Time, hydrologic landscape and the long-term storage of peatland carbon in sedimentary basins

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Abstract

Peatland carbon may enter long-term storage in sedimentary basins preserved as either coal or lignite. 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. By applying this extrapolation, we deduce that the amount of time required to account for the carbon in 1 – 10 m thick coal seams must represent 105 to 106 years, an order of magnitude more than assumed in current interpretations of stratigraphic frameworks. Extrapolating peat growth to periods of 106 years requires consideration of the conditions of landscape, hydrology, accommodation space and crustal deformation required to ensure the sustained growth and accommodation of peat deposits. We conclude that the generation of accommodation space at low rates (0.1 to 0.2 mm/yr) can adequately accommodate thick peat accumulation over periods >105 yrs. However, generation of accommodation space at high rates (>1mm/yr) cannot accommodate significant peat accumulation. Key to this process is the maintenance of a saturated peat body above the level of clastic deposition. This long-term stability of the system has implications for our understanding of the processes that limit peatland growth under very low accommodation rates and the long-term validity of current peat growth models.

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Key Points:

- To understand how peat enters long term carbon storage requires consideration of peat accumulation over periods of 10^5 to 10^6 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

Abstract

Peatland carbon may enter long-term storage in sedimentary basins preserved as either coal or lignite. 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. By applying this extrapolation, we deduce that the amount of time required to account for the carbon in 1 – 10 m thick coal seams must represent 10^5 to 10^6 years, an order of magnitude more than assumed in current interpretations of stratigraphic frameworks. Extrapolating peat growth to periods of 10^6 years requires consideration of the conditions of landscape, hydrology, accommodation space and crustal deformation required to ensure the sustained growth and accommodation of peat deposits. We conclude that the generation of accommodation space at low rates (0.1 to 0.2 mm/yr) can adequately accommodate thick peat accumulation over periods $>10^5$ yrs. However, generation of accommodation space at high rates (>1mm/yr) cannot accommodate significant peat accumulation. Key to this process is the maintenance of a saturated peat body above the level of clastic deposition. This long-term stability of the system has implications for our understanding of the processes that limit peatland growth under very low accommodation rates and the long-term validity of current peat growth models.

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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 consider by either peat scientists or coal geologists, and the absence of this analysis results, not 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 studied coal;its sedimentology, geochemistry and stratigraphy. Many approaches (Diessel 1992; Dai et al., 2020) have been applied to interpret coal stratigraphy. Currently, the most favoured approaches integrate coal into stratigraphic frameworks using the framework proposed by Bohacs and Suter (1997) and subsequently developed and refined (Diessel et al., 2000; Holz et al., 2002; Jerrett et al., 2011a; Jerrett et al., 2011b). In this stratigraphic framework, growth of the water-saturated precursor peat responds to the rate of change of the space available for sedimemnt 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, landscape) that influence peat accumulation. By doing this, coal is integrated into stratigraphic models (Davies et al., 2005; Jerrett et al., 2011b; Michaelsen et al., 2000; Staub, 2002) where it forms an interpretative bridge between the marine and terrestrial realms (Wadsworth et al., 2010).

While there is an unquestionably need to accommodate peat to form coal via the creation of accommodation space, the assumptions that underpin the interpretation of coal within stratigraphic frameworks including that 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; and they also assumes that peat properties, including thickness and composition, are highly responsive to the rate at which accommodation space is generated. The first flaw results in a gross order of magnitude underestimate of the time required to account for the carbon in coal; the second flaw devalues the interplay between hydrology, landscape and water storage in determining long-term hydrological 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 et al., 2011a; Jerrett et al., 2011b; Scott and Stephens, 2015). It also results in coal seams that must have accumulated over periods of 10^5 to 10^6 yr being interpreted as would a Holocene peat with duration of 10^4 yr, effectively ignoring the extent and potential stratigraphic and palaeoenvironmental value of the record contained within the coal. Consequently, the approach also fails to recognise the capacity 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 palaeo-landscape.

The study of Holocene peat on its own is inherently constrained by the Holocene timeframe and Holocene peat scientists rarely consider the extension of Holocene processes over timeframes in which peat may enter crustal storage or become limited within the current landscape. For example, peat growth models (e.g. Baird et al., 2012; Morris et al., 2012; Frolking et al., 2010) 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 paper, we address this issue by defining a new basis for the stratigraphic interpretation of peat, lignite and coal founded on the understanding of carbon accumulation within a hydrologic landscape. The result is a more informed model based on a wider scientific basis that encapsulates the interaction of geological structures, landscape and hydrology over a wide range of timescales and enables a greater understanding of peatland within the Earth system. Furthermore the results demonstrate that lignite and coal can provide invaluable long duration records of the conditions prevailing on the Earth surface at the time of formation.

