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Sequence stratigraphic interpretation of peatland evolution in thick coal seams: Examples from Yimin Formation (Early Cretaceous), Hailaer Basin, China

Biao Guo[a,b], Longyi Shao[a,*], Jason Hilton[c], Shuai Wang[a], Liang Zhang[a]

[a] College of Geoscience and Survey Engineering, China University of Mining and Technology, Beijing 100083, PR China
[b] School of Resources and Environment, North China University of Water Resources and Electric Power, Zhengzhou 450046, Henan, PR China
[c] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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ABSTRACT

Peat formed in mire settings sensitively records environmental fluctuations during deposition including changes in water table or base level and accommodation. On this basis coal seams, as geologically preserved peats, can provide evidence of high-resolution paleoclimatic fluctuations as well as paleobotanical evolution through periods of peat-formation. The No. 2 and No.1 (in ascending order) thick coal seams from the Early Cretaceous Yimin Formation in the Zhalainuoer Coalfield (Hailaer Basin, NE China) are investigated using sedimentological, sequence stratigraphic and petrographic analyses to understand the evolution of their peat forming environments. These 'single' thick coal seams, lacking siliciclasitic partings, are well-developed in the central area of the Zhalainuoer coalfield. Petrographic analyses demonstrate that water-table or base-level fluctuations in 'single' seams can be revealed by a number of significant surfaces formed by various events including paludification, give-up transgressive, accommodation reversal, flooding, and exposure surfaces. These surfaces can separate the single coal into a number of "wetting-up" and "drying-up" cycles. The wetting-up cycle is characterized by a gradual upward increasing trend in the huminite:inertinite ratio and in the ash yields. In contrast, the rapid drying-up cycle is characterized by an upward-increasing trend in the inertinite-dominated coal (46% on average) that represents a phase of exposure and oxidation resulting from a falling water table. This drying-up cycle can be correlated with the scouring surface in landward parts of the basin and terrestrialization surface basinward. The No. 2 coal seam occurs in the transgressive systems tract and comprises three high-frequency depositional sequences in which each coal cycle is characterized by a gradual wetting-up cycle and ends with a rapid drying-up cycle. The No. 1 coal seam occurs in the highstand system tract and consists of several high-frequency depositional sequences in which each coal cycle is characterized by a gradual drying-up cycle and ends with a rapid wetting-up cycle. These coals could also superpose to constitute the thick coal seam in which various sequence-stratigraphic surfaces can be recognized including terrestrialization, accommodation reversal and exposure surfaces. Stratigraphic relationships between coal and clastic components in the Yimin Formation enable us to demonstrate that thick coals span the formation of several coal cycles and high-resolution boundaries, allowing us to interpret the effects of accommodation on coal seam composition. Recognition that environmental changes can be recorded by thick coals has significance for studies that incorrectly suppose that peat or coal cycles can offer high-resolution and time-invariant records of paleoclimatic fluctuations and paleobotany evolution.

1. Introduction

Peat mires provide a sensitive record of water-table or base-level fluctuations throughout their accumulation (Diessel, 1992, 2007; Jerrett et al., 2010). On this basis, sediments deposited in them can record the long-term evolution of mires and swamps including rates of peat accumulation as well as recording changes in geological environments (Moore, 1989; Kosters and Suter, 1993; Winston, 1994; Banerjee et al., 1996; Bohacs and Suter, 1997; Diessel, 1998; Diessel et al., 2000). Analysis of coal seams using coal petrography, sedimentology, sequence stratigraphy and paleobotany can make comparatively accurate interpretations for conditions of peat formation, not only of the long-term

* Corresponding author.
E-mail address: shaoL@cumtb.edu.cn (L. Shao).

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changes of sedimentary environment, but also of short-term sedimentary cycles during peat-forming periods including high-resolution paleoclimatic fluctuation and paleobotanical evolution (Davies et al., 2005, 2006; Jerrett et al., 2010).

For coals to be generated, sufficient accommodation space is required to accumulate peat and to protect it against oxidation or erosion, with accommodation controlled by the height of the water table (Jervey, 1988; Cross, 1988; Bohacs and Suter, 1997). The relationship between accommodation and peat accumulation is thought to be crucial for coal formation (Banerjee et al., 1996; Diessel, 1998; Petersen et al., 1998; Diessel et al., 2000; Holz et al., 2002; Wadsworth et al., 2002, 2003). Coal seams form where the peat accumulation rate balances the accommodation increasing rate (Bohacs and Suter, 1997; Diessel, 2007), with their long-term balance providing one of the best opportunities to generate thick coal seams.

The "multi-peat superposition genetic model" (Watts, 1971; Shearer et al., 1994; Holdgate et al., 1995; Diessel and Gammidge, 1998; Page et al., 2004; Jerrett et al., 2011) considers that thick coal seams, rather than being the product of single paleo-peat bodies, might represent a succession of stacked mires separated by hiatal surfaces. Generally, autochthonous peat accumulation genesis, of a type mainly occurring in relatively stable tectonic areas, can be subdivided into continuous and discontinuous accumulation of peat, with the difference depending on whether a series of hiatal or non-hiatal surfaces develop during the coal-forming period. By contrast, the "allochthonous accumulation coal-forming model" (Wu, 1994; Wu et al., 1996; Djarar et al., 1997; Wang et al., 1999, 2000, 2001; Wu et al., 2006a) has been developed to explain the effects of storms, gravity flow and underwater debris flows discovered in the thick coal seams in small terrestrial fault basins. However, for coal geologists, studies on thick coal seams remain controversial for the following reasons:

(1) It is problematic to reconcile thicknesses of some coal seam with known modern peat thicknesses. Coal seams as much as 100 m thick are often reported in the rock record (e.g. Hu et al., 2011; Wang et al., 2016), whereas the maximum thicknesses for modern peats documented is approximately 20 m (Esterle and Ferm, 1994; Shearer et al., 1994). In view of the appreciable diagenetic compaction of peat after burial, no modern analogue has yet been discovered for the formations of thick coal seams, appearing to challenge the doctrine of ancient analogues for modern conditions. Thus, various researchers have made direct comparison of coal beds with siliciclastic deposits to interpret coal seams as composites of multiple depositional sequences and several significant surfaces (e.g., McCabe, 1984, 1987; Spears, 1987; Greb et al., 2002). Furthermore, these coal seams contain information representing not only the presence of an orderly cycle of peats but also an absence of some hiatal surfaces (Shearer et al., 1994). The recognition of wetting-up and drying-up cycles in coals in response to water-table or accommodation cycles indicates high-frequency paleoclimate changes that may be missed in siliciclastic sediments. Therefore, recognition of vertical and lateral variation of the hiatal surfaces in coal measures, along with separation of an orderly cycle, is of great significance to decipher paleoclimatic fluctuations with the high-resolution and time-significant record in peat successions.
(2) For peat to be preserved, the accommodation rate, mainly controlled by the rate of subsidence and water table level, should approximately balance the rate of peat production (Jervey, 1988; Cross, 1988; Bohacs and Suter, 1997; Wadsworth et al., 2003; Davies et al., 2005). As the accommodation rate goes far beyond peat production, the mire could be drowned with lacustrine, marine or terrestrial sediments, terminating peat accumulation. Likewise, if the accommodation rate falls below the peat production rate, the mire is exposed, becomes oxidized and is replaced by terrigenous clastic sediments. Within the comparatively narrow coal window, the accommodation rate results in the changes to the composition or stacking type of the accumulating peat. Sequence stratigraphy strives to explain sediment superposition and lateral arrangement, which are mainly controlled by the accommodation made below base level relative to the supply rate of sediments (Van Wagoner, 1995; Catuneanu, 2002; Diessel, 2007). Therefore, thick coal seams that formed either under a transgressive or regressive regime, contain different single paleo-body stacking patterns and a different composition of the accumulating peat. Recognizing that coals formed in different systems tracts can represent types of cycles of stacked mires has important implications for improving the predictability of vertical and lateral variations in coal composition for mining and coal bed methane projects.
(3) Paragenesis of uranium deposits occasionally accompanies the formation of coal, oil, gas or depositional metallic minerals. In some contexts, coals have even been the important sources of uranium for industrial utilization (Kislyakov and Shchetochkin, 2000; Seredin and Finkelman, 2008; Seredin, 2012). These coals also have high concentrations of other associated elements, including V, Mo, Se, Re and Mn, which may also have potential economic significance (Seredin and Finkelman, 2008; Seredin, 2012; Dai et al., 2015; Finkelman et al., 2018). Coal-hosted U, V and Mo deposits, produced by epigenetic infiltration, have a zoned distribution, which is also a response to the accommodation under a sequence stratigraphic framework (Wu et al., 2009; Guo et al., 2018). Uranium mineralization mainly occurs in coals formed in the highstand or lowstand systems tracts (Yang and Liu, 2006; Yang et al., 2007; Wu et al., 2009; Guo et al., 2018). The accumulation and mode of occurrence of uranium and rare metals may reflect the original peat-accumulation environments. In other words, coals that selectively preserve some depositional metallic minerals, should relate to where or how the coal was generated and impacted by interaction between peat accumulation and accommodation.

This study is based on the Cretaceous age thick coal seams from the Yimin Formation in the Zhalainuoer coalfield (Hailaer Basin, China), which are widely developed in lacustrine transgression and highstand systems tracts (Zhou et al., 1996; Yuan et al., 2008; Guo et al., 2014). As changes in base level and accommodation are important factors controlling coal accumulation, the succession in the Yimin Formation represents an ideal area to conduct sequence stratigraphic interpretation for mire evolution in thick coal seams. The aims of this paper are to: (1) describe and interpret the thick coal seams and clastic sediments deposited in the Zhalainuoer coalfield, (2) recognize the hiatal or non-hiatal surfaces in the coal seams, (3) interpret the effects of accommodation on coal seam composition and (4) evaluate coal-forming mode in a sequence stratigraphic framework in order to consider how accommodation affects coals deposition.

2. Accommodation and peat/coal formation

During peat accumulation within a mire, the basin subsidence rates and water table control accommodation. The relationship between the change of accommodation rate and peat accumulation rate directly affects peat formation and termination. Bohacs and Suter (1997) studied the phenomenon of modern peat accumulation, and quantified the relationship between the change of the accommodation rate and peat accumulation rate. Peat can accumulate during increasing or decreasing accommodation rates and may span several accommodation cycles (Wadsworth et al., 2002; Jerrett et al., 2010). In cases of high accommodation space, lacustrine or marine fine-grained sediments are firstly developed in the basin, which are not conducive to the formation of peat. As the accommodation space decreases, initiation of peat accumulation above these strata represents a terrestrialization surface (TeS), which is commonly non-hiatal indicating a transition from the shallowing-upward, subaqueous floor deposits to peat accumulation (Diessel et al., 2000; Diessel, 2007; Jerrett et al., 2010; Fig. 1). Only