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Modeling the response of the Rhine–Meuse fluvial system to Late Pleistocene climate change

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ABSTRACT

We use a landscape evolution model to infer the effect of Late Pleistocene climate change on the incision–aggradation behaviour of the Rhine–Meuse fluvial system. We model the routing of runoff and sediment in the catchment in order to predict grainsize trends and the incision and aggradation behaviour in the downstream reach, where we compare it to the sequence of events and grainsize characteristics inferred from borehole corings. This sequence starts with an important incision taking place around the MIS 3 to MIS 2 climatic transition. During the coldest part of MIS 2, a coarse-grained sedimentary unit is deposited that shows an upward increase in the sand/gravel ratio.

The model experiments do not predict an incision at the MIS 3 to MIS 2 transition. Therefore, the incision should be attributed to other causes, most likely effects of glacio-isostatic uplift. However, a relative upward increase in sand content of the sediments is predicted by the model. This increase is the result of the difference in transport rates between sand and gravel. Starting from a homogeneous pre-existing (MIS 3) deposit, the gravel content in the active layer increases because the sand is removed quickly and transported further downstream, whereas the gravel travels slowly and piles up with gravel originating from immediately upstream, resulting in a net accumulation. At a later stage, sand originating from much further upstream progrades fan-like over the gravelly deposits.

According to the record, during the early Late Glacial warming part of MIS 2 (Bølling–Allerød interstadial), neither incision nor aggradation has taken place. This is in accordance with modelling results which show that, despite the reduction of sediment input due to re-vegetation of hillslopes, sufficient sediment remains available for fluvial transport in the channel network itself. It takes several thousands of years before effects of sediment depletion in the catchment are noted downstream. That is why we argue that the inferred incision at the late Late Glacial (the start of the Younger Dryas) in our downstream study area might reflect depletion effects related to the preceding early Late Glacial conditions.

In general, our modelling results show that terraces along one large fluvial system are diachronic features. In particular, terrace surfaces are older upstream compared to downstream. In addition, complex responses to climate change are likely to occur in a large fluvial system like the Rhine–Meuse, and correlation of morphological features in the fluvial record to specific short term palaeo-climatic events, for example Dansgaard–Oeschger events could be risky without consideration of catchment (size) characteristics and associated response times.

1. Introduction

Climate affects the aggradation and incision behaviour of the rivers by controlling the sediment and water fluxes through parameters like precipitation, vegetation, temperature and weathering. Fluvial deposits documenting aggradation and incision events, like river terraces, thus form archives of climate change. However, reconstruction of past climatic conditions using such archives requires a thorough understanding of the relationships between climate and river behaviour, which unfortunately remains a challenging issue (Vandenberghe, 1995; Blum and Törnqvist, 2000; Bridgland and Westaway, 2007; Törnqvist, 2007; Vandenberghe, 2008). For example, numerous studies indicate that fluvial systems may respond in a non-linear way to changes in climate for two reasons (Schumm, 1977; Bull, 1979). First, because sediment transport and morphological adjustment take time, pronounced time lags may exist between cause in the upstream part and effect in the downstream part of fluvial systems (e.g. Bull, 1991; Törnqvist, 2007). Second, one change in the fluvial system may trigger subsequent changes, resulting in a complex

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response. For example, a valley aggradation event caused by a climate-driven increase of sediment supply from hillslopes can be followed by incision due to a reduction of sediment input caused by exhaustion of erodible soil and regolith from these same hillslopes (Knox, 1972; Schumm, 1977; Tucker and Slingerland, 1997; Knight, 2003). Thus far, non-linear features in a large river system like the Rhine–Meuse have proven difficult to quantify due to lack of required chronological accuracy in fluvial sedimentary data, the restricted time-span covered, and the fragmented nature of such records. Numerical modelling provides an alternative tool to assess the role of non-linear fluvial behaviour (e.g. Willgoose et al., 1991; Kirkby, 1994, Howard, 1996; Tucker and Slingerland, 1997).

In this paper, we apply the CHILD landscape evolution model (Tucker et al., 2001a,b) to study the response of the Rhine–Meuse catchment to past climate changes. Due to its topography and considerable size, time lags and complex responses are expected to have played an important role in patterns and timing of sediment transport in the Rhine–Meuse catchment (Busschers et al., 2007). Existing 1D simulation model studies for the Meuse (Tebbens et al., Tebbens et al., 2000; Veldkamp and Tebbens, 2001; Bogaart et al., 2003a,b) do not explicitly take such complexities into account. The erosional part of the model is calibrated to cosmogenic nuclide-derived erosion rates and long-term incision rates obtained from terrace studies. The depositional part is constrained by the paleogeographic evolution of the fluvial system. Because two bedload grainsize fractions, sand and gravel, are distinguished, we are able to determine the impact of climate change on grainsize distribution, and compare that to the depositional record as well. This is the first time such a model has been performed at this spatial scale. Two simulations are presented and discussed: the response of the fluvial system to a warm to cold transition (Scenario 1) and *vice-versa* (Scenario 2). We compare the model results to the reconstructed sequence of events during the transition from MIS 3 to MIS 2 and during climatic oscillations within MIS 2 in the depositional part of the Rhine–Meuse system. A detailed analyses based on numerous cores and OSL datings has been carried out in this subsiding area (see Busschers et al., 2005, 2007), which we refer to as our study area in the remainder of this paper.

