Chapter 4

Widespread eccentricity-driven coal deposition in the Hell Creek area (Montana, USA) as potential global CO$_2$ sink following the K-Pg boundary

ABSTRACT

Laterally extensive coal layers dominate the lower Paleocene Fort Union Formation of the Williston Basin in north-eastern Montana (USA). Widespread coal seams have been postulated as potential contributor to Paleocene global carbon cycle dynamics at eccentricity time scales. However, this hypothesis requires synchronous, basin-wide coal deposition and the existing chronostratigraphic framework does not allow for testing of this hypothesis. Recent chronostratigraphic correlations in the lower Fort Union Formation over a 15-km transect suggested that repetitive coal-clastic and aggradation-incision intervals are related to orbital eccentricity-driven climate changes. Here we test if these cycles occur at the regional scale by developing/constructing/using a transect of nearly 100-km. We integrate existing and new stratigraphic, magnetostratigraphic and sedimentary information to establish a correlation panel of the upper Hell Creek – lower Fort Union Formations in Garfield and McCona County, Montane, USA. The interpreted panel reveals that the 6 major coal zones in the lower Fort Union Fm are correlative over the panel transect, as well as 14 smaller-scale coal seam alternations. Besides, six regional incision-related hiatuses are identified over the panel transect demonstrating the importance of integration of tools for studying these complex fluvial archives built of fragments of sedimentation. Our results show that expression of eccentricity-induced coal-clastic and aggradation-incision cyclicity can be observed in the Fort Union Formation. This implies that widespread coeval coal deposition alternating with clastic deposition at eccentricity time scales could potentially contribute to the early Paleocene global carbon cycle. Superimposed on this cyclicity, we interpret the upward stratigraphic condensation to be related to long-term gradual upheaval of the region caused by the Laramide orogeny. Our case indicates that indeed global carbon cycle changes at eccentricity time scales may be related to terrestrial carbon burial in vast peat swamps. Whether more peat-regions in the world behave in the same way to come to sufficient carbon storage capacity to change carbon budgets of the exogenic carbon pool remains to be proven.
INTRODUCTION

Fluvial-deltaic peat deposition controlled by eccentricity has been hypothesized to play a role in the global carbon cycle for the late Paleocene (Zachos et al., 2010). To explain the prominent eccentricity cycles in δ13C in the marine realm, Zachos et al. (2010) suggests that during eccentricity minima annual precipitation was uniform, allowing to maintain wetlands and peat accumulation. During eccentricity maxima, higher seasonal contrasts promote sediment supply of which regional dispersal prevents widespread peat accumulation. Also possible oxidation of peat and the release of CO₂ would enhance warming, further amplifying seasonal extremes. To explore the validity of the hypothesis of Zachos et al. (2010) the regional chronostratigraphic architecture of the fluvial sediments deposited in vast Paleocene coal basins must be unravelled to test for regional extent of coal seams and the synchronicity or diachronicity of peat formation. The coal-bearing fluvial rock exposures of the uppermost Hell Creek Formation and overlying lower Fort Union Formation, in north-eastern Montana (Williston Basin, USA), are well-known for the Cretaceous-Paleogene boundary (KPB) and for their record of geobiotic recovery and evolution after the KPB (e.g. Alvarez, 1983; Smit and van der Kaars, 1984; Moore et al., 2014). Recent studies suggest that coal-clastic and aggradation-incision repetitions can potentially be linked with respectively short- and long-eccentricity-forced climate changes based on correlations of coal zones along 10 - 15 km wide transects (Noorbergen et al., 2018; Chapters 2 and 3). However, peat deposition controlled by orbital-climate forcing imply at least a regional climate control over sediment supply, discharge, weathering and vegetation. Eccentricity-induced cyclicity should therefore also be present over distances of 100 km or more.

