Geological processes that control lateral and vertical variability in coal seam moisture contents—Latrobe Valley (Gippsland Basin) Australia

Guy R. Holdgate

School of Earth Sciences, The University of Melbourne, Victoria 3010, Australia

Received 1 January 2004; received in revised form 1 January 2005; accepted 6 February 2005
Available online 20 April 2005

Abstract

A study throughout the Latrobe Valley coal measures of coal moisture distribution using downhole bore data and 3D digital models of large bore data sets indicates lateral and vertical moisture variability is controlled by a number of factors. These include burial, type of overburden, age of the seam, marine influence, coal lithotype and lateral compression on folds and monoclines. The same rules appear to apply to the adjacent Alberton coal measures in the south Gippsland Basin, suggesting these factors may be widespread in other brown coal basins where moisture contents are still equilibrating through differential compaction.

In Gippsland average moisture down seam decreases by 1–2% per seam and at a rate of approximately 1% every 20 m. Weight average moisture content for each seam decreases on average at a rate of 0.5% every 1 million years. A stepwise decrease in moisture content between the ~100 m thick major seams of 1–7% reflects large intervals of time are represented by the relatively thinner (1–10 m thick) interseam sediments. Compression by monoclinal folding can decrease moisture contents up to 7%. For any given depth, moisture content appears higher on anticlines due to a lowered intensity of compression than in adjacent synclines. It is considered likely that coals folded over anticlines are more fractured, thereby containing greater amounts of free water.

Use of the lower moisture coals and monoclinal coals may be preferable for future power station developments. Despite an increase in overburden/coal ratios, there would be significant savings in a lowered coal volume to calorific value, and a consequent reduction in greenhouse gas emission.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Moisture content; Brown coal; Greenhouse gases; Latrobe Valley; Australia

1. Introduction

Coal seam moisture in brown coals plays a significant role in the use made of these coals; it affects the volume of coal required for a given power
output in power stations, the calorific value of the coal, and the emission of greenhouse gases (Murray and Evans, 1972). Previous work on the moisture content of Gippsland Basin’s Latrobe Valley brown coals has largely omitted geological influences, concentrating more on localised variability within the scale of the individual open cut mines (e.g. Higgins et al., 1980; Brockway et al., 1983). Studies on brown coal moisture changes as a function of depth of burial can now be updated more regionally and improved with more comprehensive data. The earliest papers dealt with open cut mines of the time such as Yallourn and Yallourn North (e.g. Edwards, 1945, 1947). The effects of folding on moisture were also investigated mainly in the Yallourn area (Edwards, 1945, 1948). Petrographic (lithotype) effects on moisture were first quantified by Edwards (1945), and later in more detail by Allardice et al. (1978), Higgins et al. (1980), Hibbert et al. (1981), King et al. (1983), Gaulton (1985), and Gaulton et al. (1992). However a regional appraisal of lithotype distributions was never incorporated in these studies. Research on other factors effecting moisture content such as age of seam, overburden composition, relative abundance of wood, and geothermal gradients have not been undertaken before.

Historically, Gippsland’s brown coal open cut developments have concentrated on the shallowest higher moisture coals located on anticlines due to their earlier exploration and ease of exploitation. Discovery

Fig. 1. The Gippsland Basin of southeastern Australia, location and geological setting. Also showing the main coal and petroleum fields.
of large lower moisture coalfields such as Gormandale, Stradbroke and Longford post-date the development and delineation of the Yallourn–Morwell–Loy Yang area (Fig. 1). Therefore this project aims to determine the major factors that contribute to coal seam moisture variability both vertically and laterally across the Latrobe Valley-type brown coals. In the process it will address the important question of potential greenhouse gas emissions and the viability of burning lower moisture coals to reduce these emissions.

2. Latrobe Valley brown coals and their geological setting

The Gippsland Basin and its most westerly extension as the Latrobe Valley of southeastern Australia occupies the premier position with regard to the scale and size of its contained brown coal 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, 1980). 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 (Holdgate, 1985). Where some of these seams occur in vertical stratigraphic superposition, they can form over 400 m of continuous low ash coal (SECV drilling records).

A succession of marine carbonate limestones and marls (the Seaspray Group) accumulated as a facies equivalent to the Yallourn and Morwell Formations, and covers 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 non-marine coals and interseam sediments, and the marine carbonates (Holdgate et al., 1995). Only the older coal seams of the Traralgon Formation pass beneath the Seaspray Group and occur over most of the onshore area (Fig. 2).

In the main part of the basin the oldest T2 seam is constrained to the Seaspray Depression and Baragwanath Anticline by erosion beneath the Latrobe Unconformity—a late middle Eocene uplift and truncation event that stripped the Eocene coal measures in the offshore part of the basin (Holdgate et al., 2003). Elsewhere in the Latrobe Valley Late Eocene to Middle Miocene coal measures are largely conformable with some local erosional disconformities. All the coal seams then underwent a major period of folding, uplift and erosion in the Late Miocene timed at around 10 Ma (Dickinson et al., 2001, 2002). Subsequent burial on anticlines of this eroded subcrop surface takes place under 10–20 m thick outwash fan deposits of the Pliocene Haunted Hill Formation. As a consequence the basin margins, central Loy Yang Dome and Baragwanath Anticline possess coals readily accessible for large-scale open cut developments. A maximum burial of 200 m in the central synclines means coal in these areas are less favored for open cut development (Fig. 3).

The period of folding and erosion at 10 Ma is referred to as the Kosciusko Uplift and was brought about by changes in relative motion and forces at the boundary between the Australian and Pacific Plates, pressure along the New Zealand, New Guinea and Himalayan collision boundaries (Coblentz et al., 1995; Dickinson et al., 2001). The compressional regime that now characterizes the Australian continent resulted in reactivation of older structures as features of compression. In southeast Australia the regional stress field is orientated E–W to WNW–ESE (Tokarev et al., 1998) which is consistent with the ENE–WSW orientation of the Early Cretaceous highs, the reverse faults that bound them and the Tertiary monoclines across which the coal seams are draped.

