Chapter 1

Introduction

GENERAL INTRODUCTION

Once upon early Paleocene time in the west

The Paleocene, Pal + Eocene, refers to the old part (pal-) of the Eocene, eos-kainos in Greek, implying the dawn (-eo-) of modern (-cene) lifeforms (Schimper, 1874). The Paleocene Period is bracketed by two globally catastrophic events: at 66 Ma by the Cretaceous-Paleogene boundary (KPB, see Box 1) and at 56 Ma by the Paleocene-Eocene Thermal Maximum.

In this doctoral dissertation, a geologic rock archive across the KPB consisting of layered alternations of coal, clay-, silt-, and sandstones is studied. It spans 2 million years of time from the latest Cretaceous (66.2 Ma) to the early Paleocene (64.6 Ma). The layers are now exposed spectacularly at the steep slopes of hills in the Missouri River badlands of north-eastern Montana (USA). Back in the time, they were deposited by a large meandering river system within a densely vegetated area at relative close distance from a sea. Subsequently, these sediments were buried to depths of a few hundreds of meters. Finally, they were exposed again at the Earth’s surface during the youngest building phase of the Rocky Mountains. The outcropping fluvial successions (in Latin fluvialis refers to river) consistently show a series of alternations of coal layers and fluvial clastics (clay, silt, sand) across the north-eastern Montana badlands. These repetitions are striking for the eye, but until now we do not understand the processes that led to their formation. They may be caused by processes within the river system such as the channel taking a new course while leaving the old behind. They may also be caused by the river system responding to processes outside the system such as climate and sea-level change. Along successive summer field campaigns, between 2010 and 2017 the layers have been investigated in great detail to disentangle the processes controlling the formation of these coal-clastic alternations.

Box 1 - The Cretaceous-Paleogene catastrophe

The impact of a large asteroid, with a diameter of 10 km (the size of Manhattan) at the Yucatán Peninsula in Mexico marks the Cretaceous-Paleogene boundary (KPB) (Hildebrand et al., 1991). The energy released during the impact is thought to be about 2 million times greater than the most powerful atomic bomb (Alvarez et al., 1980). The devastating global consequences of the KPB impact, both rapid (e.g. the shock-wave, heat pulse, mega-tsunamis, global cooling by dust-induced block-out of the sun) and gradual (e.g. global warming due to accelerated massive volcanism at the Deccan Plateau in India) are held responsible for the extinction of 75% of plant and animal species including the non-bird dinosaurs (Alvarez et al., 1980; Smit and Hertogen, 1980; Renne et al., 2015; Richards et al., 2015). Evidence of the KPB can be found around the globe by a thin clay layer consisting of impact debris that fell-out from the atmosphere. The layer includes high concentrations of the element Iridium (Ir) that is extremely rare in the Earth’s crust (Alvarez, 1983). Hence the Ir-spike is an excellent geologic marker for the KPB.
Certain terminology ("jargon") is common use by sedimentologists studying fluvial successions that is not comprehensive for the general public. Commonly used jargon is explained in Box 2.

**Box 2 - Definition of terms in fluvial sedimentology**

**Aggradation.** The increase in land elevation due to the deposition of sediment

**Allogenic.** Processes, patterns, or dynamics that are driven by factors outside the landscape or sedimentary system

**Autogenic.** Processes, patterns, or dynamics that arise solely as a consequence of the interaction of the components within a system

**Avulsion.** Abandonment of an old river channel and the creation of a new one

**Base-level.** The imaginary surface to which subaerial erosion proceeds. This is effectively sea level, although rivers erode slightly below it

**Compensational stacking.** The tendency of a depositional system to compensate for landscape topography through preferential deposition in topographic lows

**Differential compaction.** Differences in the extent of sediment compaction due to differences in compactability and topographic irregularities of the surface on which sediment is deposited.