Long-distance correlation of coal-bearing fluvial rock strata is usually hampered by the scarcity of chronostratigraphic markers required for correlating isolated outcrops. However, the outcrops in north-eastern Montana provide several chronostratigraphic tie-points such as the KPB, geomagnetic polarity reversals and distinctive tephras. These can be used to determine the lateral synchronicity of lithofacies such as coals, channel sandstones and palaeosols between sections. A previous study demonstrated unique chemical and Pb isotope compositions of some tephras in the Z-coal-zone, allowing correlation of the middle part of the Z coal zone over at least 80-km (Ickert et al., 2015). However, detailed long-distance stratigraphic correlations of the Z coal zone, and of the younger Y, X, W, V and U coal zones (Collier and Knechtel, 1939) across the Garfield and McCona Counties (NE Montana) are not established so far. Building upon existent- and, adding new data we present a first high-resolution long-distance correlation panel of the lower Fort Union Formation extending from Garfield into McCona County. This panel (Garfield-McCona Panel 1; GMP-1) is established to: (1) determine the lateral synchronicity of coals, clastic intervals, and palaeosols to improve our understanding of fluvial sedimentary changes across the KPB, (2) test the hypothesis of regional-scale orbital-forcing in this fluvial system (Noorbergen et al., 2018; Chapters 2 and 3); and, (3) explore if light atmospheric carbon burial in continental peat align with positive carbon isotope excursions in the marine realm (Kroon et al., 2007), and, hence, explore potential linkage with global carbon cycling (Zachos et al., 2010).

METHODS

The GMP-1 consists of twenty-five sections (Fig. 4.1, Fig. 4.2 and Table S4.1) with 17 new sections (i.e. 10 locations have been reported in literature, but a detailed sedimentological framework was
lacking) and 8 sections from previously published work (references; Table S4.1). For 6 sections new palaeomagnetic data are reported (Fig. S4.2). The overall orientation of GMP-1 is east-west with a maximum distance of 92 km between the most western and the most eastern section.

In the field, sections were logged along a continuous transect on the outcrop or, along a transect of stratigraphically connecting trenches following the same methodologies as in Noorbergen et al. (2018) and Chapters 2 and 3 (Table S4.1). Palaeomagnetic core sampling and analysis is conform the methodologies described in Noorbergen et al. (2018). Palaeomagnetic data of the Hogs Back (HB) section (Sprain, pers. communication) are obtained according to the field and laboratorial methods described in Sprain et al. (2018). Palaeoflow directions have been obtained from sets of dm-scale cross-bedding in the channel sandstones. We measured the bed plane dip-direction of one cross-bedded set and therefore each palaeoflow direction measurement reflects a different formation in space and time. Data from individual cross-bedded channel sandstones are plotted in rose diagrams (Fig. 4.2).

For optimal vertical alignment of sections in GMP-1 the method of Noorbergen et al. (2018) was adopted, requiring the selection of one backbone section (here Flat Creek) to which the other sections are vertically aligned based on calibration of stratigraphic tie-points. We selected 8 tie-points that are distinctive and present in at least several sections (Table S4.1), although no single section contains all tie-points. The Flat Creek sections (composed of Flat Creek West FC-W,
Main FC-M and North FC-N) combined contain the 8 tie-points and use an extrapolated tie-point (reversal C28r/C28n) from the Coal Mine Divide West section (CMD-W), assuming equal stratigraphic thicknesses of Chron 28r between CMD-M and FC-N. After vertical alignment, we created a simple fence panel based on stratigraphic correlation of the tie-points and interpretation of their position in case they were not recorded (dashed lines, Fig. 4.2). Finally, we complete GMP-1 by correlating the coal-clastic successions (Noorbergen et al., 2018; Chapters 2 and 3) whilst distinguishing between (1) peat mire coals, (2) channel-splay sand-siltstones (goldish and yellowish), (3) valley-fill channel sandstones and bayou mudstones and, (4) inter-valley bleached palaeosols (for detailed sedimentology, see Noorbergen et al., 2018; Chapters 2 and 3).

