# HIGH RESOLUTION SEQUENCE STRATIGRAPHIC ANALYSIS OF PARALIC COAL SEAMS FROM THE BOOK CLIFFS, EASTERN UTAH, USA

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Thesis submitted in accordance with the requirements of the
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by

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# ABSTRACT

The petrographic characteristics of the Sunnyside coal of the Upper Cretaceous Blackhawk Formation in eastern Utah were investigated through detailed maceral and vitrinite reflectance analysis of 281 samples from seven vertical sections covering approximately 30 km of depositional dip. Systematic variations in inorganic mineral content, inertinite content and mean vitrinite reflectance enable the identification of a detailed record of accommodation change throughout the deposition of the Sunnyside coal. The stratigraphic relationships between the coal and the siliciclastic components of the Sunnyside Member enable this record to be correlated with that identified in the time-equivalent shallow-marine strata. On the basis of this correlation, it can be clearly demonstrated that the Sunnyside coal spans two high-frequency depositional sequences, including two fourth order sequence boundaries and a parasequence-bounding marine flooding surface.

Further petrographic analysis of coals from the Aberdeen and Desert Members of the Blackhawk Formation was undertaken in order to compare the characteristics of the Sunnyside coal with seams formed in higher and lower accommodation conditions. Differences in the bulk composition and internal organisation of the three coals demonstrates that the terrestrial component of the Blackhawk Formation provides a comparable record of long-term accommodation change to the time-equivalent shallow-marine strata.

This thesis provides an improved understanding of the sequence stratigraphic significance of paralic coals seams by demonstrating that they record high-resolution records of base level change that can be correlated with changes in relative sea level. It also shows that they may preserve a higher resolution and more complete record of base level change than the time-equivalent marine or terrestrial clastic sediments. The ability to identify sequence boundaries and marine flooding surfaces within vertical sections through coal seams has important implications for improving the predictability of lateral facies variations such as coal seam splits and incised valleys. The ability to predict lateral variations in the petrographic characteristics of coal seams may also be applicable in related commercial activities such as coal bed methane exploration and evaluation of source rock potential.

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This thesis is dedicated to the 1500 miners who lost their lives working in the Utah coal mines during the Nineteenth and Twentieth Centuries.

“…black! black! black! It’s all black!”

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# CHAPTER 1: INTRODUCTION, AIMS AND THESIS LAYOUT

*This chapter introduces the aims of this thesis, outlines the contents of each chapter, and gives the current status of work that has been submitted for publication in international geological journals.*

## 1.1 INTRODUCTION

Over the past twenty or so years, sequence stratigraphy has been successfully applied to marine strata in a wide range of tectonic, geographic and climatic settings (e.g. Sloss, 1963; Vail et al., 1977; Vail, 1987; Van Wagoner et al., 1987, 1990; Posamentier and Vail, 1988; Mitchum and Van Wagoner, 1991; Posamentier and Allen, 1993; Van Wagoner, 1995). By comparison, however, sequence stratigraphic concepts have only been applied to a limited extent in terrestrial (or non-marine) depositional settings (e.g. Schumm, 1993; Shanley and McCabe, 1993, 1994; Boyd and Diessel, 1994; Aitken and Flint, 1994, 1995; Hampson, 1995; Diessel, 1998; Legaretta and Uliana, 1998; Zaitlin et al., 2002). This is primarily due to the paucity of regionally extensive marker beds, and limited availability of chronostratigraphic and biostratigraphic controls in terrestrial strata (Shanley and McCabe, 1994; Boyd and Diessel, 1994; Zaitlin et al., 2002; Wadsworth et al., 2003).

Initially, most sequence stratigraphic studies of terrestrial strata focused on the relationship between stacking patterns of fluvial sandstones and changes in depositional base-level (e.g. Shanley and McCabe, 1991, 1993; Schumm, 1993; Allen and Posamentier, 1993; Aitken and Flint, 1994, 1995; O'Mara and Turner, 1999; Sprague et al., 2002). Using this approach, it is possible to produce sequence stratigraphic models for fluvial strata, which are loosely comparable to models for parasequence stacking patterns in shallow-marine strata (e.g. Shanley and McCabe, 1993, 1994). However, whilst such models do provide a basic framework for interpreting the sequence stratigraphy of terrestrial strata, they are often difficult to apply on a regional scale, and rarely provide a link to the adjacent marine strata.

An alternative method is to focus on coal seams formed in paralic settings (e.g. Cross, 1988; McCabe and Parrish, 1992; Boyd and Diessel, 1994; Flint et al., 1995; Banerjee et al., 1996; Bohacs and Suter, 1997; Diessel, 1998; Petersen et al., 1998; Diessel et al., 2000; Holz et al., 2002; Wadsworth et al., 2002, 2003). This approach has a distinct advantage over that based on fluvial architectures, in that paralic coals are commonly very laterally extensive, and relatively easy to correlate over large distances (Bohacs and Suter, 1997; Diessel, 1998; Holz et al., 2002). Furthermore, the peat bodies from which they formed were highly sensitive to changes in depositional conditions, including fluctuations in the height of paralic groundwater tables (Clymo, 1987; Moore, 1989; Winston, 1994). In situations where the paralic groundwater table was hydraulically linked to the sea (e.g. Kosters and Suter, 1993; Törnqvist, 1993), they may also provide the potential for correlating between terrestrial and marine records of accommodation change. On this basis, coal seams formed in paralic settings probably provide the best opportunity for improving the understanding of sequence stratigraphic expressions in terrestrial strata.

## 1.2 THESIS AIMS

The aim of this thesis is to produce a high-resolution sequence stratigraphic model, which enables terrestrial strata to be reliably correlated with the time-equivalent shallow-marine strata. This objective is primarily achieved through a detailed study of the petrography of the Sunnyside coal of the Upper Cretaceous Blackhawk Formation in the Book Cliffs of eastern Utah, USA. The reasoning behind the choice of study area is outlined in Chapter 4.

Particular attention is paid to identifying the expressions of key sequence stratigraphic surfaces within the Sunnyside coal, as these provide a framework for linking accommodation trends identified in the coal with those recorded in the time-equivalent shallow-marine strata. Coal seams from the Aberdeen and Desert Members of the same formation are also considered, in order to explore how longer-term accommodation trends are expressed within the terrestrial component of the Blackhawk Formation. A secondary aim of this thesis is to consider the potential wider usefulness of a range of field and laboratory methods for coal analysis.

Since coal seams are in themselves an important natural resource, an enhanced ability to predict their occurrence and lateral continuity within sedimentary basins has potentially significant economic implications. Furthermore, the improved ability to predict vertical and lateral variations in coal composition has implications for a range of related commercial activities, including the exploitation of coal bed methane and assessment of source rock potential in conventional oil and gas exploration.

## 1.3 THESIS LAYOUT

This thesis is based on a series of independent manuscripts that have been submitted for publication in international geological journals (Chapters 5 to 7). The results, interpretations and conclusions presented in these manuscripts are supplemented by three introductory chapters and an extended discussion section. The contents of each chapter are summarised below:

- Chapter 2 provides an introduction to the sequence stratigraphic concepts upon which this study is based. This is followed by an overview of the analytical methods used to obtain the primary dataset (Chapter 3), and a discussion of the stratigraphy and sedimentology of the main study area (Chapter 4).
- The first manuscript (Chapter 5) introduces the primary dataset and evaluates how well a range of petrographic parameters work as indicators of accommodation change for the Sunnyside coal. This is an important part of the study as it justifies the methodology used in the subsequent chapters.
- The second manuscript (Chapter 6) builds on the first by using the petrographic dataset to make a detailed sequence stratigraphic interpretation of the Sunnyside coal. This interpretation is then integrated with evidence from the time-equivalent shallow-marine strata, in order to produce an integrated model for the development of the entire Sunnyside Member.
- The final manuscript (Chapter 7) expands the scope of the study by comparing the characteristics of the Sunnyside coal with seams from the Aberdeen and Desert Members of the Blackhawk Formation. Differences in their composition and internal organisation are used to demonstrate that the terrestrial component of the Blackhawk Formation provides a comparable record of accommodation change to that recorded in the time-equivalent shallow-marine strata.
- Chapter 8 contains further discussion of important points that were not covered in sufficient detail in the three manuscripts, and considers the relevance of their findings in a broader scientific context. This is followed by a consolidated set of conclusions and a list of recommendations for further study.
- The petrographic dataset for the three coals is presented in graphic form in the Appendix, and as an Excel spreadsheet on the enclosed CD.
- A list of references cited in the text can be found at the end of each chapter.

## 1.4 STATUS OF MANUSCRIPTS

At the time of submission, the status of the manuscripts collated in this thesis is as follows:

CHAPTER 5: Davies, R., Diessel, C., Howell, J., Flint, S., and Boyd, R., *in press*, Vertical and lateral variations in the petrography of the Upper Cretaceous Sunnyside coal of eastern Utah, USA – implications for the recognition of high-resolution accommodation changes in paralic coal seams: *International Journal of Coal Geology*.

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| Submitted: | 12th March, 2004 |
| Resubmitted: | 19th June, 2004 |
| Accepted: | 24th June, 2004 |

CHAPTER 6: Davies, R., Howell, J., Boyd, R., Flint, S., and Diessel, C., *in review*, High-resolution sequence stratigraphic correlation between shallow-marine and terrestrial strata: Examples from the Sunnyside Member of the Cretaceous Blackhawk Formation, Book Cliffs, eastern Utah: *American Association of Petroleum Geologists Bulletin.*

Submitted: 19th July, 2004

CHAPTER 7: Davies, R., Boyd, R., Howell, J., Flint, S., and Diessel, C., *in review*, Testing a model for recognising high-resolution accommodation changes in paralic coal seams in the Book Cliffs, eastern Utah: *Geology.*

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## 1.5 CONTRIBUTION BY AUTHORS TO MANUSCRIPTS

The contribution by the listed authors to each manuscript is summarised below:

CHAPTER 5: R. Davies; principal investigator and author.
C. Diessel; microscopy assistance, discussion, manuscript review.

J. Howell; fieldwork assistance, discussion, manuscript review.
S. Flint; discussion and manuscript review.
R. Boyd; discussion and manuscript review.

CHAPTER 6: R. Davies; principal investigator and author.
J. Howell; fieldwork assistance, discussion, manuscript review.
R. Boyd; discussion and manuscript review.
S. Flint; discussion and manuscript review.
C. Diessel; microscopy assistance and discussion.

CHAPTER 7: R. Davies; principal investigator and author.
R. Boyd; discussion and manuscript review.
J. Howell; fieldwork assistance, discussion, manuscript review.
S. Flint; discussion and manuscript review.
C. Diessel; microscopy assistance.

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# CHAPTER 2: CONCEPTS IN TERRESTRIAL SEQUENCE STRATIGRAPHY AND COAL GEOLOGY

*This chapter provides an overview of the concepts involved in the application of sequence stratigraphy to coal bearing strata. A brief discussion of the application of sequence stratigraphy to marine and fluvial strata is included for comparison, however, this is not intended to be an exhaustive review.*

## 2.1 INTRODUCTION

Over the past twenty or so years, sequence stratigraphy has provided geologists with a range of powerful new tools and concepts that have revolutionised the way in which we correlate and interpret sedimentary rocks (e.g. Sloss, 1963; Vail et al., 1977; Vail, 1987; Van Wagoner et al., 1987, 1990; Posamentier and Vail, 1988; Mitchum and Van Wagoner, 1991; Posamentier and Allen, 1993). Perhaps the most fundamental concept in sequence stratigraphy is accommodation, that is, the space made available for potential sediment accumulation (Fig. 2.1, Jervey, 1988). This is a dynamic volume, the vertical limits of which are defined by the height of the sediment surface and base level (the level above which erosion will occur). Changes in the amount of accommodation available are controlled by the interplay of eustacy, tectonics, sediment supply and compaction (Jervey, 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990; Posamentier and Allen, 1993).

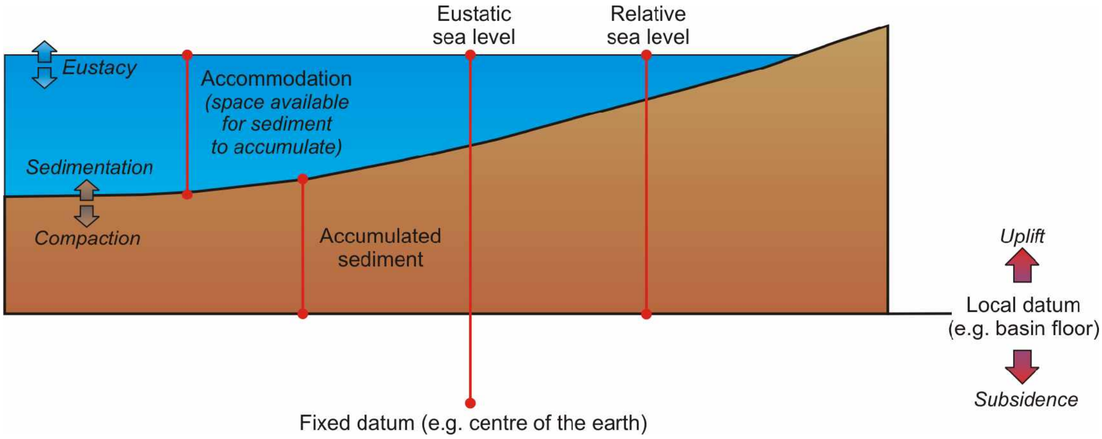

**Figure 2.1.** Cartoon to illustrate the concept of accommodation, and how it is controlled by the interplay of eustacy, tectonics and the thickness of the accumulated sediment. Note that relative sea level incorporates the effects of subsidence and uplift by referring to the position of sea level with respect to a datum at or near the sea floor (e.g. basement rocks), whereas eustatic sea level (i.e. global sea-level) is the variation of sea level with reference to a fixed datum, such as the centre of the Earth.

In shallow-marine settings, accommodation is a relatively straightforward concept, as base level is effectively the same as sea level (Posamentier et al., 1988). Changes in the amount of accommodation through time are reflected in the vertical stacking patterns of marine shoreface strata (Posamentier and Vail, 1988; Posamentier et al., 1988). During periods of slowly rising or slowly falling relative sea level, there is usually insufficient accommodation for sediment to be deposited in the near shore area; this results in progradational (basinward) stacking of shoreface strata (Fig. 2.2 A). As the rate of relative sea level rise increases, the resultant increase in accommodation in the near shore area leads to aggradational (no lateral change) stacking of shoreface strata (Fig. 2.2 B). Even higher rates of relative sea level rise result in the creation of large amounts of accommodation and retrogradational (landward) stacking of shoreface strata (Fig. 2.2 C).

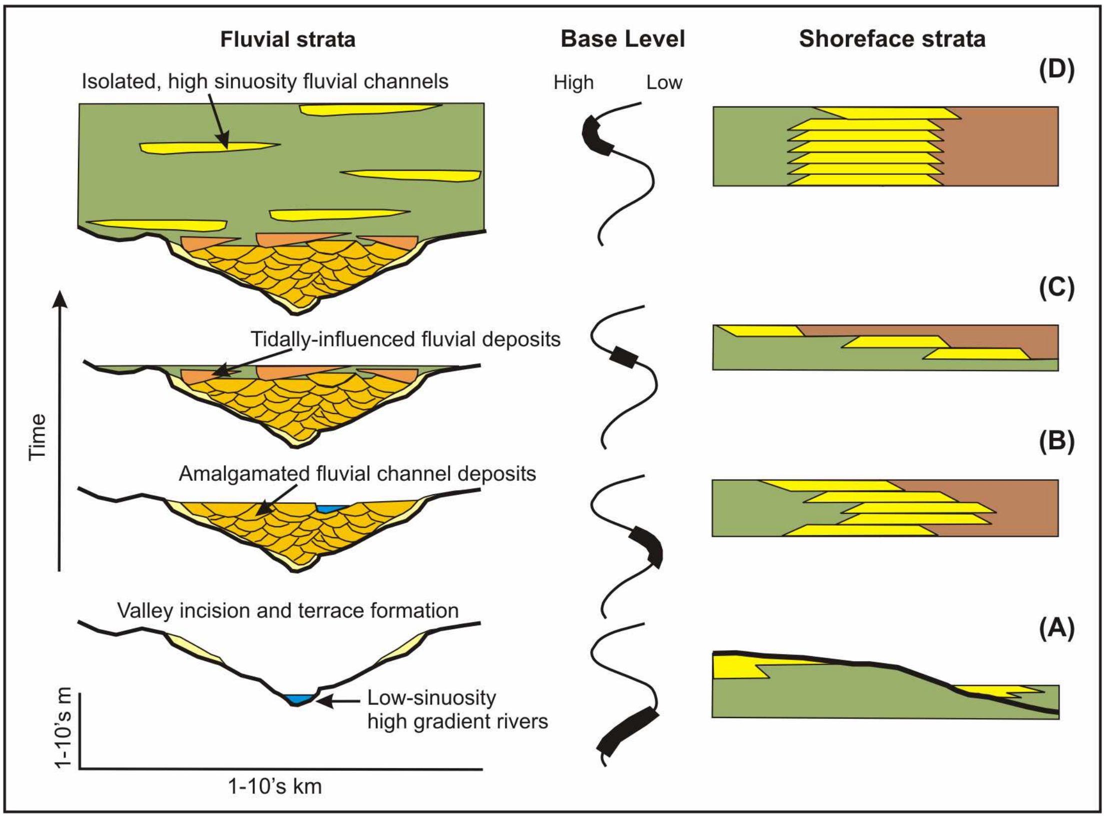

**Figure 2.2.** Summary of the response of fluvial and shoreface systems to changes in depositional base-level. (A) Slow rates of base-level rise leading to base-level fall. (B) Reduced rates of base-level fall and a change to slowly rising base-level. (C) Increased rates of base-level rise. (D) Reduced rates of base-level rise balanced by rates of sedimentation (from Shanley and McCabe, 1993).

## 2.2 SEQUENCE STRATIGRAPHY OF FLUVIAL STRATA

Identifying expressions of accommodation change becomes inherently more difficult landward of the shoreline, as the influence of glacio-eustatic sea level diminishes and a wide range of other allocyclic controls increase in importance (Fig. 2.3, Shanley and McCabe, 1994; Boyd and Diessel, 1994).

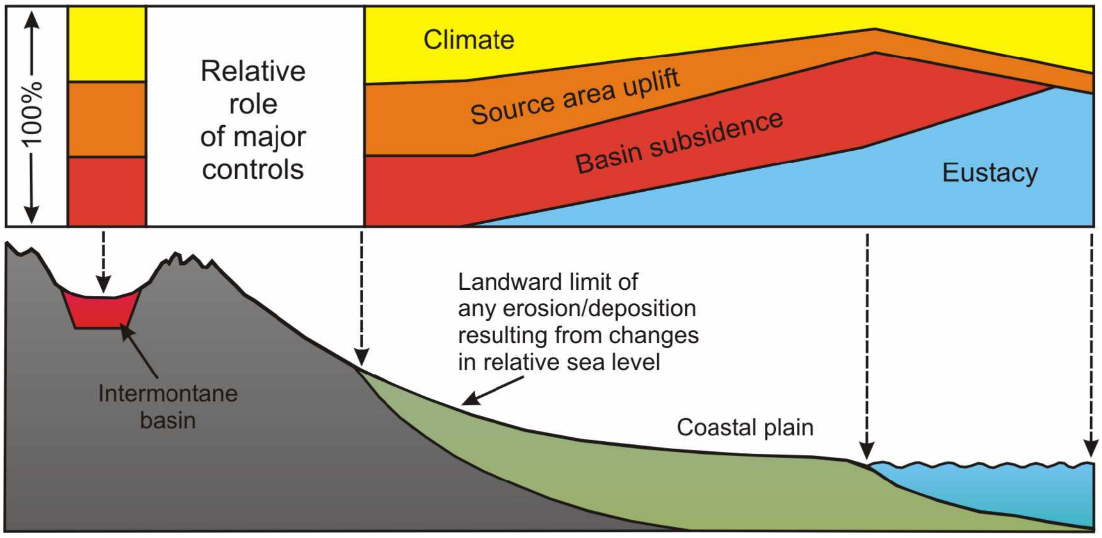

**Figure 2.3.** Terrestrial depositional systems respond to a wide range of allocyclic controls, the relative importance of which varies with distance from the shoreline (from Shanley and McCabe, 1994).

Initial attempts to translate sequence stratigraphic concepts into the terrestrial realm were primarily focused on fluvial strata (e.g. Shanley and McCabe, 1991, 1993; Schumm, 1993; Allen and Posamentier, 1993; Aitken and Flint, 1994, 1995; O'Mara and Turner, 1999; Sprague et al., 2002). The definition of base level is not straightforward in fluvial systems, as it cannot be approximated to sea level as in marine settings (Shanley and McCabe, 1994). In the lower coastal plain, the graded fluvial profile is commonly used to approximate an equilibrium surface that is loosely analogous to base level. A graded river is defined by Mackin (1948) as one that adjusts its slope so that its velocity is just sufficient to transport the load supplied by its drainage basin. It is therefore a system in equilibrium in which neither erosion or deposition occurs. A change in any of the controlling factors (e.g. eustacy, climate, subsidence, uplift) will result in a displacement of the equilibrium as the river attempts to absorb the effect of the change. In some cases it may be possible to use this concept to relate changes in the styles of fluvial systems to changes in sea level (e.g. Fig. 2.4, Posamentier et al., 1992; Shanley and McCabe, 1993, 1994).

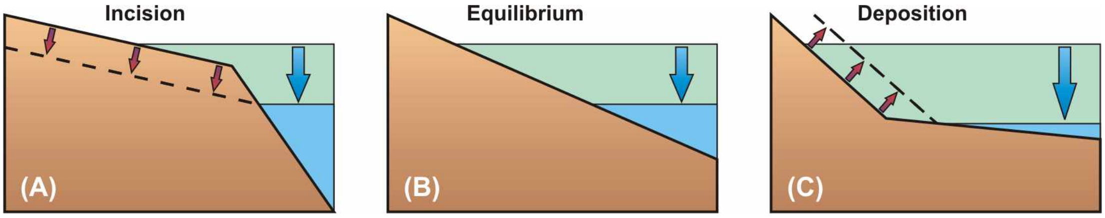

**Figure 2.4.** Fluvial response to a fall in relative sea level is largely dependent on the gradient of the marine shelf in relation to that of the fluvial system. (A) Where a steep shelf is exposed, incision is likely as the fluvial system attempts to return to equilibrium. (B) Where the shelf has a similar gradient to the fluvial system, incision is unlikely as the system remains in equilibrium. (C) Where the shelf slope is less than that of the fluvial system, fluvial profiles may be extended resulting in deposition as the system attempts to return to equilibrium (modified from Posamentier et al., 1992).

A number of authors have incorporated this concept into models that relate fluvial strata to changes in depositional base level (e.g. Posamentier and Vail, 1988; Posamentier et al., 1988; Shanley and McCabe, 1991, 1993, 1994; Schumm, 1993; Boyd and Diessel, 1994; Aitken and Flint, 1995; Sprague et al., 2002). An example of this approach is shown in the left hand column of Figure 2.2. Low rates of base level fall result in the formation of incised valleys and sediment bypass as there is no accommodation available for sediment to accumulate in the coastal plain (Fig. 2.2 A). Early stages of base level rise result in deposition of amalgamated channel bodies as sediment fills the limited amount of accommodation created within the incised valley (Fig. 2.2 B). Continued base level rise results in the creation of an increasing amount of accommodation in the coastal plain and the deposition of tidally influenced channels and flood plain deposits (Fig. 2.2 C). As the rate of base level rise begins to decelerate, the channels become increasingly sinuous due to the reduced rate of accommodation creation in the coastal plain (Fig. 2.2 D).

Although these models provide a basic framework for interpreting changes in accommodation in terrestrial settings, they are often difficult to apply on a regional scale, and rarely provide a link to the adjacent marine strata (Shanley and McCabe, 1994, Wadsworth et al., 2003). An alternative approach to terrestrial sequence stratigraphy is to focus on coal seams formed in paralic settings; this has a distinct advantage over that based on fluvial architectures, as paralic coals are commonly very laterally extensive and therefore more likely to reflect regional scale changes in base level (Diessel, 1992; Diessel, 1998). Coal seams may also preserve a record of base level fall (in addition to base level rise), whereas fluvial strata cannot preserve evidence of this part of the relative sea level curve due to the widespread erosion associated with negative accommodation (Diessel 1998, Wadsworth et al., 2003).

## 2.3 SEQUENCE STRATIGRAPHY OF COAL BEARING STRATA

### 2.3.1 Coal forming depositional environments

Coal seams are formed through the burial and compaction of organic matter that accumulated in mire or swamp systems (McCabe, 1984; Diessel, 1992). Given the sensitivity of vegetal matter to environmental conditions, they should preserve a detailed record of palaeoenvironmental conditions throughout their deposition (Cohen and Spackman, 1972, 1977, 1980; Diessel, 1985, 1986). However, until recently they have rarely been utilised in sequence stratigraphic studies (e.g. Cross, 1988; Boyd and Diessel, 1994; Hampson, 1995; Flint et al., 1995; Banerjee et al., 1996; Bohacs and Suter, 1997; Diessel, 1998; Petersen et al., 1998; Diessel et al., 2000; Holz et al., 2002; Wadsworth et al., 2002, 2003).

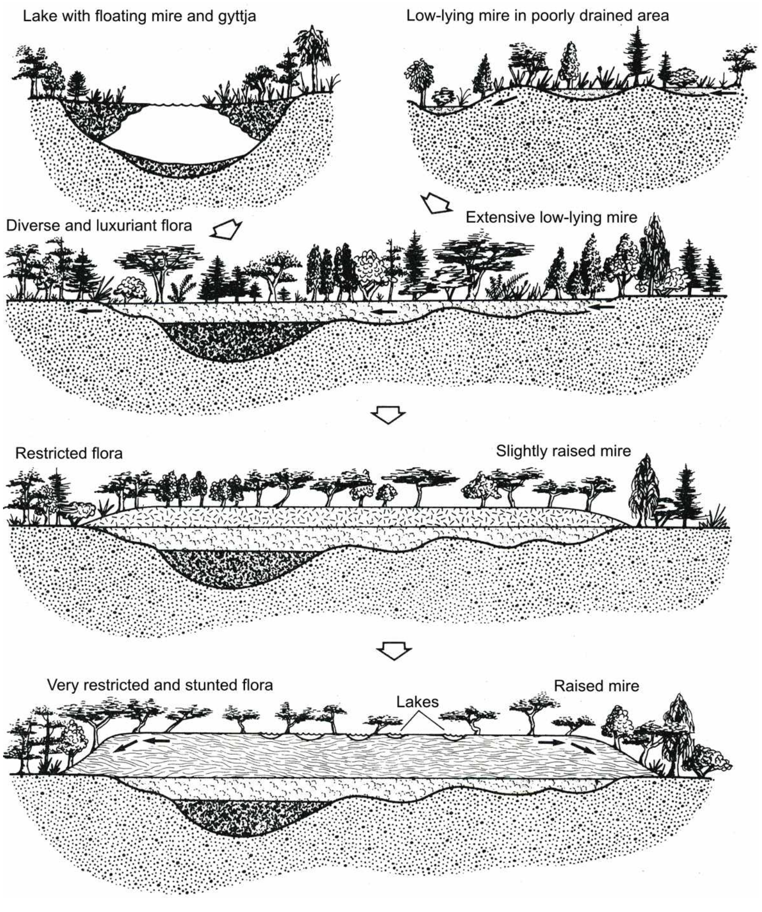

**Figure 2.5.** Evolutionary sequence of mire types associated with the development of a raised mire with vertical zonation of peat types. The small black arrows indicate the direction of groundwater movement (from McCabe, 1984).

Mires are usually initiated as low-lying features formed by the infilling of lakes or poorly drained areas with organic matter (Fig. 2.5, McCabe, 1984, 1987; Moore, 1989). They may then begin to build upwards resulting in the formation of raised or domed mires (McCabe, 1984, 1987; Greb et al., 2002). These can grow up to 20 m above the level of the regional groundwater table (Bruenig, 1990; Esterle and Ferm, 1994) due to the sponge-like retention of water within the peat. However, the reduced flow of groundwater in such peats results in nutrient starvation and the development of a rather stunted floral assemblage (McCabe, 1984, 1987; Clymo, 1987; Winston, 1994). Coal seams derived from mires that evolved in this way should display vertical compositional variations that reflect the different peat types associated with the various stages of mire evolution (Greb et al., 2002).

Paralic mires also exhibit a strong degree of variation in relation to distance from the shoreline (Cohen and Spackman, 1977; 1980). Figure 2.6 shows a schematic model of a paralic mire from Greb et al., (2002). The distal (rheotrophic or limnotelmatic) part of the mire is permanently covered by up to several metres of surface water. This passes landwards into an intermittently submerged mesotrophic zone, and an ombrotrophic zone that sits above the high water mark. Differences in the plant types supported by these zones should give rise to differences in the composition of the resultant coal (Spackman and Cohen, 1977, 1980; Diessel, 1985, 1986). There should also be a landward reduction in the inorganic content of the coal, as the ombrotrophic part of the mire sits above flooding levels and is therefore able to largely exclude clastic sediments (McCabe, 1984, 1987; Clymo, 1987). Further discussion of the origin and significance of the various organic and inorganic constituents of coal can be found in Chapters 3 and 5 of this thesis.

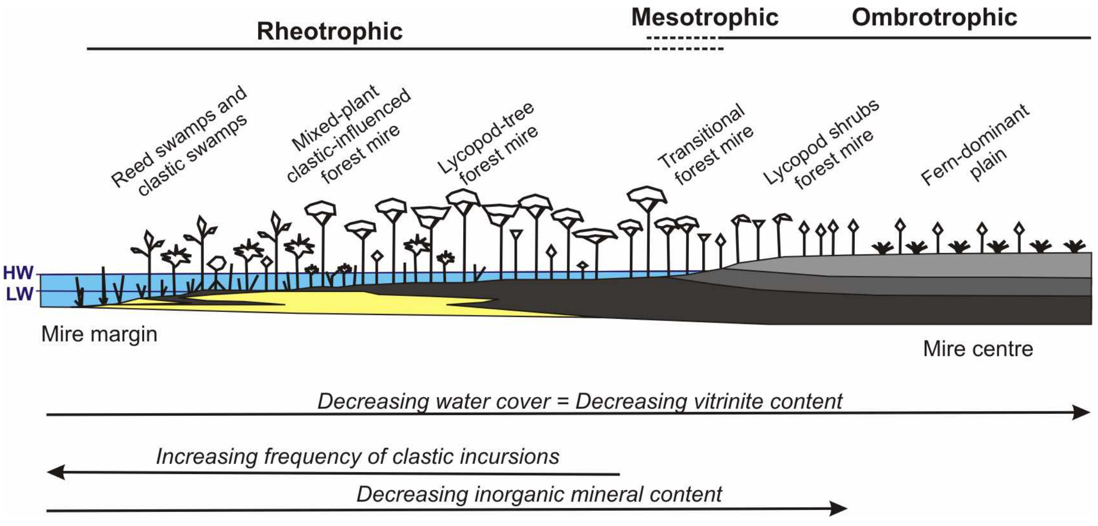

**Figure 2.6.** Schematic model of a paralic mire system to show variations in vegetation and peat composition with distance from the shoreline (modified from Greb et al., 2002). Vitrinite = woody material, inorganic minerals = inorganic material such as clastic sediments.

Changes in relative sea level through time should result in the landward or basinward migration of the various mire zones, which in turn should give rise to systematic vertical variations in the composition of the resultant coal (e.g. Fig. 2.7, Cohen and Spackman, 1977, 1980; Diessel et al., 2000). Studies of modern peat forming environments have shown that changes in relative sea level can influence groundwater tables up to 150 km inland of the shoreline (Törnqvist, 1993). This underlines the sequence stratigraphic significance of paralic coal seams, as they are one of the few terrestrial rocks that reflect regional scale changes in relative sea level in this way (Diessel and Boyd, 1994; Diessel 1998; Diessel et al., 2000).

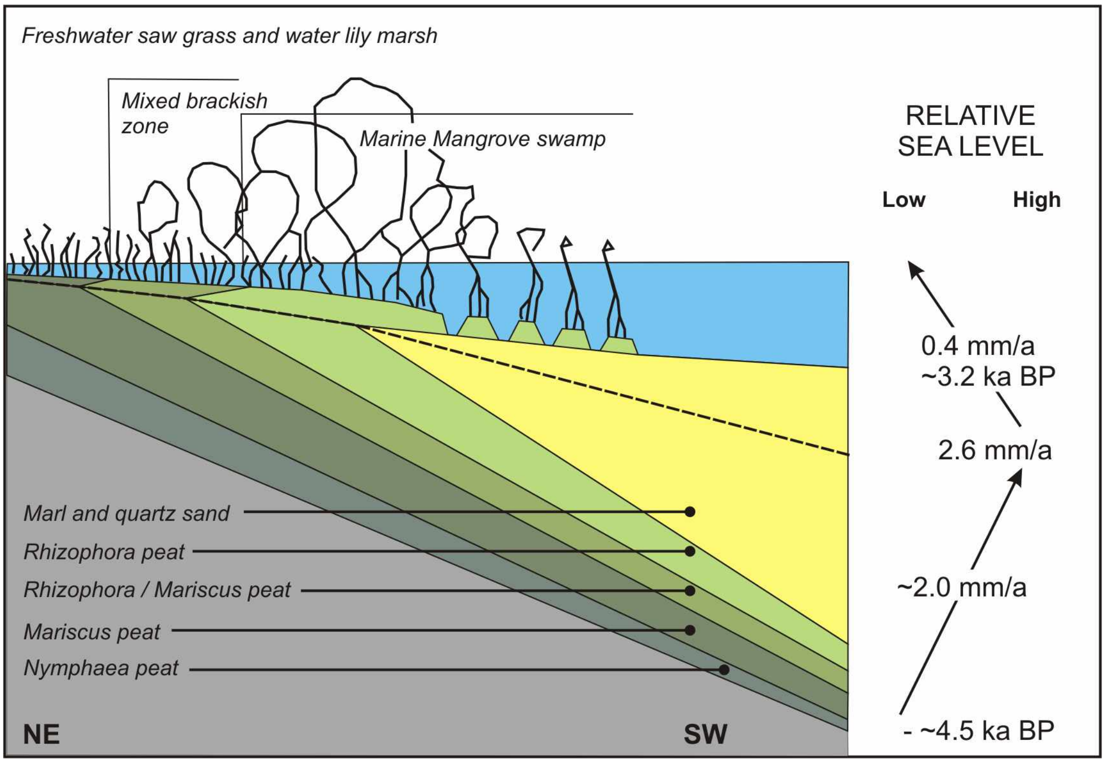

**Figure 2.7.** An example of a modern peat forming environment responding to changes in relative sea level, from the Ten Thousand Islands Area in SE Florida: The upward succession of freshwater (Nymphaea) to marine (Rhizophora) peat formed during a marine transgression is reversed during the subsequent regression. This should be reflected in the composition of the resultant coal (modified from Diessel et al., 2000).

## 2.3.2 Role of accommodation and climate in coal formation

In peat forming depositional environments, the height of the mire water table provides a good approximation of base level as it defines the level above which peat is exposed to oxidation and decay. In paralic settings, the height of the mire water table is governed by a combination of relative sea level and precipitation (Clymo, 1987; Moore, 1989; Kosters and Suter, 1993; Törnqvist, 1993; Winston, 1994), whilst accommodation is controlled by the height of the mire water table and auto-compaction of the peat. In order for peat to accumulate and be preserved, accommodation has to be created at a rate that approximately balances the rate of peat production (Fig. 2.8, Cross, 1988; Bohacs and Suter, 1997). If the rate of accommodation creation exceeds the rate of peat production, the mire is flooded and drowned by marine or lacustrine sediments. Conversely, if the rate of peat production exceeds the rate of accommodation creation, the mire is exposed, oxidised and reworked.

Studies of Holocene mires show that although the rate of peat production[1] varies considerably between climatic zones, it varies relatively little within them (Fig. 2.9 C, Diessel et al., 2000). On this basis, accommodation can be considered to be the key variable responsible for changes in the ratio of accommodation creation to peat production within any single geographic locality.

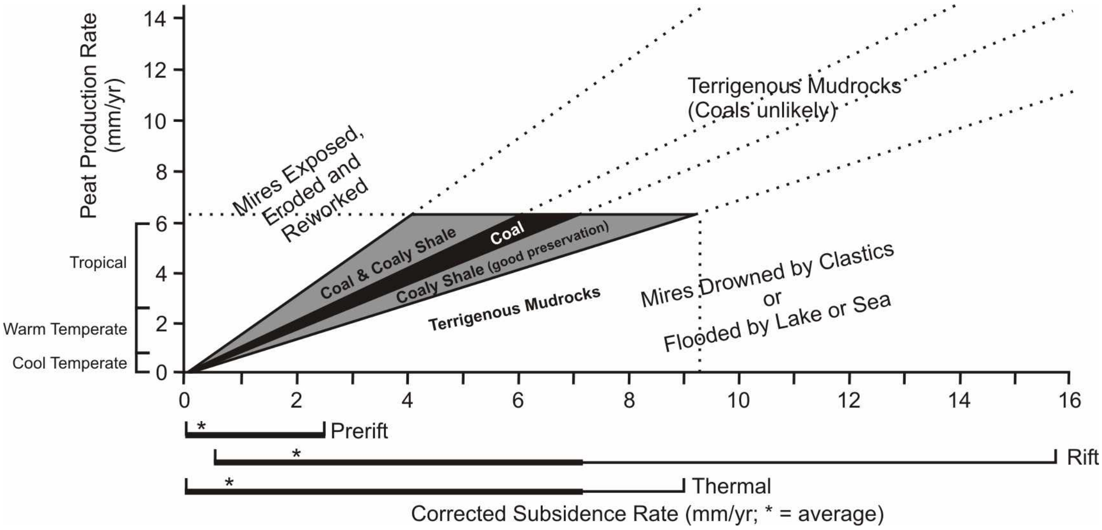

**Figure 2.8.** In order for peat to accumulate and be preserved, the rate of accommodation creation must approximately balance the rate of peat production, typical rates of peat production and subsidence for major climatic zones and tectonic settings are shown alongside for comparison. The shaded areas on the graph represent the conditions of formation for various forms of terrigenous organic-rich rocks; in order for true coals with inorganic contents of less than 30% to form, the rate of accommodation creation to peat production must be between 1.0 and 1.18, coaly shales and coals with high inorganic contents may form where the ratio falls between 0.5 and 1.5. These figures were calculated using a series of mathematical equations that account for the interplay of peat production, sedimentation, compaction, subsidence and eustacy (from Bohacs and Suter, 1997).

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[1] It is important to understand the distinction between peat production and peat accumulation. Peat production refers to the rate at which organic matter is produced, and is primarily a function of geographic latitude. Peat accumulation refers to the rate at which organic matter is preserved and added to the peat mass, and is controlled by the balance between accommodation and peat production.

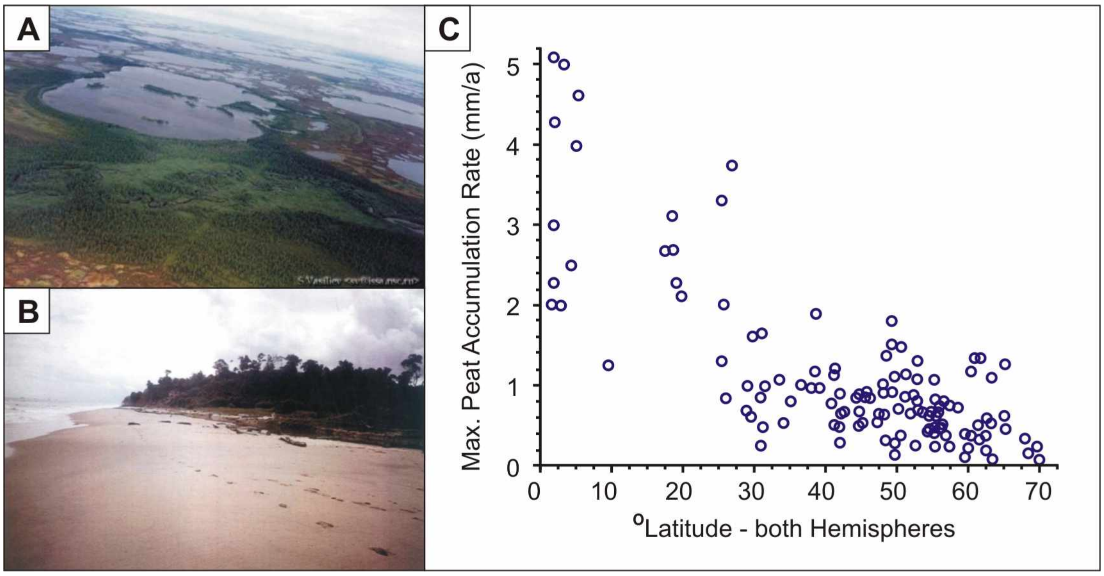


**Figure 2.9.** Modern peat forming environments can be found in all climatic regions from sub-arctic to tropical. (A) Large paralic mire in sub-arctic eastern Siberia (from http://infoteka.nsk.ru/~sv/CSSP/). (B) Paralic mire in tropical Borneo (from Howell and Flint, 2003). (C) A compilation of maximum peat accumulation rates from studies of Holocene mires in wide range of geographic latitudes (from Diessel et al., 2000). The maximum rate of peat accumulation observed in each locality provides a good approximation of the rate of peat production.

### 2.3.3 Occurrence of coals within depositional cycles

Historically, most ‘sequence stratigraphic’ studies of coal-bearing strata have primarily focused on predicting the occurrence of coals (or coal forming conditions) within depositional cycles (Weller, 1930; Duff and Walton, 1962; Horne et al, 1978; Fielding, 1987; Cross, 1988; McCabe and Parrish, 1992; Boyd and Diessel, 1994; Aitken and Flint, 1995; Flint et al., 1995; Hampson, 1995). In the majority of these studies, coal seams are interpreted as occurring mainly within the transgressive systems tract, where the rising depositional base-level favours high groundwater tables, and the relatively low siliciclastic sediment supply enables peat to accumulate without being inundated by inorganic material.

Bohacs and Suter (1997) refined this model by emphasising the importance of the rate of accommodation creation, as opposed to the amount of accommodation available (Fig. 2.10). Above a threshold level of accommodation creation, mires may be initiated but forced to expand laterally as they rapidly fill the available accommodation, resulting in thin but laterally extensive coals. Increased rates of accommodation creation enable mires to grow to their full potential forming thicker but more isolated coals. At very high rates of accommodation creation, mires are inundated by sediment or standing water resulting in limited preservation of coals.

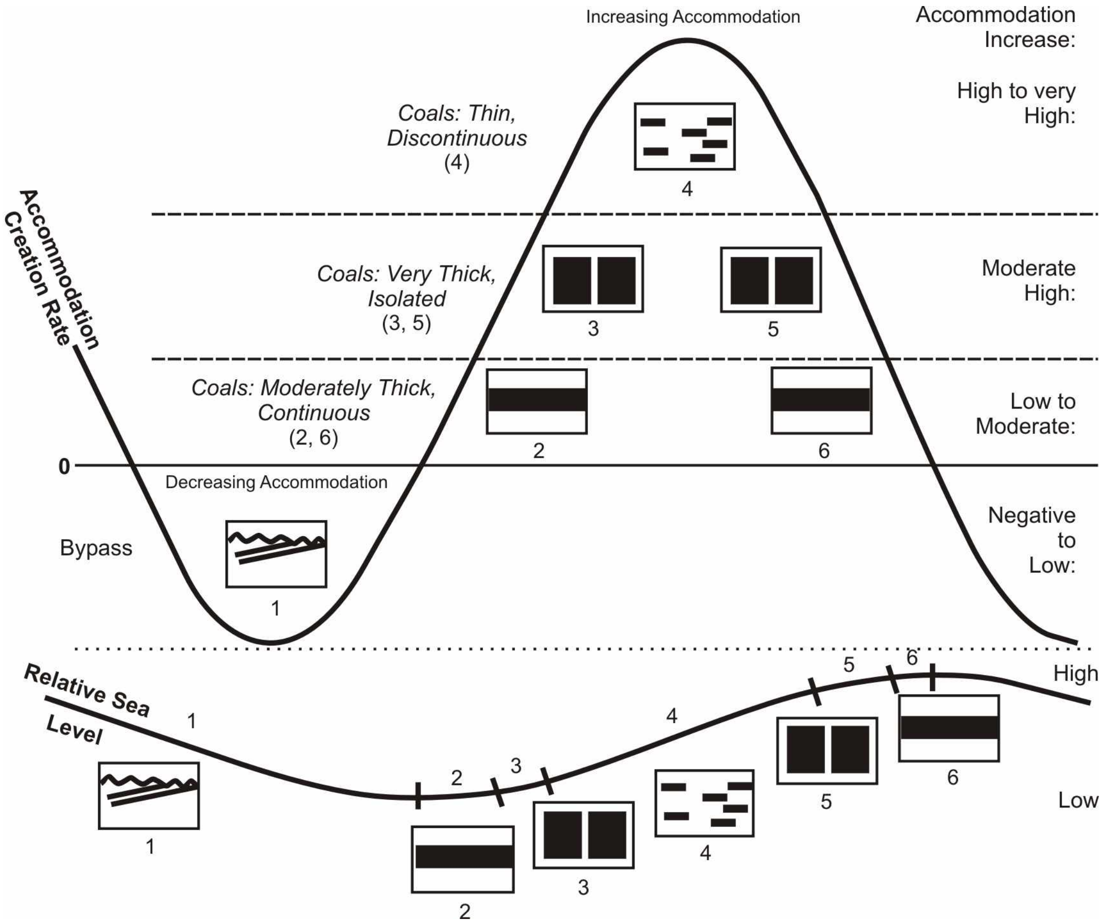
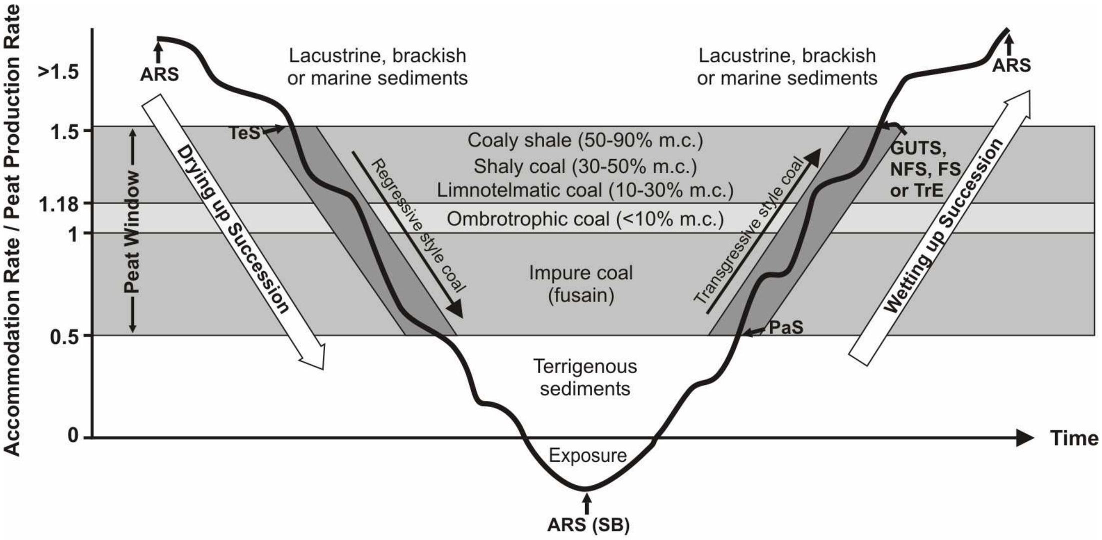


**Figure 2.10.** Model to predict the geometry of coals associated with different rates of accommodation creation (modified from Bohacs and Suter, 1997). Note that lower rates of accommodation creation favour laterally extensive coals, whilst higher rates give rise to thicker but less extensive coals. Coal formation is rarely associated with very high or very low rates of accommodation creation.

### 2.3.4 High-frequency cycles within coal seams

A number of recent studies have explored the high-frequency accommodation changes that can be interpreted from changes in the internal characteristics of coal seams (e.g. Banerjee et al., 1996; Diessel, 1998; Petersen et al., 1998; Diessel et al., 2000; Chalmers, 2001; Holz et al., 2002; Wadsworth et al., 2002, 2003). These studies have yielded several important advances in the understanding of the significance of coal seams in depositional cycles. The most significant of these are that coals may form in response to either increasing or decreasing accommodation creation, and may also span multiple high-frequency sequences.

Building on these recent studies, Diessel et al. (2000) and Wadsworth et al. (2002, 2003) defined seven key sequence stratigraphic surfaces that can be interpreted from the vertical succession of facies within coal seams or coal-bearing strata (see Fig. 2.11). This is a particularly significant advance as it provides a previously unavailable ability to recognise terrestrial equivalents of marine flooding surfaces and sequence boundaries. The most important of these newly defined surfaces is the accommodation reversal surface (ARS), which marks the change from increasing to decreasing accommodation conditions or vice versa. Where an ARS forms the upper bounding surface of a seam it may indicate a hiatus and be the equivalent of a sequence boundary. Alternatively, where an ARS marks the boundary between transgressive and regressive facies trends within a seam, it may represent the terrestrial equivalent of a marine flooding surface. Further discussion of the coaly facies referred to in this model can be found in Chapter 3 of this thesis. The model itself and the key surfaces it introduces are discussed at length in Chapters 6 and 7.



| | Surface | Explanation | Hiatal / Non-Hiatal |
|---|---|---|---|
| **TeS** | Terrestrialisation Surface | Initiation of peat formation due to upward shallowing | Non-Hiatal |
| **PaS** | Paludification Surface | Initiation of peat formation due to upward deepening | Hiatal or Non-Hiatal |
| **GUTS** | Give-up Transgressive Surface | Gradual termination of peat formation due to upward deepening | Non-Hiatal |
| **ARS** | Accommodation Reversal Surface | Transition between shallowing and deepening upward (and vice-versa) | Hiatal or Non-Hiatal |
| **NFS** | Non-marine Flooding Surface | Abrupt deepening of non-marine facies | Hiatal |
| **FS** | Marine Flooding Surface | Abrupt deepening of marine facies | Hiatal |
| **TrE** | Transgressive Surface of Erosion | Abrupt deepening of facies associated with sediment reworking | Hiatal |

**Figure 2.11.** Idealised curve to show the relationship between paralic accommodation rate (AR), peat production (PPR), coaly facies and terrestrial key surfaces. The left hand limb of the curve shows the succession of facies and surfaces formed in response to decreasing accommodation creation, the right hand limb shows the succession formed in response to increasing accommodation (modified from Wadsworth et al., 2003). The figures 30-50% m.c. etc refer to the inorganic mineral contents of the different coaly facies within the peat window. In general coals with higher mineral contents reflect higher rates of accommodation creation, as these provide a mechanism for the transport of water-borne detrital minerals into the mire. Impure coals with high inertinite contents are associated with lower rates of accommodation creation, as these favour oxidation and burning of the peat.

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# CHAPTER 3: ANALYTICAL METHODOLOGY

*The primary dataset for this study is derived from detailed petrographic analysis of over 300 samples from the Sunnyside, Desert and Aberdeen coals. This chapter outlines the methods employed in obtaining these samples, preparing them for microscopic analysis, and determining their petrographic composition and mean vitrinite reflectance values.*

## 3.1 COAL PETROGRAPHY

Coal petrography is a branch of coal science that focuses on the microscopic recognition of the different organic and inorganic constituents of coal (Stach et al., 1975). It was chosen as the main analytical tool for this study as there is a well documented relationship between petrographic composition and conditions at the time of peat formation (see discussion in Chapter 5). It has also been successfully utilised in a number of 'coal sequence stratigraphic studies' (e.g. Banerjee et al., 1996; Diessel, 1998; Petersen et al., 1998; Diessel et al., 2000). Palynological methods of interpreting the evolution of mires often rely on spores to identify plant species, and would therefore be difficult to apply in this study due to the inherently low spore content of the Cretaceous coals it focuses on (Diessel, 1992). The slightly weathered nature of the outcrop samples used in this study would also severely compromise the reliability of methods based on geochemical analysis.

## 3.2 FIELD LOGGING AND SAMPLING

The samples used in this study are derived from a combination of outcrop and underground mine sites. In outcrop localities, it is often necessary to excavate the coal to a depth of approximately 1 m prior to commencing logging and sampling (Fig. 3.1 A), as weathering may affect the results of subsequent analysis (Stach et al., 1975). Vitrinite reflectance values are particularly sensitive to outcrop weathering (Diessel and Gammidge, 1998). In underground mine localities, it is usually only necessary to clean back the top few centimetres of coal (Fig. 3.1 B).

The next stage is to produce a log of the macroscopically identifiable banding within the coal in order to determine the required sampling resolution and to minimise the chances of potential key surfaces being sampled across (see Fig. 3.2,

Table 3.1). Although this type of logging can be used to estimate the composition of the coal, it was not used for this purpose in this study as the macroscopic appearance of the various constituents of coal can vary considerably, especially when the coal is partially weathered, as is the case with the coals sampled in this study. Furthermore, the detailed petrographic analysis that was subsequently undertaken provides significantly more detailed and reliable results.

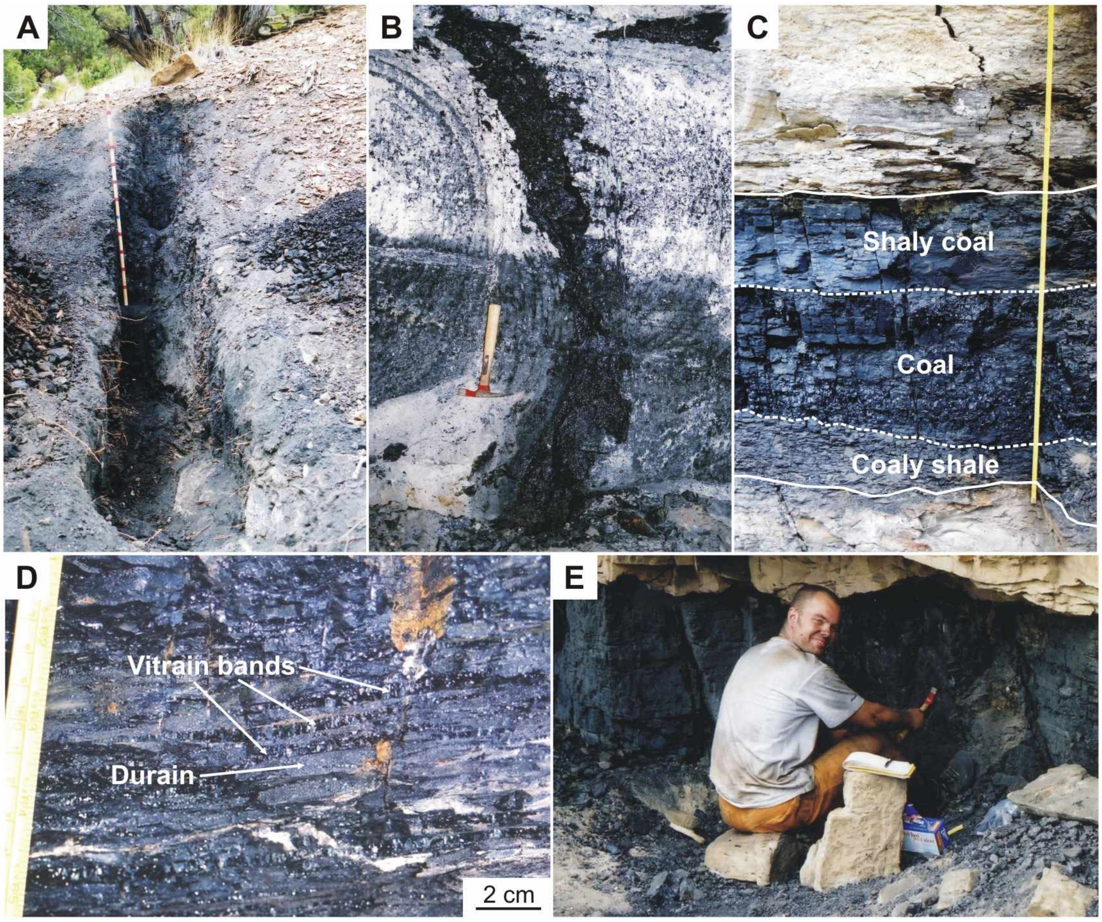

**Figure 3.1.** Photographs to show various stages of the sampling process: (A) In outcrop localities, coal is excavated to a depth of approximately 1 m in order to remove excessively weathered material (1.2 m stick for scale). (B) In mine localities it is usually only necessary to clean back the top few cm of coal. (C) Coaly shales and shaly coals can be distinguished from true coals on the basis of their appearance in the outcrop (thickness of seam shown = 80 cm). (D) Prior to sampling, a detailed log is produced of the macroscopically identifiable banding within the coal. This is used to determine the required sample spacing, and to ensure that key surfaces are not sampled across. (E) Sampling is carried out by cutting a series of 5 – 10 cm thick blocks through the entire thickness of the seam.