**Facies.** The overall characteristics of a rock unit that reflect its origin and differentiate the unit from others around it. Mineralogy and sedimentary source, fossil content, sedimentary structures, and texture distinguish one facies from another

**Fluvial graded profile.** The longitudinal profile of surface topography from the source area to the final water body into which the river flows

**Incision (degradation).** The decrease in land elevation due to the erosion of sediment

**Lithology.** The rock type, such as shale or sandstone, showing a specific color, mineral composition, and grain size

**Concepts of auto- vs allogenic controls on fluvial sedimentation**

According to Beerbower (1964), fluvial stratigraphic repetitions could be produced by autogenic or allogenic controls. Autogenic controls are processes that act intrinsic to the sedimentary system, such as delta-lobe switching and fluvial point-bar migration. They tend to be instantaneous geologic events with few interregional feedback me chanisms. Clastic sedimentation in laboratorium-controlled experiments showed that autogenic channel avulsion and lateral channel migration can build compensational-stacked stratigraphy showing cyclic patterns and that the individual stacked-units show high lateral continuity (Hajek and Straub, 2017). Allogenic controls act outside the local sedimentary system and can be both regular and random in time and space, such as climate, base-level, and tectonics. They lead to changes in the variables controlling fluvial system behavior such as weathering, vegetation, discharge, and sediment supply. Allogenic controls include phenomena such as orbital climate forcing and base-level fluctuations. Such controls can produce stratigraphic patterns that may be periodic and that can be recognized over long distances potentially allowing stratigraphic correlation (Hilgen et al., 2015). The historical development of auto- and allogenic concepts in coal sedimentology started in sedimentary deltaic environments in North America (Rahmani and Flores, 1984; Langenheim et al., 1992), with the great debate of cyclothems as an example (Box 3).
Controls on the formation of coal-bearing fluvial strata

Stratigraphic hierarchy of coal seams in siliciclastic fluvial and delta successions frequently appears to be laterally continuous and repetitive (e.g. Fielding & Webb, 1996; Paproth et al., 1996; Michaelsen & Henderson, 2000). The commonly accepted autogenic mechanism to explain coal-clastic alternations is crevasse-splaying or avulsion triggered by differential peat compaction (e.g. Fielding, 1984; Rajchl and Uličný, 2005). Nevertheless, Van Asselen et al. (2009) describe that peat compaction can have multiple autogenic influences on channel behavior: (1) the channel can migrate laterally if the accommodation space of the channel decreases, (2) the channel can aggrade if high-cohesive peats resist for lateral migration which can lead to crevasse-splaying/avulsion if accommodation space in the channel decreases, and (3) the channel can become super-elevated with respect to the peatland if the peat oxidizes and, hence, floodplains become more sensitive for crevasse-splaying/avulsion. In all scenarios, a time series of channel responses to peat compaction will produce a coal-bearing fluvial succession in which the siliciclastic channel and overbank sediment gradually passes into the lateral-existing coal (McCabe, 1984). Lateral-extensive coal seams that do not gradually pass into time-equivalent channel sandstones, however, cannot be explained by an autogenic model (Belt, 1993; Fielding and Webb, 1996).

Successive sequences of fluvial aggradation that are stratigraphically interrupted by deep incision often reveal regular scales of alternation (Posamentier and Vail, 1988). In the sequence stratigraphy of fluvial systems, the process of fluvial incision is generally ascribed to downstream base-level fall (e.g. Wright and Marriott, 1993; Shanley and McCabe, 1994; Posamentier and Vail, 1988). In these sequence-stratigraphic models the basinward motion of base-level (i.e. the fall) causes opposed-directed headward incision along the coastal plain. This concept of fluvial incision caused by base-level fall cannot be straightforwardly applied to every fluvial setting mainly because fluvial incision cannot be triggered by base-level fall at coastal plain-shelf gradients that are concave-up (Miall, 1991; Quirk, 1996; Schumm, 1993), because the effect of base-level fall on fluvial incision is only limited to c. 200 km upstream (Miall, 2014; Blum and Törnqvist, 2000), and because