To explore the role of coal deposition in the global carbon cycle, we compare our chronostratigraphic (Wheeler) diagram of GMP-1 with the carbon isotope record of bulk marine sediment ($\delta^{13}$C$_{bulk}$) of ODP site 1262, Walvis Ridge, Atlantic Ocean (Kroon et al., 2007). To make our Wheeler diagram and $\delta^{13}$C$_{bulk}$ records comparable in time we used an age model that is independent of the different radio-isotopically calibrated ages of the KPB clustering around 66 Ma (Renne et al., 2013; Clyde et al., 2016; Sprain et al., 2015; Sprain et al., 2018) or the ones combined with astronomical tuning (Kuiper et al., 2008; Hilgen et al., 2010; Hussen et al., 2011; Vandenbergh et al., 2012; Batenburg et al., 2012; Dinarès-Turell et al., 2014). Instead the age model is based on 21-kyr precession cycle counting within the Maastrichtian part of C29r (Batenburg et al., 2012) and within the Danian C29r, C29n, C28r, and C28n polarity chrons (Dinarès-Turell et al., 2014). We compare our floating age model with the La2010d-revised astronomical solution (i.e., La2010d of Laskar et al. (2011) with stable 2.4 Myr cycle), which provides the best fit with the eccentricity-related cycle patterns in the deep marine Zumaia section (Hilgen et al., 2017), by anchoring our time-series to the estimated mean age of 66 Ma for the KPB (see above).

RESULTS

Correlation of the coals

On top of the 8 major coals in the Z-W coal zones in McCone County (Noorbergen et al., 2018), the total number of numerically labelled coals in the transect sums up to fifteen (Fig. 4.2 and 3). These 15 coals are now shown to be correlative over the 92 km that our records are located apart. These coal seams show clear lateral continuation, although merging of coals particularly occurs in the Lower Tullock Member (lowest Fort Union Fm) and erosion, i.e. regional hiatuses, in the Upper Tullock and Lebo Shale Members (Fig. 4.2). The chronostratigraphic tie-points do not reveal major diachronicity of the coal seams.

The upper part of the Z-coal zone and Y-coal-zone (Collier & Knechtel, 1939) merge from east to west, along a distance of 10-km between the Garbani Hill and GH and White Horse Divide (WHD) sections (Fig. 4.2). The merged ZY coal zone in the Hauso Flats (HF) area (Figs. 4.1B and 4.2), has also been labelled the HFZ-coal (Swisher et al., 1993). The X-, W-, V- and U-coal-zones do not merge along GMP-1. Based on the new data from GMP-1, the second coal (#2-Z) of Noorbergen et al. (2018) must be revised as minor coal.

Regional hiatuses

Six regional-scale hiatuses were identified (blue solid lines, Fig. 4.2) based on observations of sharp undulating tops of bleached palaeosols, i.e. overprinted white sand-mudstones or dull-black coal, laterally passing into the erosional bases of incised channel sandstones. The hiatuses I and II occur
Legend:
- Peat mire coal (dark-brown-black)
- Splay silt- (gold-grey variegated) and channel sandstone
- Splay silt- (yellow-grey variegated) and channel sandstone
- Bayou mud- (greenish-grey) and valley-fill channel sandstone
- Inter-valley bleached compound palaeosol (whitish-grey)
- Distinctive tephra
- Polarity reversal
- K-Pg boundary (KPB)
- Regional hiatuses
- Palaeoflow indication (n crossbeds)
- Preserved ejecta from the Chicxulub impact at the K-Pg boundary
- Tie-points (KPB, tephra, reversal)
in the uppermost Hell Creek Formation, III in upper Tullock Member, and IV, V and VI in the Lebo Shale Member. Hiatuses IV and IV correspond to the top of AIS-1 and AIS-2 (Chapter 3), respectively. Some of the incised sandstones local names are indicated on Figure 4.2.

**Palaeoflow directions**
The rose diagrams (Fig. 4.2) show that palaeoflow directions in the sandstone channels varied between location and through time. Flow directions were mainly S to SE in the uppermost Hell Creek Fm, SE/E to N/W in the lowermost Tullock Member, multidirectional to N/NW between the Z- and X-zones, E to N/E/S between the X- and W-zones, NW/SW between the W- and V-zones and, E/SE between the V- and U-zones.