2. Setting

The present Rhine fluvial system drains 185,000 km^2 of Alpine, central and north-western Europe before it debouches in to the North Sea (Fig. 1). The Rhine originates in the Swiss Alps and has several large tributaries, including the Mosel, Neckar, Main and Meuse (Fig. 1). Present-day mean annual discharge at the Dutch–German border is 2300 m^3 s^{-1}. The mean annual peak discharge is around 12,000 m^3 s^{-1}, and results from a combination of snowmelt and rainfall events in central and Alpine Europe.

2.1. Tectonic setting

The Rhine drains an active subsiding rift system (Fig. 1, Ziegler, 1990, 1994; Van Balen et al., 2005). The upstream rift structure is the Upper Rhine Graben (URG; Fig. 1). Together with the glacially scoured Lake Constance (Bodensee) in the Alpine foreland, the URG forms an important trap for sediments that are eroded from the Alpine thrust belt (Ellwanger, 2003). The downstream rift is the Lower Rhine Graben (LRG). The LRG is characterized by several adjacent tectonic blocks, representing horsts, grabens and half-grabens (Boenigk, 2002; Van Balen et al., 2005; Boenigk and Frechen, 2006). The Dutch part centered around the Roer Valley Graben is called the Roer Valley Rift System (RVRS). Our study area is situated in the RVRS. The URG is tectonically linked to the LRG through the Rhenish Shield. This area is

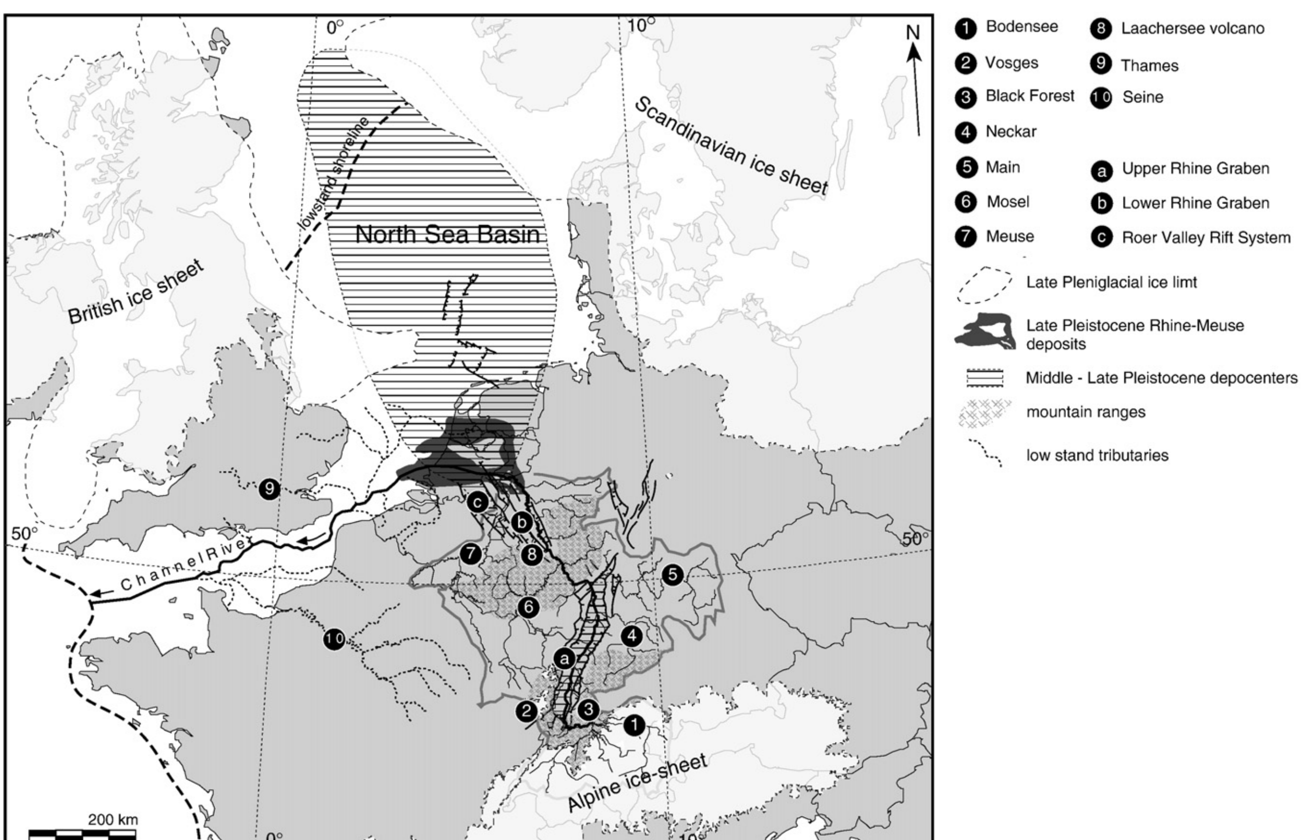

Fig. 1. The setting of the Rhine catchment. Structural data were taken from Ziegler (1990, 1994). Late Pleniglacial ice limits are based on maps compiled for the QUEEN project (Ehlers and Gibbard, 2004). RVRS = Roer Valley Rift System, URG = Upper Rhine Graben, LRG = Lower Rhine Graben.