Coaly shales and shaly coals, with inorganic mineral contents in excess of 30% and 50% respectively, are relatively easy to distinguish from true coals on the basis of their appearance in the outcrop (Fig. 3.1 C, Schopf, 1960; Stach et al., 1975). It is also useful to log true coals in more detail, as their composition may vary considerably despite appearing to be relatively homogenous in the outcrop. This type of logging is carried out on a lithotype basis, differentiating between bands of bright and dull coal, known as vitrain and durain respectively (Fig. 3.1 D). Bands of vitrain and durain less than 5 mm thick are grouped together and logged as clarain, which can be further sub-divided into bright and dull clarain, depending on the dominant lithotype within it (Schopf, 1960; Stach et al., 1975; Diessel, 1992).

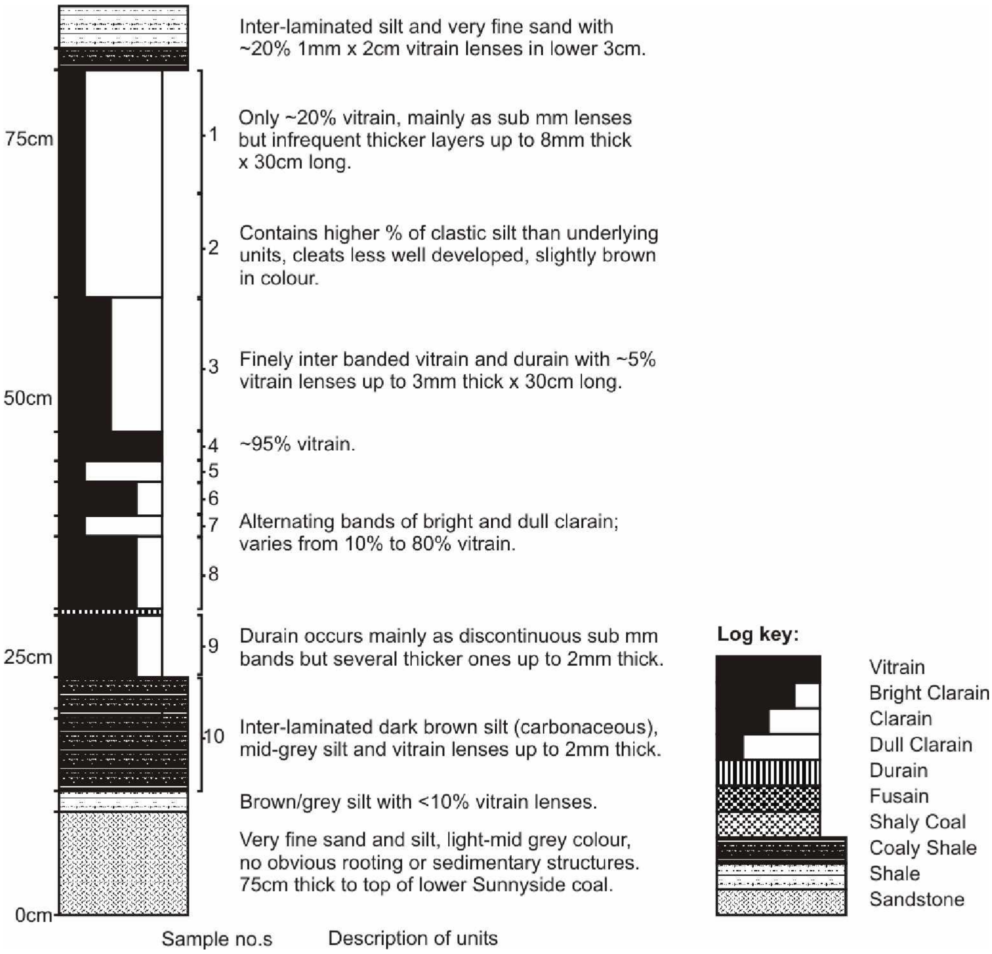

**Figure 3.2.** Example of a coal lithotype log to illustrate the scale at which macroscopically identifiable variations in the coal were logged prior to sampling. This type of log provides a basis for determining the sampling resolution required and helps ensure that potential key surfaces are not missed during the sampling process.

Once a section has been logged in this manner, it is then sampled by cutting a series of closely spaced blocks through the entire vertical thickness of the seam (Fig. 3.1 E). Care should be taken not to cross boundaries on the log when sampling, as these may correspond to significant compositional differences. The average sampling resolution used in this study was 5 – 10 cm, although a resolution of approximately 2.5 cm was achieved in one of the underground mine localities.

**Table 3.1.**
Lithotypes differentiated when logging coals in outcrop / mine localities.

| Lithotype | Description |
|---|---|
| Vitrain | Bands of bright coal with vitreous lustre, at least 5 mm thick |
| Bright Clarain | Sub 5 mm bands of bright and dull coal, with at least 60% bright bands |
| Clarain | Sub 5 mm bands of bright and dull coal, approximately 50% of each |
| Dull Clarain | Sub 5 mm bands of bright and dull coal, with at least 60% dull bands |
| Durain | Bands of dull coal, at least 5 mm thick |
| Fusain | Charcoal; dull appearance and leaves ‘dirty’ residue when touched |
| Shaly Coal | Coaly rock with shaly appearance, at least 30% inorganic material |
| Coaly Shale | Organic rich shale with at least 50% inorganic material |

## 3.3 SAMPLE PREPARATION

Where possible, the samples used in this study were kept intact and prepared as polished block samples in order to preserve the original millimetre-scale depositional layering of the coal. This improves the possibility of locating the precise expressions of key surfaces. Those samples too brittle to be kept intact were crushed to a top size of 2 mm, and representative sub-samples prepared as grain mounts instead. In both cases sample preparation was carried out in accordance with Australian Standard AS 2061-1989 (1989). The procedure is outlined below.

1) Samples are kept in an oven at 50ºC for 24 hours prior to preparation in order to remove any residual moisture, as this may adversely affect the curing process as well as the results of subsequent vitrinite reflectance analysis.
2) The samples are then placed in latex moulds, mixed with epoxy resin, and left to harden for up to 24 hours (Fig. 3.3 A – C).
3) Once set, the samples are cut in half in order to produce a flat surface that can be prepared for microscopic analysis. Solid block samples are cut perpendicular to the depositional layering so that all the layers in the sample are represented in the final polished face. Crushed samples are cut vertically so that the full range of grain sizes is included in the cut face (Fig. 3.3 D).
4) The rough-cut faces are flattened using fine grade emery paper under running water (Fig. 3.3 E). They are then finely polished using progressively finer polishing solutions down to 0.05 μm (Fig. 3.3 F).

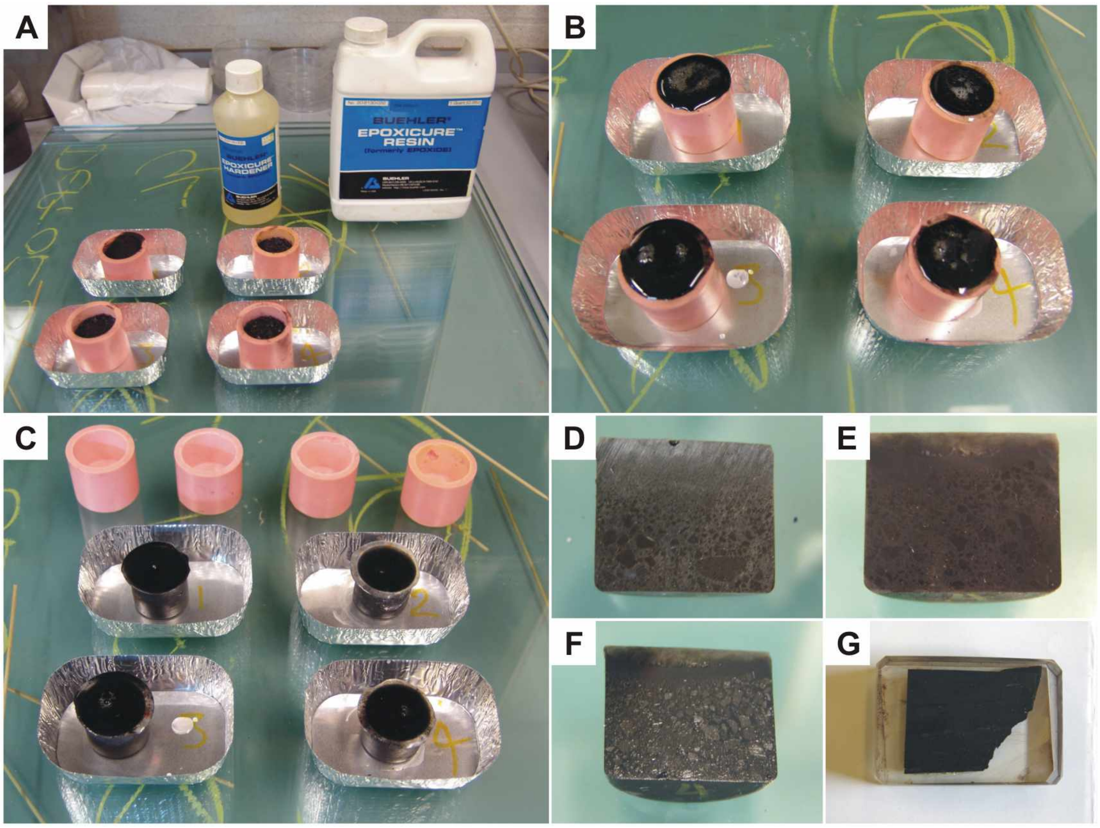

**Figure 3.3.** Photographs to show various stages of sample preparation: (A) A batch of four samples of crushed coal ready for preparation as grain mounts. (B) The crushed coal is mixed with epoxy resin in latex moulds. (C) Samples after curing. (D) Once set, the samples are cut in half in order to produce a flat surface. (E) The rough cut surface is flattened using fine grade emery paper. (F) The surface is then finely polished using 0.05 μm polishing media. (G) High quality samples from underground mine sites may be strong enough to be kept intact and prepared as a solid polished blocks instead.

## 3.4 MACERAL ANALYSIS

Macerals are discrete particles that can be grouped into a specific field of chemical and physical composition on the basis of their morphology and reflectance when viewed under the microscope (Stopes, 1935). Their relative proportions within a coal provide an indication of the palaeoenvironmental conditions at the time of deposition; they are therefore analogous to minerals in clastic sedimentary rocks (Cohen and Spackman, 1972, 1977, 1980; Diessel, 1985, 1986). The composition of each sample in this study was determined by counting 500 points in accordance with Australian Standard AS 2856.2-1998 (1998), using a point counter attached to a microscope suitable for viewing samples in reflected light and oil immersion (Fig 3.4). The twelve macerals differentiated during point counting fall into four main groups; vitrinite, liptinite, inertinite and inorganic minerals. The definition and appearance of macerals belonging to each of these groups are described below.

Figures 3.5 – 3.7 illustrate the typical appearance of a range of macerals when viewed in reflected light, using oil immersion objectives with between 25x and 50x magnification.

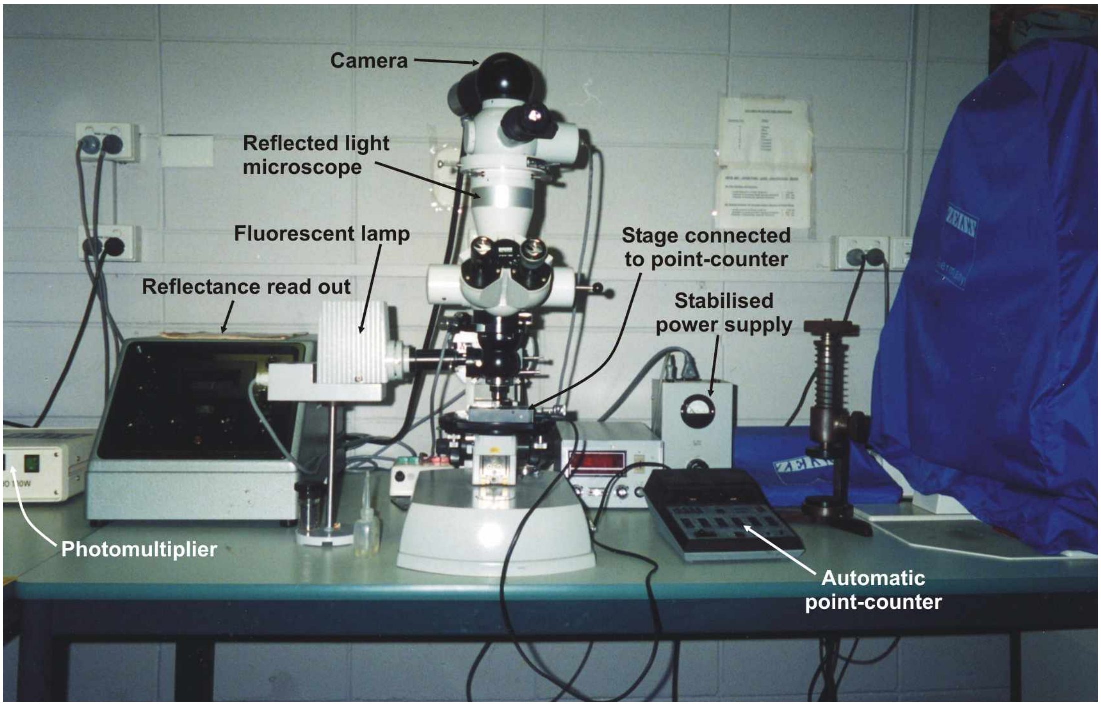

**Figure 3.4.** Photograph to show the microscopy equipment used for maceral and vitrinite reflectance analysis of polished coal samples.

### 3.4.1 Vitrinite group

Vitrinite is derived from stem, root, bark and leaf tissues that have undergone humification prior to preservation (Cohen and Spackman, 1972; Diessel, 1985, 1986, 1992). Its most characteristic petrographic property is its reflectance in relation to liptinite and inertinite. It usually exhibits higher reflectance (and therefore appears brighter) than liptinite in coals between brown and medium-volatile bituminous rank, and lower reflectance than inertinite in coals up to low-volatile bituminous rank (Australian Standard AS 2856.2-1998, 1998). For the purposes of this study, vitrinite has been subdivided into two subgroups; telovitrinite and detrovitrinite (Table 3.2).

**Table 3.2.**
Properties of macerals of the vitrinite group (from Australian Standard AS 2856.2-1998, 1998).

| Maceral | Shape and size | Colour / reflectance | Polishing relief | Origin |
|---|---|---|---|---|
| Telovitrinite | Discrete bands or elongate fragments, subparallel to bedding and exceeding 0.02 mm in largest dimension. | Varies between dark grey and white depending on rank. Generally lighter than detrovitrinite. | Lower than inertinite and liptinite, but usually slightly higher than detrovitrinite. | Plant tissue, especially wood, that has survived burial intact and displays remnants of cellular structure. |
| Detrovitrinite | Often occurs as groundmass material, incorporating smaller clasts of other macerals. | Varies between dark grey and white depending on rank. Generally darker than telovitrinite. | Lower than inertinite and liptinite, and usually slightly lower than telovitrinite. | Plant debris deposited as fine-grained attritus prior to undergoing humification. |

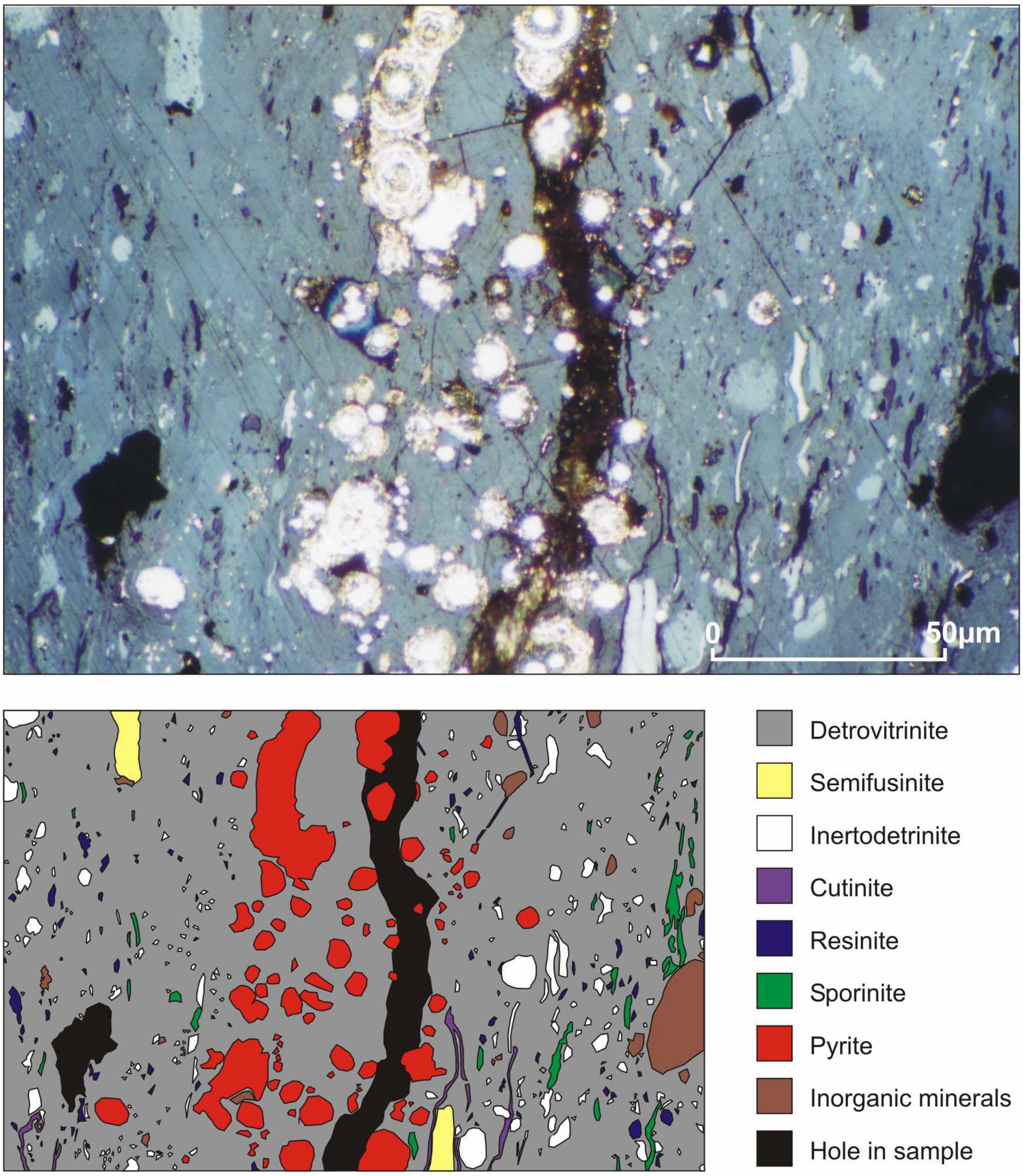

**Figure 3.5.** Photomicrograph of a polished block from the Sunnyside coal in reflected light and oil immersion. The sketch below provides a guide to the macerals shown.

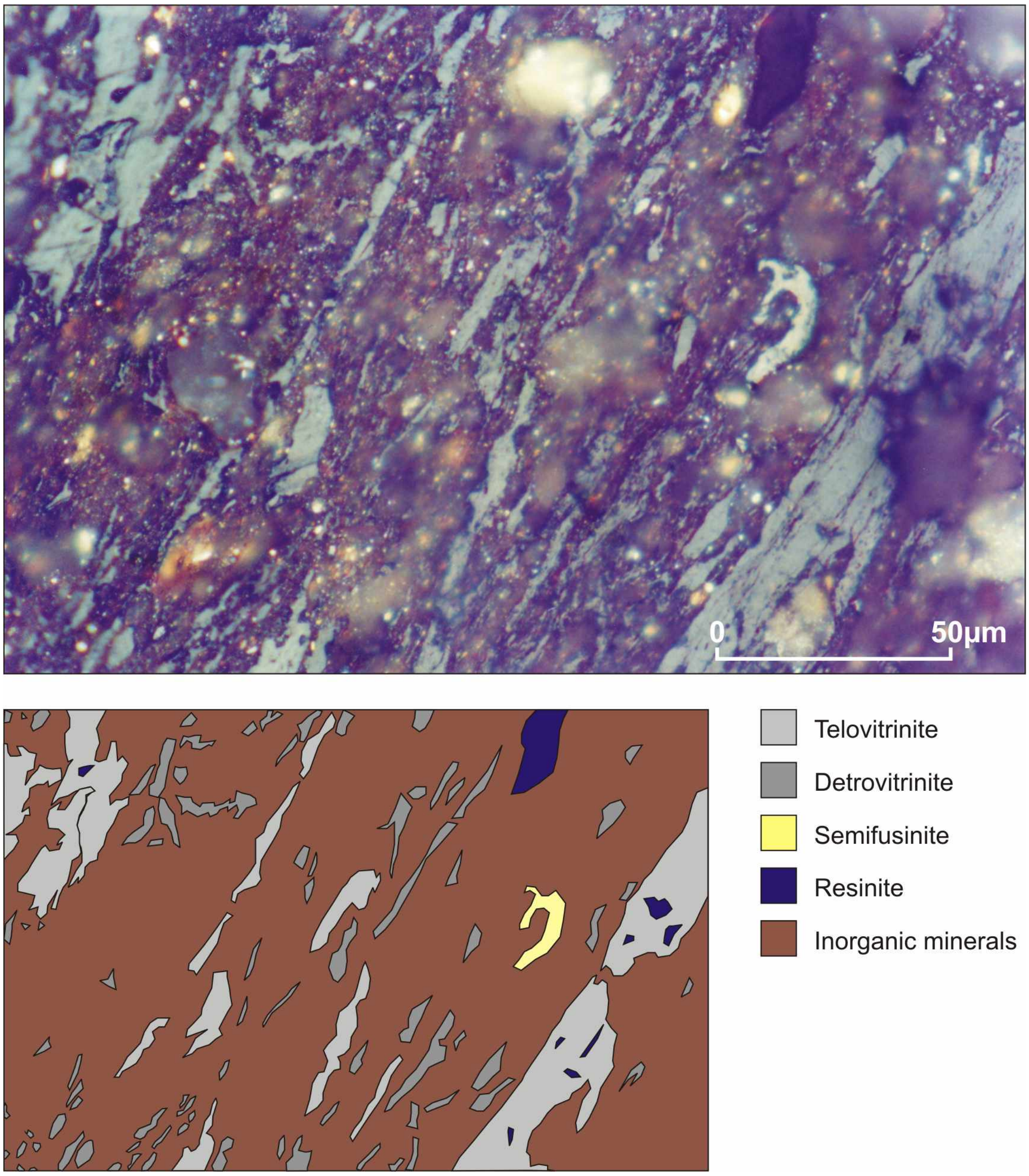

**Figure 3.6.** Photomicrograph of a polished block from the Sunnyside coal in reflected light and oil immersion. The sketch below provides a guide to the macerals shown.

### 3.4.2 Liptinite group

Liptinite macerals are derived from oily, waxy and resinous plant tissues such as spores, resin and cuticles (Cohen and Spackman, 1972; Diessel, 1986, 1992). Their most distinctive characteristic is their low reflectance relative to vitrinite and inertinite, however, this can make them difficult to recognise where large amounts of low reflecting mineral matter are present (Australian Standard AS 2856.2-1998, 1998). For the purposes of this study, three liptinite macerals have been differentiated, their characteristics are outlined in Table 3.3.

**Table 3.3.**
Properties of macerals of the liptinite group (from Australian Standard AS 2856.2-1998, 1998).

| Maceral | Shape and size | Colour / reflectance | Polishing relief | Origin |
|---|---|---|---|---|
| Sporinite | Round, triangular or spindle form in section. Size varies from 0.01 mm to 0.25 mm. | Rusty brown, dark grey or black. Exceeds that of vitrinite at very high ranks. | Shows marked polishing relief in lower ranked coals, but less so in high rank coal. | Spores and pollen grains. |
| Cutinite | Serrated or non-serrated bands of varying thickness. | Black to dark grey. Exceeds that of vitrinite at very high ranks. | Displays positive relief relative to vitrinite except at very high ranks. | Cuticles of needles, shoots, stalks, leaves, roots and stems. |
| Resinite | Discrete circular, oval or rod-shaped forms with a size consistent with the dimensions of plant cells. | Black to dark grey with paler internal zones. Reflectance is between that of other liptinites and vitrinite. | Weak to no relief where it occurs as impregnations, more marked relief when it occurs as discrete bodies. | Resins, fats, waxes and oils. |

### 3.4.3 Inertinite group

The inertinite maceral group is composed of plant tissues that have undergone a degree of oxidation due to partial combustion or biological degradation (Cohen and Spackman, 1977; Scott, 1989). They are primarily distinguished from vitrinite and liptinite on the basis of their higher reflectance (Australian Standard AS 2856.2-1998, 1998). For the purposes of this study five different inertinite macerals have been differentiated, their diagnostic characteristics are outlined in Table 3.4.

**Table 3.4.**
Properties of macerals of the inertinite group (from Australian Standard AS 2856.2-1998, 1998).

| Maceral | Size and shape | Colour / reflectance | Polishing relief | Origin |
|---|---|---|---|---|
| Micrinite | Granular, less than 0.002 mm in diameter. | Light grey to white, high reflectance. | No apparent relief relative to vitrinite. | Fine detritus or product of reactions. |
| Macrinite | Collomorphous texture, often as a groundmass. Lower size limit 0.03 mm. | Light grey to white, slightly higher reflectance than vitrinite. | Low or no relief relative to vitrinite. | Jellified plant material that has undergone some oxidation. |
| Semifusinite | Bands, lenses or irregular masses in excess of 0.03 mm. Cell tissues often well preserved. | Light grey to white. Higher reflectance than associated vitrinite. | Usually shows positive relief relative to vitrinite. | Partial combustion or biological oxidation of plant material. |
| Fusinite | As for semifusinite. | White or yellow. High reflectance. | High positive relief. | As for semifusinite. |
| Inertodetrinite | Fragments of inertinite less than 0.03 mm in their longest dimension. | Light grey to white to yellow-white. Higher reflectance than vitrinite. | Usually shows positive relief relative to vitrinite. | Fragments of cell walls from fusinite and semifusinite. |

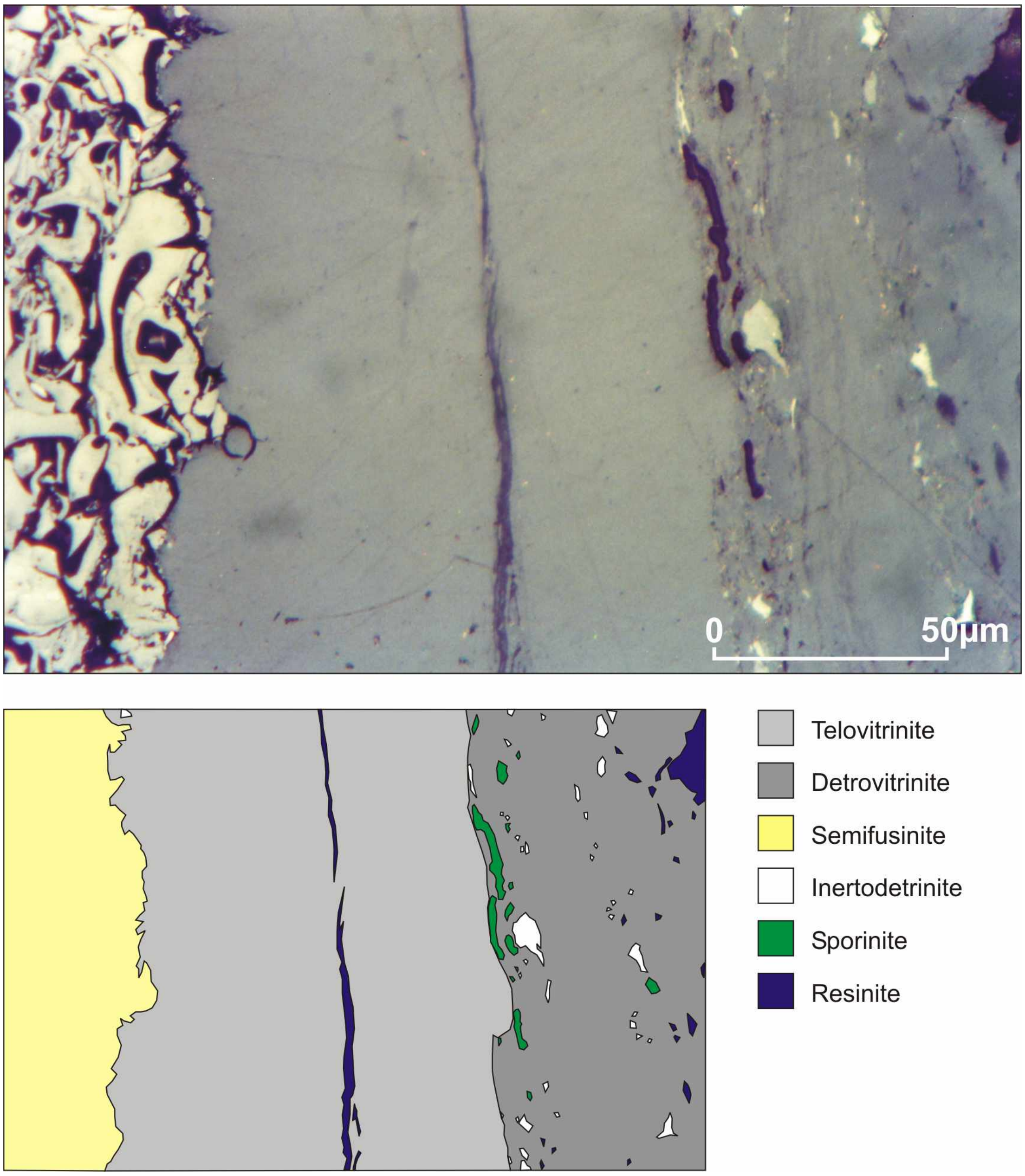

**Figure 3.7.** Photomicrograph of a polished block from the Sunnyside coal in reflected light and oil immersion. The sketch below provides a guide to the macerals shown. Note the contrast between the telovitrinite in the centre of the frame, and the less reflective detrovitrinite to the right. The large semifusinite grain to the left of the frame shows a high degree of preservation of cellular structure.

### 3.4.4 Inorganic minerals group

The inorganic minerals group encompasses all inorganic material found in coals (Spears, 1987; Ward and Swaine, 1995). They are generally relatively easy to differentiate from organic matter due to their mottled texture and their very high or very low reflectance. However, it is generally difficult to distinguish between different types of inorganic minerals in reflected light (Australian Standard AS

2856.2-1998, 1998). For the purposes of this study the group is subdivided into two groups, their characteristics are defined in Table 3.5. Epigenetic minerals (i.e. minerals that have formed after deposition in cracks in the coal) are not counted in this study, as they have no relevance to conditions at the time of peat formation.

**Table 3.5.**
Properties of the inorganic minerals group (from Australian Standard AS 2856.2-1998, 1998).

| Mineral | Size and shape | Colour / reflectance | Polishing relief | Origin |
|---|---|---|---|---|
| Detrital minerals | Various. Sand grains typically appear as discrete oval bodies. Clay minerals as bands or groundmass. | Various shades of grey and brown. Low reflectance for clay minerals and quartz. Low to medium for carbonate grains. | Varies depending on composition of grains. | Sand and silt grains transported into the mire, plus inherent inorganic material produced by plants. |
| Syngenetic pyrite | Mainly framboidal, concentric and radial forms. | Very high reflectance and brassy yellow colour. | High polishing relief. | Forms in peats with marine or brackish water. |

## 3.5 VITRINITE REFLECTANCE ANALYSIS

Vitrinite reflectance is a measure of the intensity of light reflected back from polished surfaces of vitrinite grains (Seyler, 1943, McCartney, 1952, Murchinson, 1958). Since this property correlates closely with a coal’s moisture, volatile, carbon and hydrogen contents, it has been used for many years as a method of determining coal rank. This is an indication of the degree of coalification (diagenesis) that a coal has undergone (Taylor et al., 1998). More recently, however, it has been recognised that subtle variations in vitrinite reflectance occur within isometamorphic vertical sections through coal seams. Such variations can only be attributed to conditions at the time of peat formation, and can therefore be utilised as palaeoenvironmental indicators. In general, higher vitrinite reflectance values indicate slight oxidation of the vitrinite precursors due to dry conditions at the time of deposition, whilst lower reflectance values are associated with wetter conditions and marine or brackish influence in the mire groundwater (Diessel 1996; Diessel and Gammidge, 1998).

The mean random vitrinite reflectance of each sample used in this study was calculated from 50 measurements, obtained in accordance with Australian Standard AS 2486-1989 (1989). The proportion of light reflected back from the surface of vitrinite grains in each sample was recorded using the equipment shown in Figure 3. A monochromatic filter was used to produce a light wavelength of 546 nm, and the voltage input to the light source was stabilised in order to ensure that no fluctuations in light intensity occurred between measurements. The photomultiplier was also calibrated between samples, using blocks of leucosapphire and yttrium-aluminium garnet, which have known reflectance values of 0.61% and 0.91% respectively. This methodology enables measurements to be obtained to approximately ± 0.01% accuracy (Australian Standard AS 2486-1989, 1989).

In order to minimise the influence of differences in the nature of the original plant precursors, measurements were restricted to the structured subgroup telovitrinite (Fig. 3.7, Table 3.2). Telovitrinite also provides more reliable, homogenous polished surfaces than detrovitrinite, thus further improving the reliability of reflectance measurements (Diessel, 1996; Diessel and Gammidge, 1998).

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# CHAPTER 4: STUDY AREA

*The study area selected for this project is located in the Book Cliffs of eastern Utah, USA. This chapter contains a brief review of previous studies of the area, and provides additional information on the stratigraphy and sedimentology of the Blackhawk Formation in order to support statements made in Chapters 5 to 7.*

## 4.1 INTRODUCTION

The Book Cliffs form a sinuous escarpment, up to 300 m high, which runs for almost 300 km from the town of Helper in Utah to Grand Junction in Colorado (Fig. 4.1). The numerous canyons that cut the cliffs add a three-dimensional quality to the exposure. The rocks in the area have a shallow structural dip (between 3° and 7° E), contain no major folds or faults, and have little vegetation cover due to the semi-desert climate of south-western USA (Fig. 4.2 A). These factors enable stratal surfaces and rock bodies to be traced over many kilometres, and make the Book Cliffs one of the world's foremost localities for outcrop-based sedimentological and stratigraphic research (Van Wagoner, 1995; Howell and Flint, 2003).

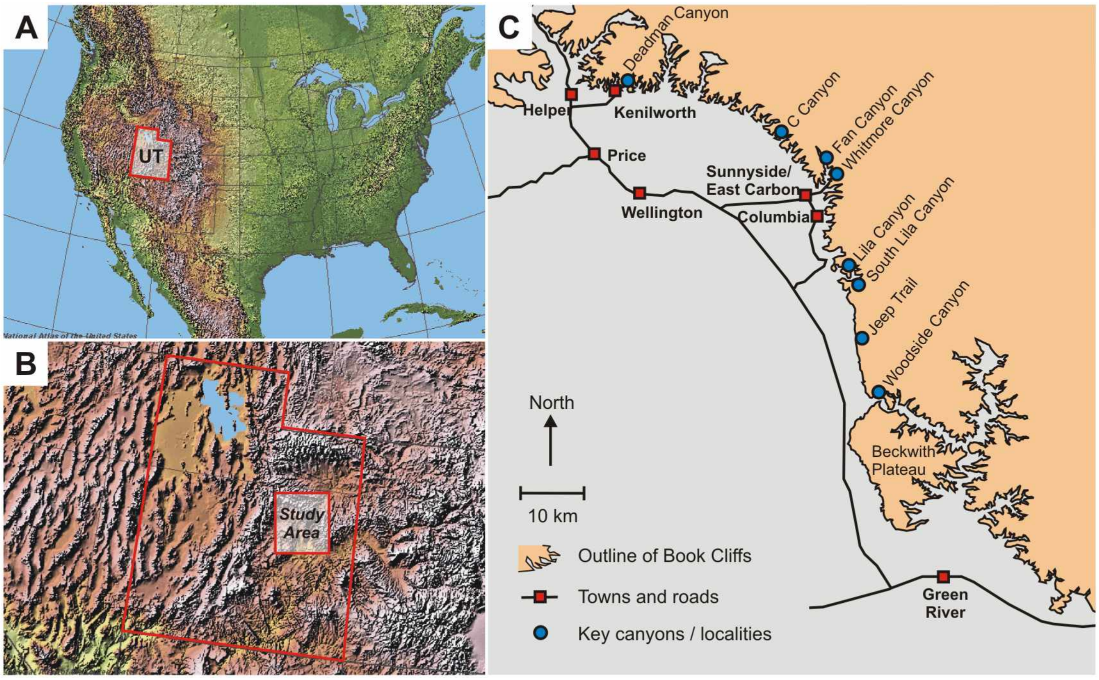


**Figure 4.1.** (A) Position of Utah state boundaries on relief map of North America. (B) Location of study area in relation to Utah state boundaries (maps from http://nationalatlas.com). (C) Outline map of the Book Cliffs with position of towns and key localities (modified from Howell and Flint, 2003).

The Book Cliffs have long been a focus for geological studies. During the late nineteenth and early twentieth centuries, the interest in the area was primarily driven by the exploration and exploitation of its numerous coal seams. From the earliest coal discovery in 1854 (Watt, 1997), the Book Cliffs area played a major role in making Utah one of the United States' largest coal producers by the end of the nineteenth century (Fig. 4.2 B, D). The number of mines in the area steadily declined throughout the twentieth century, however, there are several still active today (Fig. 4.2 B, C). These mines further enhance the three-dimensionality of the Book Cliffs' exposure by enabling logging and sampling of coals deep within the cliffs.

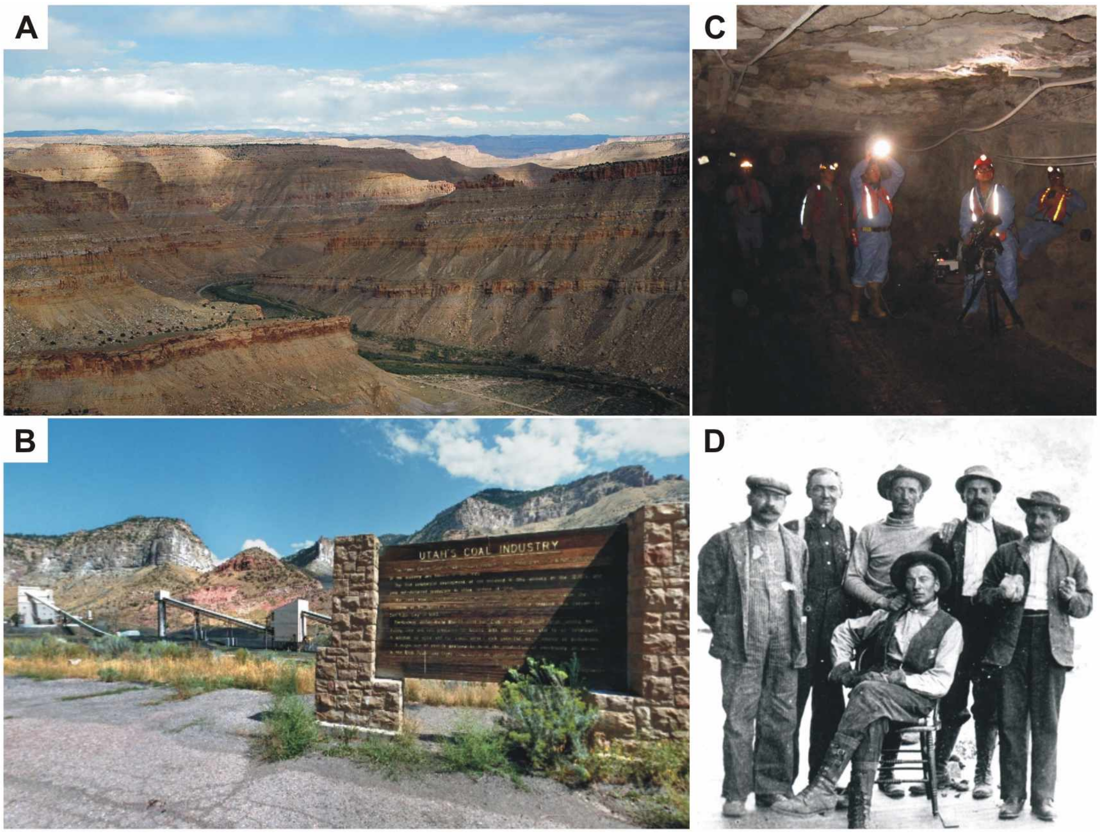


**Figure 4.2.** (A) Photograph of Woodside Canyon in the Book Cliffs. This view illustrates the excellent exposure and sub-horizontal bedding of the strata in the study area. (B) A board commemorating the history of the coal mining industry in Utah standing in front of the modern mine workings of the Castlegate mine. (C) Inside an active coal mine in Deer Creek during fieldwork in 2001. (D) A group of Utah coal miners circa 1900 (photograph from http://altahistory.org).

More recently the Book Cliffs have been extensively studied as one of the classic examples of wave-dominated shoreface and delta systems (e.g. Young, 1955, 1957; Balsley, 1980). Since the 1980s they have also become one of the key localities for the development and testing of high-resolution sequence stratigraphic concepts (e.g. Van Wagoner et al., 1990; O'Byrne and Flint, 1995; Pattison, 1995; Van Wagoner, 1995; Howell and Flint, 2003). The well understood sequence stratigraphic evolution of the shallow-marine strata in the area is essential to this study, as it provides a framework with which to calibrate the coal sequence stratigraphic models presented in Chapters 5 to 7.

## 4.2 DEPOSITIONAL SETTING

### 4.2.1 Palaeogeography and tectonic setting

The opening of the North Atlantic Ocean during the Cretaceous Epoch was associated with the westward drift of the North American Plate. This in turn led to the formation of a subduction zone along the western margin of the continent, where the Farralon Plate was forced beneath it (Cross, 1986). The associated period of mountain building is known as the Sevier Orogeny, and resulted in the formation of a narrow mountain range that ran approximately north-south from Alaska to New Mexico (Armstrong, 1968; Heller et al., 1986). The combination of flexural loading caused by the newly uplifted mountains, and the dynamic topographic effects of the subducting oceanic plate led to the formation of a retro-arc foreland basin further to the east, called the Western Interior Basin (Cross, 1986; DeCelles et al., 1995; Booth, 2000). Throughout much of the Late Cretaceous this basin was occupied by an epicontinental seaway, into which sediments eroded from the Sevier Mountains were deposited. The seaway extended for more than 5000 km from Northern Canada to the Gulf of Mexico (Fig. 4.3), was approximately 1500 km wide, and up to 500 m deep (Williams and Stelck, 1975; Kauffman, 1977; 1984).

The high sediment supply associated with the wet, subtropical climate (Kauffman, 1977, 1984) and proximity to the Sevier Mountains caused the depositional system to prograde into the basin. Consequently the shoreline migrated eastwards through time, and the fill of the basin became increasingly non-marine upwards (Speiker, 1949; Young, 1955, 1957). The subtropical climate also resulted in the formation of delta plains with luxuriant vegetation behind the shoreline. These included regionally extensive peat swamps that gave rise to the thick coal measures observed in the area today (Kauffman, 1977, 1984).

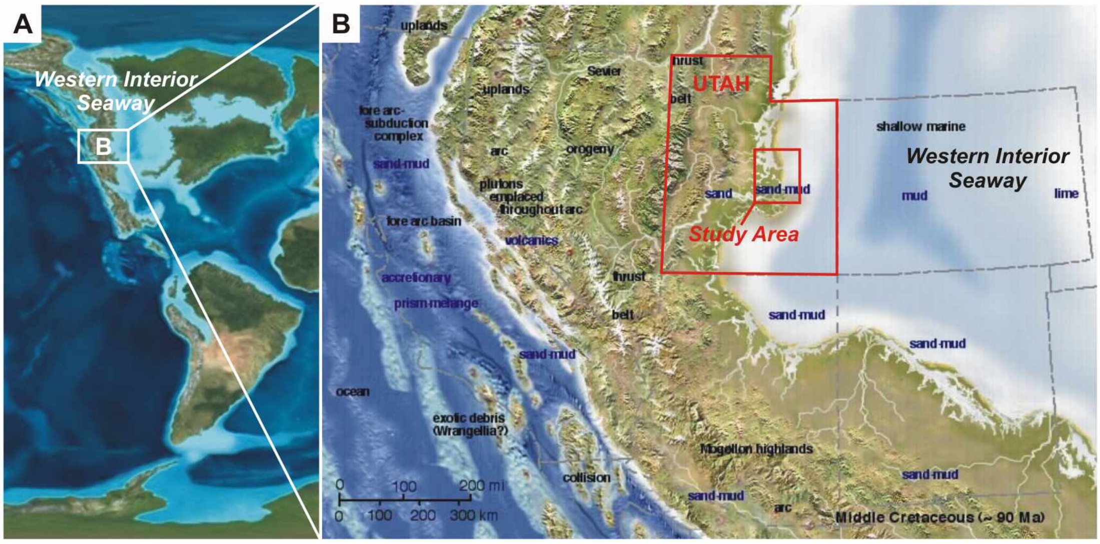


**Figure 4.3.** (A) Late Cretaceous palaeogeography of North and South America, showing the position of the Western Interior Seaway. (B) Location of study area in relation to the western margin of the Western Interior Seaway (palaeogeographic reconstructions by R.C. Blakey; http://jan.ucc.nau.edu/~rcb7/).

### 4.2.2 Controls on accommodation creation

The relative role of various controls on accommodation creation in the Western Interior Basin has been subject to considerable debate in the literature. Some authors have attempted to correlate changes in the fill of the basin with the global eustatic sea-level curve using ammonite biostratigraphy (e.g. Van Wagoner, 1995), while others (e.g. Posamentier and Allen, 1993; Yoshida et al., 1998) have suggested that tectonic subsidence played a more significant role in controlling the rate of accommodation creation, especially in the area closest to the thrust belt. High-frequency relative sea-level changes have also been linked to Milankovich processes, however, there are some difficulties involved in this due to the paucity of evidence for continental ice-caps during the Cretaceous (Howell and Flint, 2003). The most likely scenario is that no single control was responsible for driving changes in the rate of accommodation creation, and that changes in the fill of the basin reflect high-frequency glacio-eustatic sea-level cycles superimposed on lower-frequency tectonically driven cycles of thrust sheet emplacement and erosion (Fig. 4.4).

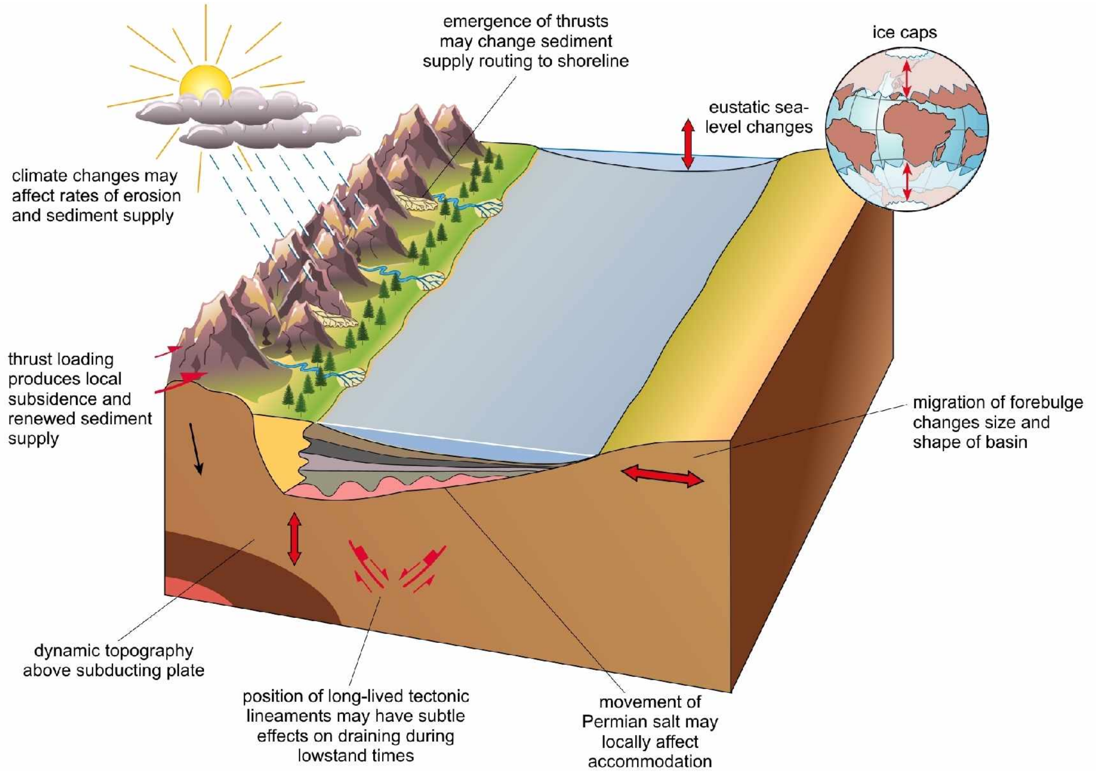


**Figure 4.4.** Schematic block diagram to show factors influencing the rate of accommodation creation in the Western Interior Basin. Note that there are complex feedback systems between variables, which makes it difficult to isolate the effect of changes in a single variable (from Howell and Flint, 2003).

## 4.3 STRATIGRAPHY

### 4.3.1 The Blackhawk Formation

The shallow-marine clastic sediments that were deposited along the western margin of the Western Interior Basin during the Late Cretaceous are collectively known as the Mesa Verde Group (Fig. 4.5). Towards the east, these deposits overlie and inter-tongue with offshore-marine mudstones of the Mancos Shale (Young, 1955, 1957. In the Book Cliffs area, the Mesa Verde Group is subdivided into the Star Point and Blackhawk Formations. This study is focused on the Blackhawk Formation. Young (1955) identified six lithostratigraphic members within the Blackhawk Formation, each of which represents a shallow-marine shoreface complex, separated by tongues of marine shale. Immediately landward of these shallow-marine members is a 300 m thick wedge of undifferentiated coastal plain deposits, which contains numerous thick coal seams. Also time-equivalent are the sandstones and heterolithic strata of the Prairie Canyon Member, which represents a series of lowstand shoreline systems (Hampson et al., 1999; Howell and Flint, 2003).

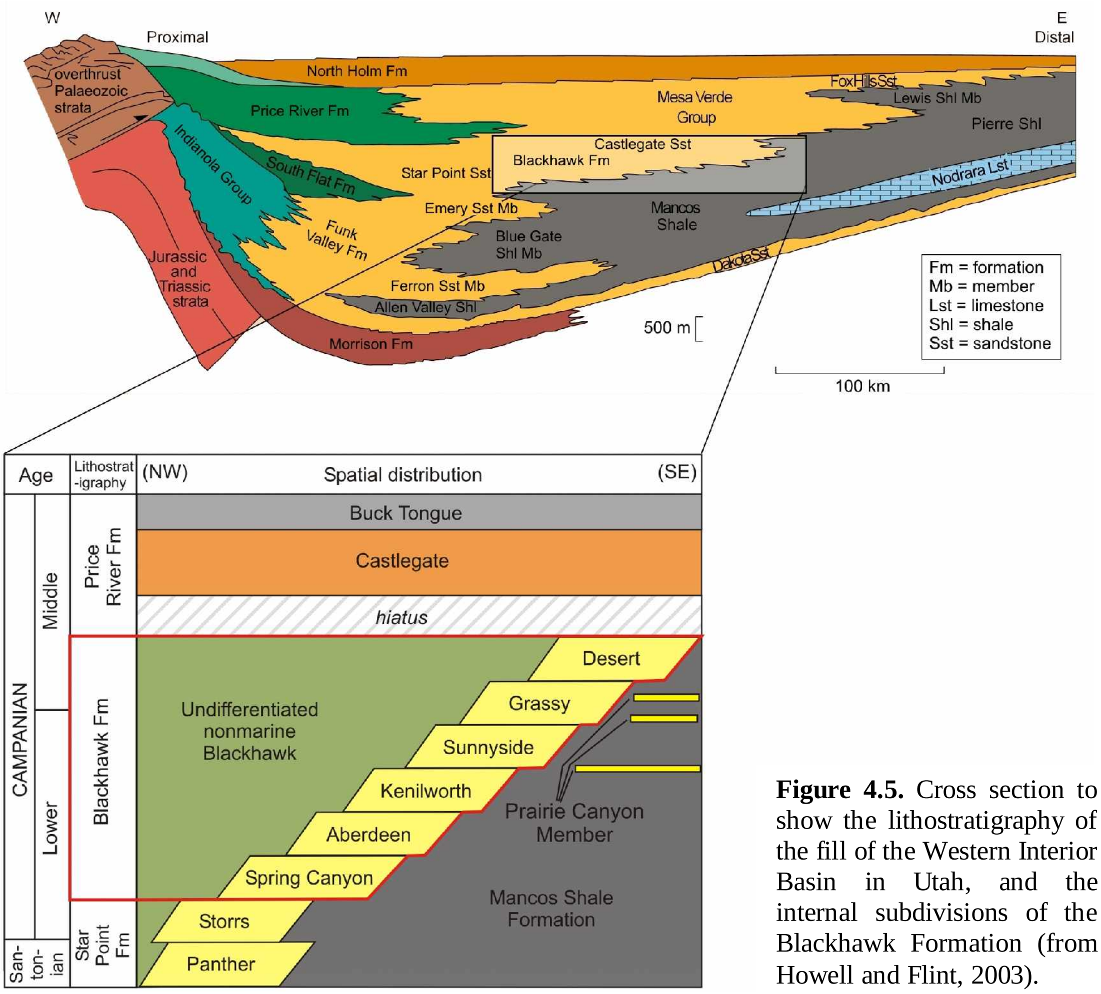
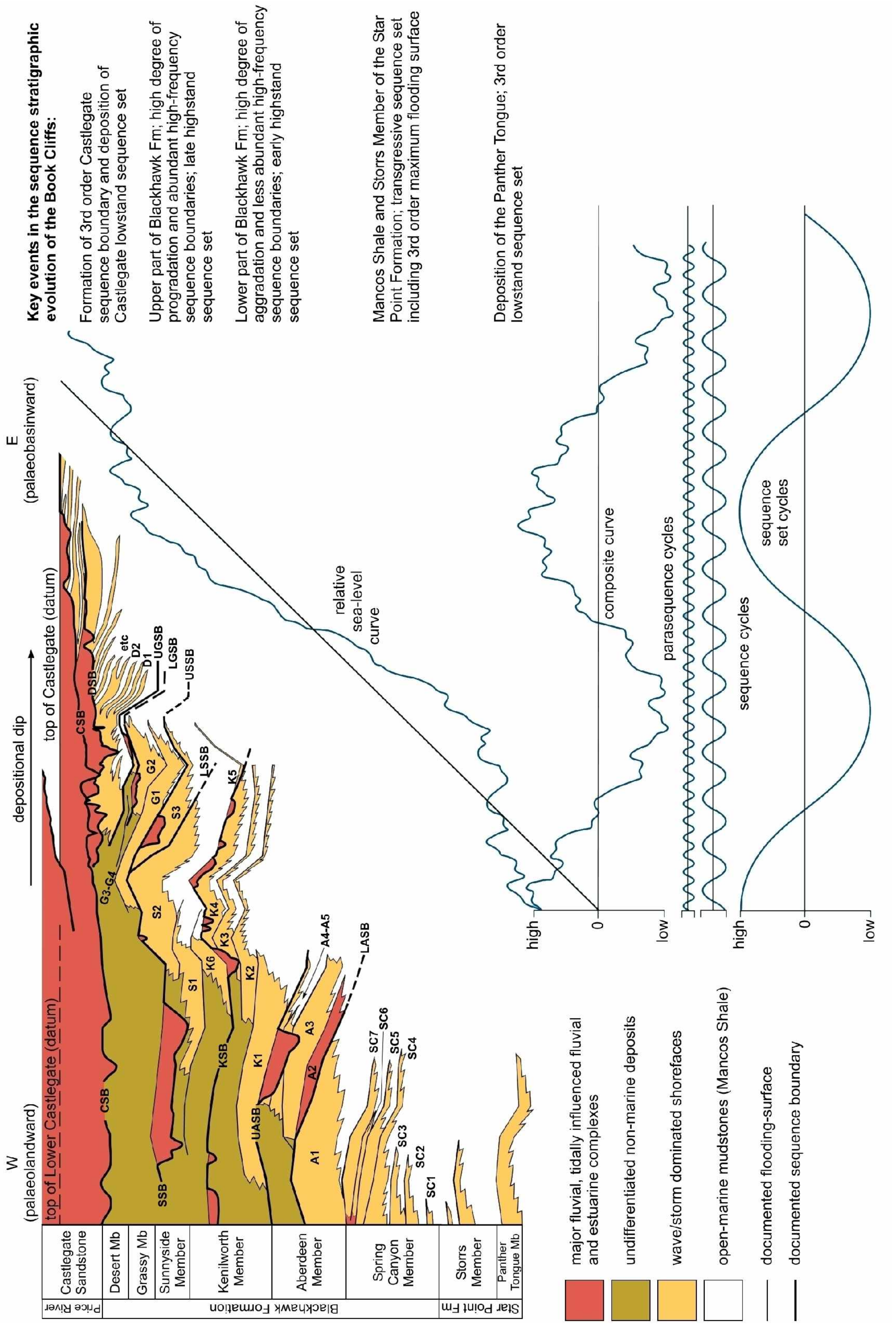


**Figure 4.5.** Cross section to show the lithostratigraphy of the fill of the Western Interior Basin in Utah, and the internal subdivisions of the Blackhawk Formation (from Howell and Flint, 2003).