**Time control**
Figure 4.3 is a generalized chronostratigraphic (Wheeler) diagram of GMP-1 showing the major peats, clastic sediments, and hiatuses. The Wheeler diagram shows that major coal seams generally occur c. 100-kyr apart (Fig. 4.3). The duration of regional hiatuses I and II is ~20-kyr above/in palaeosols and ca 100-kyr above/in channel incisions. Hiatuses III to VI are approximately two orders of magnitude higher/longer with resp. c. 40- and 200-kyrs for palaeosols and channel incisions. Hiatuses III & IV and hiatuses V & VI both span c. 200-kyr and are separated c. 350-kyr at 65.3 and 64.95 Ma (Fig. 4.3). This roughly corresponds to the c. 400-kyr of eccentricity based timescales.

Do coals align with positive shifts in marine δ¹³C at times of 100-kyr eccentricity minima?
For the first seven major coals seams of Z, Y, X, and W, the marine record reveals correlative up to 1 ‰ positive shifts in marine δ¹³C during short-eccentricity minima. The major coal seams in the V and U zones also align with short-eccentricity minima but the temporal-resolution of the marine δ¹³C record in this interval is too low to reveal clear variations on the 100-kyr scale.

**DISCUSSION AND CONCLUSIONS**

**Paleocene carbon cycle perturbations**
Our identified phase relation of coals corresponding to short-eccentricity minima is in agreement with Zachos et al. (2010) hypothesizing extensive continental peat formation during these phases being a potential global sink for atmospheric CO₂. The alignment of major coals seams 1 - 7 with the up to 1 ‰ positive 100-kyr shifts in marine δ¹³C confirms this hypothesis. Nevertheless if the coals were a true sink of global CO₂ they must account for the storage of a significant portion of organic carbon required for a 1 ‰ carbon isotope excursion. We calculated from equation 4a in Kurtz et al. (2003) that such an excursion (dδc = 1 ‰) requires 4758 Gt organic carbon burial (Favg = 5.66 mol C/kyr) over 70 kyr duration of the carbon isotope excursion (dt), by assuming the average
Figure 4.3. A. Generalized chronostratigraphic (Wheeler) diagram of GMP-1. B. Left. La2010d-revised 100-kyr eccentricity curve (red) (Laskar et al., 2011) and its 405-kyr bandpass filter (black) (Paillard et al., 1996). Right. Bulk marine sediment δ¹³C record of ODP site 1262, Walvis Ridge (Kroon et al., 2007). The age models of the Wheeler diagram and δ¹³Cbulk record are tied to an age of 66 Ma for the KPB and use the number of precession cycles counted in the late Maastrichtian C29r chron (B12, Batenburg et al., 2012) and in the early Danian C29r, C29n, C28r, and C28n chrons (D14, Dinarès-Turell et al., 2014). * numerically labelled coal seams 1-8 (Noorbergen et al., 2018) and 9-15 (this study).
\[ \delta^{13}C \text{ fractionation (}\Delta) = -26 \% \text{ (Arens & Jahren, 2000), one ocean-atmosphere reservoir (}\delta^C_0 = 0 \%), and by adopting the values in Kurtz et al. (2003, therein Fig. 1) for the other requested variables (}\text{F}_W = 2.5, \delta^C_W = -4, M^C_0 = 3.3): \]

\[ F_{\text{org}} = \frac{F^C_W (\delta^C_W - \delta^C_0) - \frac{d\delta^C}{dt} M^C_0}{\Delta^C} \quad (4a) \]