Brown coal lithotypes in the Latrobe Valley refers to coal-banding visible in air-dried coal, usually seen where moisture losses of ~2–5% occur in the top few centimeters of the open cut faces. Air drying brown coal brings out a layering effect in the coal, characterized by variations in colour, texture, gelification and shrinkage weathering patterns. Individual layers may be sharply bounded or gradational, and vary from 0.2 m to 5.0 m in thickness. 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.
In brown coal, various classifications exist 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, lignitic into medium dark and dark, and pollen coal as the pale lithotype. When going 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. Maximum gelification occurs in the regional

<table>
<thead>
<tr>
<th>Layer</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower sequence</td>
<td>Unconformity</td>
</tr>
<tr>
<td>Middle sequence</td>
<td>Unconformity</td>
</tr>
<tr>
<td>Upper sequence</td>
<td>Unconformity</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>Unconformity</td>
</tr>
<tr>
<td>Permian</td>
<td>Unconformity</td>
</tr>
<tr>
<td>Triassic</td>
<td>Unconformity</td>
</tr>
</tbody>
</table>

Fig. 2. Diagrammatic cross-section showing the main Latrobe Valley Group coal measures, facies and their correlation to the Seaspray Group marine formations. Also shown are the ages of the main sequences based on marine fossils (foraminifera), palynology, and sequence ages. Inset shows location of cross-section (Carter, 1958; Stover and Partridge, 1973; Abele et al., 1988; Haq et al., 1988).
dark lithotypes suggesting their deposition in relatively wetter and anoxic environments (Holdgate et al., 1995).

The main coal forming formations of the Gippsland Basin include from the oldest.

2.1. Traralgon Formation

This is the oldest Tertiary Formation that includes useful economic accumulations of brown coal. It is Middle Eocene to Early Oligocene in age. Where the formation subcrops below the Pliocene Haunted Hill Formation along the basin margins economically winnable coal seams can be found. Uplift along the Baragwanath Anticline block has brought the deeper coal seams near-to-surface. Such areas include all the major coalfields along the Baragwanath Anticline (Gormandale, Willung, Holey Plains, Coolungoolun, Longford Dome, Stradbroke, Boodyarn, and Won Wron) and also on the Loy Yang and Gelliondale Domes (Fig. 1). Calculated economically recoverable reserve figures for these fields total 10 Gt, but currently no Traralgon Formation coal has ever been mined. The Traralgon Formation coal seams are subdivided from the youngest into the Traralgon 0 (T0), Traralgon 1(T1) and Traralgon 2(T2) seams. The T1 seam at Gormandale, Flynns 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. Near the Pliocene subcrop the Traralgon Formation seams contain, with some exceptions, the lowest moisture content (average 55%) for any Gippsland Basin coals, but with deeper burial or folding, moistures below 45% can be found.

In the Seaspray Depression a number of Traralgon seams aggregate up to 150 m of coal in places (Figs. 1 and 2), but little is known of their quality. Here, the overlying limestone cover varies between 100 and 700 m in thickness. The only fully cored section in which the coal was analysed is from Wulla Wulloch-7 (WW-7) bore, where the seams between 500 and 700 m averaged 47% moisture (Fig. 4). A few samples analysed from deeper oil wells indicate similar coal qualities with respect to ash yield, but as is to be expected, are higher in rank, i.e. bed moisture content may be as low as 30%. The coal resource in the Seaspray Depression is estimated to

---

Fig. 3. Location map for cross-sections in the Latrobe Valley (Figs. 8–13, 18, 20). Also shown are the main coalfields subcrop area and the boundaries for the 3D digital model.
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.

2.2. Morwell Formation

The Morwell Formation consists of a complex unit of thick coal seams that disconformably overlie the Traralgon Formation in the Latrobe Valley Depression. The Morwell Formation is confined to that part of the onshore Gippsland Basin west of the maximum point of marine transgression for the Seaspray Group (Fig. 2). The oldest Morwell 2 seam attains a maximum thickness of 140 m in the area between Maryvale and Glengarry, and at shallow subcrop along the Yallourn Monocline was mined in the past at Yallourn North and Extension Open Cut Mines (Fig. 3). At Loy Yang the total coal seam interval occurs as three splits known as the Morwell 2A, 2B and 2C seams. Here they aggregate over 80 m of coal. They are currently mined at Loy Yang. The Morwell Formation coals where mined range between 60% and 63% moisture content, but where deeper buried in the Traralgon Syncline (e.g. M3047—Fig. 4) moistures below 50% may occur.

The Morwell 1B seam has wider extent and overall greater thickness than any other seam in the Latrobe Valley Depression, covering some 650 km², reaches a maximum thickness of between 100 and 120 m where it is mined in the Loy Yang Open Cut Mine. 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. 3), and is currently being mined in the Morwell Open Cut Mine. 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 is up to 80 m thick. East of Rosedale the Morwell 1A and 1B seams grade laterally into Seaspray Group barrier sands of the Balook Formation (Figs. 1 and 2).

2.3. Alberton coal measures

In the South Gippsland area occurs the Alberton coal measures. These are not directly connected to the
Morwell Formation in the Latrobe Valley due to uplift and erosion on the intervening Baragwanath Anticline. However they are of the same age and grade eastwards into the marine Seaspray Group (Holdgate, 1982). The coal deposits at Alberton (Fig. 1) contain an upper A seam (55 m thick) and a lower B seam (15 m thick). They average 60% moisture.

