PS Coal Seams as Sensitive Recorders of Base-Level Change: Implications for Predicting Vertical and Lateral Variations in Coal Composition: Examples from the Pennsylvanian, Kentucky, USA*

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Abstract

Coal seams formed in coastal plain and delta-top settings preserve a high-resolution record of water table (and hence base-level) fluctuation throughout their deposition. Detailed (cm-scale) study of their petrography provides a means of identifying intra-seam surfaces that separate spatially and temporally distinct phases of mire development and mark abrupt changes in palaeoenvironmental conditions.

The regionally extensive Westphalian B Fire Clay coal, up to 1.5 m-thick, was deposited in a delta-top environment, in an ever-wet, palaeoequatorial setting in the Central Appalachian Basin. The petrographic composition of three hundred samples collected from eleven localities along a 150-km depositional dip transect was analysed in order to determine the internal stratigraphy of the coal seam. Correlation between localities was aided by the presence of a volcanic ash-fall horizon (“tonstein”) within the coal, which provides an independent time-line (~310 Ma).

The results of these analyses reveal cyclic changes in the composition of the Fire Clay coal, which are correlatable over distances of more than 100 km. Each of the correlatable sub-units of coal shows a trend of peat deposition under progressively drier conditions. The top of each unit is represented by a “dry maceral assemblage”, high in inertinite and resistant peat components, indicating high rates of oxidation and biomass loss. The base of each subsequent unit is marked by an abrupt change to a “wet maceral assemblage” interpreted as the response to an abrupt rise in the water table. Each of these genetic sub-units has a different spatial distribution, indicating that the coal represents several spatially and temporally distinct phases of peat accumulation.
Understanding the internal stratigraphy, as well as the spatial and temporal development of regionally extensive coal seams in this way, may have significant implications for improving the predictability of vertical and lateral changes in coal composition, which in

turn may have commercial applications for mining and coalbed methane exploitation of coal bed resources. In order to visualise the results of the Fire Clay coal study, the data collected for this project have been used to construct a detailed 3D model using Petrel reservoir modelling software. This model clearly demonstrates the composite nature of the Fire Clay coal, and it could be used as tool to predict coal composition in as yet un-exploited parts of the seam.

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Coal seams as sensitive recorders of base-level change
Implications for predicting vertical and lateral variability in coal composition:
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1. Introduction

What is the value of this study to the mining and hydrocarbon industry?

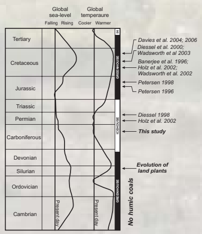
By understanding the spatial and temporal evolution of coal seams, it is possible to improve the predictability of vertical and lateral variability in coal thickness and quality.

In this approach, detailed analysis of compositional changes in multiple vertical sections through a single coal seam have been used to interpret water-table fluctuations that occurred during the accumulation of the original peat.

In coastal settings (where 80% of the world's exploitable coal reserves were deposited) relative sea-level and climate are the dominant controls on the regional water-table. These are basin-wide controls, so reconstructing water-table fluctuations in the original mire can help to predict the composition of the coal formed elsewhere in the basin.

This is the first high-resolution (over 300 samples analysed at an average of 2.8cm / 1.1 inch spacing) study to apply these principles to a Pennsylvanian coal, when it is known that many of the fundamental controls on coal composition (plant types, magnitude of sea-level and climate fluctuation) were different from much of geological time.

The Mahakam delta, Borneo. Modern -day coastal mires potentially analogous to the Pennsylvanian peatlands. From www.tripalbum.net/borneo/mahakam



Global sea-level curve and climatic curve through time. This is the first detailed study of the sequence stratigraphy of an "icehouse" Pennsylvanian coal, when high-magnitude sea-level and climatic fluctuations were operating.

Coal geology and sequence stratigraphy

The approach of this study is based on the following concepts:

1. In peat-forming environments, accommodation (the space in which peat can accumulate) is controlled by the relative height of the water table (above which peat is exposed to oxidation and degradation).

2. For peat to accumulate, the accommodation rate must approximately balance the peat production rate.

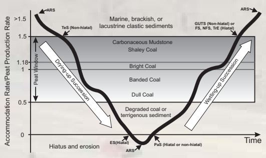
3. If the accommodation rate outpaces the peat production rate, the mires is inundated by marine, lacustrine or lagoonal conditions.

