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Complex fluvial response to Lateglacial and Holocene allogenic forcing in the Lower Rhine Valley (Germany)

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ABSTRACT

The Rhine catchment experienced strong changes in upstream allogenic forcing during the last 20,000 years. Climatic changes of the glacial–interglacial transition and steadily growing human impact during the second half of the Holocene forced the Rhine to adapt, resulting in changes in the fluvial morphology. The lower Rhine left two late Weichselian terraces and many Holocene palaeo-meanders in the Lower Rhine Valley (western Germany). This well-preserved terrace sequence is used to investigate the exact course of events of the lower Rhine response to changes in allogenic forcing. Five detailed cross-sections that integrate new and existing borehole data were constructed, and the deposits were analysed with regards to abandonment of terraces, changes in number of active channels, fluvial style, terrace gradients, and overbank sedimentation during the Lateglacial and Holocene. We improved and expanded the chronology of the Lower Rhine Valley deposits by dating new samples (^{14}C, OSL), and integrated these with existing dating evidence (archaeological and historical data, cross-cutting relationships). Twice during the glacial–interglacial transition, the lower Rhine changed from braided to meandering fluvial style. During both transitional episodes (meandering) secondary channels existed alongside the main channel, with a life span up to 2500 years. The findings imply that the lower Rhine was inherently slow to complete the full morphological transition to a single thread meandering system. On specific aspects of response, the morphological response (point bar/terrace formation, contraction to a single thread) extended over relatively long periods of time, whereas discharge-related response (e.g. fluvial style change, abandonment of braidplains, channel bed lowering/incision) seems to have been near instantaneous. Reach-specific conditions determine the degree to which the geomorphic response is delayed and the complexity of the resultant morphology. Increased human-induced sediment delivery (last 2000–3000 years) is expressed as relative thicker and coarser overbank deposits in the entire study area. In the downstream part of the Lower Rhine Valley it accelerated high-stand deltaic backfilling and decreased incision. The response to human activities occurred relatively quickly in contrast to the long-term fluvial response to the glacial–interglacial transition, because the human impact mainly involved change in delivery of the suspended load.

1. Introduction

Alluvial valley landforms (e.g. river terraces) are the geomorphic expression of river response to combined internal (autogenic) controls and changes in external (allogenic) forcing factors. Accordingly, geomorphologists have long studied river terraces to understand fluvial adjustment to environmental change. Such work augmented understanding of fluvial systems and their controls, and introduced concepts of thresholds in the fluvial system and degrees of forcing (e.g. Schumm, 1973, 1979; Vandenberghe, 1995, 2003) that have to be crossed to trigger specific response. Many workers conceptually addressed the spatial and temporal variation in response, e.g. the complex response concept (e.g. Schumm, 1973, 1977; Bull, 1991), and the delayed response concept (e.g. Vandenberghe, 1995, 2003; Huisink, 1997; Törnqvist, 1998; Blum and Törnqvist, 2000; Gibbard and Lewin, 2002). The common notion of all these concepts is that although the resultant morphology may appear

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straightforward, the trajectory between the initial forcing and the eventual valley-geomorphology is a complicated course of events that took considerable time. This is due to the interaction of internal and external factors (the former modulating the latter) and implies that one should take care when directly coupling (regional) geomorphological observations to past forcing events (e.g. Buch, 1988; Erkens et al., 2009). Certain aspects of landform change (e.g. transition from incision to aggradation, changes in fluvial style) may have different response time to a forcing than others. Once a time lag between the forcing and the fluvial development is recognized, the problem arises whether the fluvial system is responding near instantaneously to a lagging forcing (for example slowly changing discharge and sediment regimes as result of delayed vegetation and soil formation) or is it showing autogenic-modulated delayed response to an initial forcing (e.g. Huisink, 1997; Van Balen et al., 2010).

Most northern hemisphere catchments at temperate latitudes have experienced strong allogenic forcing during the last 20,000 years (Knox, 1995), with marked climatic change of the last glacial–interglacial transition (i.e. degradation of permafrost, switch from nival to pluvial runoff-generation, establishing vegetation cover, altered pedogenesis) and steadily growing human impact (i.e. deforestation) in the second half of the Holocene. Although these two main forcing events differ in timing, duration, magnitude and nature, they both have caused geomorphic response in many of these catchments – including the Rhine system in north-western Europe (Fig. 1). Surprisingly, despite the fact that the Rhine catchment is amongst the best-studied catchments in the world, the exact course and timing of the different aspects of response of the Rhine to both climate change and human impact have so far not been described in detail. Since it is the longest and largest river of north-western Europe, one may expect it to show more delayed response than surrounding lower-hierarchy rivers.

The response of the Rhine to catchment-scale allogenic forcing can best be studied along a downstream part of the Rhine trunk river. Fortunately, fluvial deposits are relatively well preserved in certain reaches of the Rhine trunk valley (Hoffmann et al., 2007), providing a record of response to the aforementioned forcings. The Lower Rhine Valley (LRV) is located just upstream of the Rhine delta (Fig. 1) and is characterised by a well-developed and preserved late Weichselian and Holocene terrace sequence. During the Weichselian late pleniglacial and Lateglacial, the lower Rhine accumulated two terraces, which show clear evidences of a braided channel pattern (see Section 2 for references). During the Holocene, the lower Rhine was predominantly meandering and reworked a large part of the former Weichselian floodplain. Although Holocene palaeo-meanders in the LRV have been extensively mapped (Klostermann, 1992; Zhou, 2000; Shala, 2001, and several published geological maps with explanatory booklets – see list in references), direct dating evidence of geomorphic features (i.e. terraces) is insufficient to accurately establish the activity period, moment of abandonment, and synchronicity of events. These limitations have prevented precise understanding of relationships between allogenic forcing and fluvial responses.

