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Time, Hydrologic Landscape, and the Long-Term Storage of Peatland Carbon in Sedimentary Basins

**Key Points:**

- To understand how peat enters long term carbon storage requires consideration of peat accumulation over periods of 0.1–1 Myr years
- Peat accumulation over these timeframes requires sustained storage of water above depositional base level
- This has profound implications for our understanding of peat in the earth system and the interpretation of the geological record



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Abstract Peatland carbon may enter long-term storage in sedimentary basins preserved as either coal or lignite. The time required to account for the carbon in 1–10 m thick coal seams must represent 10⁵–10⁶ years, an order of magnitude more than previously assumed. To understand the process by which this happens requires extrapolation of our understanding of peatland carbon accumulation over timescales that greatly exceed those of Holocene peat. We analyze the consequences of extrapolating peat growth to periods of 10⁶ years. We deduce that that key to sustained peat growth are hydrologic landscapes that can maintain a saturated peat body above the level of clastic deposition. Contrary to current stratigraphic frameworks, we conclude that the generation of accommodation space at low rates of 0.1–0.2 mm/yr can adequately accommodate thick peat accumulation over periods >10⁵ years. However, generation of accommodation space at rates >0.5 mm/yr cannot. The low rates that permit accommodation of thick peat are typical of the rates of subsidence in specific tectonic settings, particularly foreland basins, and this has implications for our understanding of the links between terrestrial carbon burial, tectonics and the carbon cycle. The long-term stability of extensive peatland required to form coal also requires sediment bypass, modifying basin wide sediment transport and deposition. Limits to peatland growth under very low accommodation rates must exist but the relative importance of the limiting process is not understood. Finally, we discuss the consequences of these factors for predicting the future of the peatland carbon reservoir.

Plain Language Summary Over the past 300 million years peatland carbon has accumulated in sedimentary rocks where it occurs as coal and lignite. This process is important as it removes carbon dioxide from the atmosphere and stores it as carbon in the Earth's crust, providing a long-term cooling mechanism for global climate. In this context, recent research has shown that layers of coal previously thought to have accumulated over 10,000 years have accumulated over periods of a hundred thousand to one million years. This marks a huge shift in our understanding of the periods over which peat can accumulate continuously. In this study, we explore the consequences of this for our understanding of the surface and tectonic processes that lead to the storage of peatland carbon in sedimentary rocks. We show that the key to continuous peat accumulation and crustal storage of carbon are landscapes that maintain stable hydrology with lower rates of subsidence than previously thought. Applying these observations, we provide a new framework for interpreting peat, lignite and coal. We then highlight links between tectonic process and peatland carbon storage, and discuss gaps in our understanding of peatland processes, particularly the limits to peat accumulation within a landscape.

1. Introduction

Peatland carbon may enter into long-term crustal storage in sedimentary basins where it occurs as either coal or lignite. To understand the process by which this happens requires a conceptual bridge between peatland processes measured on Holocene timescales and processes over the much greater timescales required to explain features of substantial deposits of coal and lignite. Key to this conceptual bridge are the consequences of extrapolating Holocene peatland processes over long timeframes. However, these consequences are not considered by either peat scientists or coal geologists, and the absence of this analysis results not

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only in flawed stratigraphic interpretation, but also undermines our ability to understand peat within the Earth system on timescales that greatly exceed those of the Holocene.

Coal is one of our most significant energy resources and generations of geologists have studied coal sedimentology, geochemistry and stratigraphy. Many approaches have been applied to interpret coal stratigraphy (Dai et al., 2020; C. F. K. Diessel 1992) and currently, the most favored approaches (e.g., C. Diessel et al., 2000; Holz et al., 2002; Jerrett, Davies, et al., 2011, Jerrett, Flint, et al., 2011), are founded on the stratigraphic framework proposed by Bohacs and Suter (1997). In this stratigraphic framework, growth of the water-saturated precursor peat responds to the rate of change in the space available for sediment accumulation, known as the accommodation space. The balance between the rate at which accommodation space changes (on account of tectonic subsidence, change in sea level and sediment accumulation) and the peat production rate determines the resulting thickness, areal extent and composition of the peat. This stratigraphic framework acknowledges but does not focus on other factors (e.g., climate, groundwater, vegetation, and geomorphology) that influence peat accumulation. By applying this stratigraphic framework, coal is integrated into stratigraphic models (Davies et al., 2005; Jerrett, Flint, et al., 2011; Michaelsen et al., 2000; Staub, 2002) where it forms an interpretative bridge between the marine and terrestrial realms (Wadsworth et al., 2010).

If coal is to form, the need for both peat accumulation and accommodation space is unquestionable. However, the assumptions that underpin the interpretation of coal within stratigraphic frameworks, including those of Bohacs and Suter (1997), are not firmly grounded in the processes that determine the formation and accumulation of peat. Specifically, there are two flaws. Stratigraphic frameworks consider only the volumetric growth of peat (predominantly water) and subsequent compaction, while ignoring the processes that determine carbon accumulation. They also assume that peat properties, including thickness and composition, are highly responsive to the rate at which accommodation space is generated. The first flaw results in an order of magnitude underestimate of the time required to account for the carbon in coal (Large & Marshall, 2015). The second flaw devalues the interplay between hydrology, geomorphology and water storage in determining the long-term stability and duration of a peat body. Consequently, stratigraphic interpretations based on the approach of Bohacs and Suter (1997) treat coal as a relatively transient component of the stratigraphic record, which in turn requires the inference of significant stratigraphic hiatuses (e.g., Jerrett, Flint, et al., 2011, Jerrett, Davies, et al., 2011; Scott & Stephens, 2015). It also results in coal seams that must have accumulated over periods of 10^5 – 10^6 years being interpreted as would a Holocene peat with duration of 10^4 years, effectively ignoring the extent and potential stratigraphic and paleoenvironmental value of the record contained within the coal. Consequently, the approach also fails to recognize the capacity of peat to modify sediment transport and storage within a basin, and the capacity of coal to inform our long-term understanding of basin hydrology and its evolution relative to active structures and paleo-landscape.

The study of Holocene peat is inherently constrained by its 10 kyr timeframe and peat scientists rarely consider the consequence of extending their inferences over the timeframes in which peat may enter crustal storage or become limited within the landscape. For example, peat growth models (e.g., Baird et al., 2012; Froking et al., 2010; Morris et al., 2012) are never extended over timeframes that greatly exceed those of the Holocene. Consequently, their validity with respect to long-term crustal storage of peat remains untested.

