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Stratigraphic style of coal and non-marine strata in a tectonically influenced intermediate accommodation setting: the Mannville Group of the Western Canadian Sedimentary Basin, south-central Alberta

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ABSTRACT

Coal-bearing strata from the Lower Cretaceous upper Mannville Group (south-central Alberta) were investigated in order to evaluate the nature of coal-bearing non-marine to marginal marine sediments developed in an intermediate accommodation setting, located centrally within the Alberta Foreland Basin. Downdip and lateral correlations to the northwest and east link upper Mannville Group strata to the Falher sequences and the Waseca to Lloydminster sequences, respectively, and indicate that a higher order of stratigraphic subdivision, controlled by transgressive–regressive cycles, must also be present in the upper Mannville.

Stratigraphic analysis of the upper Mannville Group in the study area, based on over 1200 km of borehole cross-sections and 50 cores, revealed a number of features that can be considered characteristic of intermediate accommodation in non-marine sediments. These include abundant, compound coal seams and numerous incised valleys with even distribution of sediments between incised valleys and adjacent interfluves. The incised valleys may correlate laterally into horizons within the compound coals, indicating that the coal seams contain sequence boundaries within them and therefore span relative sea level cycles. However, the occurrence of coal seam splits in multiple directions suggests that seam splitting in the upper Mannville Group was at least partially controlled by differential subsidence. This is attributed to fault reactivation on the underlying irregular Paleozoic basement, and maps of inferred fault planes indicate a horst and graben style of extensional faulting. Fault planes appear to be associated with relatively steeply dipping basement topography, and areas of thickest cumulative coal preferentially occur above horst blocks. Although these particular features may be unique to the Mannville Group, they suggest that underlying structures and paleotopography are likely to exert a strong influence on sedimentation patterns in intermediate accommodation settings, because the rates of vertical accretion are insufficient to suppress the effects of differential subsidence. Other expressions of basement control are the localization of single and compound incised valleys along structural lows.

Coal composition analysis is based on photometric and maceral analyses of three upper Mannville Group coals. The aim was to test various methods of identifying small-scale accommodation trends in the coal and use them to identify a characteristic accommodation signature for each coal. The Glauconite, Medicine River and informally named Hackett coals were shown to be significantly more complex than simple ‘transgressive’ or ‘regressive’ style coals. They comprise a number of wetting- and drying-upwards cycles representing repeated episodes of peat deposition under rising or falling accommodation conditions, with or without internal hiatuses between the cycles. These accommodation cycles are driven by changes in groundwater levels that are in turn hydraulically linked to relative sea level, and thus form the basis for identifying a characteristic non-marine sequence stratigraphic style.

RÉSUMÉ

Les strates houillères du Crétacé Inférieur du Groupe du Mannville Supérieur (centre sud de l'Alberta) ont été examinées afin d'évaluer la variation entre les sédiments non marins et les sédiments marins marginaux. Ceux-ci sont développés dans un milieu d'accomodation intermédiaire situé dans la partie centrale de l'avant pays de l'Alberta. Des corrélations en aval-pendage et latérales au Nord Ouest et à l'Est lient respectivement les strates du Groupe du Mannville Supérieur aux séquences Fahler ainsi que les séquences Waseca à Lloydminster. Ces corrélations représentent un ordre supérieur de subdivision stratigraphique qui est contrôlé par des cycles transgressifs–régressifs devant être également présents dans le Mannville Supérieur.

L'analyse stratigraphique du Groupe du Mannville Supérieur effectuée dans la région étudiée qui est basées sur plus de 1200 km de coupes transversales de sondage et de 50 carottes, a révélé un nombre de particularités qui peuvent être considérées comme étant caractéristiques d'une accomodation intermédiaire dans des sédiments non marins. Ces particularités comprennent des filons houillers juxtaposés qui sont en abondance, et de nombreuses vallées entaillées avec une distribution uniforme de sédiments entre les vallées entaillées et les interfluves adjacents. Les vallées entaillées peuvent être corrélées latéralement avec des horizons qui sont inclus dans les houilles juxtaposées, indiquant que ses filons houillers contiennent entre eux des limites de séquences, et par conséquent, s'étendaient à travers des cycles du niveau marin relatifs. Cependant, la présence de filons houillers intercoupés en directions multiples suggère que la séparation des filons du Groupe du Mannville Supérieur a été partiellement contrôlée par une subsidence différentielle. Ceci est attribué à une réactivation de faille sur le socle Paléozoïque irrégulier sous-jacent, et des cartes de failles suggérées indiquent que ces dernières sont du même style que les failles de distensions formées dans des horsts et des grabens. Les plans de failles apparaissent comme étant associés à une topographie de socle plongeant relativement à pic, et les régions présentant les plus épaisses accumulations de houille se situent de préférence au-dessus des horsts. Bien que ces caractéristiques particulières puissent être uniques au Groupe du Mannville, elles suggèrent que les structures sous-jacentes et la paléotopographie exercent probablement une forte influence sur les configurations de sédimentation dans des milieux d'accomodation intermédiaire, par le fait que les taux d'accrétion verticale sont insuffisants pour supprimer les effets de subsidence différentielle. D'autres manifestations du contrôle du socle sont la localisation de vallées entaillées isolées et juxtaposées le long des dépressions structurales.

L'analyse de la composition de la houille est basée sur des analyses de photométrie et de macéraux de trois couches de houille du Groupe du Mannville Supérieur. Le but visé a été de tester plusieurs méthodes d'identification de tendances d'accomodation de la houille à petite échelle, et de les utiliser afin d'identifier la signature caractéristique d'accomodation de chacune. Les houilles de Glauconite, Medicine River et celles officieusement appelées Hackett Coals se sont révélées beaucoup plus complexes que le simple style houiller "transgressif" ou "régressif". Elles consistent en un nombre de cycles humides et secs ascendants représentant des épisodes répétitifs de dépôts de tourbe selon des conditions d'accomodation montante ou tombante, avec ou sans hiatus internes entre les cycles. Ces cycles d'accomodation sont provoqués par des changements de niveaux de la nappe phréatique, reliés à leur tour par l'énergie hydraulique associée avec le niveau relatif de la mer, et donc forment le fondement pour l'identification d'un style caractéristique de stratigraphie séquentielle non-marine.

Traduit par Gabrielle Drivet

INTRODUCTION

Non-marine strata have traditionally been difficult to correlate, and this has inhibited construction of summary stratigraphic models. This is because individual stratigraphic units are typically difficult to distinguish; marker beds are less common and less continuous, and chronostratigraphic and biostratigraphic control is commonly lacking or inadequate. In contrast, coastal and shallow-marine strata are characterized by distinctive, laterally continuous facies, have better age control, and can be subdivided by the passage of the shoreline in transgressive and regressive packages. It is not surprising then, that the principles embodied in sequence stratigraphy (e.g. Posamentier and Vail, 1988; van Wagoner et al., 1990) were initially applied to wave- and river-dominated coastal and shallow-marine strata. The development of sequence stratigraphic models for environments further removed from the shoreline, in both terrestrial and deep marine settings, has proved to be more difficult.

The accommodation concept probably offers the best method to develop an organized approach to non-marine stratigraphy (c.f. Blum and Törnquist, 2000). "Accommodation" is the space available for potential sediment accumulation and subsequent preservation (Jervey, 1988). It has both tectonic (subsidence or uplift) and eustatic components (e.g. Posamentier and Vail, 1988). The accommodation concept applies to basins experiencing cyclic variations of relative sea level (RSL) derived from changes in tectonic, eustatic and climatic driving forces. The characteristics of the sedimentary basin response can then be considered to result from the relationship between accommodation and sediment flux supplied to the basin. In this paper the term "accommodation" is used in both a temporal and a spatial sense. In the temporal sense, accommodation is applied to the rate of change of accommodation during a cycle of relative sea level. As such, it can be compared with, for example, the rate of peat growth, and hence the character of a resulting coal bed. In the spatial sense, accommodation refers to variation in the amount of space available for sediment accumulation at a particular basin location. This variable amount of space could result from part of a RSL curve, a complete RSL curve, or the sum total of many relative sea level curves. In this sense, for example, a specific basin location could be regarded as having low net accommodation if, over a number of RSL cycles exhibiting abundant sediment supply, only a limited amount of sediment accumulated there.

Our approach to investigating the problems of non-marine sequence stratigraphy has been to conduct a series of detailed field studies over a range of both spatial and temporal accommodation settings. This has allowed us to document the influence of accommodation in each case study and to use the integrated results of these studies to synthesize a non-marine stratigraphic model (see preliminary results in Boyd et al., 1999, 2000). We have used the Western Canadian Sedimentary Basin (WCSB, Leckie and Smith, 1992; Cant and Abrahamson, 1996; Zaitlin et al., 2002) because of its clear Early–mid Cretaceous variation from a low subsidence cratonic margin to a high subsidence foredeep western margin, and also its gradient in accommodation rate from south (low) to north (high). A further advantage of the WCSB is the high quality, publicly-available subsurface database, enabling us to access thousands of wireline logs and cores across the basin.

The present contribution presents a detailed field study of Mannville Group non-marine strata in an intermediate spatial accommodation setting in south-central Alberta, mid-way between the cratonic and foredeep margins of the basin (Fig. 1). In this sense this study provides a central point in a spectrum between other WCSB detailed studies conducted by our group of low accommodation settings in the Basal Quartz Formation (Zaitlin et al., 2002) and the Lower Cretaceous of southern Alberta and Saskatchewan (Leckie et al., 1997), and higher accommodation settings in the Falher Member and Gates Formation of north west Alberta and north east British Colombia (Leckie, 1986; Diessel et al., 2000). Previous studies (e.g. Diessel, 1992; Diessel et al., 2000; Plint et al., 2001) have illustrated the significance of key lithologies such as interfluve paleosols, lacustrine strata, and coal in understanding non-marine stratigraphy. In the current study we have chosen to concentrate on coal-bearing strata because of their abundance and variability in the study area, and their potential to provide information on fluctuations in groundwater, which is a critical accommodation parameter. The objectives of this study of the Mannville Group are twofold: 1) to document the style of non-marine to marginal marine stratigraphy that characterizes an intermediate accommodation setting, and 2) to investigate the role of coal-bearing sediments and use their properties as a tool for detailed stratigraphic interpretation and correlation. Because the WCSB is a major petroleum producing basin and the Mannville Group in south-central Alberta is a significant contributor to total WCSB petroleum production, the results of this study will provide a better regional stratigraphic framework and an improved basis for petroleum (including coal bed methane) exploration in the region. The results will provide a better understanding of factors controlling non-marine stratigraphy including the influence of basement topography, the accumulation and preservation of peat, and the role of incised valleys.

An Approach To Non-marine Sequence Stratigraphy

Recognition of accommodation cycles, linked to relative sea level cycles, and surfaces of sequence stratigraphic significance in non-marine strata is inherently more difficult than in marine deposits (e.g. Plint et al., 2001). An exception to this occurs when the terrestrial sediments contain paralic coals. Coals formed in deltaic and coastal-plain settings have a well documented compositional cyclicity (e.g. Snedden and Kersey, 1981; Heckel, 1986; Diessel, 1992) because the original peat bodies were affected by marine influences as their groundwater tables responded to relative sea level changes. Organic matter reacts with great sensitivity to groundwater oscillations and their associated changes in pH and redox potentials so that even weak changes in the hydrologic regime of peat mires may be translated into compositional differences in the subsequent coal seams (Frenzel, 1983). Because of the genetic dependence in coastal settings of groundwater position on sea level, and, in many cases, their considerable lateral extent, paralic coal seams provide a good non-marine indication of sea level variations. However, in the literature to date, the sequence-stratigraphic interpretation of coal measures has mostly made use of the geometry, stacking pattern, and position of whole coal seams within paralic depositional cycles (Aitkin and Flint, 1995; Hampson et al., 1999, 2001; Montgomery et al., 2001), and relatively few investigations have focussed on the significance of the internal composition and organization of coal seams (Diessel et al., 2000 and references therein).

Accommodation in a mire is defined as the maximum height to which a peat can accumulate (McCabe, 1993). To determine the usefulness of coal as a non-marine sequence stratigraphic tool, we examine the premise that variations in the balance between the rates of accommodation and peat production result in vertical changes in the composition of a coal seam (Fig. 2). Peat is only able to accumulate if environmental conditions allow peat production to occur, and accommodation is sufficient to allow the peat to be preserved (Boyd and Diessel, 1995; Bohacs and Suter, 1997; Diessel et al., 2000). A compilation of Holocene maximum peat accumulation rates in relation to geographic latitude (Fig. 2 in Diessel et al., 2000) indicates that rates of peat production may differ greatly between various climatic zones, but are relatively small within zones. This implies that imbalances in accommodation rate/peat production rate ratios are mainly due to increases and/or decreases in accommodation (Shanley and McCabe, 1994; Boyd and Diessel, 1995).

A number of petrographic indicators in coal show systematic variations with changing accommodation (see discussions in Diessel and Gammidge, 1998; Diessel et al., 2000) and can

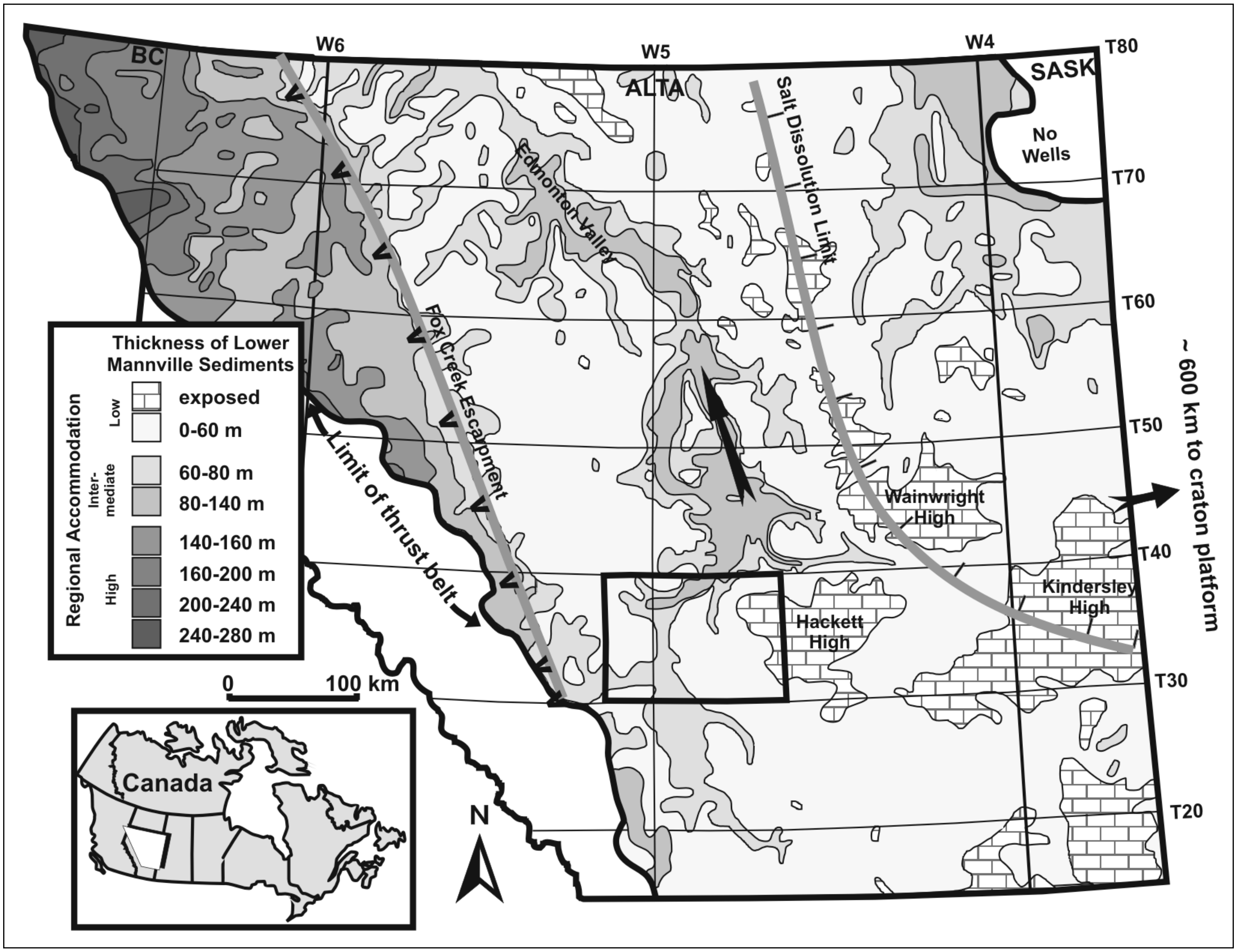
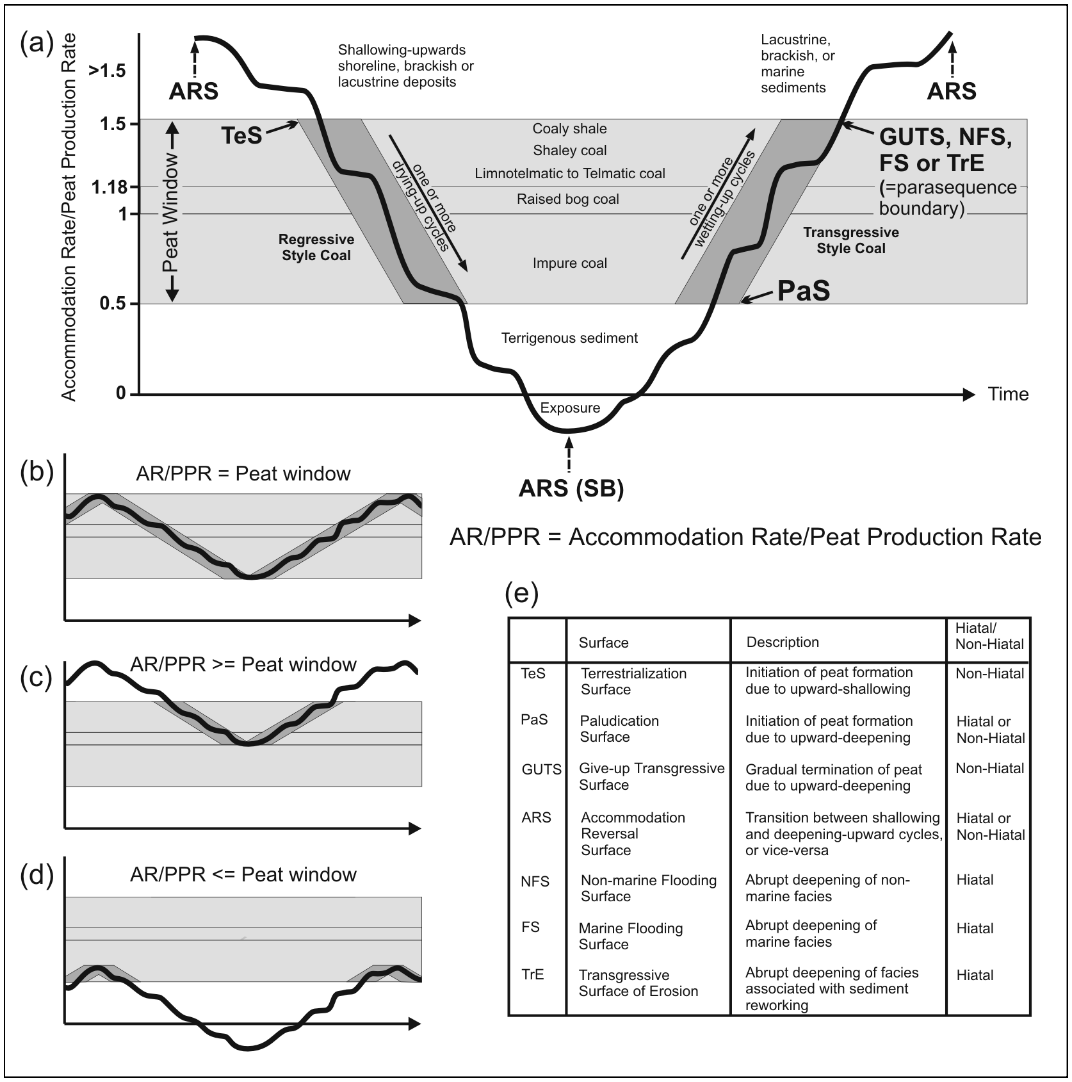


Fig. 1. Map of Alberta Foreland Basin showing the location of the south-central Alberta study area. The isopach contours represent thickness of the lower Mannville Group (modified from Cant and Abrahamson, 1994 and after Diessel et al., 2000) which can be used as a proxy for regional subsidence and accommodation patterns. Areas of low, intermediate and high subsidence-driven accommodation are defined on the basis of sediment thickness. This map suggests that the study area lies within a region of broadly intermediate accommodation, but paleofeatures such as the Hackett high and a paleovalley related to the Edmonton valley, may have provided localized effects superimposed on regional subsidence patterns. Arrows indicate paleodrainages (from Leckie and Smith, 1992). Inset map shows position of study area within Canada.

be used to identify two types of peat cycles. Figure 2 is a schematic model illustrating how cyclic changes in the accommodation rate and peat production rate can produce a single regressive coal seam followed by a transgressive seam. Mires in which the ratio of accommodation rate to peat production rate remains well-balanced (between 1 and 1.18) for a long period of time may lead to the formation of thick, often ombrotrophic (i.e. “raised”) mires with minimum ash content and maximum tissue preservation (see Fig. 3 in Bohacs and Suter, 1997). Drying-upward cycles are represented by a changing accommodation/peat production rate ratio from balanced (or high) to low. As the ratio drops to between 1 and 0.5, the ash content of the peat increases because of oxidation and occasional burning of organic matter, leading to an ‘impure’ coal. If the ratio falls below about 0.5, peat cannot be preserved (even though it may still be produced, as occurs in a raised mire) and terrigenous sediments may be deposited instead. A negative ratio results in sediment exposure, erosion and reworking. In contrast, wetting-upward cycles are represented by a changing accommodation/peat production rate ratio from balanced (or low) to high. As the ratio rises from 1.18 to 1.5, coal facies may grade from limnotelmatic, to shaley coal (mineral content 30-50%), to coaly shale (mineral content of 50-90%), and finally to pure shale as peat production ceases. An accelerated accommodation rate causes frequent flooding of the peat that raises the adventitious mineral content, resulting in reduced thickness and quality of coal in areas away from the optimum peat-forming conditions.

Several non-marine sequence stratigraphic surfaces (Fig. 2) have been identified in coal (Diessel et al., 2000). Of greatest importance is the accommodation reversal surface (ARS), which delineates the surface across which accommodation



	Surface	Description	Hiatal/ Non-Hiatal
TeS	Terrestrialization Surface	Initiation of peat formation due to upward-shallowing	Non-Hiatal
PaS	Paludication Surface	Initiation of peat formation due to upward-deepening	Hiatal or Non-Hiatal
GUTS	Give-up Transgressive Surface	Gradual termination of peat due to upward-deepening	Non-Hiatal
ARS	Accommodation Reversal Surface	Transition between shallowing and deepening-upward cycles, or 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

Fig. 2. Idealized curves showing relationship between paralic accommodation rate (AR) and peat production rate (PPR). The latter is assumed to remain relatively constant for an individual coal seam, and therefore accommodation is the key variable. The "peat window" occurs where AR/PPR falls between 0.5 and 1.5 (Bohacs and Suter, 1997). **(a)** If the amplitude of the AR/PPR curve is greater than the amplitude of the peat window, then both regressive and transgressive coals separated by hiatal surfaces may form. **(b)** If AR/PPR curve lies entirely within the peat window, then a compound coal seam, with no internal hiatal surfaces, may develop. **(c)** If the AR/PPR curve lies mainly above the peat window, then the coals will be dominated by shaley, limnotelmatic, telmatic or raised mire coals. **(d)** If the AR/PPR curve lies mainly below the peat window, then the coals will be impure and characterized by exposure surfaces. **(e)** Summary of sequence-stratigraphic surfaces associated with coal.

conditions change from decreasing to increasing, or *vice versa*. Recognition of this surface indicates whether the peat has formed on a single rising or falling limb of the accommodation curve. If a coal contains an ARS within it, then it is a composite seam spanning more than one relative sea level cycle. The accommodation rate/peat production rate curve (Fig. 2) shows a range of deposits and surfaces which might form in a paralic environment during a single episode of increasing and decreasing accommodation conditions, with superimposed smaller-scale accommodation variations (i.e. higher frequency curves superimposed on main curve). The left hand side of the hypothetical curve shows, for simplicity, a peat seam containing multiple horizons that formed during decreasing accommodation conditions, such as occurs at the final stages of the terrestrialization (Frenzel, 1983; Boron et al., 1987). Such peats correspond to 'regressive' style coals (Diessel, 1992), and are separated from their underlying subaqueous floor sediments by a terrestrialization surface (TeS). This surface is commonly non-hiatal because, as water depth and accommodation rates gradually decrease, there is no break in sedimentation, but rather a shift from predominantly allochthonous clastic sedimentation to autochthonous peat accumulation. The subsequent coal represents a continuation of the shoaling-upwards succession, and typically contains one or more drying-up cycles reflecting smaller-scale accommodation variation. The upper bounding surface is often hiatal in nature due to sediment reworking, and may correspond to a subaerial unconformity (possibly equivalent to a sequence boundary) and an accommodation reversal surface (ARS).

