A Review of Tertiary Brown Coal Deposits in Australia—Their Depositional Factors and Eustatic Correlations[1]

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ABSTRACT

The paleogeographical setting, sequence stratigraphy, and timing for six Tertiary brown coal deposits along the southern seaboard of Australia indicate a concentration of major coal-forming phases to periods of significant coastal onlap coupled with frequent sea level oscillations.

Structural settings for thick seam development include grabenlike depressions adjacent to a major basin, embayments often barred from the main marine basinal sedimentation by a barrier sand buildup across the entrance, and paleovalleys incised into hard rock. A correlation also occurs between thick brown coals and warm-temperate to subtropical climatic conditions with evidence for multicyclic stacking of raised mires and ombrotrophic conditions similar to the modern tropical peats of Indonesia.

Common periods for thick seam development can be tied to the Exxon coastal onlap charts in the late middle Eocene and late Eocene sequence cycles TA3.5 to TA4.3 (36.0 to 42.5 Ma) and the late early to early middle Miocene sequence cycles TB2.1 to TB2.3 (15.5 to 21.0 Ma).

Knowledge of the timing and disposition of coaly rocks provides useful information to the petroleum explorationist regarding source potential and distribution within these time periods.

INTRODUCTION

By comparing the timing of development and depositional setting of six significant brown coal (lignite) deposits in Australia, the development of Tertiary-aged coal measure sedimentation can be placed in a more regional context. Establishing synchronous brown coal developments within widely spaced basins also would suggest a eustatically driven mechanism governing their timing of development, in preference to a more localized structural control (Dott, 1992). In assessing the regional picture for Australian Tertiary brown coals, a review of literature (e.g., Kress et al., 1978; Elms et al., 1982; Meyer, 1982; Abele et al., 1988; Kremor and Springblett, 1995; Preston, 1995) pertaining to brown coal deposits was done and in some cases reinterpreted. Previous workers on regional brown coal comparisons have tended to concentrate on the differences in coal qualities (Gloe, 1991). Few workers expressed the view of synchronous Tertiary-aged coal seam developments connected to eustatic sea level changes beyond a single basin or localized setting, for example in the Gippsland and Bass basins (Partridge, 1976) and in the Eocene coal basins of South Australia (Harris, 1980; McGowran, 1991).

With increasing emphasis today on eustatically controlled worldwide coastal onlap cycles and sequence analysis in sedimentary basins, it is considered timely that these methods should also be applied to the major Tertiary brown coal deposits in Australia.

The Gippsland Basin, together with its grabenlike inland offshoots known as the Latrobe Valley and Alberton depressions, contains by far the largest reserves of brown coal in Australia, and arguably the world (Gloe, 1991), and is Australia's premier basin for hydrocarbons. Through intensive study, the basin provides a set of criteria by which other basins can be compared (Holdgate et al., 1995). The Gippsland Basin is also the easternmost sediment accumulation system in a series of seven or more linked Cretaceous–Tertiary basins developed along the southern seaboard of the Australian continent, all of which have some brown coal deposits (Figure 1). From east to west, these basins include the Gippsland, Torquay/Port Phillip, Otway, Murray, St. Vincent's, Eucla, and Bremer basins. References specifically referring to the brown coals of basins other than those in the Gippsland Basin

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are comparatively rare but include Kress et al. (1978), Elms et al. (1982), Meyer (1982), Abele et al. (1988), Kremor and Springblett (1995), and Preston (1995).

The lower Eocene coals have been incorporated into previous eustatic and sequence analysis studies in the offshore Gippsland Basin (e.g., Partridge, 1976, 1982; Rahmanian et al., 1990). They are considered one of the sources for the prolific offshore hydrocarbons in this basin (Smith, 1981; Smith and Cook, 1984; Rahmanian et al., 1990). Discoveries to date comprise some 3.2 billion bbl of oil, 0.8 billion bbl of condensate and gas liquids, and 8.7 tcf of gas reserves. Discoveries in other southern Australian basins believed to come from coals and coal measure sediments include 0.8 tcf of gas in the Otway Basin and 0.7 tcf of gas in the Bass Basin. All other basins in this study remain underexplored. The younger Miocene coals described here lack the burial depths to be likely hydrocarbon sources in the offshore basins, but through their more extensive exposure and coal mining history, provide essential parameters for this study.

GENERAL STRATIGRAPHY AND COAL QUALITY

Although the internal stratigraphies vary in detail, a common theme through many of these basins is the gradual transition in the Tertiary from nonmarine to marine with time. This reflects the progressive opening of the Southern Ocean from the west, and separation of Australia from Antarctica. By the Oligocene–Miocene, most of these basins had become largely marine in character with exceptions in the easterly Port Philip and Gippsland basins, where nonmarine coal-bearing sequences continued to accumulate in marginal basin settings and graben offshoots. A summary of the coal-bearing stratigraphies in southern Australia is shown in Figure 2. A more precise age correlation of the main coal seams and other important related stratigraphies by sequence analysis and comparison to international chronostratigraphic coastal onlap charts (Haq et al., 1988) is also shown on Figure 2.

Selected coal parameters are shown on Table 1 for each of these deposits. The parameters provide the basis for comparison of coal properties in support of subsequent interpretations but are limited in that the results are averaged across all coal seams.

THE GIPPSLAND BASIN MODEL

Marine influence within the Latrobe Valley/Alberton Coal Measures of the Gippsland Basin was predicated on the occurrence of marine fossils (foraminifera and dinoflagellates) within interseam sediment partings between the coal seams and subseams (Holdgate and Sluiter, 1991; Holdgate, 1996). Some 17 interseam sediment partings east of Loy Yang were found to contain at some levels marine microfossils, which indicated a close relationship between the coal-forming environments and nearby marine conditions.

Sequence analysis methods were applied in the onshore Gippsland Basin to the study of the Latrobe Valley/Alberton Coal Measures (Holdgate, 1996). The methodology allows a better analysis of the relationships between periods of coal formation, marine carbonate formation, and sea level changes. Seven sequence boundaries were identified within the coal measures as being zones of significant coal truncation at the top of major (up to 100-m-thick) coal seams. In most cases, regionally transgressive sandstone aquifer interseam sediments overlie the coals. These grade upward into further major coal seams. The sequence boundaries also largely equate with the traditional major coal seam boundaries and include, from oldest to youngest, the T2, T1, T0, M2, M1B, M1A, and Yallourn sequences. The youngest four sequences are shown on the cross section of Figure 3.

Each sequence contains a series of coal lithotype and interseam depositional cycles that can be equated to parasequence successions. Marine flooding surfaces were used to define the parasequence boundaries and were identified by criteria such as marine fossil–bearing interseam and subseam sediment splits and increased organic sulfur content in the adjacent coal seams. Within thick, continuous coal seams without clay splits, parasequence boundaries at comparable stratigraphic levels can be distinguished as prominent brown coal lithotype cycle boundaries (Holdgate, 1992; Holdgate et al., 1995). Also occurring at parasequence boundaries are changes in the palynofloral compositions (Sluiter, 1984; Holdgate and Sluiter, 1991) and high-sulfur-content coal layers where marine-derived organic sulfur in coal is double the normal organic sulfur background values (Holdgate, 1992). Sequence boundaries were traced into the juxtaposed Seaspray Group marine carbonate sediments where microfossil foraminiferal zonation with international correlation is available (Holdgate and Gallagher, 1997) (Figure 3). Correlations of the onshore Gippsland Latrobe Valley/Alberton coal sequences to the international coastal onlap charts (Haq et al., 1988) using the palynological and foraminiferal dating are shown on Table 2, together with estimated ages and peat depositional rates.

Distribution of organic sulfur content in the brown coals (the major form of sulfur in the Latrobe Valley/Alberton depressions) follows a downward dispersion pattern over 1–4 m from overlying marine

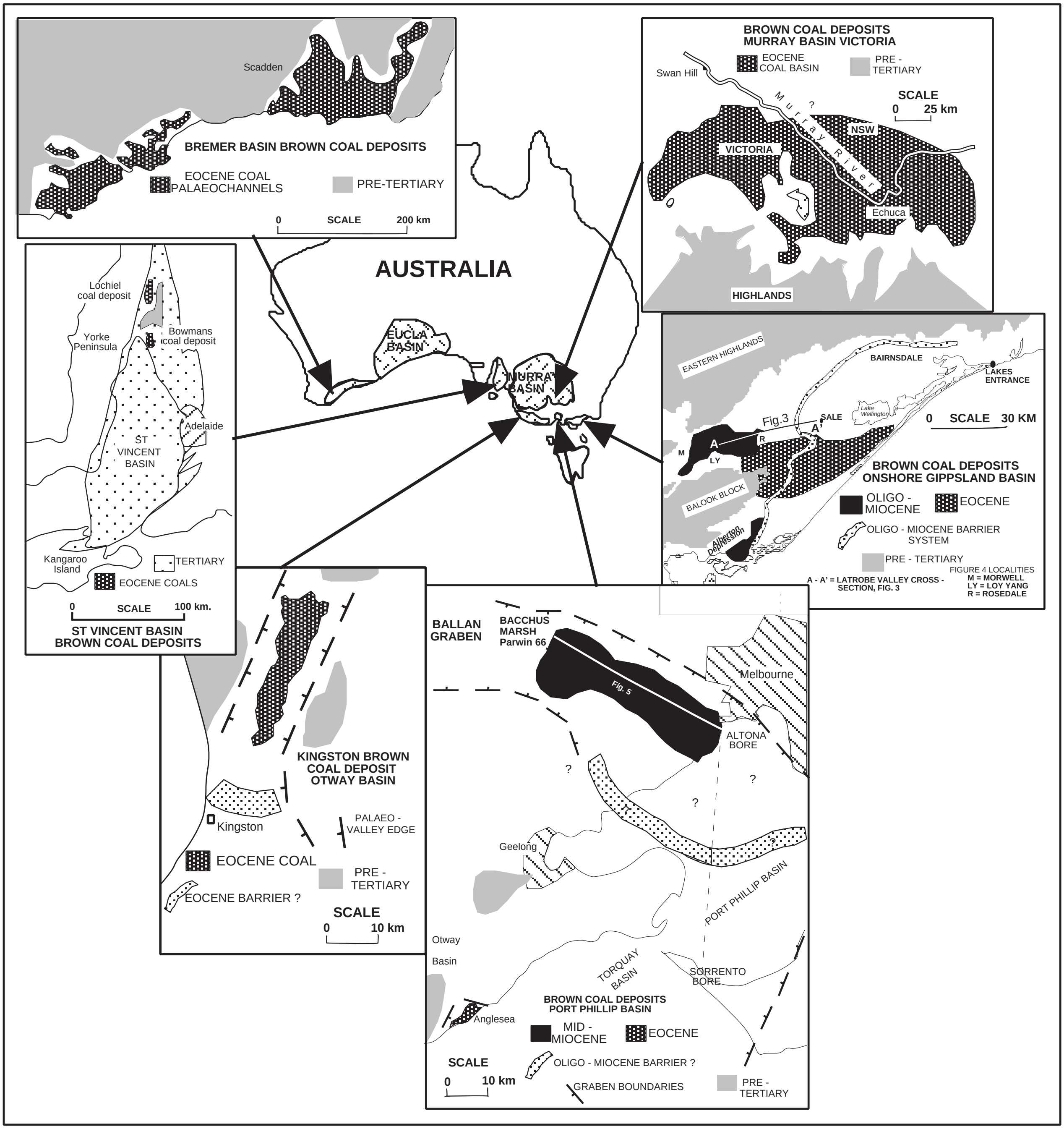

Figure 1—Locality maps and general geological setting for the main Southern Australian brown coal basins.

transgressions. The westward extent of marine influence can be mapped from sulfur highs even within continuous coal. At some stratigraphic levels, such as the M1A-M1B coal seam boundary, this sulfur high appears to cover the entire Latrobe Valley area. In other stratigraphic levels, the sulfur high may occur only over the eastern marine-influenced half of the Latrobe Valley, depending on the relative magnitude of coastal onlap (Figure 4).

