Fluvial responses to orbital-forced climate changes in the North American Western Interior early Paleocene

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Chapter 6

Synthesis

SUMMARY

Brief review

The work in this thesis has corroborated that fluvial sedimentary rocks may have partly been formed under the influence of orbital-forced climate changes. The identification of astronomical control on fluvial deposition could, therefore, provide us important new insights on how global and regional climate change may impact fluvial environments. There may be regular and hierarchic stratigraphic patterns in fluvial successions hinting towards Milankovitch cycles, but they do not necessarily have to be. Flume experiments show that autogenic processes including channel avulsion and lateral migration can produce clastic compensational stacking patterns resembling the regularity and hierarchy of Milankovitch cyclicity (Hajek and Straub, 2017). Disentangling orbital from autogenic controls on stacking patterns within fluvial deposits solely dominated by clastic deposition is therefore a high challenge or, even, an endless task. The game changes when channel-induced clastic stratigraphy bears pronounced intercalations of lower-energy overbank soil facies such as red palaeosols (Abels et al., 2013) and coals (Fielding and Webb, 1996; Noorbergen et al., 2018). The architecture and lateral extent of such overbank soil facies, namely, can provide an important criterion to disentangle autogenic from allogenic control (Chapter 2). In case of autogenic compensational stacking the accumulation of overbank sediments is synchronous to channel bed aggradation resulting in the channel lithofacies gradually passing into the lateral overbank facies. When this architecture is not found and when the channel-soil facies stratigraphically succeed one another at Milankovitch timescales, an orbital control on such alternations can be rectified (Chapters 2, 3, and 4). The application of this time-architecture dual-criterion has most potential in soil-bearing fluvial successions that can be well dated while their outcrops are regionally well-exposed (Chapter 4). In the studied successions of north-eastern Montana (USA), coal-bearing fluvial deposits of the lower Paleocene Fort Union Formation are spectacularly exposed and contain multiple chronostratigraphic marker levels. The successions have proven to be excellent archives for detailed sedimentological and chronostratigraphical analyses (Chapters 2, 3, and 4) as well as they appeared highly valuable for the generation of high-resolution geochemical proxy records within coal (Chapter 5). They allowed for testing challenging research hypotheses such as the role of orbital forcing in building coal-bearing fluvial stratigraphy as well as the potential implication of orbital control on widespread peat formation to global carbon cycle dynamics (Zachos et al., 2010).

Key findings, uncertainties, and future needs

In **Chapter 2**, we have found laterally persistent, on average 6.8-m thick, alternations between major coal seams and fluvial clastic intervals along a 10-km long transect of 13 sections perpendicular to east paleoflow in the Tullock Member of McCone County. Based on succession durations of c. 100-kyr and the high lateral continuity of the major coals without being interrupted due to gradual passing into channel sandstones a short-eccentricity climate mechanism is proposed for the formation of major successions (Fig. 2.11). Nevertheless, the maximum length of autogenic clastic compensational stacking was mostly -but not- always reached for every major succession along the transect. Hence, the transect should preferably be extended. Another question remaining is how allogenic and/or autogenic controls may have influenced sub-scale minor coal-clastic successions? The often local occurrences of minor successions are insufficiently constrained by the horizontal resolution of this transect. Detailed outcrop modelling such as drone-based photogrammetry could provide an improved 3D image of minor succession architecture.

In **Chapter 3**, we have found three laterally persistent 400-kyr-scale aggradation-incision sequences (AIS) superimposed to ten major coal-clastic successions along a 15-km long transect of 12 sections semi-perpendicular to southeast paleoflow in the Lebo Shale Member of McCone County. Based on the second stratigraphic occurrence of Facies Association B occurring within the magnetochron C28r long-eccentricity minimum (Dinarès-Turell et al., 2014), we hypothesized that fluvial incision and subsequent valley-fill in the Lebo Shale were connected to long-term relaxations of the hydrological cycle towards and within long-eccentricity minima. The incision followed by valley-fill aggradation could than have been upstream controlled by sustained increase of discharge relative to sediment supply due to expansion of vegetation on the one hand. On the other hand, aquifer-eustatic sea-level rise and, hence, base-level rise flattened the longitudinal graded profile and could have indirectly caused incision upstream of the terrace intersection. Nevertheless, the possible time-equivalency of expanding vegetation upstream as well as rising sea-level downstream are not constrained by this study. We therefore recommend future chronostratigraphic correlations of the AIS in the Lebo Shale Member of north-eastern Montana into the time-equivalent upstream strata in the Bull Mountain coal field of central Montana (e.g. Woolsey et al., 1917) and downstream strata in the Little Missouri Badlands of southwestern North-Dakota (e.g. Moore, 1976).