Box 3 - The great debate of cyclothems

The term cyclothem was introduced in 1932 by Wanless and Weller to denote a regressive-transgressive sequence of coal-bearing deltaic and limestone-bearing marine sediments in the Illinois Basin deposited during the Pennsylvanian Period (323 – 299 Ma). In the following decades, Pennsylvanian cyclothems were generally thought to be the result of allocycles, either controlled by recurrent tectonic events (Weller, 1930), glacio-eustatic sea level fluctuations (Wanless and Shepard, 1936) or variation in rainfall (Swann, 1964). When geologists as Moore (1959) and others started to rigorously compare cyclic sequences with modern analogues such as the Mississippi delta, this concept of allocycles was abandoned. Ferm (1970) concluded that the origin of Pennsylvanian cyclothems could be best explained by the autocyclic process of delta lobe switching leading to episodic progradation and decay. Conform the autocyclic concept of delta shifting, cyclothems are only local features and its constituent coal beds must be lateral discontinuous. This is opposed to the allocyclic concept, which assumes even interbasinal correlation of cyclothems and associated lateral continuity of the coal beds. Currently, there is consensus that glacio-eustatic sea-level fluctuations played a major role in the formation of the Carboniferous cyclothems (Heckel, 2008; Cecil et al., 2014). In different studies it was concluded that the sea-level fluctuations may originate from gradual changes in solar radiation driven by the Milankovitch cycles (Davydov et al., 2010; Jirásek et al., 2017; van den Belt et al., 2015).
upstream tectonic- and climatic-regulated processes such as discharge, weathering, vegetation, and sediment supply can exert a more important control on fluvial incision (Ethridge et al., 1998; Blum and Törnqvist, 2000; Bogaart and Van Balen, 2000).

Because of the issues mentioned above with generally accepted ideas of autogenic and downstream controls on fluvial sequence development, this thesis will be focused on an alternative allogenic and upstream depositional control, that is orbital-forced climate change.

In fact, orbital-forced climate change, by its impact on discharge, weathering, vegetation, and sediment supply, could exert a potential alternative control on repetitive peat formation in fluvial systems (Fielding and Webb, 1996), and on fluvial incision (Blum and Törnqvist, 2000).

**Tracing auto- and allogenic controls on peat formation and clastic deposition in fluvial systems**

Fully separating auto- from allogenic controls on peat formation and clastic deposition in fluvial systems is very complex, if not impossible. However, in an attempt to trace autogenic and allogenic controls, it is crucial to identify the interrelationship between the overbank-peat mire facies and the channel facies, since different controls will result in different stratigraphic architectures. As outlined in the previous paragraph, an autogenic model for fluvial systems in which peat formation occurs, starts with a channel-belt that exists simultaneous with peat formation in the adjacent flood-basins.

With time, the peat accumulation and channel-sand aggradation will laterally pass into one another resulting in an interfingering pattern (McCabe, 1984), Fig. 1.1). This process will continue until the channel becomes super-elevated with respect to the flood-basin thereby triggering avulsion. Places of highest flood-basin subsidence due to peat compaction caused by either consolidation or sediment-overburden, may trigger channel avulsion (e.g. Fielding, 1984; Van Asselen et al., 2009). The autogenic avulsion model generally applies for present-day low-gradient fluvial environments, but seems not always applicable to coal-bearing fluvial strata. In the Permian Bainmedart coal measures of Antarctica, for example, Fielding and Webb (1996) showed coal-bearing fluvial stratigraphic architectures in which the lateral continuity of coals was not interrupted by gradual passing into lateral channel sandstones. They interpreted that phases dominated by peat aggradation episodically succeeded phases dominated by clastic aggradation. Biostratigraphic age control and cyclostratigraphic tests suggest that these peat – clastic alternations were formed by a climate control on sediment supply, driven by the ca 21-kyr orbital precession cycle.

![Figure 1.1. Backswamp peat formation gradually passing into time-equivalent channel sand aggradation. Repetitive overbank flooding laterally introduced sediment into backswamp leading to an interfingering pattern. Re-printed from (McCabe, 1984).](image-url)
Tracing upstream and downstream controls on fluvial incision

If we consider the relative role of up- and downstream controls on fluvial incision, we consider these factors changing the fluvial graded profile. Downstream base-level and/or upstream sediment supply-discharge changes can cause fluvial aggradation, degradation (incision) or a fluvial equilibrium profile, i.e. the river at grade (Schumm, 1993; Blum and Törnqvist, 2000). Headward fluvial incision propagating in upstream direction, can only be caused by downstream base-level fall if the slope of the shelf is steeper than the slope of the coastal plain (e.g. Quirk, 1996; Schumm, 1993). Instead, upstream discharge changes can cause incision independent of relative proportions of coastal-plain to shelf gradients. Namely upstream climatic variables such a vegetation, precipitation, and weathering can determine specific places along the graded profile where stream power/bedload transport ratio could be significantly larger than 1, i.e. incision or lower than 1, i.e. aggradation (Fig. 1.2, re-printed from Blum and Törnqvist, 2000). In case of the downstream scenario of base-level fall causing headward incision, paleo-valleys created by the incision are also expected downstream in the coastal area. If fluvial incision was triggered by upstream sediment supply-discharge changes, it is not necessary to have downstream incision: for example in the coastal area the upstream-enhanced stream power : bedload transport ratio could have faded due to a downstream reduction of channel flow velocities.