Australian brown coals are prominently banded, typically on a scale from 1 to 10 m. The banding is referred to five main lithotypes (George, 1982)

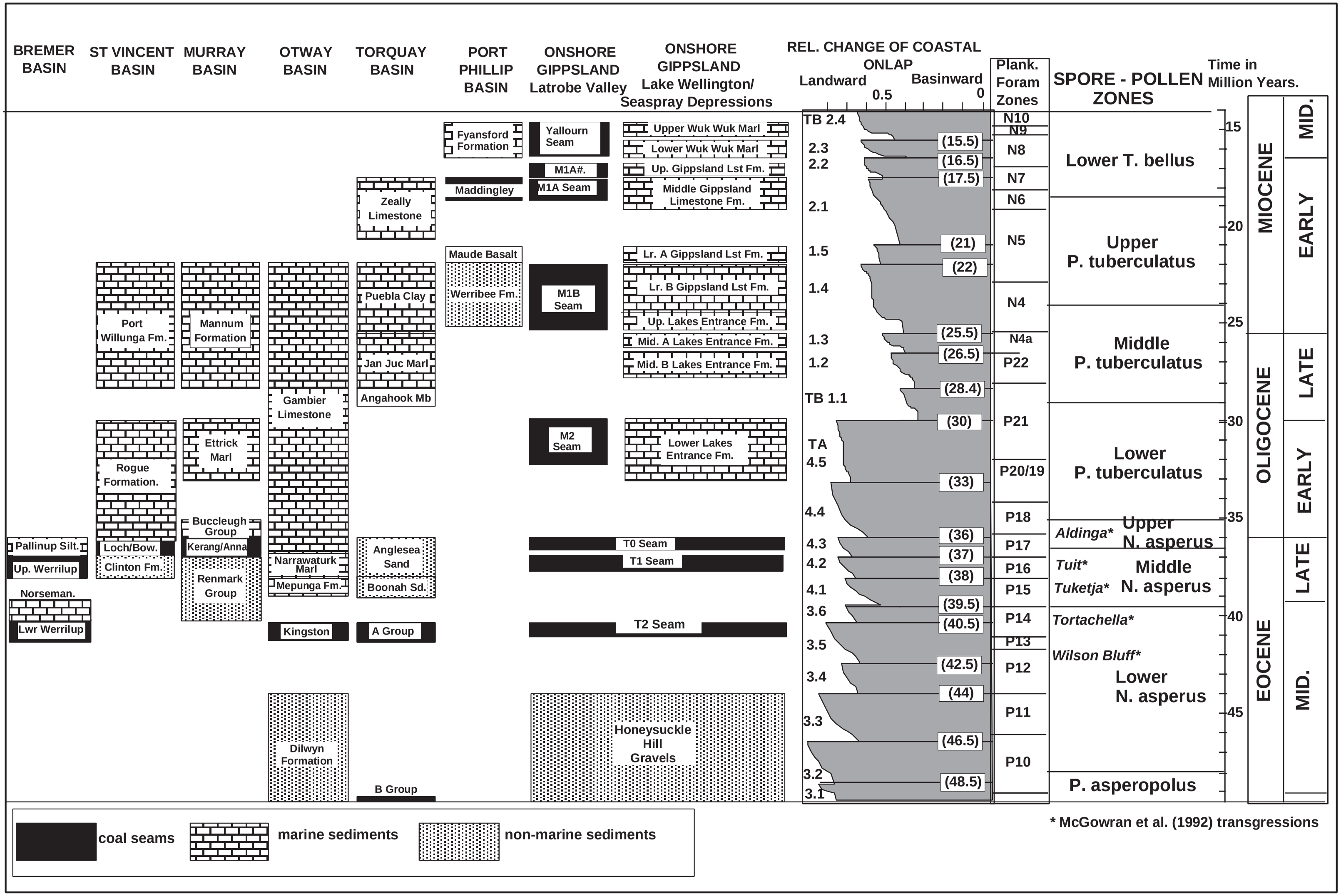

Figure 2—Correlation diagram between Tertiary stratigraphic units for Southern Australian brown coal basins, the foraminifera zones of Blow (1969) and Berggren (1972), the spore-pollen zones (Stover and Partridge, 1973), and the sequence chronostratigraphic coastal onlap chart of Haq et al. (1988). The McGowran et al. (1992) Eocene transgressions for the St. Vincent and Bremer basins are also shown.

Table 1. Average Range for Selected Coal Qualities in Southern Australian Brown Coal Deposits*

Coalfield Area, Abbreviation,** and Basin	Moisture (%ar)	Ash (%db)	Calorific Value (MJ/kg)	Sulfur (%db)
Latrobe Valley (LV), Gippsland Basin	50–65	0.5–5.0	23.6–26.7	0.2–0.5
Alberton (ALB), Gippsland Basin	55–66	2.5–5.5	24.0–26.0	0.4–0.9
Bacchus Marsh (BM), Port Phillip Basin	55–60	2.5–10.0	23.0–26.0	2.0–4.5
Altona (ALT), Port Phillip Basin	55–60	5.0–6.0	21.0–23.0	2.0–4.5
Anglesea (AN), Torquay Basin	44–48	4.0–6.0	25.0–27.0	3.0–4.0
Wensleydale (W), Torquay/Otway Basins	50–55	1.6–4.3	23.7–25.8	1.2–2.7
Kingston (KI), Otway Basin	54–56	5.0–15.0	23.0–25.0	2.5–3.0
Murray Basin (K/C), Victoria	54–58	8.0–11.0	23.0–26.0	1.0–2.0
Murray Basin (A/M), South Australia	54–60	15–24	21.6–22.5	3.8–5.6
Llochiel/Bowmans (L/B), St. Vincent Basin	55–62	14–15	21.0–23.0	2.9–5.0
Scadden (SC), Bremer Basin	60–66	10–15.0	22.0–24.0	4.0–6.0

*Figures derived from Abele et al. (1988), Gloe and Holdgate (1991), Gloe (1991), and Barton et al. (1995). ar = as arrived, db = dry basis, MJ/kg = megajoules/kilogram.

**See Table 3.

defined by coal color, degree of shrinkage, and presence of gelification (a shiny black amorphous gel within woody tissue). The lithotypes subdivide into dark, medium dark, medium light, light, and pale brown coal lithotypes. Palynofloral composition differs among different lithotypes (Luly et al., 1980; Kershaw and Sluiter, 1982; Blackburn and Sluiter, 1994). This difference is thought to reflect variations in depositional conditions at the time of peat formation, such as pH, E_h, water level, nutrient supply, and peat swamp flora, and the initial postdepositional conditions in the early stages of coalification. The brown coal lithotypes generally cycle by lightening upward over approximate 12–18 m intervals of coal (Mackay et al., 1985). Each cycle is interpreted to represent one parasequence cycle (Holdgate et al., 1995), and the boundaries of the cycles occur at times of marine flooding (high organic sulfur, marine interseam splits, etc.) (Figure 4).

The appearance of regionally widespread, 2–10-m-thick, highly gelified dark lithotypes immediately above each marine flood/parasequence boundary represents the commencement of a new cycle of peat accumulation and a new parasequence. The regional dark bands contain enhanced organic sulfur content in the basal laminated layer and a ubiquitous high gelification index. They also contain palynofloral components that were taken to indicate a warming of climate, such as increase in warm species *Myrtaceae* pollen (Sluiter, 1984) (Figure 4). The gelification, lamination, and high organic sulfur content were taken to indicate deposition in subaqueous, brackish water environments prior to ombrogenous growth (Holdgate et al., 1995).

The light and pale lithotype coals commonly occurring at the top end of each lithotype/parasequence cycle contain biochemical and petrological evidence for aerobic degradation, as demonstrated in cycle models by Anderson and Mackay, 1990. The light lithotypes have been interpreted to indicate the final stages of ombrogenous peat growth, where accumulation rates have slowed and nutrient starvation is common (Holdgate et al., 1995). The medium light and medium dark lithotypes constitute the major part of each parasequence cycle. They are interpreted to represent the bulk of the peat accumulated in each peat development phase.

OTHER BROWN COAL/LIGNITE DEPOSITS

Table 3 summarizes key paleogeographical and stratigraphic aspects for the Southern Australian brown coal deposits, and Figure 1 shows the generalized geology of the deposits within Australia.

Bacchus Marsh/Altona (Port Phillip Basin)

The Bacchus Marsh/Altona deposit of brown coal in the Parwan trough at the north end of the Port Phillip Basin is probably the largest Australian accumulation of brown coal outside the Gippsland Basin. Recent drilling (Figure 5) has now established the seam continuity over the whole area (Preston, 1981) and its paleogeographical setting within a large graben/paleovalley off the main Port Phillip Basin (Figure 6).

