Quaternary Science Reviews 123 (2015) 31–57

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Terrace styles and timing of terrace formation in the Weser and Leine valleys, northern Germany: Response of a fluvial system to climate change and glaciation

Jutta Winsemann [a,*], Jörg Lang [a], Julia Roskosch [a], Ulrich Polom [b], Utz Böhner [c], Christian Brandes [a], Christoph Glotzbach [a], Manfred Frechen [b]

[a] *Institut für Geologie, Leibniz Universität Hannover, Callinstraße 30, D-30167 Hannover, Germany*
[b] *Leibniz Institute for Applied Geophysics (LIAG), Stilleweg 2, D-30655 Hannover, Germany*
[c] *Niedersächsisches Landesamt für Denkmalpflege, Scharnhorststraße 1, D-30175 Hannover, Germany*

ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form
1 June 2015
Accepted 4 June 2015
Available online 24 June 2015

Keywords:
Fluvial terrace architecture
Climate
Base-level
Glacio-isostatic adjustment
Luminescence dating
Shear wave seismics

ABSTRACT

In glaciated continental basins accommodation space is not only controlled by tectonics and sea-level but also by the position of ice-sheets, which may act as a regional base-level for fluvial systems. Although the Pleistocene terrace record of major river systems in northwestern Europe has been investigated by many authors, relatively little attention has been paid to base-level changes related to glacier advance–retreat cycles and how these regional changes in base-level interacted with river catchment processes. This study provides a synthesis of the stratigraphic architecture of Middle Pleistocene to Holocene fluvial terraces in the upper Weser and middle Leine valley in northern Germany and links it to glaciation, climate and base-level change. The depositional architecture of the fluvial terrace deposits has been reconstructed from outcrops and high-resolution shear wave seismic profiles. The chronology is based on luminescence ages, ^{230}Th/U ages, ^{14}C ages and Middle Palaeolithic archaeological assemblages.

The drainage system of the study area developed during the Early Miocene. During the Pleistocene up to 170 m of fluvial incision took place. A major change in terrace style from strath terraces to cut-and-fill terraces occurred during the early Middle Pleistocene before Marine Isotope Stage MIS 12, which may correlate with climate deterioration and the onset of glaciation in northern central Europe. During this time a stable buffer zone was established within which channels avulsed and cut and filled freely without leaving these vertical confines. Climate was the dominant driver for river incision and aggradation, whereas the terrace style was controlled by base-level changes during ice-sheet growth and decay. A major effect of glacio-isostatic processes was the post-Elsterian re-direction of the River Weser and River Leine.

The Middle Pleistocene fluvial terraces are vertically stacked, indicating a high aggradation to degradation ratio, corresponding with a regional base-level rise during glacier advance. At the beginning of the Late Pleistocene the terrace style changed from a vertical to a lateral stacking pattern, which is attributed to a decrease in accommodation space during glacier retreat. The formation of laterally attached terraces persisted into the Holocene.

Major incision phases took place during MIS 5e, 5d, 5c, and probably early MIS 4, early MIS 3 and MIS 2 (Lateglacial). During MIS 5e and the Lateglacial the braided river systems changed into meandering rivers, indicated by preserved organic-rich flood-plain and point bar deposits. The Late Pleistocene braided river systems (MIS 5c to MIS 3) are characterized by a high sinuosity, which may be a direct effect of an increased downstream gradient after deglaciation when the channel lengthened and the river adjusted to the increased gradient by increasing sinuosity. These Middle Pleniglacial fluvial deposits are unconformably overlain by Lateglacial to Holocene meandering river deposits, which form laterally attached terraces, recording millennial-scale channel shifts. The lack of Late Pleniglacial deposits might be related to Late Weichselian forebulge formation.

---

* Corresponding author.
E-mail address: winsemann@geowi.uni-hannover.de (J. Winsemann).

http://dx.doi.org/10.1016/j.quascirev.2015.06.005
0277-3791/

1. Introduction

Fluvial deposits and landforms provide important terrestrial archives, recording climate and base-level change. Rivers incise or aggrade to maintain the optimal longitudinal profile, which is determined by the interplay of transport capacity and sediment supply (Blum and Törnqvist, 2000; Holbrook et al., 2006; Blum et al., 2013). In a steady state, when averaged over $>10^6$ years, the long profiles of fluvial systems reflect a balance between incision rates and rates of uplift (Whipple, 2001) and the drainage area and relief are the first order controls on sediment supply. Over shorter time scales incision is unsteady, and punctuated by periods of lateral migration, channel incision and aggradation, leading to the formation of fluvial terraces (e.g., Blum and Törnqvist, 2000; Holbrook et al., 2006; Archer et al., 2011; Bridgland and Westaway, 2014).

Climatic controls on fluvial systems are exerted by long-term and short-term variations in discharge and sediment supply, promoting aggradation or degradation (e.g., Blum and Törnqvist, 2000; Holbrook et al., 2006). In non-glaciated areas, climate change over a full interglacial–glacial cycle may cause variations in sediment supply in the range of 20–30% (Syvitsky and Milliman, 2007). In glaciated areas, glacial erosion and the related sediment supply might be considerably higher (Haeuselmann et al., 2007).

The fluvial response to Pleistocene cyclic climatic changes in northwestern Europe has been investigated by many authors and major results are summarized in Vandenberghe (2008), Gibbard and Lewin (2009), Lewin and Gibbard (2010) and Bridgland and Westaway (2014).