In this study, we define a new stratigraphic framework for the interpretation of peat, lignite and coal founded on an understanding of carbon accumulation within a hydrologic landscape. Using the carbon accumulation basis for determining time in coal, defined by Large and Marshall (2015), we determine the implications for the processes leading to crustal storage of peatland carbon over extended time scales of peat accumulation. The result is a more informed interpretative framework that encapsulates the interaction of geological structures, geomorphology and hydrology over a wide range of timescales and enables a greater understanding of peatlands within the Earth system.

2. Basis for a New Hydrologic Landscape Approach

In the sections that follow, we define base level as the local graded stream profile, the level at which clastic deposition and erosion balance (Catuneanu, 2006). For simplicity, and to align with the terminology used in the stratigraphic model of Bohacs and Suter (1997), the rate at which accommodation space is generated (Catuneanu, 2006) is referred to as the accommodation rate.

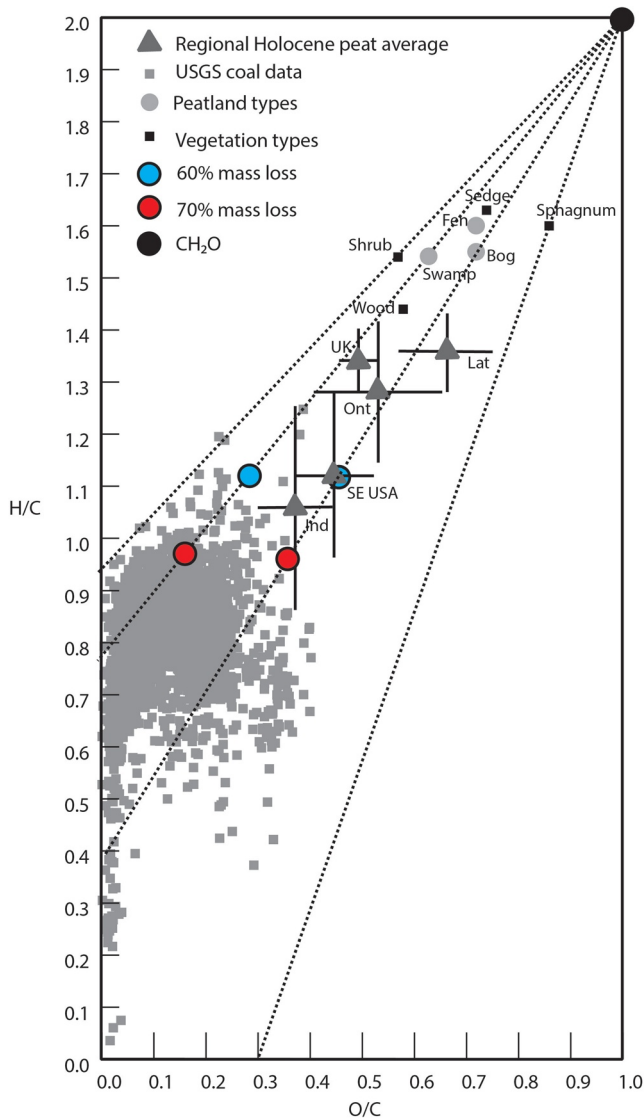


Figure 1. A van Krevelen diagram illustrating the continuous relationship between the C-O-H composition of vegetation, peat, lignite and coal. Coal data spanning the compositional range from lignite to anthracite, ranging in age from Neogene to Carboniferous is from the USGS coal quality database ($n = 7,000$). Mean peat, peatland and vegetation compositions are from Moore et al. (2018) and references therein. Mean peat data is shown for UK, Latvia (Lat), Ontario (Ont), Indonesia (Ind), and Southeast USA. Projection lines are indicated assuming mass is lost as mean organic matter CH_2O equivalent to loss of CO_2 and CH_4 in equal proportions. Positions of average swamp and bog are shown after 60% and 70% loss of mass.

For ease of reference, we use the term coal as the generic term to refer to both coal and lignite. In this context coal is a readily combustible rock containing more than 50 percent organic matter by weight (on a dry basis), which was formed from the compaction and alteration of plant remains (Alpern & de Sousa, 2002; Jackson, 1997; Schopf, 1956). There is no single formal definition of peat. For the purpose of this paper we use the definition, modified after Schopf (1966), that peat is an un-consolidated, hydrophilic, carbonaceous sediment, formed by accumulation of partially fragmented and decomposed plant remains. The precursor to coal is always peat, however, not all materials classed as peat could form coal.

2.1. Carbon Accumulation and Time

As coal is predominantly carbon, a carbon basis for determining the duration of a coal seam is far more appropriate and robust (Large & Marshall, 2015) than volumetric alternatives. The reason for this is that the processes determining the rate of carbon accumulation in peat and subsequent loss of carbon during coalification are well understood and quantifiable (Clymo, 1984; C. F. K. Diessel, 1992; Large & Marshall, 2015). For example, starting with a range of peatland vegetation chemistry (sphagnum, sedge, shrub, and wood) the relative positions of vegetation, peat and coal on a van Krevelen diagram (Figure 1) are consistent with a continuous process of transformation of vegetation to coal. Loss of CO_2 and CH_4 in equal proportions can account for this trend (Figure 1) as can loss of more complex mixtures including dissolved organic carbon (Moore et al., 2018). The positions of coal, peat and vegetation (Figure 1), are also consistent with a similar mix of peatland vegetation C-O-H chemistry accounting for all coal compositions throughout geological time. This illustrates that the mass balance during the transition from peat to coal is a predictable and measurable process. By accounting for the mass lost during the transition from peat to coal it is also possible to predict (Large & Marshall, 2015) the coal thickness equivalent to 20 kyr of carbon accumulation (Figure 2) for a range of carbon accumulation rates that are typical of global rates in the Holocene.

