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Constraints on Pleistocene glaciofluvial terrace age and related soil chronosequence features from vertical ^{10}Be profiles in the Ariège River catchment (Pyrenees, France)

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ABSTRACT

Sequences of alluvial fill-terraces record the long-term variation of fluvial transport regimes in response to Quaternary climatic changes. Through a production of increasingly precise chronologies, the broadening range of sediment dating methods in recent years has improved our understanding of correlations between alluvial dynamics and external forcing mechanisms. However, results in this field have mostly focused on periglacial and other mid-latitude settings. These may not readily apply to glaciofluvial environments, where alluvial regimes are narrowly dependent on the behavior of the adjacent ice-field. Here we constrain the ages of three glaciofluvial fill terraces based on five vertical ^{10}Be age profiles in the Ariège River catchment, and produce a chronofunction of related contrasts in terrace tread topsoil characteristics. Each profile consists of 9 to 11 gravel samples collected over depths of 4.6 to 15 m. Terrace T1 (+15 m above the current riverbed) was sampled at ~4, 22 and 53 km downstream from the Last Glacial Maximum terminal moraine system of the Ariège outlet glacier. The profiles of T2 (+30 m) and T3 (+50 m) complete the data set. Beryllium-10 age profiles date the age of terrace tread abandonment as a result of fluvial incision. Results show that the incision of T1 occurred over a protracted period during the Last Termination, beginning ca. 17.5 $^{-3.5}/_{+2.0}$ ka. Prior to this, aggradation occurred from MIS 4 to the global Last Glacial Maximum (LGM), i.e., under maximum ice extent conditions, and lasted a few thousand years thereafter. The protracted influx of debris after the LGM was sustained by paraglacial storage release in the catchment and promoted by strong coupling between slope and channel processes. Fluvial incision of T1 occurred during the post-LGMcold-to-warm transition after a time (supported by paleobotanical evidence) when the vegetation cover was capable of ensuring catchment-wide slope stability. The wave of incision propagated downstream between 17.5 $^{-3.5}/_{+2.0}$ ka (proximal profile) and 13.0 $^{-0.5}/_{+3.5}$ ka (distal profiles). The exposure-age confidence intervals for T2 and T3 are much larger than for T1 (60–145 ka and 204–226 ka, respectively) but the data nonetheless allow the aggradation of T2 and T3 to be attributed to MIS 6 and MIS 8, respectively. The soil chronosequence permitted by the fill-terrace age sequence indicates that the Luvic Cambisols capping T1 formed after ~13–16 ka, i.e., during the Holocene; (ii) the Haplic Luvisols capping T2 required at least ~130 ka, i.e., two interglacials; and (iii) the deeply rubified, highly eluviated Luvisols capping T3 required at least ~250 ka, i.e., at least three interglacials.

1. Introduction

A fluvial terrace is an abandoned floodplain surface. River valleys often contain vertical sequences of alluvial terraces that reflect long periods of fluvial response to external forcing factors. Fluvial terraces are formed by one or more changes in three variables that control a river's longitudinal profile: base level, water discharge, and sediment supply. The river adjusts its channel to the new conditions and sometimes forms a new floodplain at a lower or higher level than the original ones. Sediment aggradation, i.e., net deposition, will produce a fill terrace, and subsequent incision (degradation) will lower the level of the active channel and abandon the fill terrace. When incision of a fill terrace is interrupted by pauses that allow the stream to cut laterally into its channel banks rather than vertically into its channel floor, this may produce cut terraces.

The scope for testing the validity of these concepts has increased in the last 20 years, largely through the benefit of a broadening range of

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sediment dating methods (e.g., Stokes et al., 2012), which has allowed environmental forcing hypotheses to be investigated at different scales (Merritts et al., 1994; Blum and Törnqvist, 2000; Bridgland, 2000; Gibbard and Lewin, 2009). It is now widely accepted that forcing ascribable to intrinsic catchment variables (e.g., topographic gradients, valley width, and catchment lithology) causes relatively short-term imbalances (10–1000 years) and small-scale bedform changes, whereas external forcing (climatic change, crustal deformation, sea-level variations) operate on longer time scales and are responsible for catchment-scale changes (Maddy et al., 2001). Catchment-scale alluvial dynamics are primarily driven by climate. This includes the lower reaches of fluvial systems, particularly among those connected to wide continental shelves that were extensively exposed during the glacial stages of the Pleistocene (Bridgland, 2000; Vandenberghe and Maddy, 2001; Vandenberghe, 2003; Bridgland and Westaway, 2008). When catchments reach narrow continental shelves, sea-level changes are more likely to modify channel gradients and thus control the potential for alluvial channel aggradation or incision over distances reaching far inland from base-level (Schumm, 1993; Merritts et al., 1994; Törnqvist, 1998; Viveen et al., 2013). The density of vegetation cover plays a key climate-related control over slope stability, and thus over the quantity and median size of debris reaching the active river channels (Vandenberghe et al., 1984; Huisink, 2000; Millar, 2000; Van Huissteden and Kasse, 2001). Precipitation regime and intensity also control stream power more narrowly than mean annual rainfall or temperature. Vandenberghe (2001) has emphasized the importance of permafrost, which increases surface runoff over infiltration in cold-climate environments. Non-climatic environmental factors such as active tectonic might in some cases modulate the fluvial style by changing the slope of the longitudinal profile. These may also change catchment-scale denudation rates, although this will mostly be relevant to active orogens (Schumm et al., 2000). Finally, valley topography is also critical because it controls the accommodation space for alluvial aggradation (Rose, 1995; Kasse, 1998; Mol et al., 2000). All of these external and internal environmental forcing factors control changes in stream power and resisting power and thus changes in fluvial style but alternations between aggradation and incision in a fluvial catchment allow for the development of terraced sequences only when the area is affected by positive crustal uplift (Bridgland, 2000; Schumm et al., 2000; Kiden and Törnqvist, 1998; Bridgland and Westaway, 2008). Accordingly, alluvial terrace treads are used in tectonic geomorphology to quantify uplift rates (Maddy, 1997; Antoine et al., 2000; Maddy et al., 2000; Maddy and Bridgland, 2000; Starkel, 2003; Brocard et al., 2003; Westaway et al., 2006, 2009; Carcaillet et al., 2009; Wang et al., 2012).