2.4. The Yallourn Formation

The Yallourn Formation is the youngest coal-bearing formation in the Latrobe Valley and is Middle Miocene in age. In a similar manner to the Morwell Formation, which it conformably overlies, the Yallourn Formation grades laterally eastwards into barrier sands (Balook Formation) of the Seaspray Group. The Yallourn Seam is currently mined in the Yallourn, Yallourn East, and proposed Maryvale Open Cut Mines. In Maryvale there is a continuous seam up to 100 m thick (Fig. 3). Because of its younger age and shallow depth of burial, the Yallourn Seam averages 65–67% moisture content where it is mined at Yallourn Open Cut. In the Traralgon and Latrobe Synclines, the seam can be buried by up to 200 m of younger Hazelwood and Haunted Hill Formation clays and as a consequence the moisture content may reduce to below 60% (Fig. 4).

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. Most of the brown coal deposits in the Latrobe Valley were delineated by the end of the 1950s. Discovery of newer fields outside the Latrobe Valley Depression, such as Gormandale, Stradbroke, Alberton, Moe, Yarragon and Longford, occurred since the 1960s but by this time open cut developments had become focussed within the Latrobe Valley. Proving drilling on a grid basis of 400 m or less was undertaken in defined coalfields. Coal core was sealed, composited by crushing and separation to provide for in situ moisture and ash analysis on 3-m basis, inorganic and mineral ash definition on 6-m basis, and a proximate and ultimate analysis on 12-m basis. Detailed coal quality analyses of many hundreds of bores are available from the coal quality database (former SECV) that contains the results of over 140,000 sample analyses. This paper will be the first to study the geological controls on the moisture data. This is important since it will allow a reassessment of priorities for alternative and future brown coal developments in the region.

3. Moisture content, definitions and data collection

Volumetrically water is one of the most important constituents in low rank coals. In the peat stage water contents may reach up to 90% (George and Mackay, 1991). As coalification proceeds moisture content decreases to about 60–65% for lignite B—Latrobe Valley coals (Figs. 5 and 6). As moisture decreases further through the lignite A to sub-bituminous ranks volatile matter also decreases. When bituminous ranks are reached moisture content becomes static at around 10% but volatiles continue to decrease through to anthracite ranks.

An extensive brown coal moisture data set of over 140,000 sample analyses is available throughout the Latrobe Valley (Allardice and Evans, 1971). This includes vertical profiles in bores and open cuts of bed (in situ) moisture contents, ash and volatile matter. This database is used in the current open cut mines to predict boiler performance (which is affected by changes in moisture and calorific values). For this paper the composited 3 m interval moisture data in some 8000 bores was used to establish regional trends. This significantly improves previous figures quoted for individual coalfields as weighted averages for the main coal seams, or in coal zones (e.g. Gloe, 1980).

By definition water-in-coal is the water present as water molecules (H₂O) which can be released at 105–110 °C by oven drying. This moisture occurs as: (i) free water; (ii) water of decomposition; and (iii) water of hydration (Law et al., 1983). Free water occurs in fractures and macropores and is easily released at low temperatures. Water of decomposition is most abundant in low rank coals and is bound to the oxygen containing functional groups (–OH, –COOH, –C–O) by hydrogen bonding. It is released along with CO₂ at temperatures <100 °C (Allardice and Evans, 1971; Murray and Evans, 1972). As coal rank increases there is a loss of functional groups and consequent loss of associated water of hydration. Between the three states, water is lost in a continuum. It has been found that for Victorian brown coals where moistures...
are greater than 40%, the moisture holding capacity (as used in some brown coal basins) is substantially lower (by > 20%) than the bed moisture content (Figs. 5 and 6). Therefore moisture holding capacity is not a suitable parameter for the characterization and classification of such low rank coals (Perry et al., 1984). The moisture analysis from which all the data for this paper is derived measures bed moisture content. This method uses two Standards Association of Australia Procedures (1984a,b, 1986) - (Allardice, 1991). AS 2434.5 (1984b) covers azeotropic distillation in toluene for moisture determination in bulk samples of brown coal. AS 2434.7 (1986) involves oven drying in nitrogen at 105–110 °C of the brown coal “analysis sample”, with the moisture collected in an absorption tube containing magnesium perchlorate. A fully automated microprocessor controlled equipment (e.g. LECO MAC-400) is mainly used to obtain moisture, volatile matter and ash yield in a single determination.

4. Methods

Downhole moisture trends were plotted from 3 m composite samples and are presented in Figs. 4 and 7. This illustrates the traditional method of presenting coal quality data in the Latrobe Valley, and is referred to as flag diagrams. Additional methods used in this paper comprise interpretation of cross-sections from a block model of 3D computer-based data sets. Moisture data from 8000 bores on a 200 m grid have been built into a regional Latrobe Valley geological model (VIMP, 2003). The roofs and floors of each seam over an area of 1100 km² were interpreted from the GIS layers and their structure presented in ArcView and MapInfo format (Fig. 3). Block models of the coal resource and coal quality for 16 parameters can be presented in a three dimensional form, and blocks of 160 × 160 × 12 m can be queried to show single or combined parameters. For this study a series of regional north–south and east–west moisture sections were produced and correlated to the known geological cross-sections along the same lines (Figs. 3, 8–11). From the block models a series of moisture isolines could be drawn to depict moisture variability across the whole Latrobe Valley. Where data coverage in the deeper parts of the basin is poor, extrapolation of

Fig. 5. (A) The different stages of coalification (modified from Stach et al., 1982) showing location of the Latrobe Valley brown coals in relation to Australian, German and USA coal rank parameters. (B) Proximate coal analysis showing coal rank versus fixed carbon, volatile matter and moisture content (modified from Law et al., 1983).
Fig. 6. The basic properties of Latrobe Valley brown coals showing their chemistry, physical chemistry and petrology.
moisture contents below 55% was undertaken by hand from the few bores available.

5. Results

Using the downhole moisture profiles and the computerized 3D block models the following features appear to govern the lateral and vertical variability in Latrobe valley moisture contents.