Another type of simple coal seam (Fig. 2) occurs when peat accumulates under a regime of increasing accommodation by the processes of paludification (Frenzel, 1983; Boron et al., 1987), leading to the formation of 'transgressive' style coal (Diessel, 1992). The base of the coal is referred to as a paludification surface (PaS), which often rests on a well-developed soil horizon. The coal is characterized by one or more wetting-upward cycles, as shown by increased detrital-mineral content and other indicators of increasingly allochthonous dispersal of organic and inorganic peat components such as sporinite and inertodetrinite. If accommodation continues to increase beyond the maximum rate of peat production, peat formation will be replaced by lacustrine or floodbasin deposits in the non-marine realm, or by marine deposits. The rate of accommodation increase is the main factor determining at what point peat formation is replaced by clastic sedimentation (Diessel, 1998). If the increase in accommodation is gradual, peat will accumulate, albeit under less than optimal conditions, until the mire becomes flooded and a give-up transgressive surface (GUTS*)* caps the coal seam. Alternatively, if flooding of the peat is abrupt, then a non-marine (NFS) flooding surface or an estuary/lagoon to marine flooding surface (FS) forms the top of the coal seam. The distinction between a GUTS and a NFS hinges on the relative rate of accommodation increase; the former surface is gradational and non-hiatal, whereas the latter is abrupt, hiatal, and may coincide with an ARS. In view of the hydrologic connection between sea level and groundwater table in paralic coal measures, an open to marginal marine flooding surface correlates landwards to a non-marine flooding surface (NFS). The replacement of marine by non-marine flooding signifies a landward decline in the magnitude (and to a lesser extent, rate) of the accommodation increase, so that the abrupt rise in relative sea level near the coast translates landward into a weaker rise of the connected groundwater table.

In reality, as opposed to the schematic diagram of Figure 2, many coal seams show evidence of regional splitting and amalgamation and therefore cannot be described as simple transgressive or regressive coals. These compound coals, with or without internal hiatuses, have been formed over several relative sea level cycles so that they combine transgressive and/or regressive elements in one seam (Diessel, 1998). In the following sections, we examine the stratigraphy and internal characteristics of some of the Falher Member and Gates Formation coals, in order to determine the nature and correlatability of their accommodation signatures.

REGIONAL SETTING

The Mannville Group (Glaister, 1959; Williams, 1963; Rudkin, 1964) is a thick clastic wedge deposited in the WCSB during the Early Cretaceous (Aptian to mid-Albian). Sediments were derived mainly from the rising Cordillera to the west, and were transported axially towards the north (Monger, 1989; Leckie and Smith, 1992), into the shallow water, brackish Boreal Sea (Williams and Stelck, 1975). Strata of the Mannville Group (Fig. 3) are bounded above by a transgressive ravinement surface at the base of the Joli Fou Formation, and below by a major angular unconformity separating tilted Paleozoic limestone and/or Jurassic clastics from overlying Mesozoic age strata (Leckie and Smith, 1992). Paleotopography on this irregularly-shaped unconformity surface was up to 100 m and had a considerable effect on sedimentation patterns, stratal thickness and continuity. Ridges of resistant limestone formed regional barriers that separated drainage systems (e.g. the Wainwright and Hackett highs), whereas topographic lows and valleys formed sediment transport fairways, such as the Edmonton valley (Fig. 1). Local subsidence, caused by underlying salt dissolution, fault reactivation, and limestone cave collapse, also appears to have affected sedimentation patterns by focusing river drainage networks (Cant and Abrahamson, 1996). Climate during upper Mannville deposition is considered to have been warm and humid, and there is some evidence of concomitant volcanic activity within the Western Cordillera (Norris, 1964).

The Mannville Formation was first defined by Nauss (1945). Subsequently it was raised to Group status and informally subdivided into the lower and upper Mannville Group (Glaister, 1959; Rudkin, 1964; Hayes et al., 1994). The lower Mannville Group was interpreted as a transgressive systems tract by Cant and Stockmal (1993), and consists mainly of non-marine, estuarine and backstepping shoreface sediments. In the Medicine River study area of Central Alberta, the lower Mannville consists of the Detrital Unit, the Ellerslie Member (also known as the Basal Quartz Formation), the Ostracod Member, and a thin, mainly shale interval thought to be equivalent to the Glauconite Formation (Fig. 3). By the end of Ostracod sedimentation, most of the relief on the pre-Cretaceous erosion surface had been filled, leaving only isolated islands of Paleozoic highs (Leckie and Smith, 1992). The upper Mannville was interpreted as a highstand systems tract by Cant and Stockmal (1993) and consists of a regressive wedge that prograded northwards into the Boreal Sea. In south-central Alberta, this wedge consists mainly of undifferentiated coal-bearing fluvial and estuarine deposits, representing an extensive coastal plain.

STUDY AREA

The study area in south-central Alberta (Fig. 4) was chosen because it represents an intermediate accommodation setting, centrally located in the foreland basin (Fig. 1). It contains abundant coal seams, including the Medicine River coal, with up to 12 m cumulative coal thickness (Fig. 5). In several places the coal had been cored and was therefore available for petrographic analysis. Figure 4 illustrates the location of cross-sections and sample sites used in this study, as well as some of the main palaeogeographic features. The location of the detailed maps of basement topography (Fig. 6) and total coal thickness (Fig. 7) is highlighted by a black outline from townships 30 to 40 and ranges 19W4 to 4W5.

The sequence stratigraphy of the upper Mannville Group in central Alberta has not been resolved in detail owing to its dominantly non-marine character. Current interpretations suggest that the upper Mannville forms a third-order highstand systems tract (Cant and Stockmal, 1993). Figure 3 illustrates how downdip and lateral correlations to the Falher sequences in the Bullmoose Mountain and Elmworth areas (Cant, 1984; Leckie, 1986; Rouble and Walker, 1997), and the Waseca to Lloydminster sequences in the Lloydminster area (McPhee, 1994) indicate that a higher order of stratigraphy, controlled by transgressive–regressive cycles, must also be present in the upper Mannville. This relationship means that it is not unreasonable to expect some evidence of accommodation cyclicity related to relative sea level changes to be preserved in the coal-bearing non-marine strata.

Methods

In order to establish a stratigraphic framework and understand the depositional context of the coal-bearing non-marine strata, stratigraphic cross-sections were constructed and correlated, using a database of over 600 subsurface wireline-logs and 50 cores, ranging from 5 to 25 m in length each. Additional insights into the paleogeography, basement topography and coal distribution patterns were obtained from published information (Carmichael, 1983; Leckie, 1986; Cant and Stockmal, 1993; Cant and Abrahamson, 1994, 1996; Chiang, 1985; Langenberg et al., 1997). The stratigraphic framework served to independently characterize the coal samples in terms of (1) their position within the accommodation rate/peat production rate cycle, (2) their internal complexity (simple or amalgamated), and (3) the underlying causes of seam-splitting and amalgamation.

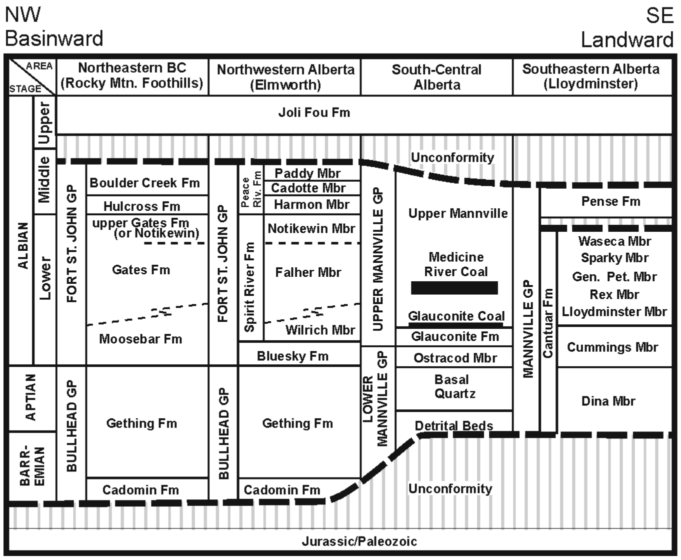


Fig. 3. Stratigraphic nomenclature of the Lower Cretaceous strata, Western Canadian Sedimentary Basin (modified after McLean, 1977; Hayes et al., 1994; Christopher, 1984). The interval of interest in this paper ranges from the Ostracod Member to the upper Mannville Group in south-central Alberta.

Analysis of various coal-petrographic constituents and their derived parameters was carried out from cores, following the methodology described in Diessel et al. (2000). Samples were taken on the basis of the lithotype distribution in the coal seams, at a spacing of between two to five centimetres. All samples were crushed to less than 2 mm diameter, and a representative portion of each was set in epoxy resin as raw coal. After curing, the samples were cut and polished according to standard methods for microscopic analysis in incident light. Telovitrinite reflectance (% Rrt) was measured in oil immersion according to Australian Standard 2486-1989, and telovitrinite fluorescence intensity (I 650 wt) was measured in water immersion at a wavelength of 650 nm after excitation at 436 ± 8 nm. Maceral and maceral group analysis were carried out in accordance with Australian Standard 2856-1986.

Tectonic, Subsidence and Accomodation Setting of the Mannville Group in south-central Alberta

In a ramp-style foreland basin setting such as the Alberta Foreland Basin, there is a range of accommodation that results from regional subsidence patterns. Subsidence rates are greatest on the tectonically active side adjacent to the orogen, where the thrust belt creates flexural loading (e.g. Beaumont, 1981). Towards the tectonically passive cratonic side, subsidence rates gradually decrease. The actual magnitude of accommodation generation is dominantly controlled by the interplay between eustasy and subsidence (Posamentier and Vail, 1988). During times of eustatic sea level rise, there will be a relatively smooth increase in accommodation space from the craton towards the thrust belt. In contrast, eustatic sea level fall will tend to counteract the effects of subsidence, creating a pattern of differential rates of accommodation (Posamentier and Allen, 1993). Superimposed on this regional subsidence pattern is the local basement control which alters, often significantly, the regional linear subsidence patterns (e.g. Pang and Nummedal, 1995).

The relative accommodation patterns in the Mannville Group can be identified from isopach maps of total sediment thickness and total coal thickness (Figs. 1, 5, 6 and 7). Isopachs (Fig. 1) indicate that the lower Mannville Group ranges in thickness from 0 to 280 m. The simple pattern of flexure-driven sediment thinning towards the craton is modified by two regional scale features that define three zones of different accommodation style (Cant and Abrahamson, 1994, 1996). The eastern zone (Fig. 1) is affected by Devonian salt dissolution which produces locally irregular accommodation patterns. The western zone is characterized by enhanced subsidence and is bordered to the east by a westward-facing erosional slope cut on the basal unconformity, called the Fox Creek Escarpment (McLean, 1977; Cant and Abrahamson, 1996). Between these occurs a central zone where Paleozoic basement has been eroded by north-flowing drainage networks, such as the Edmonton valley.

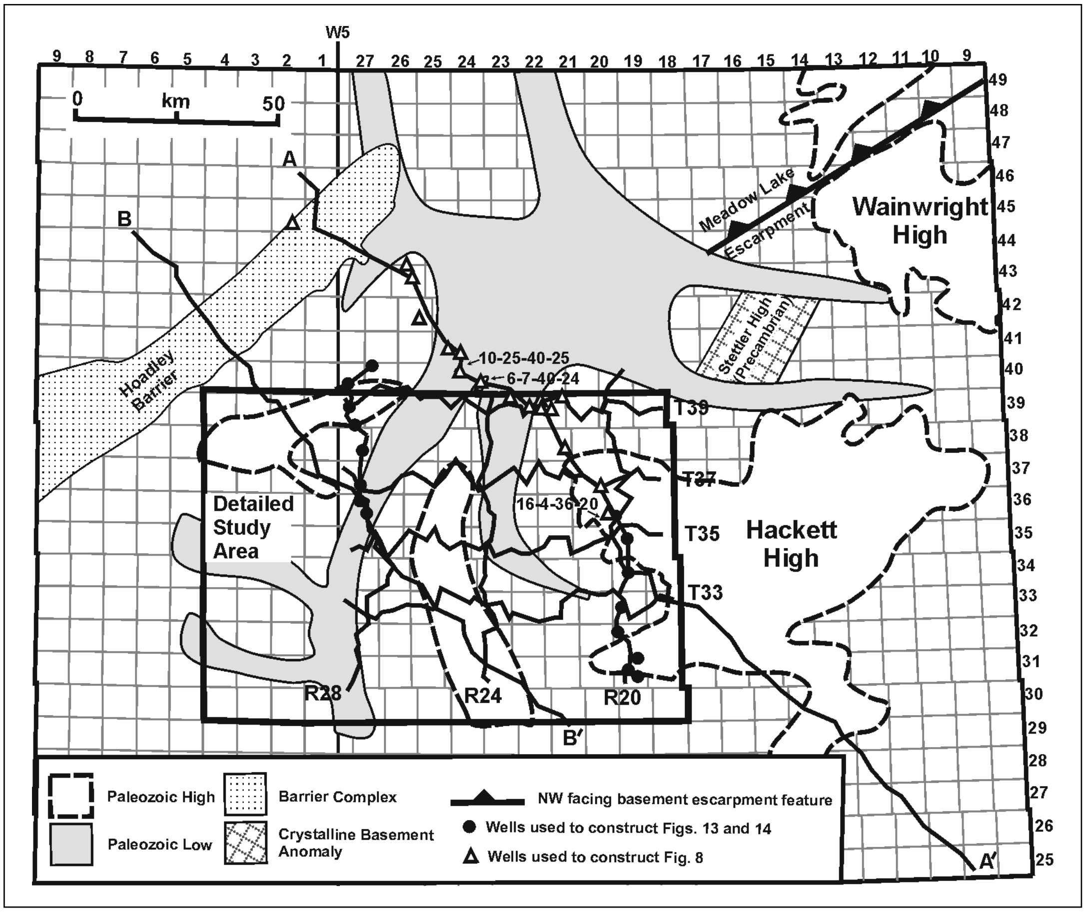


Fig. 4. Location map of the south-central Alberta study area and paleogeography. Data for the regional study area (large outer box) were derived mainly from cross-sections A–A′ and B–B′ (Fig.10), with paleogeographic and basement features inferred from various sources discussed in the text. Data for the smaller detailed study area (T39-30, R4W5-R19W4) were derived from a grid of seven cross-sections (Figs. 11, 12), as well as maps of sediment thickness and cumulative coal thickness (Figs. 5, 6, 7). White triangles indicate location of wells used in Figure 8, black dots indicate wells used to construct Figures 13 and 14. Wells sampled for coal analysis are highlighted by name.

True sedimentation rates cannot be determined because chronostratigraphic control is insufficient to determine the age range of the lower Mannville Group, and therefore we cannot conclusively estimate the duration of sedimentation. Distinctions between areas of high, low, and intermediate accommodation are therefore somewhat arbitrary, but we suggest that a reasonable classification scheme would indicate that areas of low accommodation have less than 60 m of lower Mannville Group stratal thickness; areas of intermediate accommodation have between 60 and 140 m; and areas of high accommodation have more than 140 m. This suggests that, although the study area lies within an intermediate position in the foreland basin, during lower Mannville deposition, it actually comprises an eastern region of low accommodation associated with the Hackett high (a paleotopographic high with a thick underlying Jurassic section), and a central region of intermediate-to-high accommodation associated with the Edmonton valley (Fig.1).

Sedimentation rates during the upper Mannville Group may well have been different than during the lower Mannville, but the analysis outlined above at least provides a general view of accommodation in the area. The distribution pattern of total cumulative coal from the upper Mannville Group and the time-equivalent Falher coal zone roughly follows this basinwide pattern of subsidence (Fig. 5), with the greatest thickness of coal (up to 16.5 m) occurring near the orogen, and the smallest occurring near the cratonic margin (Carmichael, 1983; Langenberg et al., 1997; c.f. Bohacs and Suter, 1997). Coal seams are thicker and more widely separated toward the orogen, whereas in Eastern Alberta they are thinner and partly eroded by extensive transgressions (Langenberg et al., 1997). However, in detail, the total coal distribution patterns do not correspond directly to the regional accommodation patterns indicated by the isopach map in Figure 1. Here the average value of total cumulative coal thickness ranges from 6–15 m, which is anomalously high considering its position in an overall low-to-intermediate accommodation setting.

An isopach map of the Mannville Group (from the relatively flat regional base of the overlying Joli Fou Formation to the top of the Paleozoic unconformity) in south-central Alberta

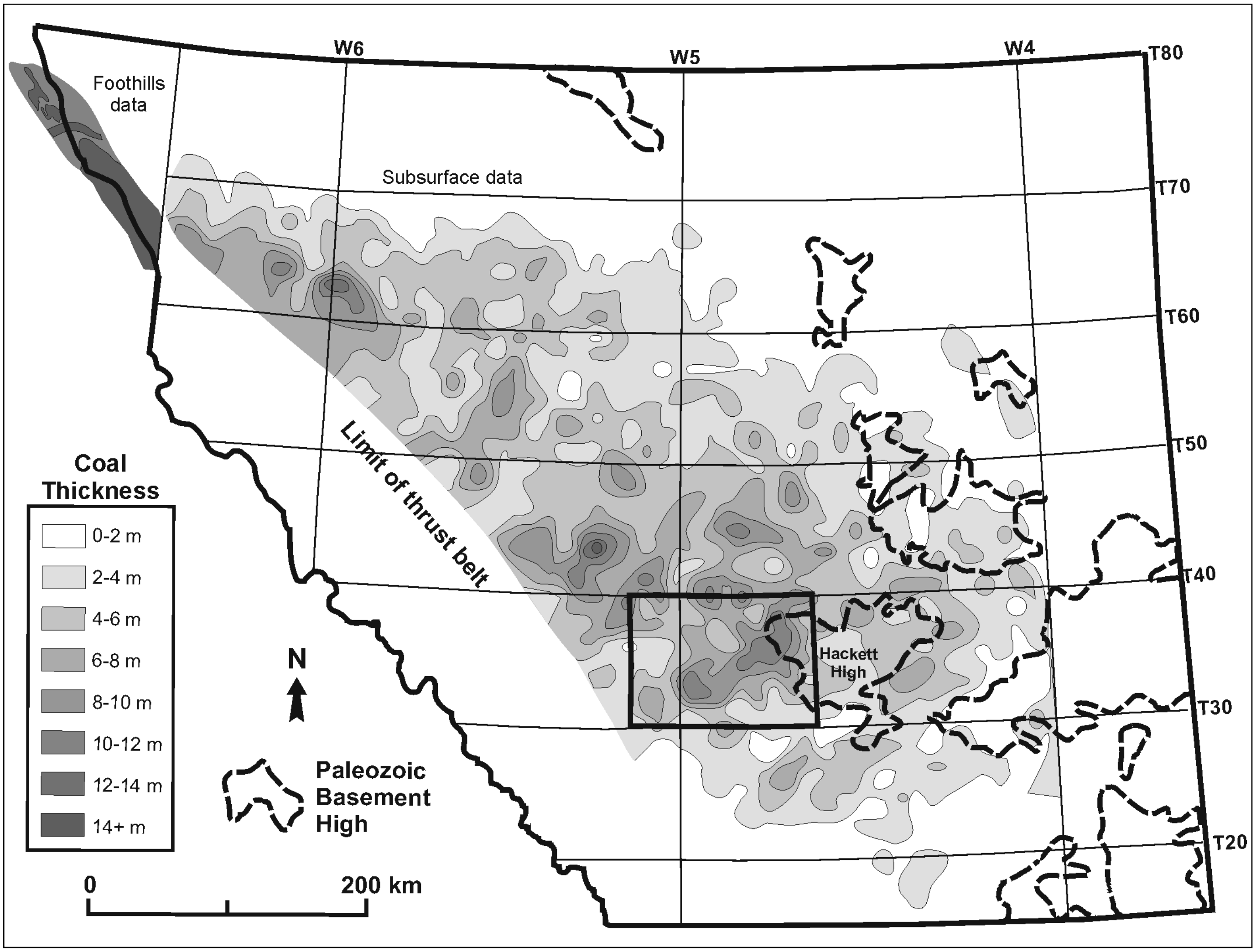


Fig. 5. Isopach map of the cumulative coal thickness of the upper Mannville/Falher/Gates coal-bearing strata (summarized from Carmichael, 1983; Leckie, 1986; Langenberg et al., 1997). Underlying Palaeozoic basement highs are shown in thick dotted outline.

provides a reasonable approximation of basement topography (Fig. 6), and can also be used to make gross generalizations about accommodation settings. The thickness of the Mannville Group varies from less than 60 m in the northeast above the Hackett high (i.e. low accommodation), to more than 240 m in the E–W and N–S trending erosional basement lows in the west (i.e. intermediate to high accommodation).

The Hackett high also influenced coal distribution patterns. A detailed isopach map of total cumulative coal (Fig. 7) was constructed by summing as many as six to eight distinct coal seams. Seams less than 0.3 m thick were not included. The minimum cumulative coal thickness is 1.5 m, the average is 6 m, and the maximum is 15.2 m. The thickest coal accumulations occur in the northern and central area. The thinnest coal accumulations occur in the southeast and west. A comparison of this map with the Mannville total cumulative coal map (Fig. 5) reveals that south-central Alberta contains some of the greatest coal reserves of the entire Mannville Group. A comparison of Figures 6 and 7 reveals that there is an inverse correlation between thickness of the cumulative coal and thickness of the Mannville Group, which in turn is directly related to Paleozoic basement topography. Maximum cumulative coal thickness occurs where the succession onlaps major paleotopographic highs. This may have been because these areas were subject to lesser amounts of differential compaction and subsidence, and as a result formed stable, raised coastal plain areas. Clastic sources would have been diverted away from these areas of slightly higher relief, and thick, laterally continuous peats would have been preferentially formed and preserved instead. An example of this style of fluvial diversion is reported from the Price River Formation in Utah (Guiseppe and Helley, 1998).