This leads to three important implications. First, the duration of coal seams is about an order of magnitude greater than previously considered for example, 1 m of bituminous coal formed under temperate paleoclimatic conditions at a carbon accumulation rate of $20 \text{ g/m}^2/\text{yr}$ would represent 100 kyr rather than the typically assumed 10 kyr (e.g., C. Diessel et al., 2000; Jerrett, Davies, et al., 2011). Second, most of the inorganic matter in coal can be accounted for by the deposition of atmospheric mineral dust at rates of $0.02\text{--}20 \text{ g/m}^2/\text{yr}$ (Large & Marshall, 2015; Marshall et al., 2016). Third, global variations in the composition of coal are predictable using uniformitarian assumptions of carbon accumulation rate and dust deposition (Large & Marshall, 2015; Marshall et al., 2016). This indicates that

First, thick coal seams (1– >20 m) can be of sufficient duration to span, without hiatus, periods of 0.1– >1 Myr and may account for more time than inter-seam clastic sediments (Large & Marshall, 2015). This has been previously inferred from field observation. For example, Broadhurst and France (1986) and Broadhurst and Simpson (1983) noting that coal seams were more strongly influenced by active structures and associated geomorphic features than the interseam sediments concluded that the duration of coal seams was considerably greater than that of the intervening sediments. Similarly, in the UK Carboniferous, Scott

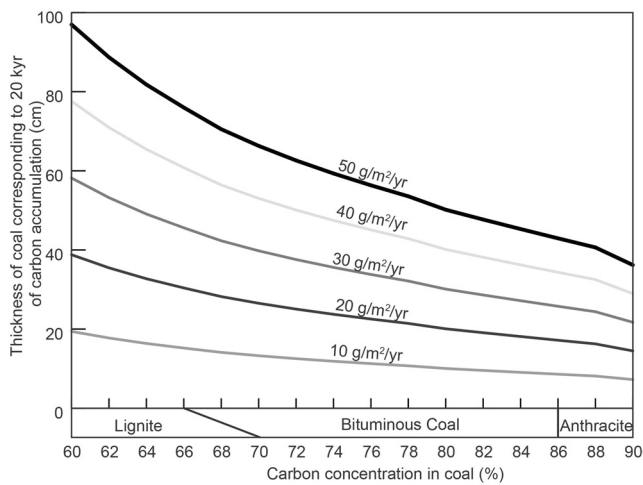


Figure 2. Plot showing the relationship between the coal seam stratigraphic thickness equivalent to 20 kyr of carbon accumulation, carbon concentration in coal on a dry ash free basis, and carbon accumulation rate in the precursor peat ($\text{g}/\text{m}^2/\text{yr}$). Carbon accumulation rates are chosen to represent the greater part of the range of reported Holocene rates, so are equivalent to the long-term rates measured over ~ 10 kyr. Coal thicknesses were calculated using the empirical carbon loss model of Large and Marshall (2015) and a starting carbon concentration in the precursor peat of 52% by weight on a dry ash free basis. The processes of carbon accumulation in peat have not varied markedly over geological time (Large & Marshall, 2015; Marshall et al., 2016). Four stratigraphic implications arise from these conclusions.

and Stephens (2015) concluded that a greater amount of time must be recorded in coal layers than by clastic sediments.

Second, coal is indicative of periods of sediment bypass during which fluvial clastic deposition is excluded. This conclusion arises as long-term siliciclastic deposition rates in coal forming environments (floodplains, estuaries and deltas) are typically in the range 0.02–1 mm per year (Einsle, 2000). At typical bulk soil densities of 1,200–1,600 kg/m^3 this corresponds to mass deposition rates of siliciclastic sediments of 24–1,600 $\text{g}/\text{m}^2/\text{yr}$. Supply of siliciclastic matter to peat at rates greater than 35 $\text{g}/\text{m}^2/\text{yr}$ would result in a rock with greater than 50% inorganic matter that could not be classed as a coal, and even the lowest of these rates would produce a low-quality coal containing at least 20% inorganic matter. These long-term rates are also much less than the rates of specific clastic depositional events (Schumer & Jerolmack, 2009). This conclusion matters as there is a prevalent view that a significant proportion of the inorganic matter in some coals can originate from fluvial clastic deposition (Dai et al., 2020; C. F. K. Diessel, 1992; Glasspool, 2003)

Third, in a given paleogeographic setting, the long-term rate of carbon accumulation tends to be constant and lie within the global Holocene range. This does not mean that the rate of carbon accumulation does not vary; it only implies that given suitable hydrology the conditions of nutrient supply (via atmospheric deposition), climate and productivity will tend to produce a stable long-term average rate in a given paleogeographic setting. It is therefore more appropriate to assume that for coals of similar paleogeography and rank, thicker coal accumulated over longer periods of time, not at a faster rate.

Finally, the accumulation of peat over long periods requires sustained supply of fresh water, which in turn requires sustained hydrological stability.

2.2. Water Storage

With typical dry bulk densities of $\sim 0.1 \text{ g}/\text{cm}^3$ (Clymo, 1984), by mass and by volume, peat is predominantly water. The exclusion of clastic sediment from raised peatland in low-lying areas is therefore due to the storage of a volume of water above base level. In upland areas of blanket bog, landscape incision and consequent sediment bypass are responsible for the exclusion of clastic sediment from the peat. Therefore, accumulation and preservation of peat is not only a matter of balancing rates of peat growth and accommodation; it is also a matter of sustaining water storage in the form of peat above the level of clastic sediment deposition. This is an important and fundamental difference between this approach and previous approaches (e.g., Bohacs & Suter, 1997; C. Diessel et al., 2000).

Evidence of being either in a state of clastic supply or clastic exclusion is the typically abrupt transition from clastic sediment to coal and *vice versa* (C. F. K. Diessel, 1992). Even gradual stratigraphic transitions tend to be characterized by intercalated thin coal and clastic horizons rather than gradual dilution of clastic sediment with organic matter (C. F. K. Diessel, 1992). If we accept there is more time in the coal than the clastic sediment, then the intercalation of clastic sediment and thin coal requires extremely limited accommodation space at the point where coal seams start to establish. A conclusion that is consistent with the base of coal seams being unconformable (Haszeldine, 1989).

The hydrological stability required to initiate and sustain a volume of water above the graded stream profile is strongly influenced by the capacity of groundwater to maintain the water-saturated state of a peat body during periods of water shortage (Glaser et al., 1997, 2004). Consequently, the position of peat within a landscape is strongly related to the discharge (or seepage) of groundwater (Winter, 2000) and

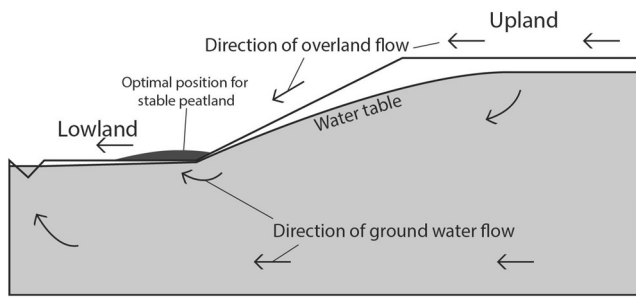


Figure 3. A schematic representation of the fundamental hydrologic landscape unit described by Winter (2000) illustrating the optimal position for peat accumulation.

the response of this discharge to crustal deformation (Glaser et al., 2004). Peatland supported by discharge from large groundwater catchments will be resilient to climate change. Peatland associated with small groundwater catchments that are highly dependent on annual rainfall will be less resilient (Hokansen et al., 2016; Winter, 2000).