5.1. Simple burial effects on moisture

In the Latrobe Valley the first description of burial effects on moisture are by Edwards (1945, 1947) who described a typical Latrobe Valley moisture profile of downhole decreasing moisture values varying from 0.5% to 1.0% every 30 m. With more data as presented in Figs. 4 and 7 a figure of 1% every 20 m seems to be more accurate although the variability is between 0.4% and 1.1% every 20 m. However a consistent moisture decrease with depth is not present in Latrobe Valley Coals and indeed may be comparatively rare (Figs. 4 and 7). Most of Edwards’ (1945, 1947) examples came from the structurally higher areas such as Morwell, Yallourn and Loy Yang where moisture in sequential thick seams tends to be more consistent. (e.g. Loy Yang-546 in Fig. 7). An example of moisture change with depth and lithotype from the central Latrobe Valley Syncline is shown by bore M3047 in Fig. 4. In this case moisture does not decrease regularly but markedly decreases across the major seam boundaries. This pattern occurs across much of the central Latrobe Valley.

The weight averaged whole seam moisture contents (Figs. 4 and 7) decreases between 1% and 2% below major seam boundaries irrespective of burial depth, but within split seams, moisture content tends to remain constant. This pattern is best explained if all the coal seam splits from one major seam accumulated

---

Fig. 7. Latrobe Valley coals—west to east section from Loy Yang to Rosedale showing downhole moisture profiles, gradients, moisture isolines, coal seam stratigraphy and sequence boundaries.
over a comparatively short time period whereas between major seams there are comparatively long time breaks allowing coalification jumps.

5.2. Burial effects from overlying sediments on moisture

The interseam sediment thickness overlying each seam appears to have an influence on moisture content. For example in Fig. 7 moistures tend to be higher and show a more regular downwards decreasing moisture gradient, where successive thick seams overlie each other such as at Loy Yang. In contrast where thick sediment (clay–sand) interseams overlie or interbed with coals, moisture is substantially decreased for the same depth of burial, such as the R325 bore in the Traralgon Syncline. Moisture values in these areas appear to show a

![Diagram of geological cross-section between Latrobe River and south of Churchill showing coal moisture isolines as determined from 3D digital data.](image)
lower gradient profile down seam (Fig. 7). This reflects the greater weight per volume of clay–sand sediment (approximately twice that of the coal). The sandy marine sediment ingressions at the eastern end of the Latrobe Valley also have this effect on seam moisture content. For example for each seam, moistures decrease 3–4% laterally without significant changes in burial depth. An example of this is the coals immediately underlying the M1A and M1B aquifer sands (Fig. 12). A second pronounced example occurs below the Yallourn Open cut area between the Morwell and Latrobe Rivers (Figs. 8 and 13). The northerly trend in interseam thickness above the M1B and M2 coal seams progressively decreases the moisture content of these seams irrespective of seam depth. This effect is localised to coal seams below the sediment wedge, and the overlying Yallourn and M1A seams show relatively flat moisture isolines.

5.3. Differential compaction effects on moisture

Differential compaction, which by definition must involve moisture (volume) loss, has been considered an important factor influencing the geometry and architecture of the coal depocentres in the Latrobe Valley (Holdgate, 1985). It is also discussed for German brown coals by Hager and Kothen (1981).
Other examples of differential compaction have similarly been recorded in black coals, e.g. Edwards et al. (1944) on Cretaceous Wonthaggi coal; Mallett and Dunbavan (1984) and Johnson (1984) on Permian Queensland black coals. These examples imply moisture and volatile loss must occur during the early stages of differential compaction and coal formation, because after sufficient burial, coalification and time, the less compacted areas have equalized in moisture content. In the Latrobe Valley where coals are still in the lignite stage, equalization is still in progress, consequently areas of the same seam where loaded by more sediment tend to contain lower moistures for the same depth of burial.

To estimate the volume decrease accompanying for example an 11% moisture decrease for M1B seam at Loy Yang (63%) and Traralgon Syncline (52%), the following calculations were made taking the measured specific gravity of dry coal at Loy Yang as being 1.44:

\[
\text{63\% moisture coal} = 630 \text{ g H}_2\text{O} + 370 \text{ g coal}
\]

\[
\therefore \text{volume for } 630 \text{ cm}^3 \text{ is } \frac{370}{1.44} \text{ ml coal}
\]

\[
= 256.94 \text{ ml coal}
\]

For 52\% moisture coal \( \frac{x}{370 + x} = 0.52 \)

\[
\therefore x = 0.52x + 0.52 \times 370
\]

\[
x = 0.52x + 192.4
\]

\[
\therefore 48x = 192.4
\]

\[
x = 400 \text{ g} = 400 \text{ ml}
\]

Fig. 10. East–west geological cross-section between Rosedale fault and Yallourn Fault showing the coal moisture isolines as determined from the 3D digital data. Section below shows the same moisture data presented as a shaded display of moisture intervals. Section takes in the coalfields of Morwell and Loy Yang. For location of cross-section see Fig. 3.
Initial volume of coal at 63% moisture:

\[ 1 \text{ kg} = 630 + 256.9 = 887 \text{ ml} \]

Same coal after compaction = 256.9 + 400

= 656.9 ml

\[ \therefore \% \text{ shrinkage} = \frac{887 - 656.9}{887} \times 100 \]

\[ \therefore \text{ for a change of 63% to 52% moisture a 26% volume decrease must occur.} \]

From the above calculation the volume decrease was calculated for each 5% change in moisture in the brown coal ranks and is graphed in Fig. 14. It was noted that volume decrease diminishes with decreasing moisture, i.e. between 70% and 60% moisture volume decreases 27%, whereas between 60% and 50% volume decreases 23%. For coals below 40% moisture content this moisture-volume decrease is presumed to further reduce until sub-bituminous ranks are reached. At this point moisture losses almost cease, but volatile losses cause further volume decrease (Figs. 5 and 6). Because most Latrobe Valley coals have moisture contents in the 50–65% range...
they lie within the zone of rapidly changing volumes that can make a significant impact on coal volumes required for power station use. Therefore the thinning of coal seams towards the marine boundary in Fig. 12 may in part be due to dewatering volume losses accompanying sediment loading. This volume decrease is supported petrographically in bore R-324 near the marine margin where the coal macerals appear more gellified and compacted, and the liptinite macerals appear more flattened than their equivalents at Loy Yang (Bolger, 1984).