The Blackhawk Formation is interpreted as a third-order, prograding highstand systems tract, which contains a number of higher frequency fourth-order sequences (Van Wagoner 1995; Howell and Flint, 2003). Using the terminology of Mitchum and Van Wagoner (1991) it is therefore also a highstand sequence set. Ammonite-based correlation with the geological time-scale indicates that the entire formation was deposited between 83.1 Ma and 79.5 Ma (Fouch et al., 1983). Each of the six lithostratigraphic members is therefore assumed to represent approximately 500 Ka. There is a change from aggradational to strongly progradational stacking of individual marine parasequences towards the top of the formation (Fig. 4.6). Combined with an upward decrease in the vertical spacing of fourth-order sequence boundaries, this indicates a long-term decrease in accommodation creation, which culminates in a third-order sequence boundary at the base of the overlying Castlegate Sandstone (Van Wagoner, 1995; Taylor and Lovell, 1995; Howell and Flint, 2003).



**Key events in the sequence stratigraphic evolution of the Book Cliffs:**

Formation of 3rd order Castlegate sequence boundary and deposition of Castlegate lowstand sequence set

Upper part of Blackhawk Fm; high degree of progradation and abundant high-frequency sequence boundaries; late highstand sequence set

Lower part of Blackhawk Fm; high degree of aggradation and less abundant high-frequency sequence boundaries; early highstand sequence set

Mancos Shale and Storrs Member of the Star Point Formation; transgressive sequence set including 3rd order maximum flooding surface

Deposition of the Panther Tongue; 3rd order lowstand sequence set

**Figure 4.6.** Depositional-dip cross-section through the Blackhawk Formation (excluding the Prairie Canyon Member) alongside a model to show the interaction of various scales of sea-level cyclicity throughout its deposition. The letters SC1, A2, S3 etc refer to the parasequences within each member, whilst LASB, SSB etc refer to sequence boundaries. Note the change from aggradational to strongly progradational stacking of marine parasequences towards the top of the formation, and the upward decrease in the vertical spacing of sequence boundaries (modified from Howell and Flint, 2003).

### 4.3.2 The Sunnyside Member

A significant part of this study (Chapters 5 and 6) is specifically focused on the Sunnyside Member, which contains the thickest and most laterally extensive coal within the Blackhawk Formation (Doelling, 1972; Bohacs and Suter, 1997). This member was chosen because the stratigraphic relationships within it suggest that the Sunnyside coal should contain expressions of up to three key sequence stratigraphic surfaces (Howell and Flint, 2003; Howell et al., in press). It is has also been extensively mined in the Book Cliffs area (Doelling, 1972; Doelling et al., 1979). Access to these mines increased the number of potential sampling sites, and provided high quality, unweathered samples. This is particularly important for vitrinite reflectance analysis, as previously discussed in Chapter 2.

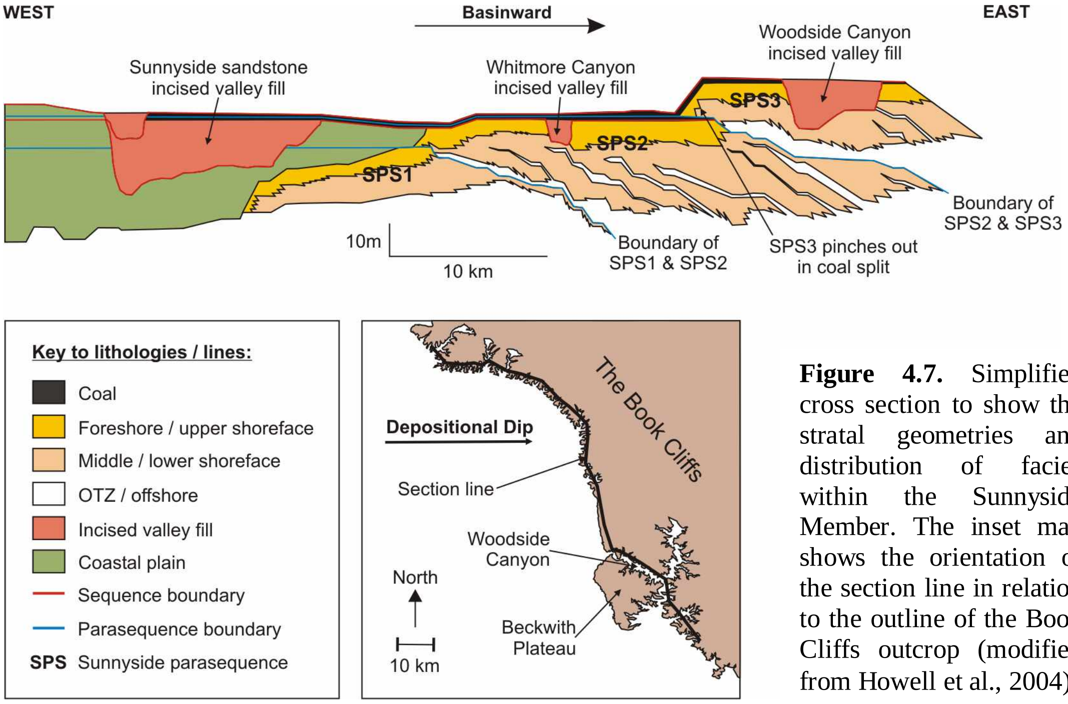


**Figure 4.7.** Simplified cross section to show the stratal geometries and distribution of facies within the Sunnyside Member. The inset map shows the orientation of the section line in relation to the outline of the Book Cliffs outcrop (modified from Howell et al., 2004).

Figure 4.7 shows a summary of the stratal geometries and distribution of facies within the Sunnyside Member based on 29 outcrop logs from Howell et al. (in press). A more detailed version, including the original logs, can be found in Chapter 6 of this thesis. Note that the section line runs highly obliquely to depositional dip for part of its length, as the outcrop is generally only accessible along the front of the cliffs. In order to produce a depositional dip cross section, it is therefore necessary to project the positions of the logs onto a depositional dip line. In some cases this means that logs are projected laterally over 10’s of kilometres of depositional strike. Although not ideal, this approach can be justified due to the lack of lateral facies variation observed along the north-south oriented stretch of the Book Cliffs.

The landward pinch-out of the third Sunnyside parasequence within the coal (Fig. 4.7) indicates that the seam spans the formation of two shallow-marine parasequences. On this basis, the thick unsplit coal in the northwestern part of the study area should contain an expression of the flooding surface that marks the boundary between Sunnyside parasequences two and three. The coal is also cut out and replaced by incised valley fill deposits at two different stratigraphic levels. This suggests that it may also span the formation of two fourth-order sequence boundaries[1]. Identifying the expressions of these key surfaces within the Sunnyside coal is one of the central aims of this study, as discussed in Chapter 1.

#### 4.3.2.1 Coal decompaction and stratigraphic correlation

The thickness of the Sunnyside coal is shown on an uncompacted basis in stratigraphic correlations throughout this thesis, as the relationship between the coal and Sunnyside parasequences two and three is clear without adjusting the measured thicknesses. It should also be noted that the practice of decompacting coals in stratigraphic sections is often over zealously applied by sedimentologists. Firstly the ratio of peat to coal compaction is not easy to determine and ratios as low as 1.2 and as high as 30 can be found in the literature (Elliott, 1985; White, 1986; Winston, 1986; Stout and Spackman, 1989; Nadon, 1998). Secondly, and perhaps more importantly, studies of the timing of peat to coal compaction suggest that the majority of compaction occurs shortly after deposition due to autocompaction of the peat (Stout and Spackman, 1989; Nadon, 1998). On this basis, sections showing a 50 m thick layer of peat for a 5 m thick coal are somewhat unrealistic.

The fact that the Sunnyside coal represents a longer period of deposition than the same thickness of clastic sediments is fully acknowledged, however, and is discussed in detail with respect to the chronostratigraphic correlation of the Sunnyside Member presented in Chapter 6 of this thesis.

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[1] The upper Sunnyside sequence boundary has been previously described as the lower Grassy sequence boundary (O’Byrne and Flint, 1995).

## 4.4 FACIES AND DEPOSITIONAL ENVIRONMENTS

The sedimentary deposits in the Blackhawk Formation can be grouped into marine, coastal-plain, barrier island / lagoon, and estuarine facies associations (Howell and Flint, 2003). The characteristics of each of these groups are described below, with the aid of a series of block diagrams and schematic graphic logs (Figs. 4.8 and 4.10 to 4.12). Photographs of selected facies are shown in Figure 4.9.

### 4.4.1 Marine facies associations

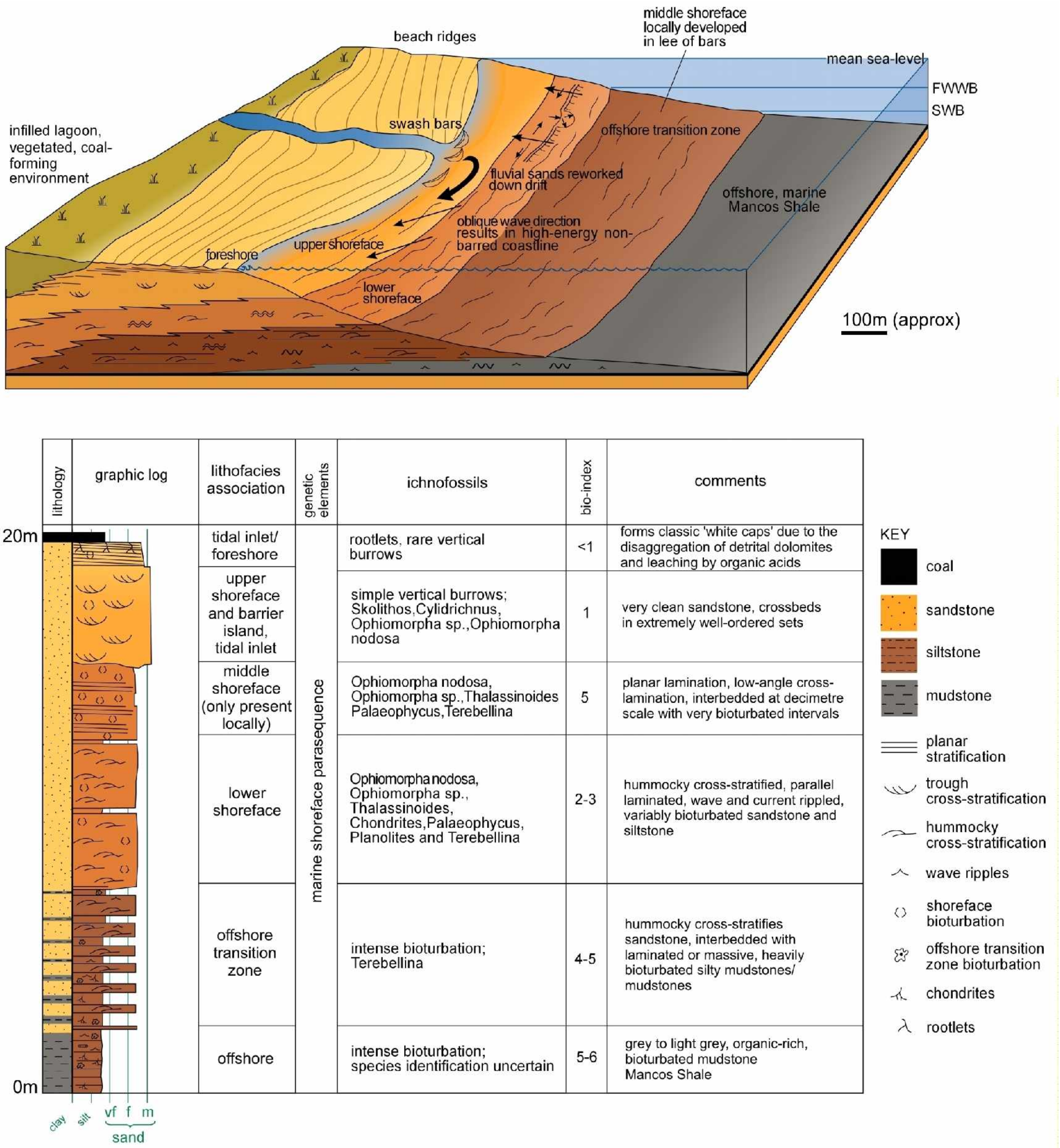
The marine strata in the Blackhawk Formation were deposited in a wave-dominated delta / shoreface setting (Young, 1955; 1957). Sediment introduced to the shoreline by fluvial systems was remobilised by fairweather and storm wave processes, and redistributed along the coastline as a series of elongate, shoreline-parallel deposits. Figure 4.8 shows a schematic representation of this depositional system, along with a graphic log of a typical vertical succession, which contains six lithofacies associations that can be summarised as follows.

Intensely bioturbated, offshore marine mudstones pass upward into interbedded hummocky cross-stratified sandstones and laminated / bioturbated mudstones (Fig. 4.9 A). These deposits belong to the offshore transition zone (OTZ), which represents the area between storm and fairweather wave-bases. The OTZ deposits are overlain by amalgamated hummocky cross-stratified (HCS) sandstones of the lower shoreface, representing deposition by storms in water depths between storm wave-base and fairweather wave-base. The top of the amalgamated HCS beds may be locally overlain by a heavily bioturbated middle shoreface unit. Where present, this interval consists of fine-grained, planar laminated sandstones with a wide range of open marine ichnotaxa including *Ophiomorpha, Thalassinoides, Palaeophycus, Cylindrichnus* and *Skolithos* (Howell et al., in press). These in turn are overlain by the trough cross-stratified sandstones of the upper shoreface, which represent the movement of sand on the sea-bed during fairweather conditions (Fig. 4.9 B). The trough cross stratification within these deposits is generally very well ordered with a constant thickness of 10 – 40 cm, and little or no bioturbation. The succession is capped by planar-laminated foreshore sandstones, the tops of which are often penetrated by roots from the vegetation that grew at the top of the beach (Fig. 4.9 C).

The clean, mineralogically and texturally mature deposits that occur beneath coals at the tops of these successions are commonly referred to as whitecaps (Young, 1955).

The coarsening upward profiles observed in the Blackhawk Formation (like that shown in the graphic log in Figure 4.8) are interpreted as marine parasequences (sensu Van Wagoner et al., 1990). The gradual shallowing upward is therefore interpreted as representing shoreface progradation into accommodation generated by rapid rises in relative sea-level (Posamentier et al., 1988; Kamola and Van Wagoner, 1995). The thickness of individual facies associations (e.g. the offshore transition zone) within such successions can be used to estimate the depths of the various wave-bases within the system (Howell and Flint, 2003). For the Blackhawk Formation, storm wave-base was typically between 15 and 40 m, whilst fairweather wave-base was between 5 and 15 m. The thickness of the planar-laminated unit at the top of the succession can also be used to estimate the tidal range, as it represents the inter-tidal swash zone on the beach. For the Blackhawk Formation this was typically between 2 and 4 m (mesotidal).

The shallow-marine deposits of the Blackhawk Formation also contain smaller scale coarsening upward successions known as ‘bedsets’ (Young, 1955; Balsley, 1980; Pattison, 1995; O’Byrne and Flint, 1995; Howell et al., in press). The boundaries between bedsets may superficially resemble parasequence boundaries in individual logged sections, however, when traced between sections they disappear into the upper shoreface (e.g. see SPS2 in Fig. 4.7). The lack of any landward dislocation in either the upper shoreface or the position of the shoreline means that they cannot have been formed by rises in relative sea-level, and are therefore not parasequence boundaries. Possible explanations for their formation include temporary changes in the sediment supply to the lower shoreface and OTZ, short-term changes to the position of the mean wave bases, and deep regional scours associated with large magnitude, low frequency storms (Howell et al., in press).



| lithology | graphic log | lithofacies association | genetic elements | ichnofossils | bio-index | comments |
|---|---|---|---|---|---|---|
| | | tidal inlet/ foreshore | marine shoreface parasequence | rootlets, rare vertical burrows | <1 | forms classic 'white caps' due to the disaggregation of detrital dolomites and leaching by organic acids |
| | | upper shoreface and barrier island, tidal inlet | | simple vertical burrows; Skolithos,Cylidrichnus, Ophiomorpha sp.,Ophiomorpha nodosa | 1 | very clean sandstone, crossbeds in extremely well-ordered sets |
| | | middle shoreface (only present locally) | | Ophiomorpha nodosa, Ophiomorpha sp.,Thalassinoides Palaeophycus,Terebellina | 5 | planar lamination, low-angle cross-lamination, interbedded at decimetre scale with very bioturbated intervals |
| | | lower shoreface | | Ophiomorpha nodosa, Ophiomorpha sp., Thalassinoides, Chondrites,Palaeophycus, Planolites and Terebellina | 2-3 | hummocky cross-stratified, parallel laminated, wave and current rippled, variably bioturbated sandstone and siltstone |
| | | offshore transition zone | | intense bioturbation; Terebellina | 4-5 | hummocky cross-stratifies sandstone, interbedded with laminated or massive, heavily bioturbated silty mudstones/ mudstones |
| | | offshore | | intense bioturbation; species identification uncertain | 5-6 | grey to light grey, organic-rich, bioturbated mudstone Mancos Shale |

**Figure 4.8.** Block diagram and graphic log to show the typical features of wave-dominated shoreface deposits in the Blackhawk Formation (not to scale vertically). The tidal range was typically 2 – 4 m, FWWB 5 – 15 m, and SWB 15 – 40 m (from Howell and Flint, 2003).

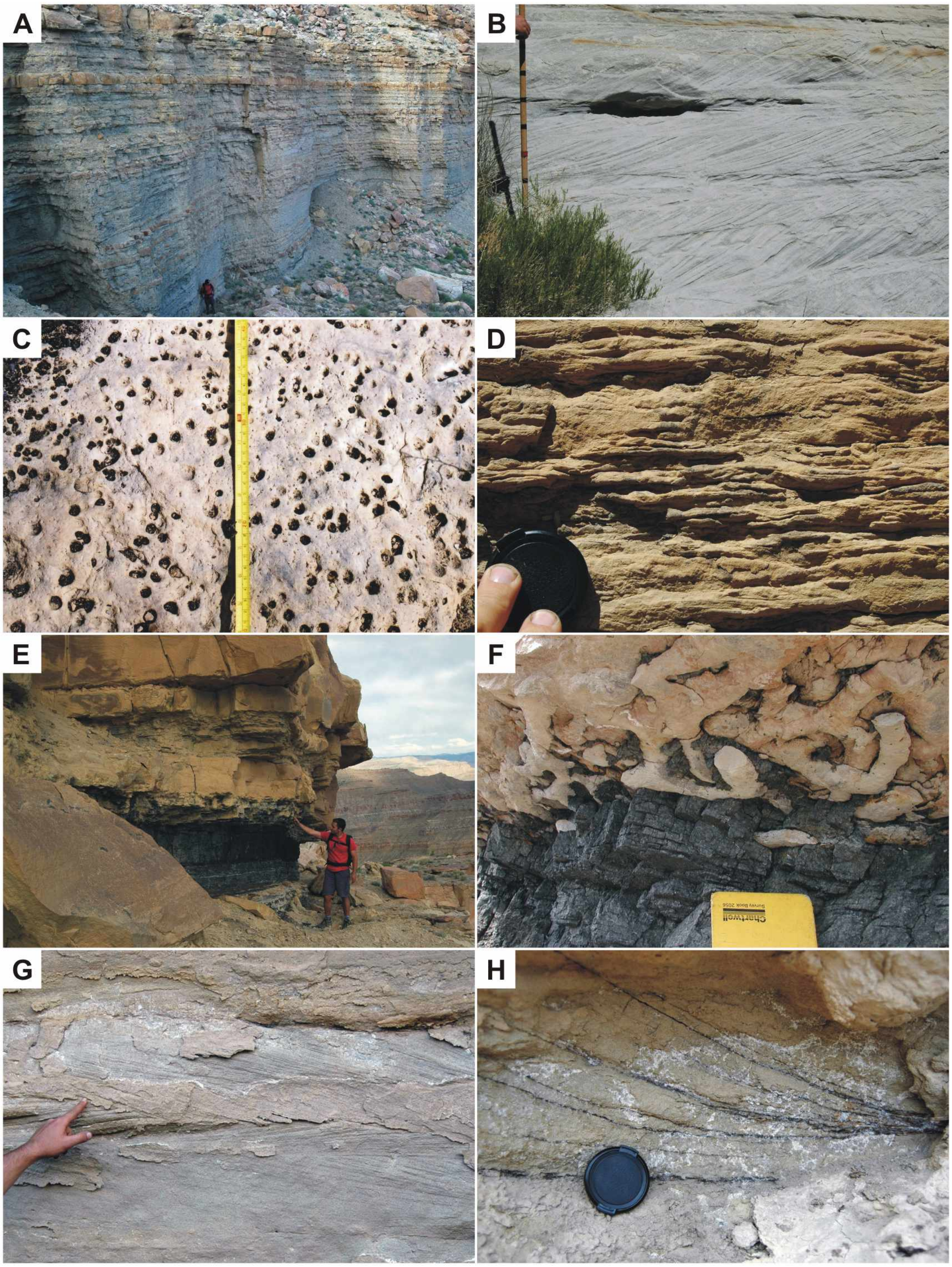


**Figure 4.9.** Photographs to show examples of the facies observed in the Blackhawk Formation: (A) Interbedded sandstones and siltstones of the offshore transition zone in Woodside Canyon. (B) Classic trough cross-bedded, upper shoreface deposits in Lila Canyon. (C) Top down view of heavily rooted, upper shoreface / foreshore deposits beneath the Sunnyside coal in Lila Canyon. (D) Finely interbedded lagoonal sandstones and siltstones overlying the Sunnyside coal in Lila Canyon. (E) The Sunnyside coal in Woodside Canyon. (F) Sand filled *Thalassinoides* burrows penetrating the top of the Sunnyside coal in South Lila Canyon. (G) Herringbone cross-stratification in tidally influenced estuarine deposits in Woodside Canyon. (H) Cross-stratified sandstones with organic-rich mud drapes in tidally influenced estuarine deposits in Woodside Canyon.

### 4.4.2 Barrier island and lagoonal facies associations

In addition to the progradational shoreline systems described above, the Blackhawk Formation also contains limited evidence for transgressive shoreline systems that were deposited when the rate of accommodation creation exceeded the rate of sediment supply (Van Wagoner et al., 1990; Kamola and Van Wagoner, 1995; Howell and Flint, 2003). These systems are characterised by barrier islands and lagoons, as illustrated in Figure 4.10.

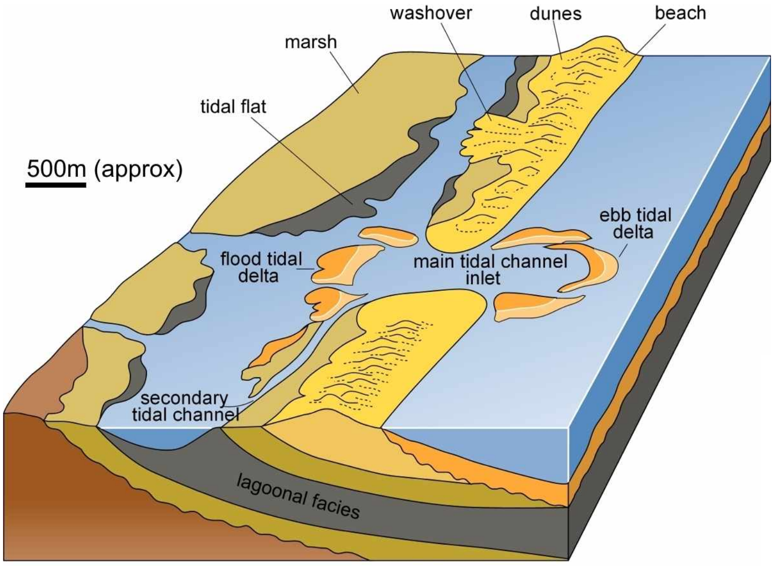


**Figure 4.10.** Block diagram to show the depositional setting associated with barrier island and lagoonal deposits of the Blackhawk Formation (not to scale vertically). From Howell and Flint (2003).

Barrier islands are narrow, sand-dominated features that form along wave-dominated shorelines during periods of relative sea-level rise. Depositional processes on the seaward side are comparable to those in shoreface systems, except that the lagoon on the landward side isolates the system from fluvial sediment supply (Leatherman et al., 1977; Hayes, 1980; Schwartz, 1982). Gradual relative sea-level rise causes the barrier to migrate in a landward direction through erosion on the seaward side and washover fan deposition on the landward side. The constant cannibalisation of the barrier means that preserved examples of these systems are relatively rare. Within the Blackhawk Formation they are mainly found in the high accommodation Spring Canyon Member (Fig. 4.6, Van Wagoner et al., 1990; Kamola and Van Wagoner, 1995; Howell and Flint, 2003).

The sheltered lagoon on the landward side of the system is gradually filled by sediment washed over from the front of the barrier, which is preserved as landward dipping, current-rippled to planar-laminated washover fans (Fig. 4.9 D). Small flood tidal deltas may also be deposited within the lagoon where the barrier is cut by tidal inlets. Once transgression ceases, the lagoon is filled with river-derived sediment prior to the progradation of the next shoreface system (Leatherman et al., 1977; Hayes, 1980; Schwartz, 1982).

### 4.4.3 Coastal plain facies associations

The 300 m thick coastal plain complex in the Blackhawk Formation has two main depositional components; fluvial channels / associated overbank deposits, and topographically raised, coal-forming peat swamps (Howell and Flint, 2003). Figure 4.11 shows a schematic representation of this depositional setting, along with a graphic log to show the typical expression of the main depositional components.

The fluvial channel deposits are usually between 1 and 4 m thick, with fining upward grain-size profiles, and lateral accretion surfaces that indicate deposition in meandering river systems. The amalgamated sand bodies produced by these rivers maybe up to 1 km wide, although the width of individual channels did not exceed 100 m (Howell and Flint, 2003). The overbank deposits consist of laminated mudstones, and fine-grained, rippled sandstone sheets. The widespread rooting that occurs throughout these deposits indicates that they were laid down during periodic flooding events when rivers burst their banks. The sandstone sheets represent rapid deposition in crevasse splay lobes (Howell and Flint, 2003).

The non-marine component of the Blackhawk Formation also contains at least 15 coal seams in excess of 1 m in thickness (Doelling, 1972; Bohacs and Suter, 1997). In the Sunnyside Member, coals account for the majority of the non-marine deposits in the area immediately landward of the shoreface deposits (Fig. 4.9 E). Most of the coals in the Blackhawk Formation have inorganic mineral contents below 10% (Doelling, 1972; Doelling et al., 1979). This suggests that they formed in topographically raised-mires, which were able to largely exclude clastic sediment. The coals usually overlie well-developed rooted horizons (Fig. 4.9 C), and have sharp tops with extensive *Thalassinoides* bioturbation (Fig. 4.9 F).

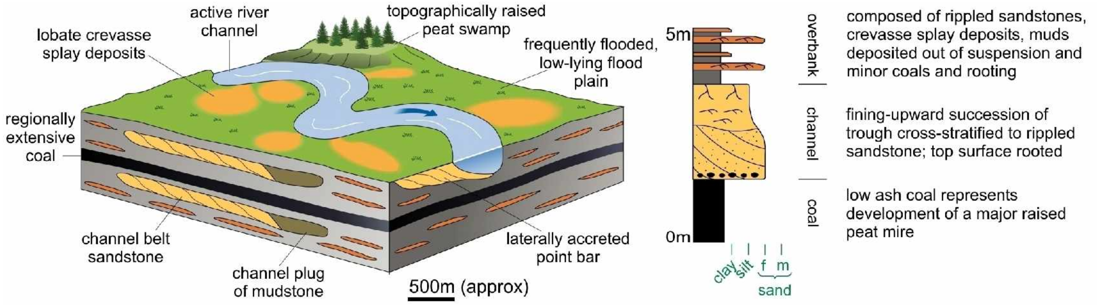


**Figure 4.11.** Block diagram and graphic log to show typical features of the non-marine component of the Blackhawk Formation (not to scale vertically). These include meandering fluvial channels, overbank deposits, and topographically raised peat swamps (from Howell and Flint, 2003).

### 4.4.4 Estuarine facies associations

The Blackhawk Formation contains numerous tidally influenced estuarine complexes, interpreted as the fills of incised valleys that were cut during periods of relative sea-level fall and filled during the subsequent rise (Fig. 6, Van Wagoner, 1995; Howell and Flint, 2003). These represent complex depositional systems, in which the interplay of fluvial, tidal and wave processes result in a large number of localised sub-environments including meandering point bars, tidal flats and minor estuarine deltas (Dalrymple et al., 1992; Zaitlin et al., 1994). Figure 4.12 shows a schematic model of a tidally influenced estuary, along with a series of graphic logs to illustrate the facies associated with different parts of the system. In general, tidal deposits are heterolithic and display evidence of frequent changes in the magnitude or direction of depositional energy, such as herringbone cross-stratification (Fig. 4.9 G) and cross-stratified sandstones with mud drapes (Fig. 4.9 H).

The estuarine deposits in the Blackhawk Formation are of considerable importance for understanding its sequence stratigraphic evolution (Van Wagoner, 1995; Howell and Flint, 2003). Consequently it is useful to describe and interpret each of them individually. The Sunnyside Member includes four exposed estuarine valley fill complexes that occur at two different stratigraphic levels (Howell and Flint, 2003; Howell et al., in press). The most important of these with respect to the sequence stratigraphic interpretation of the member (see discussion in Chapter 6) are the ‘Sunnyside sandstone’, which is associated with the lower Sunnyside sequence boundary and the ‘Woodside Canyon incised valley fill’, which is associated with the upper Sunnyside sequence boundary (Fig. 4.6, Fig. 4.7).

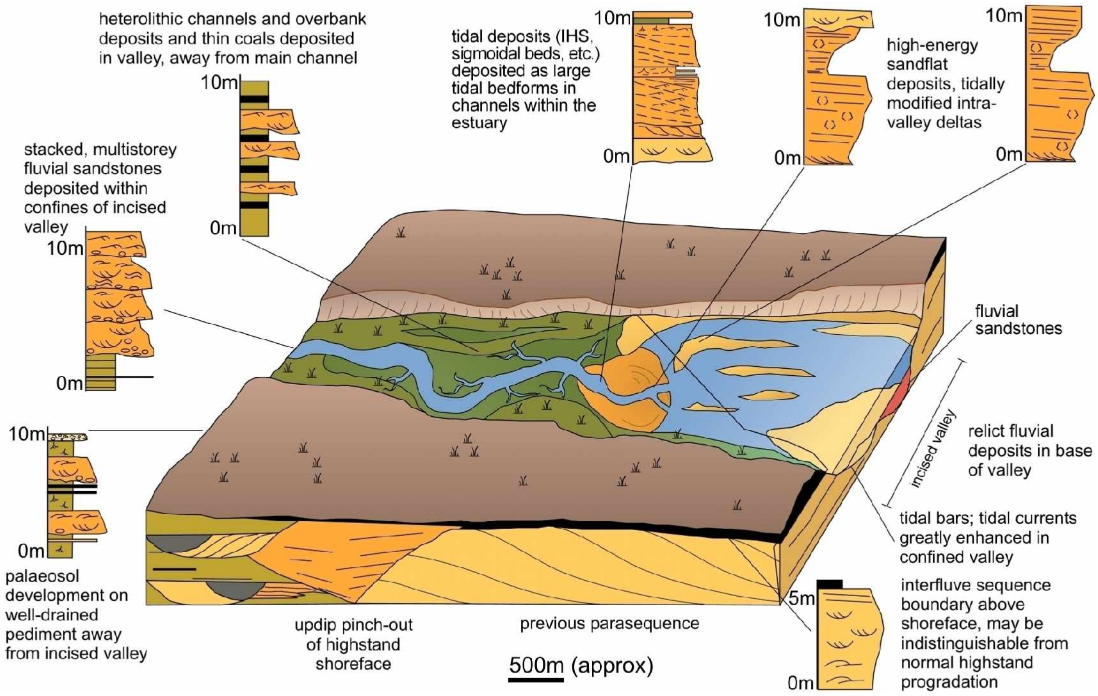


**Figure 4.12.** Block diagram and mini-graphic logs to show typical features of the estuarine deposits of the Blackhawk Formation (not to scale vertically). From Howell and Flint (2003).

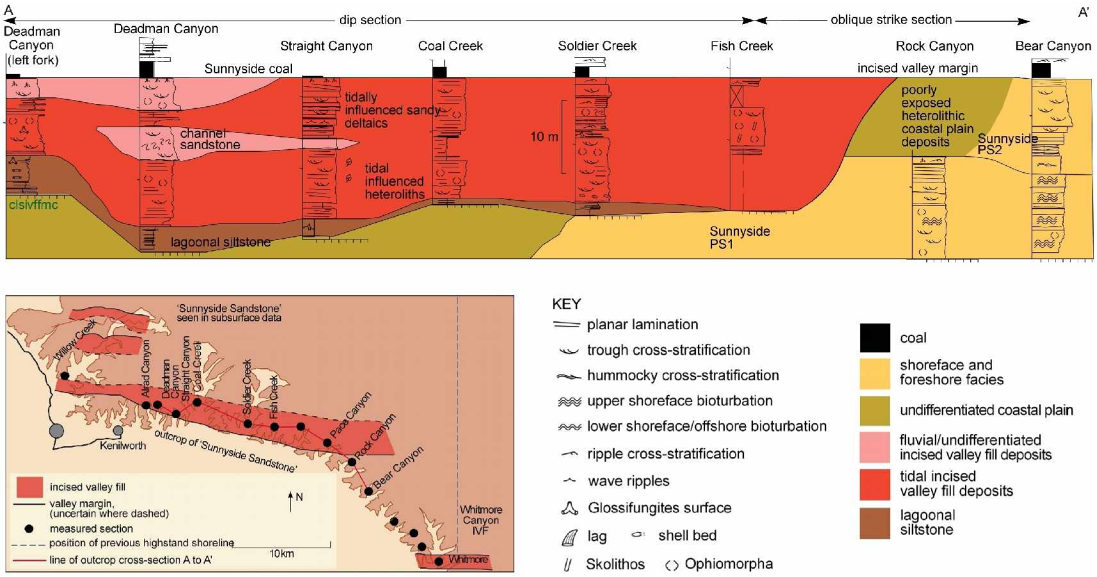


**Figure 4.13.** Cross section through the Sunnyside sandstone incised valley complex. The inset map shows the orientation of the Sunnyside sandstone and the other valleys associated with the lower Sunnyside sequence boundary in relation to the Book Cliffs outcrop, the dashed blue line shows the position of the previous highstand shoreline (from Howell and Flint, 2003).

### 4.4.4.1 The Sunnyside sandstone incised valley fill

The Sunnyside sandstone is a 20 m thick, sandstone rich interval that underlies the Sunnyside coal over a depositional dip distance of 17.4 km in the north-western part of the study area (Howell et al., in press). It is composed of two units, separated by a planar surface (Fig. 4.13). The lower unit comprises clean, well-sorted, planar laminated sandstones, fine to medium grained sandstones with large-scale trough cross stratification with well developed paired, organic drapes, and well-sorted fine grained sandstones with *Ophiomorpha* bioturbation. The upper unit coarsens upward from wave rippled and planar laminated heteroliths with abundant paired drapes, to clean fine-grained sandstones (Howell and Flint, 2003; Howell et al., in press). The entire succession is interpreted as a tidally influenced estuarine valley fill, deposited during the period of relative sea-level rise that followed the formation of the lower Sunnyside sequence boundary. Its sand rich nature is attributed to the reworking of shoreface deposits that were eroded during this transgression (Howell et al., in press).

#### 4.4.4.2 Woodside Canyon incised valley fill

The Woodside Canyon incised valley fill is a coarse-grained, fluvio-tidal unit that locally replaces marine shoreface deposits and the Sunnyside coal in the Woodside Canyon area (Howell and Flint, 2003). The excellent exposure of the valley fill in this area is essential for understanding its stratigraphic relationship with the adjacent shallow-marine strata and the Sunnyside coal (Fig. 4.14, Fig. 4.15).

The basal part of the Woodside Canyon incised valley fill is composed of medium to coarse-grained trough cross-stratified sandstones with soft sediment deformation, woody debris and rare rip-up clasts (Fig. 4.15). This unit is overlain by large-scale inclined heterolithic strata, horizontally bedded heterolithic deposits with wave and current ripples, poorly drained palaeosols and minor coals up to 30 cm thick. The succession shows little evidence of bioturbation with the exception of the uppermost 1.5 m, which contains an extensive network of sand-filled *Thalassinoides* burrows (Howell et al., in press). The lower part of the succession is interpreted as the product of fluvial deposition. The inclined heterolithic strata represent deposition within transgressive tidally-influenced meandering channels. The horizontally bedded heterolithics are interpreted as tidal flat deposits, with the palaeosols and coals representing supra-tidal marshland within the valley (Howell and Flint, 2003; Howell et al., in press). The complex, multi-storey nature of the succession indicates a complex fill history, the significance of which will become apparent in Chapter 6.

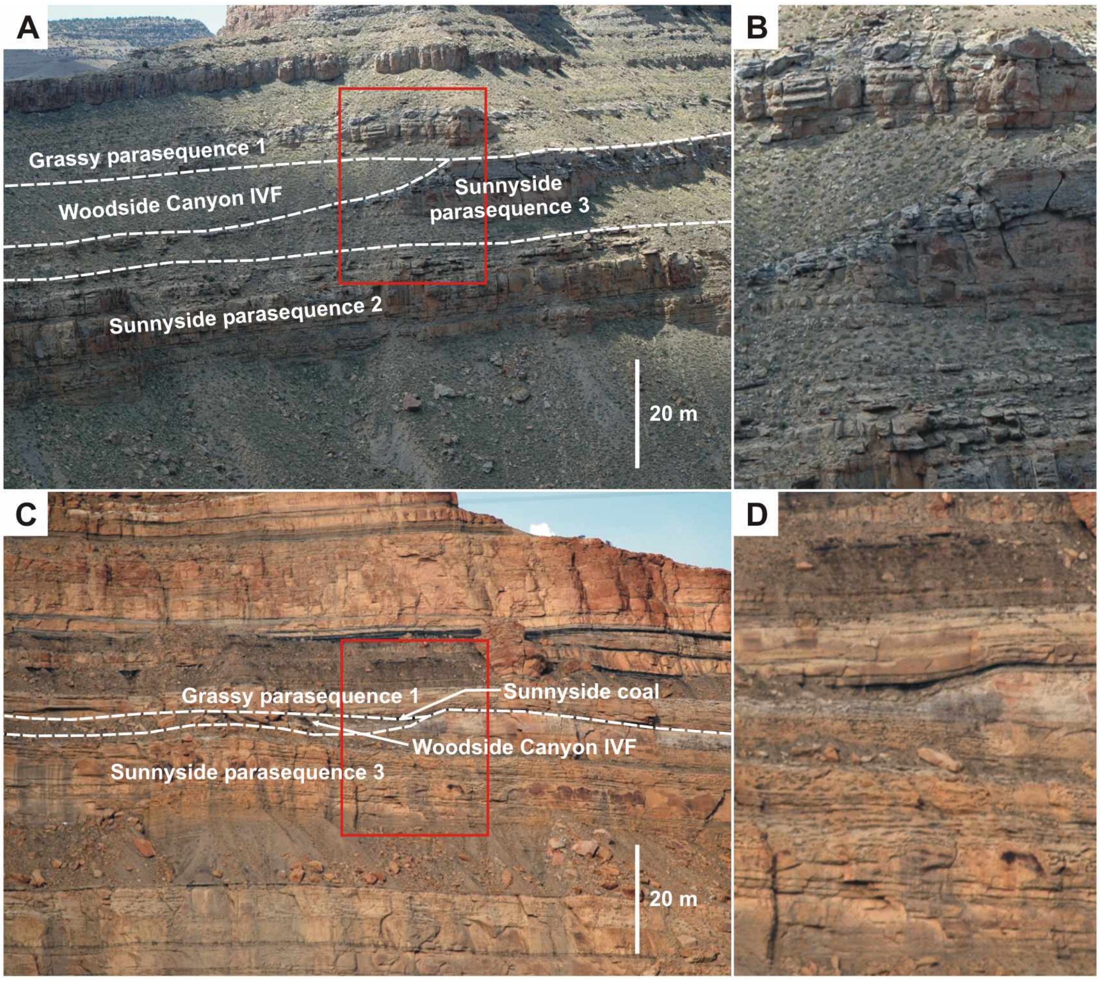


**Figure 4.14.** Photographs to show the stratigraphic relationships between the Woodside Canyon incised valley fill, marine shoreface parasequences and the Sunnyside coal in the Woodside Canyon area. See Fig. 4.15 for map view of the valley fill in relation to the Book Cliffs outcrop. (A) The northern margin of the Woodside Canyon incised valley fill as seen on the southern side of Woodside Canyon; Sunnyside parasequence 3 is clearly removed by the sequence boundary that runs along the base of the valley fill. (B) Close up of the northern margin of the valley fill, see red box on previous photo for location and scale. (C) The southern margin of the Woodside Canyon incised valley fill as seen on the western side of the Beckwith plateau. (D) Close up of the area outlined in red on the previous photo, note that the Sunnyside coal extends over part of the valley fill, this is an important observation as it means that the cessation of peat formation must post date the incision and filling of the valley; see further discussion in Chapter 6.

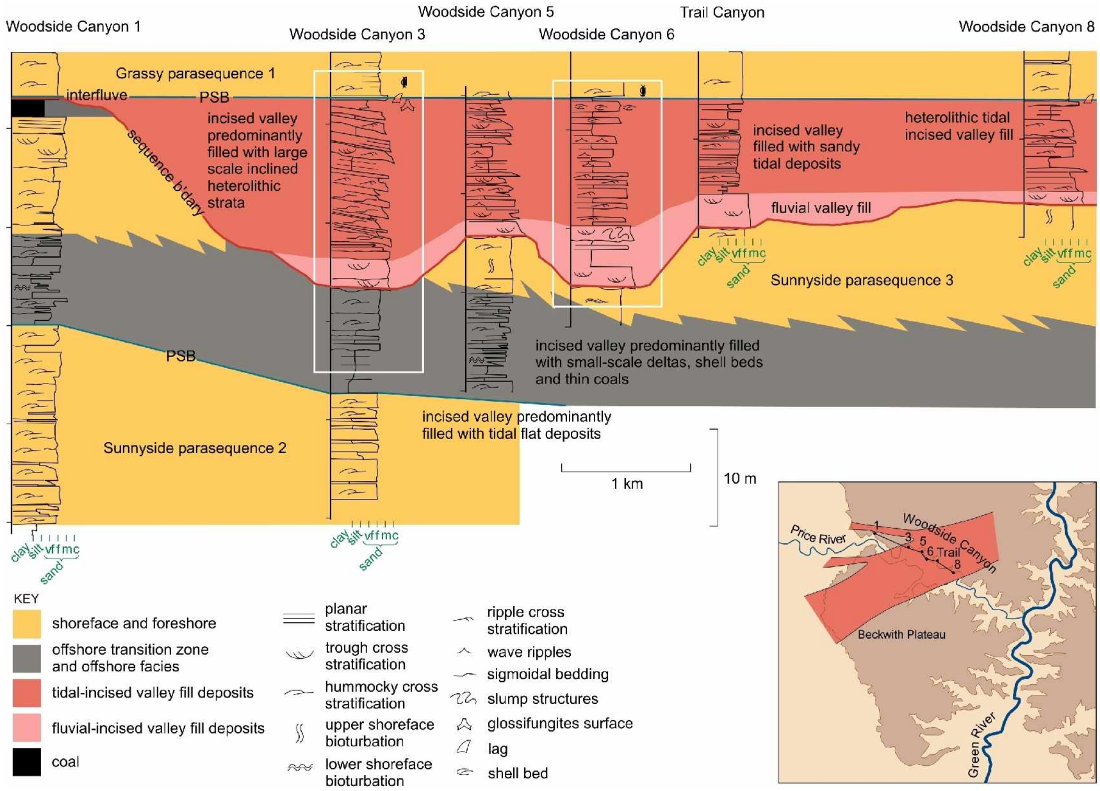


**Figure 4.15.** Cross section through the Woodside Canyon incised valley complex. Note the truncation of shoreface deposits by the upper Sunnyside sequence boundary which runs along the base of the valley, and the complex multi-storey nature of the valley fill. The inset map shows the orientation of the valley in relation to the Book Cliffs outcrop (from Howell and Flint, 2003).

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# CHAPTER 5: VERTICAL AND LATERAL VARIATION IN THE PETROGRAPHY OF THE UPPER CRETACEOUS SUNNYSIDE COAL OF EASTERN UTAH, USA – IMPLICATIONS FOR THE RECOGNITION OF HIGH-RESOLUTION ACCOMMODATION CHANGES IN PARALIC COAL SEAMS

*This chapter introduces the primary dataset and evaluates the usefulness of a range of petrographic parameters as indicators of accommodation change for the Sunnyside coal. This approach is preferred to presenting the entire dataset as it focuses on finding out which parameters are most useful for understanding the evolution of the Sunnyside coal. A full sequence stratigraphic interpretation of the Sunnyside coal follows in Chapter 6. The full petrographic dataset can be found in the Appendix at the end of this thesis and on the enclosed CD.*

## ABSTRACT

The Sunnyside Member of the Upper Cretaceous Blackhawk Formation in the Book Cliffs of eastern Utah is composed of coal-bearing coastal-plain strata and wave-dominated shoreface deposits. The member includes a thick (up to 6 m), laterally extensive coal seam, which formed in a large ombrotrophic raised mire, parallel to the shoreline of the Western Interior Seaway. The petrographic composition of the Sunnyside coal was investigated by means of maceral analysis and telovitrinite reflectance determinations of closely spaced samples taken from seven vertical sections through the seam. Sampling was carried out in a combination of outcrop and underground mine sites, using lithotype logging to determine sample spacing. The excellent exposure in the study area enables accurate stratigraphic correlation between sampling localities, which are spread over more than 30 km of depositional dip and 50 km of depositional strike. The correlation of petrographic trends between the seven sampled sections demonstrates the reproducibility of the results and suggests that they represent regional-scale accommodation changes, as opposed to localised variation in the mire. On this basis we are able to identify a high-resolution record of accommodation change throughout the deposition of the Sunnyside coal, spanning two cycles of increasing and decreasing accommodation.

We are also able to identify a marine flooding-surface within the coal, which can be traced down depositional dip into the time equivalent shallow marine strata, where it represents a parasequence boundary. The proportion of detrital minerals is used as the main discriminator of accommodation trends within the coal. Other useful indicators of conditions in the mire include semifusinite, pyrite and isometamorphic variations in telovitrinite reflectance.

## 5.1 INTRODUCTION

Accommodation is the space between the sediment surface and local depositional base level in which sediment can accumulate and be preserved (Jervey, 1988). In mire depositional systems, accommodation is governed by the height of the mire water table, which in turn is controlled by a combination of regional base level, precipitation and autocompaction of the peat (Moore, 1989; Kosters and Suter, 1993; Winston, 1994; Banerjee et al., 1996; Bohacs and Suter, 1997; Diessel, 1998; Diessel et al., 2000). In order for peat to accumulate, accommodation has to be created at a rate that approximately balances the rate at which peat is produced (Cross, 1988; Bohacs and Suter, 1997). If the rate of accommodation creation outstrips peat production, the mire is drowned and inundated with lacustrine or marine sediments. Conversely, if peat production exceeds the rate of accommodation creation, the mire is exposed, oxidised, and reworked (Fig. 5.1). Variations in the rates of accommodation creation and peat production within the comparatively narrow “coal window” should result in changes in the composition of the accumulating peat.

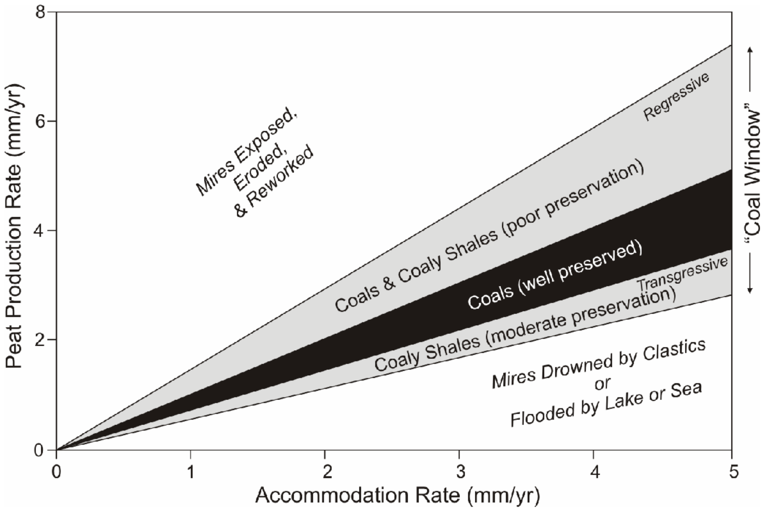

**Figure 5.1.** In order for peat to accumulate and be preserved, the rate of accommodation creation must balance the rate of peat production. The shaded areas represent the conditions of accumulation for various terrigenous organic-rich rocks (modified from Bohacs and Suter, 1997).

Although the study of accommodation changes in coal-bearing strata is a relatively new topic in name, the dynamics of peat accumulation have long been of interest to coal geologists and stratigraphers. Historically, most studies in this field have been primarily concerned with the significance of whole coal seams within depositional cycles (Weller, 1930; Duff and Walton, 1962; Horne et al, 1978; Fielding, 1987; Cross, 1988; McCabe and Parrish, 1992; Aitken and Flint, 1995; Flint et al., 1995; Hampson, 1995). More recently, a number of studies (Banerjee et al., 1996; Diessel, 1998; Petersen et al., 1998; Diessel et al., 2000; Holz et al., 2002; Wadsworth et al., 2002, 2003) have explored the high-resolution accommodation changes that take place within the “coal window” of Figure 5.1 by recognising changes in the internal, petrographic characteristics of vertical coal sections. One of the key advances they demonstrate is that coal seams may form in response to either increasing or decreasing accommodation, and may span multiple, high-frequency fourth and fifth order accommodation cycles.

The aims of this paper are to identify high-resolution accommodation changes within the Sunnyside coal seam of the Cretaceous Blackhawk Formation in the Book Cliffs of eastern Utah, and to evaluate the effectiveness of a range of petrographic parameters as indicators of accommodation change for paralic coal seams. Particular attention will be paid to how well accommodation trends based on petrographic parameters can be correlated between multiple sampled sections, as this has important implications for assessing the extent to which coal seams record regional-scale accommodation changes as opposed to localised variation in mire conditions. Our approach is based on the following consideration of petrography-based palaeoenvironmental studies.

Coal macerals and microlithotypes have long been used to elucidate the conditions of coal formation at the peat stage. In some cases the presence of key macerals within a coal seam is taken as being indicative of a specific depositional environment. For example, the occurrence of alginite, or more specifically telalginite (Hutton et al., 1980; Cook et al., 1981), indicates the existence of subaqueous conditions in the mire. Whereas a high proportion of fusinite or semifusinite indicates dryness and probably burning of the peat (Scott, 1989; Scott and Jones, 1994). Petrography-based palaeoenvironmental studies have also frequently relied on specific associations of macerals and microlithotypes, often in the form of ratios. Teichmüller's (1950) four peat facies and Hacquebard’s double triangle (Hacquebard and Donaldson, 1969; Hacquebard and Barss, 1970) are typical examples of this approach. Other examples include the tissue preservation index (TPI)[1] of Diessel (1985, 1986) and the groundwater influence index (GWI)[2] of Calder (1991).

More recently, emphasis has been placed on the environmental significance of subtle variations in the optical properties of vitrinite in isometamorphic coals (Diessel, 1996; Diessel and Gammidge, 1998; Diessel et al., 2000). For example, higher than seam-average telovitrinite reflectance values are believed to result from slight oxidation of the vitrinite precursors in low accommodation conditions. Lower than seam-average telovitrinite reflectance is attributed to a consistently high water table, in extreme cases resulting from influxes of brackish or marine water into the mire. The scatter of reflectance measurements about the mean, or coefficient of variation[3], was also found to provide an indication of depositional conditions in the mire, with higher deviations associated with increased dispersal and higher accommodation.

The minerals contained in coal have also been employed in palaeoenvironmental studies (Spears, 1987; Cohen et al, 1987; Ward and Swaine, 1995). Coals with mineral contents below 10% are usually attributed to peat accumulation in ombrotrophic mires, which are able to build up above flooding levels, thus preventing the influx of clastic sediment into the mire (Clymo, 1987; Staub, 1991; Diessel et al., 2000). Coals with higher mineral contents are usually associated with low-lying, rheotrophic mires and high accommodation / peat production ratios, as these provide a mechanism for the transport of water-borne, detrital minerals into the mire (Diessel 1992; Greb et al., 2002). Where high detrital mineral content is associated with framboidal pyrite (Cohen et al., 1987; Brown and Cohen, 1995; Petersen and Andsbjerg, 1996; Staub, 2002) or suppressed vitrinite reflectance (Hutton et al., 1980; Diessel and Gammidge, 1998), it can be interpreted as the result of marine or brackish incursion into the mire.