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). The rate at which accommodation space (Catuneanu, 2006) is generated is, for simplicity and to align with the use in the stratigraphic model based on Bohacs and Suter (1997), referred to as the accommodation rate.

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 (Jackson,

1997; Alpern and de Sousa, 2002; Schopf, 1956). There is no single formal definition of peat so for the purposes of this paper we use a definition modified after Schopf (1966) in which 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 and 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 (Large and Marshall, 2015; Clymo, 1984; Diessel, 1992). For example, starting with a range of peatland vegetation chemistry (sphagnum, sedge, shrub, wood) the relative positions of vegetation, peat and coal on a van Krevelen diagram (Fig 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 (Fig 1) as can loss of more complex mixtures including dissolved organic carbon (Moore et al 2018). The positions of coal, peat and vegetation (Fig 1) are also consistent with a similar mix of peatland vegetation 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 measureable process. By accounting for the mass lost during the transition from peat to coal it is also possible to predict (Large and Marshall, 2015) the coal thickness equivalent to 20kyrs of carbon accumulation (Fig.2) for a range of carbon accumulation rates that are typical of global rates in the Holocene.

This leads to three important conclusions. First, the duration of coal seams is about an order of magnitude greater than previously considered e.g. 1 m of bituminous coal formed under temperate palaeo-climatic conditions at a carbon accumulation rate of $20 g/m^2/yr$ would represent 100 kyrs rather than the typically assumed 10 kyrs (e.g. Diessel et al, 2000; Jerrett et al, 2011a). Second, most of the inorganic matter in coal can be accounted for by the deposition of atmospheric mineral dust at rates of 0.02 to 20 $g/m^2/yr$ (Large and 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 and Marshall, 2015; Marshall et al., 2016). This indicates that

