaging 3%. The Truganina seam contains 5.25% sulphur (dry basis). Ash content can be over 10%, but at Bacchus Marsh averages 5%.

A lithotype log of bore Parwan-66 through the Maddingley Seam in the Maddingley No. 2 Opencut indicated an unusually high percentage of medium light to light lithotypes (81.3%) compared to a typical figure of <60% for Latrobe Valley coals. The medium dark lithotypes occur near the base and top of the seam and dark lithotypes are absent (Higgins et al., 1981). However the darker lithotypes increase southwards towards Altona and are thought to reflect an increasing marine influence in this direction (Holdgate et al., 2002a). The seam is also known to be conspicuously woody, with common species of Kauri wood occurring in the medium-light layers every 6–8 m.

Coal ages
The Maddingley Seam is dated by palynology at Bacchus Marsh and Altona into the upper part of the Lower Miocene (Upper P. tuberculatus zone; Partridge, 1971; 1997c). It is disconformably overlain by shelly marine clays of the upper Longfordian Stage (Carter 1964; Parr, 1942; Taylor, 1963, Gallagher, personal communication, 1997). Older Volcanics basalts underlaying the seam in the Melbourne area have been radiometrically dated at 20–22 Ma. Therefore the Maddingley Seam is constrained to a time interval that is no older than 20 Ma and an oldest age for Fossil Unit 8 of 16.6 Ma (Haq et al., 1988).
The disconformity at the top of the seam is a significant unconformity erosional surface between the dominantly nonmarine coally sediments of the Werribee Formation and the marine clays of the Fyansford Formation. The distribution and thickness of the coal seams, in particular the Maddingley Seam, appear to be strongly affected by this subsequent erosional event, and the seam shows a better preservation potential in the Parwan Trough. Holdgate et al. (2002a) considered the boundary between the Werribee and Fyansford Formations to be a sequence boundary in the sense of Van Wagoner et al., (1990) and therefore can be equated to the sequence boundary dated at 17.5 Ma by Haq et al. (1988). This suggests that the Maddingley Seam is a probable time equivalent of the Latrobe Valley’s Morwell 1A Seam (Fig. 16.8).

The Truganina Seam is nearly as widespread as the Maddingley Seam, but is considerably thinner. It is interbedded within marine shelly clays of Faunal Unit 8 Zone (upper Longfordian Stage) age (Parr, 1942; Taylor, 1963). The foraminifera dates suggest the Truganina Seam and adjacent Fyansford...
Formation are probably time equivalents of part of the Yallourn Seam in the Latrobe Valley and the marine Wuk Wuk Marl Member in the Gippsland Basin (Fig. 16.8). This interpretation is supported in the Maddingley No. 2 Opencut, where ligneous clays 2 m above the Maddingley Seam contain plant macrofossils (Fig. 16.8). Various ages are recorded for coal seams underlying the Maddingley Seam. They include Middle Eocene Lower N. asperus and Early Eocene Lower M. diversus spore–pollen Zones (Partridge, 2001c). These ages are similar to the ages for the A and B Group coal seams of the Eastern View Group at Angelsea (Holdgate et al., 2002a).

**Palaeogeography**

The elevated (>4%) sulphur contents for the Maddingley and Truganina seams at Altona, together with a higher ash content and propensity for increased sand splits, suggest a depositional environment close to brackish-marine waters, where sulphur-fixing bacteria were active. The relatively high component of medium light to light lithotypes in the Maddingley Seam at Bacchus Marsh suggests that coals in this area represent a more distal inland location for the peat swamp, removed from the marine interface south of Altona (Fig. 16.21). Strata of equivalent age encountered in bores on the Nepean Peninsula appear to comprise fully marine Fyansford Formations clays and marls. A barrier sand unit between the Maddingley Seam and marine carbonates of the Fyansford Formation was also located in the Mambourin-1 and CRA MB/92 bores immediately east of Werribee (Fig. 16.20), suggesting the marine interface is also present between Werribee and Geelong (Holdgate et al., 2002a).

**Anglesea (Torquay Basin)**

**Introduction**

Small-scale brown coal mining activities commenced in the 1870s in the Torquay Basin at the type section outcrop of the Eastern View Formation, which is on the coast 15 km southwest of Anglesea. Large-scale mining activities began in 1959 following the discovery of a large resource of brown coal immediately inland of the township of Anglesea. Today over 1 million tonnes of brown coal are mined annually from Alcoa Australia’s opencut to supply fuel to the adjacent coal-fired power station. Some 160 million tonnes of economic coal are available in the field area, with about a half of the more accessible reserves already mined.

**Stratigraphy**

The Tertiary stratigraphy of the Torquay Basin (Abele et al., 1988) consists of nonmarine (mostly) Paleocene to Eocene Eastern View Group unconformably overlying Lower Cretaceous Otway Group. The Eastern View Group in turn, is unconformably overlain by paralic and volcanic facies of the Eocene to Oligocene Demons Bluff Group and the Oligocene to Miocene Torquay Group (see Chapter 10).

