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River terraces as a response to climatic forcing: Formation processes, sedimentary characteristics and sites for human occupation

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A R T I C L E I N F O

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A B S T R A C T

Climate impact on the fluvial processes led to morphological and sedimentological differentiation of a terrace. This diversity in the fluvial environment determined how people could adapt to the river. Although the climatic impact on development and initiation of river terraces seems to be well accepted, a number of pertinent questions disturb this simplicity. For instance:

- The exact terrace development within a climate cycle is still under debate. Different kinds of terraces and their sedimentary successions may originate either from aggradation, incision or lateral migration.
- Is there a typical sedimentary succession below terraces? What is the genetic origin of each sedimentary layer?
- What are the relative ages of those layers and erosion phases within a climate driven erosion–aggradation cycle? The variability in staircase preservation in relation to climatic cyclicity is analysed in three scenarios. Specific scenarios depend essentially on the preservation of the fluvial deposits dating from the warm periods.

Finally, a preliminary inventory is presented of the most favourable sites for human occupation in fluvial valleys as derived from a random selection of archaeological findings. Generally, human occupation in that morphological position seems to be linked with, at least temporarily, dry conditions. Climatic conditions do not seem to play the major role. The termination of a settlement may have been due to increased risks of flooding, apart from other than natural fluvio-environmental reasons.

1. Introduction

A river terrace is defined as a flat surface adjacent to a (former) river representing a floodplain that was abandoned by erosion (for a discussion, see Leopold et al., 1964, p. 460–461). Fill (accumulation) terraces may be distinguished from cut (erosional) terraces. We prefer the term 'erosional terrace' rather than 'strath terrace' as the latter seems to be restricted by some scientists to 'cut in bedrock' (Leopold et al., 1964). Thus, 'erosional terraces' include also terraces that are formed in unconsolidated sediments, for instance, in older fluvial gravels. Fill terraces comprise predominantly stacked deposits, while the formation of erosional terraces is characterized by lateral or vertical erosion and only a relatively thin veneer of (bedload) sediment is preserved. The thickness of the fluvial sediment linked to the erosional terrace is usually assumed to be equivalent to the height of the topographic highs of the river bed at the most. Terraces may further be subdivided after additional criteria (e.g. Bull, 1991; Lewin and Gibbard, 2010).

Terrace staircases develop as a result of alternating aggradation or stability and downcutting. It is logic to assume that incision is only possible when the base level is in a state of relative fall to create sufficient accommodation space (e.g. Kiden and Törnqvist, 1998; Busschers et al., 2007). As exemplified in numerous catchments, terrace staircases appear to develop as a combined effect of a background of relative base-level drop (for instance by tectonic subsidence or eustatic sea-level drop) or by tectonic uplift in the upstream catchment, and superposed climate alternations of shorter duration (e.g. Maddy, 1997; Antoine et al., 2000; Maddy et al., 2001; Bridgland and Westaway, 2008). In those cases, climate change may lead to a disturbed energy balance in the river system by steepening of the longitudinal gradient due to sea-level

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changes at the exit of the river system (e.g. Viveen et al., 2013) or by changes in vegetation and subsequent modification of slope processes and thus changes in sediment supply to the river (Vandenberghe, 1993a). An alternative scenario at smaller scale is that of an initial, relatively strong incision, for instance due to climatic change at the end of the last glacial or by tectonic movements, superposed by terraces formed as a result of human interference or intrinsic evolution (e.g. Schumm, 1977; Bull, 1991).

River terraces and floodplains appear to be preferred sites for human settlement. Specifying the climate impact on the processes that lead to the morphological and sedimentological differentiation of a terrace is a prerequisite to understand the reasons for the concerned site locations and the way how people adapted to changing environmental conditions on the terrace. This is the focus of the present review assessing evidence from existing publications. Although climate-induced fluvial development seems to be well understood (e.g. Bridgland, 1994, 2010; Maddy, 1997; Maddy et al., 2001; Vandenberghe, 2002), there are a number of pertinent questions that need further inquiry. For instance, the exact terrace development within a climate cycle is still under debate. Further, by specifying the terrace-forming erosion process, a typical sedimentary succession below terraces may be defined, and also the genetic origin of each sedimentary layer and the relative ages of those layers and erosion phases within a climatic (cold–warm–cold) cycle. After discussion of these specific topics, potential staircase development in relation to climatic cyclicity is established in three scenarios. Finally, the most favourable sites for human occupation in floodplains are derived from a selection of archaeological findings.

2. Terrace deposits

2.1. General sediment succession

Although numerous sections have been described of the sedimentary succession below a terrace, no systematic and complete succession seems available. The present overview illustrates especially fluvial systems with relatively moderate longitudinal gradient, as it is clear that upland systems or valleys with a steep longitudinal gradient are not in equilibrium and are thus constantly incising without any terrace formation, or with only strath-terrace formation with no or limited sediment cover (Vandenberghe, 1995c). In those cases, terraces that may have developed during short phases of stability during otherwise constant incision have only limited preservation potential.