Foraminiferal dating of overlying Fyansford Formation marine marls (Parr, 1942; Taylor, 1963; S. J. Gallagher, 1999, personal communication), together with the palynological dates on the seam (Partridge, 1971, 1997; Greenwood, 1981), has constrained the

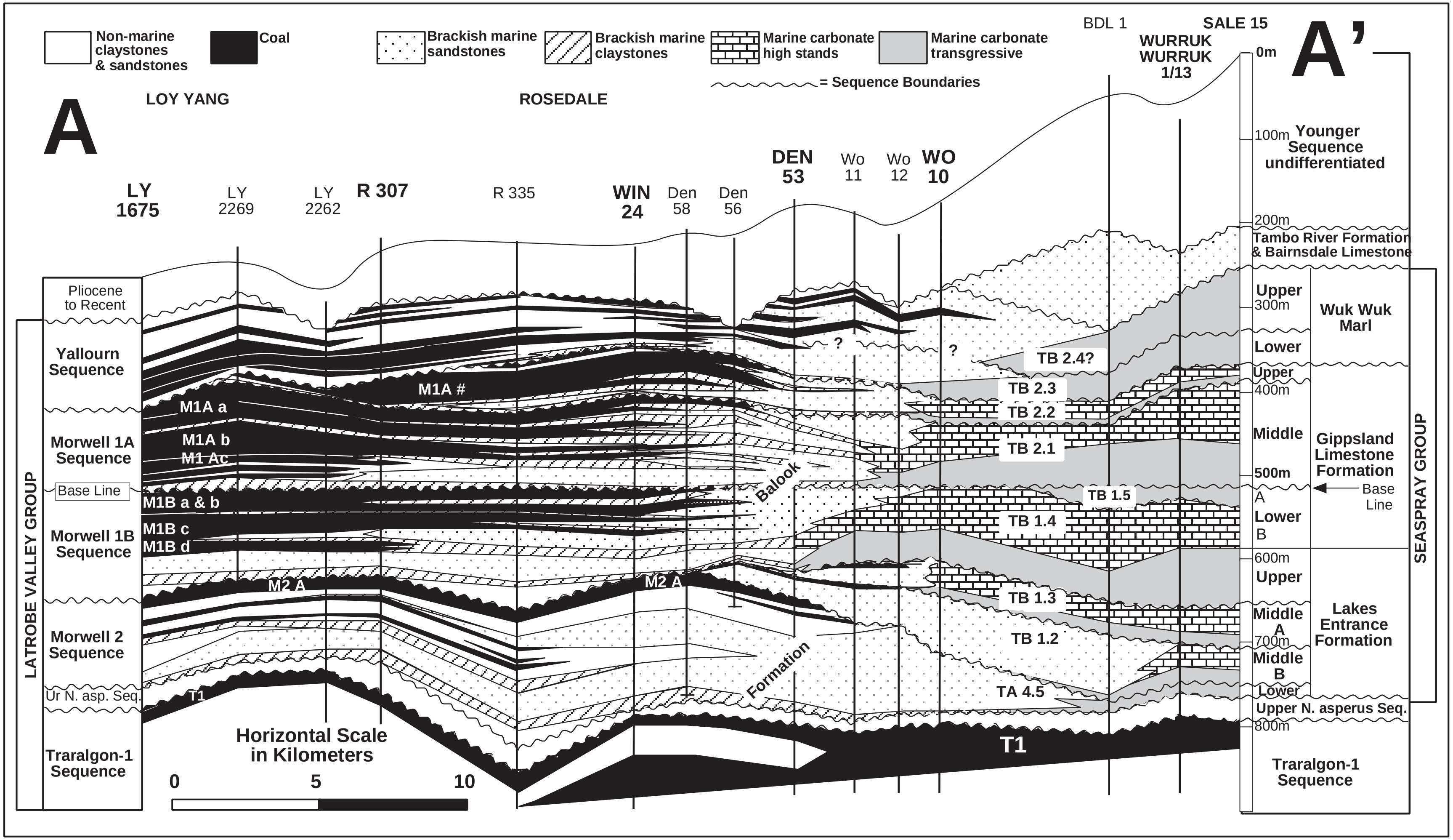

Figure 3—Borehole cross section between Loy Yang and Sale (Gippsland Basin) showing the lithofacies and sequence stratigraphy of the Oligocene–Miocene terrestrial to marine transition in the Gippsland Basin (adapted from Holdgate and Gallagher, 1997). For location of cross section, see Figure 1.

Table 2. Correlations of Gippsland Basin Coal Sequences to the Coastal Onlap Chart of Haq et al. (1988), and Derived Peat Accumulation Rates*

Coal Seam and Sequence	Sequence Cycle of Haq et al. (1988)	Age (m.y.)	Interpreted Coal Systems Tract	Implied Max. Duration of Coal Deposition (m.y.)	Maximum Coal Thickness (m)	Decomp. Ratio for Brown Coal to Peat	Decompacted Peat Accumulation Rate (m/k.y.)
Yallourn	TB 2.3–2.4?	13.8–16.5	HST	0.5	110	0.5 to 1.0	0.44
M1A	TB 2.1	17.5–21.0	HST	1.0	100	0.5 to 1.0	0.20
M1B	TB 1.4	22.0–25.5	HST	2.8	120	0.5 to 1.0	0.08
M2	TA 4.5	30.0–33.0	HST	2.0	150	0.5 to 1.0	0.15
T1	TA 4.2	37.0–38.0	HST	0.5	100	0.5 to 1.0	0.40
T2	TA 3.5	40.5–42.5	HST	0.7	100	0.5 to 1.0	0.28

*After Holdgate et al. (1995). Max. = maximum, Decomp. = Decompaction, HST = highstand systems tract.

seam age to late early to early middle Miocene. Its extent south under Port Phillip Bay is undefined, but drilling at Sorrento indicates that the comparable-age strata is entirely marine carbonates, and a facies transition similar to Gippsland occurs somewhere beneath the bay. Comparable-age coal in the Gippsland Basin is the M1A seam, which is also associated with the late early to early middle Miocene climatic optimum period.

Figure 7 illustrates lithotype logs for the connected 30-km-long Bacchus Marsh/Altona coal deposit immediately west of Melbourne [the lithotype log for the Maddingley seam at Bacchus Marsh is derived from Higgins et al. (1981) with our additional logging and sulfur analysis in the Maddingley open-cut mine]. We created the Altona coal lithotype log and sulfur analysis on a fully cored Altona bore at the Melbourne University Earth Sciences Department. The 20–35-m-thick Maddingley seam can be subdivided into two lithotype cycles each more than 15 m thick and each showing general lightening-upward trends. They are separated by a high-sulfur dark lithotype in the middle of the seam, which was also located and sampled in the Maddingley open-cut mine. Sulfur also increases at the top of the seam where marine overlying beds occur, particularly at Altona. Percentage sulfur and medium dark to dark lithotypes increase toward the Altona (marine) end of the deposit, with a facies transition into fully marine beds in Port Phillip Bay (Figure 5).

Increasing sulfur-in-coal (>3%) toward the southeast suggests that the Maddingley seam was deposited and influenced in this direction by proximity to a brackish to marine environment where sulfur-fixing bacteria were active. The relative high component of medium light to light coal lithotypes in the Maddingley seam at Bacchus Marsh is unusual for a coal seam in a near-marine environment. In the Latrobe Valley in general, the coals appear to have a darker lithotype component when they are in proximity to the marine boundary (Figure 4), suggesting that the Bacchus Marsh area represented a distal inland location for the Maddingley seam peat swamp, where greater fluctuations in the water table allowed a greater degree of aerobic degradation and a more acidic environment. This differentiation is likely a consequence of the confinement of marine influence to the mouth of the graben/paleovalley nearer the Altona end of the deposit.

Torquay Basin (Anglesea)

The Anglesea syncline on the western margins of the Torquay Basin contains three major brown coal seam intervals (A, B, and C groups) (George, 1962). The seams and interseam sediments form the upper part of the Paleogene Eastern View Formation. The youngest A group coal seam can be up to 40 m thick where mined. Older B and C group seams can be up to 20 m thick.

The A group seam is confined to the downwarped Anglesea syncline, where it is overlain with a prominent unconformity by less folded sands and silty clays of the Anglesea Formation, including the basal Boonah Sand Member. Palynological dating places the Anglesea Sand into the upper Eocene (middle *N. asperus* zone), the A group seam into the late middle Eocene (Lower *N. asperus* Zone), and the underlying B and C group seams into the lower Eocene (*M. diversus* and *P. asperopollis* zones) (see Figure 8) (Christophel et al., 1987; Macphail, 1995). No fully marine carbonate facies equivalent to the coal seams are known in the offshore part of the basin, but some dinoflagellate incursions have been identified in the overlying Anglesea sand in the mine (Smith, 1998).

Additional dating of the nearby extensive coastal cliff exposures of Anglesea and Angahook Formation