Changes in the detrital mineral content within a coal provide a useful basis for the interpretation of changes in accommodation and the structure of the mire throughout its formation. For example, upward increases in detrital mineral content,

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[1] TPI is the ratio of structured macerals (telovitrinite, fusinite and semifusinite) to unstructured macerals (detrovitrinite, macrinite and inertodetrinite).

[2] GWI is the ratio of telovitrinite to detrovitrinite plus detrital minerals, the latter being associated with high groundwater tables.

or “wetting-upward” trends, may indicate peat accumulation during increasing accommodation. Conversely, upward decreases in detrital mineral content, or “drying-upward” trends, may indicate peat accumulation during decreasing accommodation (Diessel et al., 2000; Wadsworth et al., 2003). It may also be possible to divide a seam into multiple benches that represent different phases of mire development. For instance, ombrotrophic mires may begin and end as rheotrophic mires (Moore, 1989; Greb et al., 2002). However, interpretations of palaeomire type and accommodation change cannot always be reliably based on mineral content, as not all rheotrophic mires produce coals with high mineral contents. The reasons for this can include doming of the peat and a lack of clastic sediment influx into the mire (McCabe, 1984, 1987). Furthermore, the mineral content of peat and coal may be altered by diagenetic fluids, regardless of the original mire type and depositional setting (Spears, 1987; Greb et al., 2002).

## 5.2 GEOLOGICAL SETTING OF STUDY AREA

The Blackhawk Formation of eastern Utah, USA comprises coal-bearing coastal-plain and wave-dominated, shallow marine strata that inter-tongue with the marine Mancos Shale (Young, 1955, 1957; Balsley, 1980). This succession was deposited during the Late Cretaceous, within and along the margins of the intra-continental seaway (Fig. 5.2) that occupied much of central North America at this time (Speiker, 1949; Young, 1955). Young (1955) identified six lithostratigraphic members within the Blackhawk Formation (Fig. 5.3), each extending further eastward (basinward) than the underlying one due to long term progradation (basinward stepping) of the shoreline. This study is focused on the Sunnyside Member, which contains the thickest and most laterally extensive coal seam within the formation (Bohacs and Suter, 1997). Further descriptions of the sedimentology, stratigraphy and depositional environments of the Blackhawk Formation can be found in Young (1955, 1957), Balsley (1980), and Van Wagoner (1995).

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[3] The coefficient of variation of mean random telovitrinite reflectance, c(%Rrt), is calculated by dividing the standard deviation of measurements by the sample mean.

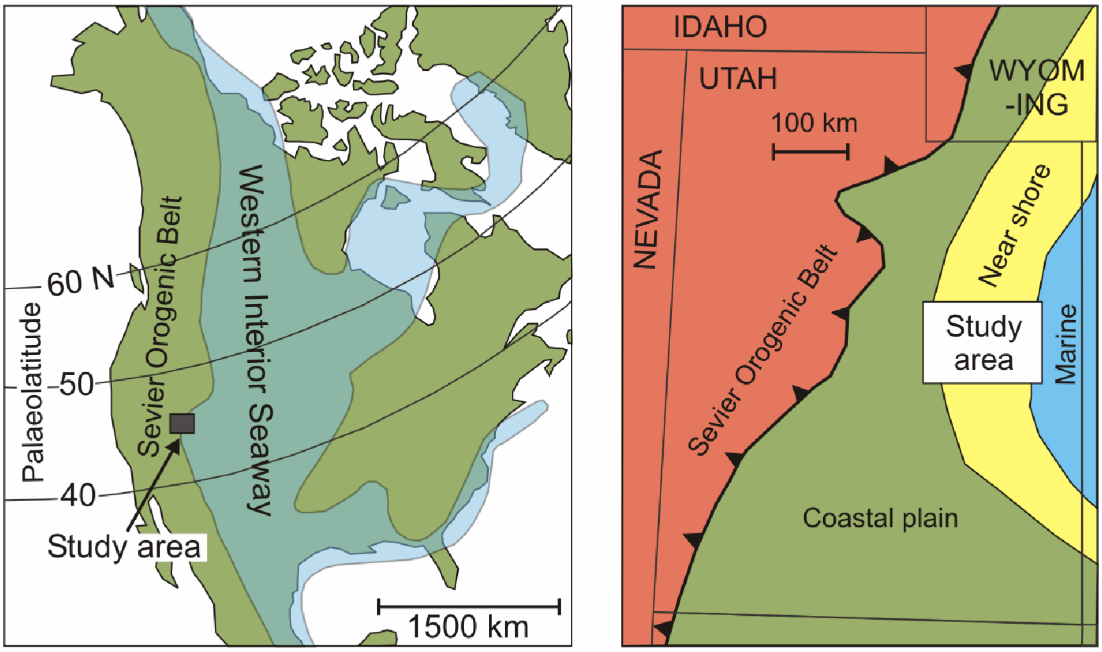


**Figure 5.2.** Location of study area in relation to the Late Cretaceous palaeogeography of south western USA and Utah state boundaries (from Howell and Flint, 2003).

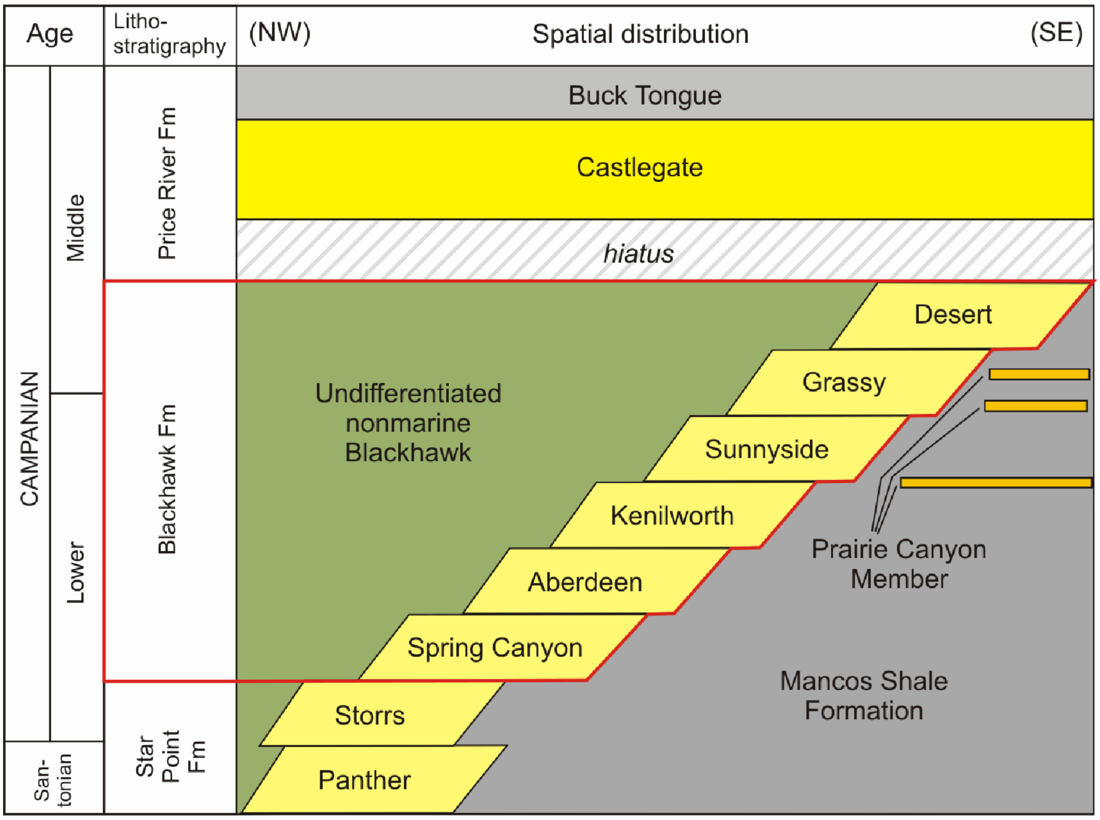
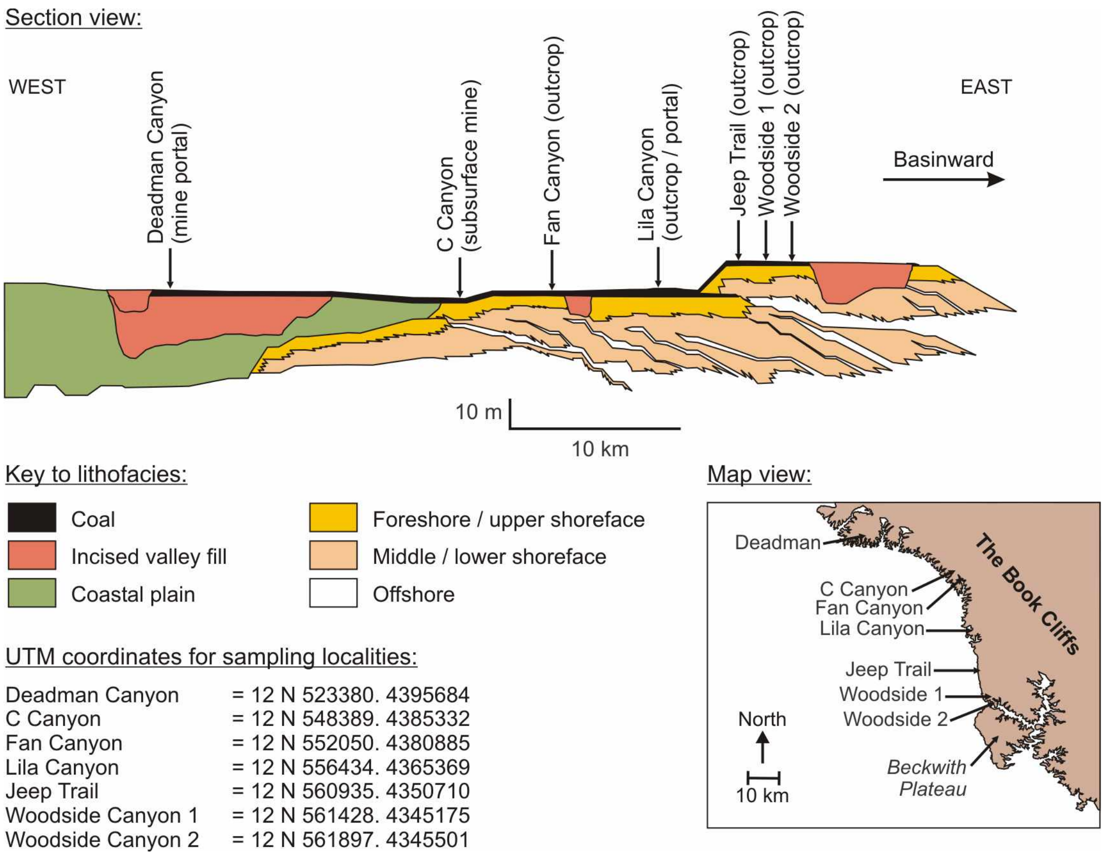


**Figure 5.3.** Lithostratigraphy of the Blackhawk Formation (from Howell and Flint, 2003).

The Sunnyside Member is composed of three shallow marine parasequences, marginal to non marine strata, and discrete packages of fluvial/tidal sediments interpreted as incised-valley fills (Fig. 5.4). The Sunnyside coal formed in a very large continuous mire parallel to the shoreline (Doelling et al., 1979) at a palaeolatitude of approximately 40° N (Kauffman, 1977; Howell and Flint, 2003). The seam is up to 6 m thick and crops out almost continuously over at least 40 km of depositional dip, allowing a high degree of confidence in correlation between sampled sections (Doelling, 1972; Doelling et al., 1979). The coal is underlain by rooted shoreface deposits (Fig. 5.5) in the eastern part of the study area, and by grey lagoonal siltstones and incised-valley fill deposits in the west (Howell et al., in press). In the most basinward part of the area, the Sunnyside coal is split into two daughter seams, separated by a 15 m thick package of shallow marine sediments (Balsley, 1980; Howell et al., in press). Elsewhere in the study area, it also contains several smaller, localised splits (Young, 1955; Doelling, 1972; Doelling et al., 1979) interpreted as fluvial channel and crevasse splay deposits (Fig. 5.6). The top of the seam is overlain by a major member-bounding flooding surface across the entire area (O’Byrne and Flint, 1995).



UTM coordinates for sampling localities:

| | |
|---|---|
| Deadman Canyon | = 12 N 523380. 4395684 |
| C Canyon | = 12 N 548389. 4385332 |
| Fan Canyon | = 12 N 552050. 4380885 |
| Lila Canyon | = 12 N 556434. 4365369 |
| Jeep Trail | = 12 N 560935. 4350710 |
| Woodside Canyon 1 | = 12 N 561428. 4345175 |
| Woodside Canyon 2 | = 12 N 561897. 4345501 |

**Figure 5.4.** Depositional dip cross section of the Sunnyside Member and location of sampled sections (modified from Howell et al., in press).

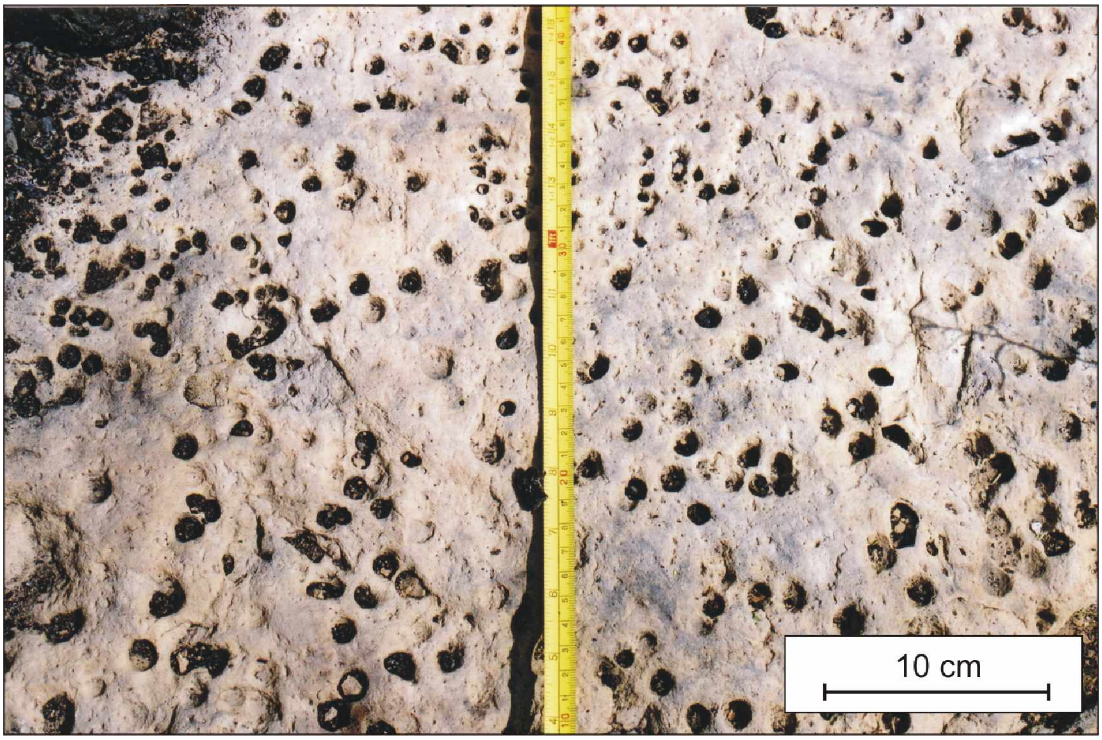


**Figure 5.5.** Photograph looking down at coalified plant roots penetrating marine-shoreface sandstones below the Sunnyside coal at Lila Canyon, Book Cliffs, eastern Utah.

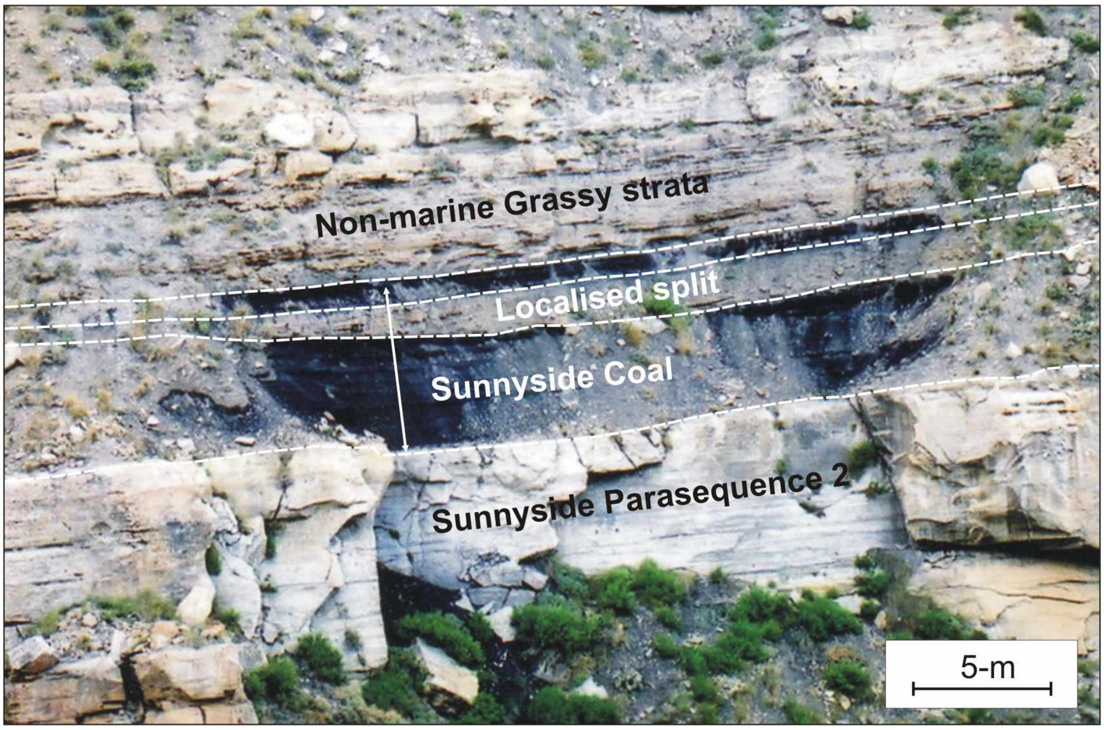


**Figure 5.6.** Photograph of fine-grained, clastic split near the top of the thickest part of the Sunnyside coal at Lila Canyon, Book Cliffs, eastern Utah.

## 5.3 SAMPLING AND ANALYTICAL METHODS

The primary data set for this paper is derived from the results of 281 maceral analyses and telovitrinite reflectance determinations carried out on samples obtained from five outcrop and two subsurface mine sections through the Sunnyside coal. Figure 5.4 shows the spacing of the sampling localities in map and section view. A lithotype log was produced at each site prior to sampling in order to ensure that no potential key surfaces were crossed. Where the coal was sampled in the outcrop, it was first excavated to a depth of approximately 1 m in order to remove excessively weathered material.

Where possible, samples were kept intact in order to preserve the original depositional layering. Those samples too brittle to be kept intact were crushed to a 2 mm top size and a representative sub-sample prepared as a grain mount instead. All samples were cured in epoxy resin as raw coal and then cut and polished in accordance with standard methods for microscopic analysis in incident light. Maceral analyses were based on 500 points per sample in accordance with Australian Standard guidelines (Australian Standard AS 2856.2–1998, 1998). Mean random telovitrinite reflectance (%Rrt) was determined from 50 measurements per sample, but otherwise in accordance with Australian Standard guidelines (Australian Standard AS 2486–1989, 1989).

## 5.4 RESULTS

### 5.4.1 Bulk coal composition

Figure 5.7 shows photomicrographs of some of the macerals observed in our samples, while Table 5.1 gives the average composition of the Sunnyside coal for each of the sampled sections, plus the overall average of all 281 maceral analyses. The mean detrital mineral content of 8.0% suggests that the seam was probably deposited in either an ombrotrophic raised mire or a limnotelmatic mire protected from the influx of clastic sediment. Throughout much of the seam, the detrital mineral content is actually below the 3% to be expected due to inherent (plant derived) minerals (Diessel et al., 2000), which further strengthens the case for deposition in an ombrotrophic setting. The very low mean pyrite content of 0.2% suggests that the mire groundwater was predominantly fresh, however, this Figure

5.should be treated with caution as weathering may have removed pyrite from some of the outcrop samples. The mean vitrinite to inertinite ratio of 4:1 indicates that accommodation and peat production were generally well balanced, and that loss of peat due to oxidation was limited.

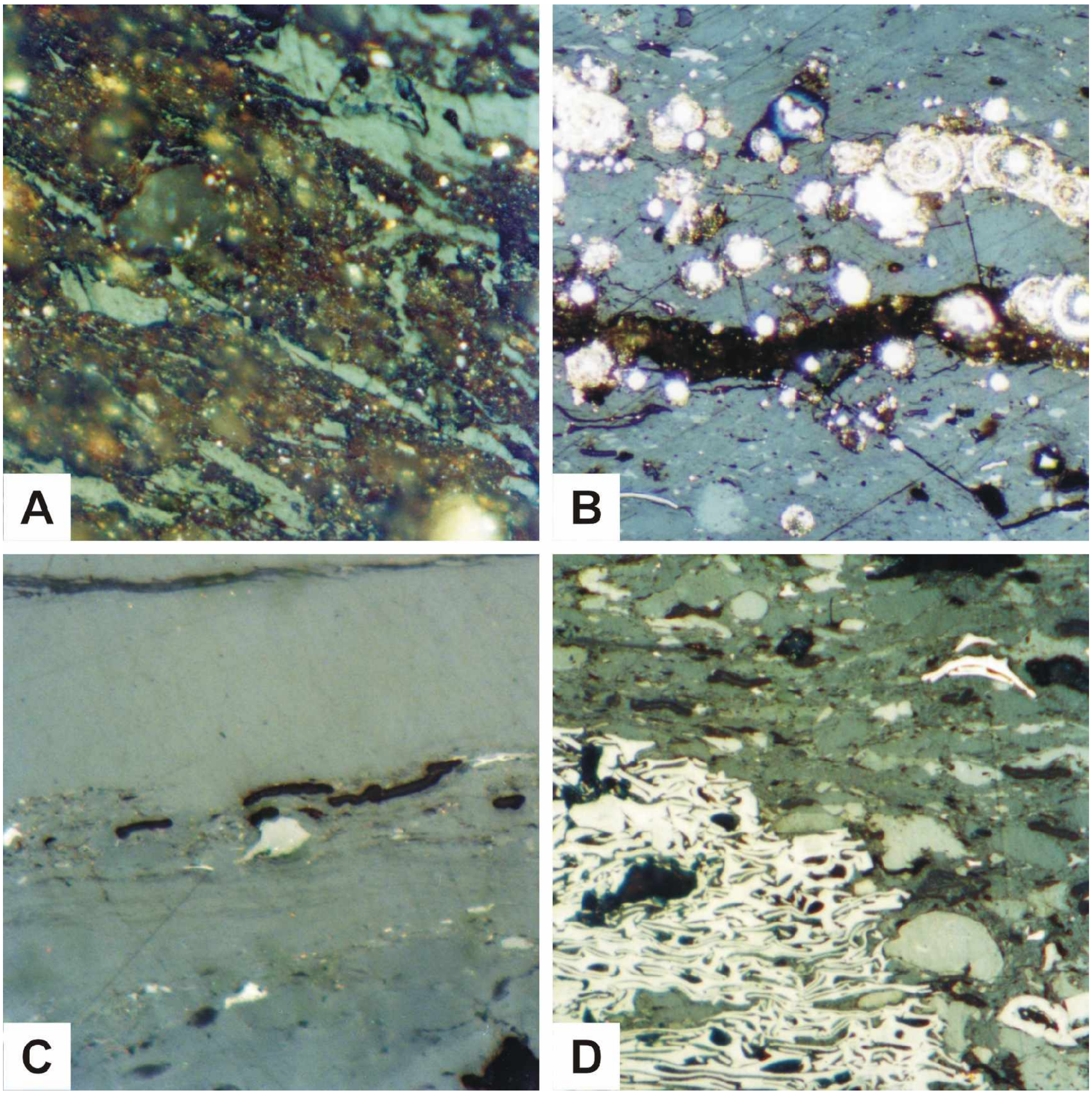


**Figure 5.7.** Photomicrographs of the Sunnyside coal taken in incident white light, oil immersion and one polariser. (A) Detrital minerals (darker) with telovitrinite (uniform grey bands). (B) Framboidal and concentric pyrites (bright circles) with detrovitrinite (mid grey) and semifusinite (light grey). (C) Contrast between higher reflecting telovitrinite (upper part of frame) and lower reflecting detrovitrinite (lower part of frame). (D) Inertodetrinite (small white and light grey grains) and semifusinite (large white grain, bottom of frame) in detrovitrinite matrix (mid grey). The true width of each photomicrograph is approximately 0.2 mm.

**Table 5.1.**
Average composition of the Sunnyside coal by sampled section, and for all 281 samples combined.

| Maceral / Group | Deadman Canyon | C Canyon | Fan Canyon | Lila Canyon | Jeep Trail | Woodside Canyon I | Woodside Canyon II | All Samples |
|---|---|---|---|---|---|---|---|---|
| Telovitrinite | 23.3% | 23.9% | 17.9% | 22.3% | 21.6% | 16.2% | 17.3% | 21.7% |
| Detrovitrinite | 45.6% | 52.9% | 48.2% | 46.3% | 39.1% | 37.7% | 52.6% | 47.4% |
| Sporinite | 1.9% | 1.3% | 2.8% | 2.8% | 2.4% | 2.2% | 1.7% | 2.2% |
| Cutinite | 1.1% | 1.0% | 1.0% | 1.5% | 1.5% | 1.3% | 1.7% | 1.3% |
| Resinite | 2.8% | 2.1% | 3.1% | 2.8% | 3.1% | 2.5% | 2.4% | 2.6% |
| Micrinite | 0.9% | 0.6% | 1.7% | 1.4% | 1.3% | 0.7% | 0.6% | 1.1% |
| Macrinite | 1.4% | 1.2% | 1.1% | 1.4% | 1.0% | 0.3% | 0.2% | 1.2% |
| Semifusinite | 9.0% | 6.8% | 8.0% | 7.8% | 6.2% | 4.1% | 5.4% | 7.2% |
| Fusinite | 0.5% | 0.5% | 1.2% | 0.7% | 0.6% | 0.3% | 0.3% | 0.7% |
| Inertodetrinite | 6.1% | 5.6% | 9.7% | 7.2% | 4.9% | 3.8% | 3.1% | 6.4% |
| Detrital Mins | 7.2% | 3.7% | 5.2% | 5.6% | 17.7% | 30.6% | 14.7% | 8.0% |
| Pyrite | 0.1% | 0.3% | 0.1% | 0.1% | 0.7% | 0.3% | 0.1% | 0.2% |
| Total Vitrinite | 69.0% | 76.8% | 66.0% | 68.6% | 60.7% | 53.9% | 69.9% | 69.1% |
| Total Liptinite | 5.8% | 4.4% | 7.0% | 7.1% | 7.0% | 6.0% | 5.8% | 6.1% |
| Total Inertinite | 18.0% | 14.8% | 21.7% | 18.6% | 14.0% | 9.2% | 9.5% | 16.6% |
| Total Minerals | 7.2% | 4.0% | 5.3% | 5.6% | 18.4% | 30.9% | 14.9% | 8.2% |

### 5.4.2 Evaluation of indicators of accommodation change

Table 5.2 shows the correlation coefficients for individual macerals, maceral groups, some maceral ratios, and telovitrinite reflectance computed from all 281 samples. Considering that the strength of correlation between the fresh mine samples and the outcrop coal may have been adversely affected by the slight weathering observed in the latter, positive and negative correlation values greater than 0.6 are regarded as indicating strongly related properties. It may also be possible to infer weaker relationships from positive and negative values between 0.4 and 0.6.

**Table 5.2.**
Correlation matrix of individual macerals, maceral groups, tissue preservation index (TPI), groundwater influence index (GWI), mean random telovitrinite reflectance (%Rrt) and coefficient of variation of random telovitrinite reflectance [c(%Rrt)] computed for all 281 samples from the Sunnyside coal

| | Tvit | Dvit | Spo | Cut | Res | Mic | Mac | Sem | Fus | Ind | Det | Pyt | Vit | Lip | Int | Min | TPI | GWI | %Rrt | c%Rrt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Telovitrinite | 1.00 | -0.27 | -0.16 | 0.05 | -0.20 | -0.23 | -0.21 | -0.29 | -0.16 | -0.40 | -0.31 | -0.11 | 0.59 | -0.17 | -0.39 | -0.31 | 0.75 | -0.34 | 0.28 | -0.27 |
| Detrovitrinite | -0.27 | 1.00 | 0.02 | 0.21 | 0.05 | 0.02 | 0.08 | 0.17 | 0.10 | 0.11 | -0.67 | -0.35 | 0.62 | 0.13 | 0.16 | -0.67 | -0.49 | -0.38 | 0.39 | -0.38 |
| Sporinite | -0.16 | 0.02 | 1.00 | 0.11 | 0.29 | 0.46 | 0.05 | 0.06 | 0.14 | 0.34 | -0.14 | -0.21 | -0.11 | 0.72 | 0.25 | -0.14 | -0.15 | -0.16 | -0.25 | 0.23 |
| Cutinite | 0.05 | 0.21 | 0.11 | 1.00 | 0.19 | -0.03 | -0.20 | -0.17 | -0.14 | -0.18 | -0.17 | -0.09 | 0.22 | 0.58 | -0.21 | -0.17 | -0.12 | -0.15 | -0.03 | -0.13 |
| Resinite | -0.20 | 0.05 | 0.29 | 0.19 | 1.00 | 0.31 | 0.22 | 0.15 | 0.12 | 0.36 | -0.16 | -0.16 | -0.13 | 0.74 | 0.31 | -0.17 | -0.15 | -0.15 | -0.23 | 0.11 |
| Micrinite | -0.23 | 0.02 | 0.46 | -0.03 | 0.31 | 1.00 | 0.27 | 0.30 | 0.34 | 0.52 | -0.19 | -0.20 | -0.17 | 0.39 | 0.53 | -0.19 | -0.16 | -0.12 | -0.28 | 0.17 |
| Macrinite | -0.21 | 0.08 | 0.05 | -0.20 | 0.22 | 0.27 | 1.00 | 0.52 | 0.25 | 0.48 | -0.26 | -0.22 | -0.11 | 0.05 | 0.66 | -0.27 | -0.09 | -0.10 | 0.12 | -0.07 |
| Semifusinite | -0.29 | 0.17 | 0.06 | -0.17 | 0.15 | 0.30 | 0.52 | 1.00 | 0.37 | 0.52 | -0.39 | -0.23 | -0.09 | 0.03 | 0.86 | -0.39 | -0.04 | -0.17 | 0.17 | -0.09 |
| Fusinite | -0.16 | 0.10 | 0.14 | -0.14 | 0.12 | 0.34 | 0.25 | 0.37 | 1.00 | 0.34 | -0.23 | -0.18 | -0.05 | 0.07 | 0.49 | -0.23 | -0.08 | -0.12 | 0.06 | -0.03 |
| Inertodetrinite | -0.40 | 0.11 | 0.34 | -0.18 | 0.36 | 0.52 | 0.48 | 0.52 | 0.34 | 1.00 | -0.28 | -0.27 | -0.24 | 0.28 | 0.86 | -0.29 | -0.22 | -0.11 | -0.02 | 0.02 |
| Detrital Mins | -0.31 | -0.67 | -0.14 | -0.17 | -0.16 | -0.19 | -0.26 | -0.39 | -0.23 | -0.28 | 1.00 | 0.52 | -0.81 | -0.23 | -0.40 | 1.00 | -0.07 | 0.68 | -0.50 | 0.50 |
| Pyrite | -0.11 | -0.35 | -0.21 | -0.09 | -0.16 | -0.20 | -0.22 | -0.23 | -0.18 | -0.27 | 0.52 | 1.00 | -0.38 | -0.23 | -0.30 | 0.55 | -0.03 | 0.27 | -0.32 | 0.18 |
| Total Vitrinite | 0.59 | 0.62 | -0.11 | 0.22 | -0.13 | -0.17 | -0.11 | -0.09 | -0.05 | -0.24 | -0.81 | -0.38 | 1.00 | -0.03 | -0.19 | -0.81 | 0.21 | -0.60 | 0.55 | -0.54 |
| Total Liptinite | -0.17 | 0.13 | 0.72 | 0.58 | 0.74 | 0.39 | 0.05 | 0.03 | 0.07 | 0.28 | -0.23 | -0.23 | -0.03 | 1.00 | 0.19 | -0.23 | -0.21 | -0.22 | -0.26 | 0.12 |
| Total Inertinite | -0.39 | 0.16 | 0.25 | -0.21 | 0.31 | 0.53 | 0.66 | 0.86 | 0.49 | 0.86 | -0.40 | -0.30 | -0.19 | 0.19 | 1.00 | -0.40 | -0.15 | -0.17 | 0.08 | -0.04 |
| Total Minerals | -0.31 | -0.67 | -0.14 | -0.17 | -0.17 | -0.19 | -0.27 | -0.39 | -0.23 | -0.29 | 1.00 | 0.55 | -0.81 | -0.23 | -0.40 | 1.00 | -0.07 | 0.67 | -0.50 | 0.49 |
| TPI | 0.75 | -0.49 | -0.15 | -0.12 | -0.15 | -0.16 | -0.09 | -0.04 | -0.08 | -0.22 | -0.07 | -0.03 | 0.21 | -0.21 | -0.15 | -0.07 | 1.00 | -0.14 | 0.16 | -0.08 |
| GWI | -0.34 | -0.38 | -0.16 | -0.15 | -0.15 | -0.12 | -0.10 | -0.17 | -0.12 | -0.11 | 0.68 | 0.27 | -0.60 | -0.22 | -0.17 | 0.67 | -0.14 | 1.00 | -0.31 | 0.29 |
| %Rrt | 0.28 | 0.39 | -0.25 | -0.03 | -0.23 | -0.28 | 0.12 | 0.17 | 0.06 | -0.02 | -0.50 | -0.32 | 0.55 | -0.26 | 0.08 | -0.50 | 0.16 | -0.31 | 1.00 | -0.68 |
| c(%Rrt) | -0.27 | -0.38 | 0.23 | -0.13 | 0.11 | 0.17 | -0.07 | -0.09 | -0.03 | 0.02 | 0.50 | 0.18 | -0.54 | 0.12 | -0.04 | 0.49 | -0.08 | 0.29 | -0.68 | 1.00 |

The low mineral content of the Sunnyside coal suggests that layers with above seam-average detrital minerals indicate flooding of the mire due to accommodation exceeding peat production. This notion is supported by the strong negative correlation between mineral content and the proportion of total vitrinite (-0.81), as well as the layered nature of the quartz and clay minerals observed under the microscope (Figure 5.7). Furthermore, the lack of any positive association between increased mineral content and inertinite and liptinite content indicates that concentration of detrital minerals by oxidative loss of biomass is not a significant factor in this coal. The positive correlation between detrital minerals and pyrite (0.52) is also worthy of note as this suggests that high detrital mineral contents are associated with increased marine influence. This relationship would probably be even stronger but for the loss of pyrite from some of the outcrop samples.

The negative correlation between mean random telovitrinite reflectance (%Rrt) and detrital mineral content (-0.50) suggests that lower %Rrt values are indicative of flooding of the mire and high accommodation / peat production ratios. Similarly, the positive correlation between mineral content and the coefficient of variation of telovitrinite reflectance (0.49) suggests that high c(%Rrt) values occur as a result of mixing of autochthonous and allochthonous telovitrinite precursors during flooding of the mire and periods of higher accommodation creation.

The inertinite content does not correlate particularly strongly with detrital mineral content (-0.40), but is potentially a useful indicator of accommodation changes in the parts of the seam where the detrital mineral content is relatively constant. Semifusinite (the dominant structured form of inertinite in our samples) is probably a more reliable indicator of dry conditions than total inertinite, due to the ambiguity associated with inertodetrinite, which may also indicate increased dispersal associated with higher accommodation conditions (Diessel and Gammidge, 1998; Diessel et al., 2000). Whilst the whole-coal values of semifusinite content do not correlate well with other indicators of accommodation change, better correlations are obtained when subsections of the seam, e.g. the top and bottom portions, are considered. This will be discussed later in the paper.

The groundwater influence index (GWI) correlates strongly with detrital mineral content (0.67), which suggests that it should be a useful indicator of accommodation change. However, this is only true in the parts of the seam where detrital mineral content is highest. In the middle of the seam, the very low telovitrinite content results in anomalously high GWI values that do not correlate with other indicators of accommodation change. Similar problems are encountered when applying the tissue preservation index (TPI) to this coal.

As the Sunnyside coal is of Cretaceous origin, its total sporinite content is low compared with the Carboniferous and Permian coals, on which most of the petrographic palaeoenvironmental indicators are traditionally based. The other liptinite macerals do not show any significant concentrations either, so are of little use as indicators of accommodation change as far as this study is concerned. The same applies to the remainder of the macerals listed in Table 5.2, as they correlate poorly with each other and the properties discussed above, apart from the obviously related entities, e.g. semifusinite and inertinite, and their derived ratios, e.g. TPI and telovitrinite.

### 5.4.3 Detailed results by sampled section

Based on the above discussion, we consider the detrital mineral content to be the best indicator of accommodation change for the Sunnyside coal, followed by mean random telovitrinite reflectance (%Rrt) and semifusinite content. Figures 5.8 to 5.10 show vertical profiles of these three properties for each of the seven sampled sections, along with the accommodation trends interpreted from them. Each of the sampled sections has also been subdivided into a set of depositional units, numbered from bottom to top, based on the dominant petrographic / accommodation trends within them. The thickness of these units varies slightly depending on the property they are based on. This is to be expected as different petrographic parameters react to changes in accommodation at different rates. The reasoning for this approach is outlined below along with a brief description of each sampling locality.

#### 5.4.3.1 Deadman Canyon

Deadman Canyon is the most landward locality in which the Sunnyside coal was sampled, approximately 15 km up depositional dip from the next locality at C Canyon. The coal here sits above the trough cross-bedded Sunnyside Sandstone, interpreted as an incised-valley fill by Howell et al. (in press), and is overlain by non marine coastal-plain deposits of the Grassy Member (O’Byrne and Flint, 1995). Sampling was carried out in an abandoned portal at Deadman Canyon Mine.

The 1.5 m thick section has been divided into two units on the basis of the trends shown in Figures 5.8 to 5.10. Decreasing detrital mineral content and increasing semifusinite content indicate decreasing accommodation during the deposition of unit 1 as the mire changed from low-lying rheotrophic to raised ombrotrophic conditions. These trends are reversed in unit 2, suggesting that accommodation gradually increased throughout the deposition of the upper part of the seam. The lack of any significant trends at the top of the section suggests that the top of the seam may have been removed prior to the deposition of the overlying Grassy Member.

#### 5.4.3.2 C Canyon

At C Canyon, the Sunnyside coal rests directly on shallow marine shoreface sandstones of the second Sunnyside parasequence, and is overlain by non marine coastal-plain strata of the Grassy Member (O’Byrne and Flint, 1995). A complete channel sample for this locality was obtained from an active long-wall mine.

The 2.5 m thick section has been subdivided into four depositional units. The detrital mineral and semifusinite trends in unit 1 indicate rapidly decreasing accommodation. The subsequent increase in detrital mineral content and abrupt decrease in semifusinite content in unit 2 are interpreted as the result of a marine incursion into the mire due to the associated increase in pyrite content. Detrital mineral content decreases significantly in unit 3, indicating that this part of the seam formed under declining accommodation conditions as the rheotrophic swamp developed into an ombrotrophic raised mire. The upward increases in semifusinite content and telovitrinite reflectance are consistent with this interpretation. Unit 4 contains several small wetting-upward trends interpreted as small flooding events associated with gradually increasing accommodation. The decline in telovitrinite reflectance towards the top of the section suggests that the mire was inundated with marine or brackish water prior to the cessation of peat accumulation.

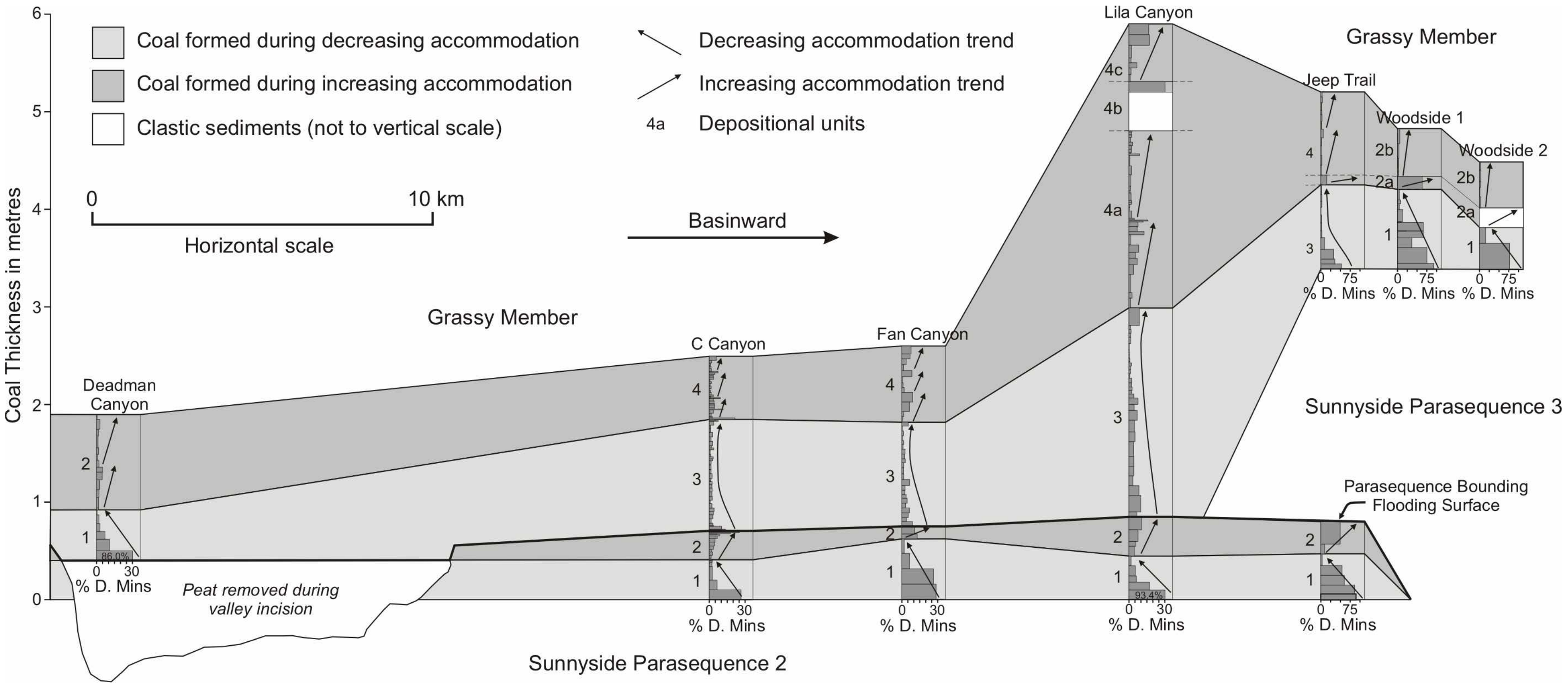


**Figure 5.8.** Correlation of detrital mineral profiles, accommodation trends and depositional units for all seven sampled sections through the Sunnyside coal. Note that different horizontal scales are used for the three most basinward sections. The top of the second Sunnyside parasequence is used as a datum for C Canyon, Fan Canyon, Lila Canyon and the lower part of Jeep Trail. The top of the third Sunnyside parasequence is used for the upper part of Jeep Trail and the two Woodside Canyon sections. The correlation between Deadman Canyon and C Canyon is based on compositional trends and its stratigraphic relationship with the Sunnyside Sandstone incised-valley fill, see text for further explanation.

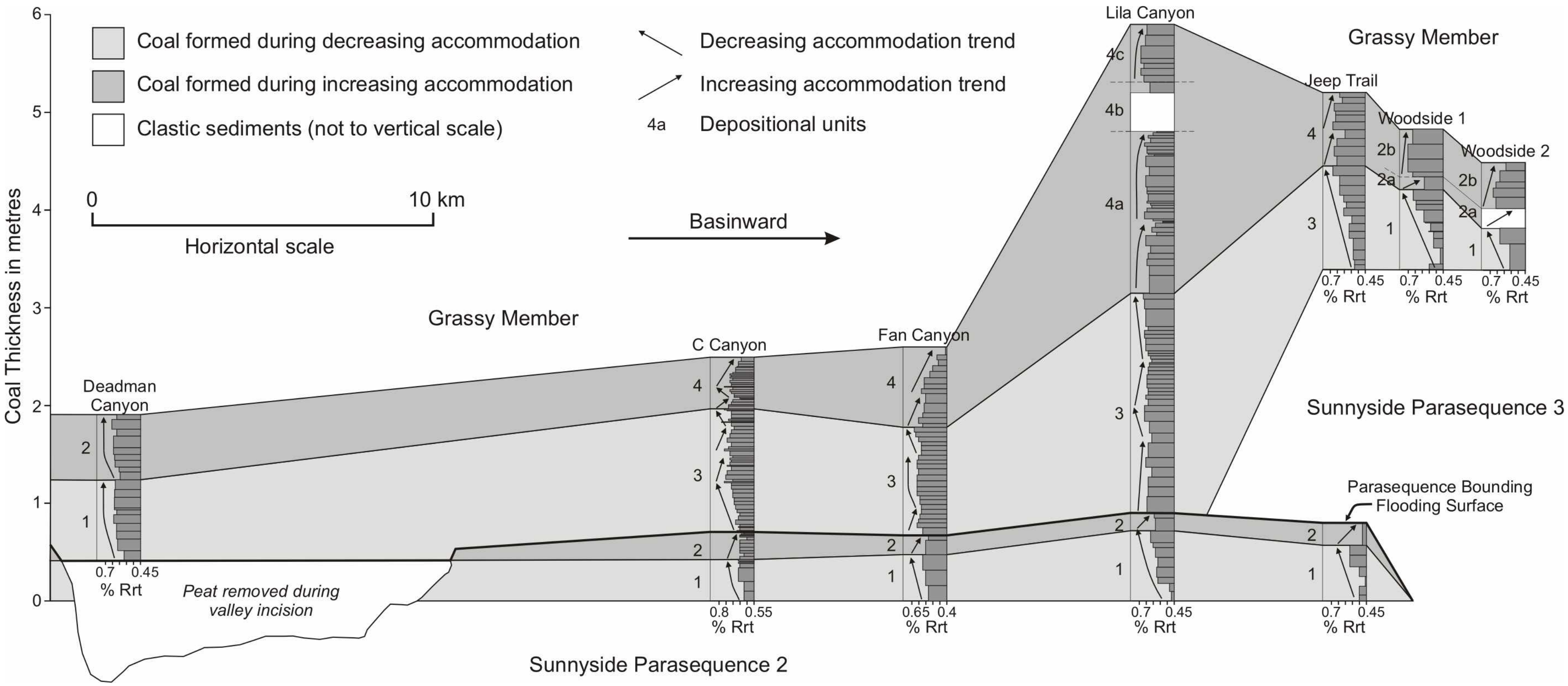


**Figure 5.9.** Correlation of mean random telovitrinite reflectance profiles, accommodation trends and depositional units for all seven sampled sections through the Sunnyside coal. Note that the baselines of the profiles are reversed in order to maintain the convention that arrows pointing to the left indicate decreasing accommodation and arrows pointing to the right indicate increasing accommodation, and that different horizontal scales are used for the C Canyon and Fan Canyon sections. See caption to Figure 5.8 for further explanation.

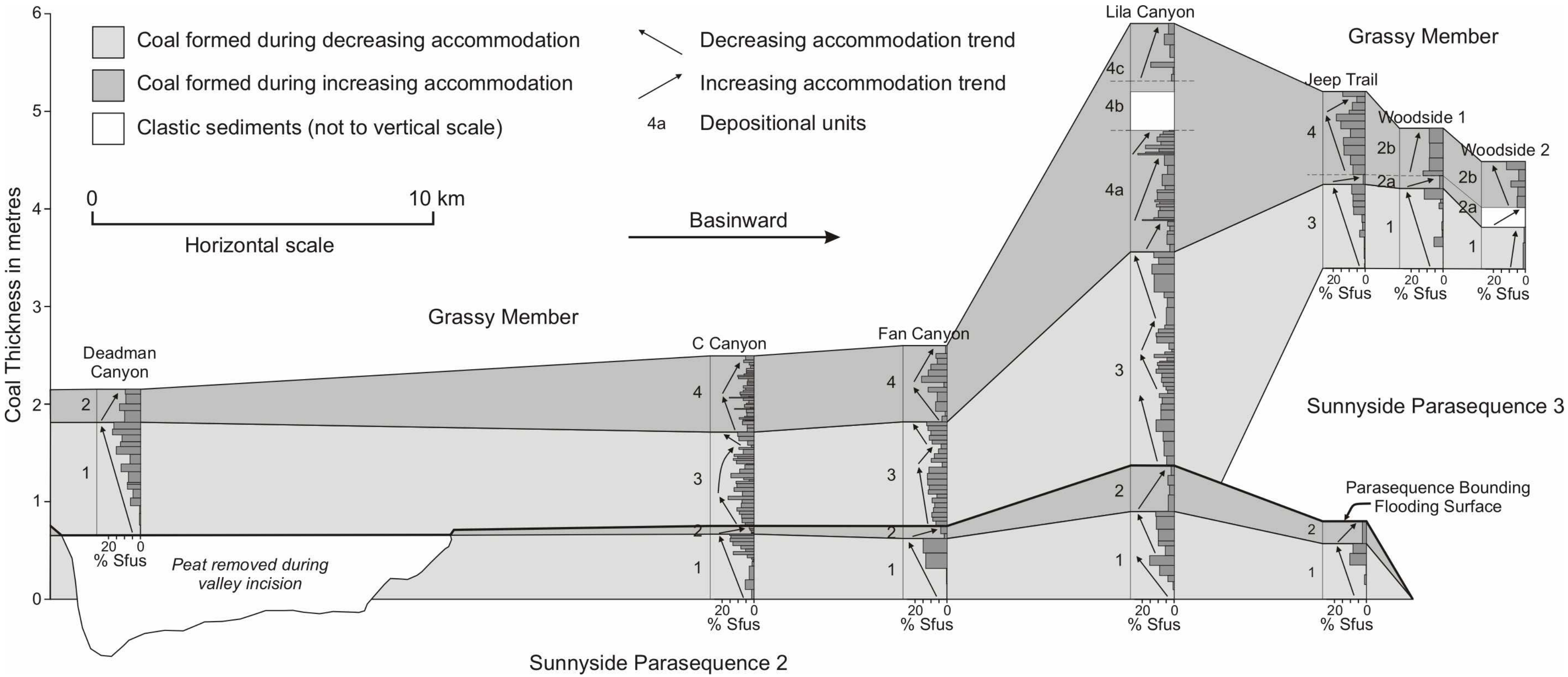


**Figure 5.10.** Correlation of semifusinite profiles, accommodation trends and depositional units for all seven sampled sections through the Sunnyside coal. Note that the baselines of the profiles are reversed in order to maintain the convention that arrows pointing to the left indicate decreasing accommodation and arrows pointing to the right indicate increasing accommodation. See caption to Figure 5.8 for further explanation.

### 5.4.3.3 Fan Canyon

The Fan Canyon section was sampled entirely in the outcrop close to the entrance of the old Fan Canyon mine. The coal here sits directly on the rooted shoreface sands of the second Sunnyside parasequence, and is overlain by non marine strata of the Grassy Member (O'Byrne and Flint, 1995).

The 2.6 m thick section is divided into four depositional units (Figs. 5.8 to 5.10). Unit 1 shows a drying-upward trend similar to that observed in the basal part of the C Canyon section. The subsequent increase in detrital mineral content and decreased semifusinite content in unit 2 indicate a short-lived flooding of the mire, due to an abrupt increase in accommodation. Upward-decreasing mineral and increasing semifusinite trends indicate declining accommodation during the deposition of unit 3 as the peat grew upwards to form an ombrotrophic raised mire. The multiple wetting-upward trends indicated by increasing detrital mineral content, and the reduction in semifusinite content and telovitrinite reflectance in unit 4, suggest that accommodation was increasing prior to the cessation of peat accumulation.

### 5.4.3.4 Lila Canyon

The Sunnyside coal is at its thickest in the area around Lila Canyon. As at Fan Canyon, it rests directly on the heavily rooted shoreface sands of the second Sunnyside parasequence and is overlain by non marine Grassy Member strata (O'Byrne and Flint, 1995). Sampling was carried out both in the outcrop and within an abandoned portal of the old Lila Canyon Mine. The 6.3 m thick sampled section includes 0.8 m of silt and very fine sandstone that splits the coal near the top of the seam (Fig. 5.6). This clastic interval is interpreted as representing a localised increase in accommodation creation and is not laterally persistent into the canyons on either side of Lila Canyon (Howell et al., in press).

The seam is divided into four depositional units; units 1 and 2 show similar trends to the basal parts of the Fan and C Canyon sections. Unit 3 shows an upward decrease in detrital mineral content combined with an increase in semifusinite, indicating decreasing accommodation associated with the development of a raised mire. The slightly suppressed telovitrinite reflectance and very low semifusinite content in the middle of this unit are probably due to the presence of a stagnant lake in this area as they are associated with increased liptinite content and very low detrital mineral content. Unit 4 contains three wetting-upward trends indicating gradually increasing accommodation; the second of these culminates in the above mentioned 0.8 m thick package of clastic sediments in unit 4b. The increased detrital mineral content at the top of unit 4c supports our interpretation that the cessation of peat growth was caused by a rapid increase in accommodation outpacing peat production and flooding the mire.

#### 5.4.3.5 Jeep Trail

The Jeep Trail section is critical to correlating compositional trends between all the sampled sections, as this is the only locality where we were able to sample the coal both above and below the third Sunnyside parasequence (see Fig. 5.4). The basal 0.8 m of the seam overlies the second Sunnyside parasequence, whilst the remaining 1.8 m overlies the third Sunnyside parasequence, and is overlain by marine sediments of the Grassy Member (Howell et al., in press). Coalified plant roots penetrate into the tops of the shoreface sandstones of both the second and third Sunnyside parasequences.

Both parts of the seam have been divided into two units (Figs. 5.8 to 5.10). The composition of unit 1 shows that the initiation of peat accumulation in this area occurred in a low-lying mire with significant clastic -sediment input. Drying-upward trends indicated by mineral content, semifusinite and telovitrinite reflectance signify decreasing accommodation towards the top of this unit. A reversal of these trends occurs in unit 2, indicating an abrupt increase in accommodation prior to the deposition of the 15 m thick, marine-clastic split. The basal part of the ‘upper seam’ (unit 3) shows strong drying-upward trends in all three accommodation indicators, which is consistent with the development of a raised mire. The high semifusinite content, low detrital mineral content and enhanced telovitrinite reflectance of unit 4 suggests that accommodation remained relatively low throughout most of its formation. However, the three wetting-upward trends in detrital mineral content, and the decline in semifusinite content towards the top of the seam indicate gradually increasing accommodation prior to the cessation of peat accumulation.

#### 5.4.3.6 Woodside Canyon I

The Woodside Canyon I section was sampled in the outcrop close to the entrance of Woodside Canyon. Unlike at Jeep Trail, the coal only occurs above the third Sunnyside parasequence and is overlain by marine Grassy strata (Howell et al., in press).