The Eastern View Group consists of a sequence of brown coals, clays and sands that onshore can be over 500 m thick. Most of the significant coal seams occur in the upper part. At Anglesea the brown coal seams are folded into the Anglesea Syncline, the axes of which plunges south below the town of Anglesea. Coal mining takes place north of the township where the seams are shallowest. Further north of the mine, the syncline closes against the prominent west-pitching Bald Hills Anticline, which cuts across the coastline at Janosite Headland (Holdgate et al., 2001). Only minor uneconomic seams occur north of this structure. Earliest mining at Roche Brothers’ opencut took place along the western flanks of the Anglesea Syncline, within the older B Group Seams. Currently, mining by Alcoa (Australia) takes place across the centre of the Anglesea Syncline.

The uppermost, thickest and only currently mined coal seam is known as A Seam or A Group (George, 1962). The seam is up to 36 m thick, but locally splits near the base into the A1 and A2 subsheams. From palynological dating (Christophel et al., 1987), the seam is correlated with the Lower *Nothofagidites asperus* spore–pollen Zone.

The deeper B Group seams are interbedded with clays and sands over about a 60–70 m thick interval. Dated samples in some recent water bores (Stanley, 1994) showed the B Group interval to lie within the *M. diversus* spore–pollen zone. George (1962) subdivided the B Group into the B1, B2 and B3 seams, with individual seam thicknesses of up to 12 m. Separating the B and the deepest C Group seams is a 10–15 m interval of fine sands and silty clays. The C Group consists of one 20-m thick seam at the top (the C1 seam) which is best developed on the western flank of the Anglesea Syncline. This unit overlies a series of interbedded thin coals (<5 m thick), sands and clays, which extend for another 50 m. Dating of this interval (Stanley, 1994) indicates a Lower *M. diversus* spore–pollen zone age.

**Coal quality**

The A Seam, as mined, has the lowest moisture content of any economic brown coal in Victoria, but a relatively high sulphur content of 3.8% (Table 16.8). One bore (Angahook–82) logged for lithotype showed the seam to consist of banded coal every 1–2 m (Higgins et al., 1981). The bedding chiefly comprises medium light (52%) and medium dark (30%) lithotypes, with the remaining 18% being dark and light lithotypes. A Seam appears to contain up to five upward-lightening cycles, each between 6–8 m thick (Holdgate et al., 2001a).

**Stratigraphy and ages of beds overlying the coal measures**

Exposed in the Anglesea Opencut high wall are sands and carbonaceous clays that unconformably overlie the A Seam and increase in thickness from 10–70 m towards the south. These sediments were allocated to the upper beds of the Eastern View Formation by Christophel et al., (1987). They are now subdivided into (from the base) the Boonah Formation, Salt Creek Formation and Anglesea Formation – all part of the Demons Bluff Group. They are separated from the Eastern View Group by a low (up to 5°) angular unconformity (Holdgate et al., 2001a) (Fig. 16.22). The Salt Creek and Anglesea formations contain spore–pollen dates of the Middle *Nothofagidites asperus* Zone (Christophel et al., 1987). The Boonah Formation remains undated in the mine area but in the offshore basin is of the same zonal age.

The basal coarse channel gravels of the Boonah Formation overlie the A seam with a significant erosional unconformity. It is therefore along this unconformity surface that the boundary between the Eastern View Group and the Demons Bluff Group is better defined (see Chapter 10).

**Otway Basin**

**Introduction**

The Otway Basin in general is poor in resources of Tertiary brown coals and economic deposits are confined to the extreme eastern and western ends. This distribution appears to be a result of intermittent marine transgressive phases in the Paleocene, Eocene, Oligocene and Miocene, which affected the entire basin up to the northern basement outcrops. The main coal-bearing units of the Otway Basin are in the upper parts of the Dibsyn Formation, which forms the upper half of the Wangerrip Group. This stratigraphic level is the same age as for the equivalent coal-bearing intervals in the Eastern View Group in the adjoining Torquay Basin.

**Stratigraphy and age of the Wensleydale/Deans Marsh deposits**

Three small coal deposits – Wensleydale, Deans Marsh and Berwerrin – occur at the northeastern extremity of the Port Campbell Embayment. Mining of these deposits commenced in 1899 and some 3 million tonnes of coal were produced. Most came from the Wensleydale deposit, where a thicker seam of up to 40 m occurs in a localised syncline on the edge of the Otway Ranges (Thomas & Baragwanath, 1950, 1951; Gloe, 1976; Knight, 1975b). Analysis of the Wensleydale Seam is shown in Table 16.8. The Deans Marsh and Wensleydale deposits have been dated respectively by Archer (1986, personal communication) and Morgan (1992) into the Lower *Nothofagidites asperus* spore–pollen Zone. Dates of the Wensleydale and Deans Marsh deposits suggest they correlate in time to the A Group Seam at the top of the Eastern View Group. At Berwerrin, a 2.5-m thick coal seam has been dated by Archer (1986, personal communication) as being in the older Paleocene Lower *Lygistepollenites bahruma* spore–pollen zone.