4. If the accommodation rate falls below the peat production rate, peat accumulation is limited, the mire is exposed, oxidised and reworked.

5. High-resolution variations in the rate of accommodation production result in changes in the composition of the accumulating peat.

6. Since the rate of peat production in a given latitudinal zone is relatively constant, compositional changes in the peat are primarily a function of accommodation change.

Coal seams should therefore provide a sensitive record of ancient water-table fluctuations.

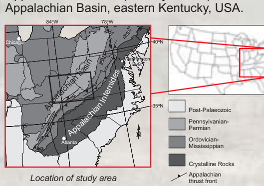


Relationship between accommodation creation rate and peat production rate, coaly facies, and key sequence stratigraphic surfaces. TeS=Terrestrialisation surface; ES=Exposure surface; PaS=Paludification surface; GUTS= Give-up transgressive surface; FS=Flooding surface; NFS=Non-marine flooding surface; TrE=Transgressive surface of erosion; ARS=Accommodation reversal surface. Modified from Wadsworth et. al (2003).

2. Geological Setting

Location and palaeogeography:

Upper Carboniferous (Pennsylvanian) of the Central Appalachian Basin, eastern Kentucky, USA.



Location of study area

Late Carboniferous palaeogeography from http://jan.ucc.nau.edu/~rcb7/globaltext2.html

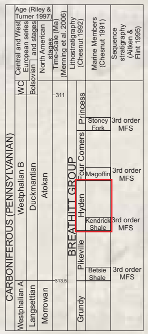
During the Late Carboniferous, the Central Appalachian Basin was a minor depocentre within the Alleghanian/Variscan foreland located near the palaeoequator. Siliciclastic debris shed westward into the basin from the orogenic belt in a series of delta lobes. Fluvio-deltaic sedimentation was punctuated by regular marine incursions from the S and W resulting from high-magnitude glacio-eustatic fluctuations.

Hyden Formation (Breathitt Group):

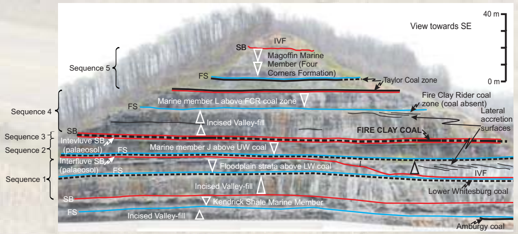
Succession of coal-bearing coastal plain, marine and fluvial strata.

Bound by regional major marine units interpreted as maximum flooding surfaces to 3rd-order (1-1.5 Ma duration) sequences (Aitken & Flint 1995).

The Hyden Formation comprises five to six 4th-order (~100 ka duration) sequences characterised by fine-grained marine, marginal or terrestrial strata that coarsen-up into heterolithic overbank strata and a palaeosol. Coarsening-up successions are commonly truncated by coarse-grained trough cross-bedded fluvial sandstones which fine-up into heterolithic strata that display lateral accretion surfaces. Cycles are capped by a regionally extensive coal bed or zone.



Litho-, bio- and chrono-stratigraphy of the Breathitt Group. Hyden Formation highlighted.



Road-cut exposure of the Hyden Formation at Garrett showing typical lithologies and sequence stratigraphic interpretation. SB= sequence boundary; FS=flooding surface.

Sequence stratigraphy of the Hyden Formation.

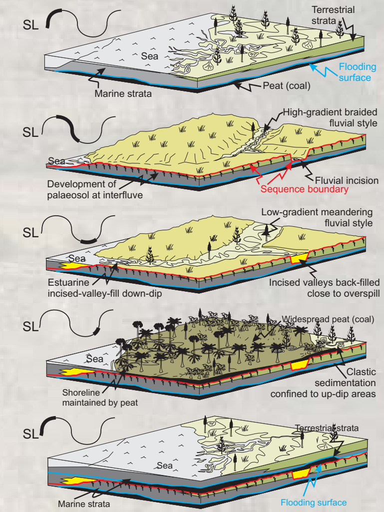
Late TST and early HST
Rates of base level rise outpace maximum rates of peat accumulation. Mires are drowned as marine/ lagoonal conditions transgress the delta plain. As rates of base-level rise begin to decrease, clastic distributaries prograde basinward.