The 1.5 m thick section is subdivided into two units. Detrital mineral content, semifusinite content and %Rrt all show decreasing accommodation throughout the deposition of the basal part of the seam (unit 1), consistent with progression from rheotrophic into ombrotrophic conditions. This is followed by a brief resumption of limnotelmatic conditions in unit 2a, probably caused by a slight increase in accommodation in the basinward part of the mire. The lower detrital mineral content, increased semifusinite content, and higher telovitrinite reflectance in unit 2b indicate a return to low accommodation conditions. The top of the seam appears to have been removed due to transgressive erosion, but the slight increase in detrital mineral content throughout unit 2b suggests that accommodation was gradually increasing prior to the cessation of peat formation.

#### 5.4.3.7 Woodside Canyon II

A second section was sampled further into Woodside Canyon, 300 to 400 m down depositional dip from the first. This 1.9 m thick section is again divided into two units which, not surprisingly, show similar accommodation trends to those observed in the first Woodside Canyon section. Unit 2a in this section is comprised of a 1.1 m thick, fine-grained, organic-rich, clastic split. This is almost certainly the lateral equivalent of the 15 cm thick coaly shale in unit 2a of the Woodside I section. Both are probably the result of a short-lived marine incursion into the basinward part of the mire.

## 5.5 DISCUSSION

### 5.5.1 Correlation of accommodation trends between sampled sections

The basal parts (units 1 and 2) of the C Canyon, Fan Canyon, Lila Canyon, and Jeep Trail sections are relatively easy to correlate as they are of similar thickness and display similar trends in detrital minerals, semifusinite and telovitrinite reflectance (Figs. 5.8 to 5.10). The relatively high detrital mineral content in these units suggests that the lower part of the seam formed in a rheotrophic or limnotelmatic mire which colonised the shoreface of the second Sunnyside parasequence as it prograded out into the basin. The base of the seam is probably not of the same age in all these sections, as it is unlikely that the shoreface prograded as far as Jeep Trail prior to the initiation of peat formation at C Canyon. The subsequent wetting-upward trends are more likely to be approximately synchronous, as they are almost certainly related to the marine incursion that resulted in the onlap of the third Sunnyside parasequence onto the basinward part of the mire. The base of the Deadman Canyon section is correlated with the base of unit 3 in C Canyon, as it does not display the same compositional trends as the basal parts of the other sections. This is probably due to the removal of peat in this area during the formation of the incised-valley that underlies the coal in the Deadman Canyon section.

The drying-upward trends in the basal parts of the Deadman Canyon, Woodside I and Woodside II sections correlate well with similar trends in unit 3 of the C Canyon, Fan Canyon, Lila Canyon and Jeep Trail sections. This drying-upward was probably due a combination of the change from limnotelmatic into ombrotrophic conditions and shallowing-upward associated with the progradation of the third Sunnyside parasequence. Again, these trends were probably not all synchronous, as a significant amount of progradation must have occurred prior to the initiation of peat formation in the Woodside Canyon area. The uppermost units of each section show at least two wetting-upward trends, which indicate gradually increasing accommodation during the deposition of the upper part of the seam. Although none of the sections show conclusive evidence for the cause of the cessation of peat growth, these wetting-upward trends and the fact that the coal is overlain by a regionally extensive flooding surface, suggests that the mire eventually drowned as peat production failed to keep up with increasing accommodation. The pronounced thickening of the coal just up-dip of the landward pinch out of the third Sunnyside parasequence (i.e. around Lila Canyon) is probably the result of increased accommodation towards the split axis, as the regional groundwater table was closest to the top of the peat in this area.

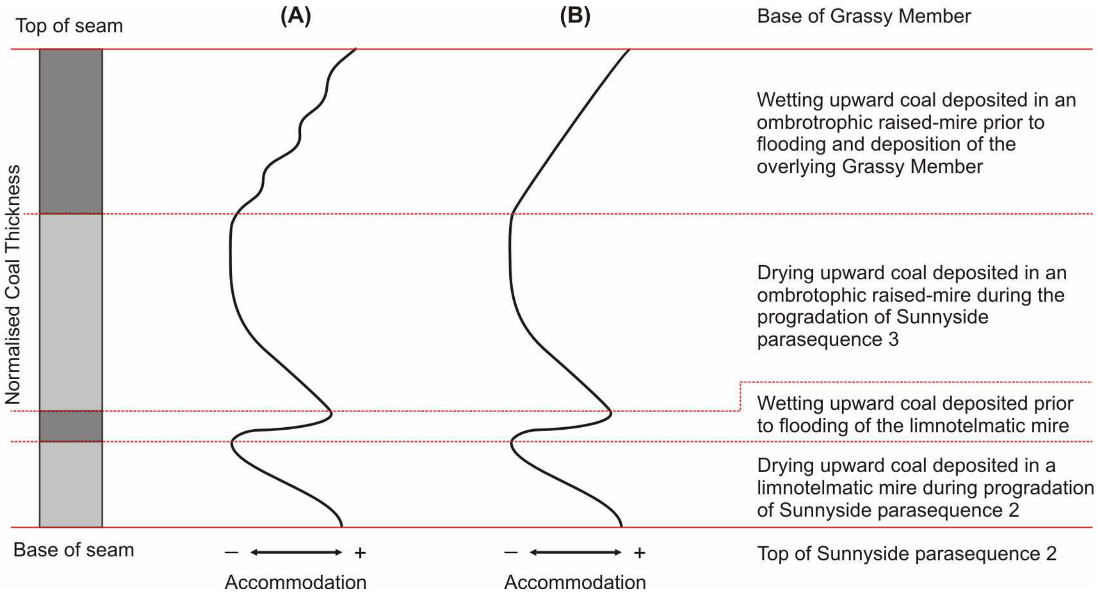


**Figure 5.11.** Two slightly different models for accommodation change throughout the deposition of the Sunnyside coal seam, based on the correlation of compositional trends from all seven sampled sections. (A) Multiple wetting upward-trends in the upper part of the seam interpreted as the result of periodic increases in accommodation. (B) Multiple wetting-upward trends in the upper part of the seam interpreted as the result of continually increasing accommodation.

The good correlation of petrographic trends across all seven sampled sections enables confidence in the reproducibility of the results, and suggests that they formed in response to regional-scale accommodation changes, as opposed to localised variations in the mire. Figure 5.11 shows two slightly different generalised accommodation curves for the duration of the deposition of the Sunnyside coal. In the first (curve A), the multiple wetting-upward trends in the upper part of the seam are interpreted as the result of periodic increases in accommodation, whilst in the second (curve B) they are interpreted as the result of a continuous, gradual increase in accommodation. In either case, these small wetting-upward trends represent a more gradual increase in accommodation than the single wetting-upward trend in the lower part of the seam. This is probably related to the nature of the mire during each period of increasing accommodation. During the first, the lower-lying limnotelmatic mire was flooded as soon as accommodation began to increase. Whereas during the second, the ombrotrophic raised mire kept pace with increasing accommodation for a considerably longer period of time.

### 5.5.2 Palaeoenvironmental significance of telovitrinite reflectance

The relationship between telovitrinite reflectance and palaeoenvironmental conditions identified by this study has significance beyond the recognition of accommodation changes. It is perhaps best illustrated by the difference in mean telovitrinite reflectance values between the lower part of the seam, which we believe formed in a limnotelmatic mire, and the upper part of the seam, interpreted as having formed in an ombrotrophic raised mire. Table 5.3 gives the telovitrinite reflectance properties and average composition by maceral group of the upper and lower parts of the C Canyon section. The average mean random telovitrinite reflectance is 0.64% in the basal 70 cm of the seam (units 1 and 2) and 0.70% in the upper 180 cm (units 3 and 4). This is a significant difference since the lower Figure 5.indicates a coal rank of high-volatile C bituminous, whilst the higher Figure 5.indicates a rank of high-volatile B bituminous (Taylor et al., 1998). Furthermore, the scatter of measurements, as expressed by c(%Rrt), is relatively small and almost identical for both parts of the seam, so the mean values are truly reflective of the respective sample populations.

**Table 5.3.**
Average composition and telovitrinite reflectance properties for the upper and lower parts of the Sunnyside coal at C Canyon.

| Property | Units 1 & 2 | Units 3 & 4 |
|---|---|---|
| Total vitrinite | 78.3% | 76.4% |
| Total liptinite | 4.3% | 4.4% |
| Total inertinite | 10.5% | 15.9% |
| Total minerals | 6.9% | 3.3% |
| %Rrt | 0.64% | 0.70% |
| c(%Rrt) | 0.050 | 0.052 |

All the samples in the C Canyon section were obtained from a single cut in the wall of an underground mine with several hundred metres of overburden, so weathering of the samples should not be a significant factor. There is also no evidence of an unconformity within the coal or any epigenetic mineralisation that could explain the variation in telovitrinite reflectance between the two parts of the seam. On this basis, the difference between them is almost certainly related to palaeoenvironmental conditions at the time of peat accumulation. Whilst it is possible that the variation in reflectance values is the result of enhanced telovitrinite reflectance associated with increased oxidation in the upper part of the seam, this is unlikely as the inertinite content of the upper part of the seam is still relatively low and not much higher than that of the lower part of the seam. The influence of liptinite can also be discounted as it only occurs in small quantities in both parts of the seam. The most likely explanation is that an influx of sea water over the top of unit 2 altered the chemistry of the peat sufficiently to suppress telovitrinite reflectance in the resultant coal. The generally wetter limnotelmatic environment in which the lower part of the seam formed may have also contributed to its lower telovitrinite reflectance values. The brief drop in %Rrt to 0.64% that occurs 40 cm from the top of the C Canyon section, and the gradual decline to a similar level at the top of the seam, are probably also related to periods of increased marine or brackish influence.

As mentioned previously, both %Rrt and c(%Rrt) show relatively strong correlations with detrital mineral content, which we believe to be the best palaeoenvironmental indicator for this seam. Figure 5.12 (A) shows a cross plot of detrital mineral content against %Rrt for all 281 samples. The negative correlation (-0.50) is probably due to suppression of telovitrinite reflectance in samples with higher detrital mineral contents, as both are associated with influxes of marine or brackish water into the mire. If we only plot samples from the lower part of the seam (B) this relationship is even stronger (-0.74), as the limnotelmatic mire in which it formed was more susceptible to flooding than the raised mire in which the upper part of the seam formed. The positive correlation (0.49) between detrital mineral content and c(%Rrt) shown in cross plot (C) is also due to both being associated with increased dispersal and flooding of the mire.

The lack of any significant correlation between %Rrt and any of the inertinite or liptinite macerals suggests that variations in telovitrinite reflectance values within the Sunnyside coal are mainly due to suppression during flooding of the mire, as opposed to enhancement at times of increased oxidation and biodegradation of the peat. This notion is supported by the strong negative correlation (-0.68) between %Rrt and c(%Rrt) shown in cross plot (D), which indicates that variation in %Rrt is more closely associated with low telovitrinite reflectance values.

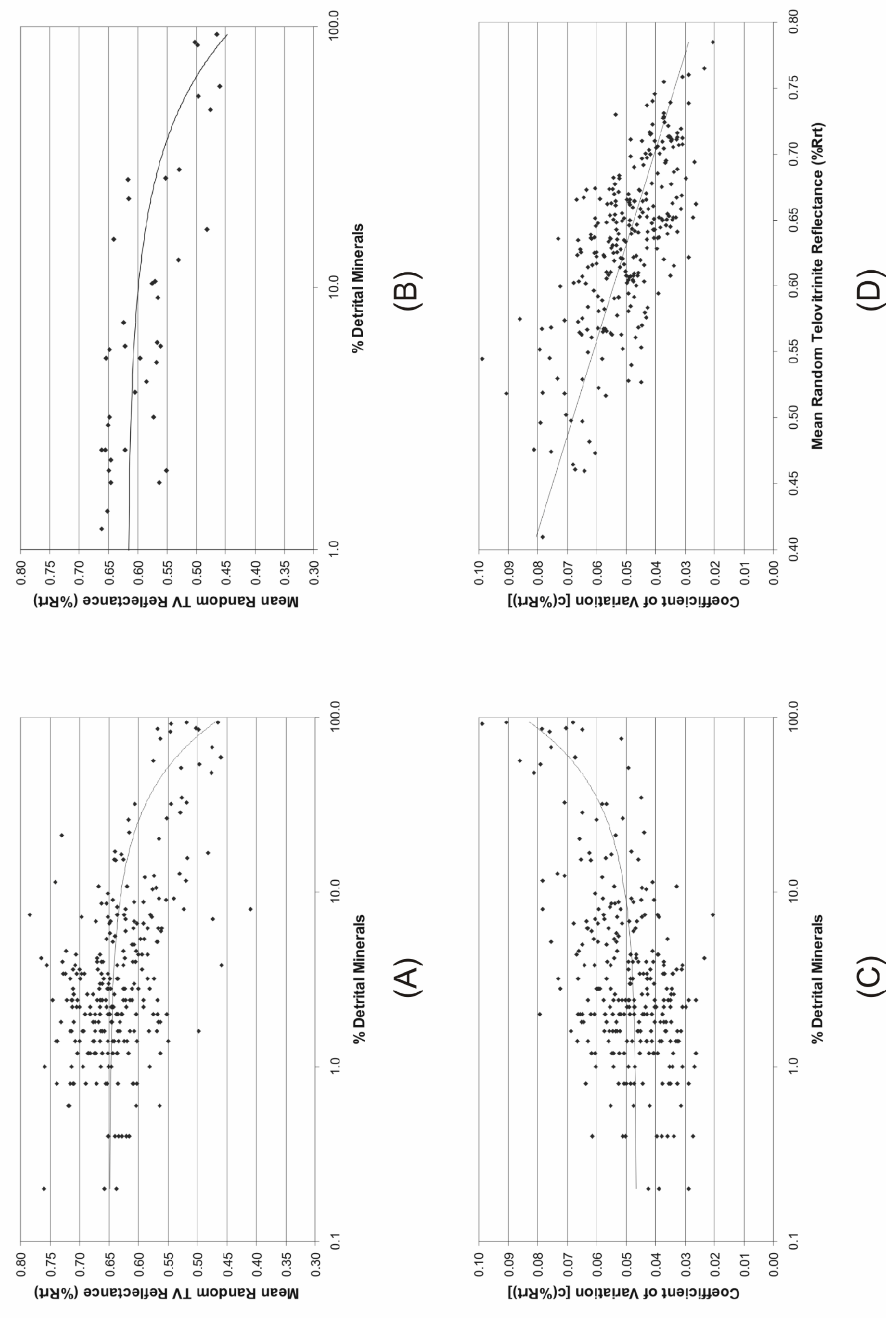


**Figure 5.12.** (A) Cross plot of the relationship between detrital mineral content and %Rrt for all 281 samples, detrital mineral content is plotted on a logarithmic scale as most values are clustered between 0 and 10%. (B) Cross plot of the relationship between detrital mineral content and %Rrt for the lower part of the Sunnyside coal. (C) Cross plot of the relationship between detrital mineral content and c(%Rrt) for all 281 samples. (D) Cross plot of the relationship between %Rrt and c(%Rrt) for all 281 samples.

## 5.6 CONCLUSIONS

Our investigation of vertical and lateral variation in the petrography of the Sunnyside coal has identified a high-resolution record of accommodation change throughout its formation. The correlation of accommodation trends across more than 30 km of depositional dip and 50 km along strike suggests that they reflect regional-scale accommodation changes as opposed to localised variations in the mire. This is further supported by the identification of a marine flooding surface within the coal, which is almost certainly the same flooding surface as that which forms the base of the shallow marine parasequence that pinches out within the seam. This correlation provides a basis for integrating marine and non marine records of accommodation change, and for pushing the resolution of sequence stratigraphic study beyond parasequence resolution.

High detrital mineral content and suppressed telovitrinite reflectance in the lower part of the seam indicate deposition in a low-lying, limnotelmatic mire with moderate clastic sediment input and marine influence. Lower detrital mineral content and increased telovitrinite reflectance and semifusinite content in the upper part of the seam indicate lower accommodation conditions associated with peat accumulation in an ombrotrophic raised mire. Increasing detrital mineral content and decreasing telovitrinite reflectance and semifusinite content towards the top of the seam, suggest that the cessation of peat accumulation occurred when increasing accommodation creation finally outpaced peat production, resulting in drowning of the mire.

Of the range of petrographic indicators of accommodation change we considered, detrital mineral content provides the clearest and most widely correlateable trends, and is therefore considered the best indicator of accommodation change for the Sunnyside coal. This strengthens the case for linking accommodation and mineral content in paralic coals. Variations in telovitrinite reflectance and semifusinite content are also considered to be good indicators of accommodation change for this seam.

Finally, we wish to emphasise the link between telovitrinite reflectance and palaeo-environmental conditions demonstrated by this study. This is especially remarkable considering the slightly weathered nature of some of the outcrop samples. The low %Rrt values in the basal part of the seam and negative correlation between %Rrt and detrital mineral content suggest that the variation in %Rrt in our samples is primarily due to suppression of reflectance values associated with influxes of marine or brackish water into the mire.

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# CHAPTER 6: HIGH-RESOLUTION SEQUENCE STRATIGRAPHIC CORRELATION BETWEEN SHALLOW-MARINE AND TERRESTRIAL STRATA: EXAMPLES FROM THE SUNNYSIDE MEMBER OF THE CRETACEOUS BLACKHAWK FORMATION, BOOK CLIFFS, EASTERN UTAH

*This chapter builds on the previous one by using variations in the most effective indicator of accommodation change (detrital mineral content) to make a detailed sequence stratigraphic interpretation of the Sunnyside coal. This is then integrated with evidence from the time-equivalent shallow-marine strata, in order to produce an integrated model for the evolution of the entire Sunnyside Member.*

## ABSTRACT

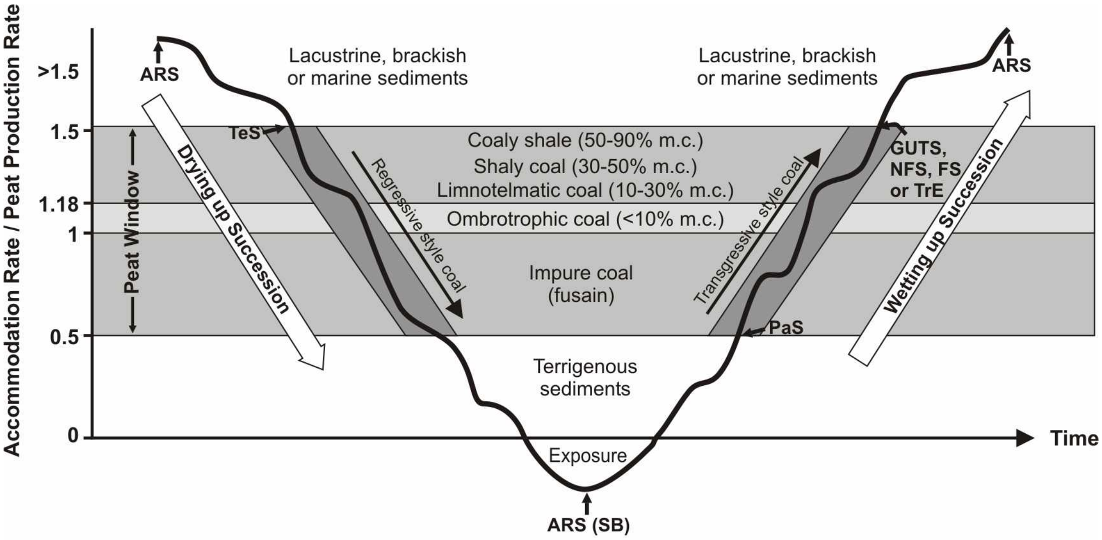
The Sunnyside Member of the Upper Cretaceous Blackhawk Formation in the Book Cliffs of eastern Utah provides an ideal opportunity to investigate high-resolution sequence stratigraphic correlation between shallow-marine and terrestrial strata in an area of outstanding outcrop exposure. The thick, laterally extensive coal seam that caps the Sunnyside Member is critical for correlating between its shallow-marine and terrestrial components. Petrographic analysis of 281 samples obtained from seven vertical sections spanning >30 km of depositional dip enables us to recognise a series of transgressive / regressive coal facies trends within the seam. On this basis we are able to identify a high-resolution record of accommodation change throughout the deposition of the coal, as well as a series of key sequence stratigraphic surfaces. The stratigraphic relationships between the coal and the siliciclastic components of the Sunnyside Member enable us to correlate this record with that identified in the time-equivalent shallow-marine strata, and to demonstrate that the coal spans the formation of two marine parasequences and two high frequency, fourth-order sequence boundaries. This study has important implications for improving the understanding of sequence stratigraphic expression in terrestrial strata, and for correlating between marine and terrestrial records of base-level change. It may also have implications for improving the predictability of vertical and lateral variations in coal composition.

## 6.1 INTRODUCTION

One of the key issues to be addressed in modern stratigraphic research is the correlation and integration of the terrestrial and shallow-marine records. Although sequence stratigraphic schemes have been developed for both marine strata (e.g. Posamentier and Vail, 1988; Mitchum and Van Wagoner, 1991) and terrestrial strata (e.g. Boyd and Diessel, 1994; Shanley and McCabe, 1994; Zaitlin et al., 2002), few studies have succeeded in correlating between them. The aim of this paper is to address this issue by using a combination of terrestrial organic facies and transgressive / regressive marine strata to produce an integrated model for the sequence stratigraphic evolution of the Sunnyside Member of the Cretaceous Blackhawk Formation in the Book Cliffs of Eastern Utah.

Recognising expressions of base-level change in terrestrial strata is inherently more difficult than in marine strata (Boyd and Diessel, 1994; Shanley and McCabe, 1994). An exception to this occurs where terrestrial strata contains coal seams formed in paralic settings, due to the sensitivity of the original peat bodies to changes in depositional conditions (Clymo, 1987; Moore, 1989). Historically, most studies of the ‘sequence stratigraphy’ of coal-bearing strata have been primarily concerned with the significance of whole coal seams within depositional cycles (e.g. Duff and Walton, 1962; Flint et al., 1995; Hampson, 1995). However, a number of more recent studies (e.g. Banerjee et al., 1996; Diessel, 1998; Petersen et al., 1998; Holz et al., 2002; Wadsworth et al., 2003) have explored the high-resolution accommodation changes that can be identified from variations in the internal characteristics of coal seams. One of the key advances demonstrated by these studies was that coal seams can form in response to either increasing or decreasing accommodation, and may span multiple high-frequency accommodation cycles.

In mire depositional systems, accommodation is governed by the height of the mire water-table, which is controlled by a combination of regional base-level, precipitation and auto-compaction of the peat (Moore, 1989; Kosters and Suter, 1993; Winston, 1994). In order for peat to accumulate and be preserved, accommodation has to be created at a rate that approximately balances the rate at which peat is produced (Cross, 1988; Bohacs and Suter, 1997). If the rate of accommodation creation exceeds the rate of peat production, the mire is drowned and inundated with marine or lacustrine sediments. Conversely, if peat production outstrips the rate of accommodation creation, the mire is exposed, oxidised and reworked. Studies of Holocene mires (see fig. 2 in Diessel et al., 2000 and references therein) suggest that the rate of peat production is directly related to geographical latitude. On this basis, it is assumed that localised changes in the ratio of accommodation creation to peat production are mainly due to changes in the rate of accommodation creation.



| | Surface | Explanation | Hiatal / Non-Hiatal |
|---|---|---|---|
| **TeS** | Terrestrialisation Surface | Initiation of peat formation due to upward shallowing | Non-Hiatal |
| **PaS** | Paludification Surface | Initiation of peat formation due to upward deepening | Hiatal or Non-Hiatal |
| **GUTS** | Give-up Transgressive Surface | Gradual termination of peat formation due to upward deepening | Non-Hiatal |
| **ARS** | Accommodation Reversal Surface | Transition between shallowing and deepening upward (and vice-versa) | Hiatal or Non-Hiatal |
| **NFS** | Non-marine Flooding Surface | Abrupt deepening of non-marine facies | Hiatal |
| **FS** | Marine Flooding Surface | Abrupt deepening of marine facies | Hiatal |
| **TrE** | Transgressive Surface of Erosion | Abrupt deepening of facies associated with sediment reworking | Hiatal |

**Figure 6.1.** Idealised curve to show the relationship between accommodation creation, peat production, coaly facies and terrestrial key surfaces. The left hand limb shows the succession of facies and surfaces formed in response to decreasing accommodation, the right hand limb shows the succession formed in response to increasing accommodation (from Wadsworth et al., 2003).

High-frequency changes in the balance between accommodation creation and peat production within the ‘peat-forming window’ should result in changes to the nature of the coaly rocks that are deposited (Fig. 6.1). Higher rates of accommodation creation should give rise to coaly shales and shaly coals with inorganic mineral contents in excess of 30%, as a rapidly rising base-level provides a mechanism for the transport of water-borne, detrital minerals into the mire (Spears, 1987; Diessel, 1992). Lower rates of accommodation creation should result in the formation of 'limnotelmatic' and 'ombrotrophic' coals, with mineral contents below 30% and 10% respectively. Very low rates of accommodation creation may result in increased mineral content due to oxidation and burning of the peat, giving rise to an 'impure coal' characterised by a high inertinite content[1] (Scott, 1989; Wadsworth et al., 2003). Variations in the character, geometry and vertical succession of these coaly facies should reflect equivalent changes in the rate of accommodation creation through time. Upward increases in inorganic mineral content (wetting-upward successions) indicate increasing accommodation creation. Upward decreases in inorganic mineral content (drying-upward successions) indicate decreasing accommodation creation. If the AR/PPR curve[2] remains within the peat-forming window for several periods of increasing and decreasing accommodation, a composite coal may form, containing multiple wetting and drying-upward units.

Using these concepts, Diessel et al. (2000) and Wadsworth et al. (2003) identified seven key terrestrial sequence stratigraphic surfaces (Fig 1). This is an important advance as it provides a previously unavailable ability to recognise terrestrial equivalents of marine flooding surfaces and sequence boundaries. The most important of these newly defined surfaces is the accommodation reversal surface (ARS), which marks the change from increasing to decreasing accommodation conditions or vice versa. Any coal that contains an ARS is a composite seam, spanning more than one depositional cycle. Where an ARS forms the upper bounding surface of a seam it may indicate a hiatus and be the equivalent of a sequence boundary. The initiation of peat formation above marine strata represents a terrestrialisation surface (TeS). This is generally non-hiatal as it indicates a gradual shift from clastic sedimentation to peat accumulation in response to shoreline progradation. The initiation of peat formation above subaerial, terrigenous strata represents a paludification surface (PaS) formed in response to upward deepening, and may be either hiatal or non-hiatal. Where the upper bounding-surface of a seam follows a gradual upward deepening of facies, it represents a give-up transgressive surface (GUTS) formed in response to a gradually increasing rate of accommodation creation. Alternatively, where the transition is abrupt, the seam is capped by either a non-marine flooding surface (NFS) in the up-

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[1] Inertinite is a maceral formed through oxidation or partial burning of plant material at the peat stage.

[2] AR/PPR = accommodation creation rate / peat production rate.

dip area, or by an estuarine, lagoonal or marine flooding surface (FS) in the down-dip area near the shoreline. If there is evidence of removal of peat during transgression, the top of the seam may also represent a transgressive surface of erosion (TrE).

## 6.2 GEOLOGICAL SETTING OF STUDY AREA

The Cretaceous Blackhawk Formation in eastern Utah comprises coal-bearing coastal-plain and wave-dominated shallow-marine strata that inter-tongue with the offshore, marine Mancos Shale further to the east (Young, 1955; 1957). These sediments were deposited within and along the shoreline of the Western Interior Seaway (Speiker, 1949; Young, 1955), which occupied much of central North America during the Late Cretaceous Epoch (Fig. 6.2 B). This intra-continental seaway occupied a retro-arc foreland basin that formed in response to flexural loading associated with the subduction of the Farallon plate beneath the North American plate (Cross, 1986). Siliciclastic sediment was supplied to the basin from the newly uplifted Sevier Orogenic Belt approximately 100 km to the west.

The Blackhawk Formation is interpreted as a third-order, prograding highstand sequence set, which contains a number of higher-frequency fourth-order sequences (Van Wagoner et al., 1990). Young (1955) identified six lithostratigraphic members within the Blackhawk Formation, each of which represents a marine shoreface sandstone complex separated by tongues of marine shale (Fig. 6.2 C). Landward of these shallow-marine members is a time-equivalent coastal-plain complex, which includes numerous coal seams that can be traced basinward onto the tops of marine parasequences. Each member within the Blackhawk Formation extends further eastward (basinward) than the underlying one due to long-term progradation of the shoreline. There is also an overall change from aggradational to strongly progradational stacking of individual parasequences towards the top of the formation. Combined with an upward decrease in the vertical spacing of sequence boundaries, this indicates a long-term decrease in accommodation creation (Taylor and Lovell, 1995). The top of the formation is marked by a third-order sequence boundary at the base of the Castlegate Formation. Detailed reviews of previous work on the Blackhawk Formation can be found in Van Wagoner (1995) and Howell and Flint (2003).

This study is focused on the Sunnyside Member, which occurs in the middle of the Blackhawk Formation (Fig. 6.2 C), at the change from aggradational to progradational stacking described above. It contains the thickest and most laterally extensive coal seam within the Blackhawk Formation (Bohacs and Suter, 1997). The Sunnyside coal was deposited in a very large (>1800 km$^2$), continuous mire oriented approximately NNE-SSW, parallel to the shoreline of the Western Interior Seaway (Young, 1957; Doelling et al., 1979). Heavily rooted shoreface deposits underlie the seam across most of the study area, indicating that the mire developed directly behind the shoreline as a result of continued progradation and terrestrialisation.

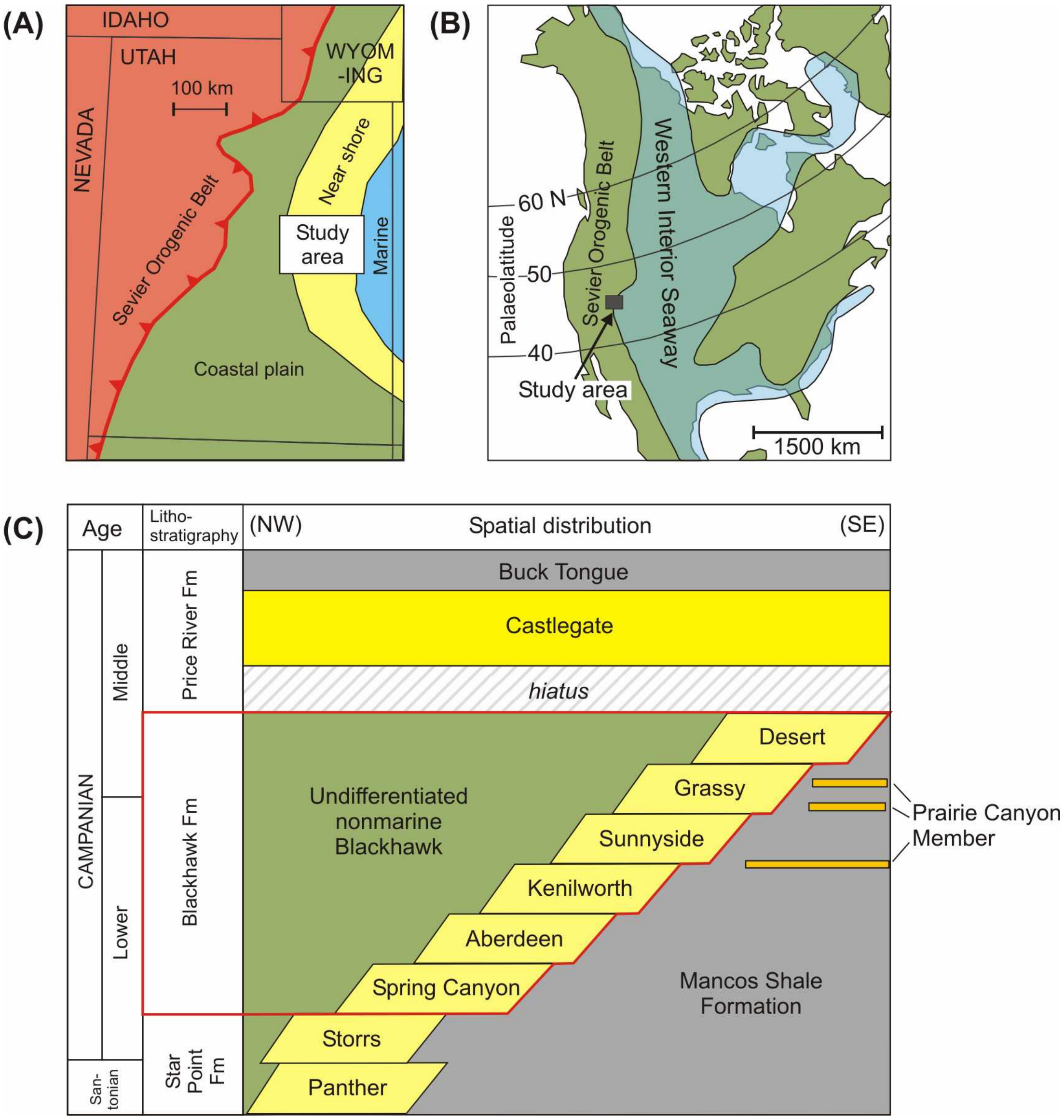


**Figure 6.2.** (A) Location of study area. (B) Late Cretaceous palaeogeography of southwestern USA. (C) Lithostratigraphy of the Blackhawk Formation (from Howell and Flint, 2003).

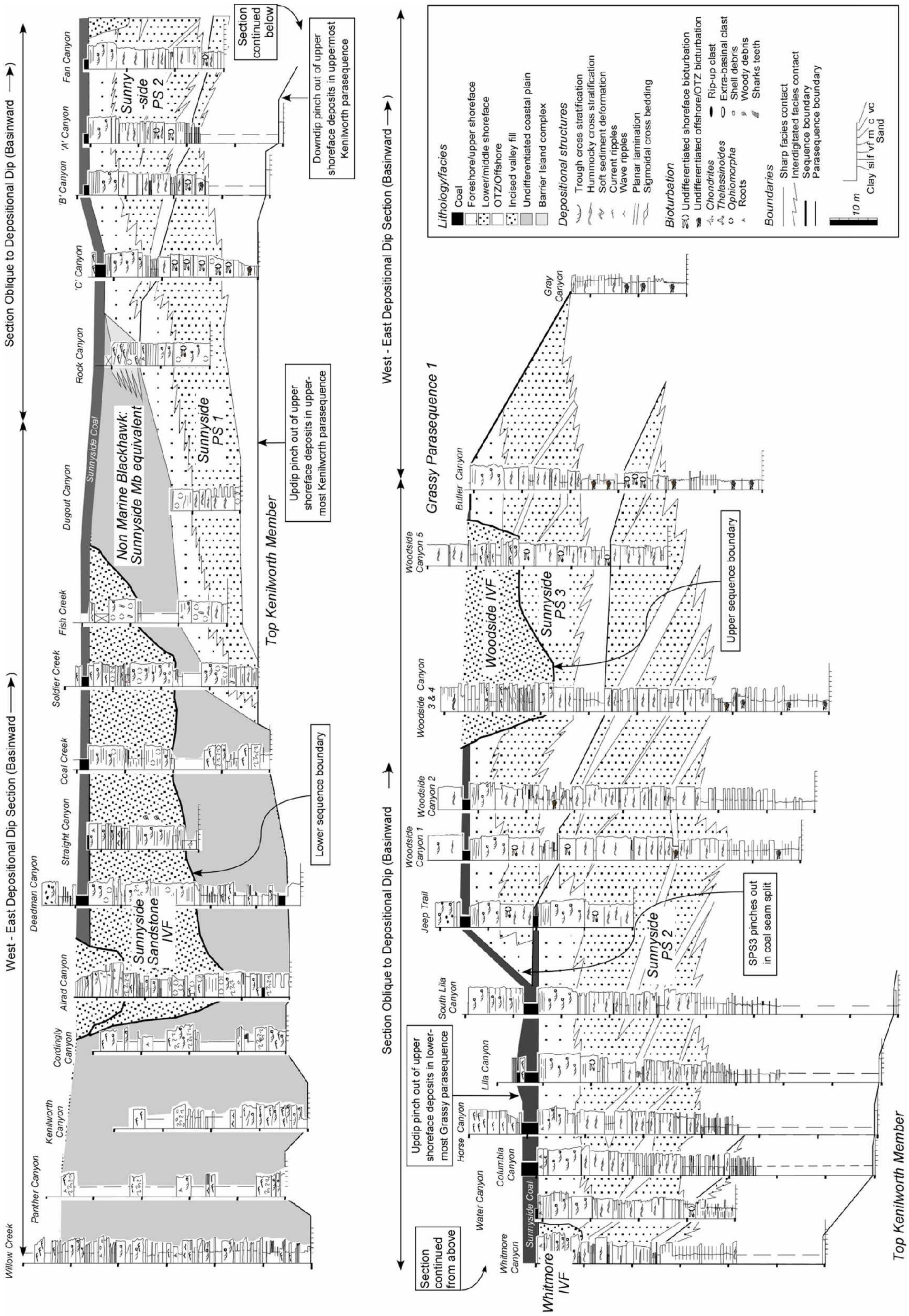


**Figure 6.3.** Correlation panel showing 29 outcrop logs through the Sunnyside Member and equivalent marginal to non-marine deposits (from Howell et al., in press). The total depositional dip extent of the section is approximately 50 km.

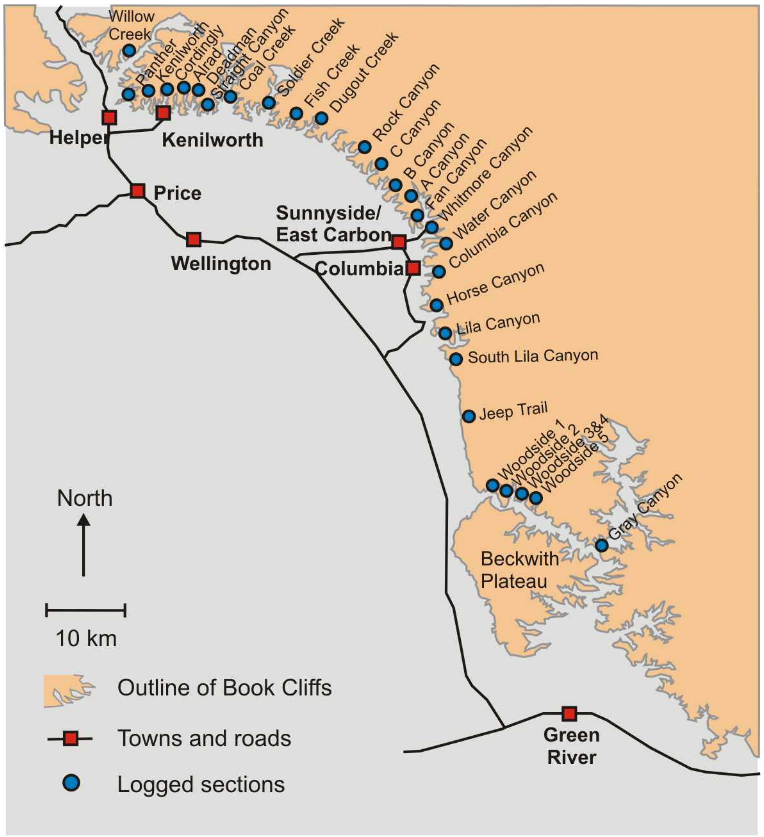


**Figure 6.3.** Map to show the location of logged sections shown in Fig 6.3 in relation to the outline of the Book Cliffs.

## 6.3 THE SUNNYSIDE MEMBER

The Sunnyside Member is composed of three wave-dominated shoreface parasequences, time-equivalent coastal-plain strata and discrete packages of fluvial / tidal sediments interpreted as incised valley fills (Young, 1955). The distribution of facies and stratal geometries observed in the Sunnyside Member are shown in Figure 6.3. The excellent outcrop exposure in the Book Cliffs enables a high degree of confidence in the correlations drawn between the twenty-nine outcrop logs shown in this panel. More detailed descriptions of the siliciclastic facies and their depositional environments can be found in Howell and Flint (2003) and Howell et al. (in press).

Figure 6.4 shows a schematic summary of the sequence stratigraphic evolution of the Sunnyside Member as interpreted by Howell et al. (in press). The base of the member is a laterally extensive shale tongue that represents the maximum flooding surface to a high frequency, fourth-order sequence that has its lower boundary within the underlying Kenilworth Member (Taylor and Lovell, 1995; Pattison, 1995). The two lower Sunnyside parasequences (SPS1 and SPS2) represent the highstand systems tract of this sequence. The top of SPS2 is marked by a sequence boundary associated with valley incision across much of the northwestern part of the study area (Howell et al., in press). This sequence boundary is overlain locally by tidal, estuarine valley fill successions, which in turn are overlain by the Sunnyside coal, which also extends onto the adjacent interfluves. All of the valley fill successions are capped by a considerable thickness of coal, indicating that the sequence boundary must have predated the formation of most of the seam.

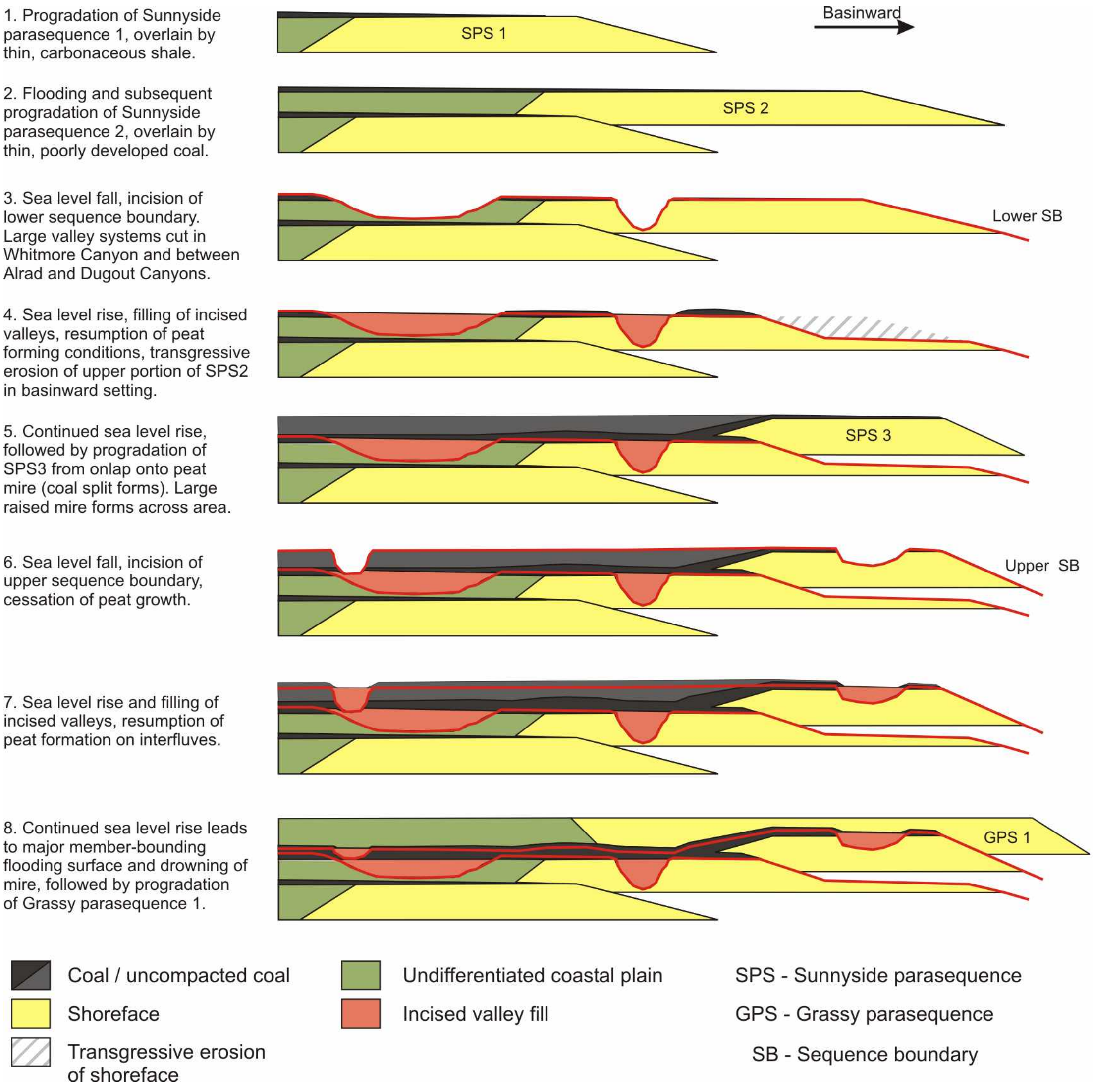


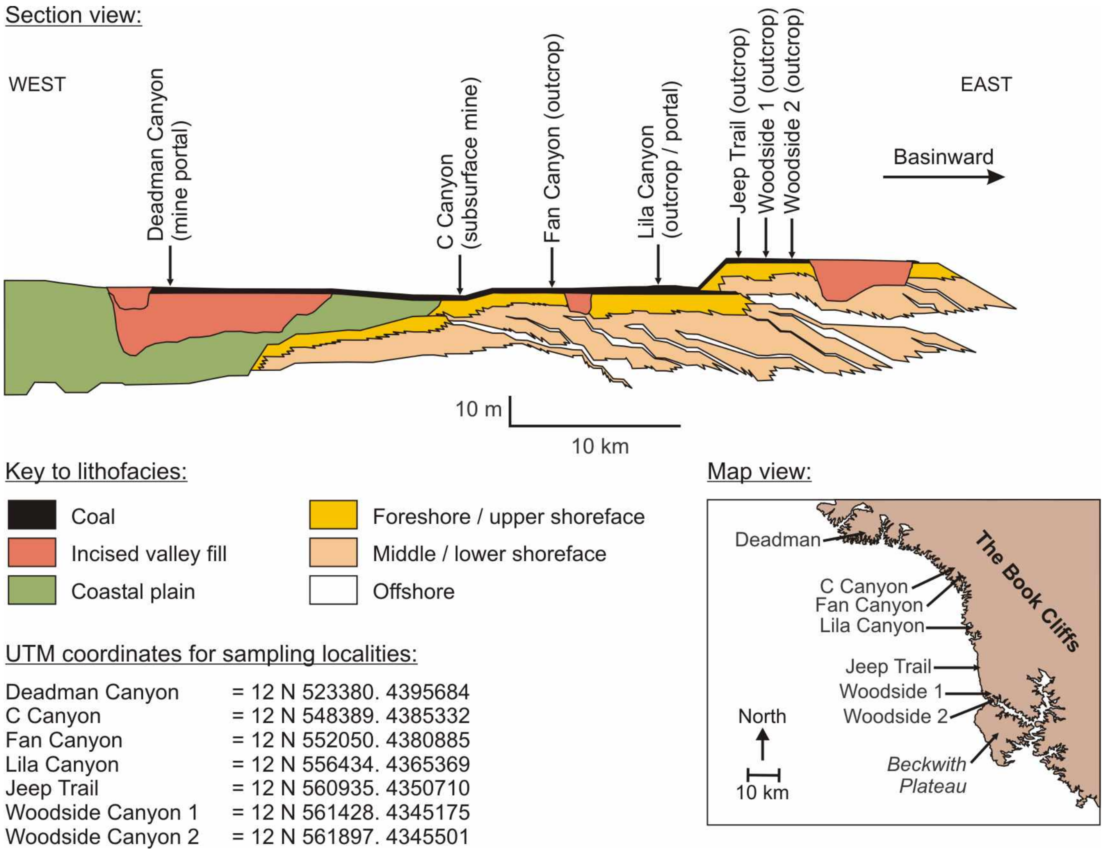
**Figure 6.4.** Schematic model for the sequence stratigraphic evolution of the Sunnyside Member (modified from Howell et al., in press).

A transgression occurred (Fig. 6.4, stage 5) prior to the deposition of the third Sunnyside parasequence (SPS3), resulting in transgressive erosion of the basinward portion of SPS2, and the onlap of shoreface deposits onto the basinward part of the mire. SPS3 represents a highstand systems tract, which was terminated by the fourth-order sequence boundary that produced the Woodside incised valley in the southeastern part of the study area. Subsequent transgression filled this valley, and resulted in the regionally-extensive landward dislocation of facies that marks the lithostratigraphic boundary with the overlying Grassy Member (O'Byrne and Flint, 1995).

Based on the above sequence stratigraphic model, the Sunnyside coal spans the time interval from the top of SPS2 to the base of GPS1. It should therefore contain expressions of at least two fourth-order sequence boundaries, and the flooding surface associated with the formation of the main coal seam split. This makes it an ideal candidate to attempt to integrate high-resolution shallow-marine and terrestrial records of accommodation change. In order to achieve this objective we have used coal petrographic analysis (as described in the following section) to identify a high-resolution record of accommodation change within the Sunnyside coal.

## 6.4 COAL SAMPLING AND ANALYSIS

The main primary data-set for this study was derived from detailed petrographic analysis of 281 coal samples obtained from seven vertical sections through the Sunnyside coal, spanning >30 km of depositional dip and 50 km of depositional strike (Fig. 6.5). The choice of sampling localities was partly controlled by the shape of the Book Cliffs escarpment and localised burning of coal in the outcrop. Prior to sampling, a detailed log of macroscopically identifiable variations in the coal was produced at each locality. This provided an indication of the required sampling resolution and ensured that no potential key surfaces were sampled across. In the five outcrop sections (Fig. 6.5) the coal was excavated to a depth of approximately 1 m prior to logging and sampling in order to remove excessively weathered material. For most sections the average sample spacing was 5 to 10 cm, although a sampling resolution of approximately 2.5 cm was achieved for the section sampled in an active, subsurface mine at C Canyon. Where possible, samples were kept intact in order to preserve the original depositional layering, cured in epoxy resin and then cut and polished in accordance with standard methods for microscopic analysis in incident light. Those too brittle to be kept intact were crushed to a top size of 2 mm and a representative sub-sample prepared as a grain mount instead.



UTM coordinates for sampling localities:

| | |
|---|---|
| Deadman Canyon | = 12 N 523380. 4395684 |
| C Canyon | = 12 N 548389. 4385332 |
| Fan Canyon | = 12 N 552050. 4380885 |
| Lila Canyon | = 12 N 556434. 4365369 |
| Jeep Trail | = 12 N 560935. 4350710 |
| Woodside Canyon 1 | = 12 N 561428. 4345175 |
| Woodside Canyon 2 | = 12 N 561897. 4345501 |

**Figure 6.5.** Simplified cross section through the Sunnyside Member and outline map of the Book Cliffs to show the spacing of sampling localities in section and map view (modified from Howell et al., in press).

The petrographic composition of each sample was determined by counting 500 points per sample in accordance with Australian Standard guidelines (Australian Standard AS 2856.2–1998, 1998). Mean random telovitrinite reflectance (%Rrt) was also determined, based on 50 measurements per sample, but otherwise in accordance with Australian Standard guidelines (Australian Standard AS 2486–1989, 1989). This type of analysis provides a detailed breakdown of the composition of the organic and inorganic constituents of the coal, which can be used to make detailed interpretations of the environment in which it formed. In this paper we have primarily concentrated on coal facies differentiated on the basis of their inorganic mineral content, however, there also several other petrographic properties that can be used as indicators of accommodation change. A brief summary of these is given in Table 6.1 (compiled from Spears, 1987; Cohen et al., 1987; Scott, 1989; Diessel, 1992; Petersen et al., 1998; Diessel, 1998; Diessel and Gammidge, 1998; Staub, 2002).

**Table 6.1.**
Summary of petrographic indicators of accommodation change within coal seams

| Property | Definition | Significance |
|---|---|---|
| Vitrinite | Humified plant material, especially woody and cellulose rich parts of plants. | High vitrinite content, especially the structured sub-group telovitrinite, indicate a high mire water table and balanced rates of accommodation creation and peat production. |
| Inertinite | Oxidised or partially combusted plant material. | High inertinite content, especially the structured sub-groups fusinite and semifusinite, indicate a low mire water table and exposure and oxidation / burning of the peat. |
| Liptinite | Resistant plant materials including spores, pollen, cuticles, waxes and resin. | High liptinite content indicates loss of other biomass due to either harsh preservation conditions associated with flooding of the mire or oxidation associated with dry conditions. |
| Inorganic Minerals | Detrital, authigenic and plant derived inorganic material. | High mineral content is usually associated with deposition in high accommodation settings and flooding of the mire. |
| Syngenetic Pyrite | Framboidal and concentric forms of pyrite deposited concurrently with the peat. | High pyrite contents indicate marine or brackish influence in the mire groundwater. |
| Vitrinite Reflectance | A measure of the intensity of light reflected from polished surfaces of vitrinite grains. | Suppressed vitrinite reflectance is associated with wetter conditions and marine or brackish influence. Enhanced vitrinite reflectance is associated with slight oxidation / dry conditions. |

## 6.5 SUMMARY OF RESULTS

Table 6.2 gives the average composition of the Sunnyside coal for each of the seven sampled sections and for all 281 samples combined. The relatively low mean total mineral content of 8.2% suggests that the seam formed in either an ombrotrophic raised mire or a limnotelmatic mire with limited sediment input. The increase in mineral content in the more basinward sections suggests that the mineral component of the Sunnyside coal is predominantly marine derived. The very low pyrite content suggests that the mire groundwater was mainly fresh (Cohen et al., 1987). However, this figure has to be treated with caution as weathering may have removed pyrite from some of the outcrop samples. The relatively high vitrinite to inertinite ratio of 4:1 indicates that accommodation creation and peat production were generally well balanced, and that loss of peat due to exposure and oxidation was limited. A more detailed discussion of the vertical and lateral variation in the petrography of the Sunnyside coal can be found in Davies et al. (in press).

**Table 6.2.**
Average composition of the Sunnyside coal by sampled section, and for all 281 samples combined.

| Maceral / Group | Deadman Canyon | C Canyon | Fan Canyon | Lila Canyon | Jeep Trail | Woodside Canyon I | Woodside Canyon II | All Samples |
|---|---|---|---|---|---|---|---|---|
| Telovitrinite | 23.3% | 23.9% | 17.9% | 22.3% | 21.6% | 16.2% | 17.3% | 21.7% |
| Detrovitrinite | 45.6% | 52.9% | 48.2% | 46.3% | 39.1% | 37.7% | 52.6% | 47.4% |
| Sporinite | 1.9% | 1.3% | 2.8% | 2.8% | 2.4% | 2.2% | 1.7% | 2.2% |
| Cutinite | 1.1% | 1.0% | 1.0% | 1.5% | 1.5% | 1.3% | 1.7% | 1.3% |
| Resinite | 2.8% | 2.1% | 3.1% | 2.8% | 3.1% | 2.5% | 2.4% | 2.6% |
| Micrinite | 0.9% | 0.6% | 1.7% | 1.4% | 1.3% | 0.7% | 0.6% | 1.1% |
| Macrinite | 1.4% | 1.2% | 1.1% | 1.4% | 1.0% | 0.3% | 0.2% | 1.2% |
| Semifusinite | 9.0% | 6.8% | 8.0% | 7.8% | 6.2% | 4.1% | 5.4% | 7.2% |
| Fusinite | 0.5% | 0.5% | 1.2% | 0.7% | 0.6% | 0.3% | 0.3% | 0.7% |
| Inertodetrinite | 6.1% | 5.6% | 9.7% | 7.2% | 4.9% | 3.8% | 3.1% | 6.4% |
| Detrital Mins | 7.2% | 3.7% | 5.2% | 5.6% | 17.7% | 30.6% | 14.7% | 8.0% |
| Pyrite | 0.1% | 0.3% | 0.1% | 0.1% | 0.7% | 0.3% | 0.1% | 0.2% |
| Total Vitrinite | 69.0% | 76.8% | 66.0% | 68.6% | 60.7% | 53.9% | 69.9% | 69.1% |
| Total Liptinite | 5.8% | 4.4% | 7.0% | 7.1% | 7.0% | 6.0% | 5.8% | 6.1% |
| Total Inertinite | 18.0% | 14.8% | 21.7% | 18.6% | 14.0% | 9.2% | 9.5% | 16.6% |
| Total Minerals | 7.2% | 4.0% | 5.3% | 5.6% | 18.4% | 30.9% | 14.9% | 8.2% |

## 6.6 COAL FACIES TRENDS BY SAMPLED SECTION

Figure 6.6 shows vertical coal facies trends (differentiated on the basis of inorganic mineral content) and interpreted key sequence stratigraphic surfaces for each of the seven sampled sections through the Sunnyside coal. These are presented as a series of coal facies v’s thickness plots, and schematic logs of wetting and drying-upward coal units. A summary of the accommodation trends and key surfaces identified in each sampled section is given below, along with a brief description of the nature of each sampling locality.