The total amount of organic carbon potentially stored in North America is roughly 607 Gt during one excursion, assuming that a one meter thick major lignite coal seam represents \sim 70 kyr, contains 64 % carbon (Vassilev et al., 2010), has a density of 1.15 g cm\(^{-3}\) (Xie, 2015), and extends over the major Paleocene coal basins of North-America, i.e. the Western Interior, Denver, and Raton Basins with a total area of 824804 km\(^2\) (Flores, 2003; Jerrett et al., 2015). This is a significant amount, but still 8 times less than the required 4758 Gt for a 1 % positive excursion in marine \(\delta^{13}C\). This implies that peat formation in multiple basins not only must have occurred simultaneously in North America, but world-wide with the same eccentricity phase relation, if Paleocene coals function as dominant sinks for CO\(_2\). Other vast continental coal basins of early Paleocene age, such as in China/Russia (Markevich et al., 2010; Quan et al., 2012; Huang et al., 2013; Knittel et al., 2013), Colombia/Venezuela (Villamil, 1999), New-Zealand (Vajda et al., 2001), and Greenland (Dam, 1998; Dam et al., 2009), may have acted as additional carbon sinks. In these areas, data are so far lacking to convincingly prove whether terrestrial coals were indeed responsible for the Paleocene eccentricity-scale carbon cycle perturbations.

**Implications of Garfield-McConce panel (GMP-1)**

Although the possible role of coals as carbon sink involves global scale processes, local scale processes must somehow play a role, since the fifteen coal seams are not recorded in all single sections (Fig. 4.2). However, in the field, we did not observe lateral transition of lignite into time-equivalent channel facies for these fifteen coal seams. This implies that peat formation likely did not occur coeval with clastic deposition in large channel belts. An autogenic avulsion model for peat formation requires coeval peatlands and channel belt sandstones and is therefore invalid (Belt, 1993; Fielding and Webb, 1996; Noorbergen et al., 2018). Instead, the main phases of peat formation and clastic sediment supply succeed one another at c. 100-kyr timescales, suggesting an allogenic control by short-eccentricity-induced climate cycles (Noorbergen et al., 2018). 400-kyr-scaling of incision-related hiatuses, i.e. 400-kyr from hiatus cluster III-IV to V-VI in GMP-1 (Fig. 4.3), may originate from an upstream long-eccentricity-forced climate control on incision (Chapter 3).

**Astronomically controlled fluvial system?**

The coal-clastic cycle may reflect a change from clastic-deficient densely vegetated peat mires to multidirectional flowing channel-splay systems within clastic megafans. The fluvial system change and discrete response to eccentricity-scale climate change following the KPB is striking but as yet not well understood. A possible explanation is that post-KPB global warming (Beerling et al., 2002) enhanced eccentricity-driven climate variability. Superimposed on eccentricity-induced cyclicity in GMP-1, the change from gold- to yellow clastics may be related to drying, the transition from high- to low-frequency splitting coal seams may reflect raising mires, and the increasing incision rate, i.e. around the W-coal zone, may reflect a destabilizing fluvial system. These changes may in turn be related to a gradually decreasing accommodation space associated with the superimposed long-term process of Laramide tectonic uplift.
Environmental change across the KPB

Comparable to aggradation-incision III to VI, the two closely spaced hiatuses I and II in the uppermost Cretaceous Hell Creek Formation (Figs 2 and 3) may also represent soils that formed on dry elevated platforms in between the valleys of incised rivers. The depositional environment of the KPB-interval in between the two hiatuses, as well as for other depositional intervals in the upper Hell Creek Formation, could have been a bayou system (Guccione et al., 1999). The bayou originated when channel aggradation followed the incision: valleys became filled and the river widely inundated the pedogenized silcretic platforms causing energy dispersal and poor channelization. Sandy muds were deposited on top of the bleached palaeosols within the reaches of the bayou. At the time the KPB-ejecta fell, emerging isolated peat bodies may have existed. These low-energy sites (e.g. BRB, FCM) provided high preservation potential for the KPB ejecta as well as the dry soil locations that became overgrown by peat shortly after the event (i.e. HR, WHD and FB). Rapidly followed by enhanced clastic input and erosion, individual peat bodies remained disconnected explaining the thin lenticular IrZ coal beds on top of the KPB. The erosional phase above the IrZ-coal, corresponding with the Hiatus II incision (Big Bugger Channel, BBC), may reflect a direct fluvial response to the catastrophic environmental impact of the KPB (Fastovsky and Bercovici, 2016). Subsequently, c. 50-kyr after the KPB, the widespread peat formation of coal 1-Z marks the base of the fourteen c. 100-kyr coal-clastic repetitions in GMP-1 (Fig. 4.2).
Table S4.1. Overview of sections, chronostratigraphic markers and new/re-used data.