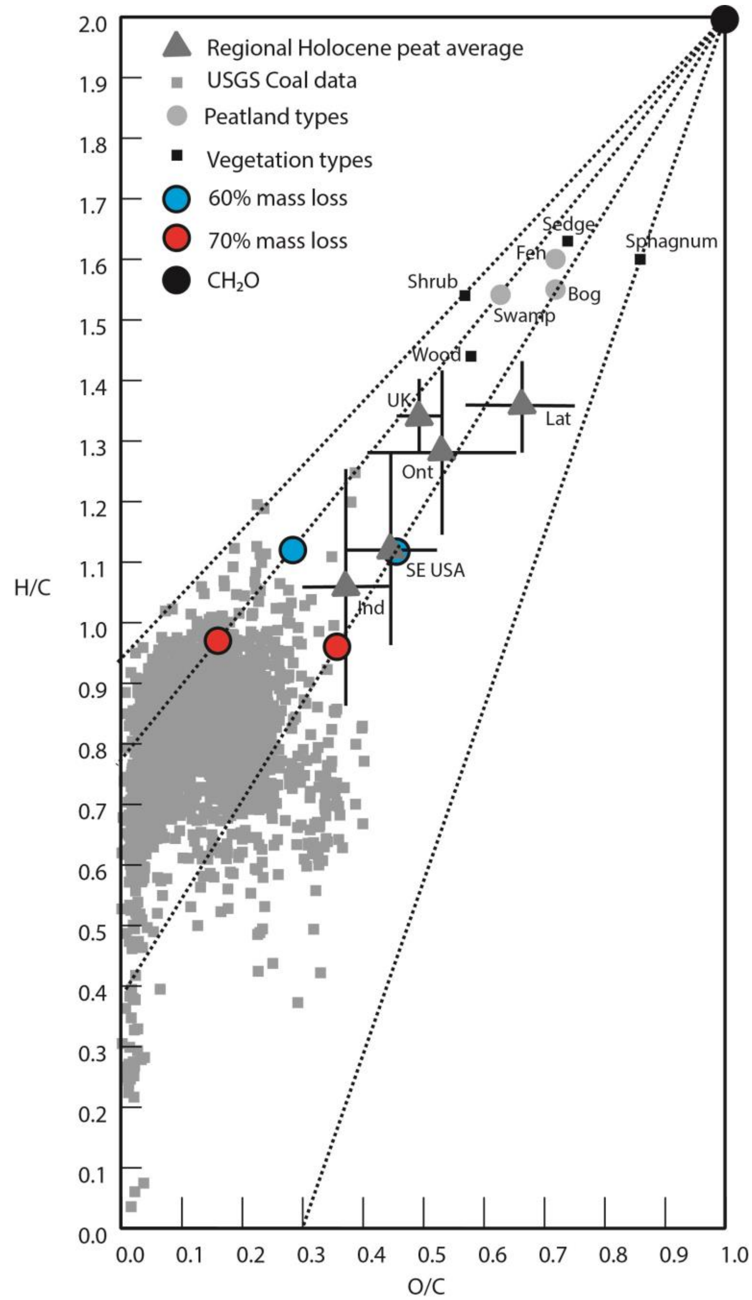

Figure 1 A van Krevelen diagram illustrating the continuous relationship between the C-O-H composition of vegetation, peat, lignite and coal. Coal data spanning the compositional range from lignite to anthracite, ranging in age from Neogene to Carboniferous is from the USGS coal quality database (n= 7000). 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.

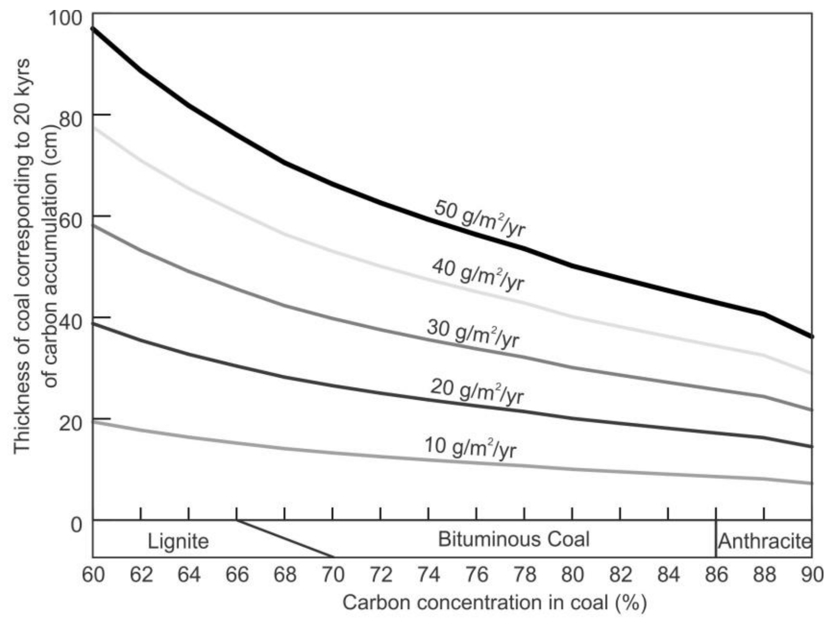

Figure 2 Plot showing the relationship between the coal seam stratigraphic thickness equivalent to 20 ky of carbon accumulation, carbon concentration in coal on a dry ash free basis and carbon accumulation rate in the precursor peat. Carbon accumulation rates are chosen to represent the greater part of the range of reported Holocene rates, so are equivalent to the long term rates measured over ca. 10 kyrs. 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 and Marshall, 2015; Marshall et al., 2016).

Several stratigraphic consequences arise from these conclusions:

1) Thick coal seams (1 m to > 20 m) can be of sufficient duration to span, without hiatus, periods of 0.1 to > 1 Ma and may account for more time than inter-seam clastic sediments (Large and Marshall, 2015).

2) Coal is indicative of periods of sediment bypass during which fluvial clastic deposition is excluded. This conclusion arises as:

   a. Silici-clastic deposition rates in coal forming environments (floodplains, estuaries and deltas) are typically in the range 0.02 to 1 mm per year (Einsele, 2000)

   b. At typical bulk soil densities of 1200 to 1600 kg/m^3 this corresponds to mass deposition rates of silici-clastic sediments of 24 to 1600 g/m^2/yr.

   c. Supply of silic-clastic matter to peat at rates greater than 35 g/m^2/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.

3) In a given palaeo-geographic 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 palaeo-geographic 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.

4) The accumulation of peat over long periods requires sustained supply of fresh water, which in turn requires sustained hydrological stability.