STRATIGRAPHY, FACIES ARCHITECTURE AND COAL DISTRIBUTION OF THE MANNVILLE GROUP IN SOUTH-CENTRAL ALBERTA

The sedimentological characteristics of the Mannville Group in this region have been investigated using 50 cores, mostly from the Ostracod Member and upper Mannville Group

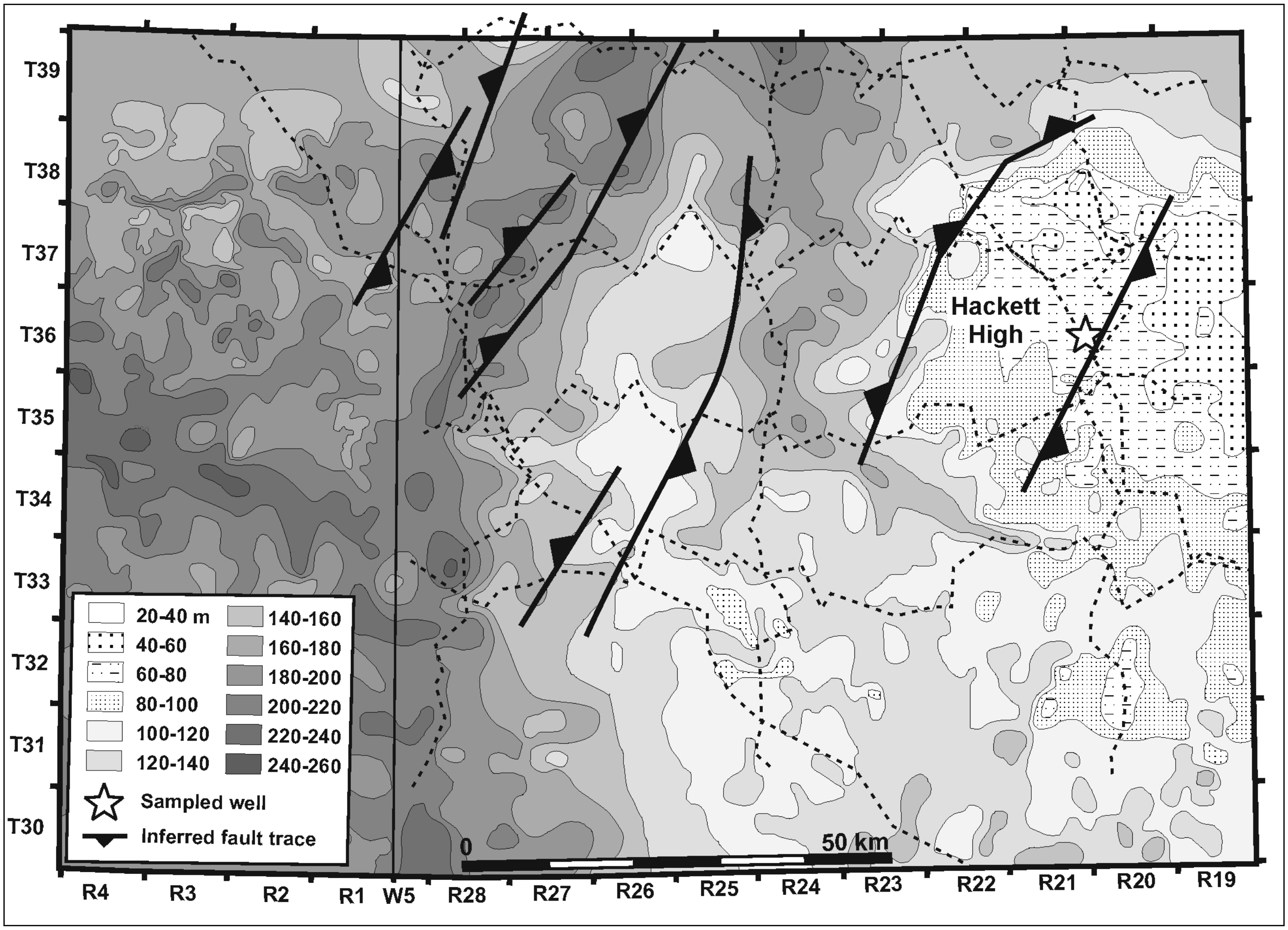


Fig. 6. Detailed isopach map of the Mannville Group in the Hackett high region, showing total thickness from top of Mannville to Paleozoic basement in metres. This map is based on an unpublished PanCanadian report by Leonhardt (1991), with the addition of our own data, for a total of approximately 2400 wells. It also shows the location of the Twp-Rng cross-section grid used in this study (dashed lines). Well 16-4-36-20W4, above the Hackett high, has been sampled for coal analysis (star). Thick black lines show the inferred location of basement fault planes (see discussion section).

between the Medicine River and Glauconite coal (which does not actually contain any glauconite). Eighteen of these cores are shown in the detailed core section (Fig. 8), which highlights the key stratigraphic relationships. The longest core (10-25-40-25W4) is illustrated in detail as a reference section (Fig. 9). Two regional cross-sections, 300 and 200 km long, together with a grid of seven shorter cross-sections, each approximately 100 km long (see Fig. 4), have been used as the basis for documenting and correlating the stratigraphy of the Mannville Group in south-central Alberta (Figs. 10-12). All of these diagrams are summary versions of more detailed cross-sections which were constructed using over 100 sets of gamma ray, resistivity and porosity logs. Cross-sections A–A′ and B–B′ (Fig. 10) are parallel, regional SE–NW trending cross-sections which span the length of the area, from the Hackett high to northwest of the Hoadley barrier. The northwestern half of cross-section A–A′ corresponds with the location of the detailed core section (Fig. 8). Cross-sections T39, T37, T35, T33, (Fig. 11) and R28, R24 and R20 (Fig. 12) are a detailed suite of E–W and N–S trending cross-sections, respectively, which focus in the area of thickest cumulative coal, immediately west of the Hackett high. Two very detailed cross-sections, which include the gamma ray and resistivity data, highlight portions of the R28 and R20 cross-sections (Figs. 13 and 14, respectively).

CHOICE OF DATUM

Traditionally, the Joli Fou flooding surface at the top of the Mannville Group is the stratigraphic datum used for the Mannville cross-sections. However, this datum is typically separated from the interval of interest by 80–180 m of upper Mannville strata, comprising variable amounts of coal, sandstone channel-fills and fine-grained strata, all of which have quite different compaction ratios, and therefore may distort the underlying stratigraphy and mask subtle stratigraphic

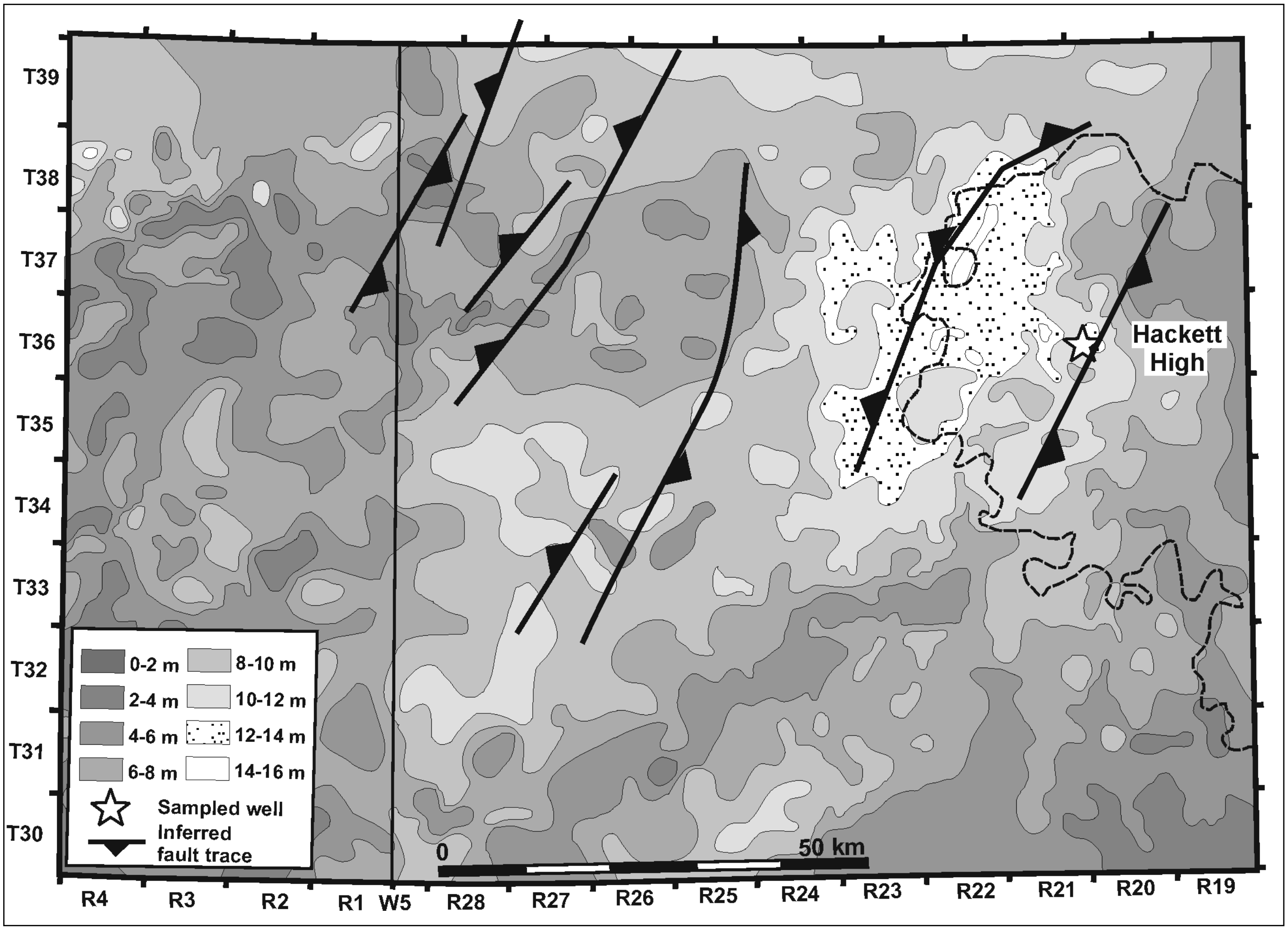


Fig. 7. Detailed isopach map of cumulative coal from the Mannville Group in the Hackett high region, based on unpublished PanCanadian report by Leonhardt (1991), with the addition of our own data (for a total of approximately 2400 wells). The dashed outline (the 120 m isopach taken from Fig. 6) shows the approximate outline of the Hackett high. Thick black lines show the inferred location of basement faults (see discussion section).

relationships. For example, any effects caused by syn-depositional differential subsidence may not be detected if the top Mannville was used as the datum. For this reason, the cross-sections have been constructed using the flooding surface that separates the uppermost Ostracod parasequence from the overlying regional lagoonal shale as a datum (Datum 1), because it is located much closer to the zone of interest. This surface is characterized by pebbles, *Glossifungites*, and is locally truncated by valleys (e.g. 7-21-43-26W4, Fig. 8), and it is therefore most likely a combined sequence boundary and flooding surface, rather than a simple flooding surface. Nonetheless, it appears to be a generally flat lying and regional surface. Towards the northwest (see Figs. 8, 10a, b) the uppermost Ostracod parasequence either pinches out or is eroded by surfaces associated with the Hoadley complex. In this case, the flooding surface on an underlying Ostracod parasequence is used as the alternative datum (Datum 2). Similarly, in some small areas above the Hackett high, where neither the lagoonal shale nor the Ostracod shorefaces are present, the base of the Medicine River coal is used as Datum 3 (Fig. 11).

Basement Influence on Stratigraphy

The Mannville strata in south-central Alberta are underlain by an irregular basement topography formed by Paleozoic limestone. Isopachs of the Mannville Group (Fig. 6) indicate the presence of basement topography, with the main areas of elevation and depression indicated on the summarized paleogeography map (Fig. 4). The cross-sections show a ‘mirror-image’ effect between the basement surface and the top of the Mannville surface. In areas where the top of Mannville is high relative to the datum, the basement is low, and in areas where the top of Mannville is low, the basement is high (Fig. 10 and T37, T35, T33 in Fig. 11). This effect is evident particularly across the margin of the Hackett high, and coincides with a number of other features, discussed below, which indicate a significant change in stratigraphic style from the southern side of the Hackett high to the northern side (around Well 18, Fig. 10a and Well 23, Fig. 10b). The margin of the Hackett high appears as a steep escarpment (Figs. 10a, b), however the slope is only 0.5º (e.g. a rise of approximately 100 m over a distance

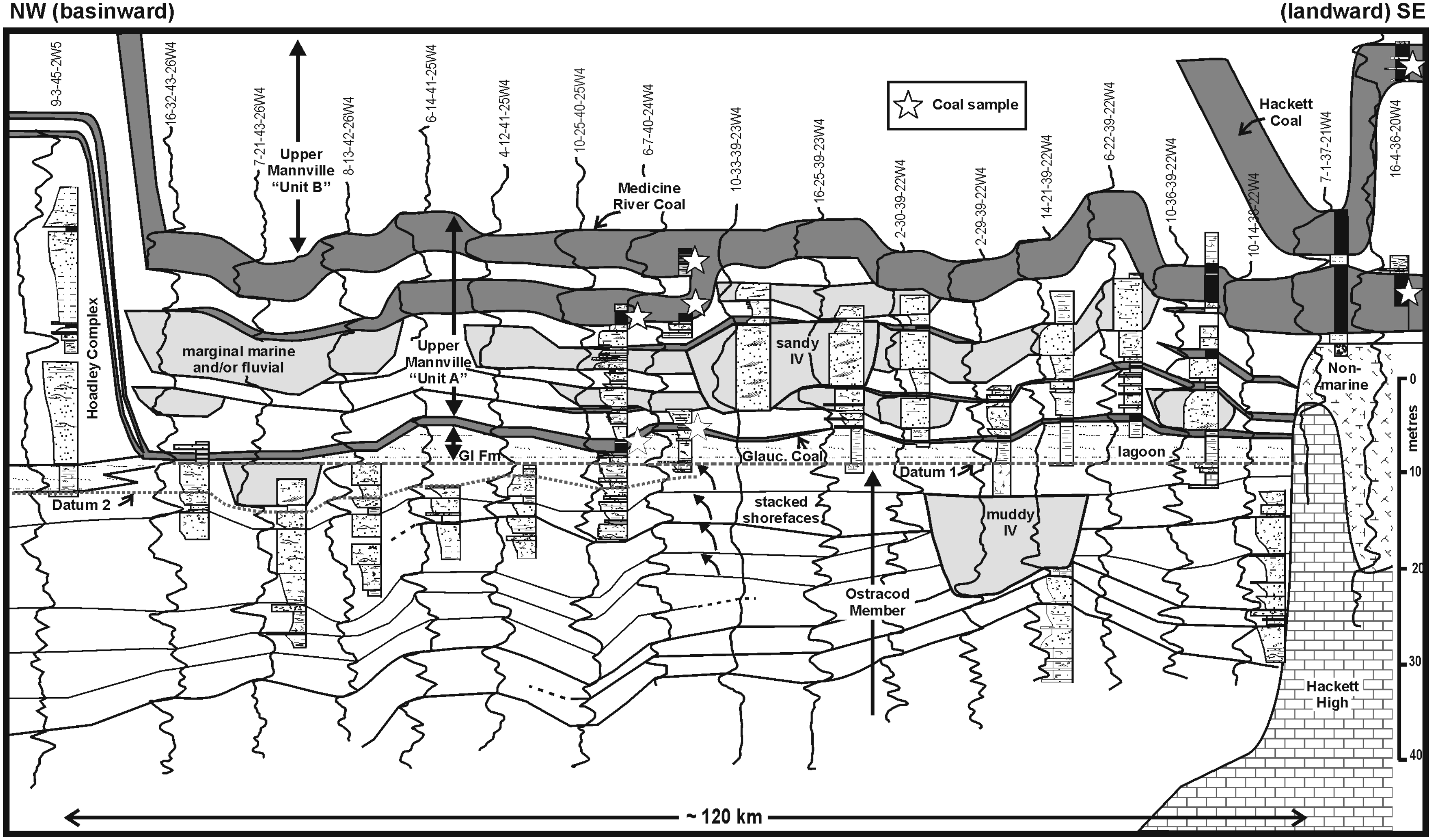


Fig. 8. Mannville Group detailed core cross-section (selected cores from the northwestern half of A–A′ regional cross-section; Fig. 4). Gamma log is shown. Datum 1 is the flooding surface on the uppermost Ostracod parasequence; Datum 2 is the flooding surface on an underlying Ostracod parasequence. This provides a different perspective of the stratigraphy than if the more traditionally-used base of Joli Fou Formation datum had been used, particularly in regards to the geometry of the Hoadley complex. Gl Fm is Glauconite Formation.

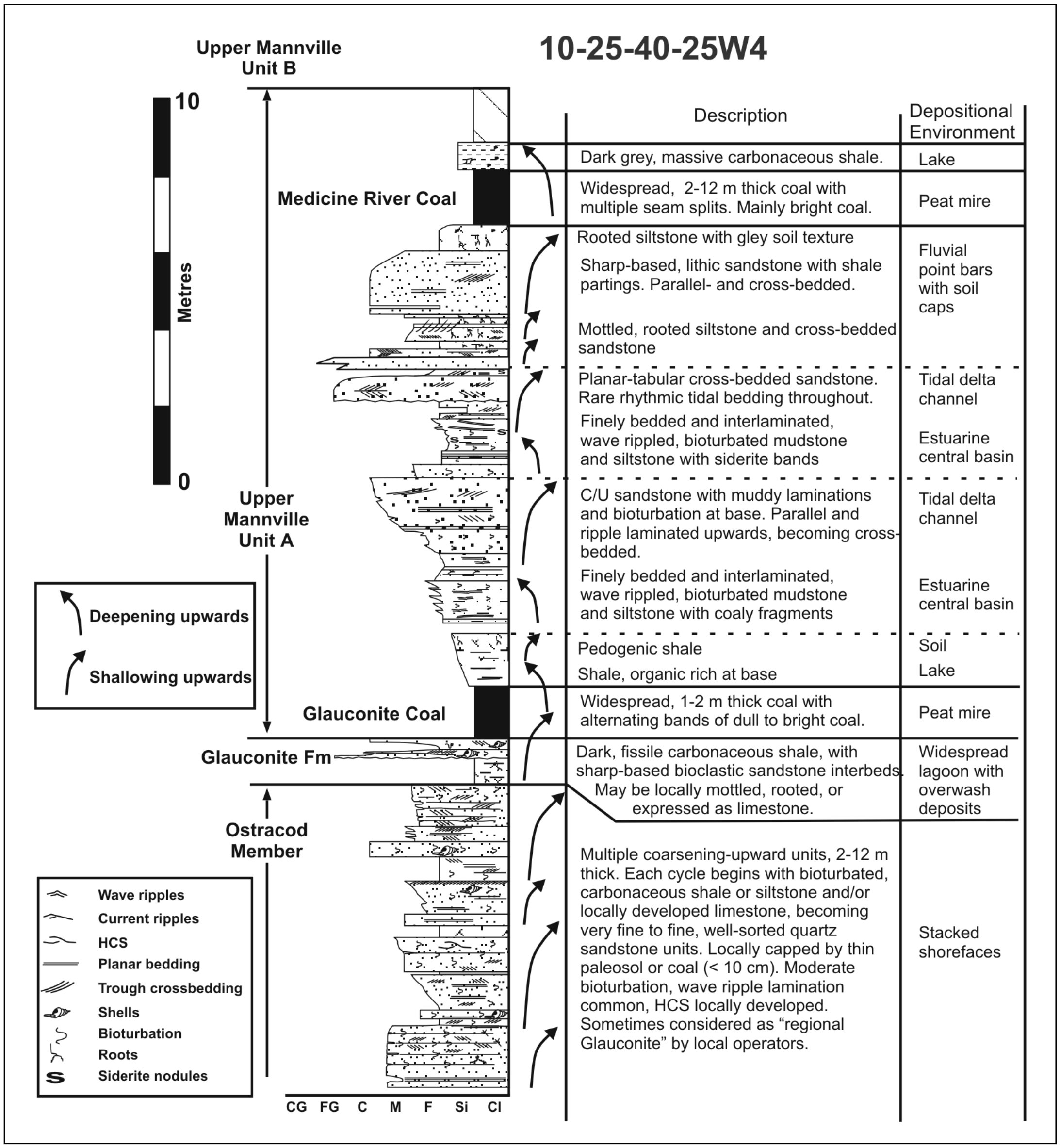


Fig. 9. Reference section well 10-25-40-25W4, located in Figure 4, and representative of the regional sedimentology (Fig. 8). In this well, the uppermost part of the Ostracod Member comprises stacked shorefaces and the Glauconite Formation is represented by a lagoonal shale. The rest of the upper Mannville Group, sometimes described as 'undifferentiated', comprises brackish bay, fluvial channel, and floodplain deposits, with coal seams. It is informally subdivided into Unit A, from the base of the Glauconite coal to top of Medicine River coal, and Unit B, from the top of Medicine River coal to top of upper Mannville Group. Based on facies characteristics alone, it is a fairly straightforward matter to subdivide the clastic sediments into deepening-upwards or shallowing-upwards packages, but it is not possible to similarly categorize the coals.

of 2 km from Wells 20 to 23, Fig. 10b). The top of the Hackett high has a slope of 0.03^{o} (e.g. a rise of 35 m over 60 km from Wells 19 to 29, Fig. 10a).

LOWER MANNVILLE GROUP

To the north and west of the study area, the lower Mannville Group is represented by the Ostracod and Ellerslie members, which cover basement topography, except where they onlap against the edges of the Hackett high (e.g. left-central part of Fig. 10a). The Ostracod Member consists of stacked, relatively thin, regionally extensive sandstone-dominated parasequences that disconformably overlie the Ellerslie Member. They are equivalent to the Medicine River sheet sands (Strobl, 1988) deposited following the first widespread transgression within the Mannville Group (McLean and Wall, 1981; Karvonen and Pemberton, 1997a). This mainly brackish water transgression flooded the Ellerslie landscape but did not completely submerge the pre-existing ridges of Devonian/Mississippian carbonates (Banerjee and Kidwell, 1991; McPhee, 1994; Holmden et al., 1997; Zaitlin et al., 2002). As a result, the Ostracod strata formed in separate sub-basins. Within the study area, the Ostracod Member is approximately 25 to 40 m thick, and

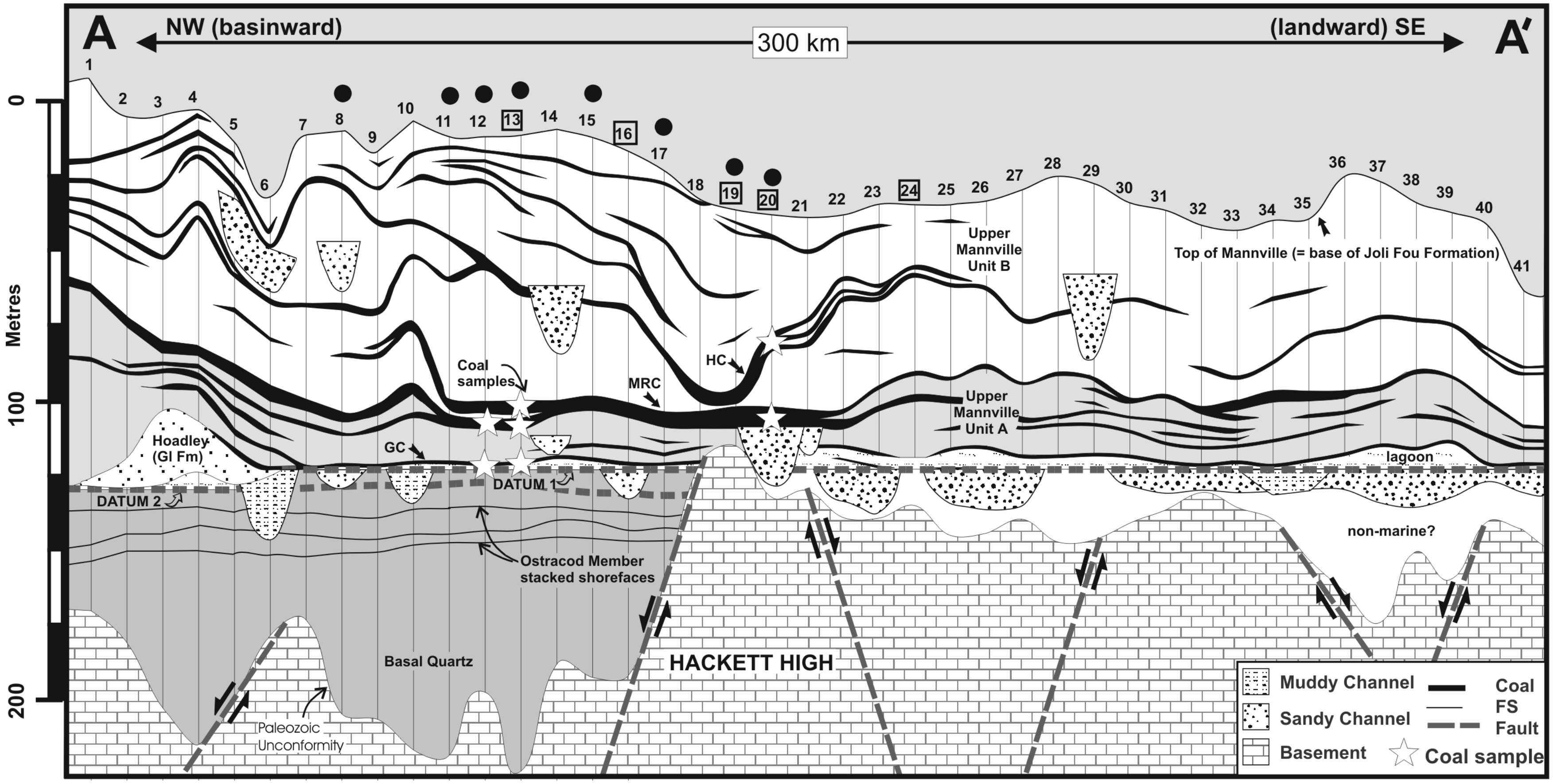


Fig. 10. (a) Schematic cross-section A–A′ and **(b)** cross-section B–B′, based on original cross-sections with over 100 pairs of gamma and resistivity wireline logs each (see location on map, Fig. 4). Datum 1 and Datum 2 are highlighted by gray dashed lines. Well names are listed in Appendix 1. Boxes around well-locations indicate tie-points with other cross-sections, and wells highlighted by black circles correspond to some of those in Figure 8. Wells are spaced from 5 to 10 km apart. Numbers 1–8 in (b) refer to the number of individual seam splits identified in the Medicine River coal (MC). Muddy and sandy channels are identified based on well log signatures alone; some of these may be incised valleys. GC = Glauconite coal, MC = Medicine River coal, HC = Hackett coal, Gl Fm = Glauconite Formation.