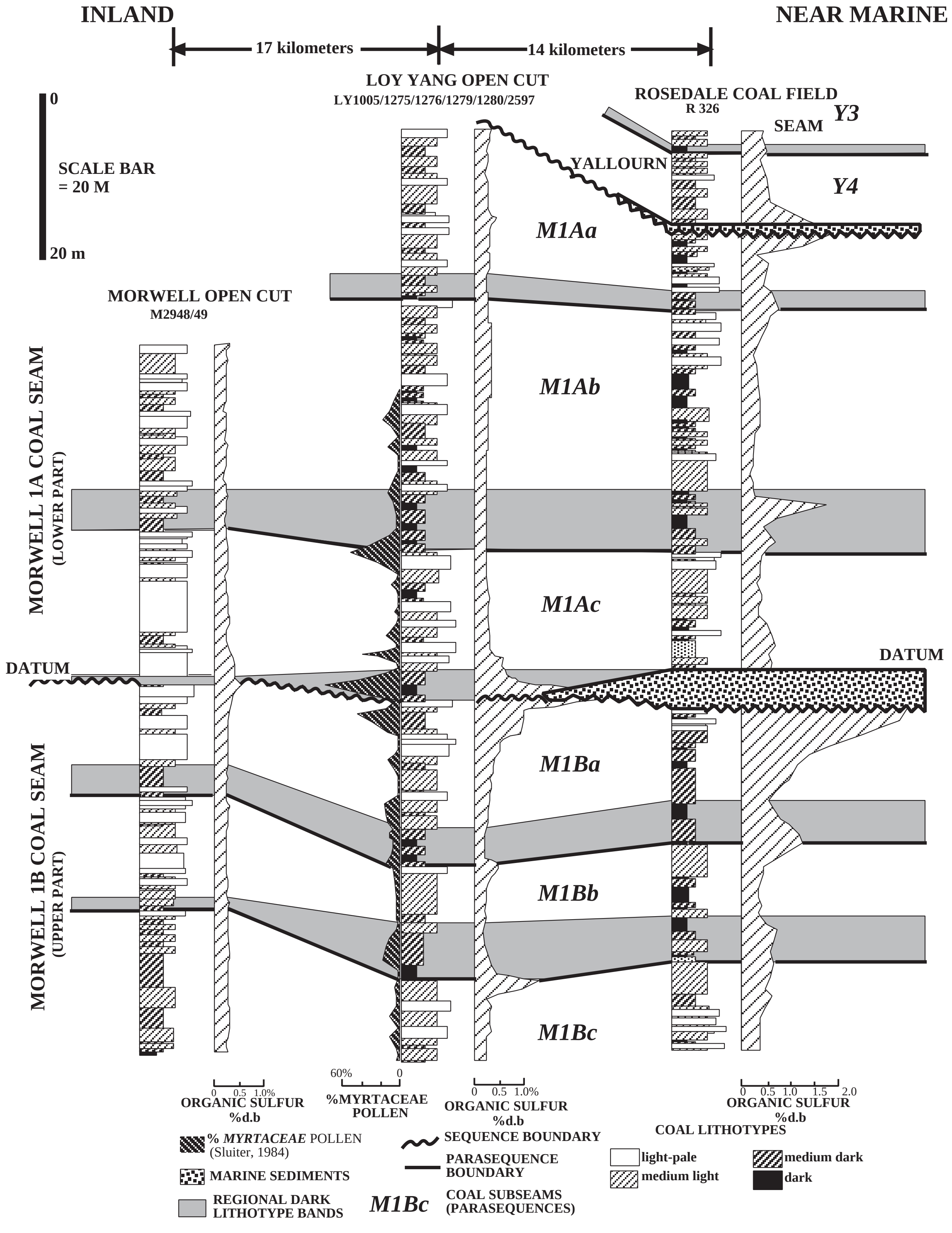

Figure 4—Stratigraphic correlation of M1A and M1B coal seams of the Latrobe Valley (Gippsland Basin) based on brown coal lithotypes, organic sulfur in coal, relative abundance of key warmer climate *Myrtaceae* pollen, and sequence and parasequence boundaries. For location of key sections, see Figure 1.

Table 3. Paleogeographic and Stratigraphic Correlations for Southern Australian Brown Coal Deposits

Coal Field[*]	Max. Coal Seam Thickness (m)	Overlying or Equivalent Paralic to Marine Fms.	Age of Overlying Beds[**] [†]	Palynological Coal-Seam Age[†]	Sequence Cycle[††]	Interpreted Paleogeographic Setting	Presence of Sulfur Highs and Lithotype Cycles (m)	Interpreted Paleoclimatic Setting
LV	See Table 2	Seaspray Gp. Balook Sand	Various (see Figs. 3, 4)	Various (see Figs. 3, 4)	Various (see Table 2)	Graben of Gippsland Basin	12–18	Subtropical
ALB	See Table 2	Seaspray Gp. Balook Sand	Various (see Figs. 3, 4)	Various (see Figs. 3, 4)	Various (see Table 2)	Backbarrier Gippsland Basin	12–18	Subtropical
BM	40	Fyansford Fm.	*T. bellus* zone[†]	Upper *P. tuber* zone	TB2.1/2	Graben to Port Phillip Basin	10–12	Subtropical
ALT	40	Fyansford Fm.	N8[**]	Upper *P. tuber* zone	Tb2.1/2	Graben to Port Phillip Basin	10–12	Subtropical
AN	36	Demons Bluff Fm.?	Upper *N. asperus* zone[†]	Lower *N. asperus* zone	TA3.5	Graben to Torquay Basin	6–8	Subtropical
W	40	No data	Pliocene	Middle *M. diversus* zone	No data	Graben to Otway Basin	No data	No data
KI	12	Nirranda Group	P14–15[**]	Lower *N. asperus* zone	TA3.5	Graben/paleochannels to Otway Basin	No data	Subtropical
K/C	40	Calivil Fm.	*P. tuber* zone[†]	Upper *N. asperus* zone	TA4.3	Infill to paleochannels	No data	No data
A/M	8	Buccleugh Gp.?	P17[**]	Middle *N. asperus* zone	TA4.2	Backbarrier to Murray Basin	No data	No data
L/B	20	Blanche Pt. Fm.	P18[**]	Upper *N. asperus* zone	TA4.3	Backbarrier in St. Vincent Basin	No data	Warm temperate
SC	17	Pallinup Sltst.	P17[**]	Lower–middle *N. asperus* zone	TA4.2	Infill to paleochannels	No data	Warm temperate

[*] See Table 1 for key.

[**] Planktonic foraminiferal zones (Blow, 1969; Berggren, 1972).

[†] After palynology zone scheme for Australia (Stover and Partridge, 1973).

[††] From Haq et al. (1988).

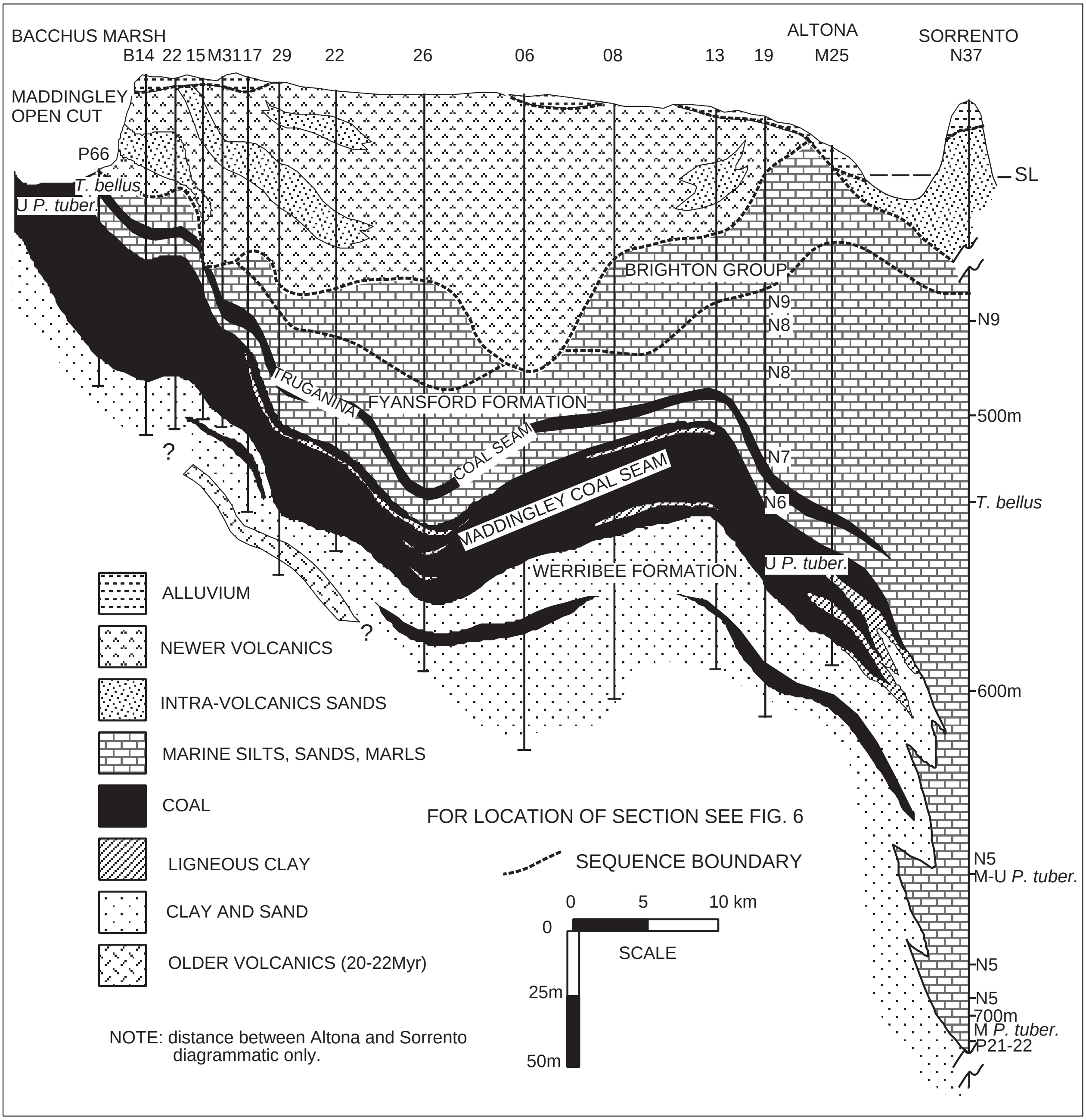

Figure 5—Borehole cross section from Bacchus Marsh, through Altona, and to Sorrento (Port Phillip Basin) along the depositional axis of the Parwan Trough. Foraminifera ages and palynology zones are also shown for key bores. For location of section see Figures 1 and 6.

identified several younger sequences extending up into the lower Oligocene (Reeckmann and Partridge, 1988; Reeckmann, 1994). Overlying upper Oligocene–lower Miocene marine carbonates of the Torquay Group are constrained by detailed foraminiferal ages (Abele, 1979; Li et al., 1998).

A lithotype bore log for the A group seam, derived from Higgins et al. (1981), was supplemented by additional logging of three lithotype transects in the present Anglesea open-cut mine exposures. Lithotype, colorimetry, sulfur, and ash content were analyzed at 1.0 m intervals (Smith,