### 6.6.1 Deadman Canyon

The most landward sampled section was obtained from an abandoned mine portal in Deadman Canyon (Fig. 6.5). The base of the 1.5 m thick seam represents a terrestrialisation surface (TeS) as the underlying ‘Sunnyside Sandstone’ incised valley fill is interpreted as being of estuarine origin (Howell et al., in press). An accommodation reversal surface (ARS) occurs approximately 60 cm from the base of the seam. This is overlain by two subtle wetting-upward trends in the upper part of the seam. The top of the coal is interpreted as a non-marine flooding surface (NFS) due to the abrupt nature of the transition into the overlying, subaqueous coastal-plain strata, which are the up-dip equivalent of the Grassy Member.

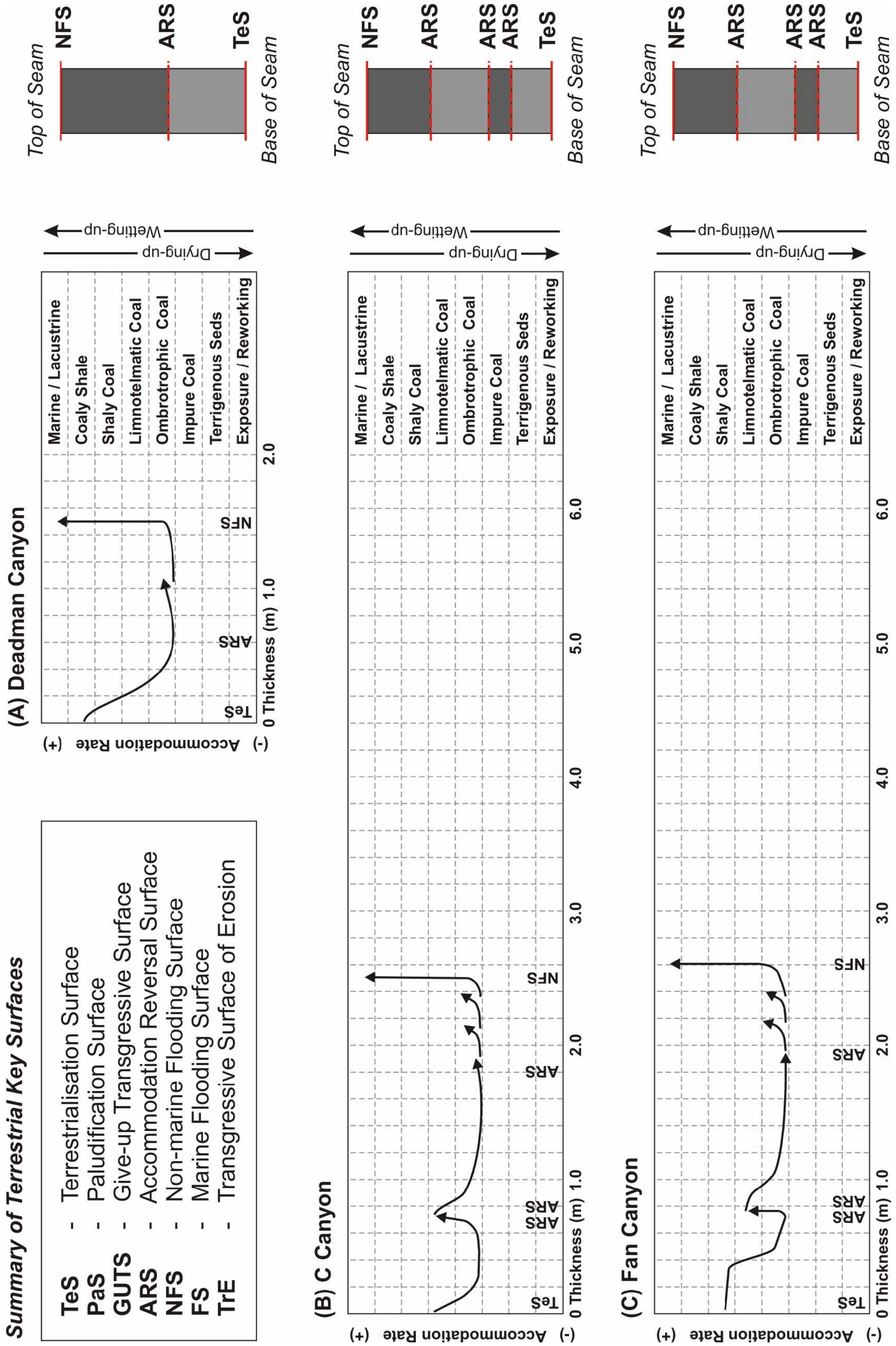


**Figure 6.6.** Coal facies trends and key sequence stratigraphic surfaces for seven sampled sections through the Sunnyside coal. Lighter grey indicates drying-upward coal, darker grey indicates wetting-upward coal. See Figure 6.5 for location of sampling localities (continued on next page).

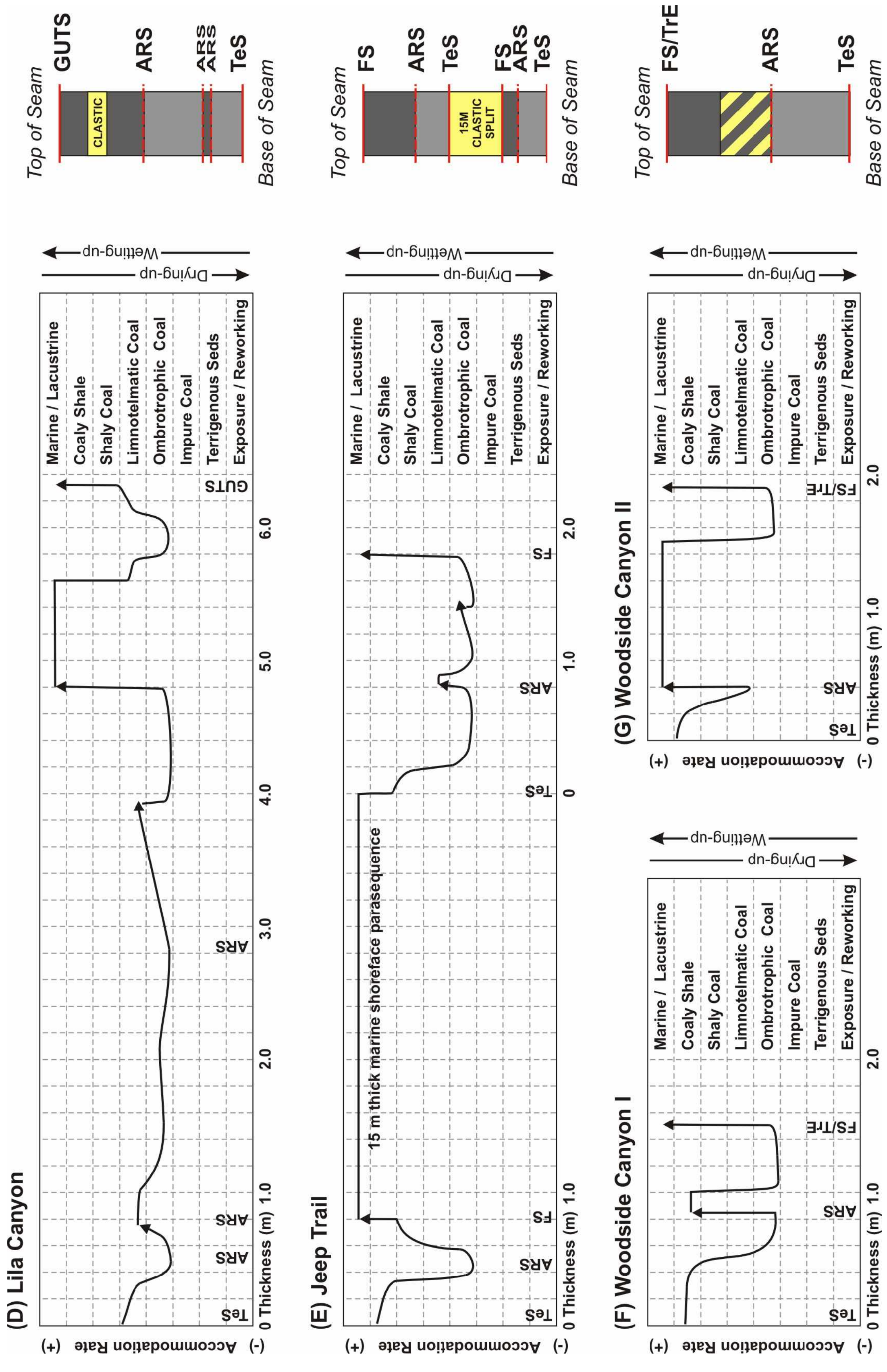


**Figure 6.6.** Coal facies trends and key sequence stratigraphic surfaces for seven sampled sections through the Sunnyside coal. Lighter grey indicates drying-upward coal, darker grey indicates wetting-upward coal. See Figure 6.5 for location of sampling localities (continued from previous page).

### 6.6.2 C Canyon

A complete ‘channel sample’ was obtained from an active subsurface mine in C Canyon (Fig. 6.5). The 2.5 m thick seam rests directly on the shallow-marine shoreface sandstones of Sunnyside parasequence 2. The base of the coal is therefore interpreted as a TeS as it appears to mark a continuation of the shallowing-upward succession associated with the progradation of this parasequence. An ARS occurs 70 cm from the base of the seam (Fig. 6.6), marking the transition from drying-upward style coal into 10 cm of coal with a similar mineral content to the basal part of the seam. This layer is interpreted as the result of an influx of marine water into the mire, as it is associated with a significant increase in pyrite content and suppressed telovitrinite reflectance. It is overlain by another ARS and a return to drying-upward style coal. A third ARS occurs 70 cm from the top of the seam, followed by three wetting-upward units that culminate in an NFS at the top of the seam, where the coal is overlain by subaqueous, coastal-plain deposits.

### 6.6.3 Fan Canyon

The Fan Canyon section was sampled entirely in the outcrop, close to entrance of the abandoned Fan Canyon mine (Fig. 6.5). As at C Canyon, the transition from shoreface sandstones into the 2.6 m thick coal is interpreted as a TeS, marking a continuation of the shallowing upward associated with the progradation of Sunnyside parasequence 2. The drying-upward trend in the basal 75 cm of the seam is capped by an ARS and a thin package of wetting-upward coal (Fig. 6.6). A second ARS and drying-upward trend occurs above this, followed by a third ARS and three wetting-upward trends in the upper part of the seam. The top of the coal is again interpreted as an NFS, and overlain by subaqueous, coastal-plain strata.

### 6.6.4 Lila Canyon

The Sunnyside coal is at its thickest in the area around Lila Canyon (Fig. 6.5). A 6.3 m thick section was sampled in the outcrop and within a portal of the abandoned Lila Canyon mine. The basal 1 m of the seam shows similar wetting and drying-upward trends to the basal parts of the C Canyon and Fan Canyon sections, including a TeS and two closely spaced ARSs (Fig. 6.6). This is overlain by 2 m of drying-upward coal before a third ARS, which marks the transition into three wetting-upward trends in the upper part of the seam. The second of these culminates in an 80 cm thick package of fine-grained, organic rich, clastic sediment (Fig. 6.3). This is not laterally persistent into the canyons on either side of Lila Canyon, and probably represents a localised influx of sediment due to increased accommodation creation in this part of the mire. The top of the seam shows a gradational change from ombrotrophic coal into shaly coal and the overlying lagoonal strata, and is therefore interpreted as a give-up transgressive surface (GUTS).

### 6.6.5 Jeep Trail

The Jeep Trail section is critical to correlating accommodation trends between the landward sections, which overlie Sunnyside parasequence 2, and the basinward sections, which overlie Sunnyside parasequence 3, as this is the only locality in the coal could be sampled both above and below SPS3 in a single vertical section (Fig. 6.5). As in the previously described localities, the base of the 0.8 m thick lower seam is interpreted as a TeS. This is overlain by an ARS, which marks the transition from drying-upward into wetting-upward coal (Fig. 6.6). The top of the lower seam is interpreted as a marine flooding surface (FS) as it marks a relatively abrupt transition from coal into shallow-marine strata. This surface also represents an ARS and marks the boundary between Sunnyside parasequences 2 and 3. The base of the upper seam is interpreted as a second TeS as it represents a continuation of the shallowing-upward succession associated with the progradation of Sunnyside parasequence 3. An ARS occurs approximately 1 m from the top of the section, followed by three wetting-upward units that culminate in a second FS at the top of the seam, which is overlain by shallow-marine strata of the Grassy Member.

### 6.6.6 Woodside Canyon I

The first Woodside Canyon section was sampled in the outcrop close to the northern side of the entrance to the Canyon (Fig. 6.5). The base of the 1.5 m thick seam, which overlies the top of Sunnyside parasequence 3, is interpreted as a TeS (Fig. 6.6). The initial drying-upward trend is followed by an ARS and two wetting-upward trends. The very abrupt transition from ombrotrophic coal into the overlying shallow-marine strata suggests that the top of the seam was removed by transgressive erosion, it is therefore interpreted as representing both an FS and a transgressive surface of erosion (TrE).

### 6.6.7 Woodside Canyon II

A second section was sampled further into Woodside Canyon, approximately 400 m down depositional dip from the first. Not surprisingly this shows very similar coal facies trends to the first Woodside Canyon section, except that the first wetting-upward trend culminates in a 109 cm thick package of fine-grained clastic sediment (Fig. 6.6). This is almost certainly the lateral equivalent of the 15 cm thick coaly shale unit in the middle of the first Woodside Canyon section, both being the result of an influx of sediment into the basinward part of the mire due to an abrupt increase in accommodation. The top of the seam is again interpreted as an FS / TrE due to the very abrupt transition from ombrotrophic coal into shallow-marine strata.

## 6.7 DISCUSSION

### 6.7.1 Correlation of accommodation trends between sampled sections

Figure 6.7 shows a schematic correlation of the drying / wetting-upward coal units and key sequence stratigraphic surfaces identified in the seven sampled sections. The TeS at the base of the Deadman Canyon section is correlated with the second ARS at C Canyon, as the first accommodation cycle observed from C Canyon through to Jeep Trail is not present at Deadman Canyon. This is probably due to the removal of peat in this area during the incision of the valley that the coal now sits above. On the basis of this correlation, the first ARS in the C Canyon, Fan Canyon, Lila Canyon and Jeep Trail sections is equivalent to the lower Sunnyside sequence boundary, and runs along the base of the Sunnyside Sandstone and Whitmore Canyon incised valley fills. Similarly, the wetting-upward coal between this and the second ARS is equivalent to the transgressive fill of these incised valleys. The second ARS in the C Canyon, Fan Canyon and Lila Canyon sections passes basinward into an FS at Jeep Trail, indicating that this surface is the terrestrial equivalent of the marine flooding surface that marks the boundary between Sunnyside parasequences 2 and 3.

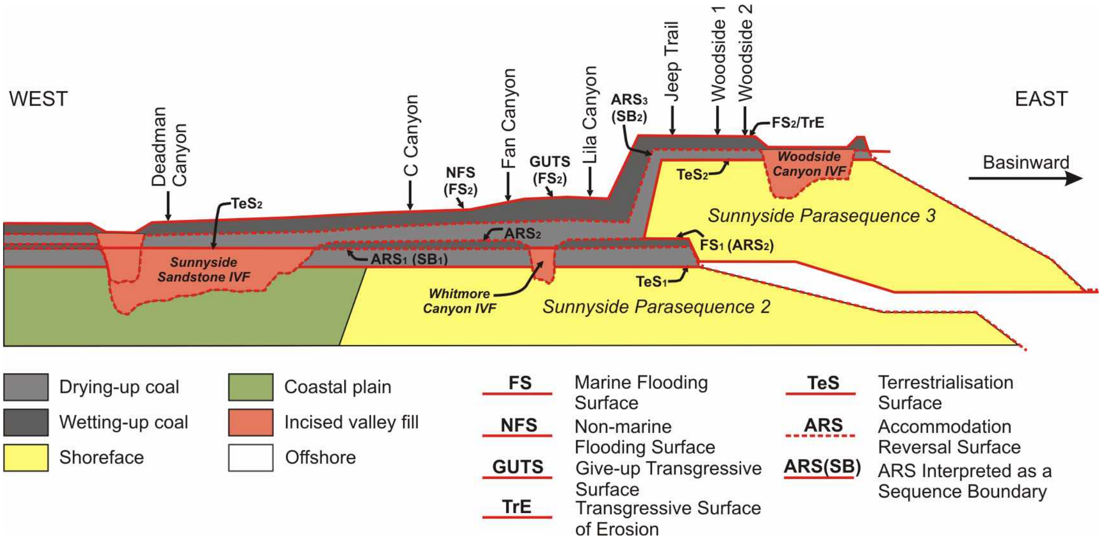


**Figure 6.7.** Schematic correlation of wetting and drying-upward coal packages and key sequence stratigraphic surfaces for seven vertical sections through the Sunnyside coal.

The third ARS in the C Canyon, Fan Canyon, Lila Canyon and Jeep Trail sections is correlated with the ARS in the middle of the Deadman Canyon and two Woodside Canyon sections, and marks a transition from drying-upward style coal to wetting-upward coal across the entire area. This surface is also interpreted as being the equivalent of the upper Sunnyside sequence boundary, as although it was not possible to sample any coal above the Woodside Canyon incised valley fill, the coal can be observed above the valley fill on the western side of the Beckwith Plateau (Fig. 6.5). This observation means that the cessation of peat formation must post-date the incision and filling of the valley, and that the upper Sunnyside sequence boundary has to be recorded within the thicker coal to the west. It also means that the lower part of the wetting-upward coal package at the top of the seam is time-equivalent to the fill of the Woodside Canyon incised valley. The top of the seam is interpreted as an NFS in the up-dip sections (Deadman Canyon to Fan Canyon), as a GUTS at Lila Canyon, and an FS/TrE in Jeep Trail and Woodside Canyon. All of these represent the drowning of the mire due to accommodation creation increasing at a rate which peat production was unable to keep up with.

### 6.7.2 Generalised accommodation curve based on coal data

The good correlation of coal facies trends and key surfaces across all seven sampling localities shown in Figure 6.7, suggests that they represent regional scale accommodation changes, as opposed to localised variations in the mire. On this basis we are able to construct a generalised accommodation curve for the duration of the formation of the Sunnyside coal (Fig. 6.8). This shows that the formation of the Sunnyside coal spanned two cycles of increasing and decreasing accommodation, including the two fourth-order sequence boundaries and flooding surface described in Figure 6.4. The upper portion of the accommodation curve includes some high-frequency ‘fifth-order’ cycles, interpreted on the basis of the multiple wetting-upward trends observed in the upper part of the coal in all seven sampled sections. The staggered nature of accommodation increase during this period is supported by the presence of palaeosols and minor coals within the time-equivalent fill of the Woodside Canyon incised valley fill. The fact that these cycles were not identified in the time-equivalent shallow-marine strata, illustrates how sensitive peat-forming depositional environments are to accommodation change. One of the main reasons for this is that peat accumulation is considerably less episodic than siliciclastic deposition, and therefore has the potential to preserve a higher-resolution and more complete record of accommodation change.

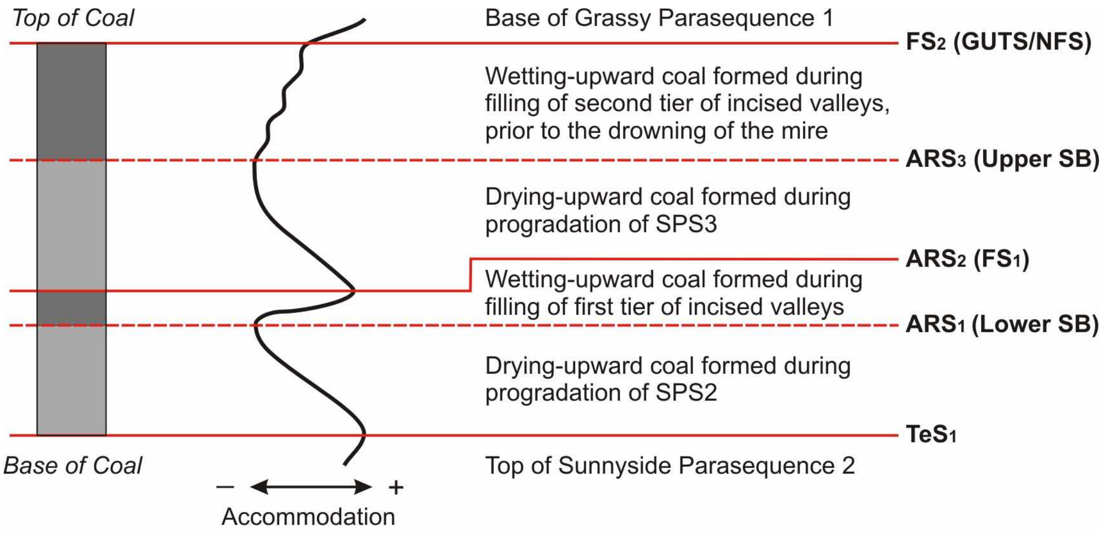
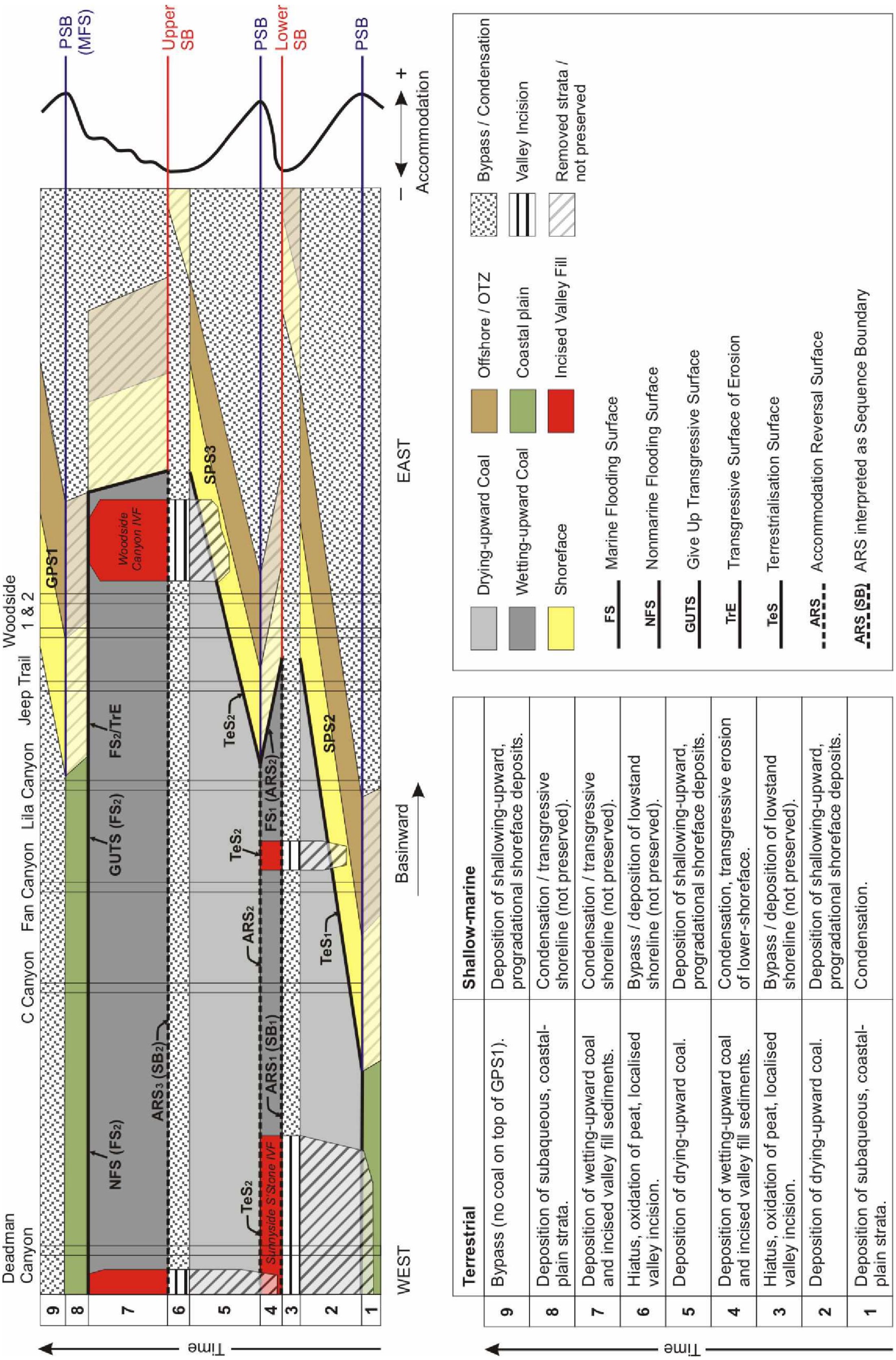


**Figure 6.8.** Generalised accommodation curve for the duration of the deposition of the Sunnyside coal, based on trends identified in all seven sampled sections.

### 6.7.3 Correlation of terrestrial and marine records of accommodation change

Figure 6.9 shows a generalised accommodation curve and schematic chronostratigraphic chart for the duration of the deposition of the Sunnyside coal. This enables us to demonstrate how the coal correlates spatially and temporally with the siliciclastic components of the Sunnyside Member. The periods of bypass and condensation in the shallow-marine sector are based on the stratal geometries shown in Figure 6.3, and models for parasequence formation in the Book Cliffs described by Van Wagoner et al. (1990), Kamola and Wagoner (1995), and Howell and Flint (2003). The periods of hiatus in the coal are based on the assumption that peat accumulation ceased during the two sequence boundaries, as peat cannot accumulate more than 20 m above the regional groundwater table (Bruenig, 1990). The accompanying table summarises the main depositional events in the terrestrial and shallow-marine sectors during each of the ‘time periods’ labelled along the left-hand edge of the chronostratigraphic chart. This table shows where correlatable accommodation changes are preserved in both terrestrial and marine strata (e.g. time periods 2 and 5), and where accommodation changes are only recorded in one sector (e.g. time periods 4 and 7).

It is notable that during periods of base-level rise in particular, a more complete record of accommodation change is preserved in the terrestrial strata. This is best illustrated by the parasequence boundaries (PSBs) in Figure 6.9. These are represented by hiatal flooding surfaces in the marine realm, but can be traced back up depositional dip into packages of coal and terrestrial strata that preserve the transition between transgression and regression, thus enabling us to better constrain the relative rates of base-level rise and fall. Similarly, the high-frequency ‘fifth order’ cycles in the upper part of the accommodation curve are not recorded in the marine realm. However, they are evident in the both the sequence of organic facies in the upper part of the Sunnyside coal, and in the sequence of facies observed in the Woodside Canyon incised valley fill. These points highlight the importance of being able to identify high-resolution records of accommodation change in terrestrial strata. Given that most accommodation is created landward of the shoreline during periods of base-level rise (Van Wagoner, 1995), it is not surprising that terrestrial sediments should preserve the best record of accommodation change during such times.



|  | Terrestrial | Shallow-marine |
|---|---|---|
| 9 | Bypass (no coal on top of GPS1). | Deposition of shallowing-upward, progradational shoreface deposits. |
| 8 | Deposition of subaqueous, coastal-plain strata. | Condensation / transgressive shoreline (not preserved). |
| 7 | Deposition of wetting-upward coal and incised valley fill sediments. | Condensation / transgressive shoreline (not preserved). |
| 6 | Hiatus, oxidation of peat, localised valley incision. | Bypass / deposition of lowstand shoreline (not preserved). |
| 5 | Deposition of drying-upward coal. | Deposition of shallowing-upward, progradational shoreface deposits. |
| 4 | Deposition of wetting-upward coal and incised valley fill sediments. | Condensation, transgressive erosion of lower-shoreface. |
| 3 | Hiatus, oxidation of peat, localised valley incision. | Bypass / deposition of lowstand shoreline (not preserved). |
| 2 | Deposition of drying-upward coal. | Deposition of shallowing-upward, progradational shoreface deposits. |
| 1 | Deposition of subaqueous, coastal-plain strata. | Condensation. |

**Figure 6.9.** Schematic chronostratigraphic chart to show the spatial and temporal correlation between the terrestrial and shallow-marine components of the Sunnyside Member. The accompanying table summarises the main depositional events in the terrestrial and shallow-marine sectors during each of the 'time periods' labelled along the left-hand edge of the chronostratigraphic chart in order to show where correlatable accommodation changes are preserved in both terrestrial and marine strata.

Figure 6.9 also illustrates several other points of interest with regard to the amount of time represented by various key sequence stratigraphic surfaces. The two terrestrialisation surfaces ($TeS_1$ and $TeS_2$) are not synchronous across the study area, as they formed throughout the progradation of Sunnyside parasequences 2 and 3 respectively. The two flooding surfaces ($FS_1$ and $FS_2$) are also slightly diachronous, as the basinward part of the mire would have been flooded sooner than its centre, due to the topography of the mire. Furthermore, although $FS_2$ and its up-dip correlatives mark the cessation of peat formation, the maximum flooding surface (MFS) at the top of the Sunnyside Member occurs slightly later due to continued regression after the drowning of the mire.

### 6.7.4 Expression of key surfaces within coal seams

As our sequence stratigraphic model for the Sunnyside coal (Figs. 8 and 9) spans surfaces interpreted as the terrestrial equivalents of marine flooding surfaces and sequence boundaries, it is useful to define the precise expression of these surfaces within the unsplit coal. The best section to use for this is the subsurface mine section from C Canyon, where the sampling resolution is at its best, and the lack of weathering enables us to comment reliably on the significance of changes in pyrite content.

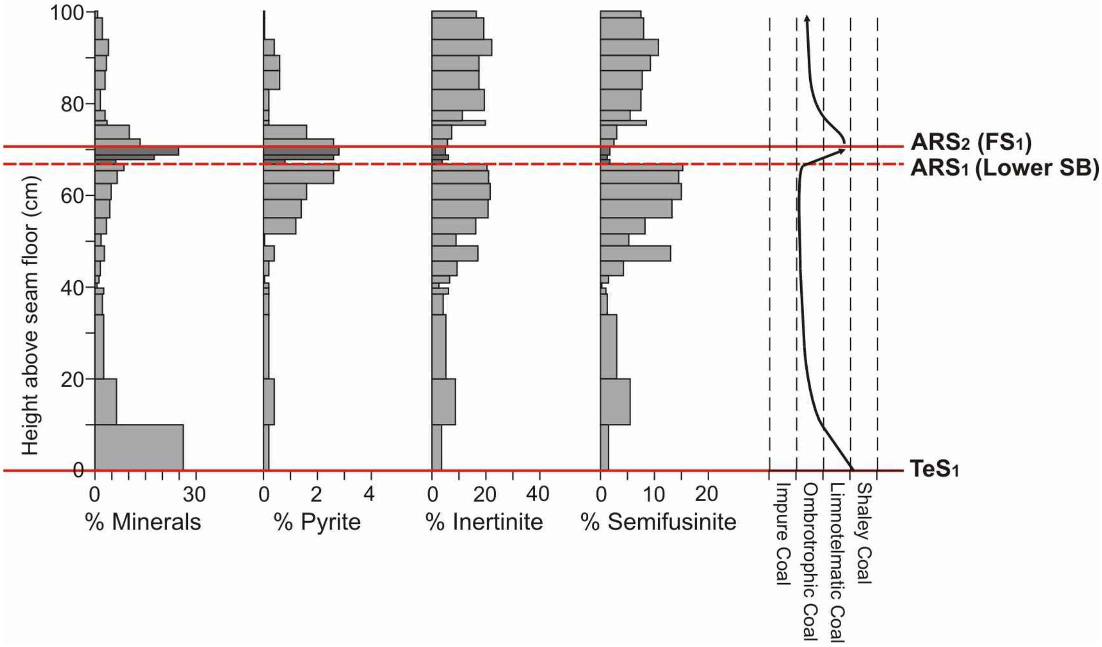


**Figure 6.10.** Selected petrographic profiles, coal facies trends and key sequence stratigraphic surfaces identified in the basal 1 of the Sunnyside coal at C Canyon.

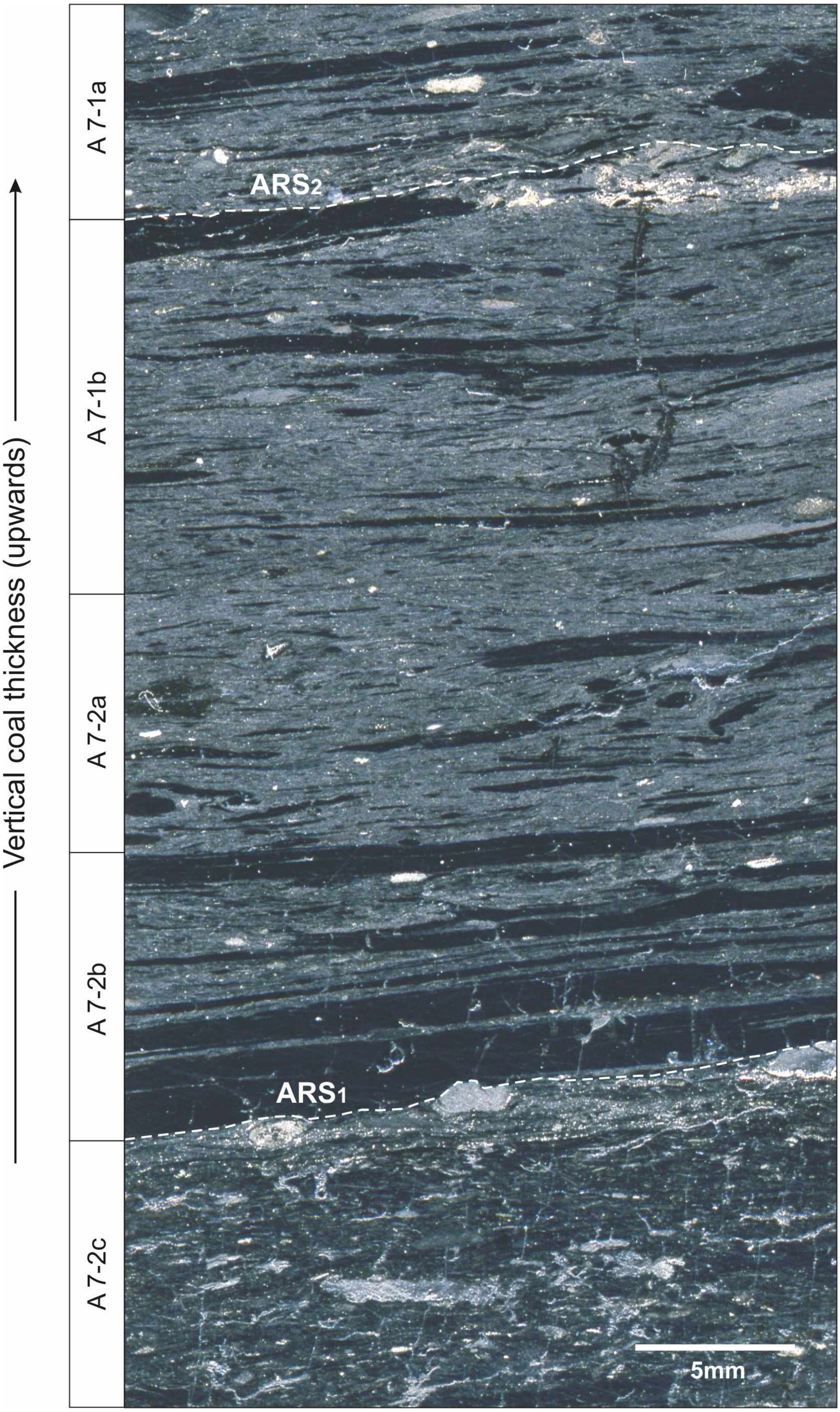


**Figure 6.11.** Photograph of polished block samples from the C Canyon section, showing the macroscopic expression of key sequence stratigraphic surfaces within the Sunnyside coal.

Figure 6.10 shows vertical profiles for mineral, pyrite, total inertinite and semifusinite content through the basal 100 cm (3.3 ft) of the C Canyon section (Fig. 6.5), along with the accommodation trends and key surfaces interpreted from them. The expression of the flooding surface that marks the boundary between Sunnyside parasequences 2 and 3 further down depositional dip is relatively easy to recognise. There is an abrupt increase in mineral content from around 5% to over 20% between $ARS_1$ and $ARS_2$. This is accompanied by an even more abrupt decrease in inertinite and semifusinite content. Both of these trends indicate a rapid increase in the height of the groundwater table, which resulted in an influx of water-borne minerals into the mire, and the cessation of the dry conditions that gave rise to the high inertinite content in the underlying coal. Furthermore, the relatively high pyrite content in this part of the seam indicates that these trends were the result of an influx of marine or brackish water into the mire. Similar expressions of flooding surfaces in coal seams are noted by Banerjee et al. (1996), Diessel et al. (2000), and Staub (2002). The build-up of pyrite over the 20 cm (8 in) of coal underlying $ARS_1$ appears to indicate a more gradual increase in water depth than the other profiles. However, this is slightly misleading, as the downward percolation of marine water probably lead to the precipitation of pyrite within the upper part of the previously deposited peat.

Studies of Holocene mires show that even in very wet climates, peat cannot accumulate more than 20 m above the regional groundwater table (e.g. Bruenig, 1990). Therefore, in the case of the lower Sunnyside sequence boundary, evidence of exposure and oxidation of the peat would be expected, as the depth of the ‘Sunnyside Sandstone’ incised valley indicates a relative sea-level fall of approximately 30 m (Howell et al., in press). The build up of inertinite (in particular its structured form semifusinite) in the 30 cm of coal below $ARS_1$ in the C Canyon section is consistent with oxidation and exposure, and therefore confirms that this surface is likely to be the expression of the lower Sunnyside sequence boundary within the coal. The slight increase in mineral content that accompanies this trend is probably the result of concentration of inorganic minerals by the oxidative loss of organic matter. It is possible that a layer with an even higher inertinite content was produced during this period of exposure, but reworked during the subsequent transgression. Diessel (1998) noted an increase in inertinite content similar to that described above when identifying the position of a sequence boundary in the Upper-Wynn / Bayswater seam of the Sydney Basin in eastern Australia. However, he also noted an increase in liptinite content and residual vitrinite reflectance. The absence of these in our case study is probably due to the inherently low liptinite content of the Sunnyside coal, and the suppression of vitrinite reflectance by the influx of marine water that followed the sequence boundary.

Figure 6.11 shows a close up photograph of the polished block samples that contain $ARS_1$ and $ARS_2$ at C Canyon. This shows that there is a clear difference in the appearance of the coal above and below $ARS_1$, where coal formed during flooding of the mire overlies a layer of coal that underwent a period of exposure and oxidation during the formation of the lower Sunnyside sequence boundary. On the basis of this photograph, it may be possible to recognise sequence boundaries in polished cores through other coal seams. The transition between wetting and drying-upward coal across $ARS_2$ is not as easy to recognise, this is to be expected as it represents a gradational transition as opposed to a hiatal surface.

## 6.8 CONCLUSIONS

1) Coal seams formed in paralic settings provide the best, and perhaps only, method of recognising high-resolution sequence stratigraphic trends in terrestrial strata, which can be correlated with marine records of base-level change.

2) Changes in the petrography of the Sunnyside coal enable the identification of a high-resolution terrestrial record of accommodation change, spanning two complete depositional sequences, including the terrestrial equivalents of two-fourth order sequence boundaries and a parasequence-bounding flooding surface.

3) Hiatal flooding surfaces in the marine realm correlate up depositional dip into packages of coal and other terrestrial rocks that preserve the transition between transgression and regression, thus providing an indication of the relative rates of base-level rise and fall.

4) The continuous nature of peat accumulation means that terrestrial coaly rocks may provide a higher resolution and more complete record of base-level change than the time-equivalent shallow-marine strata, thus enabling the identification of ‘fifth-order cycles’ that are not recorded in the marine strata.

5) Marine flooding surfaces are marked within the Sunnyside coal by an increase in inorganic mineral and pyrite content, combined with a sharp decrease in inertinite

content. Sequence boundaries are marked by a layer of coal with high inertinite content, and may also be macroscopically identifiable in polished block samples.

6) Although the petrographic analyses undertaken in this study are relatively time consuming, comparable results may be achievable from careful observation of coal lithotype successions in outcrop or core. The development of automated techniques for maceral analysis should make it easier to undertake similar studies in the future.

## ACKNOWLEDGEMENTS

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# CHAPTER 7: TESTING A MODEL FOR RECOGNISING HIGH-RESOLUTION ACCOMMODATION CHANGES IN PARALIC COAL SEAMS IN THE BOOK CLIFFS, EASTERN UTAH

*This chapter expands the scope of the study by comparing the characteristics of the Sunnyside coal with coals from the Aberdeen and Desert Members, in order to assess whether or not the terrestrial component of the Blackhawk Formation provides a comparable record of long-term accommodation change to that recorded in the time-equivalent shallow-marine strata. It was written with a short article journal such as Geology in mind, hence the shorter length and concise style. Further discussion of the points raised within it can be found in Chapter 8.*

## ABSTRACT

Systematic variations in inorganic mineral, vitrinite and inertinite content enable us to identify a high-resolution record of accommodation change throughout the deposition of coals from the Aberdeen, Sunnyside and Desert Members of the Upper Cretaceous Blackhawk Formation in the Book Cliffs of eastern Utah. By plotting this data on a conceptual coal facies diagram, we are able to demonstrate that the characteristics of these coals reflect the well-documented decrease in accommodation creation throughout the deposition of the Blackhawk Formation (approx 3.5 My). This suggests that terrestrial sediments can provide a comparable record of accommodation change to time-equivalent shallow-marine strata.

## 7.1 INTRODUCTION

Paralic coal seams provide a powerful method for identifying high-resolution records of base-level change in terrestrial strata that can be correlated with changes in relative sea level (Boyd and Diessel, 1994; Diessel 1998). Historically, most sequence stratigraphic studies of coal-bearing strata have emphasised the significance of whole coal seams within depositional cycles (e.g. Duff and Walton, 1962; Cross, 1988; Hampson, 1995). More recently, however, a number of studies have investigated the high-resolution accommodation changes that can be identified from variations in the internal characteristics of individual coal seams (e.g. Banerjee et al., 1996; Diessel, 1998; Holz et al., 2002; Wadsworth et al., 2003). One of the key advances demonstrated by these studies was that coals may form in response to either increasing or decreasing accommodation, and may span multiple high-frequency accommodation cycles.

The aim of this paper is to test a model for identifying high-resolution accommodation changes in paralic coal seams by comparing the characteristics of multiple coals from the Upper Cretaceous Blackhawk Formation in the Book Cliffs of eastern Utah. The well-documented sequence stratigraphic evolution of this formation (Van Wagoner et al., 1990; Van Wagoner, 1995; Kamola and Van Wagoner, 1995; Howell and Flint, 2003) enables us to compare our findings to the record of accommodation change preserved in the time-equivalent, shallow-marine strata. By using coals from the same formation, this study represents a controlled experiment, in which we can be reasonably confident that the observed differences between the coals are primarily due to changes in accommodation. This work has a range of important implications including: 1) documenting the effects of accommodation change on coal formation, 2) comparing the responses of temporally and spatially equivalent terrestrial and marine strata to accommodation change, and 3) integrating terrestrial and marine sequence stratigraphic models.

## 7.2 COAL FACIES MODEL

In peat forming depositional systems, accommodation is governed by the height of the mire water table, which responds to changes in relative sea level, precipitation and auto-compaction of the peat (Clymo, 1987; Moore, 1989; Winston, 1994). In order for peat to accumulate and be preserved, accommodation has to be created at a rate that approximately balances the rate of peat production (Cross, 1988; Bohacs and Suter, 1997). If accommodation creation outstrips peat production, the mire is drowned and inundated by marine or lacustrine sediments. Conversely, if peat production outpaces accommodation creation, the mire is exposed, oxidised and reworked. Studies of Holocene mires (see fig. 2 in Diessel at al., 2000 and references therein) suggest that the rate of peat production is directly related to geographical latitude (via climate), and should therefore be relatively constant within any single locality. On this basis, we assume that localised variations in the ratio of accommodation creation / peat production (AR/PPR) are primarily due to changes in the rate of accommodation creation.

High-frequency changes in the AR/PPR ratio within the ‘peat window’ (Fig. 7.1 A) should result in changes in the nature of the coals that are deposited. Higher rates of accommodation creation should give rise to ‘coaly shales’ and ‘shaly coals’ with inorganic mineral contents in excess of 30%, as a rapidly rising base-level provides a mechanism for the transport of water-borne, detrital sediment into the mire (Diessel, 1992; Bohacs and Suter, 1997). AR/PPR values around 1.0 should result in the formation of ‘limnotelmatic’ and ‘ombrotrophic’ coals, with mineral contents below 30% and 10% respectively. Lower rates of accommodation creation may result in increased mineral content due to oxidation and burning of organic matter, giving rise to ‘impure coals’ or ‘fusain’ characterised by high inertinite contents (Scott, 1989). Variations in the character, geometry and vertical succession of these coaly facies should reflect changes in the rate of accommodation creation through time (Fig. 7.1 B – D).

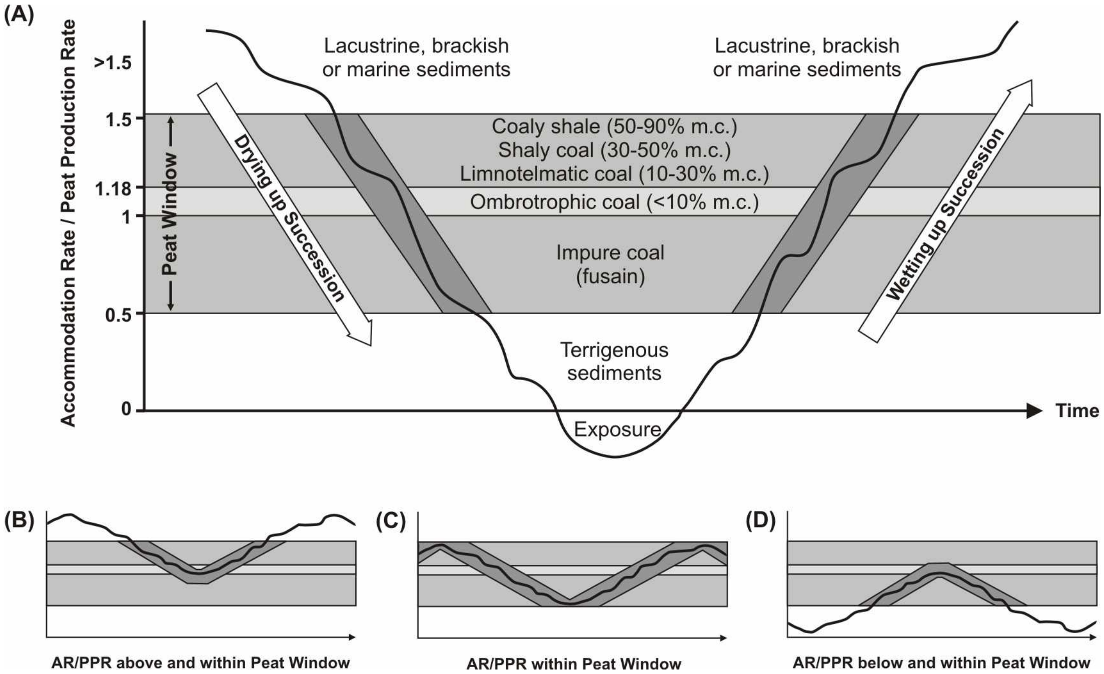

**Figure 7.1.** (A) Idealised curve to show the relationship between paralic accommodation rate (AR), peat production rate (PPR) and coaly facies. The left hand limb shows the succession of facies formed in response to decreasing accommodation creation, the right hand limb shows the succession of facies formed in response to increasing accommodation creation. (B) If the AR/PPR curve lies mainly above the “peat window”, the resultant coals will be dominated by coaly shales, shaly coals, limnotelmatic and ombrotrophic coals. (C) Where the AR/PPR curve lies within the peat window, composite coals may form spanning multiple accommodation / coal facies cycles. (D) If the AR/PPR curve lies mainly below the peat window, the resultant coals will be dominated by impure coal (modified from Wadsworth et al., 2003; AR/PPR ratios from Bohacs and Suter, 1997).

## 7.3 STUDY AREA

The Upper Cretaceous (Campanian) Blackhawk Formation in the Book Cliffs of eastern Utah was deposited along the shoreline of the Western Interior Seaway (Speiker, 1949), which occupied much of central North America during the Late Cretaceous Epoch (Fig. 7.2 B). The formation is interpreted as a third-order, prograding highstand sequence-set, which contains a number of higher-frequency, fourth-order sequences (Van Wagoner 1995; Howell and Flint, 2003). It is subdivided into six lithostratigraphic members (Fig. 7.2 A), each of which represents a shoreface sandstone complex, separated by tongues of offshore marine shale (Young, 1955). Landward of these shallow-marine members is a time-equivalent, coastal-plain complex that contains numerous coal seams that can be traced basinward on to the tops of marine parasequences. There is a progressive change from aggradational to strongly progradational stacking of individual parasequences towards the top of the formation. Combined with a decrease in the vertical spacing of fourth-order sequence boundaries, this indicates a long-term decrease in accommodation creation, which culminates in a third-order sequence boundary at the base of the overlying Castlegate sandstone (Van Wagoner 1995; Howell and Flint, 2003).

In this study we compare and contrast the internal characteristics of coals from the Aberdeen, Sunnyside and Desert Members (Fig. 7.2 A), which should represent peat formation in higher, intermediate and lower accommodation conditions respectively. Quantifiable evidence for the decrease in accommodation creation through the formation is provided by the decrease in the mean thickness of shoreface deposits from 16 m in the Aberdeen Member, to 10 m in the Sunnyside Member and 8 m in the Desert Member. There is also a significant decrease in the shoreface aggradation angle from 0.12° in the Aberdeen Member to 0.04° in the Sunnyside Member and 0.01° in the Desert Member (Van Wagoner, 1995; Kamola and Van Wagoner, 1995; Howell and Flint, 2003).

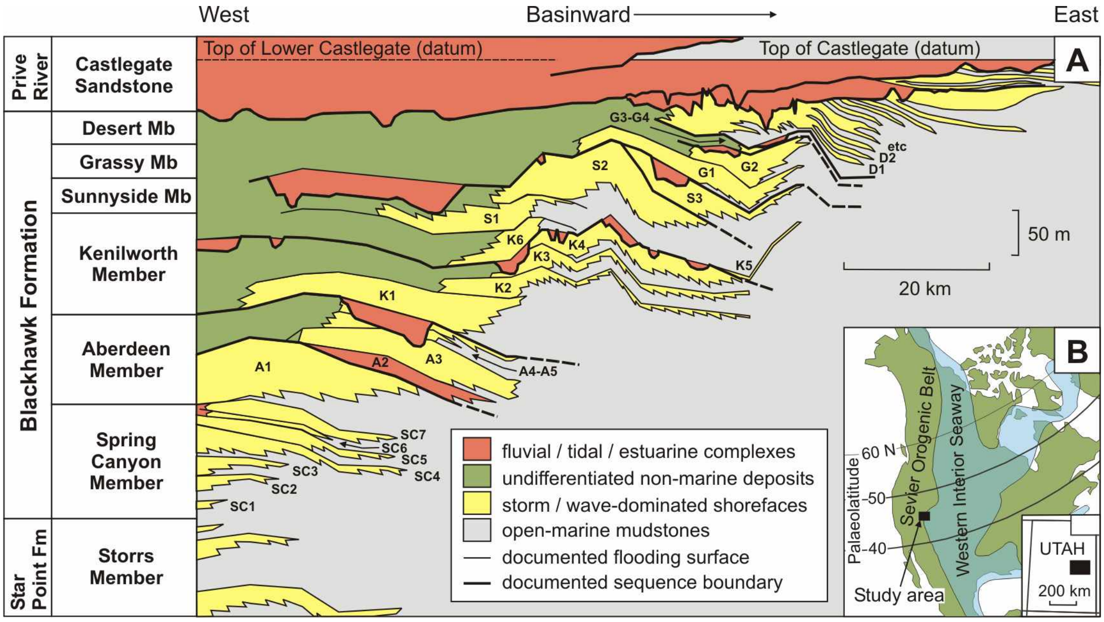

**Figure 7.2.** (A) Depositional dip cross-section of the Blackhawk Formation. The overall eastward progradation of the succession and the upward decrease in the spacing of fourth-order sequence boundaries indicate decreasing accommodation creation towards the top of the formation. The letters A1, K2, S3 etc refer to individual shoreface parasequences within each member. (B) Location of study area in relation to Utah state boundaries and the Late Cretaceous palaeogeography of the USA (modified from Howell and Flint, 2003).

## 7.4 COAL ANALYSIS

In order to determine how the coals compare with the conceptual model, we have undertaken detailed petrographic analysis of closely spaced samples obtained from vertical sections through each seam. Prior to sampling, a detailed log of the macroscopically identifiable variations in each coal was produced in order to determine the required sampling resolution, and to ensure that no important surfaces were sampled across. The coal was also excavated to a depth of approximately 1 m into the outcrop, in order to remove excessively weathered material. All samples were crushed to a top size of 2 mm, cured in epoxy resin and cut and polished for microscopic analysis in incident light.

The composition of each sample was determined by counting 500 points in accordance with Australian Standard AS 2856.2–1998 (1998). For the purposes of this study we are primarily concerned with variations in the inorganic mineral content of the coals (Fig. 7.1). Secondary to this is the ratio of vitrinite to inertinite macerals, which represent peat accumulation in wetter and drier conditions respectively (Cohen and Spackman, 1972; Diessel, 1992).