2.3. The Hydrologic Landscape

Peat, as the precursor to coal, initiates in a landscape. The base of coal seams is typically unconformable, that is on land (Haszeldine, 1989). Based on analysis of controlling variables (eustasy, tectonics, climate, and vegetation), most coal seams initiate during periods of long-term lowering of global sea level (Railsback, 1995) i.e. when land is created. A useful way of conceptualizing the relationship between peat, geomorphology and hydrology on different scales, in a variety of settings, is the

hydrologic landscape concept (Winter, 2001). In this approach, Winter (2001) uses the idea of a fundamental hydrologic landscape unit. This unit consists of an upland separated from a lowland by a steeper slope (Figure 3), and incorporates both geology and climatic setting. Associated with the hydrologic landscape unit, Winter (2001), defines a hydrologic system (the components of the total hydrologic budget for any point on the landscape). This consists of surface water controlled by slope, slope aspect and surface permeability; ground water controlled by the subsurface hydraulic characteristics; atmospheric water controlled by climate. Where the supply of water is sufficient, ground water will tend to flow toward the surface (or discharge) at the base of a slope. Given a sufficiently wet climate or large enough groundwater catchment this creates the freshwater saturation required to initiate and maintain stable wetlands or peatlands (Winter, 2000). The base of slopes will therefore be the setting in which to initiate and maintain water saturated peat deposits (Figure 3).

There are two important aspects to the hydrologic landscape concept. First, the fundamental hydrologic landscape unit operates on multiple scales that can range from the break in slope between river terraces, to the transition from mountain range to basin. Scale is important because the scale of catchment determines the vulnerability and resilience of the peatland. Small catchments relating to small landscape units will be highly dependent on precipitation to sustain associated peatlands. Whereas large-scale units and associated catchments will be capable of buffering peatlands through periods of variable climate (Winter, 2000). Second, geomorphic evolution driven by tectonics and shaped by erosion evolves slowly over periods of 10^5 – 10^7 years, whereas climate and base level may display large fluctuations over much shorter timeframes. Hence, the long periods (10^5 – 10^6 years) of hydrologic landscape stability required to account for thick coal seams (e.g., Briggs et al., 2007; Large, 2007; Large et al., 2004; Large & Marshall, 2015) must depend on hydrologic landscape units controlled by tectonics and active structures within a basin. This is essential if hydrologic stability is to be sustained during periods of higher frequency climate and base level fluctuation.

The importance of hydrologic landscape is clear in the Holocene during which long-term accumulation of peat depends more on the capacity of the landscape to sustain water storage than on the capacity to generate accommodation space. This is evidenced by the widespread accumulation of peat on various scales in a range of hydrologic landscapes (e.g., boreal lowlands, upland blanket bogs, high-altitude plateaus and coastal plains) irrespective of base level, uplift or subsidence. The short timeframe of the Holocene relative to the timescale of significant crustal deformation also tends to limit our understanding to the tectonic and structural influence of glacio-eustatic rebound on peat initiation and hydrology (Glaser et al., 2004).

An aspect not explicitly considered by Winter (2001) is that as peat accumulates it will modify the hydrologic landscape, raising the local water table and shifting the breaks in slope. An example of this phenomenon is the spring line, visible on optical satellite images, surrounding the Hongyuan peat (Large et al., 2009) and neighboring peatlands on the Qinghai-Tibetan Plateau.

2.4. Influence of Changing of Base Level

A change in base level constitutes a change in the hydrologic landscape. As base level rises, surface wetness and run off increase, and new accommodation space is generated. At the level of the local graded stream profile, deposition and erosion balance, and the accommodation space is filled with clastic sediment.

In a hydrologic landscape in which peat has initiated and accumulated at the breaks in slope, rising base level is accompanied by clastic deposition away from breaks in slope. In smaller-scale hydrologic landscape units, groundwater discharge will decrease, and the water budgets required to sustain peat accumulation above base level will become increasingly dependent on local precipitation. If the water budget is insufficient to sustain a peat body above base level, the peat will be inundated by clastic sediment. As base level continues to rise, larger-scale hydrologic landscape units will maintain continuous peat.

Falling base level will reverse this trend. Water tables will fall and peat surfaces at the basin margin will become more vulnerable and collapse. However, if the scale of the hydrologic landscape units is sufficiently large, peat growth may be sustained even during periods of falling base level. At the same time, new breaks in slope associated with topographic features on the emerging and incised land surface will provide the necessary areas of groundwater seepage to initiate new peat growth.

Note that collapse of the peat surface does not necessarily mean that the peat becomes drier, as mechanically weak peat will initially collapse and track the falling water table. Only once the water table has reached the level at which the peat has sufficient strength to resist compaction will the water table continue to fall below the peat surface resulting in drying and oxidation of the peat.

Another means of modifying the relationship between base level and the hydrologic landscape is tectonic tilting. During this process, water storage will shift down the hydraulic gradient. Up gradient peat will collapse and possibly oxidize as water is withdrawn, while the down gradient time equivalent peat will be water saturated and tend to expand. In these circumstances time equivalent peats could have developed markedly different ecosystems. If the collapsed peat surface falls below base level, then the capacity exists to rapidly infill accommodation space above the peat surface. Collapse, due to water withdrawal, could explain the burial of large in situ tree trunks immediately above some coal seams (Broadhurst & Magraw, 1961; Falcon-Lang, 2006) and in areas adjacent to incised paleochannels (Guion, 1987).