Figure 1.2. Model showing how imbalances between discharge (stream power) and sediment supply lead to either degradation (incision) or aggradation of river channels. Channels incise when stream power significantly exceeds the sediment supply, and aggrade in the reversed case. Re-printed from (Blum and Törnqvist, 2000).
Potential role of orbital-forced climate control on river drainage networks

Astronomical- (orbital-) forced climate variations are caused by periodic changes in insolation, which in turn are associated with quasi-periodic changes in the shape of the Earth's orbit and the position of the Earth's axis (Box 4). The latter is caused by gravitational interactions between the Earth and the Sun, Moon and other planets. Astronomers can calculate the changes in the Earth's orbital parameters of eccentricity, obliquity and (climatic) precession back in time with the help of astronomical solutions for the Solar System (e.g. Laskar et al., 2011; Berger et al., 1989).

The direct impact of eccentricity (cyclic changes in shape and position of Earth's orbital ellipse around the Sun with ca 100-kyr and ca 405-kyr periodicities) on annual global insolation is ca 0.25 % which would not have a significant effect on climate change (Hilgen et al., 2015). However, climate change is controlled by eccentricity because both long- and short-eccentricity cycles are modulating the amplitude of the ca 21-kyr climatic precession cycle (e.g. Hinnov, 2000; Hinnov, 2013; Zeeden et al., 2015; Hilgen et al., 2015). Changes in precession-induced insolation of c. 7 % during the last 20 Ma (Laskar et al., 2004), may invoke significant climate change that via a series of non-linear system processes (e.g. vegetation, discharge, etc.) results in sedimentary changes (Hilgen et al., 2015). Modelling studies comparing early Holocene climate with recent climate (e.g. pre-industrial) have shown that even relatively small, mainly precession-induced 5 to 7% insolation changes, can cause large 26 to 46% differences in precipitation due to shifts of low- and mid-latitude monsoonal systems from ocean to land and vice versa (Kutzbach & Otto-Bliesner, 1982; Bosmans et al., 2012). Such amplitudes of precession-induced changes in monsoonal precipitation, weakened or strengthened by eccentricity modulation through time, likely forced cyclic changes in palaeo-discharge regimes of the Nile River system in North Africa, of which fluvial responses are reflected in the bundled stratigraphic architecture of sapropels in the Mediterranean Basin (Rossignol-Strick, 1985) and, the buried river channels that were formed in the early Holocene green Sahara (McCauley et al., 1982; Pachur & Kropelin, 1987).

Imprint of orbital forcing in fluvial successions

Previous workers tried to recognize cyclic imprints of orbital forcing in fluvial sedimentary successions: both at scale of geological formations (Abdul-Aziz et al., 2008) and within individual coal zones intercalated in fluvial deposits (Wang et al., 2011; Jones et al., 1997; Large et al., 2003). Although the local cyclic patterns demonstrated by these studies may fit with the frequency-ratios of the Milankovitch cycles, a control by autogenic compensational stacking cannot be ruled out since autogenic processes can produce comparable cyclostratigraphy (Hajek and Straub, 2017). More extensive studies including both cyclostratigraphic tests at individual sites and detailed analyses of sedimentary facies at a more regional scale suggest possible orbital climate control on fluvial systems (Fielding and Webb, 1996; Abels et al., 2013; Olsen et al., 1994; Olsen, 1990). However, the hypothesis of orbital-forced regional fluvial sedimentary change remains elusive due to the lack of numerous chronostratigraphic correlation markers that would allow for determining the lateral extent and interrelationships of key sedimentary facies such as channel sandstones and coals. In addition, high-resolution age control would provide more insight into duration of stratigraphic intervals and, hence, if these may be compatible or incompatible with the durations of orbital cycles.
**Hypothesis and research statement**