Late HST, FSST and early LST
Base level falls. Fluvial systems adjust by incising previously deposited sediments. Palaeosols develop on exposed interfluves.

Late LST early TST
Base-level begins to rise. Incised valleys are back-filled with fluvial and estuarine sediments. Palaeosols continue to develop on exposed interfluves.

Middle TST
Rate of base-level rise increase and overspilling of incised valleys produces accommodation surplus. Clastic sedimentationis confined to up-dip areas; widespread peat accumulation is initiated down-dip and is balanced with high rates of base-level rise.

Late TST and early HST
Rates of base level rise outpace maximum rates of peat accumulation. Mires are drowned as marine/ lagoonal conditions transgress the delta plain. As rates of base-level rise begin to decrease, clastic distributaries prograde basinward.



The stratigraphic occurrence of coals within the Hyden Formation is not random; the majority were deposited during the transgressive systems tract of fourth-order sequences.

They represent a transition phase from subaerial exposure to marine inundation: an increase in accommodation.

Does the internal composition of these coals reflect this? Is the internal composition of the coal predictable too?

Do these coals preserve a more sensitive record of base-level fluctuations?

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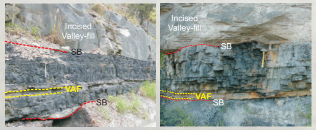
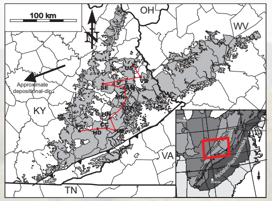
3. Target: the Fire Clay coal

- Thickest and most laterally extensive coal in the Hyden Formation (original mire area was vast: possibly >37,000 km^2).
- Located stratigraphically in the middle of the Hyden Formation.
- Contains a volcanic ash-fall horizon which provides certainty in correlating petrographic trends.
- Sampled at eleven localities along >100 km dip section in eastern Ky.

Photographs of the Fire Clay coal showing the volcanic ash-fall horizon in the middle of the coal at Isom (left) and at the base of the coal at Hazard (right).





Post-erosional extent of the Fire Clay coal across parts of five states and location of the eleven sampled sections through the coal. Line of cross-sections shown in section 5 is also shown.

4. Sampling & Analytical Procedure

Sample Collection

At each locality, the coal was excavated to remove excessively weathered material, before a lithotype log was produced to identify important lithological surfaces before sampling. 303 samples of coal were recovered representing the whole coal bed thickness at each locality. Average thickness of each speciemen was 2.8 cm

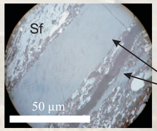
Sampling in progress

Sample Preparation

Coal specimens were removed intact in order to preserve their internal stratigraphy. Samples were cured in epoxy resin, cut perpendicular to layering and polished for reflected light microscopy. ~5% of samples too brittle to be kept intact were crushed to a maximum grain-size of 2 mm and a grain-mount produced instead.

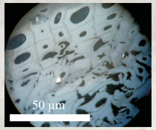
Petrographic Analysis

Maceral and mineral composition of all 303 coal specimens was determined by counting 500 points per sample. Macerals are analogous to minerals in clastic sedimentary rocks. Their relative proportions enable interpretation of the type of mire in which the coal formed, and interpret how the water-table changed during the formation of the coal.



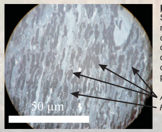
Vitrinite Maceral Group
Humified wood, bark, root and leaf tissues. High vitrinite content indicates conditions of balanced or high accommodation relative to peat production.

Telovitrinite (homogenous)
Detrovitrinite (coloidal)



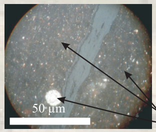
Inertinite Maceral Group
Oxidised or partially combusted plant material. High inertinite indicates dry conditions in the mire and disseminated forms of inertinite may indicate processes of exposure and reworking when accommodation is low relative to peat production.

Photomicrograph of a semifusinite maceral showing well-preserved cell-structure.



Liptinite Maceral Group
Spores, resin, cuticles and other resistant plant material. High liptinite content indicates reworking and oxidative biomass-loss may have occurred in the peat during periods of low accommodation relative to peat production.

Abundant sporinite (spores)
Resinite (resin, sap and wax)



Minerals
Detrital minerals may be imported into the mire when the accommodation is high relative to peat production. They may be concentrated further if oxidative biomass has occurred in the mire. The presence of pyrite suggests a marine or brackish influence on ground-water.