Additional volume decreases to the brown coals over and above moisture loss would also include some small losses of volatiles. Therefore such moisture and volatile changes across the Latrobe Valley can produce volume decreases of more than 20% to the coal as mined in the current open cuts; a fact not considered in the economics of locating new open cut developments where overburden to coal ratio is the primary measure used.

5.4. Regional distribution of moisture for Latrobe Valley coals and their changes through geological time

Table 1 derived from Gloe (1980) gives weighted averages for several coal properties of coal (moisture, ash, volatiles, carbon, hydrogen and derived calorific
value) in the main mining areas of the Latrobe Valley. The table uses only those figures for the shallowest buried coal where the overburden is less than 30.5 m, so that the effects of localised deeper burial are avoided. Locations of the main Latrobe Valley coal-field areas used to calculate the Table 1 values are shown in Figs. 1 and 3. Use of these figures shows the influence of geological age on regional coal properties. The data demonstrates a rank increase with down seam age (Ma) for each field, suggested by a decrease in moisture and volatiles with an increase in carbon content and specific energy.

Seam moisture contents decreases with the age of the seam irrespective of depth. On average there is a

---

**Fig. 13.** North–south cross-section of 3D digital moisture block data between Yallourn North and Morwell mine showing moisture isolines and the effects of interseam thickness variations on underlying coal seams. For location of cross-section see Fig. 3.

---

**Fig. 14.** Plot of moisture (dry basis) against moisture (wet basis) for selected Latrobe Valley coals (see Fig. 6), and the calculated percentage volume losses per each 5% moisture decrease.
decrease in moisture content between the major seams of between 1% and 7% with an average decrease between Yallourn and M1A of 4.8%, between M1A and M1B of 2.7%, between M1B and M2 of 1.8% and between Morwell 2 and Traralgon Seams of 2.7%. This appears to reflect the influence of time has on the coalification process. As losses of moisture presumably continued during the intervening time periods between seam deposition, then abrupt step-like profiles in moisture content occurs across seam boundaries (see Figs. 4 and 7).

If the weight average moisture content for each seam is plotted against seam deposition age, then an envelope can be drawn around the data from the coalfield areas of Narracan, Morwell, Loy Yang and Flynn (Fig. 15). Within this envelope, moisture decreases on average at a rate of 0.5% every 1 million years, although faster than normal coalification appears to have occurred between Yallourn and M1A which are separated by a comparatively short 2 Ma. period. This may be explained by the regional sequence boundary that occurs between the two seams and the possible existence of a thicker interseam sediment package that was eroded during Middle Miocene low stands (Holdgate, 1996).

The M1 and M2 coal seams at Yallourn and Maryvale occur outside this data envelope, and their results appear to suggest a faster rate of moisture decrease at around 2% per Ma. This is due to an increase in the thickness of interseam clays and sands between Yallourn and Morwell seams at Yallourn–Maryvale, compared to the Narracan/Morwell/Loy Yang fields which tend to have very thin interseam splits.

5.5. Marine influence effects on the regional distribution of moisture for Latrobe Valley

In the marine-influenced coals of the eastern part of the Latrobe Valley Fig. 12 shows the variation in moisture laterally along seams using weight averaged data per seam, and Fig. 7 at 3 m intervals for the same section line.