<table>
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<tr>
<th>Section</th>
<th>Section full</th>
<th>Marker</th>
<th>KPB</th>
<th>NB</th>
<th>MGB</th>
<th>GSB</th>
<th>ORA/29r/29n</th>
<th>PSA</th>
<th>SA/29n/28r</th>
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**RIGHT** Re-used section

**LEFT** Newly logged section, previously reported site

* Newly logged section and newly reported site

^ Log transect followed connecting trenches

VALUES REFER TO STRATIGRAPHIC HEIGHT (M) FROM BASE OF THE SECTION LOG (FIGURE 4.2) NEWLY REPORTED KPB (FIGURE S4.1) AND MAGNETOSTRATIGRAPHY (FIGURE S4.2 A-F)

<table>
<thead>
<tr>
<th>Marker</th>
<th>Marker full</th>
<th>Re-used</th>
<th>Reference</th>
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<tr>
<td>KPB</td>
<td>Cretaceous-Paleogene Boundary</td>
<td>MKR</td>
<td>Sprain et al. (2018)</td>
</tr>
<tr>
<td>NB</td>
<td>Nirvana Bentonite</td>
<td>FB</td>
<td>Moore et al. (2014)</td>
</tr>
<tr>
<td>MGB</td>
<td>McGuire Creek Bentonite</td>
<td>JC</td>
<td>Sprain et al. (2018)</td>
</tr>
<tr>
<td>GSB</td>
<td>Grey Sticky Bentonite</td>
<td>BC</td>
<td>Chapter 2</td>
</tr>
<tr>
<td>ORA</td>
<td>Orange Rusty Ash</td>
<td>PH</td>
<td>Chapter 2</td>
</tr>
<tr>
<td>PSA</td>
<td>Pink Straight Ash</td>
<td>CMD-W</td>
<td>Chapter 3</td>
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<tr>
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<td>Sugar Ash</td>
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<td>RP</td>
<td>Rough Prong</td>
<td>RP</td>
<td>Chapter 3</td>
</tr>
</tbody>
</table>
SUPPLEMENTARY FIGURES

Flat Creek Main (FC-M)
GPS Cretaceous/Paleogene boundary layer: 47°31'36.59"N, 106°22'17.80"W

The pencil points to microtektite-like clay-wheathered spherules of the KPB. The KPB layer occurs just below a c. 5-cm thick leafy coal in the top of a carbonaceous mudstone.

Figure S4.1. A newly reported Cretaceous-Paleogene boundary layer at the Flat Creek Main (FC-M) section.
Figure S4.2. Palaeomagnetic data.

Fig. S4.2A - Snow Creek Road Main (SCR-M)

Legend

**paleomagnetism**
- Alternating field (AF) demagnetization
- Thermal (TH) demagnetization
- AF and TH

**characteristic Munsell colours**
- 7.5Y 8/3 light grey
- 2.5Y 2/1 dark greyish olive
- 5Y 4/2 greyish olive
- 5YR 2/2 dark greyish brown
- 10YR 4/7 yellowish brown
- 10YR 1.7/1 brownish black
Fig. S4.2B - Snow Creek Road South (SCR-S)
Fig. S4.2C - Biscuit Butte (BIB)
Fig. S4.2D - Hogs Back (HB)

Magnetic Polarity

- A Sites
- B Sites
- C Sites

VGP Latitude (°)

stratigraphic height (m)
Fig. S4.2E - Flat Creek West (FC-W)
Fig. S4.2F - Flat Creek North (FC-N)

stratigraphic height (m)

-90 0 90

Inclination (°)

Declination (°)

VGP Latitude (°)

Magnetic Polarity

C28r
C29n
C29r

#11-V
#10-V
#9-V
#8-W
#7-W
#5-X