Some of the consequences above have been inferred previously. For example, Broadhurst and France (1986) and Broadhurst and Simpson (1983) examining the influence of syndepositional faulting on coal seams observed that coal seams were more strongly influenced by active structures and associated landscape than the interseam sediments. They concluded that the duration of coal seams must be considerably greater than that of the intervening sediments. Similarly, in the UK Carboniferous Scott and Stephens (2015) concluded that a greater amount of time must be in coal rather than clastic sediments.

2.2 Water storage

With typical dry bulk densities in the region of 0.1 g/cm^3 (Clymo, 1984) by mass and by volume, peat is predominantly water. The volume of water stored in peat in low-lying areas is responsible for the exclusion of clastic sediment and therefore represents a volume of water stored above base level. In upland areas of blanket bog, landscape incision and consequent sediment bypass are primarily 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 and Suter 1997; Diessel et al 2000).

Evidence for either being in a state of clastic supply or clastic exclusion is the typically abrupt transition (clastic sediment to coal and vice versa) from one state to another at the boundaries of many coal seams (Diessel, 1992). Even during more gradual transitions from clastic sediment to coal, intercalated thin coal and clastic horizons occur rather than a gradual dilution of clastic sediment with organic matter (Diessel, 1992). If we accept that there is more time in the coal than the clastic sediment this intercalation of clastic sediment and thin coal indicates that clastic accommodation space was extremely limited at the point where coal seams start to establish. A finding 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., 2004; Glaser et al., 1997). Consequently, the position of peat within a landscape is strongly related to the discharge (or seepage) of groundwater (Winter, 2000) and 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 (Winter, 2000, Hokansen et al., 2016).

2.3 The hydrologic landscape

Peat, as the precursor to coal, initiates in a landscape. The base of coal seams is typically unconformable i.e. on land (Haszeldine, 1989) and based on analysis of controlling variables (eustasy, tectonics, climate, 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 conceptualising the relationship between peat, landscape 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 (Fig 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 towards the surface (or discharge) at the base of a slope. Given a sufficiently wet climate or large enough groundwater catchment this creates the fresh water saturation required for the initiation and maintenance of istable wetlands or peatlands (Winter, 2000). The base of slopes will therefore be the setting in which to initiate and maintain water saturated peat deposits (Fig 3).

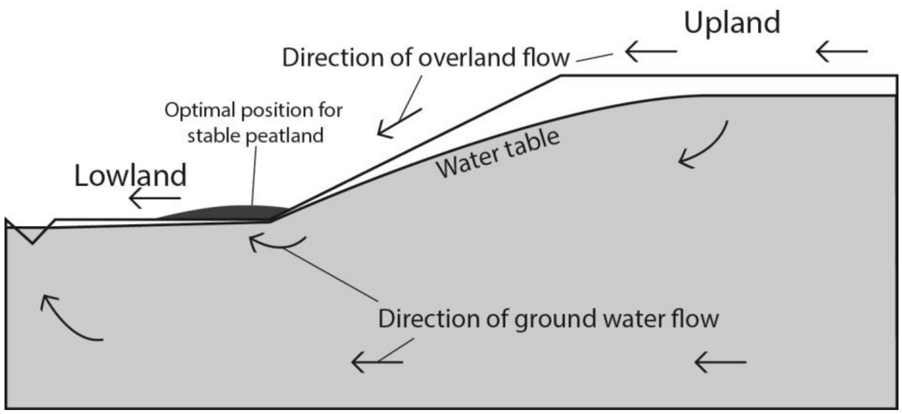

Figure 3 A schematic representation of the fundamental hydrologic landscape unit described by Winter (2000) illustrating the optimal position for peat accumulation.

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 large-scale ground water flow will be capable of buffering peatlands through periods of variable climate (Winter, 2000). Second, landscape evolution driven by tectonics and shaped by erosion evolves slowly over periods of 10^5 to 10^7 years, whereas climate and base level may display large fluctuations over much shorter timeframes. Hence, the long periods (10^5 to 10^6 years) of hydrologic landscape stability required to account for thick coal seams (e.g. Large et al., 2004; Large, 2007; Briggs et al., 2007; Large and 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 accommodate peat into long-term crustal storage. 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 of 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 neighbouring peatlands on the Qinghai-Tibetan Plateau.

2.3 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. At 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 in response to falling base level. However, if the scale of the hydrologic landscape units is sufficient 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 oxidise 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 and Magraw, 1961; Falcon-Lang, 2006) and in particular in areas adjacent to incised palaeochannels (Guion, 1987).