Table 1

<table>
<thead>
<tr>
<th>Area</th>
<th>Seam Age (Ma)</th>
<th>MOIST, % (ar)</th>
<th>Ash, % db</th>
<th>VOL, % db</th>
<th>C, % db</th>
<th>H, % db</th>
<th>NWSE, MJ/kg</th>
<th>GDSE, MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narracan Yallourn 15.5</td>
<td>68.1</td>
<td>1.8</td>
<td>51.8</td>
<td>67.1</td>
<td>4.8</td>
<td>6.3</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>Morwell Yallourn 15.5</td>
<td>66.9</td>
<td>2.6</td>
<td>51.6</td>
<td>65.4</td>
<td>4.7</td>
<td>6.5</td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td>Yallourn Yallourn 15.5</td>
<td>66.6</td>
<td>1.8</td>
<td>51.7</td>
<td>65.9</td>
<td>4.6</td>
<td>6.5</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td>Maryvale Yallourn 15.5</td>
<td>65.6</td>
<td>2.6</td>
<td>51.9</td>
<td>65.1</td>
<td>4.6</td>
<td>6.7</td>
<td>25.9</td>
<td></td>
</tr>
<tr>
<td>Loy Yang Yallourn 15.5</td>
<td>64.4</td>
<td>3.2</td>
<td>51.8</td>
<td>64.6</td>
<td>4.7</td>
<td>7.6</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td>Flynn Yallourn 15.5</td>
<td>66.3</td>
<td>2.7</td>
<td>51.6</td>
<td>65.1</td>
<td>4.7</td>
<td>6.5</td>
<td>25.8</td>
<td></td>
</tr>
<tr>
<td>Narracan M1 18–23</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>
<td></td>
</tr>
<tr>
<td>Morwell M1 18–23</td>
<td>60.9</td>
<td>3.2</td>
<td>49.8</td>
<td>67.1</td>
<td>4.8</td>
<td>8.5</td>
<td>27.3</td>
<td></td>
</tr>
<tr>
<td>Yallourn M1A 18.0</td>
<td>59.6</td>
<td>2.7</td>
<td>51.4</td>
<td>66.0</td>
<td>4.7</td>
<td>8.5</td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>Maryvale M1A 18.0</td>
<td>59.6</td>
<td>3.5</td>
<td>50.7</td>
<td>65.8</td>
<td>4.7</td>
<td>8.4</td>
<td>26.3</td>
<td></td>
</tr>
<tr>
<td>Loy Yang M1A 18.0</td>
<td>63.0</td>
<td>2.3</td>
<td>51.4</td>
<td>66.5</td>
<td>4.8</td>
<td>7.8</td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>Flynn M1A 18.0</td>
<td>64.6</td>
<td>2.2</td>
<td>50.9</td>
<td>66.5</td>
<td>4.7</td>
<td>7.1</td>
<td>26.3</td>
<td></td>
</tr>
<tr>
<td>Yallourn M1B 23.0</td>
<td>54.4</td>
<td>3.4</td>
<td>50.6</td>
<td>66.3</td>
<td>4.7</td>
<td>9.9</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>Maryvale M1B 23.0</td>
<td>56.8</td>
<td>3.0</td>
<td>50.3</td>
<td>67.3</td>
<td>4.7</td>
<td>9.4</td>
<td>26.8</td>
<td></td>
</tr>
<tr>
<td>Loy Yang M1B 23.0</td>
<td>62.5</td>
<td>1.5</td>
<td>51.3</td>
<td>68.3</td>
<td>4.8</td>
<td>8.1</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>Flynn M1B 23.0</td>
<td>62.1</td>
<td>1.7</td>
<td>50.6</td>
<td>67.3</td>
<td>4.8</td>
<td>8.0</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>Narracan M2 31.0</td>
<td>59.3</td>
<td>3.7</td>
<td>48.2</td>
<td>67.9</td>
<td>4.7</td>
<td>8.9</td>
<td>27.4</td>
<td></td>
</tr>
<tr>
<td>Morwell M2 31.0</td>
<td>59.0</td>
<td>3.9</td>
<td>46.9</td>
<td>68.2</td>
<td>4.7</td>
<td>9.1</td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td>Yallourn M2 31.0</td>
<td>56.7</td>
<td>3.8</td>
<td>47.2</td>
<td>68.0</td>
<td>4.7</td>
<td>9.6</td>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td>Loy Yang M2 31.0</td>
<td>61.0</td>
<td>1.7</td>
<td>50.5</td>
<td>69.2</td>
<td>4.9</td>
<td>8.8</td>
<td>27.6</td>
<td></td>
</tr>
<tr>
<td>Flynn M2 31.0</td>
<td>59.3</td>
<td>3.5</td>
<td>49.9</td>
<td>66.8</td>
<td>4.7</td>
<td>8.7</td>
<td>26.9</td>
<td></td>
</tr>
<tr>
<td>Loy Yang T1 37.5</td>
<td>56.4</td>
<td>2.4</td>
<td>49.6</td>
<td>69.4</td>
<td>4.9</td>
<td>10.1</td>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td>Flynn T1 37.5</td>
<td>58.5</td>
<td>2.8</td>
<td>50.1</td>
<td>67.7</td>
<td>4.9</td>
<td>9.2</td>
<td>27.4</td>
<td></td>
</tr>
</tbody>
</table>

Ma=age in millions of years, MOIST=moisture, VOL=volatiles, C=carbon, H=hydrogen, NWSE=net wet specific energy, GDSE=gross dry specific energy, db=dry basis.
Three trends are noteworthy:

(i) Average moisture down seams decreases by 1–2% per seam and at a rate of approximately 1% every 20 m.

(ii) Average moistures for each seam in Figs. 7 and 12 show an overall decrease in an easterly direction towards the marine interface which does not completely correlate to depth of burial, e.g. the values for the Yallourn Seam between Loy Yang and Rosedale decrease from 65% to 57% and the Morwell 2 seam for the same interval decrease from 55% to 45%.

(iii) In Fig. 7 the averaged moisture isolines as calculated from the averaged downhole moisture gradients show (with some fluctuations) an overall rise to the east against dip and depth.

As the easterly direction is towards the marine boundary, it is likely that lateral variability in coal lithotypes is a factor because other effects such as depth of burial, folding, tectonic uplift, weathering or thermal effects appear in this case to be less influential.

5.6. Effects of lithotype on moisture and its relation to marine influence

Fig. 16 demonstrates moisture variations as related to lithotype for the upper part of the M1B and lower part of the M1A coal seams at Loy Yang. Here and elsewhere in the Latrobe Valley the darker lithotypes have higher moisture contents (up to 66% at Loy Yang) than the lighter lithotypes of around 60%. Therefore any degree of lateral variability in the relative lithotype proportions would also influence regional whole seam moistures.

To compare stratigraphically correlatable lithotype abundances in each subseam cycle and thereby evaluate the Latrobe Valley west to east lateral variability, Fig. 17 depicts the cumulative lithotype abundance for the M1/M1A+M1B seams in each coalfield with the figures derived from 6 lithotype bores as indicated.

From west to east, mostly the medium dark and darker lithotypes increase, and the medium light and light/pale lithotypes decrease in relative abundance. This suggests that the increasing marine influence from the east favors the darker coals, which have the higher moisture. This will influence in some cases the eastward trend towards moisture decrease purely as a function of depth and relative weight of overburden material. In contrast the lighter coals occur most often in the west, and this may favor a lowering of moisture in these areas.

In the Latrobe Valley and at Alberton, there is a predominance of both light and dark lithotype end members towards seam margins compared to the dominant medium lithotypes found in the coal depocentres (Mackay et al., 1986). This also would influence seam moisture content by raising pH levels near marine influenced waters, increased bacterial activity, biodegradation and loss of biomass, and adding more bacteria derived lipids to the humic degradation products (Diessel, 1990). In consequence it might be anticipated that marine influence would increase the content of detrovitrinite, detrital bitumen and liptinite, and thereby produce greater amounts of the darker lithotype coals that
contain a relatively higher moisture content. However the influence darker wetter lithotypes have towards the east has apparently been offset by moisture reductions due to increased overburden and interburden sediments (Fig. 12).