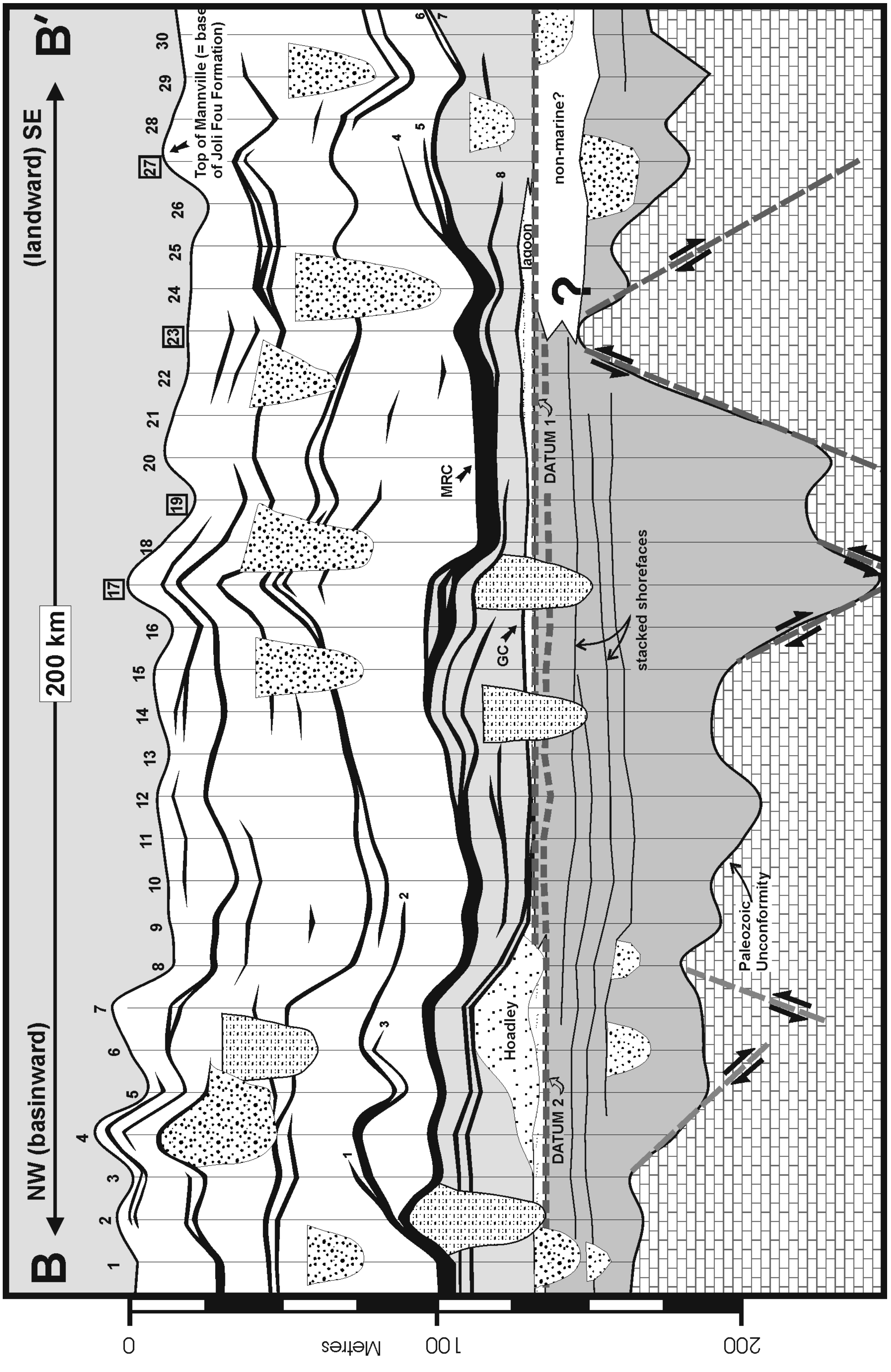
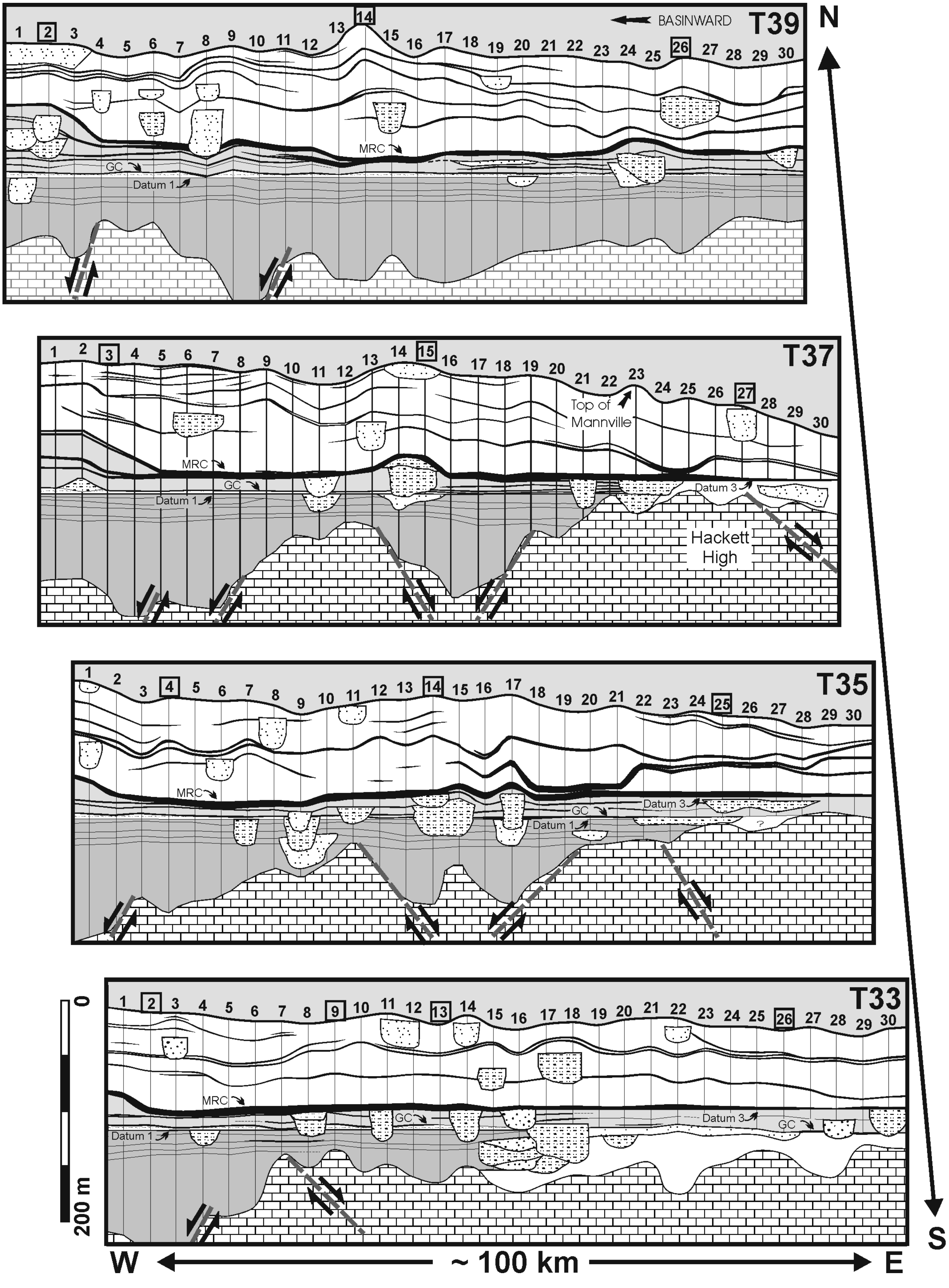

B
NW (basinward)
200 km
(landward) SE
B′
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Top of Mannville (= base of Joli Fou Formation)
1
2
3
4
5
6
7
8
MRC
GC
Hoadley
DATUM 2
DATUM 1
lagoon
?
non-marine?
stacked shorefaces
Paleozoic Unconformity
0
100
200
Metres

Fig. 10b.


T39
BASINWARD
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
MRC
GC
Datum 1
T37
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Top of Mannville
MRC
GC
Datum 1
Datum 3
Hackett High
T35
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
MRC
GC
Datum 3
Datum 1
?
T33
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
MRC
GC
Datum 1
Datum 3
GC
0
200 m
N
S
W
~ 100 km
E

consists of at least ten widespread, stacked brackish lacustrine and restricted marine shoreface parasequences (Fig. 8.) Only one of these parasequences contains any evidence of coal (western part of T33; Fig. 11). All parasequences are capped by flooding surfaces that approximately parallel the datums.

To the south and east of the Hackett high, the lower Mannville Group is represented by the Basal Quartz Member (Zaitlin et al., 2002), which is older than the Ostracod and Ellerslie members. These strata overlie the areas of highest basement topography (i.e. elevated portions of the Hackett high). They show a highly variable well-log signature that is difficult to correlate (e.g. 7-1-37-21 W4 and 16-4-36-20W4 in Fig. 8), comprising a mixture of sharp-based, low gamma ray signatures indicating sandy channel fills, and ragged, high gamma signatures suggestive of floodplain sediments.

THE GLAUCONITE FORMATION (UPPER MANNVILLE GROUP)

The Glauconite Formation comprises a northwest thickening clastic wedge that can be subdivided into a number of transgressive–regressive cycles of shoreline and shelf strata (Chiang, 1985; Rosenthal, 1988; Strobl, 1988; Leckie and Smith, 1992). These can be linked updip to fluvial-estuarine valley fills (Wood and Hopkins, 1992; Sherwin, 1994; Broger et al., 1997; Karvonen and Pemberton, 1997b). The Hoadley Barrier complex in the northwest (Fig. 4; Fig. 8, 9-3-45-2W4) comprises at least two stacked regressive marine successions (the Glauconite-B sandstone), and has an unusual mound-like geometry in our cross-sections (Fig. 10), because we have used an underlying, rather than an overlying, datum. The Hoadley complex overlies a widespread shale unit (1–8 m thick) called the 'B-marker shale' representing a major advance of the Clearwater sea (Rosenthal, 1988). In these cross-sections, this shale has a distinctive high gamma signature and lies above the Ostracod Member and below the Glauconite coal (Fig. 9). It is interpreted as a back barrier lagoon deposit with locally developed overwash deposits, which developed behind a transgressive barrier island system located near the southern margin of the Hoadley-Strachan trend (Rosenthal, 1988). Toward the southeast, above the Hackett high, the lagoon pinches out (e.g. Well 27, Fig. 10b). This unit overlies both datum 1 and 2.

UNDIFFERENTIATED UPPER MANNVILLE GROUP

This unit extends from the base of the Glauconite coal to the base of the Joli Fou Formation (Fig. 3). It is 80 to 180 m thick, and has no regionally correlative beds, other than the abundant coal seams and so has been termed 'undifferientiated' in the literature. We informally subdivide these strata into the upper Mannville Unit A and Unit B (Fig. 9).

The upper Mannville Unit A comprises the interval from the base of the Glauconite Coal to the top of the Medicine River coal. The Glauconite coal is the lowermost regionally extensive coal developed in the area. It overlies the lagoon shale and shows a remarkably uniform geometry over a great distance (1–2 m thickness over at least 250 km in a NE–SW direction; Fig. 10a). No seam splits are evident except above the Hoadley Complex, where at least two separate seams occur which thin and disappear farther northwest (left hand sides of Figs. 10a, b). The Glauconite coal also disappears towards the southeast, either onlapping against the Hackett high (e.g. Well 9 in R20, Fig. 12) or thinning and becoming patchy and laterally discontinuous above it (e.g. Well 26, Fig. 10b).

Strata between the Glauconite and Medicine River coals are 8 to 60 m thick (Fig. 8) and consists of shallowing-upwards cycles (Fig. 9) of brackish, marginal marine deposits to non-marine deposits (Wightman et al., 1987). Correlation of these cycles over distances greater than 20–30 km is generally difficult, except where thin, patchy, capping coals can be recognized (Fig. 8). At least eight of these coals correlate into the Medicine River coal (e.g. Fig. 10a and left-central and right part of Fig. 10b), the thickest and most complex of all the Upper Mannville coals (Banerjee et al., 1996). Seam amalgamation occurs toward the southeast and northwest (e.g. Well 29 and Well 33, Fig. 10a). The Medicine River coal is thickest and most amalgamated above and northwest of the crest of the Hackett high (Well 19, Fig. 10a), where it is up to 10 m thick. This relationship is repeated with total cumulative coal thickness also greatest in the area northwest of the Hackett high (Fig. 7). Elsewhere, the patchy Unit A seams are vertically stacked (e.g. left half of Fig. 10a; left-central part of Fig. 10b; left half of T39, Fig. 11), and may indicate locally enhanced subsidence.

The upper Mannville Unit B (from the top of the Medicine River coal to the base of the Joli Fou Formation; Fig. 8) is thought to be uneconomic and is generally not cored, but the well log signature indicates dominantly fine-grained strata, interpreted as non-marine. Unit B is 50 to 120 m thick and contains the next significant amalgamated coal above the Medicine River coal, which has not been formally named, and is informally designated here as the Hackett coal (sampled in 16-4-36-20W4, Fig. 14). Like the Medicine River coal, this seam is thickest above and adjacent to the flank of the Hackett high, but is not as laterally extensive (e.g. it is developed in cross-section A–A′ but not B–B′). Other coals in Unit B are thin, patchy, and

Fig. 11. T33 to T39 are west (W) to east (E) cross-sections through the south-central Alberta area, spaced approximately 20 km apart (see Fig. 4 for locations and Fig. 12 for key). Well names are listed in Appendix 1; boxes around well locations indicate tie-points with other cross-sections. Wells are spaced 2 to 4 km apart. The basement topography is highly irregular, with the highest relief in the eastern part of T35 and T37, over the Hackett high. There is a well-developed 'mirror-image' pattern between the irregular basement and the Joli Fou flooding surface particularly in T33, T35 and T37. The lower Mannville Group blankets the Paleozoic basement and onlaps the Hackett high towards the east, except in T39 (which does not cross the Hackett high). The Glauconite coal (GC) is a thin, single and widespread seam which becomes patchy or absent over the Hackett high. The Medicine River coal (MRC) is the most thickly developed coal in all sections, and is characterized by multiple seam splits. Suggested locations for basement faults are indicated by dashed lines; see discussion section for more details.

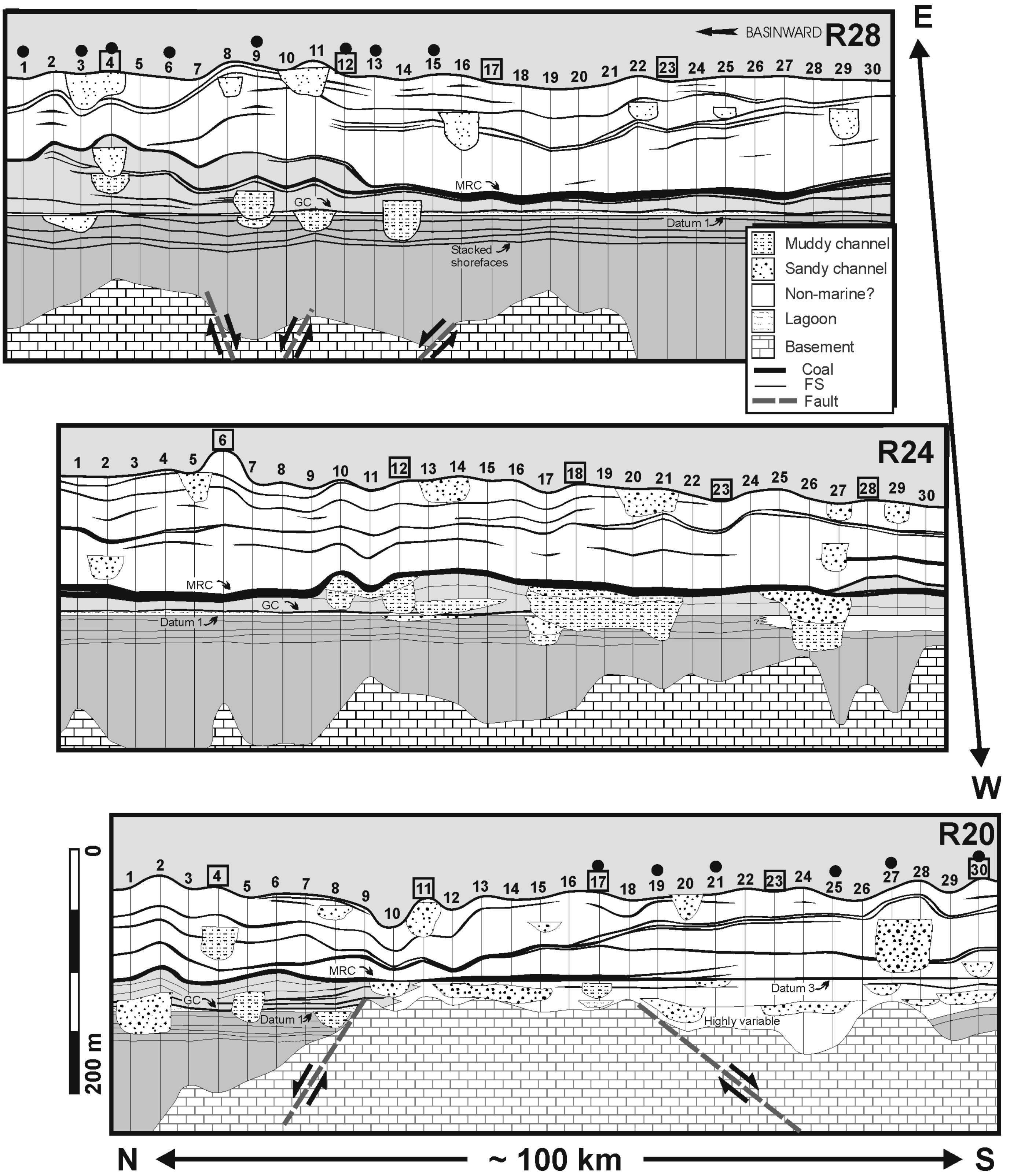


Fig. 12. R20 to R28 are north (N) to south (S) cross-sections spaced approximately 40 km apart (see Fig. 4 for locations), with wells spaced from 2 to 4 km apart. Well names are listed in Appendix 1; boxes around well locations indicate tie-points with other cross-sections, and wells highlighted by black circles correspond to some of those in Figures 13 and 14. The cross-sections show: an irregular basement topography which is mirrored by the Joli Fou flooding surface, widespread development of the Glauconite coal (but not above the Hackett high), patchy thin coals in the upper Mannville A Unit, widespread development of the thick, complex and amalgamated Medicine River coal, and moderately widespread development of the overlying coals. Suggested locations for basement faults are indicated by dashed lines; see discussion section for more details.

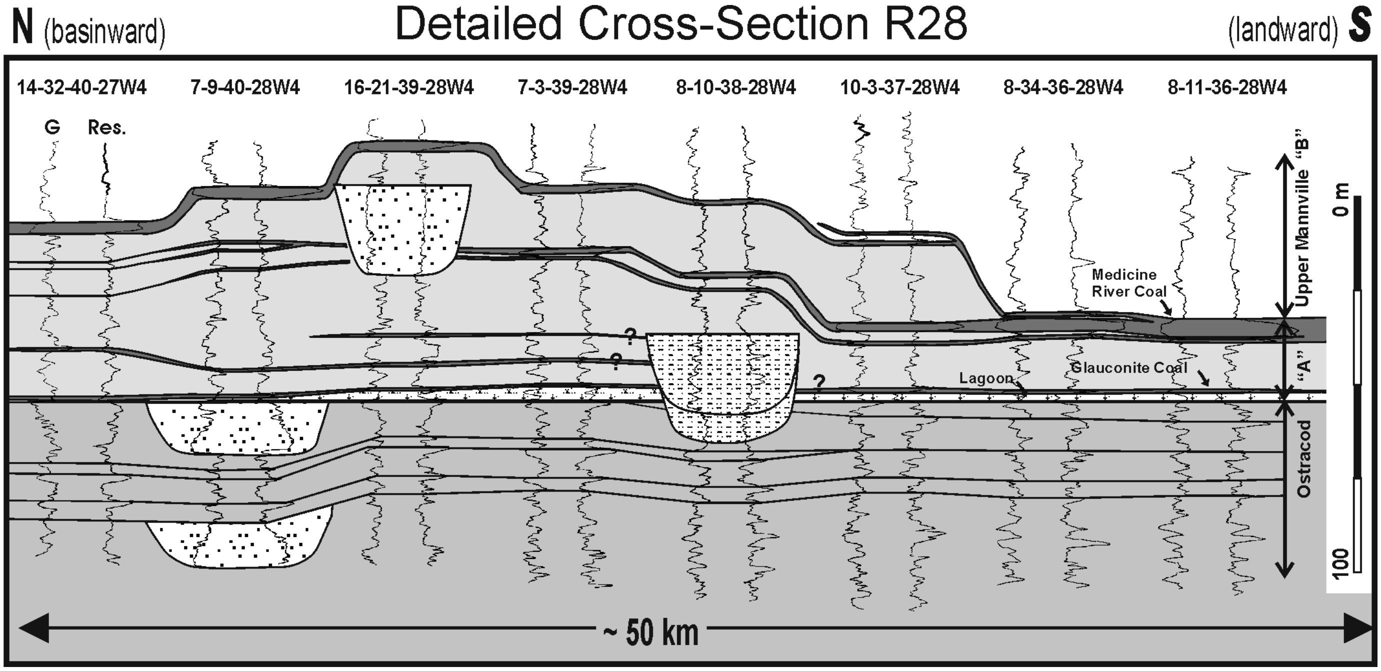


Fig. 13. Detailed view of cross-section R28, with gamma (G) and resistivity (Res.) logs shown for each well. This section contains a deep, sand-filled channel between two split seams (16-21-39-28W4) that merge northwards to become the compound Medicine River coal at 8-11-36-28W4. The thickness and erosiveness of this channel suggests that it may be an incised valley, in which case its position between two split seams indicates that a sequence boundary must exist within the amalgamated parent coal seam.