2.4 Accommodation and peat growth models

For peat to enter long term crustal storage it needs to be accommodated and rates of accommodation need to be capable of allowing continuous peat accumulation over periods of 10^5 to 10^6 yrs. To achieve this an appropriate balance of the rate of peat growth to accommodation rate is essential (Bohacs and Suter, 1997). This is complicated, as the rate of peat accumulation with respect to time is an inherently non-linear balance between the input of organic matter and the mass of organic matter lost due to decay (Clymo, 1984). Furthermore this non-linear property of peat growth is ignored in previous stratigraphic models that assume linear peat growth rates (Diessel et al., 2000; Bohacs and Suter, 1997).

A simple evaluation of the consequences of this non-linearity can be made by extending simple peat growth models (Clymo et al., 1998; Clymo 1992) which provide realistic estimates of carbon accumulation over the Holocene to periods that greatly exceed 10ka. 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 (kmolC m^{-2} 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 of time 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 on the long term trend.

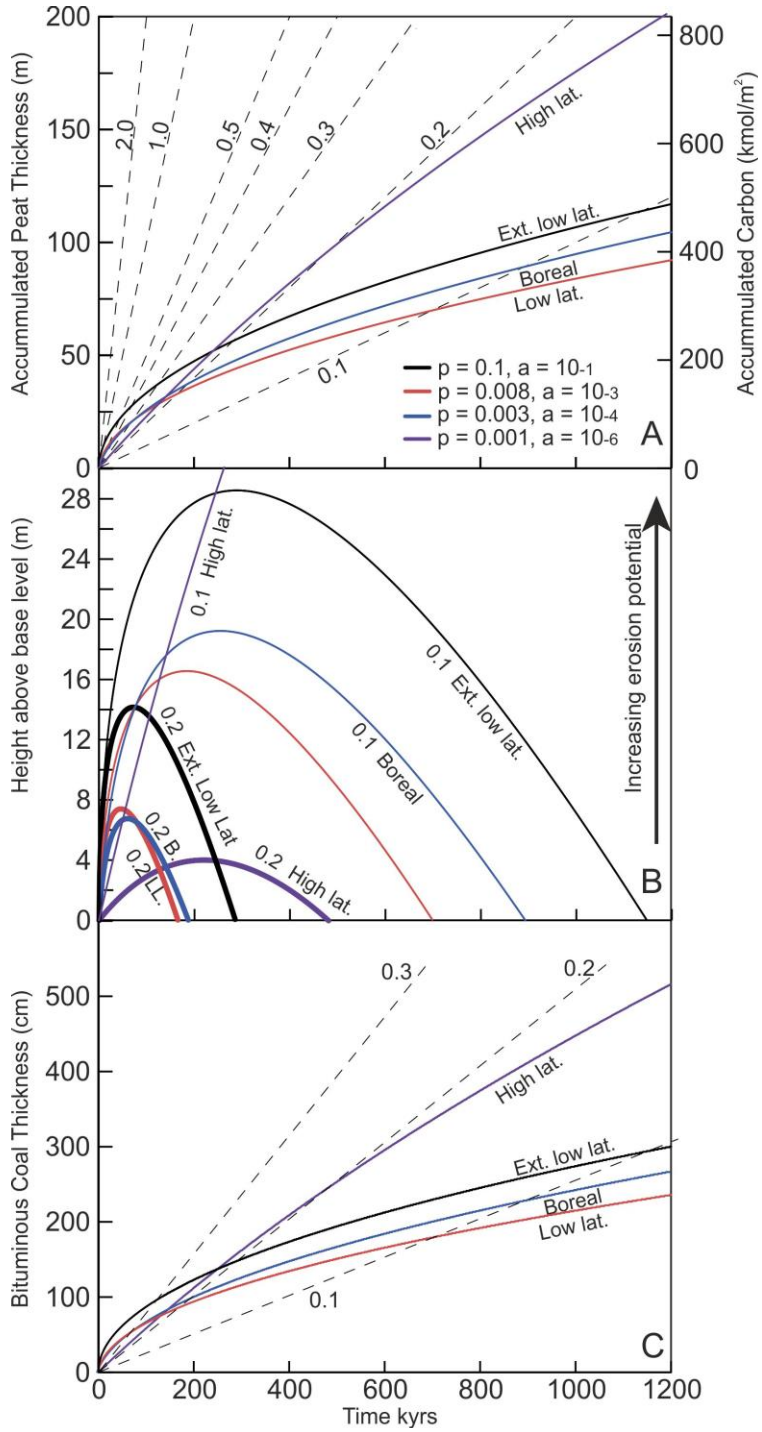

Figure 4 A) The relationship between cumulative peat thickness, cumulative peat carbon, time and linear accommodation rates (dashed lines with values given in mm/yr). Peat growth curves are derived using the quadratic model of Clymo et al (1998). Values of input (p) and initial decay rate (a) are chosen 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/cm3 and a carbon concentration of 50% on a dry ash free basis. B) Derived from 4A 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 4A. C) The results in figure 4A 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.

Clymo et al (1998).

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

Where M_t is the cumulative dry mass of carbon per unit area after time t (yr) and p and a are described above. This model is only a fixed point on continuum of possible decay rules (Clymo, 1992) and is chosen for illustrative purposes as it generates reasonable accumulation over 10^4 years and over much longer timeframes. Other points on the spectrum of possible models for example the constant decay model have unreasonable stratigraphic consequences over longer periods of time e.g. using Holocene parameters could not account for any significant coal accumulation.

Four growth curves were generated (Fig 4A) that cover a range of inputs and decay values. Values were chosen to represent: a high latitude value (p=0.001, a =10^{-6}); a boreal value (p=0.003, a=10^{-4}, similar to Clymo et al 1998); a low latitude value (0.008, 10^{-3} much greater than the boreal values of Clymo et al 1998); and an extreme low latitude value (p=0.1, a = 0.1) equivalent to a tropical net primary production and a high decay rate in tropical soil (e.g. Yule and Gomez, 2009).

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

Analysis of the relationship between accommodation rate and the modelled growth curves (Fig 4) indicates the following key features for a system in which clastic supply is sufficient to fill the available accommodation space.