The objective of this study is to investigate the exact sequence of geomorphic responses of the lower Rhine to two completely different allogenic forcings (climate and human impact), and to discuss which elements of the fluvial archive show direct, near instantaneous responses and which show delayed ('autogenic modulated') responses. Hereto, we construct five detailed cross-sections to establish changes in fluvial style, elevation of terraces (i.e. rate of vertical incision), and terrace gradients in time. We improved the chronology for lower Rhine deposits by dating new samples (^{14}C, OSL) and integrated the results with pre-existing data (geological mapping, archaeological-historical data).

2. Geological setting

The Lower Rhine Valley (LRV) is the late Pleistocene trunk valley (length: ~150 km) of the lower Rhine. The LRV is located within the Lower Rhine Embayment, a complex tectonic rift-structure that forms a lowland area in western Germany (Fig. 1). The LRV is positioned along the eastern rim of the Lower Rhine Embayment (the hillslopes of the Bergisches Land) and is flanked by uplifted Pliocene, Early and Middle Pleistocene terraces to the west (up to ~90 m above the modern floodplain). The Rhine enters the LRV near the city of Bonn (Fig. 1) at a height of ~48 m + MSL (mean annual discharge water level). At the village of Rees (mean annual discharge water level of ~12 m + MSL) the lower valley grades into the upper delta, some 10 km upstream of the Dutch–German border (Favier, 2001). The north of the Lower Rhine Embayment experiences very modest uplift (hinge zone of North Sea Basin), whereas the south experiences higher uplift rates (vicinity of the Eifel volcanic dome) and has a more expressed horst-graben block structure. Nevertheless, on the time scale of this study (~20 ka), total tectonic uplift is modest, and direct fault-tectonic control on fluvial developments is considered insignificant (cf Klostermann, 1992). The downstream end of the LRV is the tectonically stable hinge zone between the uplifting Lower Rhine Embayment and the subsiding North Sea basin (Törnqvist, 1998), which forms the local base level for the lower Rhine. As a result, sea-level changes did not impact the fluvial evolution in the LRV.

Around 150 ka, during a brief stage of maximum glaciation, Scandinavian ice sheets covered the very north of the Lower Rhine Embayment, leaving an ice limit morphology composed of ice-pushed ridges, sandur (outwash fans) and ice-marginal fluvial terraces (e.g. Klostermann, 1992, 1995; Busschers et al., 2008). The late Pleistocene valley contains two well-preserved terraces, marking the wide braidplain rivers of the last glacial: the 'Older Lower Terrace' (NT2, German: Älteren Niederterrasse) and the 'Younger Lower Terrace' (NT3, German: Jüngere Niederterrasse). Schirmer (1995) assumes the NT2 terrace to be formed between ~17.0 and 13.0 ^{14}C ka, whereas Thoste (1974), Brunnacker (1978), and Klostermann (1992, 1995) assume formation during the Last Glacial Maximum (end of the pleniglacial, ~21 cal ka). Regardless of the age of formation of the NT2 terrace, we discuss the preservation of these deposits since 20,000 years, using the 'NT2' and 'NT3' nomenclature (cf Schirmer, 1990; Zhou, 2000; Shala, 2001). The plan view geomorphology of abandoned channels and the sedimentological structures in vertical cuts testify for their origin as a braidplain (e.g. Thoste, 1974; Thome, 1984; Klostermann, 1992; Zhou, 2000; Shala, 2001).

In the north of the LRV, two secondary braidplains diverge from the central NT2 braidplain (Fig. 1), the Niers-Rhine valley to the west, and the Oude-IJssel valley to the north (e.g. Van de Meene, 1977; Van de Meene and Zagwijn, 1978; Kasse et al., 2005). Both hold dated under-fit channels of transitional and meandering fluvial style, showing that these secondary branches lost Rhine discharge during the late Weichselian, in favour of the central branch.

The NT3 terrace is easily mapped within NT2, because its channel deposits contain pumice, supplied by the Laacher See eruption (11,063 ± 12 ^{14}C BP, i.e. 13.0–13.2 cal ka BP; Friedrich et al., 1999). This constrains the NT3 deposition to the very end of the Allerød, and Younger Dryas (Thoste, 1974; Brunnacker, 1978; Schirmer, 1990, 1995; Klostermann, 1992; Zhou, 2000; Shala, 2001). During the colder phases of the Lateglacial and into the early Holocene, dry river bed sediment from the NT terraces was locally transported by wind and considerable dune formation took place (e.g. Thoste, 1974; Klostermann, 1992, 1995; Jansen, 1995; Zhou, 2000; Shala, 2001).

During the Holocene, the lower Rhine developed a meandering course (Fig. 1), thereby reworking large parts of the NT terraces.