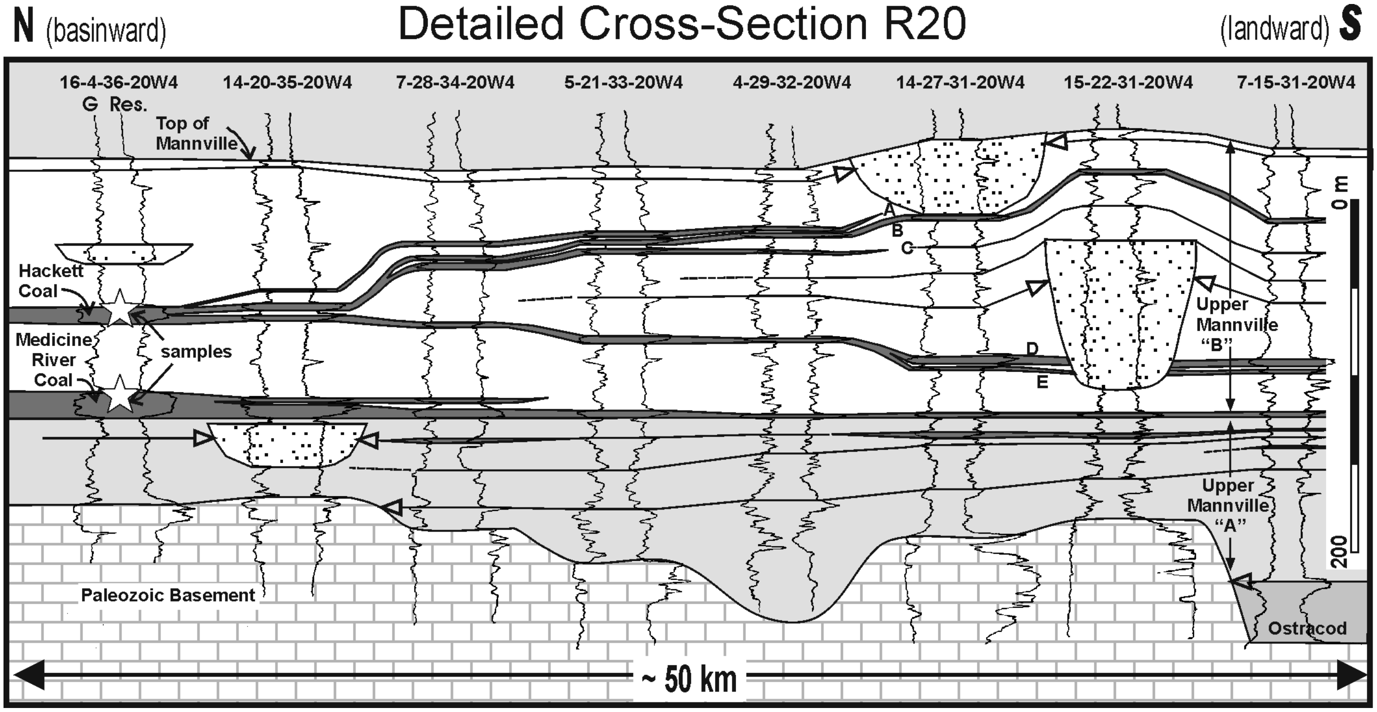


Fig. 14. Detailed view of cross-section R20 with gamma (G) and resistivity (Res.) logs shown for each well. A thick, sand-filled channel (15-22-31-20W4) which is potentially an incised valley, occurs between two split seams of the Hackett coal. This suggests that a sequence boundary may exist within the amalgamated parent coal seam (e.g. 16-4-36-20W4).

also show evidence of seam splitting. The total number of coal seams in Unit B is greatest to the north and west of the Hackett high (Fig. 10a). Most of these seams are fairly thin (1–4 m thickness) and have a patchy distribution.

INCISED VALLEYS

Channel-like features, from 10 to 90 m thick, are identified from well logs at various stratigraphic levels. In the Ostracod Member and upper Mannville Unit A they occur as both sandstone-filled and mudstone-filled successions that incised typically in shoreface strata and are capped by a parasequence flooding surface (e.g. 7-21-43-26W4 and 2-29-39-22W4, Fig. 8). Some of these channels have been interpreted as multiple generations of incised valleys, with each generation having a distinct mineralogical character (Wood, 1996; Karvonen and Pemberton, 1997a, b; Broger et al., 1997). In the non-marine upper Mannville Unit B strata, valley fills are generally only recognizable when they are sandstone-filled, due to the heterolithic nature of the surrounding strata. Lack of core means that no sedimentological evidence, such as the presence of thick interfluve paleosols, is available to determine whether they are simple fluvial channels or incised valleys associated with relative sea level fall. However, evidence based purely on wireline logs includes the following: 1) regional markers that terminate against channel margins, with no suggestion of overbank deposits, 2) underlying coal seams that are truncated by channels, indicating significant erosion, and 3) remarkably thick sandstone-bodies that suggest a compound channel. In some localities, the valleys occur as stacked clusters at multiple stratigraphic levels (e.g. central part of T33, T35, T37 cross-sections; Fig. 11), often above areas where the basement topography shows an abrupt change in gradient.

The Medicine River coal contains deep valleys between seam splits, as illustrated in the western edge of T39 and central part of T35 (Fig. 11), and in R20 and R28 (Fig. 12). If these are truly incised valleys, and therefore overlie sequence boundaries, this indicates that the Medicine River coal must span several accommodation cycles. This relationship is apparent in Figure 13, where a detailed close-up of cross-section R28 illustrates a 38 m thick sandstone-filled valley (16-21-39-28W4) between two sub-seams of the Medicine River coal, which merge toward the south. Similarly, the Hackett coal also contains incised valleys between the seam splits (Fig. 14). In well 15-22-31-20W4, a 90 m thick sand-filled valley is located between two sub-seams that merge northwards.

COAL ANALYSIS

Detailed photometric and maceral analysis were undertaken in three separate coal seams; the thin, simple and widespread Glauconite coal, and the more complex and amalgamated Medicine River and Hackett coals. The coal samples were obtained from three locations (10-25-40-25W4, 6-7-40-24W4 and 16-4-36-20W4) as indicated in Figure 15, and coal signature diagrams were constructed for each (Fig. 16). These diagrams are based on the coal compositional analysis (see Fig. 16a and Appendix 2 for details of analysis) that provides an indication of balanced and unbalanced accommodation/peat-accumulation ratios. In most cases, the coal was only partially recovered during coring, and either the bottom or top part of the seam was lost. In these cases, the total thickness of the seam is estimated from geophysical well logs. The aim of this analysis was to identify accommodation trends in the coals which, combined with the stratigraphic insights outlined in the previous section, can provide key information to develop sequence stratigraphic interpretations of the continental sediments.

The Glauconite coal has been sampled at two locations, and core recovery at both sites was nearly complete (Fig. 15). The coal property signature diagrams (Figs. 16b, c) show strong similarities. Both seams contain very little pure coal but mostly consist of high-ash coal, shaley coal, coaly shale and cannel shale. This combination suggests that peat-forming conditions were generally unfavourable due to high accommodation rates that caused frequent submergence of the mire. The basinward seam (10-25-40-25W4; Fig. 15) contains more cycles than the landward seam (6-7-40-24W4), but in both cases the coal consists of a basal terrestrialization surface overlain by drying-upwards cycles (i.e. a regressive-style coal), followed by an accommodation reversal surface (ARS) which is in turn overlain by wetting-up cycles (i.e. a transgressive-style coal). In both cases, a non-marine flooding surface (NFS) occurs at the base of the second cycle, beneath a regionally correlatable silt-laminated, burrowed, dark shale. Two give-up transgressive surfaces (GUTS) are present in the top part of the basinward coal, whereas only one GUTS is evident in the landward coal.

The Medicine River coal is similar to the Hackett coal in that stratigraphic evidence suggests that it should also contain at least one internal sequence boundary, corresponding to the base of an incised valley contained within the interseam strata (Fig. 13). Although the seam has been sampled in three locations including both amalgamated and sub-seams (Fig. 15), core recovery was poor and only partial samples were obtained. The basal part of the Medicine River coal has been analyzed at two sites, both of which occur in a bottom sub-seam (Fig. 15). In both cases core was missing, and the results of analysis are therefore somewhat ambiguous. The more distal site (10-25-40-25W4) shows a transgressive-style low-ash coal lying above a grey seat earth containing some pyrite. The coal is initiated by a paludification surface (Fig. 16d) and comprises five units, each characterized by an upwards increase in accommodation. The uppermost unit is followed by a GUTS, above which the roof is represented by a 58 cm thick dark-grey mudstone containing plant leaves. According to the electric log, it should be followed by another 2.4 m of overlying coal that is now missing. In contrast is the more proximal site 6-7-40-24W (Fig. 16e). Above this are two units characterized by drying-upward cycles of decreasing accommodation. It is unclear how the seam was terminated (i.e. NFS or GUTS) because the rest of the coal is missing (according to the electric log, core loss is approximately 2.5 m of clean coal). These

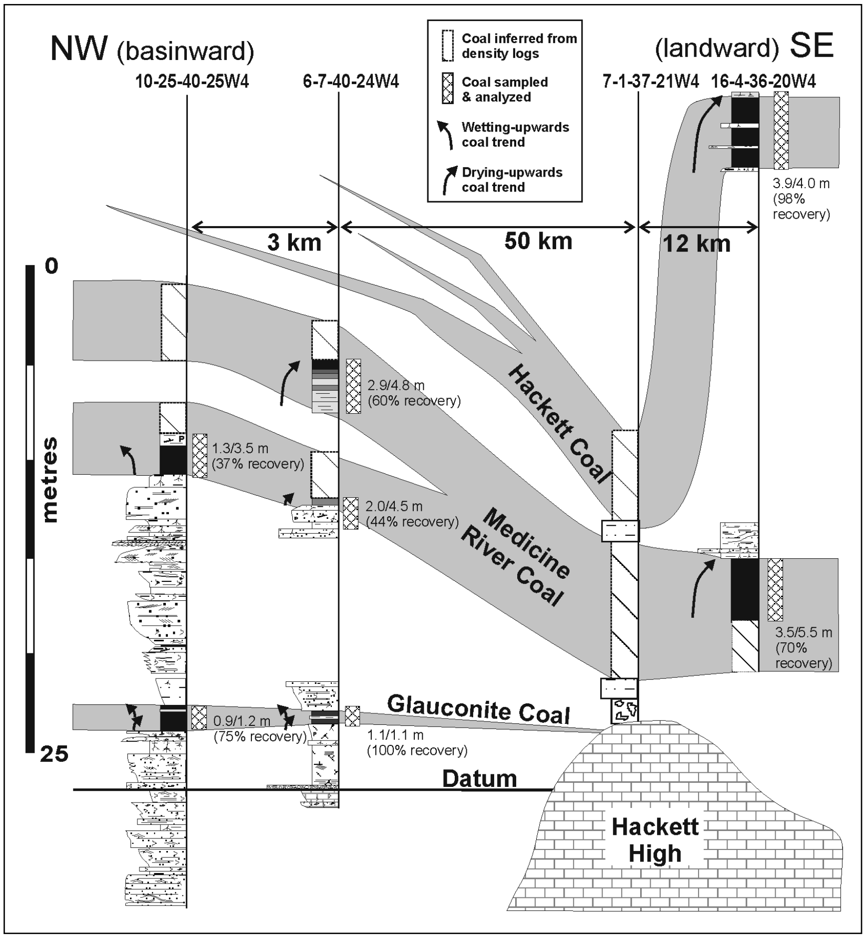


Fig. 15. Location of coal samples and their relative distances from each other, also shown in Fig. 4. Ratio of coal recovered to total amount of coal as indicated by wireline logs is shown next to each sample. Two samples of the Glauconite coal were analyzed, both with nearly full coverage of the seam. The Medicine River coal was typically destroyed during coring and only partial seam thicknesses were available for analysis. Only one sample from the Hackett seam was analyzed, but with nearly full recovery.

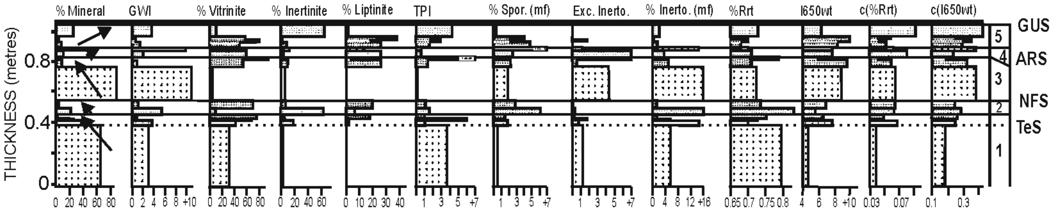
conflicting coal property signatures are difficult to interpret, and, considering the poor core recovery in this zone, we suggest that these two coal samples do not actually correlate, in a similar fashion to that shown by Chalmers (2001).

The Medicine River upper sub-seam has also been analyzed in two locations (Fig. 15). The basal 2 m of coal are missing from the sample in 16-4-36-20W4 (top 3. 5 m of core recovered out of a total seam thickness of 5.5 m). The available core shows a cannel coal of lacustrine origin (i.e. an internal seam split), initiated by a terrestrialization surface (Fig. 16f). The rest of the seam consists of clean coal that has been divided into five drying-upwards units, each terminated by a flooding horizon. Only two of these flooding horizons have been deemed to have regional significance; NFS1 correlates with a seam split and NFS2 marks the seam roof. The more distal seam in 6-7-40-24W4 (Fig. 16g) also begins with a terrestrialization surface and consists of three units which represent upward shallowing cycles of decreasing accommodation. It is unclear how the seam was terminated (i.e. NFS or GUTS) because the upper part of the seam (approximately 2 m) is missing.

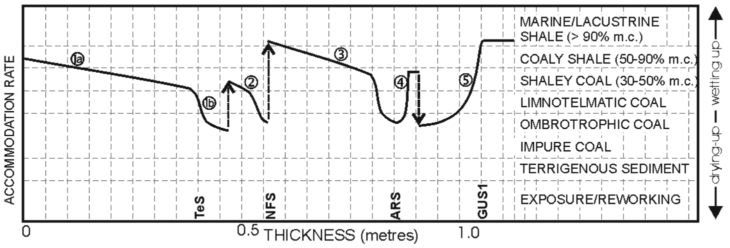
Due to poor recovery, and because the 6-7-40-24W4 seam (Fig. 16g) is a sub-seam whereas the 16-4-36-20W4 (Fig. 16f) seam is an amalgamated parent seam, it is not possible to say that they unequivocally represent the same peat body. However, both samples are characterized by drying-upwards cycles indicating an overall regressive-style coal, suggesting a degree of correlation. The more proximal core (16-4-36-20W4) contains more cycles than the distal core, but this may be due to recovery factors. Nonetheless, this coal shows a progradational development style similar to the Hackett coal, characterized by multiple drying-upwards cycles, each abruptly terminated by a hiatal surface. Fusain bands, representing zones of peat exposure and fire, are also present (Scott, 2000). One or more of these may represent a sequence boundary; otherwise there is no petrographic indication that a sequence boundary existed.

The Hackett coal has been sampled in well 16-4-36-20W4, and as indicated in Figure 15, recovery of the coal was almost total (3.9 out of 4 m). This location is above the margin of the Hackett high (Fig. 10a). The seam splits towards the southeast and merges towards the northwest, before splitting again. The

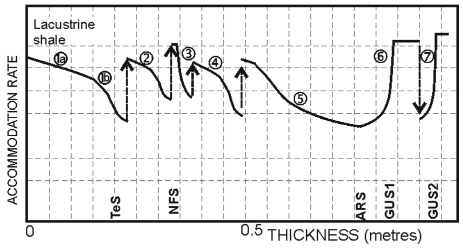
(a) Petrographic analysis details of Glauconite Coal 6-7-40-24W4 (proximal)



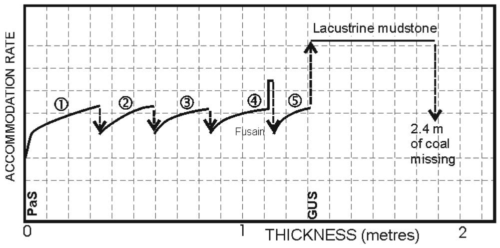
(b) Glauconite Coal 6-7-40-24W4 (proximal)



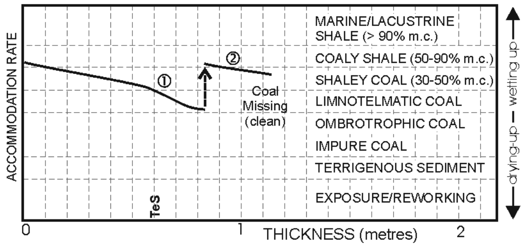
(c) Glauconite Coal 10-25-40-25W4 (distal)



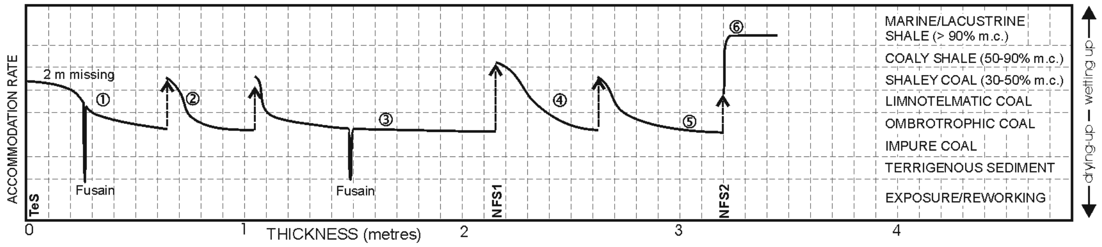
(d) Lower Medicine River Coal 10-25-40-25W4 (distal)



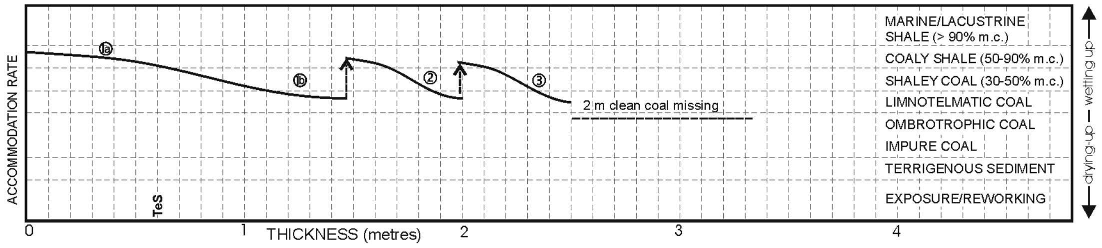
(e) Lower Medicine River Coal 6-7-40-24W4 (proximal)



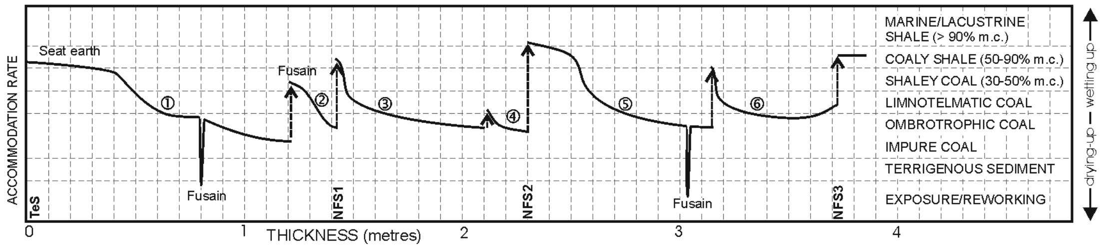
(f) Upper Medicine River Coal 16-4-36-20W4 (proximal)



(g) Upper Medicine River Coal 6-7-40-24W4 (distal)



(h) Hackett Coal (16-4-36-20W4)



coal signature diagram (Fig. 16h) reveals a relatively clean coal, mostly of raised-mire origin, initiated by a terrestrialization surface (TeS). It can be subdivided into at least six cycles, all of which show a drying-upwards pattern which is abruptly terminated by an increase in accommodation. Three of these upward-increases in accommodation are of sufficient magnitude to be termed non-marine flooding surfaces (NFS 1–3). Towards the south the Hackett coal splits into 5 sub-seams labelled A–E (Fig. 14). Each interseam area may be equivalent to one of the hiatal gaps within the sampled coal seam, corresponding to the boundary of a drying-upward coal subcycle. Figure 14 also shows an deep channel, which is possibly an incised valley, sitting in the interseam sediments of the Hackett coal. There is no obvious indication of a sequence boundary in the coal signature diagram of the Hackett coal (Fig.16g). Four possible explanations could account for this: (1) the sampling density (one sample every two to five centimetres) may not have been sufficient to pick up any indicators of a major decrease in accommodation; (2) the missing 10 cm core may contain evidence for a sequence boundary; (3) the sequence boundary may be represented by one of the fusain bands (peat exposure and fire) in units 1, 2 or 5, and therefore has no distinctive signature; or (4) the sequence boundary may be a composite surface with a non-marine flooding surface.

Discussion

The documentation of coal properties and detailed stratigraphic correlations presented above provide a fresh insight into the sequence stratigraphic behavior of coal-bearing non-marine sediments in the intermediate accommodation setting of the central WCSB. A number of features characterize the presence of intermediate accommodation over multiple sequences and long time intervals in this basin. The presence of coal seams such as the Glauconite, Medicine River and Hackett coals is in itself indicative of intermediate accommodation (Boyd and Diessel, 1995; Bohacs and Suter, 1997; Boyd et al., 2000). In lower accommodation settings (such as those more proximal to the craton or hinge line), groundwater tables are not high enough to preserve organic matter, resulting in soil profiles with rooted horizons. In higher accommodation situations, nearer the thrust belt, peat growth is unable to keep pace with the rising water table, and instead of coal seams, wet floodplain and lacustrine sediments form. The presence of incised valleys containing over 50 m of sandy strata within lateral splits of a coal seam points to the presence of unconformities within individual coal seams (c.f. Diessel, 1998; Holdgate et al., 2000). This in turn provides a second characteristic of intermediate accommodation settings: the occurrence of compound coal seams made up from multiple periods of peat accumulation.

Similarly, the possible presence of abundant incised valleys (as shown on Figs. 8, 10–14) is a third characteristic of relatively low to intermediate accommodation in this interval of the WCSB. River channels incise and form valleys in response to increased discharge or reduction in sediment volume or grain size (see Blum and Törnquist, 2000). These parameters in turn may relate to changes in base level associated with tectonic, climatic or eustatic factors. Lower accommodation such as in the underlying Basal Quartz Formation (Zaitlin et al., 2002) or time equivalent strata in southern Saskatchewan (Leckie et al., 1997) favours the preservation of strata inside valleys and relatively little sediment accumulation on adjacent interfluves. In the Saskatchewan example, much of the Lower Cretaceous sedimentation was confined entirely within large valley systems. Intermediate accommodation areas such as that seen in south-central Alberta, exhibit a more even distribution of strata between incised valleys and adjacent intervalley areas, but fluvial strata are rare outside the incised valleys. There appears to be a regional change in depositional style across the basin: in the cratonic southeastern margin of the basin, abundant incised valleys that contain most of the stratigraphic record occur; in central Alberta, a more even distribution of sedimentation occurs between incised valleys and intervalley areas; and in northern Alberta and northeastern British Columbia, few incised valleys occur in the time equivalent Falher/Gates interval (Casas and Walker, 1997).

The lack of accommodation in low to intermediate accommodation settings results in underlying structures and paleotopography exerting prolonged control on the site of deposition. A common expression of this control is to localize channels and valleys along structural or topographic lineaments, and to promote valley re-incision during subsequent cycles. Regional mapping of structural features, isopach anomalies, and coal geometry are used to interpret the depositional history of the Mannville Group and influence of underlying Paleozoic features. This topic will be discussed in more detail in the following section.