The hypothesis of orbital-forced regional fluvial system change is hard to test due to the scarcity of chronostratigraphic age control in fluvial successions. To tackle this problem, a high-resolution chronostratigraphic and laterally extensive sedimentary framework of well-exposed outcrops of rhythmic stratified fluvial sedimentary formations need to be developed. Here, we build a high-resolution sedimentologic and chronostratigraphic framework of an early Paleocene coal-bearing fluvial archive to determine the role and impact of orbital-forced upstream climate changes on fluvial system changes and how the orbital forcing may interact with autogenic mechanisms and downstream base-level changes. In addition, we explore if the results of this investigation might have implication for the hypothesis of atmospheric CO$_2$ burial in continental peat during short-eccentricity minima (Zachos et al., 2010).
Testing orbital forcing in the Fort Union Formation, Montana (USA)

The outcrops of the coal-bearing fluvial lower Paleocene Fort Union Formation in the Western Interior Williston Basin (Box 4), Montana (USA) allow to build a regional-based high-resolution timeframe by establishing transects of multiple well-exposed sections over distances of tens of kilometers. The Lower Fort Union Formation typically consist of alternations between ca 1 m thick lignite rank coal seams and ca 6 m thick intervals of light-grey channel sandstones and thin-banded, goldish-grey to yellowish-grey splay sandstones and mudstones (Collier and Knechtel, 1939; Rigby and Rigby Jr., 1990; Fastovsky and Bercovici, 2016; Retallack, 1994). The coal seams within these large-scale repetitions, could be generally traced in the field, over distances up to several kilometres. The peat formation (later compacted to lignite coal) occurred in low-lying forested mires (e.g. Fastovsky, 1987) with possible local occurrences of wildfires (Rigby and Rigby Jr., 1990). Channel bodies within the Tullock and Ludlow Members show both concentric and elongated multi-storey architecture (Rigby and Rigby Jr., 1990).

Chronostratigraphic age control is provided by magnetostratigraphy (e.g. Swisher III et al., 1993; LeCain et al., 2014) and by $^{40}$Ar/$^{39}$Ar radioisotope dating of sanidine-bearing tephras, commonly, preserved within coals (e.g. Swisher III et al., 1993; Renne et al., 2013; Sprain et al., 2015). Such age control in combination with time-stratigraphic correlations, using distinctive tephra beds and polarity reversals of multiple time-overlapping sections, are used to create stratigraphic fence panels that, if perpendicular to palaeoflow, may provide essential clues on channel-overbank interrelationships and thus in separating autogenic avulsion from allogenic climate controls. Also, the fence panels may provide unique opportunities to identify timescales and architectures involved with fluvial aggradation and incision.

The aim of this thesis is to 1) examine the lateral extent, vertical scales, and timescales of coal-clastic successions and aggradation-incision sequences in lower Fort Union Formation; 2) explore if this can be used to separate autogenic from allogenic and upstream from downstream controls; 3) determine how orbital-forced climate changes may possibly affect peat formation and incision in fluvial systems.

Box 4 - The Williston Basin

The Williston Basin is an intracratonic depocentre which formed as a cratonic-margin basin at the western margin of the Canadian Shield starting in the late Cambium (Burgess, 2008). The basin is filled with up to 4900 meter of strata (Bally, 1989). Six cratonic megasequences and seven interregional unconformities can be identified in the basin (Sloss, 1963). The fifth Zuni megasequence contains the targeted interval of this study (Fig. 1.3). During the Cretaceous, the Williston Basin was part of the Western Interior Basin: a vast foreland basin that extended from the Gulf of Mexico to the Arctic Ocean (e.g. DeCelles, 2004). The Western Interior Basin was formed on the east side of the Cordilleran orogenic belt that was formed by low-angle subduction of the Pacific Plate below the North American Plate during the Sevier orogeny (DeCelles, 2004; Stanley, 2009). Between the middle Albian (ca. 110 Ma) and early Maastrichtian (ca. 70 Ma) marine sedimentation dominated in the Western Interior Seaway including widespread deposition of marine shales (DeCelles, 2004). From the late Campanian (ca. 75 Ma) into the Eocene, subduction had shifted eastward in the central part of the western United States and caused moderate angle reversed faulting during the Laramide orogeny (DeCelles, 2004). The accompanying deformation led to the breakup of the Western Interior Basin in several anticlinal uplifts and sub-basins stretching north south from Montana to New Mexico (Dickinson et al., 1988; DeCelles, 2004; Stanley, 2009). In the Williston Basin the most important Laramide
induced tectonic changes, include the restoration of the basin axis over western North Dakota (Kent and Christopher, 1994) and uplift of Precambrian basement rocks, i.e. the Poplar Dome, Nesson Creek Anticline and Cedar Creek Anticline (Flores and Keighin, 1999). Nevertheless, these main uplift events became active in the middle Eocene suggesting that sediment deposition during the late Cretaceous and early Paleocene was less influenced by tectonics (Flores and Keighin, 1999; Cherven and Jacob, 1985).