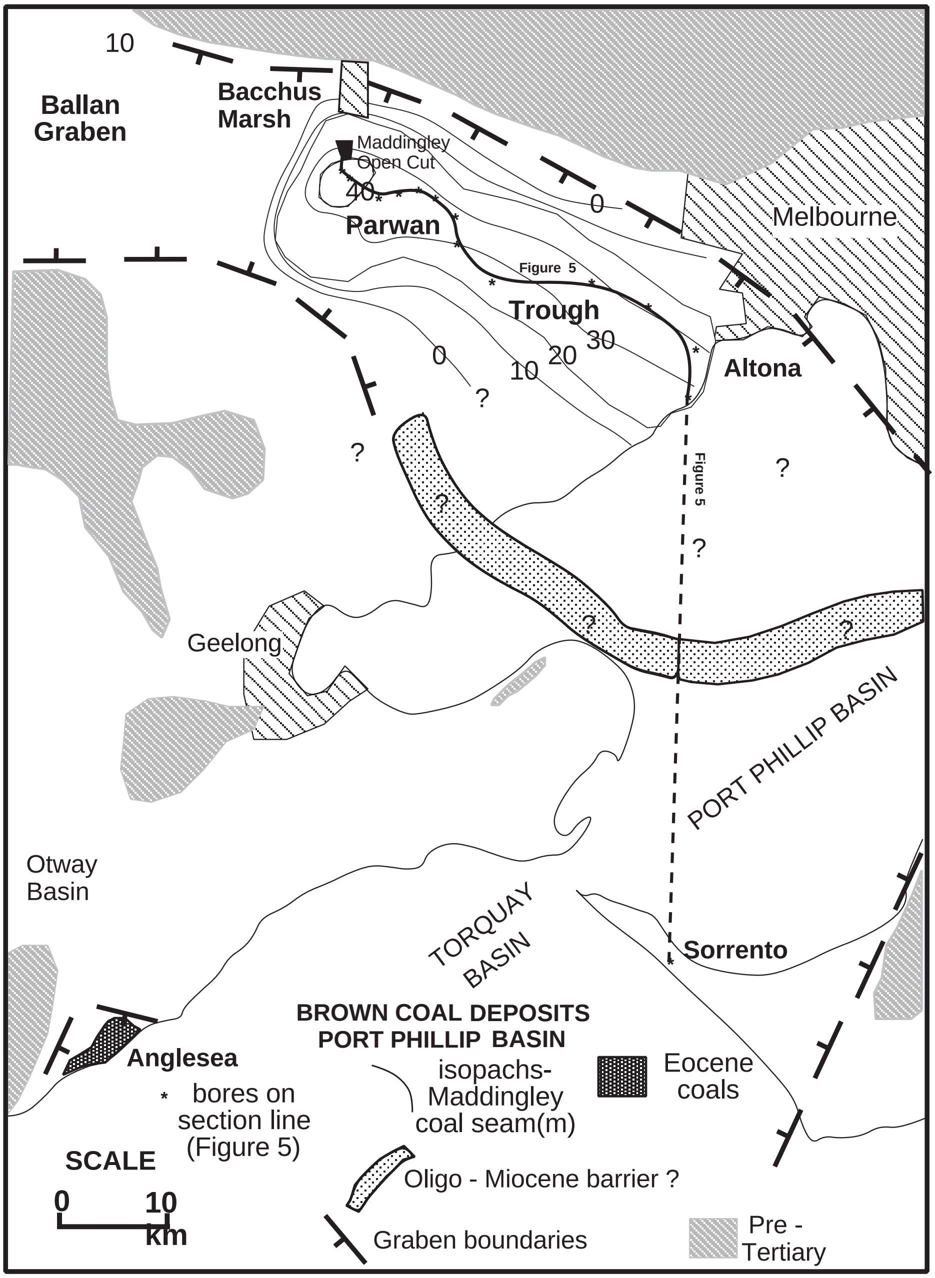

Figure 6—Maddingley coal seam thickness isopachs for the Bacchus Marsh to Altona area, (Port Phillip Basin). Also shown is the location of section line shown in Figure 5.

1998) (Figure 8). This logging illustrates five lightening-upward lithotype cycles approximately every 6–8 m, with a prominent clay split occurring between the first and second cycle toward the western side of the mine. Lithotype logs for B group and C group seams, also derived from Higgins et al. (1981), show similar cycles. The coal rank for Anglesea is higher than that of the Gippsland coal (Table 1) and, consequently, cycle thicknesses are proportionally reduced some 30% due to compaction.

Sulfur distribution shows pronounced peaks at the top and base of the A group seam, with several intraseam peaks defining some of the cycle boundaries (Figure 8). Closer sampling of less than 1.0 m may be required to pin down additional cycle boundaries. Overall sulfur content is much higher than that for typical Gippsland coal, which may also mask some of the more subtle changes.

An interpretation of the palynological dates places the A group seam contemporaneous with

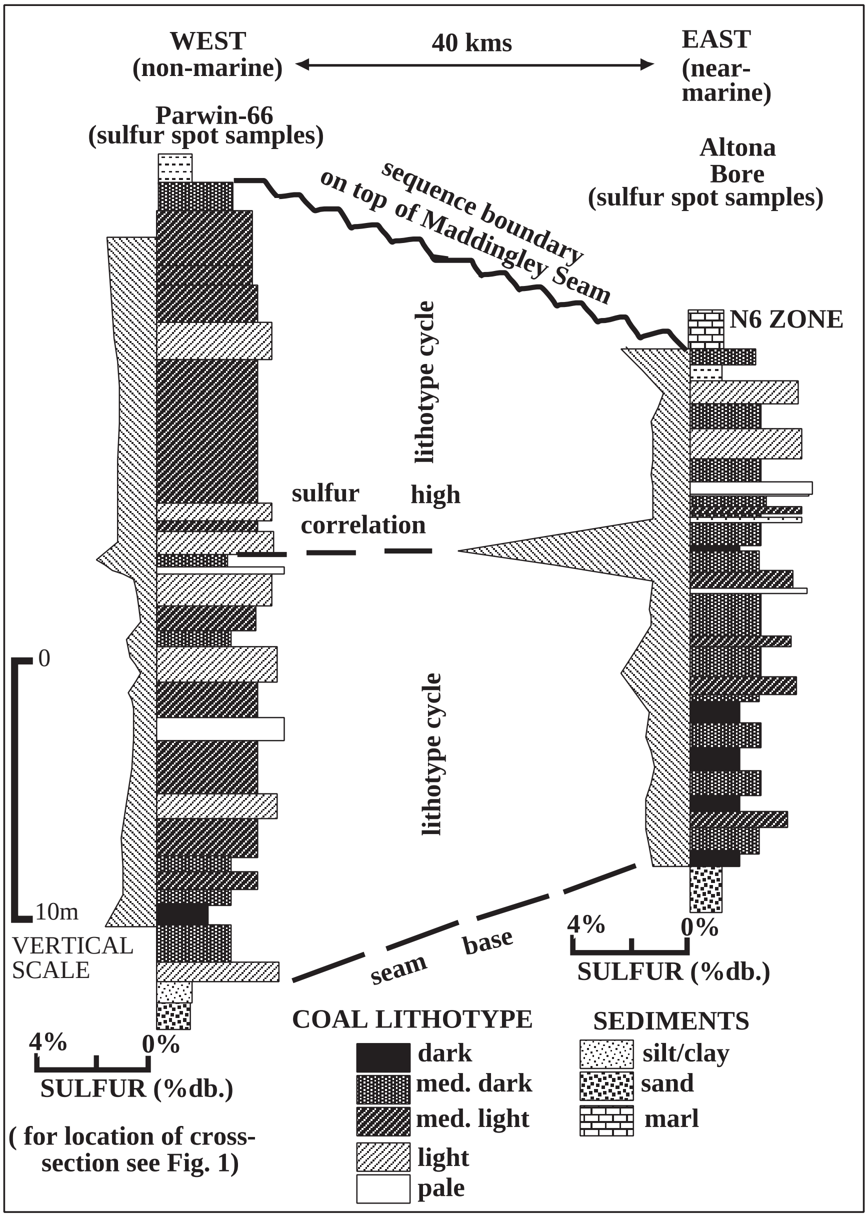

Figure 7—Brown coal lithotypes and organic sulfur in coal cross section between Bacchus Marsh and Altona bore (Port Phillip Basin). For location of cross section, see Figures 1 and 6. Location of bores Parwin 66 and Altona are shown on Figure 1. Location of Altona and Maddingley open cut (Parwin 66) are shown on Figure 6. Location of Parwin 66 bore (P66) is shown on Figure 5.

the T2 coal seam in Gippsland and correlates to the sequence cycle TA3.5 or TA3.6 of Haq et al. (1988). The prominent unconformity on top of the seam thus is correlated to the 39.5 or 40.5 Ma sequence boundary. The TA3.5 cycle is considered the more likely due to the pollen assemblage detailed by Christophel et al. (1987).

The palynological dating of the underlying B and C group seams in bores near the mine (Macphail, 1995) implies that several sequence boundaries occur within these coaly intervals. Studying the detailed bore log cross sections across the Anglesea syncline reveals several zones of significant coal losses (Holdgate, 1996) interpreted as sequence boundaries. These have been positioned where they would occur on the bore log column (Figure 8), together with their extrapolated sequence boundary ages.

The early Eocene B and C Group coals are considerably older than other onshore Eocene coals, but similar coals occur extensively offshore in the Torquay, Bass, and Gippsland basins. Broad-scale reviews of their extent have been detailed by Brown (1975), Baillie and Bacon (1989), and Baillie (1992); however, only some drill core exists, but not enough to establish lithotype successions. In most cases, the coal properties (moisture, ash,

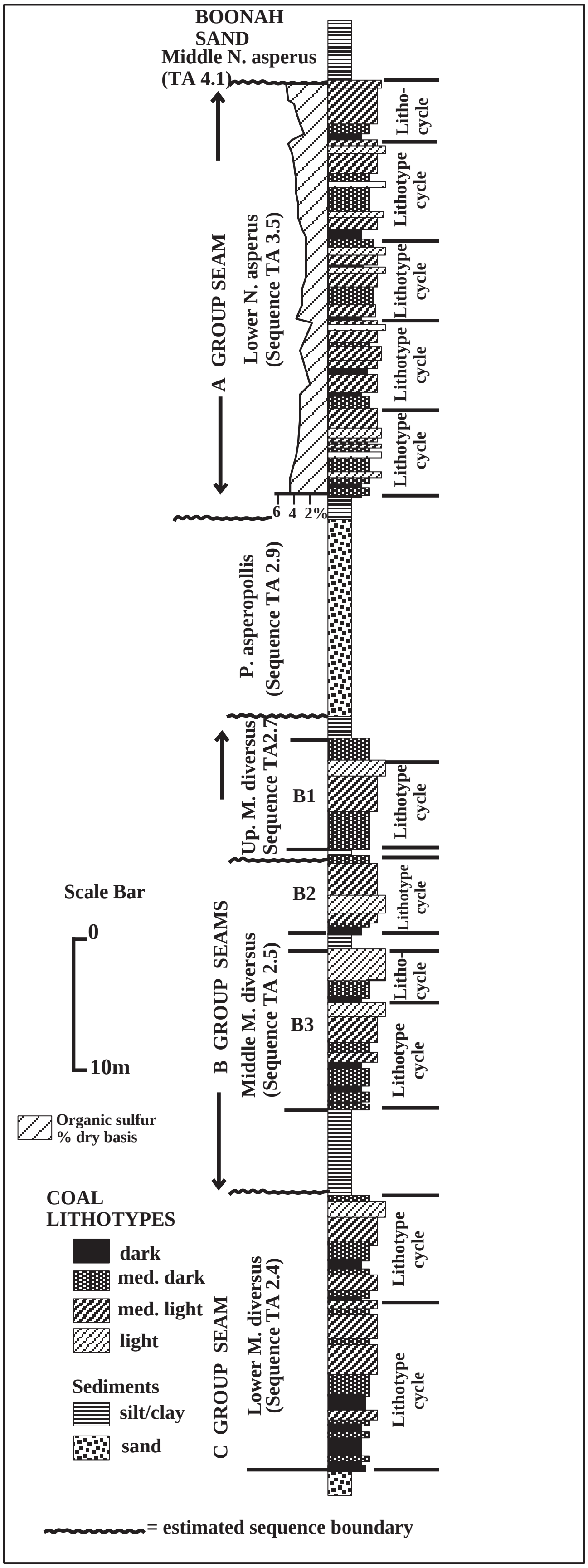

Figure 8—Coal lithotype and sulfur logs for the Anglesea Mine in the Torquay Basin. Palynology ages and suggested sequence chronostratigraphy (after Haq et al., 1988) are also shown.

calorific value, etc.) also remain largely unknown. The only comprehensive petrology on coal core and cuttings has been that undertaken by Smith (1981); consequently, the early Eocene coals are not further reviewed in this paper, although many of these coals have been incorporated in previous eustatic and sequence analysis studies (e.g., Partridge, 1976, 1982; Rahmanian et al., 1990). These coals are also considered to be one of the major sources for the prolific offshore hydrocarbons in these basins (Smith, 1981; Smith and Cook, 1984; Rahmanian et al., 1990), and some of the coals contain alginite-like material in significant amounts (Smith, 1981).