From the moisture isolines in Figs. 9 and 11 a localised reversal in the normal downhole moisture decrease is noted and previously commented on by Edwards (1948). This occurs in the Yallourn Seam (Yallourn open cut) between the Morwell River and the Morwell Monocline. This is attributed to the predominance of darker lithotypes towards the base of the seam in this area.

5.7. Compression—folding effects (tectonics) on moisture

In the Morwell–Maryvale–Yallourn North areas Edwards (1945, 1948) cited downhole moisture changes that appeared to show significantly decreased moisture contents to the norm. He attributed this to compression on the Yallourn Monocline. Reduced
moisture on monoclines appeared to be double that expected by depth alone, and for the same seam, moisture increased away from these areas of folding. Higgins et al. (1980) also established that moistures of the M2 (Latrobe) seam at Yallourn North Extension Open Cut varied from 49% on the monocline to 52–56% in the adjacent mine area.

Edwards (1948) also noted examples of moisture trend reversals in the Yallourn Seam, where moisture values increased downwards with depth. This was noted where the seam was folded into the Morwell Syncline. Edwards (1948) explained this by the greater compression occurring in the syncline axis, where the intensity of compression increased in an upwards direction. However this in part is due to the predominance of darker (wetter) lithotypes towards the base of the Yallourn Seam.

The more detailed bore data now available from the 3D model depicts widespread lateral compression tectonic effects on moisture throughout the Latrobe Valley, particularly along the basin margins and on all monoclines. Gradients also vary significantly between synclinal and anticline folds with a decrease in gradients over anticlines and an increase in gradients over synclines. For example the Yallourn and Morwell Monoclines show a pronounced decrease in moisture at the fold with a decreasing gradient away from the fold onto the uplifted block or into the adjacent syncline (e.g. Figs. 10 and 18). In contrast domal structures and anticlines show a decrease in moisture gradient and depressed moisture isolines such as the anticline between Princes Highway and Latrobe River (Fig. 9), at bore M669 in Fig. 18, and at Flynn Railway in Fig. 11.

Compression of coal seams as they are bent across a monocline is most likely the major cause of moisture loss in these areas, i.e. the bending requires some reduction in volume. The relatively lowered gradients across anticlines such at M669 (Fig. 18) are less easy to explain. Edwards’ (1948) explanation of a destressing of the coal seam towards the base of a syncline might work in reverse on anticlines if intensity of compression were to decrease in an upwards direction. This may be attributed to relatively less constraints on folding pressures in the upwards direction (where undercompacted overburden sediments overlie) compared to more incompressible basement sediments below the coal seams. Also coal seams folded into an anticline are probably more openly jointed then in synclines, which in turn would increase the relative abundance of free water in fractures and micropores. SECV drilling records of bores drilled on the crests of anticlines have recorded coal joints filled with drilling mud in cores to at least 80 m depth, suggesting that

Fig. 18. North–south cross-section of 3D digital moisture block data between Yallourn North and Traralgon Syncline showing moisture isolines. The effects of anticline development at bore M669 and folding on the Yallourn Monocline on moisture are also shown. For location of cross-section see Fig. 3.
joints were open in situ. Some anticlines have presented drilling problems when drill fluids have been lost, attributed to the openly jointed nature of the coal (Capital Energy, 1995).

High potentiometric heads in aquifers both within and below the coal seams are well known in the Latrobe Valley, and recharge areas are at higher elevations on the basin margins. Depressurization of aquifers is required in the open cut mines to prevent floor heave (Brumley et al., 1981). The high-pressure waters may readily invade the coal seams where they are more jointed.

5.8. Thermal effects on moisture

Edwards (1945) recognised a localised thermal effect on coals at the Parwan Mine near Bacchus Marsh in the Port Phillip Basin west of Gippsland. This was caused by an overlying basalt layer, which lowered seam moistures. Bolger (1984) considered the lower moistures for the R-324 bore could also be attributable to a high geothermal gradient known to occur in the central Latrobe region (Thompson, 1980; King, 1988). However as the highest geothermal gradients tend to occur in the western ends of the Latrobe Valley where moistures are also the highest (King, 1988), it appears this factor probably has little effect on the easterly decrease in moisture.

5.9. Regional distribution of moisture content in the Alberton coal measures

The weight averaged moisture contents for whole seams and moisture profiles at 3 m intervals (Fig. 19) show the Alberton coal measures follow similar trends to those in the Latrobe Valley. These are:

(i) Moisture content tends to decrease stratigraphically between seams with significant 2–3% jumps across the major seam boundaries, but can remain fairly constant within a seam or sequence.
(ii) Moisture content for each seam decreases eastward across the Alberton Field towards the marine boundary almost regardless of depth of burial (Fig. 19).

(iii) If a moisture content gradient is fitted to the bore moisture profiles, then the moisture gradient is found to decrease downhole at a rate of approximately 1% every 20 m (Fig. 19).

These major effects on moisture occur within contemporaneous but geographically isolated coal basins and suggests such phenomena may be widespread and should occur elsewhere in other brown coal basins.

6. Discussion

From the above data it is clear that moisture decrease with depth of burial in the Latrobe Valley coal seams is not a simple arithmetic progression, rather lateral and vertical variability can be controlled by at least seven different factors. As moisture content in brown coal is the main form of rank determinant then it is important to recognise their extreme sensitivity to different degrees of tectonic, petrographic and burial factors.

The timing of moisture loss appears to be a combination of primary syndepositional effects and post-depositional influences including burial depth, overburden composition and lateral petrographic/coal. These factors all play some part on moisture loss during deposition of the coal seams in an essentially conformable succession, and may take place at relatively shallow burial depths in the peat to coal transition. Intervals of non-deposition and/or localised increases in burial rate or erosion play an additional part in creating moisture jumps across major coal seam boundaries. Factors operating post-depositional include significant tectonic effects produced by folding, uplift and erosion in the last 10 Ma. These are superimposed on the syndepositional moisteres and can add to or subtract coal moiters by up to 5% depending on location. By use of the moisture models it is now possible to examine the whole Latrobe Valley coal measures and predict areas more favorable for lower moisture coals.