In **Chapter 4**, we have found that fourteen major coal-clastic successions are laterally persistent along a 92-km long transect consisting of 25 sections in the lower Fort Union Formation (Tullock and Lebo Shale Members). Similar to our observations in Chapter 2 and 3, we have not found evidence for the lateral continuity of major coal seams interrupted due to gradually passing into channel sandstones. Based on age control provided by the Cretaceous-Paleogene boundary as well as magnetostratigraphy we presented a chronostratigraphic (Wheeler) diagram (Fig. 4.3) of this first Garfield-McCone fence panel of the lower Fort Union Formation (GMP-1) showing the major peat-forming phases occurring during short-eccentricity minima. We observed that the first eight major peat formations do align with positive bulk $\delta^{13}C$ excursions in the marine realm (Kroon et al., 2007) which is in line with the hypothesis of (Zachos et al., 2010) yielding that extensive continental coal deposition during short-eccentricity minima might be a global sink for atmospheric CO2. In the assumption of a lower Fort Union lignite coal of 70-kyr duration, 1-m thickness, and covering the total size of the Western Interior, Denver, and Raton Basins (Jerrett et al., 2015) the carbon burial is 607 Gigaton (Gt) which is still 8 times lower than the 4758 Gt that is required based on atmospheric-ocean mass-balance calculation (Kurtz et al., 2003). Nonetheless, if the 607 Gt lower Fort Union coal carbon burial can be really reached must be tested by additional chronostratigraphic correlations of coals from north-eastern Montana into the other Western Interior regions. The remaining 4151 Gt carbon might be (partly) buried in other vast lower Paleocene coal basins (e.g. China/Russia, Colombia/Venezuela) but the timing as well as the extent of peat formation is largely unknown in these settings due to lack of high-resolution chronostratigraphic correlations and, hence, is a challenge for future research.

In **Chapter 5**, we identified the imprint of short-eccentricity cyclicity in a *n*-alkane compound-specific $\delta^{13}C$ record of the ZY-coal. We come to this conclusion by observing comparable patterns of $\delta^{13}C$ in mid-chain (n-$C_{21\text{-}25}$) *n*-alkanes derived from macrophytes ($\delta^{13}C_{mac}$) and long-chain (n-C_{29}) *n*-alkanes representing higher plants ($\delta^{13}C_{hip}$) suggesting that the carbon isotope variations originate from a same atmospheric pCO_2 source. In our bulk $\delta^{13}C$ record, however, we observe positive trends in $\delta^{13}C$ deviating from the compound-specific record which suggests post-depositional diagenesis due to early-stage decomposition (Esmeijer-Liu et al., 2012). This diagnetic control on bulk $\delta^{13}C$ is in contrast to a same coal analysis by Arens and Jahren (2000) who suggested that the bulk $\delta^{13}C$ reflects atmospheric pCO_2 variation. For future climate reconstruction within coal we strongly recommend the usage of compound-specific $\delta^{13}C$ analysis.

PRACTICAL IMPLICATIONS

Stratigraphic correlation of, as well as predicting heterogeneity within fluvial facies is of high value for different industries such as hydrocarbon exploration, geothermal energy, CO_2 storage, and groundwater exploitation. There is a long tendency to ascribe major fluvial rock facies to one commonly assumed control while ignoring possible other factors (Ethridge et al., 1998). For instance fluvial paleovalley fills are commonly assumed to be caused by downstream base-level fall and coal-clastic stacking to be formed by autogenic processes. By a setting-specific consideration and identification of the role of orbital-forced climate control on fluvial sedimentation and erosion, geological mapping and characterization of key fluvial rock units for applied geosciences can be drastically improved. The conceptual models presented in this thesis based on detailed sedimentologic and chronostratigraphic analyses in the lower Fort Union Formation provide a reference work for recognizing orbital-forced fluvial stratigraphy.

OUTLOOK

All fluvial stratigraphic records consisting of successive sedimentary fragments bounded by hiatuses provide a challenging archive for geological reconstructions. The highly variable sedimentation and erosion rates within river systems at short timescales, i.e. days, years, decades, centuries, millennia, complicate the stratigraphic recognition of longer timescale reciprocal external controls such as orbital-forced climate changes (10 kyr – 10 Myr) and flexural tectonic loading and unloading (> 500 kyr). The 100-kyr short and the 405-kyr long orbital eccentricity cycles in particular, encompass a time window which does not significantly overlap with strong shorter-term autogenic processes such as avulsion and with longer-term tectonism such as flexural (un)loading. Nevertheless, the imprint of short- and long-eccentricity cyclicity in the fluvial stratigraphic record goes indirectly via 20-kyr precession-induced climate change because the precession amplitude is modulated by eccentricity. Since the eccentricity climate control on fluvial system change will follow the 20-kyr modulated cycles of precession, time-overlapping autogenic avulsion to precession could potentially destroy or obscure eccentricity-related cyclicity.

Disentangling autogenic avulsion control from allogenic orbital control on fluvial system change might be only accomplished in fluvial successions that show clastic and non-clastic (e.g. red palaeosols, coals, incisions) alternations. Although such alternations can still be regulated by both controls, a regional chronostratigraphic correlation of facies could allow for assessing channel-overbank interrelationships over the maximum area of autogenic compensational stacking. If the non-clastic facies is clearly decoupled in time from the clastic channel-splay facies and if alternations between both occur at Milankovitch timescales, an orbital control can be rectified.