At Wensleydale on the Torquay-Otway Basin boundary, a localized 40 m seam is contained within a small syncline at the northeastern end of the Otway Ranges (Thomas and Baragwanath, 1950, 1951; Knight, 1975). Although exposures of the coal are poor, lithotype banding is apparent. Limited coal analyses are available (Gloe, 1991) (Table 1). Dating by palynology suggests that this coal formed during the middle of the *M. diversus* zone (Morgan, 1992), similar to the B and C Group seams at Anglesea.

Otway Basin (Kingston)

The Otway Basin contains relatively little Tertiary brown coal, with one main deposit known in the far western end near Kingston (South Australia). This appears to be a result of intermittent marine transgressive phases during the Paleocene, Eocene, Oligocene, and Miocene that flooded most of the basin up to the northern basement margins. The main Tertiary coal-bearing units of the Otway Basin are in the upper part of the Dilwyn Formation, a synonymous unit to the coal-bearing upper part of the Eastern View Formation in the adjacent Torquay Basin.

The Kingston brown coals occur in a south-trending paleovalley cut into Paleozoic granite opening into the Otway Basin (Wood, 1981; Meyer, 1982,1995) (Figure 1). The coal occurs as one main series of seams, with the thickest being 12 m. The overlying beds are mostly marine carbonates and clastics. There is a high organic-sulfur content in the Kingston coal (3%), suggesting enrichment from overlying marine beds or deposition in close proximity to a shoreline where marine influence occurred (see Murray et al., 1997). No lithotype work has been published on the coal succession. Wood (1981) found the megafloral species representative of subtropical rainforest vegetation. Meyer (1982) noted a high liptinite content (12–19%) and a low inertinite content (1–3%) in the coal.

Harris (1980) considered the Kingston deposit to be representative of a middle Eocene eustatic cycle that saw widespread brown coal deposition in the Eucla, St. Vincent, central Murray, and western Otway basins of South Australia. We extend this cycle of coal deposition into all of the onshore basins along the southern Australian seaboard.

In detail, the Kingston coal seams are dated near the top of the middle Eocene part of the Dilwyn Formation in the *P. pachypolus* zone (Harris, 1985), which is the lower *N. asperus* zone of Stover and Partridge (1973). These seams are overlain unconformably by upper Eocene marine to marginal-marine sediments of the Nirranda Group dated in the *T. magnificus* zone (i.e., the middle *N. asperus* zone). The timing of coal deposition broadly correlates with the A group seams at Anglesea. The erosion surface above the seams may also correlate with the Haq et al. (1988) sequence boundary dated at 40.5 Ma because Harris (1985) places the oldest overlying Nirranda Group beds (the Mepunga Formation) within the P14 foraminiferal zone, which has a range of between 39.4 and 41.4 Ma. The Kingston coal thus was likely to be deposited within the TA3.5 cycle (Haq et al., 1988). This dates the coal into the P12/13 foraminiferal-aged Tortachilla or Wilson Bluff transgressions of McGowran et al. (1992) and McGowran and Li (1997).

Murray Basin

The Murray Basin covers more than 300,000 km^2 of northeast Victoria, southeast South Australia, and western New South Wales (Brown et al., 1995) (Figure 1). Although it lacks a significant connection to the southern coastlands of Australia today, it was better connected throughout the Tertiary. Periodically, the basin saw significant marine ingressions with accompanying carbonate sediment deposition, principally during the Oligocene and Miocene. Prior to the Oligocene, predominantly nonmarine clastic sedimentation infilled and covered a pre-Tertiary topography developed on basement rock.

Significant brown coal deposition with seams up to 40 m thick infilled early Tertiary paleovalleys on the southern side of the basin in Victoria (Brunker et al., 1986; Preston, 1995) (Figure 1). Only a few of the seam deposits were analyzed (Gloe, 1991), and no lithotype or petrological data have been published.

On bore-log cross sections, a significant unconformity appears to truncate the coal seams over intrabasin topographic highs (Preston, 1995), and is overlain by paralic to nonmarine sediments. Palynology dating places the youngest coal seam ages in the late Eocene upper *N. asperus* zone (Macphail, 1990), and the overlying sediments to be in the Oligocene–early Miocene *P. tuberculatus* zone. This timing accords with a Brown et al. (1995) regional disconformity in the late early Oligocene, and would place the coal as contemporaneous to the late Eocene T0 coal seams

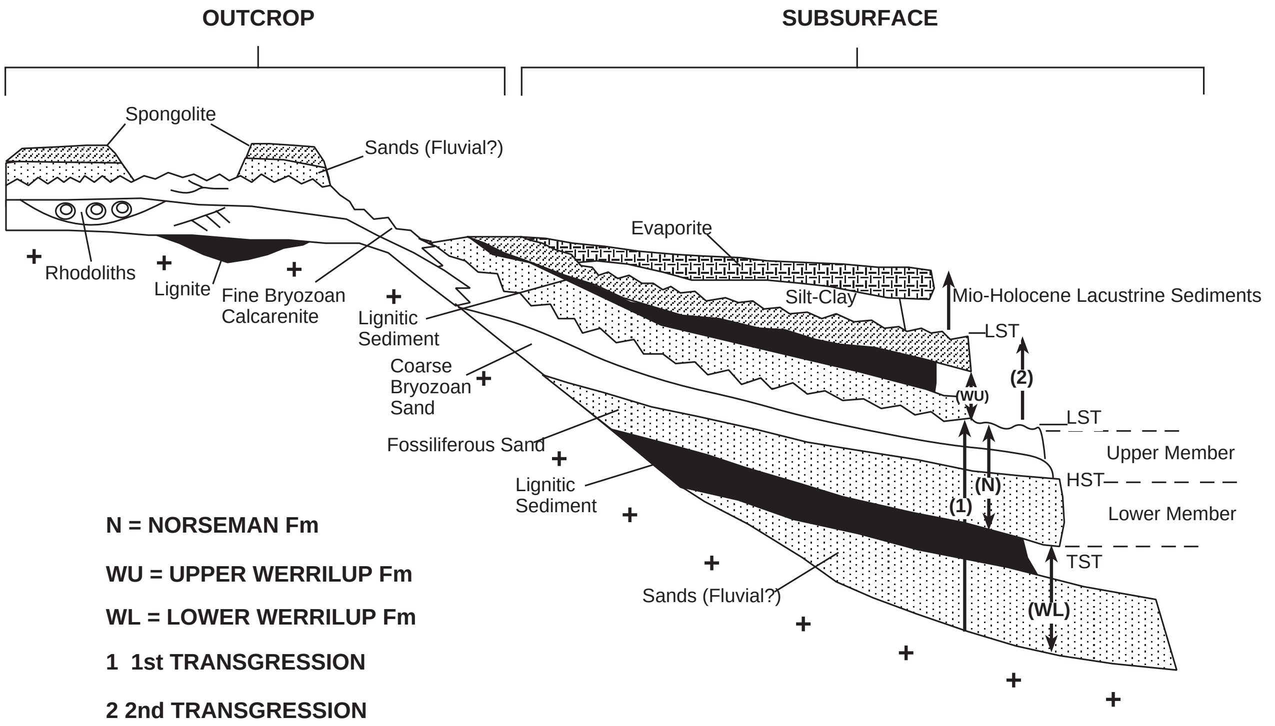

Figure 9—Sequence stratigraphy of the Bremer Basin paleovalleys (after Clarke et al., 1996).

in the Gippsland Basin, and therefore was deposited within the sequence cycle TA4.3 of Haq et al. (1988).

In the South Australian part of the Murray Basin, several smaller coal deposits occur at Anna, Bower, Moorlands, and Sedan. Here, marine carbonate sediments of the Murray Group disconformably overlie the upper coal seams and constrain the age to the late Eocene P17 foraminiferal zone (Harris, 1985; Lindsay, 1985). This indicates a likely TA4.2 sequence cycle, similar in age to the T1 coal seams in the Gippsland Basin.

St. Vincent Basin (Lochiel and Bowmans)

Eocene brown coal deposits of the Clinton Coal Measures occur at the northern end of the St. Vincent Basin near Lochiel and Bowmans. The thickest continuous seams drilled are 10 m over a total coaly interval of 60 m (Kremor and Springblett, 1995). Although detailed coal analysis and petrology has been done, little of this work has been published. A lithotype succession is not known.

Age of the coal is considered to be late Eocene–early Oligocene (i.e., within the upper *N. asperus* zone) (Harris, 1980,1985; Meakin, 1985; Alley and Lindsay, 1995). The Clinton Coal Measures are unconformably overlain by lower Oligocene P18-20 marine marls of the Port Willunga Formation (Lindsay, 1985). In the area of maximum coal seam development, the coal measures are overlain by paralic formations of the Rogue Formation, thought to be a facies equivalent to the Port Willunga Formation.

In the Adelaide area, the Clinton Coal Measures are equivalents to nonmarine sediments of the Chinaman Gully Formation, which disconformably overlies P16 marine carbonates of the Blanche Point Formation [the Tuit transgression of McGowran et al. (1992)]. In turn, they are conformably overlain by P17/18 marine carbonates of the Aldinga Member [Port Willunga Formation, which is the Aldinga transgression of McGowran et al. (1992)]. Thus, these coals were deposited during the early stages of the Haq et al. (1988) sequence cycle TA4.3, although it is possible that a slightly younger age for the more northerly Lochiel deposit (Meakin, 1985) extends into the following sequence cycle 4.4 (McGowran and Li, 1997). The Lochiel and Bowmans coal seams thus are broadly contemporaneous with coals of the T0 sequence in Gippsland.