Influence of Basement Topography on Coal Distribution: an Indication of Fault Reactivation

Many of the stratigraphic features observed in the cross-sections (Figs. 10–14) indicate that the region has experienced differential subsidence related to Paleozoic basement topography.

Fig. 16. Petrographic analysis of coal is used to develop a coal seam signature. Compare **(a)** petrographic details of Glauconite coal from 6-7-40-24W4 with **(b)** the coal signature diagram constructed from this data. The petrographic data have been used to divide the coal seams into subunits (shown by number in circle) that have either wetting-upwards or drying-upwards characteristics, caused by small changes in accommodation which affected the AR/PPR. The thickness of the coal unit is plotted against the interpreted coal facies change. Drying-upwards cycles typically grade from coaly shale or shaley coal, to a limnotelmatic, telmatic or raised mire coal. Wetting-upwards cycles are typically initiated by raised mire coal, which grades into telmatic, limnotelmatic or shaley coal, or even coaly shale and pure shale. m.c. = mineral content. Other coal signature diagrams constructed from petrographic analysis (Appendix 2) are provided for **(c)** Glauconite coal from 10-25-40-25W4, **(d)** upper Medicine River coal from 16-4-36-20W4, **(e)** upper Medicine River coal from 6-7-40-24W4, **(f)** lower Medicine River coal from 10-25-40-25W4, **(g)** lower Medicine River coal from 6-7-40-24W4, and **(h)** Hackett coal from 16-4-36-20W4.

Because the cross-sections have been drawn with the datum below the coal-bearing strata, most of the strata below the datum appear to have a similar lithology and compaction ratio, and therefore it is unlikely that differential coal compaction has played a key role. Syn-depositional basement movement is suggested in regions when the basement and the Joli Fou flooding surface feature an opposing geometry: in areas where the basement topography is high (relative to the datum), the Joli Fou flooding surface appears to be low, and in turn where the basement is low relative to the datum, the flooding surface appears to be high. A more quantitative illustration of this relationship is shown in Figure 17, where the datum to basement and datum to top-Mannville isopach values for each cross-section are compared. Most of the data points cluster along a simple regression line. The cross-sections that fit best are those that cross the Hackett high (e.g. A–A′ and T35; Figs.17b, c). The most straightforward explanation for this mirror-image relationship is that in areas where the basement topography appears low, subsidence during Mannville Group times occurred more rapidly, and therefore these areas contain an overall thicker stratigraphic package.

Another key indicator of differential subsidence is the abundant occurrence of coal seam splits. Similar behaviour in coal has been documented by Warbrooke (1981), Warbrooke and Roach (1986), and Titheridge (1993), and attributed to tectonic seam splitting. This is in contrast to autocyclic seam splitting, such as might occur due to encroachment by a clastic channel. Tectonically split coal seams have a maximum aggregate coal thickness just up-palaeoslope of the split axes, as clearly seen

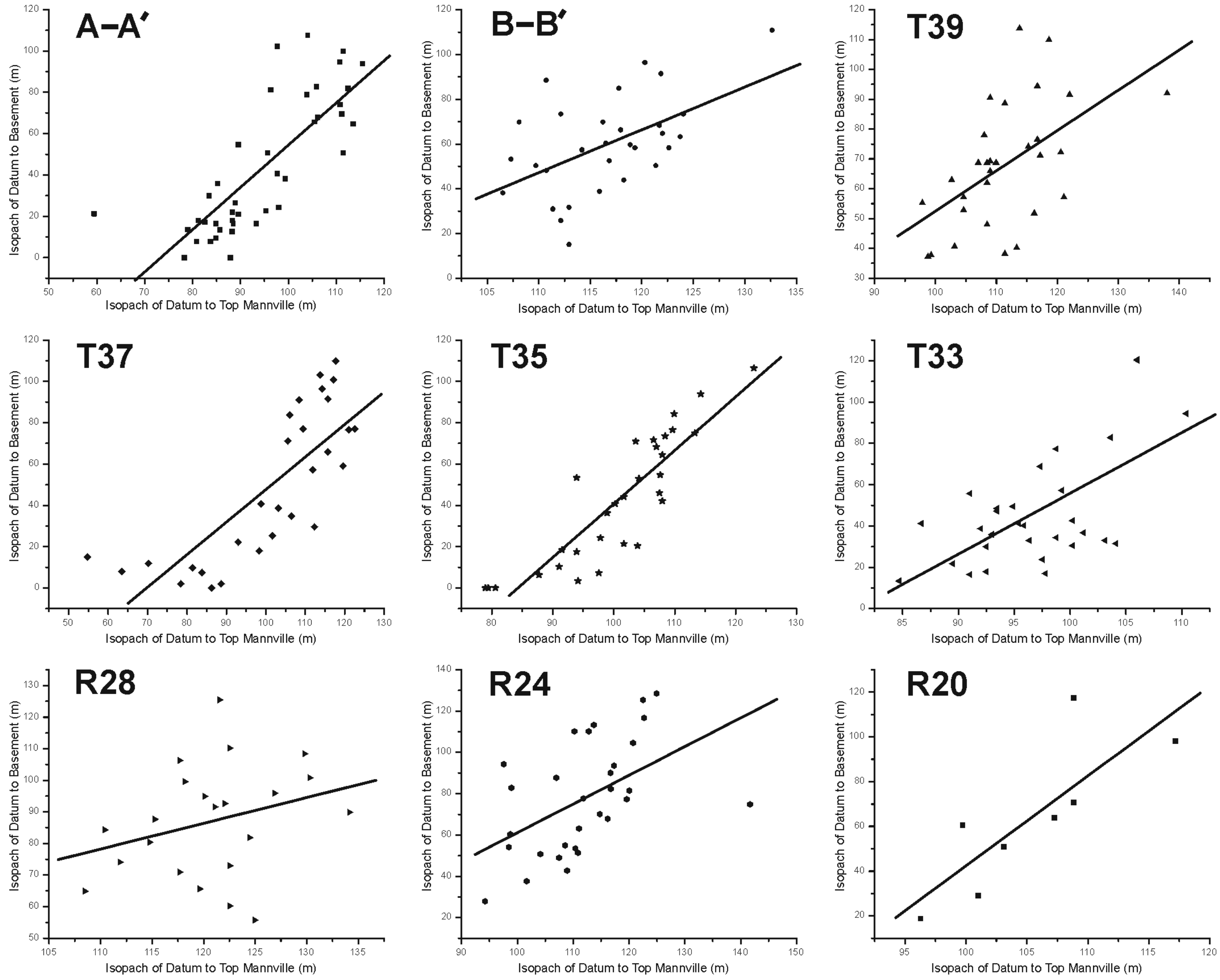


Fig. 17. Comparison of Datum 1 to basement and Datum 1 to top of Mannville isopach values for all cross-sections. The cross-sections that cross the Hackett high (A–A′, T37, T35, R20) show the strongest degree of cluster around a linear regression line. Cross-sections that cross other basement highs (B–B′, T33, R24) show a moderate degree of cluster, and cross-sections that mainly cross the basement drainage-valley low features (T39, R28) show a very low degree of cluster around the linear regression line. These data suggest that the effects of differential subsidence are strongest around basement high features, particularly the Hackett high.

in the Medicine River coal in several locations, such as Well 19 in A–A′ (Fig.10a), Wells 1, 15, and 21 in B–B′ (Fig.10b), Wells 6 and 19 in T37 (Fig. 11), Well 7 in T33 (Fig. 11), and Well 3 in R24 (Fig. 12). Similar relationships are found in the Hackett coal (Wells 12 and 19 in A–A′, Fig. 10a) and the Glauconite coal (Well 10 in B–B′, Fig. 10b). The reason for this trend is that the thickest part of the coal seam corresponds to a setting where accommodation balances peat production. At this optimum position, ash content is likely to be lowest and structured vitrinite highest. Farther landward, accommodation decreases in the conjoined part of the seam, so that relatively dry peat-forming conditions prevail, leading to a higher rate of plant decay and ablation. The result is a thinning of the coal seam, and a higher concentration of inertinite-rich, dull coal. Down-palaeoslope, increased subsidence rates indicate that accommodation outstrips peat production rates, and the seam is split into two or more subseams.

The cross-sections in Figures 10 to 12 show that there is a significant change in stratigraphic style across areas underlain by a relatively steeply changing basement gradient, which we suggest is at least partly related to differential subsidence associated with syn-depositional faulting. A good example of this is the stratigraphic transition from the southern side of the Hackett high to the northern side, with an apparent focal point along the flank of the paleohigh (e.g. Well 19 in A–A′, Fig. 10a). On the northern and western side of the margin, the Ellerslie and Ostracod members (lower Mannville) onlap against the flank. In contrast, to the south and east of the flank, above the Hackett high itself, there is no development of the Ostracod parasequences, and the Glauconite coal is less well developed, and sometimes entirely absent. Above this, the lagoon shale facies is locally well developed, though of variable thickness.

All of the overlying thin upper Mannville coals between the Glauconite and Medicine River coals disappear immediately above the Hackett high, although they tend to reappear farther to the south and east (see Fig. 10a and R20; Fig. 12 in particular). Both the Medicine River and Hackett coals thicken and become single seams immediately above and adjacent to the Hackett high (Well 19, Fig. 10a; Well 24 in T37, Fig. 11). The number of seams splits, and the interseam thickness, generally become greater with increasing distance from the margin (Fig. 10a). This type of coal behaviour suggests that the margin of the Hackett high was a site of abrupt changes in subsidence rates, as might occur across a periodically reactivated fault.

Other syn-depositional faults also appear to be present in areas where the basement gradient changes abruptly, such as immediately below the Hoadley complex. In Figures 8 and 10 a, b, the Glauconite coal splits directly above the Hoadley complex. Moreover, above and southeast of the Hoadley complex (e.g. from Well 7 to Well 1, Fig. 10a), there is an abrupt increase in the number of coal seams and seam splits. In addition, channels (or possible incised valleys) are situated at various stratigraphic levels above and below the Hoadley complex (e.g. in Wells 1, 2, 4, 5, 6, 8, Fig. 10b). All of these observations strongly suggest that differential subsidence of the basement was a key factor in providing sufficient accommodation for the wedge-shaped Hoadley complex to be deposited and preserved. Similar syn-depositional subsidence controls have been identified in positioning of Mannville Formation channel sandstone in the Cessford area (Hopkins, 1987).

In each cross-section (Figs. 10–12), the position of possible syn-depositional fault planes has been identified on the basis of coal seam splits and terminations and abrupt changes in Mannville thickness. The positions of fault planes have been mapped where they intersect the top of the Paleozoic basement and are superimposed on the maps in Figures 6 and 7. The fault traces correlate between lines and can be mapped as northwestward- and southeastward-dipping, with a roughly SW–NE to SSW–NNE trend. They are spaced 10 and 50 km apart in a horst and graben configuration. When superimposed on the Mannville Group thickness isopach map in Figure 6 (used as a proxy for basement topography), the inferred faults show a strong alignment with thickness trends, indicating at least some component of Paleozoic basement control. In particular, the northwestern margin of the Hackett high coincides with a horst feature, whereas the basement low adjacent to it corresponds to a graben feature. In Figure 7, the faults are superimposed on the coal thickness isopach maps, revealing that the area of thickest cumulative coal lies above the Hackett high horst feature. Another thick accumulation of coal (region of T34, R28W4 to T36, R26W4) also lies on a horst feature, above an area of steeply dipping basement.

The origin of the postulated syn-depositional faults in Figures 6 and 7 is not clear. Many, though not all, of the lineaments appear to be geometrically linked with areas of relatively steeply inclined Paleozoic basement, and they appear to have been active during deposition of the upper Mannville (i.e. Early Cretaceous). These faults show a similar alignment to NE–SW (and conjugate NW–SE) structural lineaments previously identified in the Mannville Group (Christopher, 1974, 1984; Cant and Abrahamson, 1996; Gregor, 1997) and the Alberta Foreland Basin in general (Haites, 1960; Jones, 1980; Simpson, 1984). Various possible mechanisms have been postulated for the origin of these features, ranging from stress-induced fractures in response to a Jurassic overthrust event (Cant and Abrahamson, 1996), Mississippian or Devonian foreland basin and peripheral bulge development (Bradley and Kidd, 1991; Savoy and Mountjoy, 1995), differential salt solution (Hopkins, 1987), to episodic reactivation of deep basement-initiated faults along Precambrian crystalline basement block boundaries (Sikabonyi and Rodgers, 1959; Greggs and Greggs, 1989). Ross and Eaton (1999) suggest that basement control on sedimentation may be caused by differential strain amplification caused by variable crustal strengths (Peper et al., 1992; Waschbusch and Royden, 1992; Heller et al., 1993; Peper, 1994).

Regardless of their ultimate origin, the stratigraphic analysis presented in this paper suggests that the Lower Cretaceous syn-depositional faults are linked to localized areas of differential subsidence, and exerted significant control on development of the coal stratigraphy. The model outlined in Figure 18 proposes that during Ostracod deposition, the region was characterized by

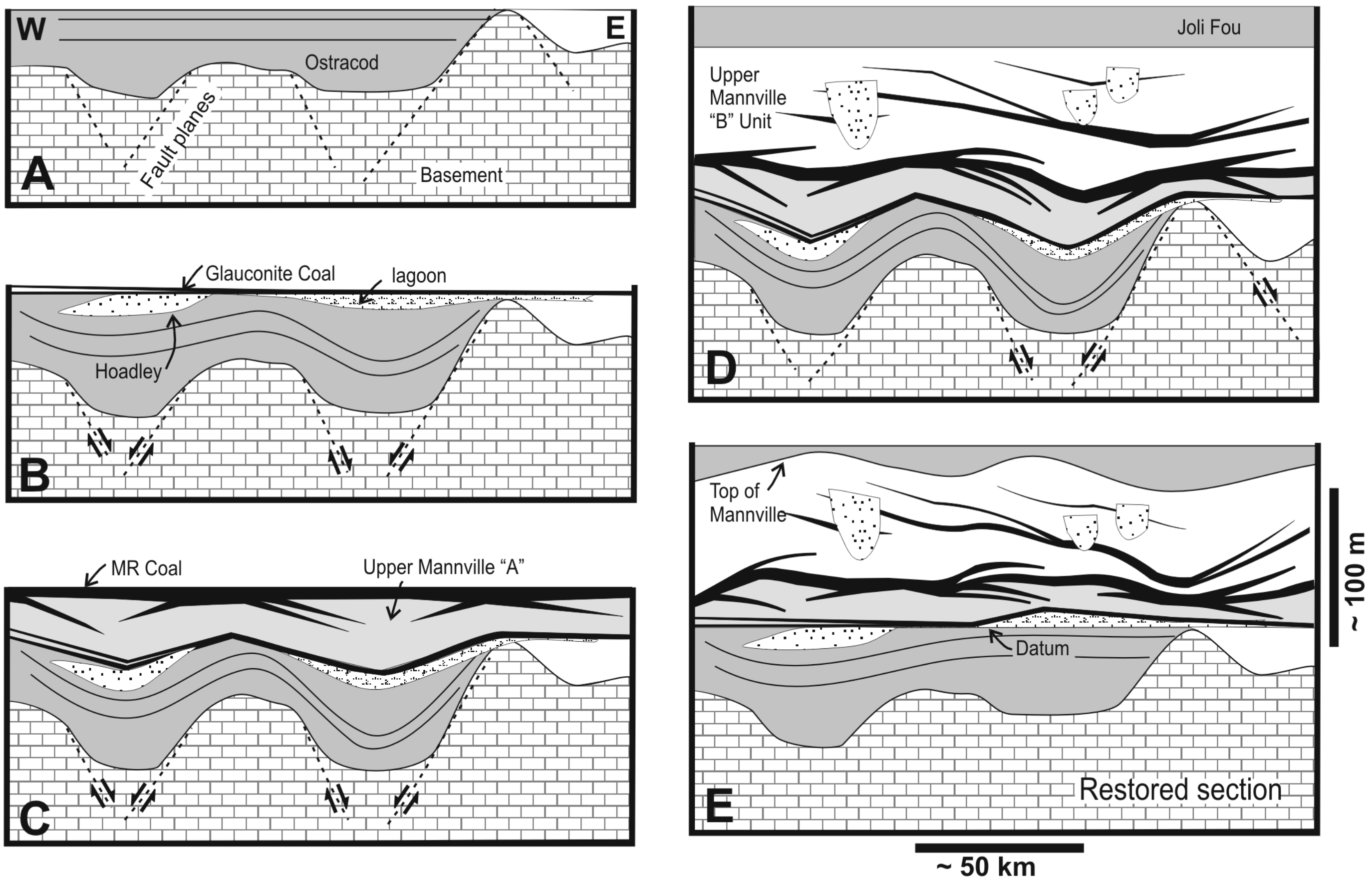


Fig. 18. Model of basement control on Mannville Group stratigraphy in the Hackett high area; **(A)** to **(E)** in chronological order. Note the similarity between the schematic diagram in Figure 18(E) and Figure 10(a). Areas where the basement is low correspond to areas where the Joli Fou flooding surface bulges upwards, suggesting that the basement lows were areas of greater accommodation and differential subsidence. Coal seams preferentially split over these areas, and therefore may be used to predict areas of differential subsidence.

moderate basement relief, with parasequences onlapping onto the emergent Hackett high (Fig. 18A). Extensional forces resulted in downward movement along pre-existing fault planes (as highlighted by arrows) resulting in locally increased accommodation and deposition of the Hoadley complex (Fig. 18B), with apparent warping of the Ostracod flooding surfaces downwards below the Hoadley complex. To the east, an extensive back barrier lagoon/swamp developed, possibly associated with downward movement of a different basement fault plane. The uniform and widespread nature of the Glauconite coal indicates that it formed during a period of basement quiescence, except above the Hoadley complex where it splits into two coals. Continued downward movement of basement blocks (Fig. 18C) created variable thickness of the Upper Mannville Unit A, and splitting of the Medicine River coal toward the east and west. During upper Mannville Unit B deposition (Fig. 18D), most of the differential subsidence and accommodation took place in the basement low immediately adjacent to the Hackett high, resulting in local splitting and rejoining of the thin upper Mannville coals, including the Hackett coal. Deposition of the Mannville Group ceased when the Joli Fou transgression occurred. In Figure 18E, the stratigraphy is redrawn using the top Ostracod flooding surface as a datum. In this figure the reconstruction gives the impression that substantial parts of the uppermost Mannville Group have been removed by ravinement, but this is an artifact caused by using an underlying datum. Note the similarity between this diagram and Figure 10b. Areas where the basement is low correspond to areas where the top Mannville surface bulges upwards, suggesting that the basement lows were areas of greater accommodation.

CONCLUSIONS

The upper Mannville Group in south-central Alberta is an example of a regional-scale, subsidence-driven intermediate accommodation setting in the WCSB. Several features of the stratigraphy identified in this study are used to identify a style of coal and non-marine strata characteristic of regional intermediate accommodation. The distribution of coal and the presence of amalgamated compound coal seams are perhaps the most obvious feature. Second, incised valleys are a common component of the stratigraphy and correlate laterally into units within the compound coals. Third, the Mannville Group accumulated slowly, and thus has been influenced strongly by underlying structure and paleotopography. Subsequent studies on non-marine and coaly strata from different accommodation settings may show contrasting stratigraphic styles.

A revised view of Mannville stratigraphy is obtained by using internal datums such as the topmost Ostracod flooding surface and the base of the Medicine River coal, as an alternative to the traditionally used base of the Joli Fou Formation.

In the south-central Alberta area, local tectonic subsidence has been superimposed on the regional intermediate accommodation pattern. In areas above basement highs, where accommodation was relatively low, the coal seams are highly amalgamated. In areas above steeply-dipping basement gradient, where accommodation was relatively high, the coal seams thicken and split.

Petrographic analysis of the coal seams reveals that they are internally more complex than simple 'transgressive' or 'regressive' style coals. They typically comprise a number of wetting- and drying-upwards cycles representing repeated episodes of peat deposition under rising or falling accommodation conditions, with or without internal hiatuses between the cycles. These accommodation cycles are driven by changes in groundwater levels that are in turn hydraulically linked to relative sea level, and are useful in identifying a style of non-marine stratigraphy.

The Glauconite coal shows a consistent thickness over the study area, and contains no splits except above the Hoadley complex. Petrographic and stratigraphic analysis indicates that the Glauconite coal is a compound coal containing multiple seams, formed during decreasing and increasing accommodation conditions, and hence records several relative sea level cycles. Subsidence rates were apparently uniform, except slightly greater over the Hoadley complex.

The Medicine River and Hackett coals are more complex than the Glauconite coal. They contain abundant splits above areas of locally greater subsidence, with incised valleys locally formed between splits, indicating the potential development of sequence boundaries within the amalgamated portion of the seams. Petrographic analysis reveals complex internal signatures of wetting- and drying-upwards cycles, indicating a history of multiple relative sea level cycles. Give-up transgressive surfaces (GUTS), accommodation reversal surfaces (ARS) and flooding surfaces (FS) are well expressed. However, there is no conclusive evidence of sequence boundaries within the coals themselves, suggesting that in regionally intermediate accommodation settings, coals do not express this type of chronostratigrahic bounding surface with a distinctive petrographic signature.

ACKNOWLEDGMENTS

This paper is part of a larger ongoing research project into the sequence stratigraphy of non-marine to marginal marine sediments formed under varying accommodation settings. We wish to thank our collaborative partners who have provided financial or technical support: PanCanadian Energy Corporation (now part of EnCana Corporation), who also kindly gave us permission to use and publish their data, and The Australian Research Council, NSW (Australia) Department of Mineral Resources. Gareth Chalmers is thanked for his analytical work. Bruce Misanchuk helped initiate the project and provided much early data, and Lorne Rosenthal provided critical analysis and feedback.

REFERENCES

Aitkin, J.F. and Flint, S.S. 1995. The application of high-resolution sequence stratigraphy to fluvial systems: a case study from the Upper Carboniferous Breathitt Group, eastern Kentucky, USA. Sedimentology, v. 42, p. 3-30.

Banerjee, I. and Kidwell, S.M. 1991. Significance of molluscan shell beds in sequence stratigraphy: an example from the Lower Cretaceous Mannville Group of Canada. Sedimentology, v. 38, p. 913-934.

_____, Kalkreuth, W. and Davies, E.H. 1996. Coal seam splits and transgressive–regressive coal couplets: A key to stratigraphy of high-frequency sequences. Geology, v. 24, p. 1001-1004.

Beaumont, C. 1981. Foreland Basins. Geophysical Journal of the Royal Astronomical Society, v. 65, p. 291-329.

Blum, M.D. and Törnquist, T.E. 2000. Fluvial responses to climate and sea-level change: a review and look forward. Sedimentology, v. 47, p. 2-48.

Bohacs, K.M. and Suter, J. 1997. Sequence stratigraphic distribution of coaly rocks: Fundamental controls and examples. American Association of Petroleum Geologists Bulletin, v. 81, p. 1612-1639.

Boron, D.J., Evans E.W. and Petersen, J.M. 1987. An overview of peat research, utilization, and environmental considerations. International Journal of Coal Geology, v. 8, p. 1-31.

Boyd, R. and Diessel, C. 1995. The effects of accommodation, base level and rates of peat accumulation on coal measure architecture and composition. American Association of Petroleum Geologists, Annual Convention, Abstracts and Program, p. 12a.

_____, _____, Wadsworth, J., Chalmers, G. and Little, M. 1999. Development of a non-marine sequence stratigraphic model. American Association of Petroleum Geologists, Annual Convention, Abstracts and Program, p. 15a.

_____, _____, _____, Leckie, D. and Zaitlin, B.A. 2000. Developing a Model for Non-Marine Sequence Stratigraphy – Application to the Western Canada Sedimentary Basin. GeoCanada 2000 – The Millennium Geosciences Summit Conference Abstract.

Bradley, D.C. and Kidd, W.S.F. 1991. Flexural extension of the upper continental crust in collisional foredeeps. Geological Society of America Bulletin, v. 103, p. 1416-1438.

Broger, E.J.K., Syhlonyk, G.E. and Zaitlin, B.A. 1997. Glauconite Sandstone exploration: a case study from the Lake Newell Project , Southern Alberta. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.). Canadian Society of Petroleum Geologists Memoir 18, p. 140-168.