2.5. Accommodation and Peat Growth Models

For peat to enter long term crustal storage accommodation rates need to allow continuous peat accumulation over periods of 10^5 – 10^6 years. To achieve this requires an appropriate balance between the accommodation rate and the rate of peat growth (Bohacs & Suter, 1997). This is complicated, as the rate of peat accumulation with respect to time is an inherently nonlinear balance between the input of organic matter and the mass of organic matter lost due to decay (Clymo, 1984). The nonlinearity of peat growth is ignored in previous stratigraphic models that assume linear peat growth rates (Bohacs & Suter, 1997; C. Diessel et al., 2000).

A simple evaluation of the consequences of this nonlinearity can be made by extending simple peat growth models (Clymo, 1992; Clymo et al., 1998) that provide realistic estimates of Holocene carbon accumulation over periods that greatly exceed 10 kyr. The shape of the peat growth curve generated by these models is governed by the initial decay rate, a (yr^{-1}), the decay rule that determines the change in decay rate as decay progresses, and the rate of input of carbon to the peat, p ($\text{kmolC m}^{-2} \text{yr}^{-1}$). Reasonable estimates can be made for rate of input and initial decay rates for the Holocene, however the decay rule over long periods is unknown. We also ignore short-term ecohydrological feedback. This is not unreasonable, as over long periods the mass balance between input and decay must shape the peat growth curve. Also, the longer-term effects of ecohydrological feedback, limited by the climate space in which the peat forms, should be represented as oscillations within the long term trend.

To illustrate the influence of nonlinear peat growth we choose the quadratic model of Clymo et al. (1998) which is expressed in Equation 1:

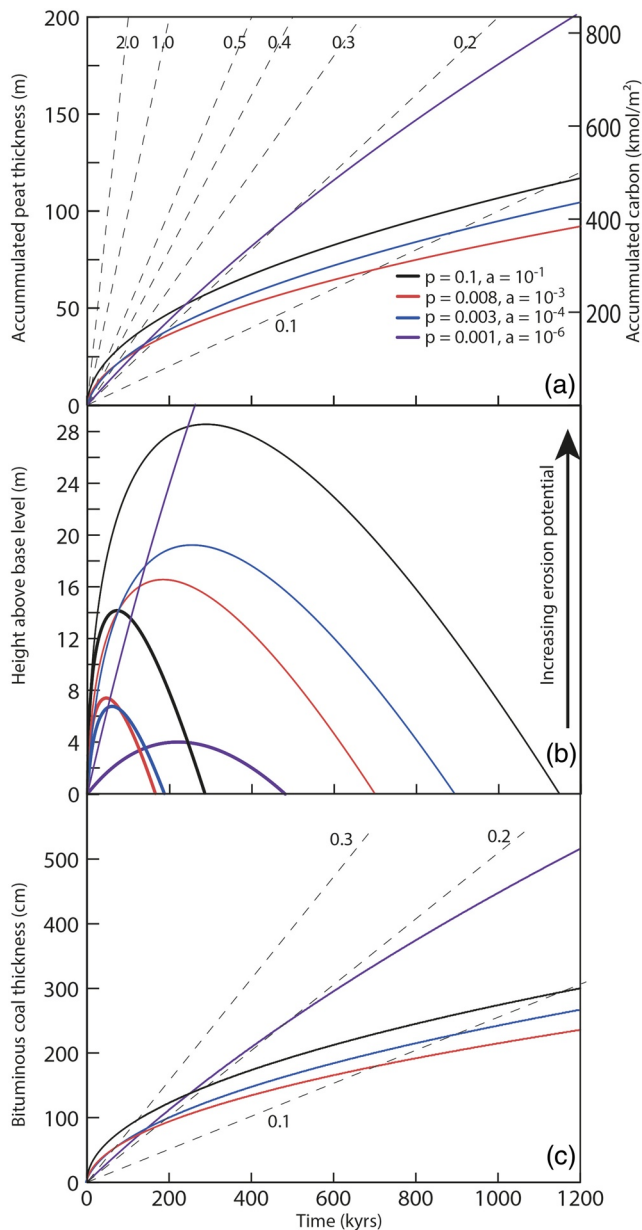


Figure 4. (a) The relationship between cumulative peat thickness, cumulative peat carbon, time and linear accommodation rates (dashed lines with values given in mm/yr). Peat growth curves are derived using the quadratic model of Clymo et al. (1998). Values of input (p) and initial decay rate (a) are chosen to represent the current range of global values: extreme low latitude, low latitude, boreal and high latitude. Conversion of cumulative carbon to thickness is based on a peat dry bulk density of 0.1 g/cm^3 and a carbon concentration of 50% on a dry ash free basis. (b) Derived from A this illustrates the height of peat accumulation above base level for accommodation rates of 0.1 mm/yr (thin lines) and 0.2 mm/yr (thick lines). Values of p and a are those given in A. (c) The results in are expressed as bituminous coal thickness. Coal thickness was calculated from the cumulative carbon using the empirical method of Large and Marshall (2015) to account for loss of organic matter during coalification.

$$M_t = \left(\frac{p}{a} \right) \left(\left(\sqrt{1 + 2at} \right) - 1 \right) \quad (1)$$

where M_t is the cumulative dry mass of carbon per unit area after time t (yr). This model is only a fixed point on a continuum of possible decay rules (Clymo, 1984) and is chosen for illustrative purposes as it generates reasonable accumulation over 10^4 years and much longer timeframes. Some other commonly used points on the spectrum of possible decay models have unreasonable stratigraphic consequences over longer periods of time. For example, using Holocene parameters and applying a constant decay rate model could not account for any significant coal accumulation. Four growth curves were generated (Figure 4a) that cover a range of inputs and decay values. Values were chosen to represent a range of environmental conditions: high latitude ($p = 0.001, a = 10^{-6}$); boreal ($p = 0.003, a = 10^{-4}$, similar to Clymo et al., 1998); low latitude ($p = 0.008, a = 10^{-3}$, much greater than the boreal values of Clymo et al., 1998); and extreme low latitude ($p = 0.1, a = 0.1$) equivalent to a tropical net primary production and a high decay rate in tropical soil (e.g., Yule & Gomez, 2009).

The peat growth curves (Figure 4) are then analyzed relative to linear accommodation rates, in effect constant subsidence. In reality accommodation rate may also be nonlinear, but this simplifying assumption helps focus our analyses on the consequences of nonlinear peat growth. To provide an understanding of what might be observed in terms of long-term crustal storage equivalent bituminous coal thicknesses (Figure 4c) are calculated based on the cumulative carbon and accounting for the loss of carbon during coalification (Large & Marshall, 2015).