Bremer Basin

Brown coals of the Bremer Basin occur in paleovalley successions within the onshore part of the basin where the basal host Werrilup Formation often exhibits thin coaly cycles (Figures 1, 9). Facies of the Werrilup Formation comprise basal gravels in the main channels between 1 and 5 m thick, overlain by a channel sand facies composed of well-sorted quartz sands with locally abundant lags of plant debris. Internally, the channel sands are organized into fining-upward parasequences 2–3 m thick. A flood-plain facies of clays occurs on either side of the central meandering channel. Their lithology consists of massive silty, kaolinitic clays with cycles 2–3 m thick marked by thin brown coal bands. Individual cycles contain coal seams with in situ tree stumps and woody fragments in a dark matrix. The coal seams overlie rootlet layers and are overlain by gray silty clays. Thicker coaly facies are rare in the upper reaches of the paleovalleys but become more common downstream where the thickness of individual seams ranges between 5 and 17 m, such as near Scadden (Figure 1).

Similar cycles are clearly allocyclic in time-equivalent sediments in the Pidinga Formation of the Lefroy paleovalley (northern Bremer Basin, Figure 1), where the coal beds locally thicken to form amalgamated mire sequences. These are interpreted as equivalent to the thick coals in the Scadden deposit.

Elms et al. (1982, 1995) described the coal as being a dull, earthy, chocolate brown in color with rare globules of resin. The overall properties of the coal (Elms et al., 1982) are that it has high ash (11.9%) and sulfur (1.9%). Oil content (Kristensen and Wilson 1986) is also high, with Fisher yields of more than 50 L/t. These data are consistent with deposition of the coal on riverine and coastal plain environments with marine-influenced groundwater either during deposition or shallow burial. The high oil yield suggests a high proportion of brackish water algae and wax-rich cuticle material; a contention supported by the presence of *Botrycoccus* and mangrove pollen in the spore and pollen assemblages (Clarke, 1994).

The Werrilup coals were deposited as two sequences by late Eocene transgressions (Figure 9). Each sequence consists of a transgressive systems tract, which contains a fining-upward clastic succession, and a highstand system tract of biogenic marine sediments. Coal and carbonaceous sediments occur throughout the transgressive systems tract. Good palynological data from the carbonaceous sediments (Clarke 1993; Clarke et al., 1996) allow correlation with the marine record of McGowran et al. (1992) and correlation to the sequence cycle chronostratigraphy of Haq et al. (1988). Thus, these deposits represent parasequences within the overall third-order cycle of the Tuketja transgressive sequence (McGowran et al., 1992).

The lower sequence, sequence 1, is of late middle Eocene age. The base is correlated with the base of TA cycle 3.5, conceivably in the P13 zone (41.4–41.9 Ma). The sequence is about 50 m thick where best preserved at Norseman but is variable due to the effect of original topography and subsequent erosion. A sequence comprises basal fluvial to marginal-marine sandstone, carbonaceous silts and clays, and brown coal is conformably overlain by cool-water limestones of the Norseman Formation (Clarke et al., 1996). The clastics and coals are interpreted to form part of the lowstand and transgressive systems tracts, and the carbonates are interpreted to form mainly under a highstand systems tract (Figure 9). The carbonate Norseman Formation was deposited during the Tortachilla (P13/14 zone) transgression of McGowran et al. (1992).

Sequence 2 (TA cycle 4.1 and 4.2, 37.0–39.5 Ma) overlies sequence 1 along a marked erosional contact interpreted as a sequence boundary. The stratigraphy and lithology is essentially the same as for sequence 1. Sequence 2 reaches a maximum thickness of about 40 m in the upper parts of the Cowan paleovalley and 70 m in the lower reaches toward the coast. As with sequence 1, thickness varies significantly because of original paleotopographic constraints and later erosion. The highstand systems tract is represented in the headwaters of the Cowan paleovalley by the Princess Royal Spongolite and along the south coast of Western Australia by its equivalent, the Pallinup Siltstone. Both units are composed of siliceous spiculite to spicular siltstone. The Werrilup Formation is confined within the paleovalleys, whereas the highstand deposits, in particular the Princess Royal Spongolite and Pallinup Siltstone, extend beyond the confines of the paleovalleys (Figure 9). The highstand is correlated with the Tuketja or Tuit (P15/16 zones) transgressions of McGowran et al. (1992).

The Bremer Basin coals of sequence 1 were thus deposited at the same time as the Kingston deposit and the A group seam at Anglesea (T2 sequence in Gippsland), with the main seams in sequence 2 being possible equivalents to the T1 sequence of Gippsland.

DISCUSSION

Specific periods of development of thick, brown coal seams in the southern Australian basins are largely confined to two major Haq et al. (1988) sequence third-order cycle groupings (see Figure 2). These groupings spread maximum coal development over successive third-order cycles providing multiseam stacking. These third-order cycle groupings are as follows.

(1) The late middle to late Eocene sequence cycles TA3.5 to TA4.3 (42.5 to 36.0 Ma), as in the Gippsland, Torquay, Otway, Murray, St. Vincent, and Bremer basins.

(2) The late early to early middle Miocene sequence cycles TB2.1–2.3 (15.5–21.0 Ma), as in the Gippsland and Port Phillip basins.

Other sequence cycles apparently lack coal deposits, with the exception of the Gippsland Basin (Latrobe Valley/Alberton M1B and M2 coals) and possibly the Port Phillip Basin (thin coals underlying the Maddingley seam). Periods of maximum coal development were characterized by the following features.

Late-Middle to Upper Eocene Sequence Cycles TA3.5 to TA4.3 (42.5 to 36.0 Ma)

Paleolatitudes for the southern Australian coastline at this time were between 55 and 60°S using sea-floor spreading reconstructions (Veevers, 1986). Paleotemperatures were initially warm (>20°C mean annual as indicated by O^{18}/O^{16} ratios) but variable compared to the previous elevated Paleocene temperatures (Bowler, 1982; Truswell and Harris, 1982). Estimated annual mean temperatures for the middle Eocene in southern Australia based on the existing palynoflora were at least 17–18°C or warmer, with a mean annual precipitation of at least 1500 mm (Sluiter, 1991). Evidence for the earliest appearance of Antarctic glaciation occurs in the late middle Eocene, and is considered to be the result of the progressive thermal isolation of Antarctica due to the opening of oceanic passages between Antarctica, Australia, and South America. This enabled the development of strong, upper sea-surface circum-Antarctic circulation (Domack and Domack, 1991; Macphail et al., 1993; Zachos et al., 1993). Deep-sea circulatory patterns could not occur until the rupture of the South Tasman rise in the Oligocene (Royer and Rollet, 1997). The widespread coal swamps along southern Australia suggest high precipitation (higher than today), which increasingly resulted from the influence of rain-bearing westerly winds triggered by the newly forming circum-Antarctic current (Berggren and Prothero, 1992).

By the late Eocene, microthermal to mesothermal rainforest flora were established in southern Australia (Carpenter and Pole, 1995). This vegetation pattern equates to paleotemperatures of 15–21°C (Carpenter and Pole, 1995). This cooling trend culminates in the earliest glaciation on the Australian continent in the earliest Oligocene (Macphail et al., 1993).

The tectonic regime of the Australia-Antarctica rifting is seen to change at sea-floor spreading anomaly 19 when global plate reorganization occurred in response to India–Asia collision (McGowran, 1989). Widespread "Khirthar" transgression followed in the upper part of foraminiferal zone P12, correlating to the late part of sequence cycle 3.4 (the Wilson Bluff transgression), or the transgressive systems tract of the following sequence cycle TA3.5 (the Tortachilla transgression). The interpreted position for commencement of coal deposition of the lower *N. asperus* zone (typified by the T2 sequence in the Gippsland Basin) begins with the Tortachilla transgression (sequence cycle TA3.5). Coal deposition was associated with the middle and upper *N. asperus* late Eocene events of the Tuketja transgression (TA4.1) and includes the Esperance coals of Bremer. The Tuit transgression (TA4.2) is typified by the T1 coals of Gippsland, and the Aldinga transgressions (TA4.3/4.4) are typified by the T0 coals of Gippsland and Murray. In the Gippsland, Torquay, Otway, and Murray examples, the thicker coals appear to have formed during the highstands and have erosional sequence boundaries on top. In contrast, the St. Vincent and Bremer basins have thinner coals mostly formed in the early transgressive systems tracts. All of these coals appear to associate with a series of rapid rises and falls in sea level immediately preceding the widespread cooling as determined from the oxygen isotope record at the Eocene–Oligocene boundary (Shackleton, 1984). Widespread coal development did not occur for another 15 m.y., except within the Latrobe Valley and Alberton embayments of the Gippsland Basin (M2 and M1B sequences of cycles TA4.5 and TB1.4). Elsewhere, widespread marine carbonate sedimentation dominated the intervening major transgressive periods across the other southern Australian basins, suggesting rapid increases in accommodation space exceeded peat accumulation rates (see Figure 3).

Late-Lower to Early Middle Miocene Sequence Cycles

Brown coals of the Haq et al. (1988) TB2.1/2.2/2.3 (15.5–21.0 Ma) sequence cycles are mainly confined to the eastern basins in southern Australia (e.g., Gippsland and Port Phillip) but are widespread in other parts of the world, such as in the New Zealand Southland Lignites (Isaac and Lindqvist, 1990) and the large German Lower Rhine and Lower Lusatia brown coals (Hager, 1993; Standke et al., 1993). Brown coals also appear to concentrate along specific paleolatitudes. Southern hemisphere brown coals generally occur between latitudes 40 and 50°S, using the sea-floor spreading reconstruction by Veevers (1986). Northern hemisphere brown coals appear to occupy similar paleolatitude zones between 40 and 50°N, using the paleogeographical reconstruction for continental positions (Smith et al., 1981; Wolfe, 1985).

Paleotemperatures were warmer than temperatures at present, as indicated by O^{18}/O^{16} ratios, palynofloras living in the peat swamps, and incursions of tropical foraminifera into the adjacent marine environments (Shackleton and Kennett, 1975; Bowler, 1982; Truswell and Harris, 1982; Li and McGowran, 1994; and Sluiter et al., 1995). Estimates using BIOCLIM© paleobotanical profiles of Gippslands early–middle Miocene coal seams indicate a climate with the following attributes: (1) mean annual temperatures averaging 19°C, (2) mean minimum monthly and maximum monthly temperatures averaging 8 and 28°C, respectively, (3) mean annual precipitation averaged 2000 mm, and (4) mean minimum monthly and maximum monthly precipitation averaging 60 and 400 mm, respectively (Sluiter et al., 1995).