The timing of moisture loss going from peat to coal is not well understood. Moisture loss for Holocene peats in the Chatham Islands decreases from 90% at ground surface to 78% at 17m depth, suggesting early moisture losses can occur at the early peat stage. Transition of peat to lignite (brown coal) has been cited as shallow as 6 m according to macroscopic studies by Bloom (1964) or 11 m (Smith and Clymo, 1984). Nadon (1998) also suggests most peat-to-coal compaction occurs essentially at the surface and not at the depths where coalification takes place. Courel (1987) suggests a 3 stage process may be involved—(i) compaction of peat, (ii) compaction of organic matter to lignite, (iii) compaction of lignite to (black) coal. Peat/coal ratios of 1.2:1 to 2.2:1 calculated by Nadon (1998) appear consistent with the compaction/volume changes as calculated within the brown coal range on Fig. 14. It is possible that Fig. 14 values indicate most compaction within the brown coal ranks (the stage 2 process) is by losses changes in the water-of-decomposition, whereas most compaction in peat (the stage 1 process) is by free water losses. However if free water can be re-introduced into the coal during post-depositional open jointing across anticline folds (Fig. 18) then the above staged processes may in part be reversible.

All current open cut mines and any near future developments in the Latrobe Valley are governed mainly by overburden to coal ratios, and are consequently programmed to exploit only the shallowest–highest moisture coals available. Coalfields like Gormandale where the Traralgon Formation seam moisters average 55% are currently not considered (Fig. 20). Yet approximately 20% less by volume of coal would be required to be mined at Gormandale for the same energy output. As this translates directly to the amount of greenhouse gas emissions made then considerable savings are possible. Currently the three operating Latrobe Valley power stations contribute over 50% of the states CO₂ emissions, about 50 Mt or about 0.1% of the global greenhouse effect. This could be reduced some 20% if lower moisture coals were mined. Under the Kyoto Protocol a limiting requirement to growth in greenhouse gas emissions in the 2008–2012 period is no more than 8% above 1990 levels. Therefore developments of any new mines should target the lower moisture coals.
New technologies to artificially reduce moisture are underway but are still in pilot or bench laboratory stages. Pre-drying using mechanical thermal expression could reduce CO$_2$ emissions by 8 Mt/year (16%) by retrofitting the present Latrobe Valley stations at a cost of $9 a tonne (Hopkins, 2000). However none of these technologies are likely to be ready by 2008–2012. In addition Victoria is forecast to need an extra 3000 MW by 2017 (assuming a modest 2% growth rate), most of which will be base load that is best covered by brown coal burning. Therefore the future scenario for the state is a requirement for doubling the generating capacity and therefore doubling the greenhouse gas emissions. Only by taking advantage of the naturally imposed dewatering geological conditions on the brown coals is it possible to meet the emission targets.

7. Conclusions

1. Average moisture down seams decreases by 1–2% per seam and at a rate of approximately 1% every 20 m.
2. Average moistures for each seam show an overall decrease in an easterly direction towards the marine interface which does not completely correlate to depth of burial due to differential compaction, relative changes in lithotype composition and an increase in interseam volume.
3. Seam moisture content decreases with the age of the seam, reflecting the influence of time on the coalification process. On average there is a decrease in moisture content between the major seams of between 1% and 7%.
4. Weight average moisture content for each seam moisture decreases on average at a rate of 0.5% every 1 million years. This can increase to 2% every 1 million years if thick interseam clays and sands occur between seams such as in the Yallourn–Maryvale area.
5. Abrupt step-like profiles in moisture content occurs across seam boundaries. Regular moisture decrease with depth is not always present but can markedly decrease across the major seam boundaries. The weight averaged whole seam moisture contents decreases between 1% and 2% below major seam boundaries irrespective of burial depth, but within split seams, moisture content tends to remain constant. This pattern indicates comparatively long time
breaks occur between each major coal forming period.

6. Moistures tend to be higher and show a more regular downwards decreasing moisture gradient, where successive thick seams overlie each other such as at Loy Yang. In contrast where thick sediment (clay–sand) interseams overlie or interbed with coals, moisture is substantially decreased for the same depth of burial. This reflects a greater weight per volume of sediment to that of the coal.

7. Differential compaction, which involves moisture (volume) loss, has not equalized in the brown coal ranks of the Latrobe Valley. The volume decrease calculated using the measured specific gravity of dry coal at Loy Yang (sg=1.44) is 27% between 70% and 60% moisture content, and 23% between 60% and 50% moisture content.

8. Compression by monoclinal folding can decrease moisture contents by up to 7% (Edwards (1945, 1948). However on most anticlines in the Latrobe Valley, moisture content for a given depth is higher because the intensity of compression is less than in the adjacent synclines and/or the anticlines are more fractured and contain higher groundwater contents.

9. Moisture trend reversals can occur where moisture values increase downwards with depth. This occurs particularly in the Yallourn Seam and relates to the abundance of the wetter darker lithotypes towards the base of the seam.

10. Eastwards along the Latrobe Valley most coal seams show an increase in the relative abundance of the wetter medium dark and darker lithotypes due to an increasing marine influence from the east (Holdgate, 1996). This may results in a reduction to the moisture losses otherwise anticipated by the increase in overburden and interburden thickness in this direction.

Acknowledgements

I wish to acknowledge previous input of data and discussion with my colleagues in the SECV, and access to the 3D-moisture model provided by GeoEng (Aust.) Pty Ltd to the Victorian State Government.

References


Standards Association of Australia, 1984b. AS 2434.5. Methods for the Analysis and Testing of Brown Coal and Brown Coal Char: Part 5. Determination of Moisture in Bulk Samples and in Analysis Samples of Char from Lower Rank Coal.