1) Peat accumulation above base level occurs if the value of p and its volumetric equivalent exceeds the accommodation rate (Fig 4A and 4B).

2) Significant peat accommodation sufficient to generate >50 cm of bituminous coal occurs at accommodation rates <0.5mm/yr (Fig 4C). Contrary to the conclusion of Bohacs and Suter (1997) it is improbable that high accommodation rates of 1 to 2 mm per year could permit thick peat accumulation.

3) Tropical peats with high values of p can grow and establish above base level more rapidly (Fig 4B).

4) Over short timeframes of <70ka apparent long-term accumulation rates appear higher in the tropics and lower at the poles whereas, over longer time frames this relationship reverses (Fig 4A). Whether or not that reversal is apparent over the timeframe of the Holocene is unclear, however currently, greater Holocene peat thicknesses are typically reported from tropical regions (e.g. Anderson, 1983; Page et al 1999)

5) 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 to 400ka of continuous peat accumulation can be accommodated with the height of peat above base level not exceeding 8 m (Fig 4B).

6) 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 (Fig 4A and 4B).

7) The ratio of the accommodation rate to the peat production rate varies throughout the period of peat accumulation and bares no necessary relationship to the condition of the peatland (Fig 4A).

8) 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 (Fig 4B).

2.5 Limits to peat accumulation.

Stratigraphic models assume that erosion and/or unfavourable 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 landscape overcomes this and explains why extensive peat continues to accumulate in actively eroding landscapes with no increase in accommodation space. Futhermore, reported Holocene peat thickness, for example those in the Northern Hemisphere database of Loisel et al (2014), rarely exceed a thickness of 8 m so the influence of erosion on thicker accumulations above base level (Fig 4B) remains untested over the timeframe of the Holocene.

From observation of Holocene peat we deduce that 10 ka 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 ka? 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 accommodation space capacity.

Three key limiting processes are:

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 determine 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 2019).

This approach is problematic for several reasons:

1. 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/cm^3 (Large et al., 2009; Page et al., 2004) and peat hydraulic conductivity may vary by several orders of magnitude (Charman, 2002). Both of which illustrate that mechanical change in the pore structure of the peat can buffer the hydrology and create large uncertainty in model outputs.

2. It ignores the role of the hydrologic landscape.

3. 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), approximately 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 and Marshall, 2015).

4. Other physical and mechanic processes, discussed below, also act to limit peat growth and the relative importance of these processes over long periods is unknown.