Cant, D.J. 1984. Development of shoreline-shelf sand bodies in a Cretaceous epeiric sea deposit. Journal of Sedimentary Petrology, v. 54, p. 541-556.

_____ and Stockmal, G.S. 1993. Some controls on sedimentary sequences in foreland basins: examples from the Alberta Basin. In: Tectonic Controls and Signatures in Sedimentary Successions. L.E. Frostick and R.J. Steel (eds.). International Association of Sedimentologists Special Publication 20, p. 49-66.

_____ and Abrahamson, B. 1994. Isopach of transgressive system Mannville Group. Map 1:2000000. Geological Survey of Canada, Open File 3090.

_____ and _____1996. Regional distribution and internal stratigraphy of the Lower Mannville. Bulletin of Canadian Petroleum Geology, v. 44, p. 508-529.

Carmichael, S.M.M. 1983. Sedimentology of the Lower Cretaceous Gates and Moosebar Formations, northeast coalfields, British Columbia. Ph.D. thesis, University of British Columbia, Vancouver, BC, 285 p.

Casas, J.E. and Walker, R.G. 1997. Sedimentology and depositional history of Units C and D of the Falher Member, Spirit River Formation, west-central Alberta. Bulletin of Canadian Petroleum Geology, v. 45, p. 218-238.

Chalmers, G.R.L. 2001. Characteristics of low accommodation coal seams, Lloydminster area, Western Canadian Sedimentary Basin. M.Sc. thesis, University of Newcastle, Callaghan, NSW, Australia, 175 p.

Chiang, K.K. 1985. The Hoadley gas field, south-central Alberta. In: Elmworth - Case Study of a Deep Basin Gas Field. J.A. Masters (ed.). American Association of Petroleum Geologists Memoir 38, p. 297-313.

Christopher, J.E. 1974. The Upper Jurassic Vanguard and Lower Cretaceous Mannville Groups. Saskatchewan Geological Survey, Department of Mineral Resources, Report No. 151, 349 p.

_____1984. The Lower Cretaceous Mannville Group, Northern Williston Basin Region, Canada. In: The Mesozoic of Middle North America. D.F. Stott and D.J. Glass (eds.). Canadian Society of Petroleum Geologists Memoir 9, p. 109-126.

Diessel, C.F.K. 1992. Coal-bearing Depositional Systems. Springer-Verlag, Berlin, 721 p.

_____1998. Sequence stratigraphy applied to coal seams: two case histories. In: Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks. K.W. Shanley and P.J. McCabe (eds.). Society of Economic Paleontologists and Mineralogists, Special Publication 59, p. 151-173.

_____ and Gammidge, L.C. 1998. Isometamorphic variations in the reflectance and fluorescence of vitrinite - a key to the depositional environment. International Journal of Coal Geology, v. 36, p. 167-222.

_____, Boyd, R., Wadsworth, J., Leckie, D. and Chalmers, G. 2000. On balanced and unbalanced accommodation/peat accumulation ratios in the Cretaceous coals from Gates Formation, Western Canada, and their sequence-stratigraphic significance. International Journal of Coal Geology, v. 43, p. 143-186.

Frenzel, B. 1983. Mires - repositories of climatic information or self-perpetuating ecosystems. In: Mires: Swamp, Bog, Fen and Moor. General Studies. A.J.P. Gore (ed.). Elsevier, Amsterdam, p. 35-65.

Glaister, R.P. 1959. Lower Cretaceous of southern Alberta and adjoining areas. American Association of Petroleum Geologists Bulletin, v. 43, p. 590-640.

Greggs, R.G. and Greggs, D.H. 1989. Fault-block tectonism in the Devonian subsurface, western Canada. Journal of Petroleum Geology, v. 12, p. 377-404.

Gregor, V. A. 1997. Mannville linears in the Lloydminster heavy oil area and their relationship to fractures and fluid flow in the Western Canada Sedimentary Basin. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.). Canadian Society of Petroleum Geologists Memoir 18, p. 428-474.

Guiseppe, A.C. and Heller, P.L. 1998. Long-term river response to regional doming in the Price River Formation, central Utah. Geology, v. 26, p. 239-242.

Haites, T.B. 1960. Transcurrent faults in western Canada. Journal of the Alberta Society of Petroleum Geologists, v. 8, p. 33-78.

Hampson, G.J., Stollhofen, H. and Flint, S.S. 1999. A sequence stratigraphic model for the Lower Coal Measures (Upper Carboniferous) of the Ruhr district, north-west Germany. Sedimentology, v. 46, p. 1199-1231.

Hayes, B.J.R., Christopher, J.E., Rosenthal, L., Los, G., Mckercher, B., Minken, D., Tremblay, Y.M. and Fennel, J. 1994. Cretaceous Mannville Group of the Western Canada Sedimentary Basin. In: Geological Atlas of the Western Canada Sedimentary Basin. G.D. Mossop and I. Shetsen (comps.). Canadian Society of Petroleum Geologists and Alberta Research Council, p. 317-334.

Heckel, P.H. 1986. Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along midcontinent outcrop belt, North America. Geology, v. 14, p. 330-334.

Heller, P.L., Beekman, F., Angevine, C.L. and Cloetingh, S.A.P.L. 1993. Cause of tectonic reactivation and subtle uplifts in the Rocky Mountain region and its effect on the stratigraphic record. Geology, v. 21, p. 1003-1006.

Holdgate, G.R., Wallace, M.W., Gallagher, S.J. and Taylor, D. 2000. A review of the Traralgon Formation in the Gippsland Basin - a world class brown coal resource. International Journal of Coal Geology, v. 45, p. 55-84.

Holmden, C., Muehlenbachs, K. and Creaser, R.A. 1997. Depositional environment of the Early Cretaceous Ostracode Zone: paleohydrologic constraints from O, C and SR isotopes. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.). Canadian Society of Petroleum Geologists Memoir 18, p. 77-92.

Hopkins, J.C. 1987. Contemporaneous subsidence and fluvial channel sedimentation: Upper Mannville C Pool, Berry Field, Lower Cretaceous of Alberta. American Association of Petroleum Geologists Bulletin, v. 71, p. 334-345.

Jervey, M.T. 1988. Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. In: Sea Level Changes: An Integrated Approach. C.K Wilgus, B.S. Hastings, C.A. Ross, H.W. Posamentier, J. van Wagoner and C.G.St.C. Kendall (eds.). Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 47-70.

Jones, R.M.P. 1980. Basinal isostatic adjustment faults and their petroleum significance. Bulletin of Canadian Petroleum Geology, v. 40, p. 198-206.

Karvonen, R.L. and Pemberton, S.G. 1997a. Sedimentology, ichnology and stratigraphy of the Ostracode Member (Lower Cretaceous) in the Jenner-Suffield Area, southeast Alberta. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.) Canadian Society of Petroleum Geologists Memoir 18, p. 103-123.

_____ and _____ 1997b. The Upper Mannville Group in southeast Alberta: an example of multiple incised valley deposits. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.). Canadian Society of Petroleum Geologists Memoir 18, p. 124-139.

Langenberg, C.W., Rottenfusser, B.A. and Richardson, R.J.H. 1997. Coal and coalbed methane in the Mannville Group and its equivalents, Alberta. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.). Canadian Society of Petroleum Geologists Memoir 18, p. 475-486.

Leckie, D.A. 1986. Rates of controls and sand-body geometry of transgressive-regressive cycles: Cretaceous Moosebar and Gates Formations, British Columbia. American Association of Petroleum Geologists Bulletin, v. 70, p. 516-535.

_____ and Smith, D.G. 1992. Regional setting, evolution, and depositional cycles of the Western Canada Foreland Basin, In: Foreland Basins and Fold Belts. R.W. Macqueen and D.A. Leckie (eds.). American Association of Petroleum Geologists Memoir 55, p. 9-46.

_____, Vanbeselaere, N.A. and James, D.P. 1997. Regional sedimentology, sequence stratigraphy and petroleum geology of the Mannville Group, southern Saskatchewan. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.) Canadian Society of Petroleum Geologists Memoir 18, p. 211-262.

McCabe, P.J. 1993. Sequence stratigraphy of coal-bearing strata. American Association of Petroleum Geologists Short Course, New Orleans, Course Notes, 81 p.

McCarthy, P.J. and Plint, A.G. 2001. Recognition of interfluve sequence boundaries: Integrating paleopedology and sequence stratigraphy. Geology, v. 26, p. 387-390.

McLean, J.R. 1977. The Cadomin Formation, stratigraphy, sedimentology and tectonic implications. Bulletin of Canadian Petroleum Geology, v. 25, p. 792-827.

_____ and Wall, J.H. 1981. The Early Cretaceous Moosebar Sea in Alberta. Bulletin of Canadian Petroleum Geology, v. 29, p. 334-377.

McPhee, D., 1994. Sequence stratigraphy of the Lower Cretaceous Mannville Group of east-central Alberta. M.Sc. thesis, University of Alberta, Edmonton, Alberta, 65 p.

Monger, J.W.H. 1989. Overview of Cordilleran Geology. In: Western Canada Sedimentary Basin. B.D. Rickets (ed.). Canadian Society of Petroleum Geology Guidebook, Calgary, Alberta, p. 9-32.

Montgomery, S.L., Tabet, D.E. and Barker, C.E. 2001. Upper Cretaceous Ferron Sandstone: Major coalbed methane play in central Utah. Bulletin of the American Association of Petroleum Geologists, v. 85, p. 199-219.

Nauss, A.W. 1945. Cretaceous stratigraphy of the Vermilion area, Alberta, Canada. Bulletin of the American Association of Petroleum Geologists, v. 29, p. 1605-1629.

Norris, D.K. 1964. The Lower Cretaceous of the south-eastern Canadian Cordillera. Bulletin of Canadian Petroleum Geology, v. 12, p. 201-237.

Pang, M. and Nummedal, D. 1995. Flexural subsidence and basement tectonics of the Cretaceous Western Interior basin, United States. Geology, v. 23, p. 173-176.

Peper, T., Beekman, F. and Cloeting, S. 1992. Consequences of thrusting and intraplate stress fluctuations for vertical motions in foreland basins and peripheral areas: Geophysical Journal International, v. 111, p. 104-126.

_____1994. Tectonic and eustatic control on Albian shallowing (Viking and Paddy Formations) in the Western Canada foreland basin. Geological Society of America Bulletin, v. 106, p. 253-264.

Plint, A.G., McCarthy, P.J. and Faccini, U.F. 2001. Nonmarine sequence stratigraphy: updip expression of sequence boundaries and systems tracts in a high-resolution framework, Cenomanian Dunvegan Formation, Alberta foreland basin, Canada. Bulletin of the American Association of Petroleum Geologists, v. 85, p. 1967-2001.

Posamentier, H.W. and Allen, G.P. 1993. Siliciclastic sequence stratigraphic patterns in foreland ramp-type basins. Geology, v. 21, p. 455-458.

_____ and Vail, P.R. 1988. Eustatic control on clastic sedimentation II - sequence and systems tract models. In: Sea Level Changes: An Integrated Approach. C.K Wilgus, B.S. Hastings, C.A Ross, H.W. Posamentier, J. van Wagoner and C.G.St.C. Kendall (eds.). Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 125-154.

Rosenthal, L. 1988. Wave-dominated shorelines and incised channel trends: Lower Cretaceous Glauconite Formation, west-central Alberta. In: Sequences, Stratigraphy, Sedimentology: Surface and Subsurface. D.P. James and D.A. Leckie (eds.). Canadian Society of Petroleum Geologists Memoir 15, p. 207-220.

Ross, G. M. and Eaton, D.W. 1999. Basement reactivation in the Alberta Basin: observational constraints and mechanical rationale. Bulletin of Canadian Petroleum Geology, v. 47, p. 391-411.

Rouble, R. and Walker, R. 1997. Sedimentology, high-resolution allostratigraphy, and key stratigraphic surfaces in Falher Members A and B, Spirit River Formation, West-Central Alberta. In: Petroleum Geology of the Cretaceous Mannville Group Western Canada. S.G. Pemberton and D.P. James (eds.). Canadian Society of Petroleum Geologists Memoir 18, p. 1-29.

Rudkin, R.A. 1964. Lower Cretaceous. In: Geological History of Western Canada. R.G. McCrossan and R.P. Glaister (eds.) Alberta Society of Petroleum Geologists, p. 156-168.

Savoy, L.E. and Mountjoy, E.W. 1995. Cratonic-margin and Antler-age foreland basin strata (Middle Devonian to Lower Carboniferous) of the southern Canadian Rocky Mountains and adjacent plains. In: Stratigraphic Evolution of Foreland Basins. S.L. Dorobek and G.M. Ross, (eds.). Society of Economic Paleontologists and Mineralogists Special Publication 52, p. 213-231.

Scott, A.C. 2000. The Pre-Quaternary History of Fire. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 164, p. 281-329.

Shanley, K.W. and McCabe, P.J. 1994. Perspectives on the sequence stratigraphy of continental strata. American Association of Petroleum Geologists Bulletin, v. 78, p. 544-568.

Sherwin, M.D. 1994. Incised channel trends: Glauconitic Member, Southern Alberta. In: CSEG-CSPG Joint National Convention 1994, Program and Extended Abstracts, p. 368.

Sikabonyi, L.A. and Rodgers, W.J. 1959. Paleozoic tectonics and sedimentation in the northern half of the west Canadian basin. Journal of Alberta Society of Petroleum Geologists, v. 7, p. 193-216.

Simpson, F. 1984. Potential for additional hydrocarbon recovery from the Colorado and Montana Groups (Cretaceous) of Saskatchewan. In: Oil and Gas in Saskatchewan. J.A. Lorsong and M.A. Wilson (eds.). Saskatchewan Geological Society Special Publication No. 7, p. 211-244.

Snedden, J.W. and Kersey, D.G. 1981. Origin of San Miguel lignite deposit and associated lithofacies, Jackson Group, south Texas. American Association of Petroleum Geologists Bulletin, v. 65, p. 1099-1109.

Strobl, R.S. 1988. The effects of sea-level fluctuations on prograding shorelines and estuarine valley-fill sequences in the Glauconitic Member, Medicine River field and adjacent areas. In: Sequences, Stratigraphy, Sedimentology: Surface and Subsurface. D.P. James and D.A. Leckie (eds.). Canadian Society of Petroleum Geologists Memoir 15, p. 221-236.

Titheridge, G.G. 1993. The influence of half-graben syn-depositional tilting on thickness variation and seam splitting in the Brunner Coal Measures, New Zealand. Sedimentary Geology, v. 87, p. 195-213.

van Wagoner, J.C., Mitchum, Jr. R.M., Campion, K.M. and Rahmanian, V.D. 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops: concepts for high resolution correlation of time and facies. American Association of Petroleum Geologists Methods in Exploration, Series 7, 64 p.

Warbrooke, P.R. 1981. Depositional Environments of the Upper Tomago and Lower Newcastle Coal Measures, New South Wales. Ph.D. thesis, University of Newcastle, Callaghan, NSW, Australia.

_____ and Roach, M.J. 1986. The relationship between seam splitting, coal forming environments and coal properties in the Newcastle Coal Measures. In: Proceedings of the 20th Newcastle Symposium on Advances in the Study of the Sydney Basin. C.F.K. Diessel (ed.). University of Newcastle, Callaghan, NSW, Australia, p. 23-27.

Waschbusch, P.J. and Royden, L.H. 1992. Episodicity in foredeep basins. Geology, v. 20, p. 915-918.

Wightman, D.M., Pemberton, S.G. and Singh, C. 1987. Depositional modeling of the Upper Mannville (Lower Cretaceous), east central Alberta: implications for the recognition of brackish water deposits. In: Reservoir Sedimentology. R.W. Tillman and K.J. Weber (eds.). Society of Economic and Petroleum Geologists Special Publication 40, p. 189-220.

Williams, G.D. 1963. The Mannville Group (Lower Cretaceous) of central Alberta. Bulletin of Canadian Petroleum Geology, v. 11, p. 350-368.

_____ and Stelck, C.R. 1975. Speculations on the Cretaceous paleogeography of North America. In: The Cretaceous system in the Western Interior of North America. W.G.E. Caldwell (ed.). Geological Association of Canada. Special Paper 13, p.1-10.

Wood, J.M. and Hopkins, J.C. 1992. Traps associated with paleovalleys and interfluves in an unconformity-bounded sequence: Lower Cretaceous Glauconitic Member, Southern Alberta, Canada. American Association of Petroleum Geologists Bulletin, v. 76, p. 904-926.

_____1996. Sedimentology and sequence architecture of incised valley-fills and interfluvial deposits, Upper Mannville interval (Lower Cretaceous), Little Bow-Turin area, southern Alberta. Bulletin of Canadian Petroleum Geology, v .44, p. 632-653.

Zaitlin, B.A., Warren, M.J., Potocki, D., Rosenthal, L. and Boyd, R. 2002. Depositional styles in a low accommodation foreland basin setting: an example from the Basal Quartz (Lower Cretaceous), southern Alberta. Canadian Society of Petroleum Geology Fluvial Volume. Bulletin of Canadian Petroleum Geology, v. 50, p. 31-72.

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Appendix 1 — Well Name Codes

Well No.	A-A'	B-B'	T39	T37	T35	T33	R28	R24	R20
1	12-11-48-3W5	7-36-44-7W5	6-32-39-28W4	10-30-37-28W4	8-8-35-28W4	10-25-33-29W4	14-32-40-27W4	10-25-40-25W4	6-26-40-20W4
2	6-20-46-1W5	16-10-44-6W5	16-21-39-28W4	6-21-37-28W4	12-15-35-28W4	16-10-33-28W4	6-22-40-28W4	6-7-40-24W4	7-16-40-20W4
3	8-10-46-1W5	11-17-43-5W5	5-26-39-28W4	10-3-37-28W4	11-12-35-28W4	6-12-33-28W4	7-9-40-28W4	11-4-40-24W4	7-5-40-20W4
4	7-13-45-1W5	4-30-43-5W5	13-5-40-27W4	6-5-37-27W4	16-30-35-27W4	6-18-33-27W4	16-21-39-28W4	11-35-39-24W4	6-29-39-20W4
5	8-5-45-1W5	11-35-42-5W5	6-9-40-27W4	6-10-37-27W4	7-20-35-27W4	11-16-33-27W4	6-16-39-28W4	15-26-39-24W4	7-18-39-20W4
6	8-23-44-28W4	3-6-42-4W5	16-2-40-27W4	6-24-37-27W4	6-4-35-27W4	10-23-33-27W4	7-3-39-28W4	16-10-39-24W4	16-8-39-20W4
7	6-2-44-27W4	14-27-41-4W5	7-8-40-26W4	6-29-37-26W4	8-31-35-26W4	10-20-33-26W4	8-26-38-28W4	6-34-38-24W4	10-29-38-20W4
8	7-21-43-26W4	8-13-41-4W5	1-34-39-26W4	11-14-37-26W4	7-22-35-26W4	7-15-33-26W4	12-14-38-28W4	14-22-38-24W4	5-21-38-20W4
9	8-24-42-26W4	6-34-40-3W5	6-35-39-26W4	1-12-37-26W4	10-36-35-26W4	15-23-33-26W4	8-10-38-28W4	12-14-38-24W4	2-16-38-20W4
10	10-28-41-25W4	8-10-40-3W5	6-32-39-25W4	11-17-37-25W4	16-18-35-25W4	6-6-34-25W4	8-34-37-28W4	14-27-37-24W4	10-22-37-20W4
11	4-12-41-25W4	6-36-39-3W5	10-22-39-25W4	16-34-37-25W4	11-9-35-25W4	14-23-33-25W4	14-22-37-28W4	10-8-37-24W4	12-13-37-20W4
12	10-25-40-25W4	14-29-39-02W5	10-36-39-25W4	8-26-37-25W4	14-14-35-25W4	10-25-33-25W4	10-3-37-28W4	4-4-37-24W4	3-4-37-20W4
13	6-7-40-24W4	11-35-38-2W5	10-30-39-24W4	6-18-37-24W4	8-8-35-24W4	6-20-33-24W4	8-34-36-28W4	4-27-36-24W4	4-33-36-20W4
14	2-4-40-23W4	13-17-38-1W5	16-10-39-24W4	8-5-37-24W4	14-15-35-24W4	14-23-33-24W4	6-26-36-28W4	7-15-36-24W4	6-25-36-20W4
15	16-25-39-23W4	7-22-37-1W5	8-24-39-24W4	4-4-37-24W4	6-2-35-24W4	16-1-33-24W4	8-11-36-28W4	12-11-36-24W4	16-4-36-20W4
16	8-29-39-22W4	3-4-37-28W4	14-20-39-23W4	6-28-37-23W4	7-8-35-23W4	14-7-33-23W4	16-36-35-28W4	14-35-35-24W4	7-32-35-20W4
17	10-14-38-22W4	6-26-36-28W4	8-22-39-23W4	7-11-37-23W4	6-3-35-23W4	8-2-33-23W4	16-30-35-27W4	1-22-35-24W4	14-20-35-20W4
18	8-28-37-21W4	16-36-35-28W4	14-11-39-23W4	6-24-37-23W4	7-2-35-23W4	3-1-33-23W4	6-4-35-27W4	14-15-35-24W4	13-3-35-20W4
19	7-1-37-21W4	16-30-35-27W4	2-30-39-22W4	7-31-37-22W4	11-8-35-22W4	13-5-33-22W4	7-33-34-27W4	12-29-34-24W4	7-28-34-20W4
20	16-4-36-20W4	6-17-35-27W4	8-29-39-22W4	8-20-37-22W4	6-21-35-22W4	16-4-33-22W4	3-20-34-27W4	10-17-34-24W4	8-15-34-20W4
21	7-27-35-20W4	11-14-34-27W4	10-36-39-22W4	6-14-37-22W4	9-24-35-22W4	10-22-33-22W4	11-8-34-27W4	16-6-34-24W4	10-4-34-20W4
22	7-28-34-20W4	8-5-34-26W4	6-19-39-21W4	6-25-37-22W4	10-6-35-21W4	14-31-33-21W4	7-34-33-28W4	6-32-33-24W4	16-29-33-20W4
23	8-19-34-19W4	15-23-33-26W4	16-4-39-21W4	15-18-37-21W4	11-10-35-21W4	16-27-33-21W4	16-10-33-28W4	6-20-33-24W4	5-21-33-20W4
24	6-27-33-19W4	6-3-33-25W4	16-14-39-21W4	14-16-37-21W4	13-14-35-21W4	16-25-33-21W4	6-2-33-28W4	16-9-33-24W4	6-5-33-20W4
25	16-20-33-18W4	6-27-32-25W4	7-18-39-20W4	7-1-37-21W4	14-20-35-20W4	14-31-33-20W4	8-29-32-28W4	7-34-32-24W4	4-29-32-20W4
26	10-31-32-17W4	14-1-32-25W4	6-29-39-20W4	15-9-37-20W4	12-34-35-20W4	15-21-33-20W4	6-16-32-28W4	14-20-32-24W4	6-15-32-20W4
27	11-16-32-17W4	6-29-31-24W4	10-23-39-20W4	12-13-37-20W4	10-36-35-20W4	7-3-33-20W4	9-8-32-28W4	6-7-32-24W4	8-3-32-20W4
28	8-36-31-17W4	12-4-31-23W4	11-8-39-19W4	8-19-37-19W4	6-31-35-19W4	16-17-33-19W4	6-33-31-28W4	6-29-31-24W4	15-22-31-20W4
29	14-9-31-16W4	10-15-30-23W4	6-15-39-19W4	1-16-37-19W4	11-21-35-19W4	6-27-33-19W4	11-8-31-28W4	6-17-31-24W4	16-9-31-20W4
30	8-36-30-16W4	6-6-30-22W4	10-13-39-19W4	10-11-37-19W4	16-23-35-19W4	10-24-33-19W4	10-6-31-28W4	9-8-31-24W4	8-4-31-20W4
31	8-9-30-15W4								
32	6-32-29-14W4								
33	6-22-29-14W4								
34	15-30-28-13W4								
35	11-20-28-13W4								
36	6-36-27-13W4								
37	12-17-27-12W4								
38	8-23-26-12W4								
39	4-18-26-11W4								
40	13-24-25-11W4								
41	8-6-25-10W4								

APPENDIX 2

DETAILS OF COAL ANALYSIS

For an explanation of the abbreviations used to describe petrographic indicators, refer to Table 1.