A rapid increase in the ^{18}O isotope ratio in the middle Miocene has been interpreted to be a result of a major growth in the size of the West Antarctic ice sheet (Shackleton and Kennett, 1975; Abreu and Anderson, 1998). This event appears to immediately follow the main coal-forming periods when ice sheet cover was comparatively low. Oxygen isotope data indicates that prevailing warmer water temperatures immediately preceded the middle Miocene cooling (Savin et al., 1981), when sea level was high (Haq et al., 1988). Bottom sea currents and circum-Antarctic circulations had become well established by the Oligocene, with the rupture of the South Tasman rise from Antarctica (Kennett et al., 1975; Royer and Rollet, 1997). The late early to early middle Miocene covers the apogee of the Miocene oscillation, which is often referred to as the middle Miocene climatic optimum (Li and McGowran, 1994).

The three coal-bearing cycles associated with the middle Miocene climatic optimum are separated by major sequence boundaries registering significant falls in sea level. They are also accompanied by regional erosion between seams along the interseam surfaces, such as the erosion boundary between Yallourn and Morwell seams in the Latrobe Valley (Holdgate, 1996), which correlates to canyon cutting in the offshore Gippsland Basin (Bernecker et al., 1997). Megafloral differences occur between seams of different cycles, for example, aseasonal closed canopy forests of the Morwell seams vs. the seasonally changing sclerophyll shrublands of the Yallourn seam with its accompanying influence of fire (Blackburn and Sluiter, 1994). Faunal changes also occurred in the contemporaneous marine carbonate sediments. The appearance of larger benthic foraminiferal in the N7 zone of the Gippsland Limestone (M1A sequence) is thought to signify warming accompanying global oceanic changes (Li and McGowran, 1994) and increased offshore carbonate depositional rates (Bernecker et al., 1997).

The three coal-bearing cycles coincide with commencement of a worldwide depletion of ^{13}C known as the Monterey carbon isotope excursion (Vincent and Berger, 1985). During this period, there was excess removal of organic carbon over and above the normal carbon cycle into sediment accumulations. This depleted the ocean atmosphere of carbon dioxide, thereby inducing the following cooling period in the middle Miocene by a reverse greenhouse effect (Berger and Vincent, 1986).

The Vincent and Berger (1985) calculations indicate that some 1500 billion m^3 of carbon became tied up in the Monterey Formation around the Pacific margins. Calculations of the total volume of carbon stored in the onshore Gippsland Basin indicate that an additional 15% could be added to this total from the contained coal seams, excluding carbonaceous sediments, from the estimated resource figures of nearly 400 billion t (Gloe and Holdgate 1991). Further large reserve figures for carbon could be calculated for the other brown coal and lignite deposits in Australia and overseas.

Although the carbon removal was considered only in terms of the marine Monterey Formation and its equivalents around the Pacific basin margins (Berger and Vincent, 1986), the tying up of carbon into widespread major brown coal deposits also would have added significantly to this depletion. Other coastal plain brown coal deposits formed at the middle Miocene climatic optima around the world, as in, for example, New Zealand (the Southland Lignites) and Germany (the Rhine Graben and the Lower Lusatia deposits). These also are timed within the Haq et al. (1988) sequences TB2.1–2.3 (Isaac and Lindqvist, 1990; Hager, 1993; Standke et al., 1993; Holdgate, 1997) and would add substantially to the carbon removal at this time.

Following the coaly accumulations of cycles TB2.1–2.3, further coastal plain coal developments occur only sporadically in the geological record and are absent from the southern Australian basins. The eustatic record, together with the other climatic indicators, records the progressive decrease in temperatures into the late Neogene, a change from a greenhouse to an icehouse world, and the consequent decline of conditions favorable to thick brown-coal deposition.

Depositional Setting and Mechanisms Favoring Thick Tertiary Brown Coal Accumulations

Bohacs and Suter (1997) have detailed fundamental controls on coaly rocks in relation to sequence stratigraphic principles. In their interpretation for paralic settings, sizable coal seams can form only when an increase in accommodation equals the production rate of peat, such as during middle lowstand and highstand systems tracts. In tropical climates, thick modern-day domed peats of coastal Indonesia have accumulated up to 20 m of peat in the last 6000 yr (a highstand), mostly above standing water, and are still growing (e.g., Esterle et al., 1989; Staub and Esterle, 1994). In regard to regional base level, these ombrogenous or domed peats thus can exceed (temporarily) accommodation space, relying on rain feed and nutrient supply from underlying peat layers and localized perched groundwater tables (Winston, 1994); therefore, we have looked toward the modern Indonesian examples in terms of their thickness, extent, and depositional rates for a useful analog to many of the thick Australian Tertiary brown coals. The Indonesian peats are forming during a highstand, and it appears that many of the Australian brown coals also relate to early highstand, aggradationally stacked shorelines.

The observed brown-coal lithotype cycles on parasequence-type scales suggest that the basic Australian brown coal seam consists in most cases of one or more stacked lightening-upward lithotype cycles, each cycle averaging between 12 and 15 m of coal. By analogy to Indonesian peats, these could form in approximately 20,000 yr. Accommodation rates play a significant part, but the coal lithotype cycling itself could be controlled by at least two other factors: (1) progressive upward (largely rainfed) ombrogenous growth followed by ultimate nutrient starvation, high acidity, and subsidence of the domed surface and (2) an overriding climatic cycle, such as may be induced on peat swamp developments by Milankovitch (forcing) cycles. The degree to which either of these scenarios could influence the brown coal/lignite cycles is difficult to determine without further detailed analysis. Without this cycling, however, with its implied interruptions to the peat-forming processes, it is difficult to see how such large thicknesses of original peat (perhaps 2.5 times the brown coal) could accumulate continuously to form brown coal seams over 100 m thick.

Coal lithotype cycles of comparable thicknesses can be recognized in the Latrobe Valley, Alberton, Bacchus Marsh, Altona, and Anglesea and may be present in the other deposits were they to be examined in detail. Thick seam development appears to be governed by the number of lithotype cycles that can be vertically stacked in the one area. For example, five cycles are recognized within the 100-m-thick M1B seam in Gippsland, whereas two cycles make up the 30 m Maddingley seam at Bacchus Marsh. With compaction and coal rank increase, the cycle thickness reduces. For example, in Anglesea, where the coal has a moisture content 20% less than the coal in Gippsland, the cycle thicknesses have reduced to average 6–7 m.

The propensity for continued coal cycle development and cycle stacking into one area without significant intervention of interseam sediment incursions appears to be a characteristic of the onshore Gippsland Basin, and in particular the Latrobe Valley; however, cycles in coal occur intermittently at some time within some of the other basins, e.g., Alberton (A seam), Bacchus Marsh/Altona (Maddingley seam), and Anglesea (A group seam). In the Latrobe Valley, Alberton, Bacchus Marsh/Altona, Kingston, and Bremer coal basins, long-standing or stacking of barrier systems at the entrance to grabens/paleovalleys is considered to be an important factor in isolating the coastal peat swamps from the more destructive marine sediment incursions.

On the Haq et al. (1988) coastal onlap curves, preservation of southern Australian brown coal seams appears to be enhanced where there is a succession of rapid oscillations in sea levels over short (1 m.y.) time periods. It also corresponds with periods of relatively high coastal onlap (e.g., the late middle to late Eocene and the late early to early middle Miocene). Abundant coals are also common in similar rapidly oscillating high coastal onlap lower Eocene cycles (TA2.2 to TA2.9) in the deeper offshore Gippsland and Bass basins (Brown, 1975; Baillie and Bacon, 1989; Baillie, 1992). Rapidly oscillating periods with relatively low coastal onlap (e.g., Pliocene–Pleistocene) are less prone to the preservation of coal, as are longer (2–3 m.y. duration), more stable sea level periods of high coastal onlap (e.g., early Oligocene and early lower Miocene). The latter condition appears to correlate with marine carbonate deposition across the whole basin with some exceptions in Gippsland (e.g., M2 and M1B sequences)

We suggest that relatively high, frequently oscillating sea levels promote rapid peat growth during highstands and short restricted erosive periods during sea level fall, followed by rapid transgressive burial by shaly sediments, then renewed peat deposition. We believe the southern Australian brown coal record supports this, with the thicker coals occurring during the highstands, and thinner (and higher ash) coals occurring during lowstands and transgressive systems tracts. Rapid turnaround, rapid coastal onlap, and rapid burial enhance the preservation potential and reduce the time for exposure to oxidation of the peat swamps. Frequent sea level oscillations also promote coal seam cycle stacking in the one place, leading to thick coal development.

CONCLUSIONS

Comparing the Tertiary brown coal deposits in southern Australia to the Gippsland Coal Measures from the viewpoint of stratigraphy, timing, paleogeographical and paleoclimatic setting, the following points of similarity can be made about all coal deposits.

(1) A concentration of major coal-forming phases into relatively short periods (0.5–1.0 m.y.) within the full Tertiary time range.

(2) A close relationship of the major coal-forming phases to the peak periods of coastal onlap (Haq et al., 1988), where sea levels were relatively higher than for other periods in the Tertiary, particularly near the end of the middle Eocene, late Eocene, and around the early middle Miocene boundary.

(3) Many of the coal deposits formed in grabenlike embayments or in paleodrainage lows adjacent to the major basinal developments. They were barred from the main marine basinal sedimentation by stacked barrier sand buildups across the entrance, effectively isolating the peat swamps for periods up to 1.0 m.y. from significant long-standing marine transgression.

(4) From those deposits that can be examined in detail (e.g., Gippsland/Alberton, Bacchus Marsh/Altona, and Anglesea), evidence for parasequence cycling can be shown through their coal lithotypes and sulfur distributions. These findings suggest that the near-coastal peats experienced short duration marine incursions (overtopping of the barriers?) exhibited at parasequence boundaries.

(5) Common warm temperate to subtropical paleoclimatic palynofloral components show affinities between the brown coals and the modern tropical peats in Indonesia despite the high paleolatitudes at the time (Wood, 1981; Carpenter and Pole, 1995; Sluiter et al., 1995).

Considering these implications, the correlation of thick coal-seam development to specific time intervals on the Tertiary coastal onlap curves (Haq et al., 1988) provides the most important new findings of this study. These findings provide a mechanism linking coal seam formation and depositional setting to eustatic changes and related climatic changes through the Tertiary. In turn, this approach goes a long way toward satisfying the eustatic criteria of "demonstrated synchronous responses on two or more separate basins and continents" (Dott, 1992, p. 2).

Equally important, our method provides evidence that some Tertiary periods were better disposed to the development and preservation of thick coal seams (e.g., the late middle and late Eocene and the late early to early middle Miocene). Other time periods of the Neogene appear to be poorly disposed toward coal formation either due to lowered sea levels, marine flooding, or climatic deterioration.

Knowledge of timing and disposition of Tertiary coals (as potential petroleum source rocks) provides useful information to the petroleum explorationist regarding coaly source rock distribution through time.

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