Although the Pleistocene terrace record of the major river systems in northwestern Europe has been investigated by many authors, the process relationships to external forcing factors such as tectonic activity, climate change and glaciation are often not well constrained. Numerical simulations basically confirm the field-based conceptional models but also clearly indicate that these models cannot be used in a straightforward manner and fluvial systems may respond in a complex non-linear way to changes in climate including considerable time lags before aggradation or incision takes place (e.g., Bogaart and Van Balen, 2000; Veldkamp and Van Dijke, 2000; Hancock and Anderson, 2002; Bogaart et al., 2003; Van Balen et al., 2010).

Especially underexplored is the response of the central and northeast European river systems to the repeated growth and decay of the Scandinavian ice sheets. In glaciated basins accommodation space is not only controlled by tectonics and relative sea-level, but also by the position of ice-sheets, which may act as a regional base-level for fluvial systems (Brookfield and Martini, 1999; Powell and Cooper, 2002; Busschers et al., 2008). During glacier advance an overall relative base-level rise will occur, when river profiles shorten. The formation of large proglacial lakes in river valleys is commonly associated with rapid rates in base-level rise, followed by instantaneous base-level falls during catastrophic lake drainage (Brookfield and Martini, 1999; Winsemann et al., 2011).

More local changes in accommodation space along river profiles may be caused by glacial and/or meltwater erosion (Brookfield and Martini, 1999; Powell and Cooper, 2002), or the formation of a forebulge (Lambeck et al., 1998, 2006; Stewart et al., 2000; Busschers et al., 2007) and reactivation of basement faults (Brandes et al., 2011, 2012) by ice loading. During deglaciation the collapse of the forebulge zone results in rapid subsidence (Stewart et al., 2000; Frischbutter, 2001).

To fully understand this control and the timing of aggradational and degradational phases in glaciated basins detailed architectural facies models of fluvial terraces are needed, which are combined with geophysical, geochronological and morphological data that allow for the reconstruction of the internal terrace architecture. Such a combined approach has rarely been undertaken in fluvial terrace studies.

The major objective of this work is to provide a synthesis of the stratigraphic architecture of Middle and Late Pleistocene fluvial terraces in the Weser and Leine valleys in northern Germany and link it to glaciation, climate and base-level change. Shear wave seismic profiles provide continuous, high-resolution two-dimensional data of the subsurface and are able to close the resolution gap between outcrop and borehole data. The chronology is based on new luminescence dating of feldspar minerals and Middle Palaeolithic archaeological assemblages, complemented by luminescence ages, ^{230}Th/U ages and ^{14}C ages determined in previous studies.

The study area is located south of the North German Lowlands, where the repeated growth and decay of ice-sheets interacted with fluvial processes. River systems had to adjust to climate change, glacial erosion and rapid base-level changes during ice-advance and–retreat cycles. The study area is therefore regarded as a key site for investigating these complex interacting processes and the fluvial terrace architecture may serve as an analogue-based predictive stratigraphic model for river systems in similar glaciated basins.

2. Geological setting and previous research

2.1. Structural setting

The study area is located in the upper Weser and middle Leine valley in northwest Germany (Fig. 1A–D). It belongs to the North German Basin, which forms part of the Central European Basin System (CEBS). Basin evolution started in the Permian and subsidence occurred until the end of the Mesozoic, leading to the deposition of thick continental and shallow marine sediments (Stollhofen et al., 2008). During the Late Cretaceous, the basin was inverted (Kley and Voigt, 2008). The present-day stress field was established during the Miocene to Pliocene transition in response to the Alpine orogeny and the North–Atlantic ridge push. This stress field caused strong subsidence in the North-Sea basin and uplift of the Mesozoic and Palaeozoic bedrock south of the North German Lowlands (Cloetingh et al., 1990; Ziegler et al., 1995). Reconstructed uplift rates since the Middle Pleistocene for the Ardennes and Rhenish Massif range between 0.03 and 0.25 m/ka (e.g., Veldkamp and Van den Berg, 1993; Veldkamp and Van Dijke, 2000; Demoulin and Hallot, 2009) and 0.05–0.06 m/ka for northern France (Antoine et al., 2007). For the Aller valley, an eastern tributary of the River Weser, Veldkamp et al. (2002) reconstructed uplift rates between 0.03 and 0.06 m/ka, but suggested that these values may be underestimated because the upper River Aller has been unable to compensate all crustal uplift. Also the morphology of the steep upper Weser valley indicates net-uplifting during the Pleistocene (Rohde, 1989; Veldkamp et al., 2002). From Late Oligocene marginal-marine deposits, which occur over an altitude range of 280–400 m a.s.l., time-averaged uplift rates of approximately 0.01 m/ka can be inferred. Late Pliocene to Pleistocene fluvial terraces, located up to 170 m above the present river floodplain (Lüttig, 1974; Meiburg and Kaever, 1977; Fromm, 1989; Rohde, 1989) imply higher time-averaged uplift rates of approximately 0.1–0.17 m/ka. However, the quantification of uplift rates based on terrace heights is rather uncertain and likely overestimated (Kiden and Törnqvist, 1998; Tebbens et al., 2000; Hancock and Anderson, 2002; Schaller et al., 2004). Schaller et al. (2004) estimated for the Meuse catchment a climate-controlled denudation of approximately 40–60 m in the last 1 Ma, reducing