Detrital minerals
Fromboidal (syngenetic) pyrite

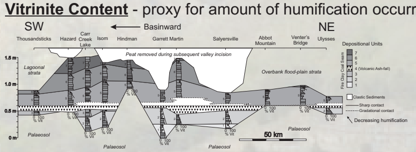
Fragmented macerals of any type represent transport or reworking, as opposed to structured maceral varieties which were well preserved *in situ*.

5. Vertical and Lateral Trends in Coal Composition

The correlation of petrographic trends is based on the identification of the volcanic ash-fall horizon at eight of the sampling localities. A striking feature of the seam is the presence of several abrupt vertical discontinuities in the composition of the seam. These discontinuities bound time-equivalent units of coal (U1-U7) which are readily traceable across >100 km.

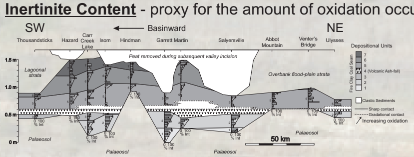
Every unit shows a trend of peat accumulation under conditions of decreasing accommodation.

Vitrinite Content - proxy for amount of humification occurring in the original mires



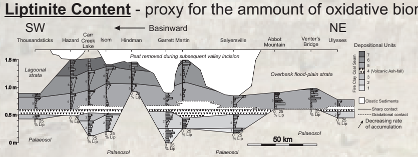
Vitrinite content decreases upwards in each unit, indicating that each unit accumulated under conditions of deceasing humification.

Inertinite Content - proxy for the amount of oxidation occurring in the original mires



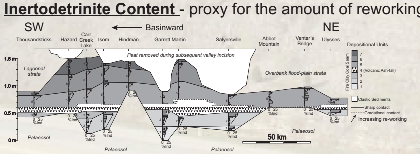
Inertinite content increases upwards in each unit, indicating that each unit accumulated under conditions of increasing oxidation.

Liptinite Content - proxy for the ammount of oxidative biomass-loss occurring in the original mires



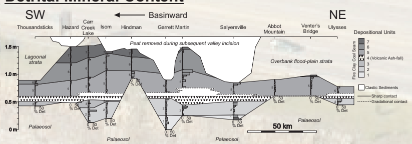
Liptinite content increases upwards in each unit, indicating that each unit accumulated under conditions of increasing oxidative biomass-loss.

Inertodetrinite Content - proxy for the amount of reworking occurring in the original mires



Inertodetrinite content increases upwards in each unit, indicating that each unit accumulated during increasing exposure and reworking.

Detrital Mineral Content



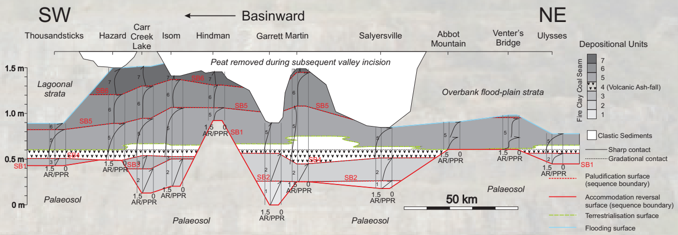
Detrital mineral content does not correlate with vitrinite or inertinite, suggesting that it occurs due to clastic import during times of excess accommodation, and it is also preferentially concentrated when accommodation is at a minimum.

6. Sequence Stratigraphy of the Fire Clay Coal

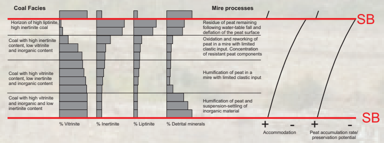
Sequence stratigraphic interpretation

Although the Fire Clay coal accumulated within the transgressive systems tract of a 4th-order sequence, petrographic trends do not reflect a single trend of increasing accommodation through the coal.

Units 1-7 represent a succession of six higher-frequency asymmetric accommodation cycles (units 4 and 5 make one cycle).



Vertical accommodation trends of each unit of the Fire Clay coal at each locality. Coal facies trends (from section 1) are plotted against the thickness of the coal.



Idealised high-frequency sequence in the Fire Clay coal, along with interpreted accommodation trend and depositional processes.

The cycles are interpreted as high-frequency sequences. This is because each cycle comprises

-a basal ARS which represents an episode of abrupt water-table rise.