Analysis of the relationship between accommodation rate and the modeled growth curves (Figure 4) leads to the following implications for a system in which clastic supply is sufficient to fill the available accommodation space.

Peat accumulation above base level occurs if the value of p and its volumetric equivalent exceeds the accommodation rate (Figures 4a and 4b). Significant peat accumulation sufficient to generate $>50 \text{ cm}$ of bituminous coal occurs at accommodation rates $<0.5 \text{ mm/yr}$ (Figure 4c). Contrary to the conclusion of Bohacs and Suter (1997) it is improbable that high accommodation rates of $1\text{--}2 \text{ mm/yr}$ could permit thick peat accumulation. Tropical peats with high values of p can grow and establish above base level more rapidly (Figure 4b) than boreal peat. Over short timeframes of $<70 \text{ kyr}$ apparent long-term accumulation rates appear higher in the tropics and lower at high latitude, whereas over longer timeframes this relationship reverses (Figure 4a). Whether or not that reversal is apparent over the timeframe of the Holocene is unclear, however although peat thickness is highly variable, greater Holocene peat thicknesses are more commonly reported from tropical regions (e.g., Anderson, 1983; Page et al., 1999). At accommodation rates of between 0.1 and 0.2 mm per year, which are at the extreme low end of the range used by Bohacs and Suter (1997), $100\text{--}400 \text{ kyr}$ of continuous peat accumulation can be accommodated with the height of peat above base level not exceeding 8 m (Figure 4b). Temperate peatlands offer the maximum capacity for long-term carbon storage as they have the right balance of input

and output to enable establishment and long-term growth above base level (Figures 4a and 4b). In contrast to the conclusion of Bohacs and Suter (1997) the ratio of the accommodation rate to the peat production rate varies throughout the period of peat accumulation and bears no necessary relationship to the condition of the peatland (Figure 4a). Given sufficient time and a constant accommodation rate all peat deposits will be terminated by inundation, however, if the accommodation rate is too low, or zero, the model effectively permits indefinite peat accumulation above base level and this process must in some way be limited by erosion (Figure 4b).

2.6. Limits to Peat Accumulation

Stratigraphic models assume that erosion and/or unfavorable hydrology rapidly limit peat growth in areas with no accommodation or falling base level. Over the short term, such as the period of the Holocene, the influence of geomorphology overcomes this and explains why extensive peat continues to accumulate in actively eroding landscapes with no increase in accommodation space. Furthermore, reported Holocene peat thickness, for example those in the database of Loisel et al. (2014), rarely exceed a thickness of 8 m, so the influence of erosion on thicker accumulations above base level (Figure 4b) remains untested over the timeframe of the Holocene. We therefore deduce that 10 kyr is generally insufficient time to observe significant limits to peat growth. So, what processes ultimately limit peat accumulation in settings with little or no accommodation space on timescales much greater than 10 kyr? The answer to this question is significant, as considerable quantities of Holocene peat occur in uplands or areas of active post-glacial uplift with limited or no capacity for long-term crustal storage. The following two key processes limit peat growth.

2.6.1. Hydrological and Oxidative Limits

Without accommodation the supply of water ultimately limits peat growth in any landscape setting. As peat growth approaches the hydrological limits of the system, oxidative decay above the water table increasingly limits carbon accumulation. This intrinsic limit in which the balance between productivity and decay determines an upper limit to carbon accumulation (Clymo, 1984) has been used to predict future long-term limits ($>10^4$ years) to northern peatland carbon stocks (Alexandrov et al., 2020).

This is problematic for several reasons. By necessity it assumes constant values for hydraulic conductivity, ignoring the poro-elastic response of the multiphase (solid, liquid, gas) peat matrix. For example, peat dry bulk density in the saturated zone can vary from 0.02 to 0.2 g/cm³ (Large et al., 2009; Page et al., 2004) and peat hydraulic conductivity may vary by several orders of magnitude (Charman, 2002). These illustrate that mechanical change in the pore structure of the peat can buffer the hydrology and create large uncertainty in model outputs. It ignores the role of the hydrologic landscape. Assuming some level of sustained input of atmospheric mineral dust at even quite low rates, the long-term consequences of oxidative limitation would be that the peat soil would transition into a mineral soil. For example, recent rates of dust deposition over peatland in western Siberia range from 1 to 12 g/m²/yr (Fiałkiewicz-Kozieł, 2016), ~5%–50% of the Holocene boreal long-term carbon accumulation rate (Loisel et al., 2014) before an oxidative limit has been reached. Some of this mass will be lost as soluble elements; however, most of the mass in the form of low solubility alumino-silicates, is retained (Large & Marshall, 2015).

2.6.2. Mechanical Deformation and Erosion

The stability of a peat body in the absence of accommodation space must be mechanically limited. The weak peat body must eventually undergo structural failure (mass movement), drainage, and subsequent erosion, even under sustained ideal conditions for peat formation. The inevitability of such mass movement has been noted and observed in specific blanket bog settings (Tallis, 1985), however, it is not generally considered as a limiting process in all settings in which accommodation space is limited or unavailable. The surface of the peat body may also wrinkle, as proposed by Pearsall (1956) and observed in one mechanical simulation (Briggs et al., 2007), possibly into the characteristic patterns of hummocks and hollows observed in the field (Morris et al., 2013; Pearsall, 1956) and in some coal seams (Broadhurst & Simpson, 1983; Rippon, 1998). Such wrinkles could conceivably generate water channels leading to erosion, drainage and oxidation of a raised peatland under sustained wet conditions.

The accumulation and growth of peat above base level is in-effect an increase in elevation, which from the perspective of erosion is no different to tectonic uplift. Observations and theories of landscape formation (e.g., Kirby & Whipple, 2012) require that an increase in elevation of the land must be constrained by erosion, particularly so in the typically wet climates associated with peat formation. Fluvial erosion has been studied in peatlands (Gradzinski et al., 2003; Li et al., 2017; Watters et al., 2007) but often from a short-term perspective of land management and carbon budgets (Cowley et al., 2018; Evans et al., 2006; Li et al., 2017) rather than the perspective of long-term limits. This lack of consideration of the limits imposed by natural erosion probably results from two peatland characteristics. First, the fibrous nature of peat is relatively resistant to erosion creating a distinctive channel morphology and limiting channel movement (Gradzinski et al., 2003; Watters et al., 2007). Second, it is difficult to quantify natural processes of erosion in highly modified (e.g., from the effects of over grazing and trampling) and managed landscapes. An additional and notable contribution to peat erosion, particularly in upland areas is aeolian deflation, which can rapidly occur following fluvial incision (Foulds & Warburton, 2007). An ideal location in which to test the relative influence of erosion, mass movement and hydrology is the Falkland Islands. Although intensively grazed, a significant proportion of Falkland Island blanket peat initiated pre-Holocene (Payne et al., 2019), is highly dissected and in optical images and in the field shows ample evidence of established erosion and mass movement that must predate human occupation of the islands.