Glauconite Seam from 6-7-40-24W4M (see Fig. 16a, b)

Unit 1 consists of a grey mudstone (Sub-unit 1a). The upper part contains vitrinitized roots. Their reflectance (%Rrt) is comparatively high, while I 650wt is quite low. Because the low coefficients of variation of both optical properties [c(%Rrt) and c(I 650wt)] exclude any mixing of root and shoot material, it is assumed that the seat earth was subjected to brief periods of drying. Sub-unit 1b begins with shaley coal as shown by moderately high mineral content, representing the transition to limnotelmatic conditions, which are also indicated by the high proportion of dispersed inertodetrinite and sporinite. However, within a few centimetres, the upward decrease in mineral content, c(%Rrt) and inertodetrinite, as well as the increase in vitrinite suggest a drop in accommodation, corresponding to raised-mire conditions. Although the high vitrinite content points to a balanced accommodation rate/peat production rate ratio, the increase in %Rrt may be related to episodes of intermittent drying.

Unit 2 is characterized by increased mineral and dispersed inertodetrinite contents, which together with a high proportion of alginite (*Botryococcus*-type), indicate a rise in accommodation (distal flooding) and a reversal to limnotelmatic or even lacustrine conditions in the lower portion of the unit. Further support for this notion comes from the exceptionally high %Rrt which might have been derived from slightly pre-oxidized drift wood. An upwards decreasing proportion of detrital minerals and other dispersal indicators suggest the re-establishment of raised-mire conditions.

Unit 3 contains a lower burrowed, silt-laminated, dark shale which represents sudden and widespread flooding above a non-marine flooding surface (NFS). Re-establishment of a balanced accommodation rate/peat production rate ratio, probably in a raised mire is indicated by high vitrinite and low detrital mineral contents. The elevated %Rrt and low I 650wt at the top of the unit suggests a period of relative dryness.

Units 4 and 5 begin with gradually increasing detrital minerals and other dispersal indicators together with decreasing vitrinite and %Rrt, indicating upward-deepening from raised-mire to limnotelmatic conditions. Both units culminate in flooding, indicated by a shaley coal band at the top. Peat formation ceases at the give-up surface above Unit 5, as the mire is covered with a silt-laminated sand containing *Planolites* burrows. The high c(%Rrt) suggests mixing of vitrinite precursors (drift wood). Tissue Preservation Index (TPI) is also high but based mainly on semifusinite.

Glauconite Seam from 10-25-40-25W4 (see Fig. 16c)

Unit 1 consists mainly of a lacustrine, dark shale with shell fragments and a moderate amount of dispersed inertodetrinite (Sub-unit 1a). Low %Rrt and high I 650wt suggest reducing conditions with little water turbulence, although the high c(%Rrt) and c(I650wt) indicate some dispersal of components. The top of this unit (1b) indicates an abrupt phase of terrestrialization, where the mineral content drops to a few percentage points while vitrinite becomes dominant. This suggests the establishment of a balanced accommodation rate/peat production rate ratio, presumably under raised-mire conditions.

Units 2, 3,4 and 5 each begin with an episode of flooding, revealed by the influx of minerals, inertodetrinite and the degree of mixing of autochthonous and allochthonous vitrinite precursors. The latter is indicated by the high mean telovitrinite reflectance (%Rrt) and moderately high c(%Rrt). Farther upward, the mineral content and other dispersal indicators decrease, which suggests a decline in accommodation. With each successive unit, the actual reduction in accommodation becomes more pronounced, indicated by high vitrinite content and TPI with a corresponding reduction in the proportion of minerals and c(%Rrt). In Unit 2 only limnotelmatic conditions are attained, whereas in units 4 and 5 ombrotrophic conditions are reached. A balance in the rates of accommodation and peat production is indicated in the middle part of Unit 4 by the high vitrinite content and high TPI but increasing %Rrt, semifusinite-based TPI and declining proportion of vitrinite and Groundwater Influence Index (GWI) suggest mild peat oxidation, possible because of reduced accommodation, towards the end of the cycle.

Unit 6 differs from the underlying ones in that it does not begin with an abrupt flooding event. Instead, its coal properties indicate a reversal of the gradual shallowing trend that characterizes the preceding cycle to one of gradual deepening. The boundary between units 5 and 6 therefore constitutes an accommodation reversal surface (ARS). The lower portion of Sub-unit 6a is still low in detrital minerals and probably of ombrotrophic origin. Farther upward, the rising detrital mineral content indicates limnotelmatic conditions due to increased accommodation. Dispersal and component mixing is suggested by high sporinite and inertodetrinite contents and increased c(%Rrt) and c(I 650wt). A further acceleration in accommodation terminates peat production so that, above a give-up surface (GUTS1), a grey mudstone is deposited.

Unit 7 represents a brief return to raised-mire conditions before the peat is finally buried underneath a thick grey mudstone by an even stronger flooding event which terminates mire development (GUTS2).

Medicine River Seam (Lower Part) from 10-25-40-25W4 (see Fig. 16d)

Unit 1 begins above a paludification surface (PaS). High vitrinite content and TPI indicate a well balanced accommodation rate/peat production rate ratio, but towards the end of the cycle, the decrease in vitrinite, and increasing detrital mineral, inertinite, sporinite and inertodetrinite contents, as well as high %Rrt and low I 650wt, suggest influx of dispersed components under increasing accommodation.

Unit 2 has an increasing vitrinite content in the lower portion, suggesting a return to a more balanced accommodation rate/peat production rate ratio under raised-mire conditions. However, decreasing T.P.I. and increasing c(%Rrt) point to another upward increase in accommodation which causes the unit to end with a layer of limnotelmatic, dull coal.

Unit 3 is characterized by very stable peat-forming conditions in a raised-mire environment. The detrital mineral content is very low, and there is little variation in the coal properties. Towards the top of the unit, accommodation increases again, which leads to another influx of detrital minerals and dispersed inorganics in the form of coaly shale.

Unit 4 begins with a reversal to low detrital mineral content, indicating ombrotrophic conditions. The initially high vitrinite content decreases upward while inertinite, inertodetrinite and sporinite increase in proportion. The carbonaceous shale capping the unit is underlain by a thin, fusain band which suggests the occurrence of peat fires.

Unit 5 begins again with relatively high vitrinite content and high TPI, indicating balanced accommodation rate/peat production rate ratio under raised-mire conditions. Towards the top, there is an increase in detrital mineral, sporinite and inertodetrinite contents. The termination of peat formation against the overlying mudstone constitutes a give-up surface (GUTS).

Medicine River Seam (Lower Part) from 6-7-40-24W4 (see Fig. 16e)

Unit 1 consists of upward-coarsening siltstone and sandstone containing plant roots and vitrinitized drift wood. The latter is indicated by the high %Rrt. Upward shallowing into a limnotelmatic mire is evident by the decline in mineral content and the increase in liptinite, inertinite, and vitrinite. The drop in %Rrt and increase in TPI suggest that much of the vitrinite is well-preserved and less pre-oxidized, but the raised c(%Rrt) indicates some mixing of autochthonous root-derived and allochthonous shoot-derived vitrinite. The presence of dispersed material is also shown by the high proportion of sporinite.

Unit 2 consists of the lower portion of an incomplete cycle of flooding and shallowing in the form of a dark grey shale containing vitrinite lenses and dispersed inertodetrinite. Telovitrinite reflectance is high, suggesting that most of the vitrinite has been derived from pre-oxidized, allochthonous shoot material (e.g. drift wood). According to the logs, this unit is overlain by some 2.5 m of coal which was not recovered.

Medicine River Seam (Upper Part) from 16-4-36-20W4 (see Fig. 16f)

Unit 1 begins with a cannel coal containing large proportions of detrital minerals, sporinite and inertodetrinite. Together with the high telovitrinite reflectance (%Rrt) and its coefficient of variation [c(%Rrt)], these properties indicate subaqueous conditions. The initially high accommodation rate/peat production rate ratio becomes more balanced and leads to largely ombrotrophic raised-mire conditions later in the cycle, which is indicated by decreasing detrital mineral, sporinite and inertodetrinite contents, as well as the declining GWI. A fusain band suggests peat exposure and burning.

Units 2 begins with a thin band of shaley coal, indicating an interval of flooding. Higher up, the low contents of detrital minerals, sporinite and inertodetrinite, as well as the low c(%Rrt) indicate raised-mire conditions.

Unit 3 shows generally very low mineral content, suggesting continuation of well-balanced raised-mire conditions, except for a 1 cm-thick claystone at the beginning of this unit, and a thin fusain band (flooding and peat exposure, respectively). Vitrinite content and TPI rise higher in the unit while the indicators of dispersal decline, except at the very top of the unit where a slight reversal occurs.

The lower part of **Unit 4** contains a very high epiclastic mineral content indicating flooding of the mire due to a sharp rise in accommodation (NFS1). All other dispersal indicators are also high. Total vitrinite content is very low, but mean %Rrt reaches its highest value in the seam and, since c(%Rrt) is high as well, most of the telovitrinite appears to have been derived from slightly oxidized, allochthonous precursors. Higher in the cycle, peat formation becomes re-established under a regime of limnotelmatic, high-accommodation conditions and a high degree of dispersal of peat components. The decline in the mineral content towards the top of the unit suggests a change to raised-mire conditions.

Unit 5 is characterized at its base by a high degree of dispersal of peat components and rise in detrital mineral content, indicating an increased accommodation/peat production ratio. This is followed by a return to well-balanced accommodation rate/peat production rate conditions indicated by increasing vitrinite content and TPI, although towards the top of the unit TPI declines again while detrital minerals, sporinite, inertodetrinite and GWI increase slightly. However, c(%Rrt) continues to decline, so that no mixing of vitrinite precursors appears to have occurred.

Unit 6 shows a drop in vitrinite content, and a sharp increase in detrital minerals and all other dispersal indicators, indicating a sudden increase in accommodation which initiates the final flooding of the mire (NFS2) and the deposition of the mudstone roof of the seam.

Medicine River Seam (Upper Part) from 6-7-40-24W4 (see Fig. 16g)

Unit 1 begins with a laminated, dark grey shale (Sub-unit 1a). Vitrinite content is low but the coefficients of variation of telovitrinite reflectance and fluorescence are high, suggesting derivation from mixed allochthonous/autochthonous sources. A terrestrialization surface (TeS) is placed at the boundary between Sub-unit 1a and 1b, above which the rock changes to a cannel shale. Microscopically, this terrestrialization is expressed by the declining mineral and increasing organic contents, particularly in the form of dispersed sporinite and inertodetrinite. Overall, this unit represents a change from open, lacustrine to stagnant water and, at the very top of the unit, the beginning of limnotelmatic coal formation.

Unit 2 begins with flooding due to an increase in accommodation. Farther upward, mineral influx decreases and dispersed sporinite and inertodetrinite increase, resulting in the formation of cannel shale.

The **Unit 3** overall upward shallowing trend is interupted by renewed flooding and, once again, the flooding is weaker and the unit is thinner than the preceding one. This pattern suggests that the source of flooding became more distal with time.

Hackett Seam from 16-4-36-20W4 (see Fig. 16h)

Unit 1 begins above a terrestrialization surface (TeS) with a grey, muddy seat earth that contains autochthonous vitrinitized roots and allochthonous organic matter (mainly inertodetrinite and sporinite). Upward decreasing mineral, sporinite and inertodetrinite contents, as well as declining GWI indicate ombrotrophic raised-mire conditions. Concurrently rising vitrinite content and TPI suggest balanced accommodation rate/peat production rate. Farther upward, accommodation decreases, as indicated by a 1 cm thick layer of fusain (peat exposure and fire). Balanced depositional conditions are suggested by the increase in vitrinite in the upper portion of the unit although the raised telovitrinite reflectance (%Rrt) and its low coefficient of variation [c(%Rrt)] suggest that the cycle finishes under slightly dry conditions.

Unit 2 begins with a thin shaly coal rich in fusain (sharp decline in vitrinite and increase in inertinite contents), indicating another fire horizon. Next, limnotelmatic conditions are suggested by the raised mineral contents and increased proportions of dispersed sporinite and inertodetrinite. Also c(%Rrt) is higher, which signals autochthonous and allochthonous mixing of vitrinite precursors. Low mineral contents point to re-establishment of raised-mire conditions toward the end of the cycle.

Unit 3 shows very high epiclastic mineral content, indicating flooding of the mire at the beginning of the cycle. Because the resultant 5 cm thick claystone appears to correlate laterally with a seam split, its base has been considered to be a regional non-marine flooding surface (NFS1) of at least 50 km lateral extent (Fig. 14). There is a large proportion of dispersal indicators (low vitrinite content, high inertodetrinite), and indicators of mixing of vitrinite precursors (high %Rrt and c[%Rrt]). Farther upward, balanced raised-mire conditions are indicated by the increasing vitrinite and decreasing inertinite contents, and by the decline in dispersed inertodetrinite.

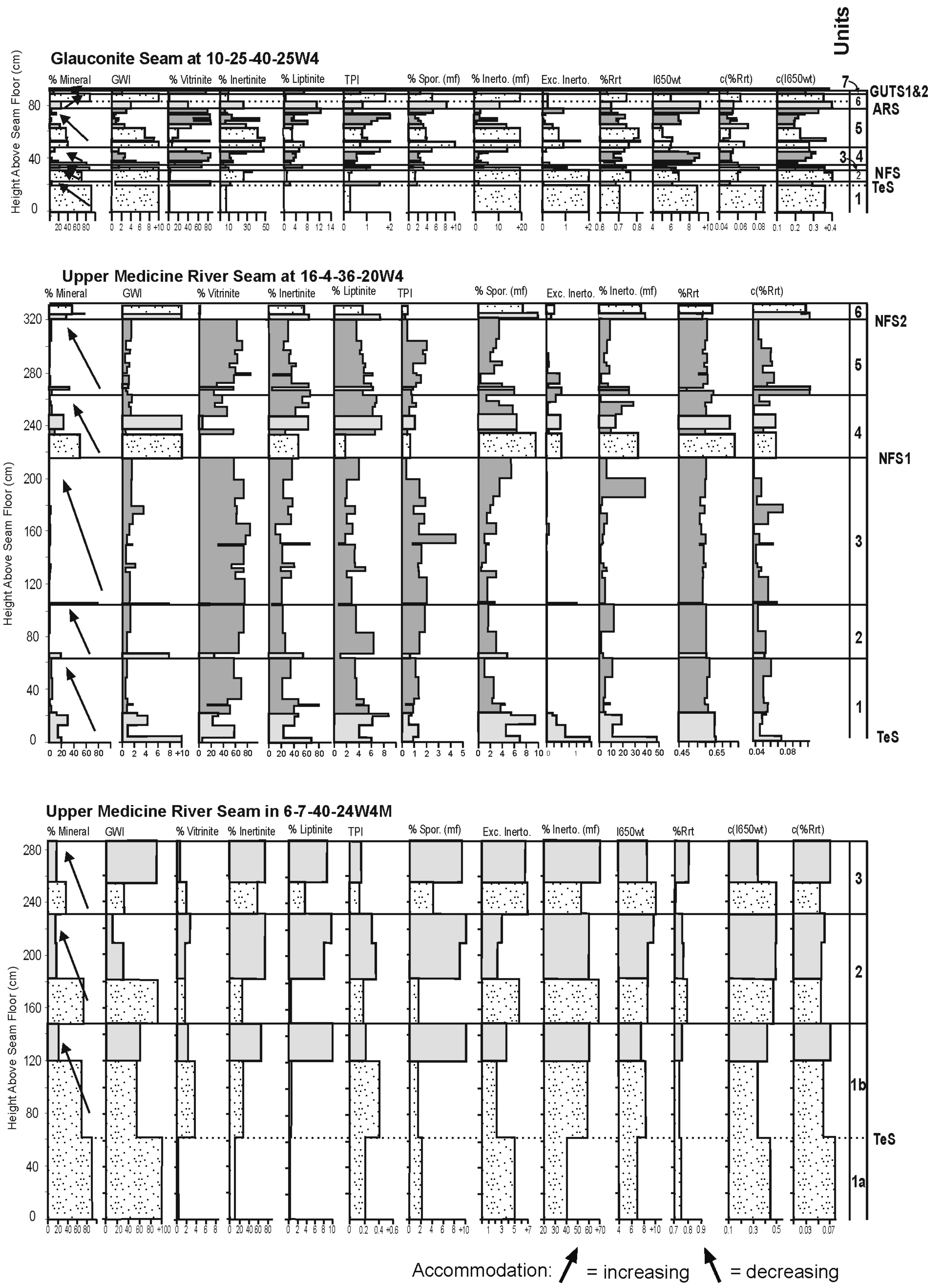
Unit 4 shows dispersal of peat components (increase in detrital minerals, inertodetrinite, sporinite) and a reversal in the proportion of vitrinite and inertinite near the base of the unit, followed by a return to balanced accommodation/peat production conditions.

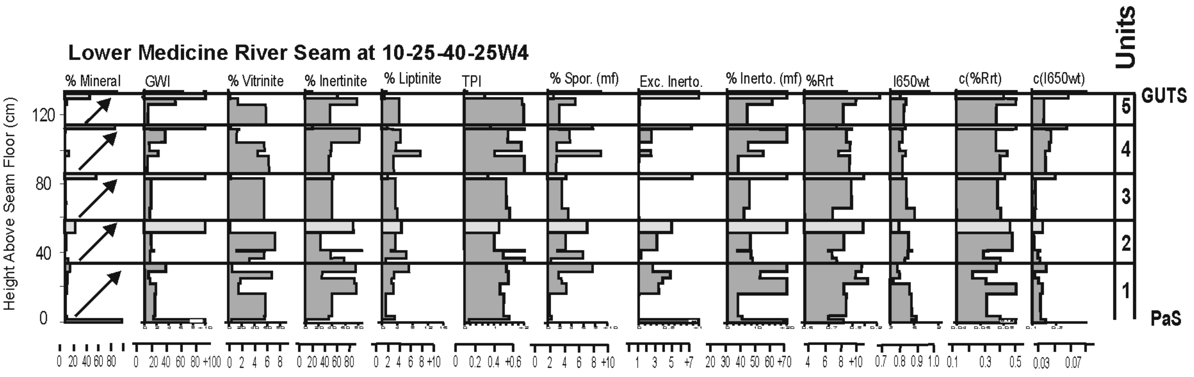
Unit 5 begins above a non-marine flooding surface (NFS2) with a grey mudstone that grades upward into shaly coal containing vitrinitized plant roots and an upward decreasing proportion of dispersed sporinite and inertodetrinite. This succession indicates a sudden increase in accommodation which gradually wanes so that balanced raised-mire conditions are indicated by the generally high vitrinite and very low mineral contents over most of the unit. In the upper portion, an increase in %Rrt and c(%Rrt), declining TPI and vitrinite content, increasing sporinite and inertinite (mainly as inertodetrinite), and occasional fusain bands correspond to rapidly changing wet and dry periods, either due to climatic variations or instability in the rate of accommodation toward the end of the cycle.

Unit 6 begins with flooding, after which balanced raised-mire conditions are re-established. Repeated thin cycles of opposing vitrinite and inertinite trends, in conjunction with similar systematic variations in TPI, c(%Rrt), sporinite, and inertodetrinite, suggest that peat accumulated under a regime of either frequently changing accommodation or climatic conditions. The increasing mineral content in the upper half of the unit indicates a slight increase in accommodation and a change from ombrotrophic to limnotelmatic peat accumulation in advance of the subsequent flooding (NFS3). The highest strata comprise carbonaceous shale in which all dispersal indicators are high.

(Appendix 2 Figure follows)

Appendix 2 — Petrographic Analysis Details

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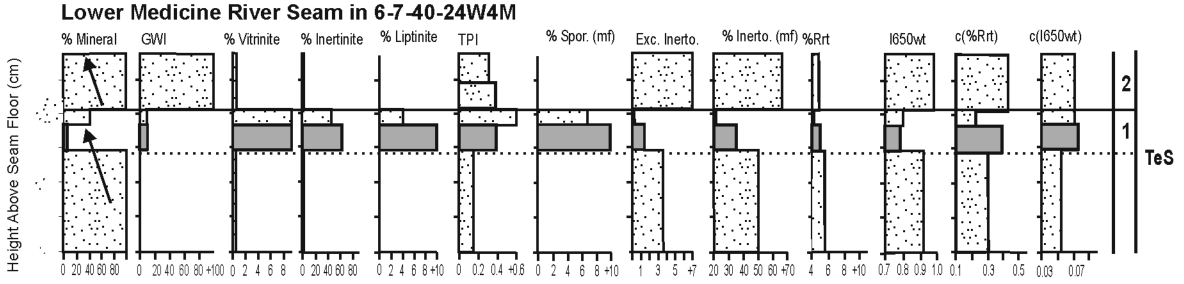
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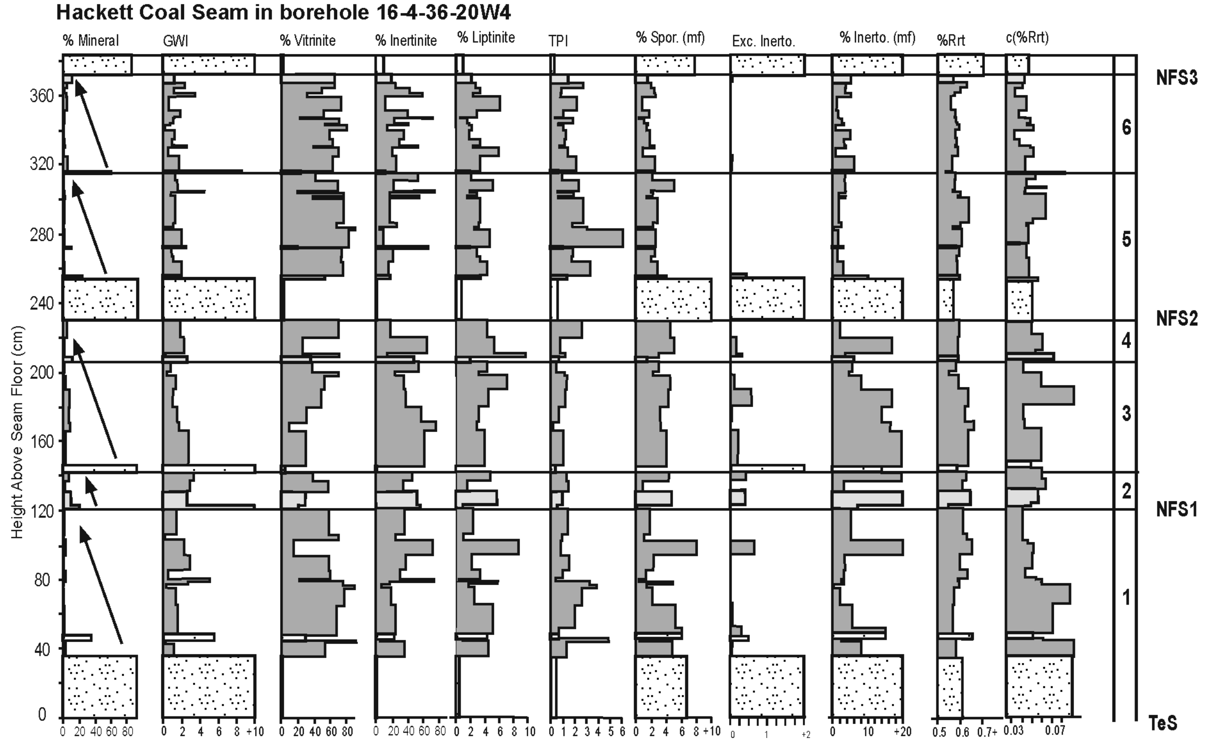
Hackett Coal Seam in borehole 16-4-36-20W4