- a drying-up succession which accumulated when the rate of water-table rise was decreasing.

-an upper, horizon rich in degraded inertinite, liptinite and detrital minerals; it represents a phase of extensive reworking and oxidative bio-mass loss from the peat during water-table fall.

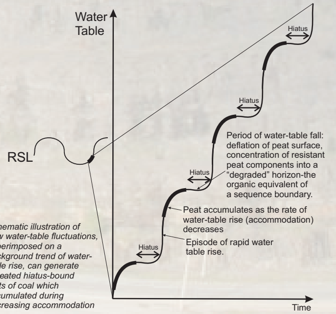
Each sequence has a markedly different overall composition and aerial distribution which supports the notion that peat accumulation was punctuated by hiatus and/or erosion. This is illustrated in the schematic on the right.

I.e. the Fire Clay coal is composed of multiple, stacked mires.

Sequence driving mechanism

The regional (>100 km) excess of the accommodation cycles indicates an allocyclic control on water-table fluctuations.

This could be either or both:-
-sea-level, as in paralic (coastal) settings, the groundwater table is hydrologically connected to the sea (Diessel, 1992). In the Pennsylvanian ice-house period, glacio-eustatic sea-level changes at multiple scales are a well-known phenomenon.
-climate, as in more landward areas the effect of precipitation and evaportaion on mire water-table in enhanced (Shanley & McCabe, 1994). However, glacio-eustatic sea-level changes were driven by climate change.



Schematic illustration of how water-table fluctuations, superimposed on a background trend of water-table rise, can generate repeated hiatus-bound units of coal which accumulated during decreasing accommodation

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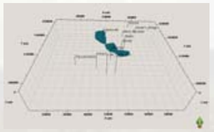
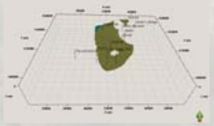
7. 3D Model Construction

A 3D model was constructed using the results from the petrographic analyses in order to visualise the vertical and lateral variatiability in the composition of the Fire Clay coal using Petrel reservoir modelling software.

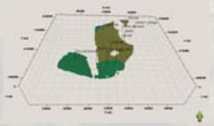
The modelling approach is similar to that used in constructing models of petroleum reservoirs. Firstly, a series of "zones" was defined, based on the thickness data for each of the seven units identified within the coal. The extent of the model is based on the approximate present day extent of the Fire Clay coal in eastern Kentucky.



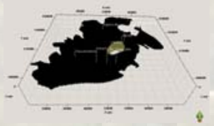
Unit 1 - the basal zone is only present at Garrett and Salyersville.



Unit 2 - the second zone is present in six localities.

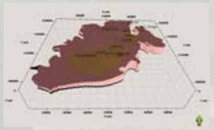


Unit 3 - the third zone is only present in the SW.

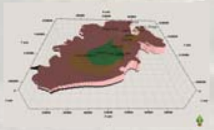


Unit 4 - the Tonstein is present across most of the model.

Unit 5 - the fifth zone is present across the entire area.

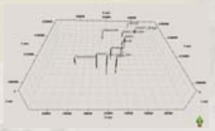


Unit 6 - the sixth zone is restricted to the central area.

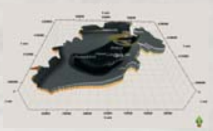


Unit 7 - the uppermost zone is also laterally restricted.

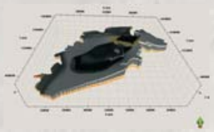
The results of the petrographic analyses at each locality were then imported into the model as 'pseudo-well logs' and upscaled to the resolution of the layering in the model (average layer thickness = 2cm / 0.8 inches). The rest of the cells in the model were then populated using a Kriging interpolation. Finally, the model was flattened on the top of the volcanic ash horizon (unit 4) which best approximates a time line.



Petrographic data imported as well logs and upscaled.



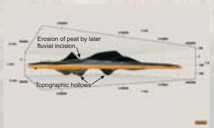
Model after population using a Kriging interpolation.



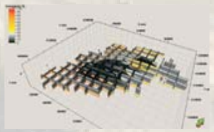
The model after flattening on the top of the volcanic ash horizon.

The completed model enables the visualisation in 3D of the thickness variation of each unit and clearly demonstrates how pre-existing topography was in-filled by the basal units of the coal.