**515**
**Murray Basin**

**Introduction**

The Murray Basin is a low-lying, saucer-shaped intracratonic basin, consisting of thin, flat-lying Tertiary sediments, which underlie an area of 300,000 km² of northwestern Victoria, southeastern South Australia and western New South Wales (Fig. 16.2).

**Stratigraphy**

Brown (1995a) subdivided the Tertiary sediments of the Murray Basin into three major depositional sequences separated by regional disconformities. They comprise an earliest Paleocene–Eocene – Early Oligocene sequence of Renmark Group beds dominated by fluvial-lacustrine sands, clays and minor coals; an Oligocene – Middle Miocene dominantly marine, sequence of Murray Group beds that are dominantly marine, and a Late Miocene – Pliocene marine to fluvial Wunghnu Group (see Chapter 10).

No economic deposits of brown coal have been located in the Murray Basin but exploration has revealed some areas of significant coal seam development. In the 1980s, drilling finds were made in the Kerang, Torrumbarry and Echuca regions of northern Victoria (Brunker et al., 1986; Preston, 1995). Here the deposits, including seams up to 40 m thick, are localised into sub-basins by earlier palaeotopographic lows in the underlying basement. They occur towards the top of the Renmark Group and are overlain disconformably by paralic to nonmarine sediments usually of the Calivil Formation (ostensibly of the Wunghnu Group). Smaller coal deposits in the adjacent South Australian part of the Murray Basin also occur within the upper beds of the Renmark Group and are comprised of seams up to 8 m thick (Kress et al., 1978). They are overlain disconformably by Oligocene – Early Miocene marine carbonates of the Buccleugh Group (=Murray Group). High ash, pyrite and high sulphur contents in the Murray Basin coals suggest that they accumulated in close proximity to a coastal environment (see Table 16.8).

**Age of coal measures**

Dating the erosion surface which truncates the Victorian Murray Basin coal seams across the intervening basement highs is important for correlation of these seams to the Victorian coal seam stratigraphy. Drilling by the (SECV) near Wycheproof and Greigwin, up-dip of the Kerang-Cohuna coal deposits, revealed a clay unit with marine affinities immediately above the upper beds of the coal-bearing Renmark Group (Holdgate & Galimberti, 1980). Palynological dating by Archer (1980) personal communication) indicated that the marine clay beds belong to the *Proteacidites tuberculatus* spore–pollen Zone of Late Oligocene – Early Miocene age, and are therefore a facies equivalent of the Murray Group. Palynological dating of the underlying coaly beds of the upper Renmark Group from the SECV bores provided ages within the Upper *Nothofagidites agens* spore–pollen Zone. Subsequent dates on bores in the Riverine Plains (Macphail, 1990) have confirmed these ages for both the coal-bearing Renmark Group and the overlying succession, which here is largely correlated with the Calivil Formation. Consequently, the age of the disconformity at the top of the coal in the Kerang–Cohuna area best correlates with the late Early Oligocene disconformity of Brown, (1995a) and is a similar age to the disconformity above the South Australian coal deposits at Bower, Moorlands and Anna. This provides a similar age for the Murray Basin seams as for the Traralgon 1 seams in the Gippsland Basin. As discussed in Chapter 10, it appears the Calivil Formation is a nonmarine facies equivalent of the marine carbonates of the Murray Group.

**Table 16.8: Average range for selected coal qualities in southern Australian brown coal/lignite deposits**

<table>
<thead>
<tr>
<th>Coal Field</th>
<th>Moisture (% ar)</th>
<th>Ash (% db)</th>
<th>Cal. Value (% MJ/kg)</th>
<th>Sulphur (% db)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latrobe Valley</td>
<td>50-65</td>
<td>0.5-5.0</td>
<td>23.6-26.7</td>
<td>0.2-0.5</td>
</tr>
<tr>
<td>Alberton</td>
<td>55-66</td>
<td>2.5-5.5</td>
<td>24.0-26.0</td>
<td>0.4-4.0</td>
</tr>
<tr>
<td>Bacchus Marsh</td>
<td>55-60</td>
<td>2.5-10.0</td>
<td>23.0-26.0</td>
<td>0.2-0.4</td>
</tr>
<tr>
<td>Anglesea</td>
<td>44-48</td>
<td>4.0-6.0</td>
<td>25.0-27.0</td>
<td>0.3-4.0</td>
</tr>
<tr>
<td>W/D</td>
<td>50-55</td>
<td>1.6-4.3</td>
<td>23.7-25.8</td>
<td>1.2-2.7</td>
</tr>
<tr>
<td>Kerang/Cohuna</td>
<td>54-58</td>
<td>8.0-11.1</td>
<td>0.23-26.0</td>
<td>1.0-2.0</td>
</tr>
</tbody>
</table>

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