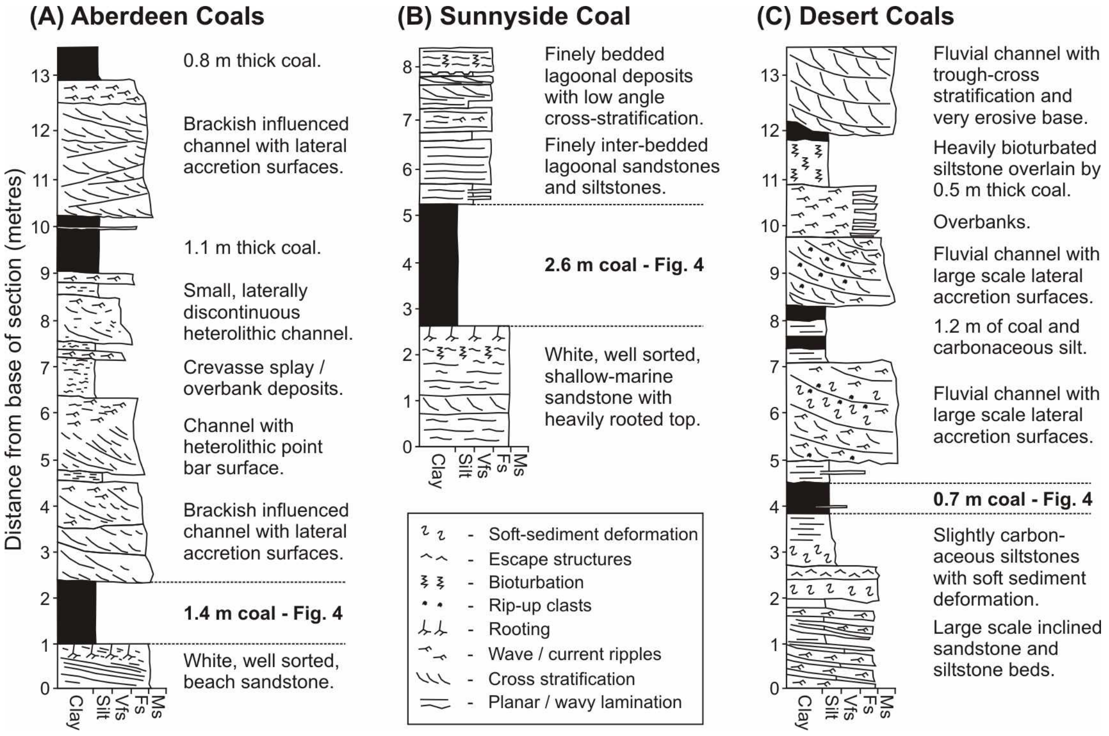

**Figure 7.3.** Sedimentary logs to show the nature of coal bearing successions within (A) the Aberdeen Member (at 12 N 511042. 4398028), (B) the Sunnyside Member (at 12 N 552050. 4380885), and (C) the Desert Member (at 12 N 0564299. 4344032) of the Blackhawk Formation.

## 7.5 RESULTS AND INTERPRETATION

The basal part of the 1.4 m thick seam sampled within the higher accommodation Aberdeen Member (Fig. 7.3 A) shows a rapid drying-upward trend from coaly shale into an ombrotrophic coal with a very low mineral content (0 - 0.4 m in Fig. 7.4 A). The base of this seam is therefore regressive, and represents a continuation of the shallowing upward trend associated with the progradation of the underlying marine shoreface. The increase in inertinite content 0.4 m from the top of the seam indicates dry conditions associated with a continued decrease in accommodation. The decrease in inertinite content and sharp increase in mineral content in the upper 0.2 m of the seam indicate a rapid increase in accommodation prior to the deposition of the overlying clastic sediments. The top of the coal is therefore transgressive.

The lower part of the 2.6 m thick coal sampled within the intermediate accommodation Sunnyside Member (Fig. 7.3 B) shows a rapid drying-upward trend from shaly coal into ombrotrophic coal with a low mineral content and high inertinite content (0 - 0.7 m in Fig. 7.4 B). The base of the seam is therefore regressive, and again represents part of the shallowing upward trend associated with the progradation of the underlying marine shoreface. The initial drying-upward trend is followed by an abrupt increase in mineral content and a sharp decrease in inertinite content approximately 0.7 m from the base of the seam. These both indicate a rapid increase in accommodation and flooding of the mire. This flooding surface is overlain by a second drying-upward trend back into ombrotrophic coal with a very low mineral content and high inertinite content. The increase in mineral content and decreased inertinite content in the upper 0.5 m of the seam indicate increasing accommodation creation prior to the deposition of the overlying lagoonal strata. The top of the coal is therefore transgressive.

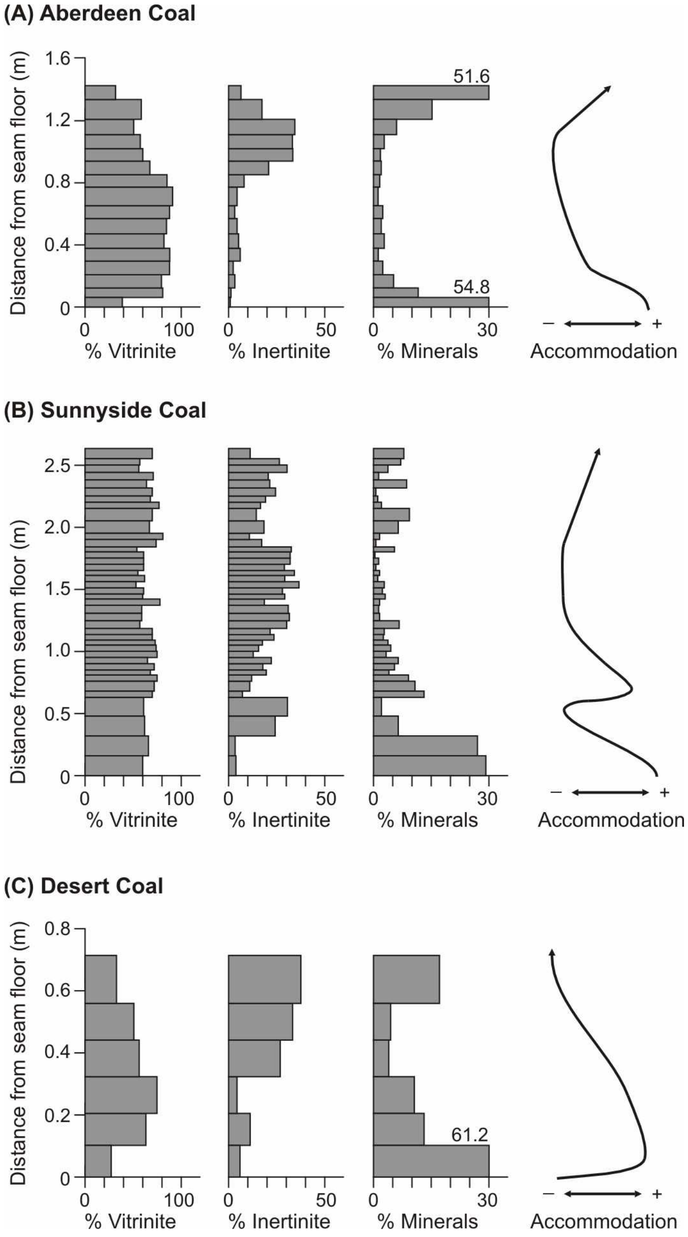

**Figure 7.4.** Petrographic profiles and interpreted accommodation curves for coals from the Aberdeen, Sunnyside and Desert Members of the Blackhawk Formation.

The base of the 0.7 m thick coal sampled within the lower accommodation Desert Member (Fig. 7.3 C) differs from the other two coals as it represents an increase in accommodation in relation to the underlying fluvial deposits (Fig. 7.1, Fig. 7.4 C). The base of this seam is therefore transgressive. The presence of approximately 6% structured inertinite grains (fusinite and semifusinite) in the basal sample (0 - 0.1 m in Fig. 7.4 C) provides evidence for a thin layer of heavily oxidised impure coal at the base of the seam that was not resolvable at the sampling resolution used in this study. The shaly coal in the lower part of the seam is followed by a gradual drying-upward trend into an ombrotrophic coal with a low mineral content and high inertinite content (0.1 - 0.5 m in Fig. 7.4 C). The increase in mineral content at the top of the seam appears to be similar to that observed in the Aberdeen coal, however, it is accompanied by a very high inertinite content and is therefore almost certainly associated with dry conditions and a continued decrease in accommodation. This interpretation is strongly supported by the very low vitrinite to inertinite ratio at the top of the Desert coal (<1.0), which is considerably lower than at any other point in any of the three seams. The top of the coal is therefore regressive.

## 7.6 DISCUSSION

In order to compare the accommodation trends interpreted from three seams, we have plotted the petrographic data on to the coal facies model discussed earlier in this paper (Fig. 7.5).

The data from the Aberdeen coal spans one cycle of decreasing then increasing accommodation creation within the upper part of the peat window (Fig. 7.5 A). The fact that the vitrinite to inertinite ratio remains above 1.5 throughout the seam indicates that peat forming conditions did not progress into the lower part of the peat window. If we assume that the brackish-influenced clastic sediments that overlie the coal (Fig. 7.3 A) plot above the peat window, we can infer that the logged succession reflects AR/PPR ratios fluctuating in and out of the top of the peat window. Given that the Blackhawk Formation was deposited at a palaeolatitude of approximately 45°N (Kauffman, 1977), the rate of peat production would have been approximately 1 mm/year (inferred from Diessel et al., 2000). On this basis, the facies trends in Figure 7.3 A suggest that the rate of accommodation creation during the deposition of the Aberdeen Member fluctuated between 1 mm/year and >1.5 mm/year.

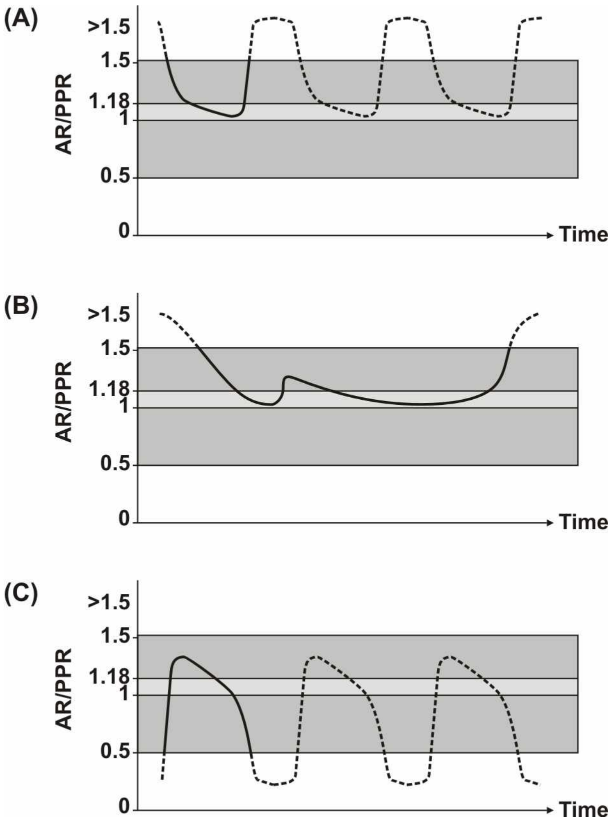

**Figure 7.5.** Coal facies trends for (A) the Aberdeen Member, (B) the Sunnyside Member and (C) the Desert Member plotted on the conceptual AR/PPR model, see Figure 7.1 for further explanation. Curves drawn with a solid line indicate facies trends based on the coal petrographic data shown in Figure 7.4. Curves drawn with a dashed line indicate trends inferred from the sedimentary logs shown in Figure 7.3.

The petrographic data from the Sunnyside coal spans two cycles of decreasing then increasing accommodation creation within the upper part of the peat window (Fig. 7.5 B). Vitrinite to inertinite ratios again remain above 1.5, indicating that peat forming conditions did not enter the lower part of the peat window. This suggests that the rate of accommodation creation remained between 1 mm/year and 1.5 mm/year throughout the deposition of most of the Sunnyside Member. This interpretation is strongly supported by our earlier detailed work on the Sunnyside coal (Davies et al., in press), which showed that it spans the formation of two complete shallow-marine shoreface parasequences.

The data for the Desert coal represents a single cycle of increasing then decreasing accommodation creation, spanning the lower two thirds of the peat window (Fig. 7.5 C). Assuming that the fluvial channels in Figure 7.3 C plot below the peat window, we can infer that the logged section reflects AR/PPR ratios fluctuating in and out of the lower part of the peat window (Fig. 7.5 C). On this basis, the rate of accommodation creation during the deposition of the Desert Member varied between 1.2 mm/year and <0.5 mm/year. This interpretation is supported by the increased incision associated with fluvial channels in the Desert Member, which indicates lower accommodation conditions compared to the Sunnyside and Aberdeen Members.

The way in which the three coals plot on the conceptual model indicates an upward decrease in accommodation creation throughout the Blackhawk Formation. Further corroborative evidence is provided by the average vitrinite to inertinite ratio for the three coals, which decreases from 6.1 in the Aberdeen coal, to 3.0 in the Sunnyside coal and 2.6 in the Desert coal, indicating an increase in oxidation and exposure of the peat towards the top of the formation. On this basis it is clear that changes in the composition and internal organisation of the three coals provide a comparable record of long-term accommodation change to that interpreted from changes in the thickness and aggradation angles of the time-equivalent shallow-marine shoreface strata.

## 7.7 CONCLUSIONS

The coal facies model tested in this paper provides a structured approach to identifying high-resolution records of accommodation change in terrestrial strata. The application of this model to coals from the Blackhawk Formation enabled us to identify a record of accommodation change throughout the deposition of each seam, and to demonstrate that terrestrial sediments can provide a comparable record of accommodation change to time-equivalent, shallow marine strata. This study also illustrates that even within a single depositional setting, coals may form in response to either increasing or decreasing accommodation, and may span multiple high-frequency accommodation cycles.

## ACKNOWLEDGEMENTS

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# CHAPTER 8: SYNTHESIS AND CONCLUSIONS

*This chapter contains an extended discussion of several points of interest that were not fully covered in Chapters 5 to 7, and considers the broader significance of this project in the context of related research. A consolidated list of conclusions and recommendations for further study can be found at the end of the chapter.*

## 8.1 EXTENDED DISCUSSION

### 8.1.1 Origin of ‘minor splits’ in the Sunnyside coal

The ‘minor splits’ in the Woodside Canyon II and Lila Canyon sections through the Sunnyside coal (Figs. 5.8 to 5.10) were not discussed in detail in the manuscripts as they are not considered to be particularly significant in the context of the sequence stratigraphic evolution of the seam. However, they are sufficiently large features to present a problem if the coal was being mined in these areas, it is therefore useful to briefly consider their characteristics and origin.

The minor split in the Woodside Canyon II section (Fig. 8.1 A) is composed of up to 1.1 m of finely laminated, slightly carbonaceous fine sand and silt that display little or no evidence of sedimentary structures or bioturbation (Fig. 8.1 B). The split is only laterally continuous for approximately 200 m, however, a number of similar splits can be found in the Woodside Canyon area. Given the close proximity of this area to the shoreline, they are interpreted as the result of sediment being washed into the margins of the mire during storms or periods of relative sea level rise.

The Lila Canyon split (Fig. 8.1 C) is composed of up to 80 cm of slightly wave-rippled very fine sand and silt (Fig. 8.1 D). It was originally interpreted as being of fluvial origin as it has a lensoid appearance in the outcrop (Fig. 5.6) and is not laterally continuous into the Canyons on either side of Lila Canyon. However, on closer inspection it has a sheet like geometry and appears to have been deposited in a localised water body, which opened up in this area during the deposition of the upper part of the Sunnyside coal. The presence of *Teredolites* wood borings within the split (Fig. 8.1 E) suggests that the water body in which it was deposited was connected to the sea (Bromley et al., 1984; Gingras et al., 2004). On this basis the sediments in the split are more likely to be of marine than fluvial origin.

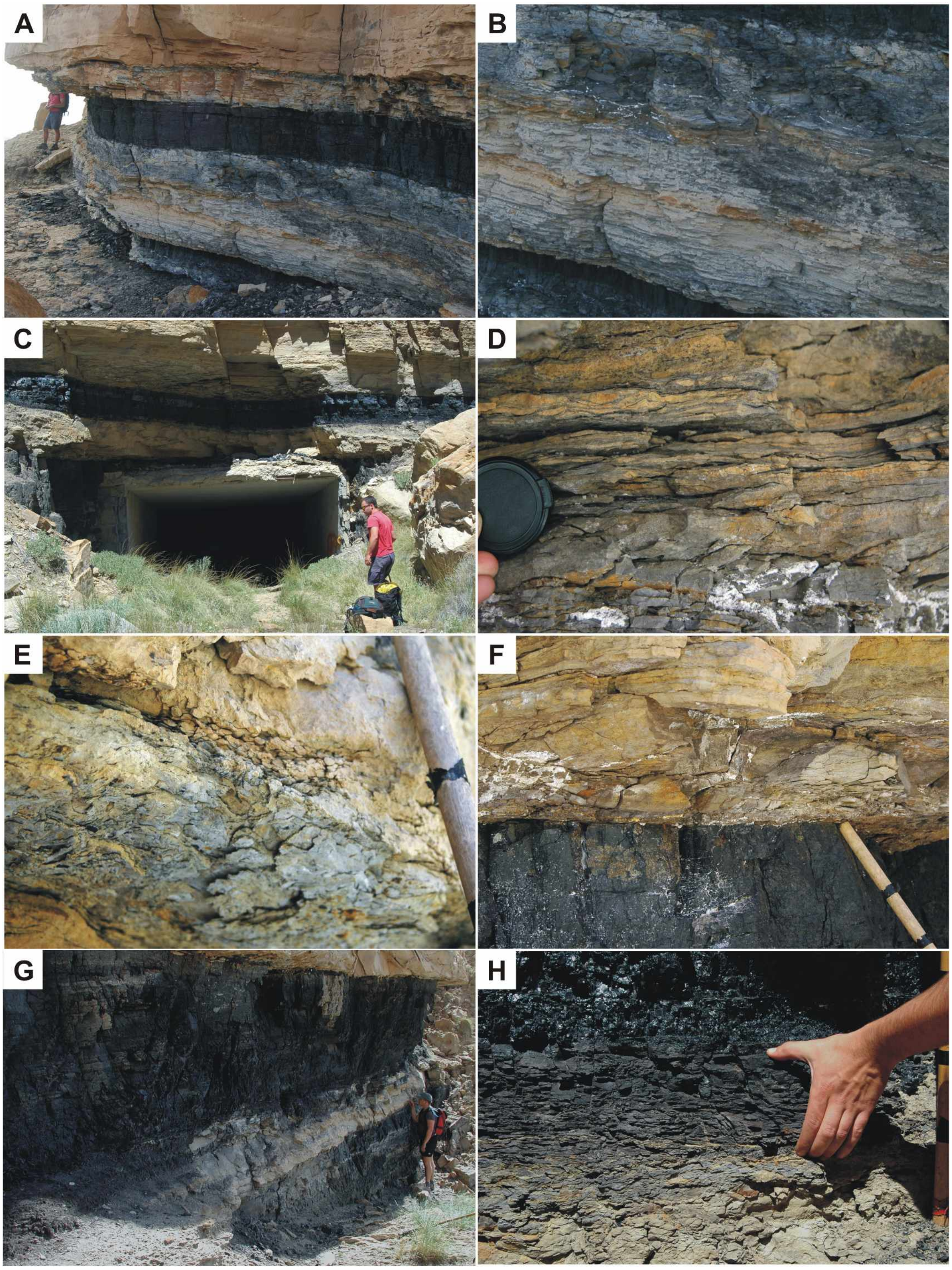

**Figure 8.1.** Photographs to illustrate the nature of 'minor splits' in the Sunnyside coal: (A) Overview of the 109 cm thick package of fine sand and silt that splits the Sunnyside coal in the Woodside Canyon II section. (B) Close up of the finely laminated, slightly carbonaceous sand and silt in the Woodside Canyon II split. (C) Overview of the 80 cm thick package of very fine sand and silt that splits the Sunnyside coal at Lila Canyon. (D) Close up of slightly wave rippled, soft sediment deformed very fine sandstone in the Lila Canyon split. (E) The presence of *Teredolites* wood borings in the Lila Canyon split suggest that the water body in which it was deposited was connected to the sea, the taped divisions on the measuring stick are 10 cm apart. (F) Close up of the base of the Lila Canyon split. (G) Inter-fingering of coal and clastic sediments along the margin of a minor split in the Sunnyside coal at South Lila Canyon. (H) Close up of the gradational transition between the top of the Lila Canyon split and the overlying coal.

The base of the Lila Canyon split (Fig. 8.1 F) is sharp with no evidence of erosion or bioturbation. It is easily distinguishable from the regional-scale flooding surface at the top of the seam due to the lack of the characteristic *Thalassinoides* burrows that penetrate the top of the coal from C Canyon down to Woodside Canyon (Fig. 4.9 F). The margins of the split are not accessibly exposed, however, a similar split can be found in South Lila Canyon (Fig. 4.1 C, Fig. 8.1 G). The inter-fingering of coal and clastic facies along the margins of this split suggest that it was deposited gradually and contemporaneously with the coal on either side. The top of the Lila Canyon split (Fig. 8.1 H) shows a gradual transition from organic rich siltstone back into coal, this is indicative of vegetation gradually recolonising the area after the water body had been filled with sediment.

### 8.1.2 Terrestrial component of the Sunnyside Member

One further point of note in the stratigraphy of the Sunnyside Member (Fig. 6.3) is that the entire terrestrial component of Sunnyside parasequences 2 and 3 is composed of coal (Howell et al., in press). Although this is partially explained by the fact that optimal peat forming conditions were present during the deposition of these parasequences (Fig. 7.5), it is still important to consider what happens to the fluvial systems supplying sediment to the shoreline. The fact that all the observed minor splits appear to be filled with marine-derived sediments suggests that there were few fluvial channels running through the mire at this time. The most likely explanation for this is that the mire was sufficiently raised to divert fluvial systems around its margins, or at least to channel them along specific points in the mire. The ability of raised mires to control clastic sedimentation in this way has been previously noted with regard to shoreface stacking patterns by McCabe and Shanley (1992).

### 8.1.3 Duration of peat formation associated with the Sunnyside coal

Having demonstrated that the Sunnyside coal spans the formation of two shallow-marine parasequences and two fourth-order sequence boundaries (Fig. 6.9), it is interesting to speculate how long it took to form. This is not straightforward as there are a number of factors that need to be taken into consideration; the rate of peat production / accumulation, the peat to coal compaction ratio, and the possibility that there is time locked up in the sequence boundaries spanned by the coal.

The rate of peat production can be estimated from the compilation of Holocene maximum peat accumulation ratios shown in Figure 2.9. Given that the palaeolatitude of the Book Cliffs was approximately 45°N (Kauffman, 1977, 1984), the rate of peat production would have been approximately 1 mm per year, or possibly slightly less. There is obviously a degree of uncertainty involved in using Holocene mires as a reference point given the warmer global climate in the Cretaceous; however, as modern peat accumulation rates are relatively constant between 45°N and 30°N (Fig. 2.9) this estimate should still be reasonably reliable.

The peat to coal compaction ratio is more difficult to estimate as values from as low as 1.2 up to more than 30 have been reported in the literature (Elliott, 1985; White, 1986; Winston, 1986; Stout and Spackman, 1989; Nadon, 1998). There is a general consensus that average values are between 7 and 10 depending on the inorganic mineral content of the coal and the amount of woody material in the peat, which compacts less than other plant tissues. Given that the average mineral content of the Sunnyside coal is less than 10% (Table 5.1) and the telovitrinite to detrovitrinite ratio of 1:2.2 suggests that the mire vegetation was not particularly woody, the higher value is likely to be more accurate in this case.

If we assume that the maximum observed coal thickness of 5.5 m at Lila Canyon (Fig. 6.5, Fig. A.4) is indicative of the total amount of peat produced, the time taken for the Sunnyside coal to form should be approximately 60 Ky (5500 mm ÷ 0.9 mm/a * 10). However, given the uncertainty inherent in both accumulation rates and compaction ratios, this figure could easily be as high as 120 Ky. It is interesting to note that this range of figures (60 – 120 Ky) is broadly similar to the documented range of estimates for the time taken for the formation of two shallow-marine shoreface parasequences in the Blackhawk Formation (e.g. Kamola and Huntoon, 1995; Kamola and Van Wagoner, 1995; O’Byrne and Flint, 1995; Van Wagoner, 1995; Hampson et al., 2001; Howell and Flint, 2003). On this basis, it would appear that calculations based on peat accumulation and compaction ratios do at least provide a reasonable method for estimating the duration of depositional sequences where no other data is available.

This issue becomes significantly more complicated when we consider the two fourth-order sequence boundaries spanned by the Sunnyside coal (Figs. 6.7 – 6.9).

The relatively subtle petrographic expression of these surfaces in the coal (Fig. 6.10) suggests that they do not represent significant periods of hiatus. For example the vitrinite to inertinite ratio below $ARS_1$ (interpreted as the equivalent of the lower Sunnyside sequence boundary) is approximately 3:1 (Fig. A.2). This figure is not particularly low and certainly does not indicate the large scale exposure and erosion of the peat that might be expected during regional base-level fall and valley incision. However, the very noticeable change in the appearance of the coal across this surface in Figure 6.11 is indicative of a significant shift in the depositional environment.

Documented examples of sequence boundaries within coal seams are rare. However, it is worth noting that the features of this surface are very similar to those associated with the sequence boundary that Diessel (1998) identified within the Upper-Wynn / Bayswater seam of the Sydney Basin in eastern Australia. On this basis, it is possible that there is a hiatus associated with the sequence boundaries in the Sunnyside coal, but that the vegetation cover and precipitation were sufficient to prevent the peat that had already been deposited being eroded or more severely oxidised. It is also possible that a thin layer of peat with a very high inertinite content was formed during the hiatus but reworked by surface processes during the subsequent base level rise.

The duration of the time gaps associated with the sequence boundaries is very difficult to estimate. The general consensus is that the fourth order sequences in the Blackhawk Formation each represent approximately 0.5 My (Kamola and Van Wagoner, 1995; O’Byrne and Flint, 1995; Van Wagoner, 1995; Hampson et al., 2001; Howell and Flint, 2003). If the Sunnyside Member took in the order of 0.5 My to form, there has to be some time locked up in the sequence boundaries unless the rate of peat accumulation was much lower than the estimate of 0.9 – 1.0 mm/a, which is very unlikely given the warm climate and high levels of atmospheric $CO_2$ associated with the Cretaceous. On this basis the sequence boundaries within the Sunnyside coal may represent in excess of 100 Ky of hiatus each, however this is somewhat subjective as the only absolute ages available are 79.5 Ma and 83.1 Ma for the top and bottom of the Blackhawk Formation (Fouch et al., 1983).

This is clearly a very difficult issue to resolve, and in the absence of additional chronostratigraphic data the exact partitioning of time through the Sunnyside coal remains unclear. However, it is worth noting that Holdgate et al. (1995) interpreted a 3.5 My hiatus within the Morwell lignite seam in the Gippsland Basin of south eastern Australia. It would therefore not be unprecedented for a coal seam to contain such large time gaps.

### 8.1.4 Comparison of Aberdeen, Sunnyside and Desert coals

The primary aim of Chapter 7 was to attempt to compare the sequence stratigraphic evolution of the Aberdeen and Desert coals with the Sunnyside coal without the need for such extensive petrographic analysis. The considerably less detailed nature of the datasets for these members clearly means that the interpretations and conclusions drawn from this chapter are less reliable than those from Chapters 5 and 6. However, it does provide an interesting expansion to the scope of this thesis and enables further consideration of the relationship between terrestrial and marine strata in a range of accommodation settings.

The way in which the Aberdeen and Desert Members were plotted on the conceptual diagram in Figure 7.5 would be somewhat contentious if it were based entirely on the nature of the clastic sediments in these sections (Fig. 7.3, Fig. 8.2). It is therefore worth reinforcing the fact that evidence from the three coals was used as the primary discriminator of accommodation trends within each member. For example, the fact that both the upper and lower bounding surfaces of the Aberdeen coal (Fig. 7.4 A, Fig. A.8) indicate wet conditions and flooding of the mire strongly suggests that the underlying and overlying clastic sediments should plot above the peat window (Fig. 7.5 A). This interpretation is supported by the marine and brackish nature of these sediments (Fig. 7.3 A).

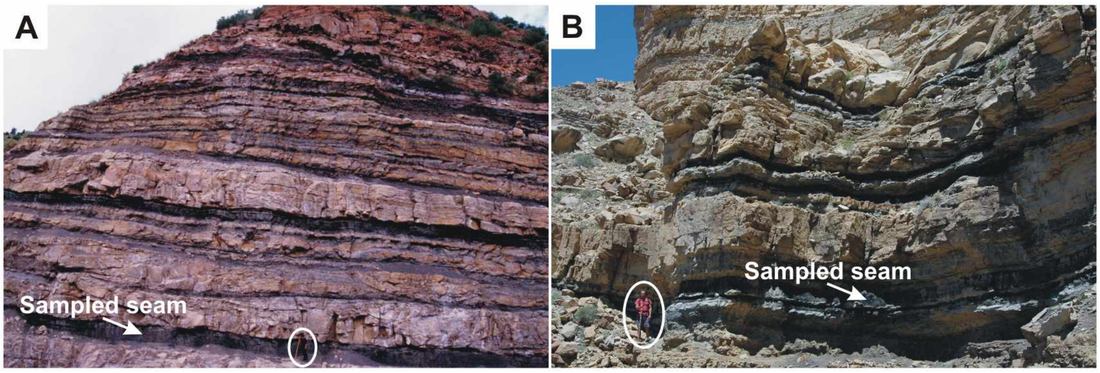

**Figure 8.2.** Photographs to illustrate the nature of coal-bearing successions in the Aberdeen and Desert Members of the Blackhawk Formation: (A) In the Aberdeen Member, the coals are interbedded with marine shorefaces, brackish-influenced channels, estuarine point bars and bioturbated fines. (B) In the Desert Member, the coals are interbedded with fluvial channels and thin layers of overbank deposits. See Fig. 7.3. for sedimentary logs through these successions.

The Desert Member is slightly more problematic as the sampling resolution was insufficient to reliably determine whether or not there was a layer of impure coal present at the base of the seam (Fig. 7.4 A, Fig. A.9). However, the structured inertinite (semifusinite and fusinite) content of the basal sample (6%) is significantly higher than in any of the other sections investigated in this study (Figs. A1 to A9). On this basis it is interpreted that dry / oxidising conditions existed prior to the deposition of the lower part of the Desert coal. The top of the Desert coal is also potentially open to misinterpretation due to its relatively high mineral content. However, the very high inertinite content and low vitrinite to inertinite ratio provide unambiguous evidence of oxidation of the peat. Therefore the presence of oxidising conditions at both the upper and lower bounding surfaces of the Desert coal suggests that the underlying and overlying sediments should plot below the peat window (Fig. 7.5 C). This is interpretation is reinforced by the fluvial nature of these sediments and the increased incision associated with channels in the Desert Member compared to the Aberdeen and Sunnyside Members (Fig. 7.3 C).

Having established confidence in the interpretations of the changes in accommodation that gave rise to the coal bearing successions in the Aberdeen and Desert Members, it is interesting to speculate how the sequence stratigraphic evolution of these members might compare with that of the Sunnyside Member. However, rather than continuing to focus specifically on the Blackhawk Formation, it is preferable to address this issue in a more generic sense by considering how terrestrial and marine sediments might be spatially and temporally related in a range of accommodation settings.

Figure 8.3 shows a series of schematic chronostratigraphic charts that illustrate the conceptual relationships between terrestrial and marine strata in higher, intermediate and lower accommodation settings. The accommodation curves alongside each figure are superimposed on a ‘coal-forming window’ that illustrates the likely variations in coal composition formed in responses to changes in accommodation in each setting. The intermediate example (Fig. 8.3 B) is closely based on the Sunnyside Member (Fig. 6.9). The higher and lower accommodation examples are based on a combination of Figure 6.9 and the facies trends observed in the Aberdeen and Desert Members respectively (Figs. 7.3 to 7.5).

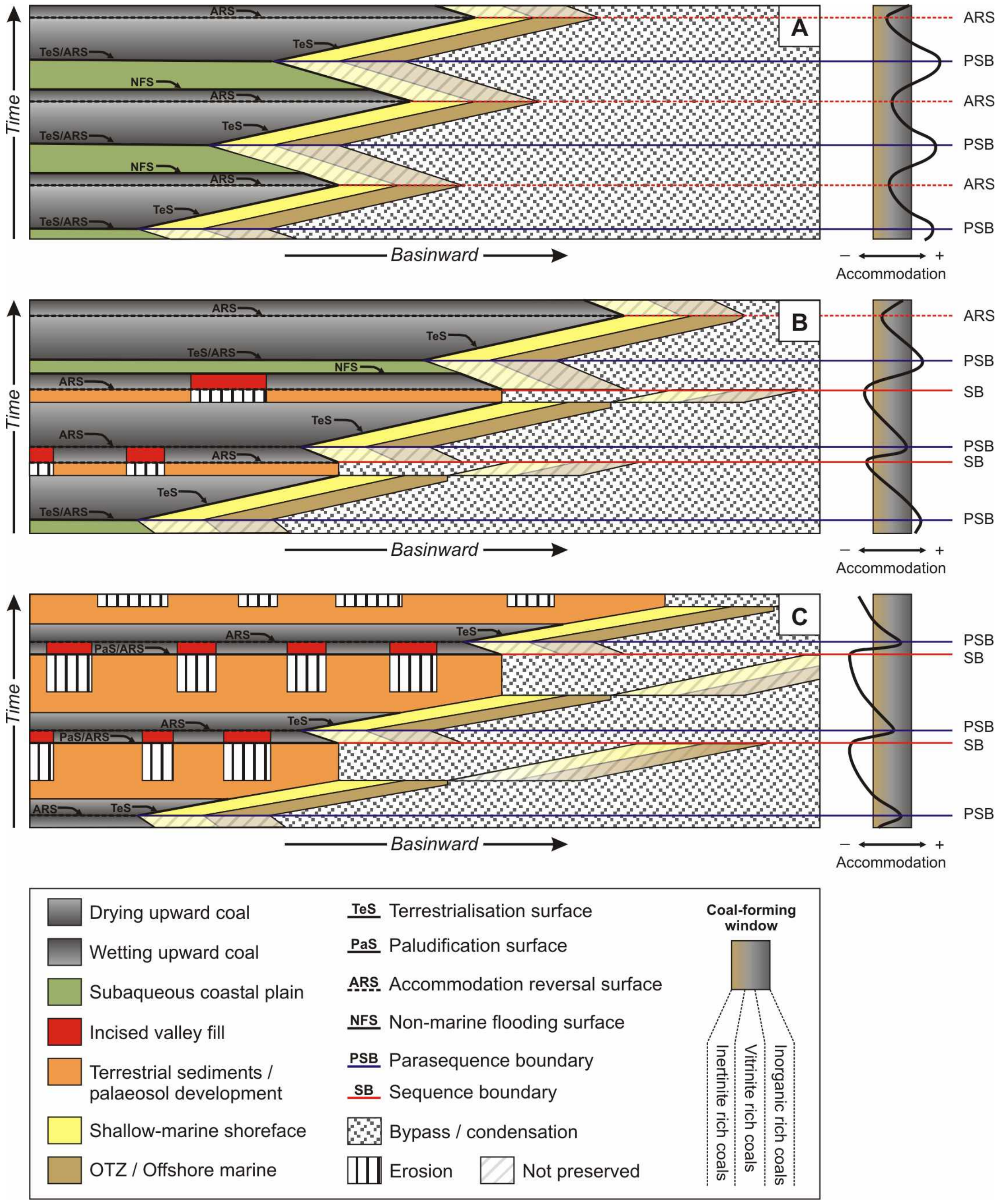

**Figure 8.3.** Conceptual chronostratigraphic charts to show the spatial and temporal relationships between terrestrial and shallow-marine strata in (A) higher accommodation, (B) intermediate accommodation, and (C) lower accommodation settings. The schematic accommodation curves alongside each chart are superimposed on a "coal-forming window" which illustrates the variations in coal composition that would be expected to occur in each example. This figure is based on the detailed chronostratigraphic chart for the Sunnyside Member (Fig. 6.9) and the comparison between the Aberdeen, Sunnyside and Desert coals shown in Figures 7.3 to 7.5.

In the higher accommodation chronostratigraphic chart (Fig. 8.3 A) the rate of accommodation creation remains within the coal-forming window except during the periods of relative sea level rise associated with the formation of parasequence boundaries in the marine sector. During these times the coastal plain is flooded and subaqueous lagoonal, estuarine and brackish sediments are deposited. This pattern of sedimentation results in the formation of relatively thick coal seams separated by layers of clastic sediments. The bases and tops of these seams should have high inorganic mineral contents, whilst their central portions should have high vitrinite contents and low inertinite contents. Sequence boundary formation is suppressed due to the inferred high subsidence rate.

In the intermediate accommodation chart (Fig. 8.3 B) the accommodation curve remains within the coal-forming window for the majority of the time resulting in the formation of very thick coals seams that span multiple parasequences and coal composition cycles. Periodically the accommodation curve may leave the upper part of the coal-forming window resulting in the deposition of estuarine, lagoonal or brackish sediments in the coastal plain. During periods of relative sea level fall, the accommodation curve may also leave the lower part of the coal-forming window, resulting in hiatus / palaeosol development and sequence boundary formation. The valleys that are cut during sequence boundary formation are filled with tidal and estuarine sediments during the subsequent periods of relative sea level rise.

In the lower accommodation chart (Fig. 8.3 C) the rate of accommodation creation remains below the coal-forming window except during the periods of relative sea level rise associated with the formation of parasequence boundaries in the marine sector. The resultant coals are relatively thin and generally have high inertinite contents. There is also widespread erosion and valley incision in the coastal plain, which limits the lateral continuity of the coals.

One other point from the comparison of the three coals that needs to be revisited is the rates of accommodation creation cited towards the end of Chapter 7. The AR/PPR ratios along the left hand side of the coal facies diagram (Fig. 7.1) are based on a complex series of equations devised by Bohacs and Suter (1997) to account for the interplay of peat production, sedimentation, compaction, subsidence and eustacy. They should, therefore, provide a reasonably reliable method of estimating rates of accommodation creation where the rate of peat production is a constant. However, given the discussion on peat accumulation rates and sequence boundaries in section 8.1.3 of this chapter, they should only be used as a guide to the relative accommodation settings of the three members.

It is interesting to note that the range of accommodation creation rates generated across the three members (<0.5 mm/a to >1.5 mm/a) is up to an order of magnitude higher than the commonly quoted average rate of accommodation creation for the Blackhawk Formation. The total thickness of the Blackhawk Formation is approximately 500 m (Van Wagoner et al., 1990; Van Wagoner, 1995; Howell and Flint, 2003). When divided by its duration (3.5 My; Fouch et al., 1983) this gives an average rate of approximately 0.15 mm/a. Even allowing for the fact that part of difference is accounted for by autocompaction of the peat, there is still a clear discrepancy in these estimates. This provides further weight to the argument that there is a considerable amount of time locked up in the fourth-order sequence boundaries within the Blackhawk Formation (Fig. 7.2).

### 8.1.5 Relative roles of eustacy and climate

For the purposes of this study, it has been assumed that variations in depositional base level are primarily due to fourth and fifth-order relative sea level cycles without attempting to differentiate between the relative roles of eustacy and climate. This is a valid approach given that they are related component phenomena of Milankovitch cycles and combine with subsidence to determine the rate of sea level change in paralic areas. However, it is important to remember that the relative importance of these controls varies considerably with distance from the shoreline (Fig. 2.3, Shanley and McCabe, 1994). With regard to peat-forming systems, the conceptual model (Fig. 2.3) can be modified to illustrate the fact that the relative importance of eustacy and climate (especially precipitation) varies considerably depending on the part of the mire in question (Fig. 8.4). The height of the mire water table in the rheotrophic part of the mire is effectively the same as sea level. However, as the influence of eustacy diminishes inland, the importance of climate increases to the point that it may become the dominant control on the height of the mire water table in the ombrotrophic part of the mire further from the shoreline.

On this basis it is interesting to consider whether or not it is possible to identify a record of higher-frequency climatic cycles in one of the more landward sections investigated in this study. The best approach to this issue is to focus on the ratio of vitrinite to inertinite macerals (which correspond to wetter and drier conditions respectively), as these may record subtle changes in the height of the mire water table that were not large enough to alter the amount of detrital sediment being washed into the mire (Large et al., 2003).

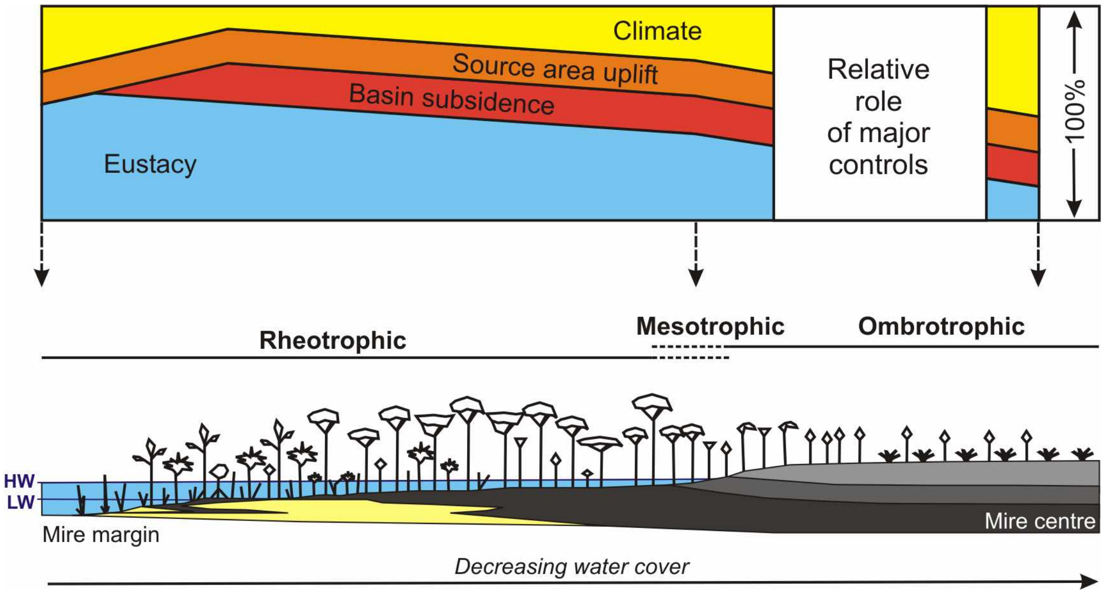

**Figure 8.4.** The relative role of climate, eustacy and other controls on paralic accommodation varies with distance from the shoreline. Although sea level is the key variable in the rheotrophic and mesotrophic parts of paralic mires, climatic factors (especially precipitation) increase in importance in more landward ombrotrophic areas (modified from Shanley and McCabe, 1994 and Greb et al., 2002).

### 8.1.6 Identifying a record of high-frequency climate change

Of all the sections investigated in this study, the one most likely to contain recognisable expressions of ‘fifth-order’ climatic cycles is the C Canyon section through the Sunnyside coal. The coal in this area was deposited at least 15 km landward of the shoreline (Fig. 6.5), and has a significantly higher sampling resolution than the other sections (86 samples / 2.5 m of coal). In order to determine whether or not an orbital / climatic signature can be recognised from the petrographic data for the C Canyon section, spectral analysis of variations in the ratio of vitrinite to inertinite macerals was undertaken using the analytical methods employed by Large et al. (2003) to identify a record of high-frequency precession cycles (~ 19-22 Ky) in the Wyodak coal of the Powder River Basin in Wyoming.

The suitability of the data (Fig. 8.5 A) for spectral analysis was improved by applying a logarithmic transformation, $\log_{10}(x)$, to the raw numbers. This has the effect of equalising the spread of values about the mean and improving the weighting attached to relative changes in small values. A smooth spline was also fitted to the data in order to improve the signal to noise ratio and to compensate for any unevenness in the sample spacing (Fig. 8.5 B). This improves the visualisation of low frequencies without altering the power spectrum in the frequency range of interest (Large et al., 2003, in press). Spectral analysis was then carried out using the MTM method with robust noise estimation in the SSA-MTM (Singular Spectrum Analysis – Multitaper Method) Toolkit 4.1 as described by Ghil et al., 2002.

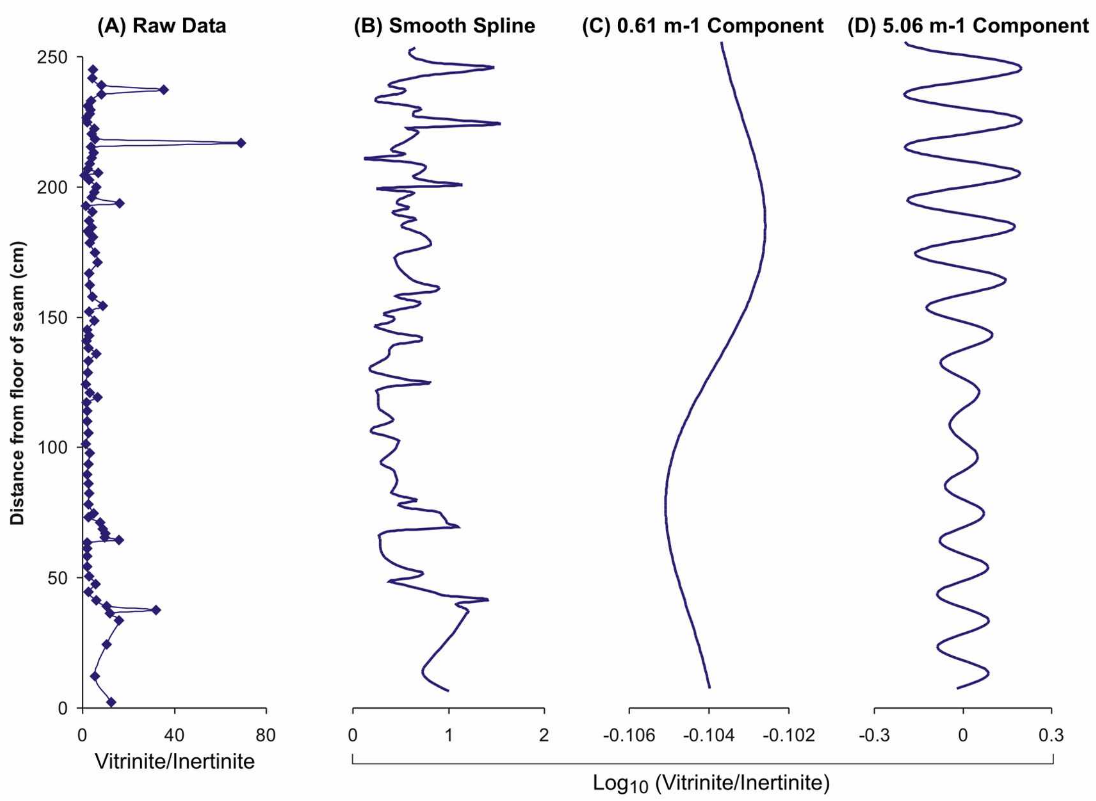

**Figure 8.5.** (A) Vertical profile of vitrinite/inertinite ratios for the C Canyon section through the Sunnyside coal. The same data after (B) $\log_{10}$ conversion and smooth spline interpolation, (C) filtering to isolate the 0.61 $m^{-1}$ component, and (D) filtering to isolate the 0.506 $m^{-1}$ component.

When the spectrum (frequency vs. power spectral density) is plotted, there are a number of peaks that lie above the 95% confidence level (Fig. 8.6). Those in the 15 $m^{-1}$ to 20 $m^{-1}$ frequency range are unlikely to be significant as they are relatively close to the sampling resolution. This leaves two other potentially important peaks at 0.61 $m^{-1}$ and 5.06 $m^{-1}$. These can be used to produce filtered signals, which have been plotted alongside the raw and smooth spline data in Figure 8.5. The 0.61 $m^{-1}$ signal (Fig. 8.5 C) does not appear to correlate with the raw data or smooth spline, it is therefore a strong possibility that this frequency represents an anomalous peak in the power spectral density (D. Large, pers. comm.). However, the 5.06 $m^{-1}$ signal (Fig. 8.5 D) is clearly expressed in the data and is worthy of further consideration.

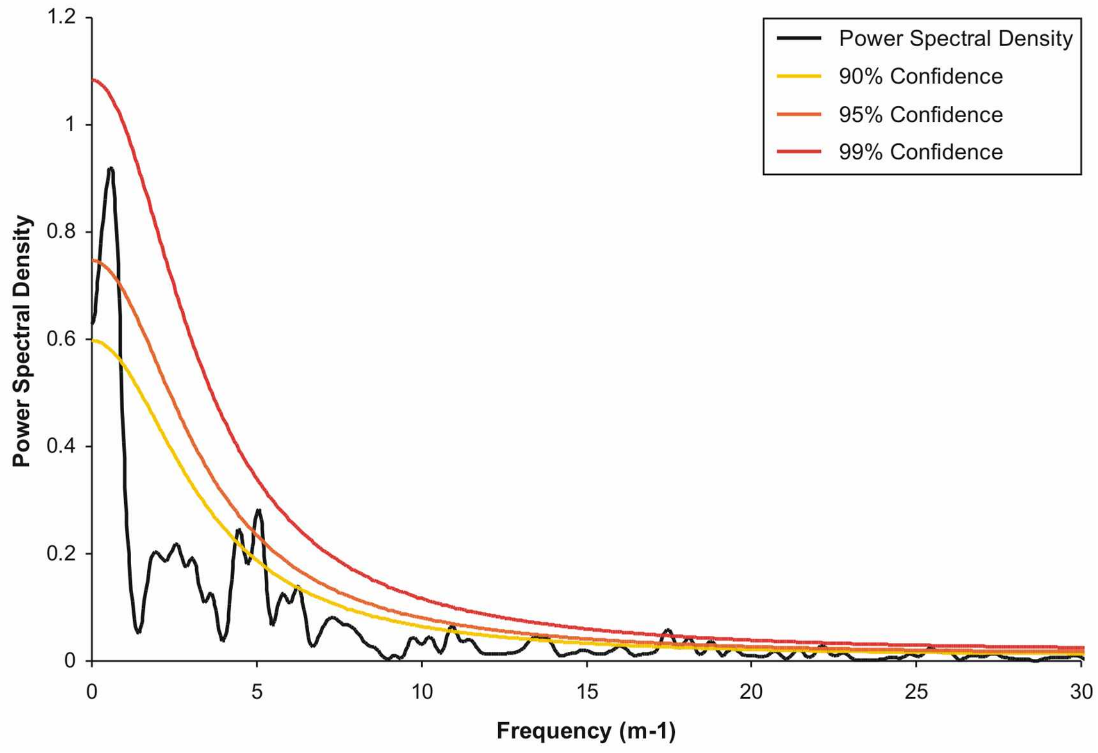

**Figure 8.6.** Plot of power spectral density against frequencies derived from $\log_{10}$ vitrinite/inertinite values for the C Canyon section through the Sunnyside coal. Various confidence levels in the data containing significant cyclicity are shown for comparison.

The significance of the 5.06 $m^{-1}$ frequency depends on the duration of peat formation associated with the Sunnyside coal. As discussed in section 8.1.3, this is not easy to determine, however, based on estimates of between 60 and 120 Ky, the 5.06 $m^{-1}$ frequency would have to be sub-orbital as it would correspond to cycles of between 5 and 10 Ky in length. On this basis it could be related to hemi-precession (9.4 Ky to 11.2 Ky). However, there are other possibilities (including that it is nothing of note) as apparently significant frequencies can arise by chance, especially given the relatively short length of the data series (D. Large, pers. comm.).

A further complication is that spectral analysis is dependent on coal thickness providing a reasonable proxy for time. The results would therefore be compromised if there were a significant amount of time locked up in the sequence boundaries spanned by the Sunnyside coal. This illustrates a potential problem with the studies carried out by Large et al. (2003, in press) on the Wyodak coal in the Powder River Basin of Wyoming and the Morwell lignite in the Gippsland Basin of Australia. Earlier studies suggested that both these seams contained significant hiatal surfaces (Flores, 1993; Holdgate et al., 1995), however, Large et al. (2003, 2004) assumed that these were not significant on the basis that they were not able to identify erosion surfaces within the coals. This is a potentially risky assumption given the subtle yet potentially significant nature of the sequence boundaries identified in this study.

On balance, there is probably insufficient evidence to conclude whether or not the Sunnyside coal contains recognisable expressions of any specific orbital / climatic frequencies. However, this analysis does at least provide evidence of very high frequency oscillations in the height of the mire water table, which are superimposed on the fourth order cycles identified in Chapters 5 and 6. It is possible that these are related to the high frequency oscillations in inorganic mineral content identified in the upper part of the Sunnyside coal (Fig. 6.8 to 6.9).

### 8.1.7 Alternative analytical methods

Although the petrographic analysis employed in this study is an effective tool for interpreting palaeoenvironmental changes in coal-bearing strata, it is relatively time-consuming and requires a somewhat specialised skill. There are several computerised systems in development, which may enable maceral analysis to be undertaken in an automated manner in the future (e.g. Creelman and Ward, 1996; Butcher et al., 2003), however, these are not yet widely available or as reliable as manual point counting. It is therefore useful to consider whether or not comparable results to those presented in this thesis could be achieved through other methods.

#### 8.1.7.1 Field observations of coaly facies and surfaces

The subject of field observation of coaly facies raises an interesting point made by McCabe (1984, 1987). Historically, most sedimentological studies of coal-bearing strata make little or no attempt to describe or interpret the significance of coal seams beyond labelling them as coal and interpreting their depositional environment as a swamp. Although the situation has improved over the past twenty or so years with the development of various facies and sequence stratigraphic schemes (see discussion in Chapters 2, 3 and 5), field description of coal seams is still relatively poorly understood by many sedimentologists.

On a basic level it should be possible to identify compositional cycles in coal seams using the concepts introduced in the early part of Chapter 3 of this thesis. True coals with mineral contents of less than 30% are relatively easy to distinguish from shaly coals and coaly shales on the basis of their general appearance in the outcrop

(Fig. 8.7 A). Therefore if a coal seam contains cyclic variations in these facies, they should be readily identifiable on the basis of a simple field log. Similarly, the various upper bounding surfaces defined in Figure 6.1 (non-marine flooding surface, give-up transgressive surface etc) should be identifiable on the basis of the nature of the contact between coal and the overlying clastic strata (Fig. 8.7 B – D).

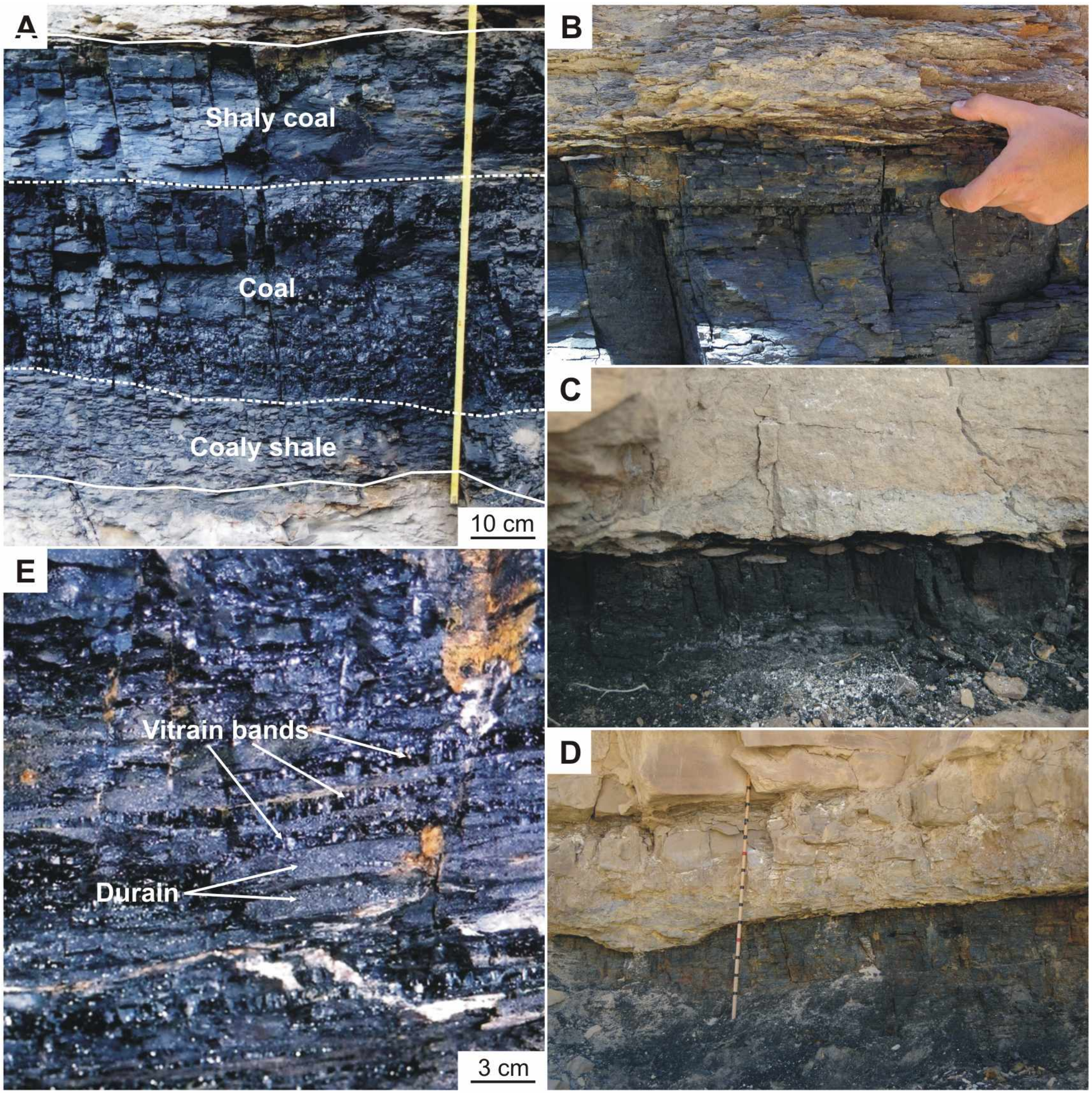

**Figure 8.7.** Photographs to illustrate the potential for identifying coal facies trends and key surfaces in the outcrop: (A) True coals with inorganic mineral contents of less than 30% are relatively easy to differentiate from shaly coals and coaly shales with mineral contents in excess of 30% and 50% respectively. (B) Where a gradational transition exists between a coal and the overlying marine or lagoonal strata the top of the coal represents a give-up transgressive surface (GUTS). (C) Where there is a sharp contact between the top of the coal and the overlying marine or lagoonal strata, the top of the coal represents a marine or non-marine flooding surface (FS or NFS). (D) Where the top of the coal has clearly been eroded prior to the deposition of the overlying marine or lagoonal strata, the top of the seam represents a transgressive surface of erosion (TrE). (E) Detailed logging of bright and dull coal lithotypes may provide an indication of variations in the vitrinite / inertinite ratio of coals.