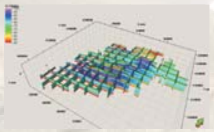
The model can be 'sliced' in any direction in order to produce a series of cross-sections through the coal, showing vertical and lateral variation in the composition of the coal.



Side on 3D view showing basal topography and erosion of the Fire Clay coal.



Cut-away view showing variation in content of inorganic minerals in the Fire Clay coal.



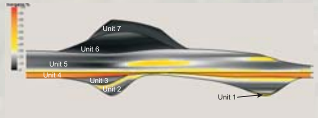
Cut-away view showing variation in vitrinite : inertinite ratio in the Fire Clay coal.

8. 3D Model Cross-sections

The figures in this panel show north-south and west-east cross-sections through the Carr Creek Lake locality, and illustrate the variability in the inorganic mineral content of the coal and the ratio of vitrinite to inertinite in the coal.

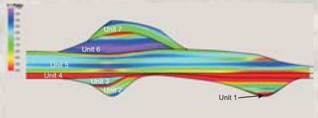
The figures on the left side of this panel show the true thickness of the layers in the model (top of volcanic ash-fall horizon is a horizontal datum). Vertical exaggeration is 20,000:1. The figures on the right side of the panel show chronostratographs (layers were restored to horizontal to approximate time-lines) produced using the 'Simbox' view in Petrel. This view is useful for demonstrating the temporal evolution of the Fire Clay coal.

Map view of the cross-sections.

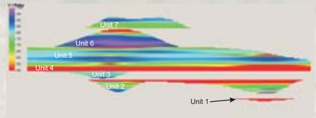


North-south cross section showing variation in inorganic content of the coal.

North-south Simbox view showing variation in inorganic content of the coal.

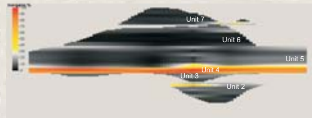


North-south cross section showing variation in the vitrinite : inertinite ratio.

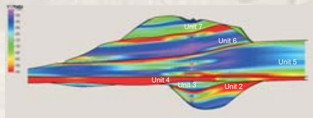


North-south Simbox view showing variation in the vitrinite : inertinite ratio.

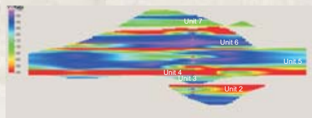
West-east cross section showing variation in inorganic content of the coal



West-east Simbox view showing variation in inorganic content of the coal



West-east cross section showing variation in the vitrinite : inertinite ratio



West-east Simbox view showing variation in the vitrinite : inertinite ratio

The cross-sections illustrate the vertical trends within each of the units (as described in sections 5 and 6). Increased inorganic content and a decreased vitrinite : inertinite ratio towards the top of each unit is due to increased oxidation of the peat. These trends are particularly well expressed in Units 2 and 6. The sections also illustrate how more localised increases in inorganic content (and/or decreased vitrinite : inertinite) can occur within the coal.

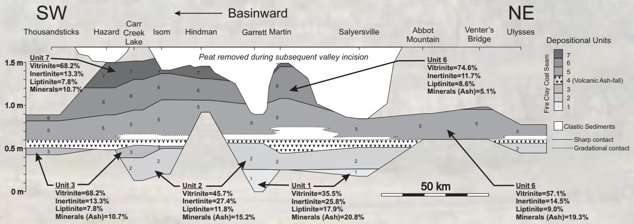
9. Summary & Conclusions

1. Coal seams have a complex internal stratigraphy that preserves a detailed record of water-table fluctuations which occurred during the accumulation of the original peat. By interpreting this water-table record, it is possible to predict lateral and vertical changes in the composition of the resulting coal.

2. Detailed petrographic study of the Fire Clay coal reveals that the coal spans six high-frequency accommodation cycles, separated by hiatal surfaces which may be the organic, terrestrial expression of high-frequency sequence boundaries.

3. The hiatal surfaces within the Fire Clay coal are expressed by a significant increase in the proportion of oxidised macerals (inertinite) and resistant peat components (liptinite and inorganic minerals), followed by an abrupt increase in humic macerals (vitrinite) and reduction in oxidised macerals at the base of the overlying unit.

4.Recognition that a coal seam may be composed of multiple, stacked mires, which accumulated under different conditions, and have different overall compositions and aerial distributions, has implications for predicting whole-seam quality and thickness beyond data points.



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