Mechanical Deformation - An alternative not explored fully by peat scientists is that the stability of a peat body in the absence of accommodation space is mechanically limited and that the weak peat body will 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 limit 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 (Pearsall, 1956; Morris et al, 2013) and in some coal seams (Broadhurst and 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.

Advective erosion – 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 and 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 peatland (Li et al, 2019; Watters et al, 2007; Gradzinski et al 2003) but often from a short-term perspective of land management and carbon budgets (Li et al, 2019; Cowley et al, 2018; Evans et al, 2006)) rather than the perspective of long-term limits. This lack of consideration of significant natural erosion limits probably results from two aspects of the peatland erosion. First, the fibrous nature of peat is relatively resistant to erosion creating distinctive channel morphology and limiting channel movement (Watters et al, 2007; Gradzinski et al 2003). 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 and 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.

2.5 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 to 10^6 years (Davies et al., 2005; Holdgate et al., 1995; Jerrett et al., 2011a). This is improbable. The generation of depositional breaks in peat requires sustained erosion or non-accumulation 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 to 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.

2.6 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.

1. The hydrologic landscape determines the position, volume and extent of a peat body.
2. Thick peat forms in areas of prolonged hydrological stability.
3. The geometry, scale and persistence of the hydrological landscape unit determines the hydrological stability of a peatland.
4. In a given palaeo-geographic and palaeo-climate setting thicker coal seams accumulated over longer periods, not at a different rate.
5. 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.
6. The thickness of a coal seam is proportional to the time integrated carbon accumulation rate.
7. Change into and out of periods of peat formation is a response to the change in the volume of water stored above base level.

8. 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.

3. Discussion

Application of these considerations and rules to the interpretation of peat and coal produces a very different understanding of the processes leading to the crustal storage of peat. It also places greater value on peat and coal as an indicator of the processes of landscape and basin evolution.

By far the biggest change in interpretation arises from the order of magnitude increase in time required to account for the carbon in coal. Why previous interpretations did not consider a carbon basis for time in coal is quite inexplicable, as the processes on which it is based are understood. The consequence that coal seams with thickness in the range 1 to 20 m must account for periods in the range 0.1 to 1 My, a range that overlaps falls within the periods of 3rd and 4th order sea level cycles (0.5-5 and 0.1-0.5 My respectively), requires greater significance to be placed on the coal record and the time therein. It also means that in many coal-bearing systems the greatest amount of time is contained within the coal not the clastic sediments. For example, when realistic 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 75-125ky (Scott and Stephens, 2014) to 0.7-1.5 My (Large and Marshall, 2015). The former value requires huge unsubstantiated hiatuses and the latter lies within chronostratigraphic estimates for the duration of the interval, confirming the assertion of Scott and Stephens that most time must lie within the coal.

By increasing the amount of time, the role of landscape in sustaining a body of water-saturated peat above depositional base level becomes essential. This also sustains the necessary sediment bypass, which when combined with long duration peat formation must have a profound influence on the supply and distribution of sediment within a basin. Basinwards, the period of peat accumulation should be marked by enhanced sediment supply and associated progradation for example thick shoreface sands. The association between thick shoreface sand deposition and extensive coastal plain coal formation is seen within many coal-bearing paralic systems. In Spitsbergen, the Todalen coals occur adjacent to the coeval Endalen Member shoreface sediments (Marshall, 2013). Thick shoreface sediments/barrier island deposition and extensive coastal peat formation can also be observed within the Cretaceous South-Western Interior Basin, USA (Pederson and Dehler, 2005), the Cretaceous Blackhawk Formation, USA (Jerrett et al., 2011a) and associated with extensive lignite deposits from the Gippsland Basin, Australia (Birch and Division, 2003).

The non-linearity of peat accumulation rates contrasts markedly with the linear peat production rate assumed in the sequence stratigraphic models. Given a finite accommodation rate, this non-linearity requires that peat accumulation will terminate if given sufficient time. However more importantly the range of subsidence rates over which significant long term peat accumulation leading to crustal storage may occur is reduced to <0.5 mm/yr. This in turn demonstrates that for many coal seams there is sufficient time for low rates of basin subsidence alone to contribute to maintaining the hydrologic landscapes necessary to sustain peat deposition in appropriate tectonic settings. Such low subsidence rates are encountered in many tectonic settings (Allen & Allen 2013) and can be associated with significant accumulations of coal. For example: On extensional continental margins subsidence rates range from 0.2 mm/yr at the initiation of rifting, decreasing to less than 0.05 mm/yr during the flexural subsidence phase, over time scales of 10^6–10^7 years (Allen and Allen, 2013). Coal bearing examples of such continental margin basins include the Gippsland Basin (Birch and Division, 2003). Foreland basins subside at rates of 0.2–0.5 mm/yr, and cratonic basins at 0.01–0.04 mm/yr. Coal bearing examples of these include the Cretaceous coal bearing western interior foreland basins of the USA (Pederson and Dehler, 2005) and the cratonic coal bearing basins of Australia the coals of which are also notably oxidised which could be a consequence of particularly low rates of subsidence (Hunt and Smyth, 1987).