Where the variations in coal composition are less pronounced (e.g. between ombrotrophic coal and limnotelmatic coal) it may not be possible to reliably identify boundaries between coal facies in the outcrop. Detailed logging of bright and dull coal lithotypes (Fig. 8.7 E) may provide an indication of subtle changes in composition on the basis that bright bands (vitrain) are usually predominantly composed of vitrinite, whereas dull bands (durain) are usually composed of inertinite and inorganic minerals (Stach et al., 1975; Diessel, 1992). However, this is not particularly reliable as macerals may be finely mixed and the macroscopic appearance of detrovitrinite may be relatively dull.

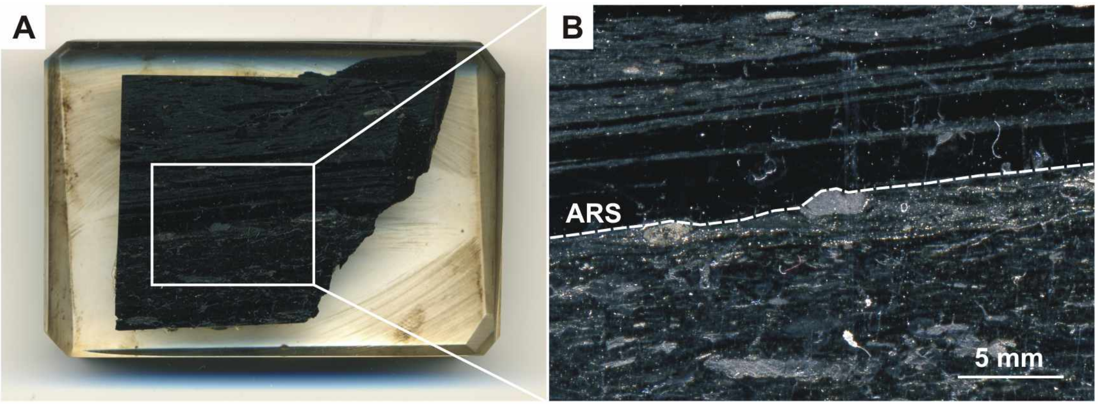

**Figure 8.8.** Images of a polished block sample from the Sunnyside coal taken with an A4 flat bed scanner: (A) Overview of a 4 cm thick polished block. (B) Close up of the same image after brightness and intensity enhancement. Note the clearly identifiable difference between the inertinite rich coal below the accommodation reversal surface (ARS) and the vitrinite rich coal above it. The horizontal black bands are layers of telovitrinite, each of which probably represents a tree trunk that was preserved during flooding of the mire. See Fig. 6.11 for a larger version of this image.

### 8.1.7.2 Observations of polished core

The next step up in detail from outcrop observations is to macroscopically study polished block samples or polished core (Fig. 8.8). As discussed in Chapter 6, this has the potential to be a very useful technique, especially for identifying significant surfaces such as sequence boundaries and flooding surfaces. This is potentially more important than being able to estimate variations in composition as the presence of key surfaces within a section can be used to predict lateral facies variations such as incised valleys and coal seam splits (as demonstrated in the Sunnyside coal case study). Making these types of observations on polished core is especially useful as it provides a high degree of confidence that key surfaces have not been missed in the sampling process, and also enables any subsequent petrographic analysis to be targeted on areas of particularly complex layering.

#### 8.1.7.3 Geophysical / wire-line log methods

The potential for identifying variations in coal composition using geophysical well logs was also considered, however, the resolution of the data available for the study area was not sufficient to identify any detail within the coals beyond the boundaries of the actual seams (Howell et al., in press). This approach was considered in more detail by Chalmers (2001) who attempted to correlate coal petrographic trends with high-resolution bulk density, neutron porosity and gamma ray logs for several coals from the Lloydminster area of the Western Canadian Sedimentary Basin. Major clastic partings (> 50 cm) correlated reasonably well with decreases in neutron porosity and increased bulk density and gamma ray response. However, more subtle variations in mineral content within the actual coals were not identifiable with any reliability. This suggests that although it may be possible to identify significant changes in coal facies (e.g. ombrotrophic coal to coaly shale) using well log data, it would not be possible to identify sufficient detail within the coals for this approach to provide an alternative to petrographic analysis.

## 8.2 SUMMARY OF CONCLUSIONS

The results, interpretations and discussion presented in Chapters 5 to 7 and section 8.1 of this chapter enable a series of conclusions to be drawn regarding the petrography and stratigraphy of the Sunnyside coal, and the sequence stratigraphic evolution of the Sunnyside Member and the Blackhawk Formation. These are followed by a set of generically applicable conclusions, a consideration of the broader significance of this study and a list of recommendations for further study.

### 8.2.1 Variations in the petrography of the Sunnyside coal

1) The low inorganic mineral content (8%) of the Sunnyside coal suggests that it formed in a topographically raised-mire that was able to largely exclude clastic sediments. The relatively low pyrite content and high vitrinite to inertinite ratio of the coal suggest that the mire groundwater was predominantly fresh and that

oxidation of the peat was generally limited. However, the moderate semifusinite and fusinite content (8%) provides evidence for periods of dry conditions when the peat was subjected to oxidation and partial burning.

2) Vertical and lateral variations in the petrography of the Sunnyside coal enable the identification of a high-resolution record of accommodation change throughout its deposition. The correlation of petrographic trends across more than 30 km of depositional dip and 50 km along strike suggests that they reflect regional-scale accommodation conditions as opposed to localised variations in mire conditions.

3) Although a wide range of indicators of accommodation change were considered in this study, the final interpretations are primarily based on variations in the inorganic mineral content of the coal. Secondary to this are variations in mean random telovitrinite reflectance and semifusinite / inertinite content. In general, high inorganic mineral contents, low semifusinite / inertinite contents and suppressed telovitrinite reflectance values indicate wetter conditions and higher accommodation. Low inorganic mineral contents, high semifusinite / inertinite contents and enhanced telovitrinite reflectance values indicate drier conditions and lower accommodation.

4) Systematic variations in these petrographic parameters suggest that the formation of the Sunnyside coal spans two cycles of decreasing and increasing accommodation creation. The fact that increases in inorganic mineral content are associated with increases in pyrite content (which indicates marine or brackish influence) suggests that these cycles are primarily driven by changes in relative sea level, and that the majority of the inorganic component of the Sunnyside coal is marine derived. This interpretation is supported by the increase in mineral content in the most basinward of the sampled sections.

### 8.2.2 Sequence stratigraphy of the Sunnyside Member

1) The stratigraphic relationship between the Sunnyside coal and the time-equivalent shallow-marine strata and incised valley fills enable the record of accommodation change recorded within the coal to be correlated with that identified from the time-equivalent shallow-marine strata. On the basis of this correlation it can be clearly demonstrated that the Sunnyside coal spans the formation of two shallow-marine shoreface parasequences and two-fourth order sequence boundaries.

2) Marine flooding surfaces are clearly expressed within the Sunnyside coal by an increase in inorganic mineral and pyrite content, combined with a sharp decrease in inertinite content. Sequence boundaries are marked by layers of coal with increased inertinite content that are macroscopically identifiable in polished block samples.

3) Estimates of the duration of peat formation associated with the Sunnyside coal based on peat accumulation and compaction rates are comparable with estimates of the time taken for the formation of the two shallow-marine parasequences it is correlated with. However, the discrepancy between these figures and estimates of the total duration of the Sunnyside Member based on ammonite biostratigraphy suggest that there is a considerable period of hiatus associated with the two fourth-order sequence boundaries spanned by the coal.

4) Subtle variations in the ratio of vitrinite to inertinite macerals in the landward portion of the Sunnyside coal enable the identification of very high-resolution changes in the height of the mire water table. Given the lack of associated increases in inorganic mineral content, it is possible that the cyclic variation in the ratio of these macerals is related to climatic changes driven by very high-frequency hemi-precession cycles.

### 8.2.3 Sequence Stratigraphy of the Blackhawk Formation

1) Differences in the bulk composition and internal organisation of coals from the Aberdeen, Sunnyside and Desert Members of the Blackhawk Formation provide a comparable record of the long-term decrease in accommodation creation to that interpreted from changes in the thickness and stacking patterns of the time-equivalent shallow-marine shoreface parasequences.

2) The terrestrial component of the higher accommodation Aberdeen Member is characterised by a cyclic stacking pattern of relatively thick coal seams and marine, estuarine and brackish clastic sediments. The coal analysed within it spans a single cycle of decreasing and increasing accommodation creation, and has a high vitrinite to inertinite ratio, which is indicative of peat formation in wet conditions with a high mire water table.

3) The terrestrial component of the intermediate accommodation Sunnyside Member is almost entirely composed of a single thick coal seam, which spans two cycles of decreasing and increasing accommodation creation. This coal has a

moderate vitrinite to inertinite ratio indicating peat formation in relatively wet conditions with an oscillating mire water table. The absence of fluvial deposits within the Sunnyside Member suggests that fluvial systems were diverted around the margins of the topographically raised mire in which the Sunnyside coal formed.

4) The terrestrial component of the lower accommodation Desert Member is characterised by a cyclic stacking pattern of thin coal seams and fluvial channels. The coal analysed within it spans a single cycle of increasing and decreasing accommodation creation, and has a low vitrinite to inertinite ratio that is indicative of peat formation in dry conditions with a low mire water table.

### 8.2.4 Sequence stratigraphic significance of paralic coal seams

1) Coal seams formed in paralic settings may provide the best approach to identify high-resolution expressions of base level change in terrestrial strata that can be correlated with changes in sea level.

2) Hiatal flooding surfaces in the marine realm may correlate back up depositional dip into packages of terrestrial coaly rocks that preserve the transition of between transgression and regression, thus providing an indication of the relative rates of base level rise and fall.

3) The continuous nature of peat accumulation means that coaly rocks may preserve a higher resolution and more complete record of base level change than the time-equivalent shallow-marine strata, thus enabling the identification of very high-frequency cycles that are not readily identifiable in marine strata.

4) Even within a single depositional setting and geographical location, coal seams may form in response to either increasing or decreasing accommodation creation. They may also span multiple accommodation cycles depending on the balance between the rate of accommodation creation and peat production.

5) Coal seams may span sequence boundaries representing significant periods of hiatus without the formation of obvious erosion or exposure surfaces. Care should therefore be taken when estimating the total amount of time spanned by coal seams in areas where there is evidence of sequence boundary formation.

6) The ability to recognise key surfaces such as sequence boundaries within cored sections through coals seams has potentially important implications for improving

the predictability of variations in the composition of coal seams and the presence of lateral facies variations such as incised valleys and coal seam splits.

## 8.3 COMPARISON WITH RELATED STUDIES

Given the increasing number of sequence stratigraphic studies of coal and coal-bearing strata being undertaken in recent years (e.g. Diessel, 1998; Petersen et al., 1998; Diessel et al., 2000; Holz et al., 2002; Wadsworth et al., 2002, 2003) it is useful to highlight the key contributions provided by this study, and to outline plans for integration of its findings with studies of coal seams from other areas.

### 8.3.1 Key contributions provided by this study

The fact that the correlation between the sampled sections through the Sunnyside coal can be backed up by tracing the seam in the outcrop is an important consideration given that similar studies by Chalmers (2001) and Wadsworth et al. (2002, 2003) were primarily based on subsurface data. This improved stratigraphic control proves beyond reasonable doubt that this study correlates lateral compositional changes within a single continuous coal seam, as opposed to matching similar trends in coals that may or may not be genetically related.

Furthermore, the quality of the correlation between the Sunnyside coal and Sunnyside parasequences 2 and 3 is almost unprecedented as far as correlation between coals and shallow-marine strata is concerned. The combination of the compositional trends identified within the Sunnyside coal and the stratigraphic relationship between the coal and these two parasequences enables the recognition of the precise expression of parasequence cycles in terrestrial strata. The quality of the outcrop exposure again confirms that this interpretation is based on a genuine correlation as opposed to matching apparently related trends.

Finally, the high resolution of this study and the fact that the Sunnyside coal spans the formation of two fourth-order sequence boundaries provides a rare opportunity to identify the precise expression of a sequence boundary within a coal seam. Although the location of the lower Sunnyside sequence boundary is reasonably clear in the petrographic profiles presented in Figures 6.10 and A.2, it is the scanned image of the macroscopic expression of this surface in Figures 6.11 and 8.8 that is most remarkable. Given the quality of this image and the weight of corroborative stratigraphic evidence, this is probably the best example of a sequence boundary within a coal seam that has been recorded to date (C. Diessel, pers. comm).

### 8.3.2 Integration with related studies

As the number of detailed sequence stratigraphic studies of coal seams and coal-bearing strata increases, there is a need for integration of their findings in order to improve the generic understanding of the influence of various environmental factors on coal forming depositional systems and coal composition. At the time of thesis submission, several publications are either envisaged or already in preparation that will integrate the findings of this study with work by Diessel (1998), Diessel et al. (2000), Chalmers (2001), and Wadsworth et al. (2002, 2003). Given the wide range of depositional and geographical settings represented by these studies, this work has the potential to make a significant contribution to the understanding of the sequence stratigraphy of coal-bearing terrestrial strata.

## 8.4 RECOMMENDATIONS FOR FURTHER STUDY

### 8.4.1 Sequence stratigraphy of the Blackhawk Formation

Despite the fact that the Blackhawk Formation is already one of the most extensively studied sedimentary successions in the world, there is still the potential for the detailed understanding of its sequence stratigraphic evolution to be significantly improved. The spatial and temporal relationships between its marine and terrestrial components in particular, are issues worthy of further study. The findings of this thesis suggest that the numerous thick coal seams within the Blackhawk Formation may provide the best approach to resolving this issue. Although it would represent a rather large undertaking in terms of the amount of petrographic analysis required, it would be very interesting to see how each of the 15 or so > 1m thick coals within the formation (and the interbedded clastic sediments) would plot on the conceptual coal facies diagram presented in Chapters 6 and 7 of this thesis. Given the large amount of data available for the time-equivalent shallow-marine strata, this has the potential to provide one of best studies of terrestrial to marine correlation ever undertaken.

There is also the potential for detailed analysis of multiple vertical sections through single seams to be used to resolve detailed correlation issues within each of the members, as was achieved with the Sunnyside coal. One area of particular interest is the relationship between the coal seams and the 8 fourth order sequence boundaries within the Blackhawk Formation, as the coals may represent the only deposition that occurred during the formation of these sequence boundaries. Although the deposition of the Sunnyside coal appears to have been interrupted by two periods of hiatus, it is possible that coals in the higher accommodation Aberdeen and Kenilworth Members may provide a complete record of conditions across sequence boundaries. Furthermore, calculation of the total duration of peat formation within the Blackhawk Formation may provide a means of estimating the amount of time represented by the sequence boundaries within it when compared with the absolute ages available for the top and bottom of the formation.

### 8.4.2 Sequence stratigraphic study of terrestrial strata

The weight of evidence from this project and other recent sequence stratigraphic studies of coal-bearing strata suggests that paralic coal seams provide the best approach to identifying expressions of base level change in terrestrial strata that can be correlated with changes in sea level. However, the detailed sequence stratigraphic study of coal seams is still in its infancy in terms of the number of published studies and the range of depositional, palaeoclimatic, geographical and temporal settings in which it has been applied. On this basis there is a need for further studies in as wide a range of settings as possible in order to test the reliability of the findings of the recent research and to further the development of predictive models such as the coal facies model presented in Chapters 6 and 7 of this thesis.

There is also an as yet unrealised potential to use regionally extensive coal seams to trace the effects of sea level change from shallow-marine strata into terrestrial sediments deposited a considerable distance landward of the shoreline. In situations where coal seams split both landwards and seawards it may be possible to trace marine flooding surfaces back up depositional dip into layers of coal with increased mineral content and then into layers of fluvial strata that contain identifiable expressions of base level change. This ultimately provides the key to fully integrating terrestrial and marine sequence stratigraphic models.

At present there is a certain degree of misunderstanding between geologists interested in identifying expressions of orbitally forced climatic cycles in coals and those interested in identifying expressions of relative sea level change (D. Large, pers. comm.). Considering that climate and sea level are related component phenomena of Milankovitch cycles it should be possible to reconcile the different approaches associated with these two schools of thought in order to further improve the understanding of the driving mechanisms of changes in coal composition.

Given the potential usefulness of improved predictability of vertical and lateral variations in coal composition to coal bed methane exploration, there is a need for interdisciplinary studies to fully identify the potential contribution of sequence stratigraphic methods to this field. Similarly, the relationship between vitrinite reflectance and palaeoenvironmental conditions identified in this study, and earlier work by Diessel and Gammidge (1998), highlights a need for further investigation given the use of the former as an indicator of source rock potential in conventional oil and gas exploration (K. Bohacs, pers. comm.).

### 8.4.3 Techniques in coal analysis

This study has demonstrated that coal petrographic analysis can be a powerful tool for identifying expressions of accommodation change in terrestrial strata. However, it is important to remember that the petrographic parameters that provide the best indication of accommodation change in one depositional setting or geographical location may not necessarily be effective in others. It is therefore essential that consideration is given to a range of potential accommodation indicators and reasons why they may or may not be effective prior to attempting to interpret the evolution of any given coal seam or coal-bearing succession.

In situations where it is not practical to undertake detailed coal petrographic analysis, observations of macroscopic variations in coal properties in polished blocks or core may provide a good indication of whether or not a seam contains significant variations in composition or key surfaces. In some cases (as was the case with the lower Sunnyside sequence boundary), it may even be easier to identify key surfaces using this approach than through microscopic analysis. It is worth reinforcing the fact that the high-resolution images presented in Figures 6.11 and 8.8 were achieved using a standard A4 flat bed scanner. Given the potential for missing such important surfaces in the sampling process, it also worth recommending that detailed coal petrographic studies should be based on cored or channel sampled outcrop sections.

As a final general comment, greater attention to detail in field observations of coaly rocks may yield significantly improved understanding of depositional conditions in a wide range of sedimentological studies.

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# APPENDIX: COAL PETROGRAPHIC DATA

*This Appendix illustrates part of the petrographic dataset for the Sunnyside, Aberdeen and Desert coals in graphical format. The entire dataset is provided in an Excel spreadsheet on the enclosed CD, which also includes PDF versions of each thesis chapter and the spectral analysis data discussed in Chapter 8.*

## VERTICAL PROFILES BY SAMPLED SECTION

The figures collated in this Appendix illustrate variations in the following palaeoenvironmental indicators as a series of vertical profiles:

i) % Inorganic minerals
ii) % Vitrinite
iii) % Inertinite
iv) % Liptinite
v) Mean random telovitrinite reflectance (%Rrt)
vi) Tissue preservation index (TPI)
vii) Groundwater influence index (GWI)
viii) % Pyrite
ix) % Telovitrinite
x) % Sporinite
xi) % Semifusinite
xii) % Inertodetrinite

See Chapters 3 and 5 for definitions and discussion of the palaeoenvironmental significance of these parameters, vitrinite reflectance analysis was not carried out on the Aberdeen and Desert coals. Note that the vertical and horizontal scales differ between figures, but are clearly labelled in each case. The parts of the profiles shaded paler grey indicate drying upward coal, the parts shaded darker grey indicate wetting upward coal.

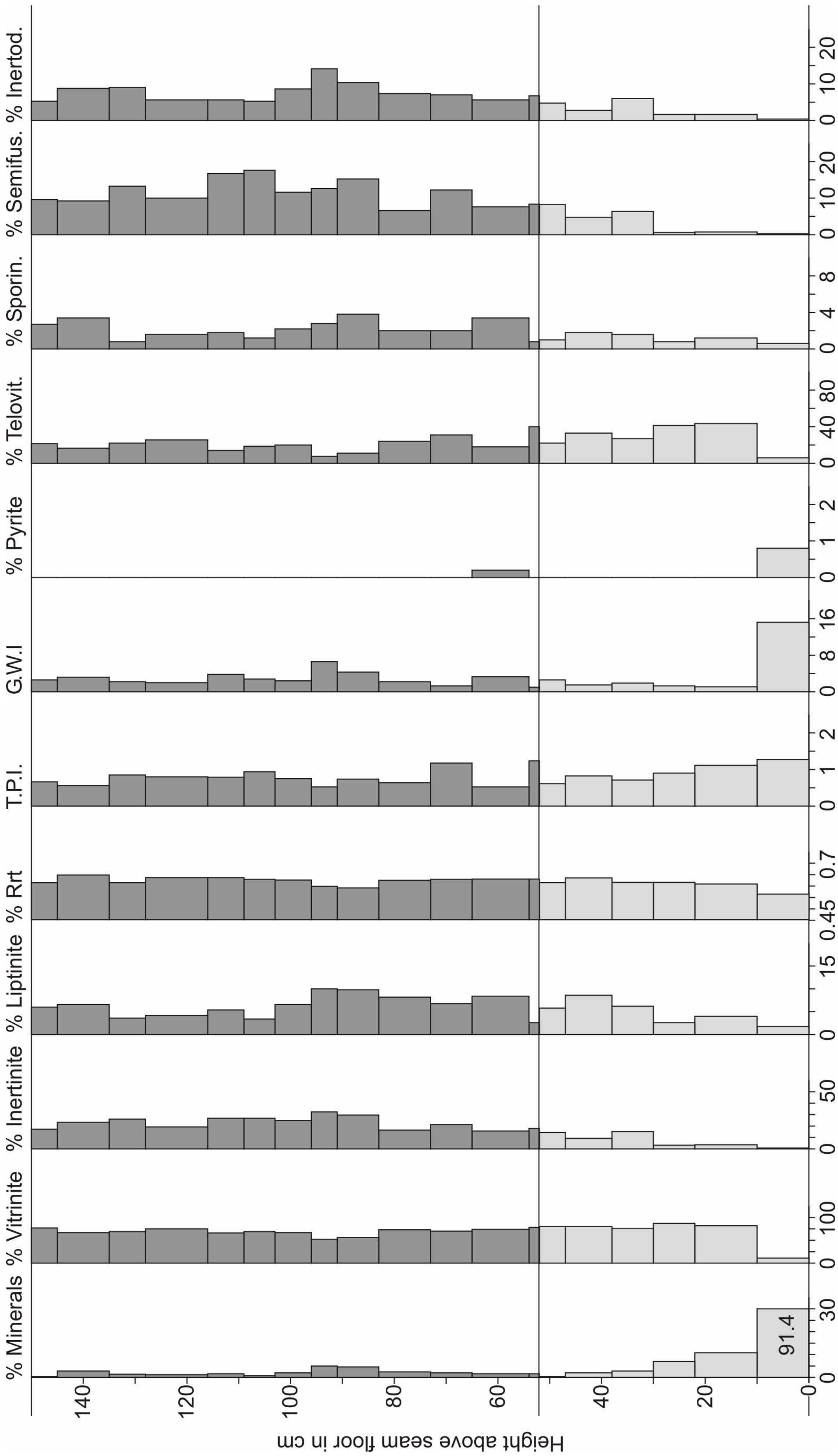

**Figure A.1.** Vertical profiles to show properties of the Sunnyside coal at Deadman Canyon.

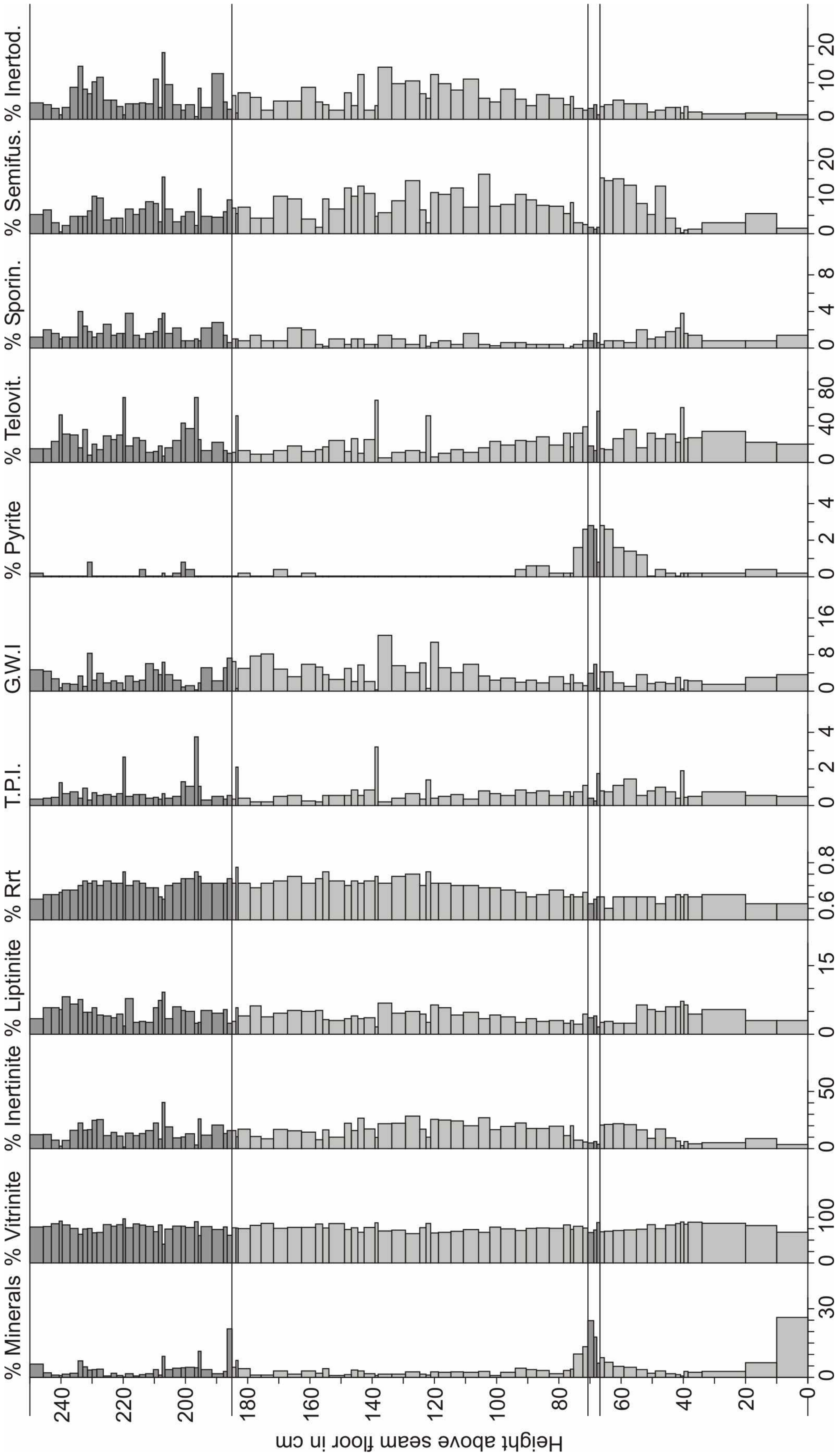

**Figure A.2.** Vertical profiles to show properties of the Sunnyside coal at C Canyon.

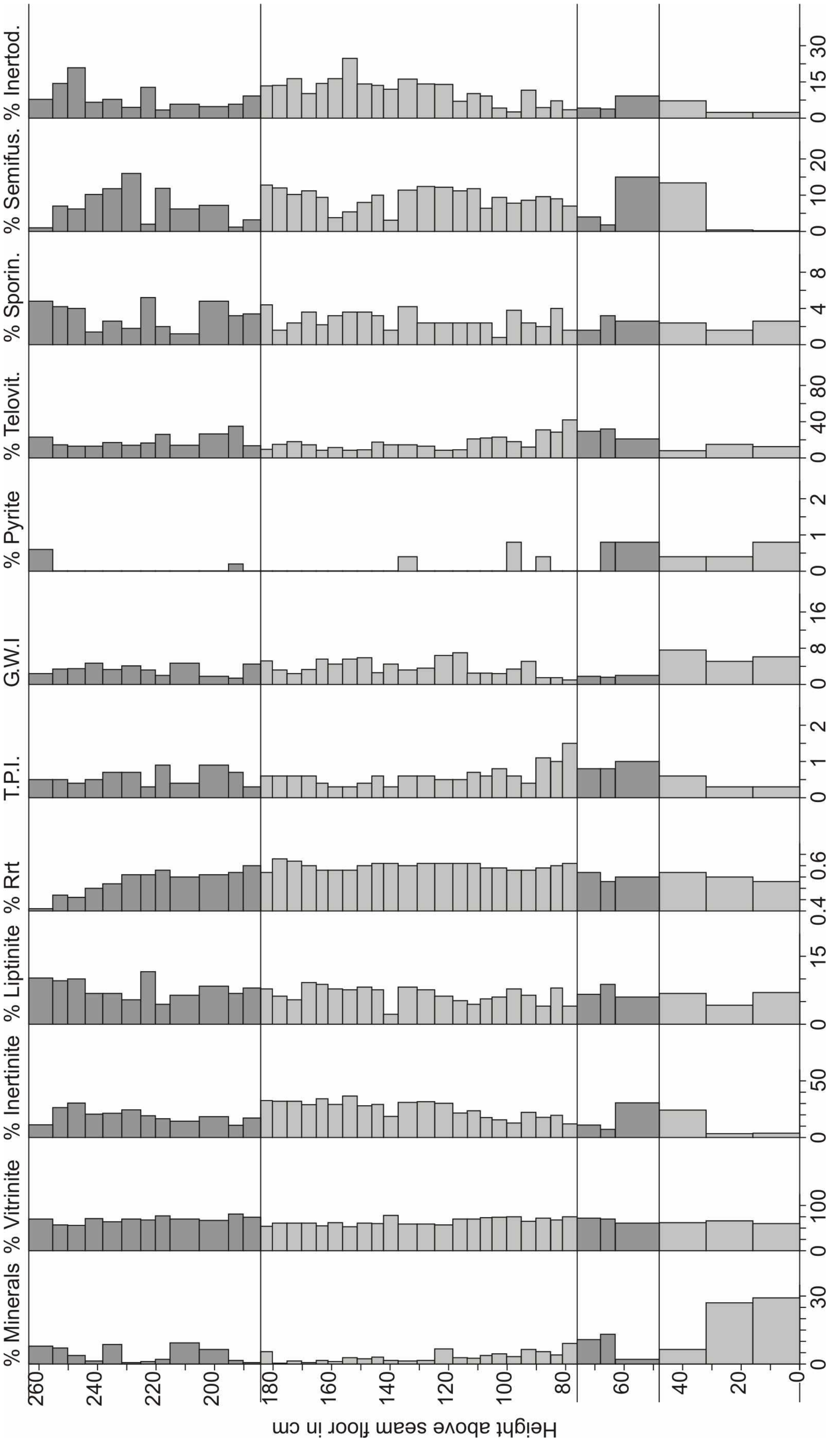

**Figure A.3.** Vertical profiles to show properties of the Sunnyside coal at Fan Canyon.

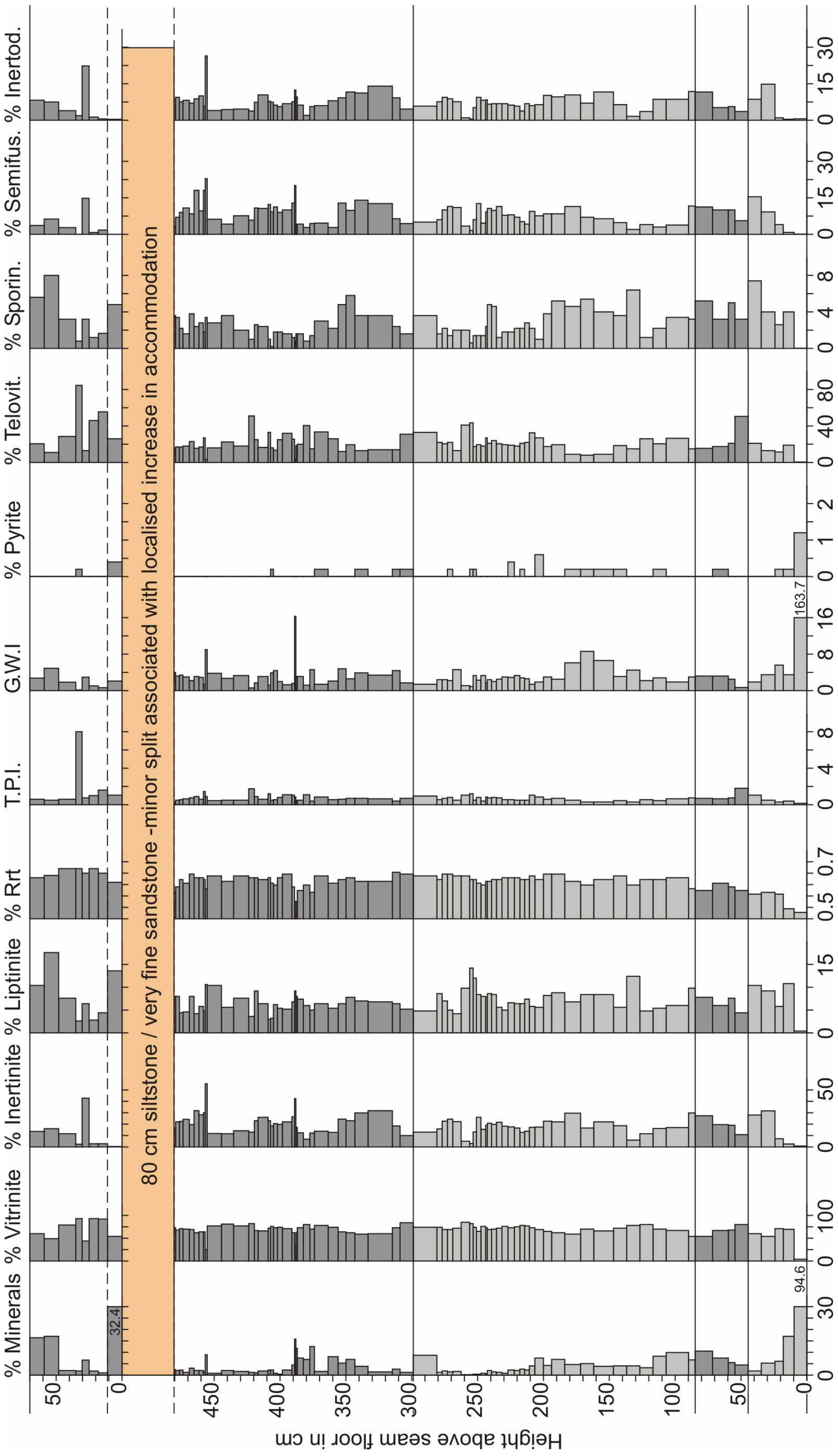

**Figure A.4.** Vertical profiles to show properties of the Sunnyside coal at Lila Canyon.

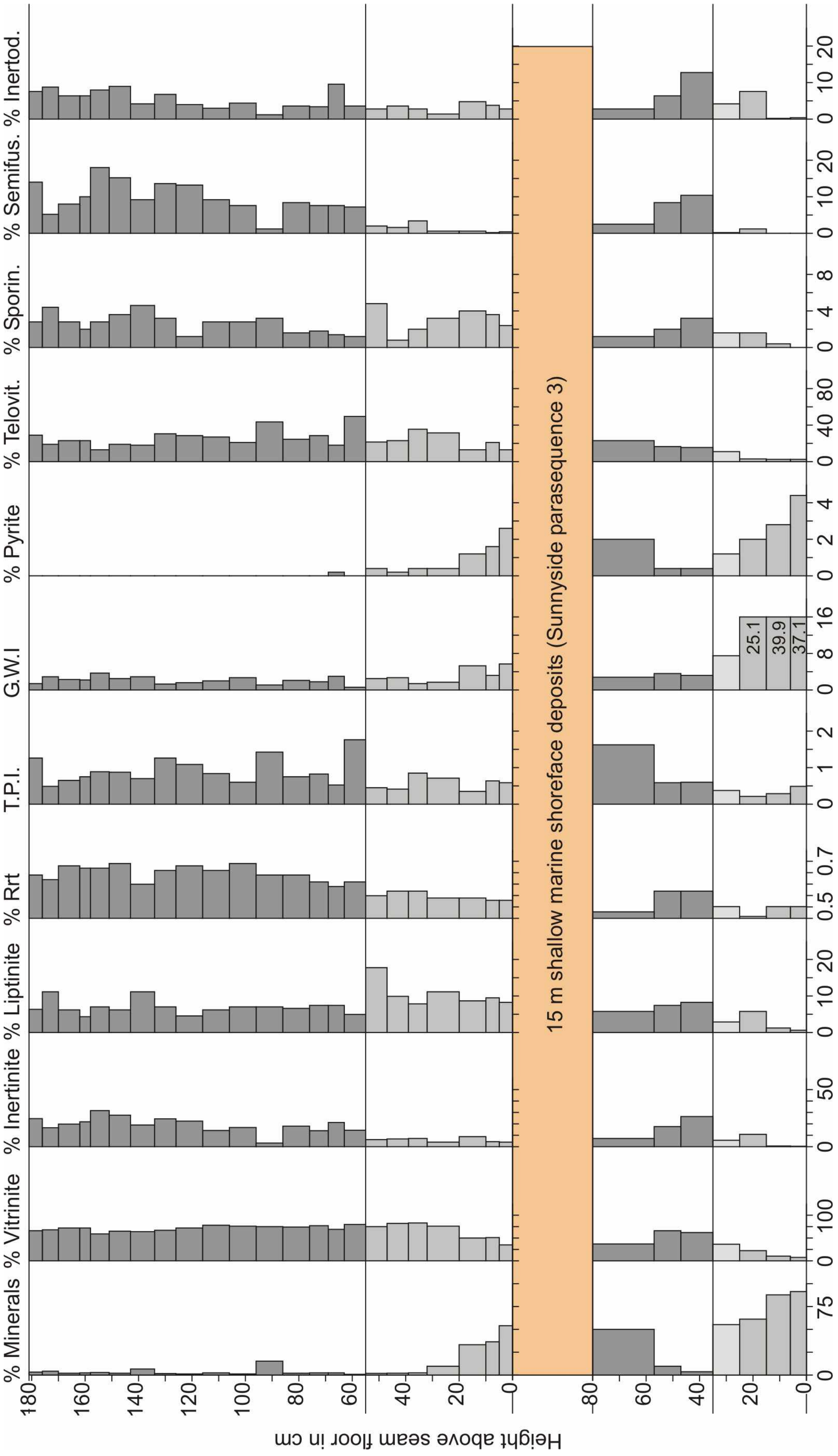

**Figure A.5.** Vertical profiles to show properties of the Sunnyside coal at Jeep Trail.

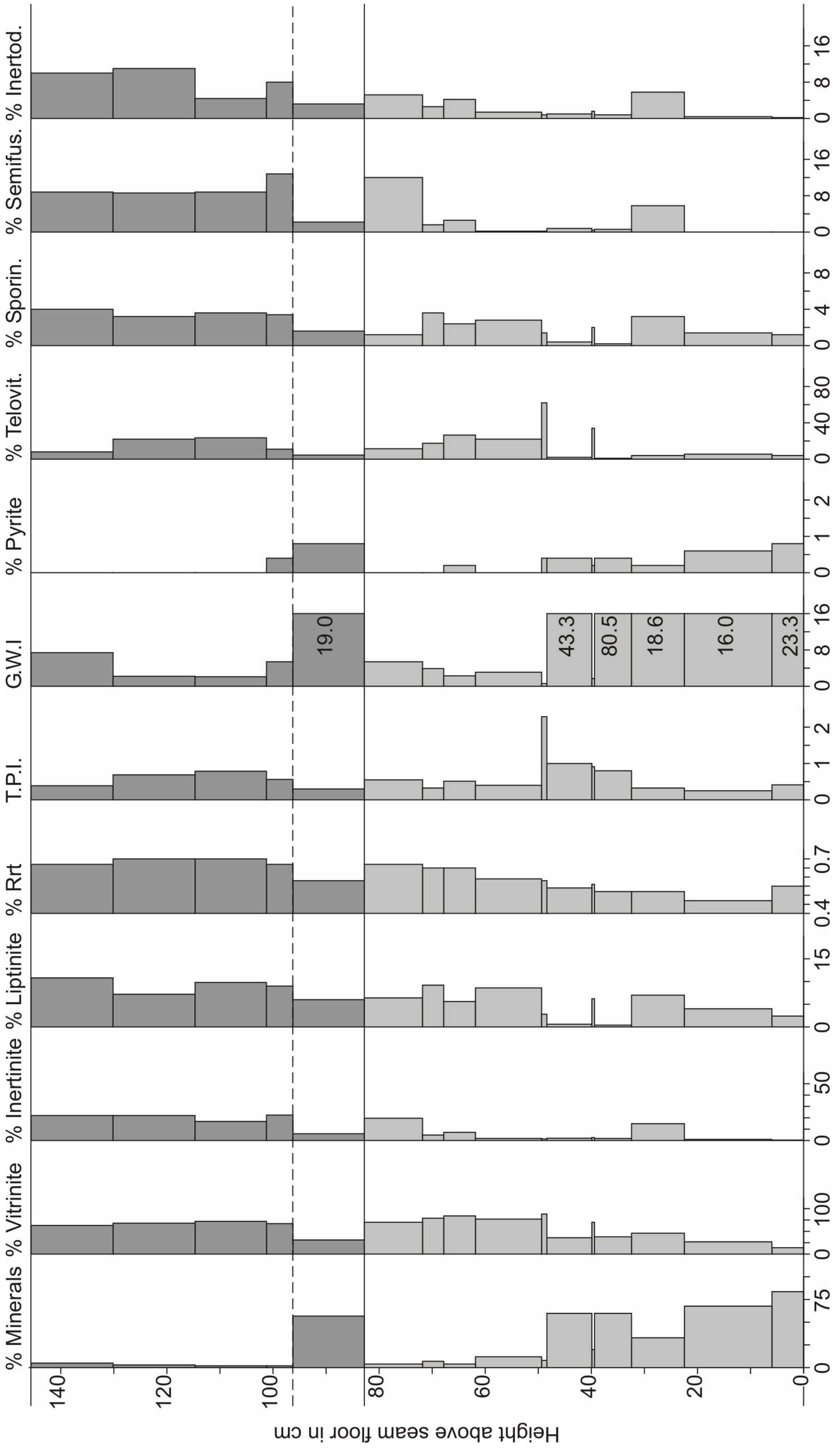

**Figure A.6.** Vertical profiles to show properties of the Sunnyside coal at Woodside Canyon I.

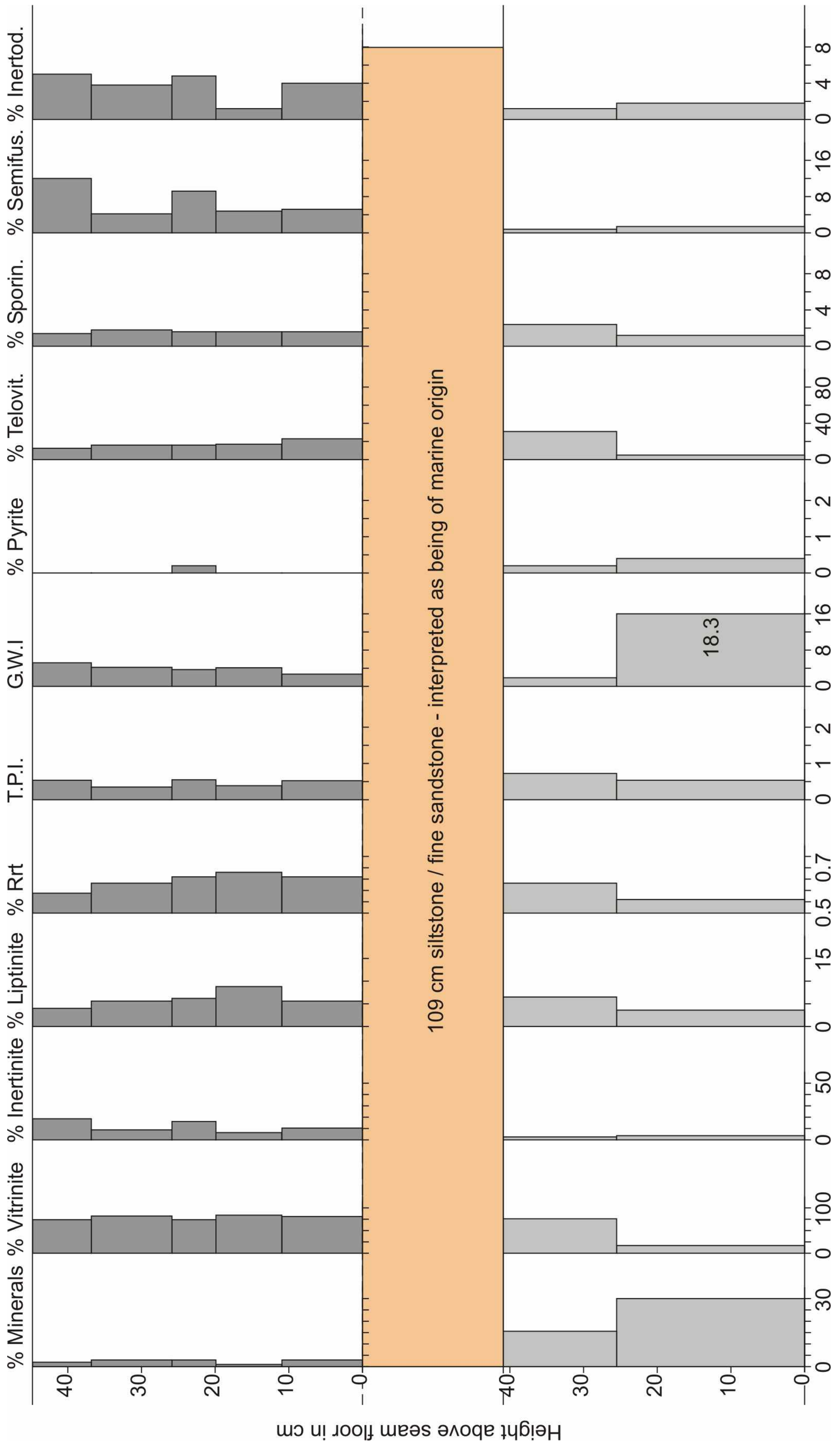

**Figure A.7.** Vertical profiles to show properties of the Sunnyside coal at Woodside Canyon II.

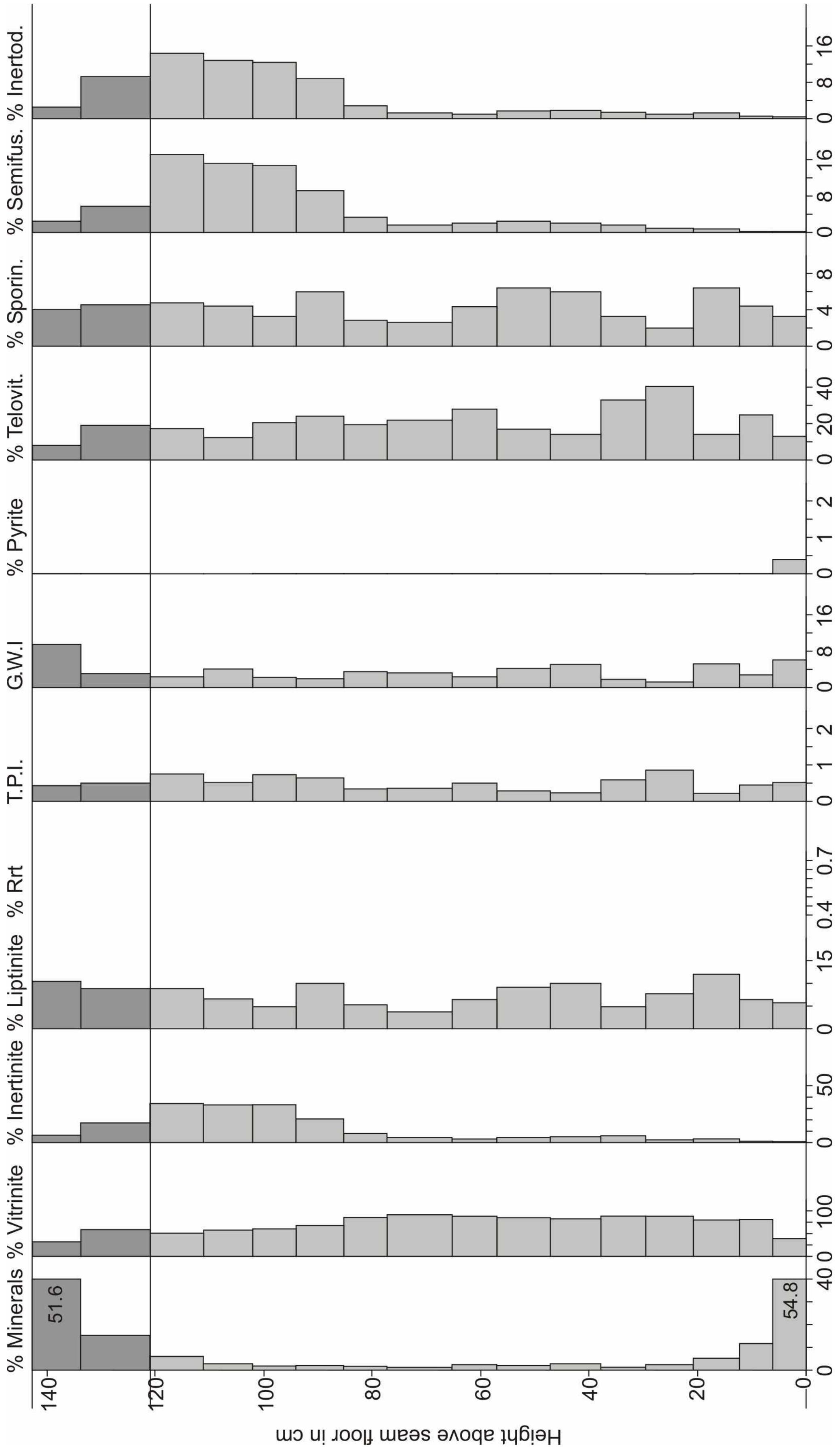

**Figure A.8.** Vertical profiles to show properties of the Aberdeen coal at 12 N 511042. 4398028.

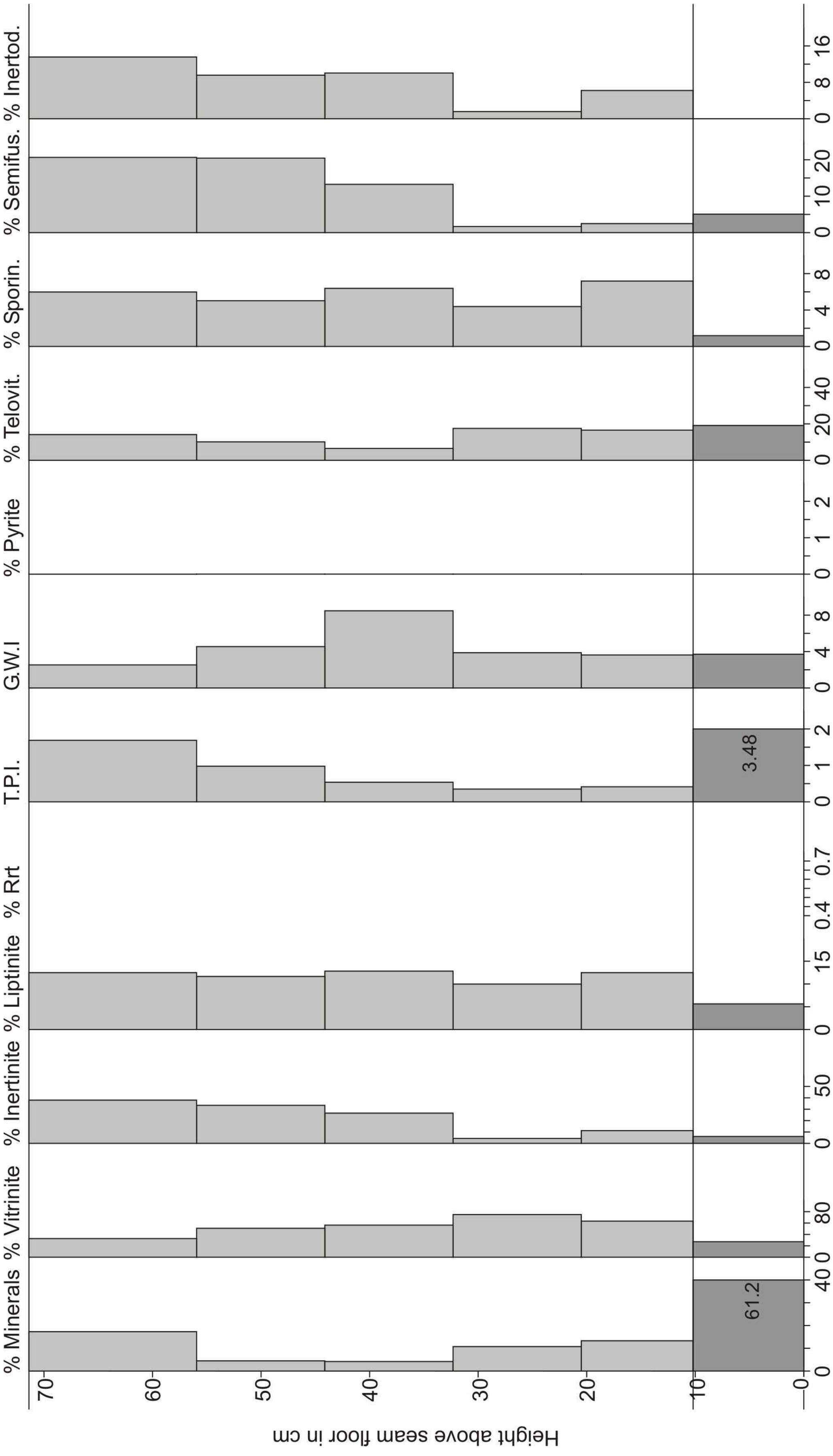

**Figure A.9.** Vertical profiles to show properties of the Desert coal at 12 N 0564299. 4344032.