**Figure 1.3.** Bottom-left: inset map showing the spatial extent of the Williston Basin, target sections (star), and transect of cross-section (dashed line) above the inset map. The upper infill of the basin (Cretaceous-Paleocene), exposed on the surface, is targeted in this study (red rectangle). Figure modified from Burgess (2008).

**Chapter outline**

In **Chapter 2**, we investigate the stratigraphic repetitions and lateral continuity of coal seams in the early Paleocene fluvial Tullock Member of the Fort Union Formation in McCone County (Montana, USA). The regional consistency and age of coal seams over 13 field sections are examined along a 10-km wide transect perpendicular to eastward paleoflow. The observed overbank-channel interrelationships, the stratigraphic age control, and cyclostratigraphic tests suggest that the major peat-forming phases, resulting in major coal seams, were driven by 100-kyr eccentricity related climate cycles. Two conceptual models were developed to explain the hypothesis of short-eccentricity-scale climate forcing.

In **Chapter 3**, we investigate if and how orbital-forced climate changes control fluvial incision and aggradation within coal-bearing clastic sediments of the lower Paleocene Lebo Shale Member of the Fort Union Formation in McCona County (Montana, USA). We test this hypothesis by creating a 15-kilometer-wide chronostratigraphic fence panel consisting of 12 sections. The panel is perpendicular to the main paleoflow and situated at ca 100 km paleo-distance from the maximum landward extent of the Cannonball Sea coastline in the east. Time-stratigraphic correlations reveal the presence of three 400-kyr-scale fluvial incision-aggradation sequences cycles. We present a
stratigraphic architectural model for a 400-kyr fluvial aggradation-incision sequence including the hypothesis of long-eccentricity-forced upstream climate control.

In Chapter 4, we establish a 92-km wide correlation panel of the Hell Creek Formation – Fort Union Formation coal-bearing fluvial rock formation across the Cretaceous-Paleogene boundary (KPB) from Garfield County into McCone County. The panel (Garfield-McCone Panel 1; GMP-1) consists of 25 sections in which we both use existing data and add new sections. The panel is used to test the hypotheses of orbital forcing developed in Chapters 1 and 2 along significantly longer distances and validate if identified cycles are truly regional. Our results show that eccentricity-induced cyclicity in the Fort Union Formation is also present along this long transect. We emphasize that our findings are significant in the context of basin-scale depositional history. In addition, we compare our age model of peat formation with the marine carbon isotope record of Ocean Deep Drilling (ODP) site 1262 and the most recent astronomical solution of the short-eccentricity cycle for the early Paleocene to test the hypothesis of atmospheric carbon burial in continental peat during short-eccentricity minima (Zachos et al., 2010).

In Chapter 5, we present high-resolution loss-on-ignition (LOI) and bulk stable carbon and nitrogen isotope records ($\delta^{13}$C and $\delta^{15}$N) for five different coal seams. We also generated a high-resolution compound-specific $n$-alkane $\delta^{13}$C climate proxy record for one coal seam. We aim to test consistency of data trends and excursions between the time-overlapping sections to distinguish autogenic influences from precession signals and to identify the presence and potential significance of hiatuses. This chapter aims to address which type of geochemical proxy-record can best be used to reveal Milankovitch cyclicity within coal or lignite.

Based on the results of this dissertation the state-of-the-art, uncertainties, and future directions will be discussed regarding the hypothesis of orbital-forced fluvial system change, in the Synthesis Chapter 6.