Typically, horizontal parallel layered or trough-bedded coarse-grained sands or gravels are separated from overlying finely laminated, fine-grained sands and silts (Schirmer, 1995; Fig. 1a, b). Generally, the boundary between both units is sharp. However, in a number of cases the coarse-grained unit may be fining upward, and silty or fine-sandy layers may be intercalated (Fig. 1c). Similarly, the fine-grained unit may contain coarse-grained channel fills or lag deposits towards the base of that unit (Fig. 1b). The coarse-grained deposits belong to the (internal) active channel belt (called 'genetic floodplain' by Nanson and Croke (1992)). In our terminology, the floodplain is restricted to the (external) periodically inundated zone next to the channel (which is the 'hydraulic floodplain' in the sense of Nanson and Croke (1992)); it is the zone where the fine-grained material is deposited. Both units are fluvial deposits which may be topped by sediments of different nature: sometimes calcareous tuff is formed at places of groundwater resurgence (e.g. Antoine and Limondin-Lozouet, 2004; Chaussé et al., 2004; Antoine et al., 2007), while slope deposits (Antoine, 1994; Antoine et al., 2007) or aeolian deposits (loess) may be preserved after retreat of the channel (e.g. Antoine, 1994; Pan et al., 2003, 2011; Antoine and Limondin-Lozouet, 2004, 2007; Bridgland, 2006; Vandenberghe et al., 2011). The basal boundary of the sediment series is mostly irregular due to erosion by trough-shaped channels. A more detailed subdivision is given in the next section (2.2) in combination with the genetic interpretation.

2.2. Origin of the terrace-forming depositional units

2.2.1. The lower coarse-grained fluvial sediments

Coarse-grained fluvial sediments are in general to be considered as bedload deposits. Several sedimentary facies types have been distinguished and extensively documented in the sedimentological literature, for instance, by Rust (1972), Bluck (1979), Miall (1996) and Lewin and Gibbard (2010). Clasts are often matrix-supported and imbricated; the grains have a large size range. Massive or crudely-bedded gravel layers are most common, often showing intra-formational scouring and trough-crossbedding. This depositional character seems to be due to migration of longitudinal bars. It is the dominant facies towards the base of this coarse-grained fluvial unit. Towards the top, the coarse-grained unit is often dominated by large-scaled horizontal beds, but individual beds may sometimes show small-scaled oblique lamination (Fig. 1a–c). This facies is probably formed towards the edges of the active channel belt where relatively quiet sedimentation is predominant rather than scouring (Vandenberghe et al., 1993). Locally unstable, broad and shallow channels with trough-cross-bedded fills occur in these upper, overall horizontal, relatively fine-grained deposits (Fig. 1c). Their size is smaller than the troughs in the basal coarse-grained unit (described, for instance by Bryant, 1983; Gao et al., 2007; Lewin and Gibbard, 2010; Vandenberghe et al., 2011). Oblique bedding in those channels points to lateral migration of meandering channels in between otherwise coarse-grained layers. They may represent remnants of secondary channels or temporary 'reactivation channels' that were functioning at high stage, i.e. when the complete channel belt is flooded. The sediment facies are mostly ascribed to the Donjek- or Scott type (Miall, 1978).

Lewin and Gibbard (2010) summarize that the coarse-grained deposits below terrace surfaces are typical for wandering to braided river types with a considerable degree of internal reworking. However, gravel layers may also be formed in meandering rivers (Alonso and Garzon, 1994; Schirmer, 1995) where sub-fossil tree trunks may be present (e.g. Starkel et al., 2007). It has been well documented that all river types may occur in all climates (Vandenberghe, 2001). However, it has also often been shown that at least this coarse-grained sediment layer is formed during cold periods. Some exceptions exist, the most striking one being the Holocene fluvial system. Also, in a number of cases, the fluvial succession is made more complex by the occurrence of an often organic, fine-grained deposit positioned within the coarse-grained lower part of the sediment series. This is, for instance, the case in many British rivers (e.g. Bridgland, 2006; Bridgland and Westaway, 2008; Bridgland, 2010 and references therein). Such cases are discussed below in scenario 3 (Section 3.3). Cryoturbations, thermal contraction cracks, ice-wedge casts, and soft sediments transported in a frozen state typify the cold-based character of the coarse-grained fluvial deposits that are sometimes intercalated with slope deposits (e.g. Bryant, 1983; Van Huissteden, 1990; Mol, 1997; Kasse et al., 2003; Gao et al., 2007; Van Huissteden et al., 2013). Briant et al. (2005) distinguish three different facies that apply to a family of cold-based river deposits (see below) of wandering to braided rivers. Although most of the cited examples are from periglacial environments, cold conditions in glacier-fed systems show a similar impact on the fluvial deposition (e.g. Panin and Nefedov, 2010; Wang et al., 2013).