A key problem of extending peat accumulation models over long periods of up to 10^6 years is that rates of decay and coalification process operating over these periods are unknown. So while there is a good knowledge of decay rates over periods <10ka and diagenetic coalification rates over periods greater than 10My there is nothing between. The only certainty is the non-linearity in the mass balance between inputs and outputs. Extension of a peat accumulation model over much longer periods is however, a good test of whether or not a given model is reasonable. If it cannot enable any reasonable thicknesses of peat to be accommodated over periods >>10ka at reasonable accommodation rates then it is unlikely to be a reasonable model. A simple example of the application of this test is the constant decay model of Clymo et al 1998, which if extended to long periods using best fit Holocene values places an absolute and nonsensical limit of <30 cm on the total thickness of coal that could ever be.

A consequence of the long-term view is that in the absence of accommodation, 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 landscapes. The answers to this could have profound consequences for current and future management of the peatland. For example, it is likely that areas of upland peat will reach their natural erosional limits faster than lowland raised bogs. Evidence of this is the eroded state of upland blanket bog some of which appears to predate human influences (Tallis, 1985). Although the effects of overgrazing may confound this judgement (Tallis, 1985), it can be argued that areas closer to their natural limits will be more vulnerable to the effects of overgrazing and other environmental pressures. The inevitability of an erosional limit in landscapes where accommodation space is not being created also requires that we account for erosional losses when attributing a carbon flux to an area of peatland. It may also imply that in landscapes without the capacity to accommodate long-term accumulation of peat that the long-term management strategy should be to minimise rates of carbon loss and sustain vegetation cover rather than promote metastable growth above the natural limits imposed by erosion and mass movement. In terms of global carbon budgets, we can also question whether it is possible to have a significantly larger peatland carbon reservoir. So for example would it be possible to double the size of the peatland carbon reservoir within the current area of peatland and if not what would be the limiting processes?

The hydrological landscape requirements for sustained accumulation of peat mean that coal seam thickness, as deduced by Broadhurst and France, (1986) and Broadhurst and Simpson (1983), will be a sensitive indicator of syn-depositional deformation and landscape evolution within a basin. Using the approach above in combination with isopach maps it is possible to use the variations in coal thickness 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 landscape and the distribution and thickness of early Palaeocene coal within the Central Tertiary Basin, Svalbard. There are also numerous examples (e.g. Ferm and Staub. 1985; Read, 1989; Guion, 1987; Haszeldine,1989; Greb et al 2001) linking coal thickness to syndepositional topography, differential compaction, and tectonics. However, they have not been interpreted in the context of a hydrological landscape over an appropriate timeframe. To fully demonstrate the application of this approach would require a complete re-analysis of data from a specific basin, which is beyond the scope of this paper.

5 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 stratigraphic models in line with modern peat observations and can be applied to all peatland and coal settings on various scales. Furthermore this approach sets limits to the interpretation of the parameters of the hydrological landscape that enable long term accumulations of peat leading to coal. For example it casts severe doubts on the notion that that thick peat accumulations form in areas of rapid subsidence. It also requires far lower and less variable accommodation rates to take peat into long term crustal storage and demonstrates that for many coal seams there is sufficient time for crustal deformation alone to sustain the necessary hydrologic landscapes.

The common stratigraphic assumption that coals are largely ephemeral features within a siliciclastic framework is a barrier to understanding environmental change, basin processes and the long-term storage of peatland carbon. The sustained periods of peat formation needed to account for the carbon in coal require recognition of a prolonged and fundamental shift in the syndepositional environment and processes of sediment transport and deposition both of which have basinwide consequences. The hydrologic landscape approach facilitates re-interpretation of these systems. It also raises questions as to the long-term validity of Holocene peat growth models and the ultimate limits to peat accumulation.

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