2.7. Hiatuses Within Peat and Coal

In many interpretations, the lateral equivalent of stratigraphic boundaries generated on account of base-level fluctuations within a subsiding basin are interpreted as intra-seam hiatuses in coal and vice versa. Evidenced by change in humification without notable siliciclastic deposition these hiatuses are interpreted to represent periods on the order of 10^4 – 10^6 years (Davies et al., 2005; Holdgate et al., 1995; Jerrett, Davies, et al., 2011). This is improbable. The generation of depositional breaks in peat requires sustained erosion or nonaccumulation of the peat surface without accommodating clastic input or atmospheric dust. This is difficult, as peat will continue to lose mass due to on-going decay, in effect creating its own accommodation space. Furthermore, organic rich peat surfaces are naturally attractive sites for plant growth and, even in the absence of clastic deposition re-establishment of peat accumulation is likely on periods much less than 10^4 years. Evidence to support this are the short periods (about 10^2 – 10^3 years) that account for hiatuses in Holocene peat known as recurrence surfaces (Borgmark, 2005). The short duration of these time gaps is not surprising as even the loss of the top 1 m of a typical Holocene peatland need not result in a stratigraphic gap of more than 10^3 years (Borgmark, 2005; Page et al., 2004). Consequently, in a subsiding basin, it is improbable that intra-seam discontinuities without clastic deposition could represent long periods.

2.8. Principles of the New Hydrologic Landscape Approach to the Crustal Storage of Peat

Based on the above it is possible to define a set of considerations and related guidelines for the interpretation of peat and coal.

First and foremost, the hydrologic landscape (Figure 3) determines the position, volume and extent of a peat body. Within that landscape thick peat forms in areas of prolonged hydrological stability the resilience of which is determined by the geometry, scale and persistence of the hydrological landscape unit. Relative change in base level will modify the hydrologic landscape but does not preclude the capacity of the hydrologic landscape to maintain peat growth above base level.

With respect to coal, in a given paleogeographic and paleoclimate setting, thicker coal seams accumulated over longer periods, not at a different rate, and the thickness of a coal seam is proportional to the time integrated carbon accumulation rate. The formation of coal requires clastic sediment bypass and hence storage of water in the precursor peat above the level of the equilibrium stream profile. Therefore, changes into and out of periods of coal formation is a response to the change in the volume of water stored above base level.

3. Discussion

Previously considered transient, coal records are now demonstrably of sufficient duration to capture global change in a manner analogous to an ice core. This most significant change in interpretation arises from the order of magnitude increase in time required to account for the carbon in coal. The capacity to ascribe

timescales to coal records without worrying about independent chemostratigraphic or biostratigraphic tie-points enables a huge post-Devonian archive of global environmental change contained in coal to be re-evaluated. This archive has the potential to yield time calibrated records of atmospheric deposition (Marshall et al., 2016), fire (Belcher et al., 2003; Scott & Glasspool, 2006), palynology (D. J. Nichols & Warwick, 2005; Phillips et al., 1985), organic geochemistry (Bechtel et al., 2008; Benner et al., 1987), plant and atmospheric $\delta^{13}\text{C}$ (Arens et al., 2000), paleotemperature (Inglis et al., 2017), and much more. Indeed, given the potential duration of coal seams it is unsurprising rather than fortuitous that several major global events have been reported from within coal seams (Collinson et al., 2009; Steinhorsdottir et al., 2016; Wang et al., 2018) and a more appropriate internal timeframe should greatly assist their interpretation.

Given sufficiently thick coal, predicted timeframes may also be tested directly. For example using Ar-Ar radiometric ages from associated volcanic ash deposits (Chen et al., 2014), or Re-Os dates from marine-influenced coal (Tripathy et al., 2015). Uncertainty in the radiogenic age is often greater than the likely duration of the seam and this may constrain useful application. Timeframes may also be indirectly tested relative to stratigraphic tie-points and whether or not they remove or create stratigraphic anomalies. For example, when our estimates of time in coal are applied to the Duckmantian-Langsettian interval of the Carboniferous, the time accounted for in the clastic sediments and coal increases from 75 to 125 kyr (Scott and Stephens, 2015) to 0.7–1.5 Myr (Large & Marshall, 2015). The former value requires huge unsubstantiated hiatuses whilst the latter does not and still lies within chronostratigraphic estimates for the duration of the interval.

Our approach has the capacity to enhance understanding of syn-depositional basin processes and the tectonic environments in which peat may enter crustal storage. Our postulated rates of basin subsidence required to sustain peat accumulation are encountered in many tectonic settings (Allen & Allen, 2013) associated with significant accumulations of coal. On extensional continental margins, such as the coal-bearing Gippsland Basin (Birch, 2003), subsidence rates range from 0.2 mm/yr at the initiation of rifting to less than 0.05 mm/yr during the flexural subsidence phase, over time scales of 10^6 – 10^7 years (Allen & Allen, 2013). Foreland basins subside at rates of 0.2–0.5 mm/yr, and cratonic basins at 0.01–0.04 mm/yr (Allen & Allen, 2013). Coals in the cratonic basins of Australia are notably oxidized, a property that is a logical consequence of particularly low rates of subsidence (Hunt & Smyth, 1989).

Foreland basins, in particular, hold vast coal deposits. For example, the Cretaceous western interior and Laramide forelands in North America (Dickinson et al., 1988; Pederson & Dehler, 2005), the Gondwana Panthalassa foreland (Veevers & Powell, 1994), and the late Carboniferous Variscan foreland in Europe (Mazur et al., 2010; Suess et al., 2007). They also collect rainwater and are first order hydrological basins (Garcia-Castellanos, 2002) or, indeed, first order hydrological landscapes. So, given a suitable climate, does the structural and hydrological evolution of a foreland basin favor the stable hydrologic landscapes required to sustain peat accumulation? If such a logical link exists on timeframes of 10^5 – 10^7 years then the concepts presented in this paper should enable a more informed incorporation of terrestrial carbon accumulation into models that integrate tectonics, hydrology, geomorphic evolution and the carbon cycle (e.g., Wong et al., 2019).

Evidence of such a link between the tectonic cycle and peat entering crustal storage may be the coincidence between type III kerogen burial (predominantly coal), an increase in the global ratio of the rates of carbon to sulfur burial (Bernier, 2003), and the burial of extensive carbon in the Variscan, Gondwana (Veevers, 2013), and Cretaceous western interior (Molenaar and Rice 1988) foreland basins. In this context, Bernier (2003) notes that a prominent peak in the ratio of carbon to sulfur burial corresponds to a lower-than-expected proportion of type III kerogen burial (coal) in the Late Carboniferous and Permian. A possible explanation for this anomaly is that the rate of Paleozoic type III kerogen burial, determined from the volumetric proportion of coal in sedimentary formations, is markedly underestimated relative to its Mesozoic and Cenozoic equivalents and not directly comparable to C/S burial derived from syndepositional stable isotope values. Peat, up to 20–40 Myr post-deposition, will typically be lignite. Carboniferous and Permian peat, ~300 Myr post deposition is typically high rank bituminous coal or anthracite. The volume of Carboniferous coal will therefore be almost half that of its Cenozoic lignite equivalent (Figure 2). Syndepositional rates of type III kerogen deposition almost twice those estimated from current coal deposits, easily remove the late Carboniferous and Permian deficit in type III kerogen burial.

The hydrological landscape requirements for sustained accumulation of peat mean that coal seam thickness should be a sensitive indicator of syn-depositional geomorphic evolution within a basin. Using our approach in combination with isopach maps, variations in coal thickness can be used to map the evolution of active structures and landscape within a basin. A specific example of this is the detailed work of Marshall (2013) who demonstrated the role of persistent structures in controlling the geomorphology, distribution and thickness of early Paleocene coal within the Central Tertiary Basin, Svalbard. There are also numerous other examples (e.g., Ferm & Staub, 1985; Greb et al., 2001; Guion, 1987; Haszeldine, 1989; Read, 1989) linking coal thickness to syn-depositional topography, differential compaction, and tectonics. However, they have not been interpreted in the context of a hydrologic landscape over an appropriate time-frame and re-analysis of these data is beyond the scope of this paper.

A hydrological landscape that sustains the stability of peatland above depositional base level must also sustain sediment bypass and modify the supply, transport, and distribution of sediment within a basin. Basinward, a period of extensive peat accumulation should be marked by enhanced sediment supply and associated progradation, for example, of thick shoreface sands. Such an association is observed in many coal-bearing paralic systems. For example, extensive coastal peat deposits are observed to pass laterally into thick shoreface sediments within the Central Tertiary Basin, Spitsbergen (Bruhn & Steel, 2003; Marshall, 2013), the Cretaceous South-Western Interior Basin, USA (Pederson & Dehler, 2005), the Cretaceous Blackhawk Formation, USA (Jerrett et al., 2011a) and in the Gippsland Basin, Australia (Birch, 2003). In all cases greater significance is placed on the capacity of clastic sediments to yield insights into basin evolution and stratigraphy, yet the coal may provide a more continuous record of syndepositional processes.

A set of implications also arise with respect to Holocene peat and the projected long-term carbon sequestration capacity of modern peatlands. Whilst there is a good knowledge of decay rates over periods <10 kyr and coalification rates over periods greater than 10 Myr there is nothing between. Therefore the only certainty on which long term models of continuous peat accumulation can be based is the nonlinearity of the mass balance between inputs and outputs. Extension of peat accumulation models over much longer periods does however provide a test of whether a given model is a reasonable basis for understanding crustal carbon storage. For example, using a Holocene parameterization, the constant decay model of Clymo et al. (1998) can provide an adequate approximation to peat growth over 10 kyr but places an absolute and nonsensical limit of <30 cm on the total thickness of coal that could ever be stored over periods >10⁶ years.

In the absence of accommodation space, there must be a limit to the quantity of peat a given landscape can hold. Therefore, an important question is how quickly, and over what spatial and temporal scales, erosion will limit the size of the peatland carbon reservoir in different geomorphic settings. Answers to this could have profound consequences for current and future management of peatland and for predictions of the capacity of the peatland carbon reservoir (Alexandrov et al., 2020; J. E. Nichols & Peteet, 2019). For example, upland blanket bog should reach its natural erosional limits faster than lowland raised bogs. Evidence of this is the eroded state of upland blanket bog (Tallis, 1985) and although land management practices may confound this judgment (Tallis, 1985), it can be argued that areas closer to their natural limits will be more vulnerable to environmental pressure. The inevitability of an erosional limit in landscapes where accommodation space is not being created also requires that we account for both spatial and temporal erosional losses when attributing a carbon flux to large areas of peatland. It also implies that in landscapes without the capacity to accommodate long-term accumulation of peat, the long-term management strategy should be to minimize rates of carbon loss rather than promote metastable growth above the natural limits imposed by erosion. In terms of global carbon budgets we can question where tectonics and hydrologic landscape are likely to enhance or limit the longevity of peat accumulation. Areas with the potential for long-term peat accumulation leading to crustal storage include the Sunda Shelf and Peruvian Amazon Basin, both foreland basins (DeCelles & Giles, 1996; Rasanen et al., 1992) holding large quantities of peat (Householder et al., 2012; Xu et al., 2018). Whereas, peatlands of the cratonic and isostatically uplifting Hudson Bay Lowlands and Scandinavia seem unlikely prospects for crustal storage.

4. Conclusions

To account for the crustal carbon contained within peat, coal, and lignite requires considerably longer periods than previously considered. In turn, this requires consideration of the parameters of the hydrologic landscape that can sustain the conditions suitable for peat formation. This approach brings coal strati-

graphic models in line with modern peat observations and can be applied to all peatland and coal settings on various scales. It sets limits on the tectonic environments that enable long-term accumulations of peat leading to coal and demonstrates that slow crustal deformation alone can sustain the hydrologic landscape necessary for thick coal formation. The sustained periods of peat formation needed to account for the carbon in coal require recognition of a prolonged and fundamental shift in the depositional environment and basinwide processes. The hydrologic landscape approach facilitates re-interpretation of these systems and raises questions as to the ultimate limits to peat accumulation.

Conflicts of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The paper does not contain new data.

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