Terrace dating has allowed constraints to be placed on the timing of catchment-wide climate-driven fluvial responses (Vandenberghe and Maddy, 2001; Bridgland and Maddy, 2002; Bridgland et al., 2004, 2007). Such studies have established that a large number of terrace sequences in NW Europe were in phase with Milankovitch cyclicity (Bridgland, 2000, and references therein), whether inferred from marine isotope- or from loess-derived stratigraphies (Kukla and Cilek, 1996; Kukla, 2005). Where permitted by finer data resolution, evidence also indicates catchment-scale incision and aggradation during the Weichselian glacial stage, for example with Marine Isotope Stage 4 (MIS 4) in NW Europe being a period of incision, and MIS 3 a period of aggradation of NW Europe(Lewis et al., 2001; Van Huissteden et al., 2001; Van Huissteden and Kasse, 2001; Kasse et al., 2003). However, millennial-scale changes such as Dansgaard–Oeschger cycles and Heinrich events do not appear to have caused major changes in fluvial style, probably because of the many degrees of freedom available to fluvial systems in their response to climatic forcing below a certain magnitude and duration (Van Huissteden and Kasse, 2001; Vandenberghe and Woo, 2002; Kasse et al., 2003; Van Huissteden et al., 2013).

Paired aggradational terraces throughout the world have been associated with Pleistocene glacial–interglacial cycles, with aggradation commonly thought to have occurred during glacial periods and incision during interglacials (Penck and Brückner, 1909; Bridgland, 2000). Contrary to these findings or assumptions, more recent work has shown that phases of channel incision were not strictly coincidental with temperate (interglacial) conditions but with situations of climatic transition (Vandenberghe, 1993, 1995; Bridgland, 2000, 2001, 2006; Maddy et al., 2001). Cold-to-warm transitions are commonly reported as periods of major fluvial incision. Warm-to-cold transitions will record weaker incision depths over shorter intervals determined by the duration of slope stability under conditions of increasing stream power caused by rising precipitation intensity while dense vegetation on the slopes still restricts debris delivery rates. Below a certain threshold of hillslope land cover, clast-size and the total volume of debris in the system rise to a threshold state that generate an aggradational episode at the beginning of the cold phase. Aggradation itself is not exclusive to glacials. After a cold-to-warm transition, the sediment flux is likely to stabilize around a new state in which aggradation occurs but will involve finer-textured sediment than during the preceding glacial period.

Progress in the understanding of these Quaternary fluvial cycles has mostly arisen from periglacial settings, i.e., at distances from ice margins sufficiently large that glacier dynamics did not directly control the sediment transfer regime. At ice margins, in contrast, sediment dynamics are narrowly dictated by the glacier dynamics. Penck and Brückner (1909) argued that glaciofluvial valley trains aggrade during periods of glacier advance and stationarity. The clues in support of this are usually stratigraphic but also topographic: glaciofluvial outwash deposits often form ramps directly connected to frontal moraines. This observation is consistent with the tendency for modern proglacial streams to aggrade and form braided channels, i.e., a fluvial style typical of irregular flow regimes and abundant sediment supply (e.g., Gurnell and Clark, 1987). Based on this geomorphological evidence, a number of studies have used the estimated ages of outwash terraces as proxies for dating the glacial stages to which they correlate (Hein et al., 2009, 2011). It follows that deglacial events are characterized by an incision of outwash deposits, explained by the transient release of glacier meltwater, corresponding to an increase in average river discharge and to a lengthening of river profiles proportional to the distance of glacier recession. Church and Ryder (1972, 1989), however, have shown that deglacial episodes generate a major sediment slug during which bedrock denudation rates and flushing of glacigenic sediments off slopes and out of catchments reach an all-time peak. Glaciofluvial aggradation also occurs in such circumstances (Jackson et al., 1982; Owen and Sharma, 1998; Oetelaar, 2002; Barnard et al., 2004, 2006). Numerical modeling has suggested that the duration and intensity of paraglacial episodes depends (i) on the mass of glacigenic sediments initially present at the ice margin, (ii) on the intensity of hillslope processes, and (iii) on a wide range of environmental parameters that control denudation efficiency such as postglacial climate, revegetation, and catchment size, topography and geology (Church and Slaymaker, 1989; Harbor and Warburton, 1993; Ballantyne, 2002, 2003). Modeling has also shown that deglacial episodes may affect fluvial catchment dynamics for 1 and up to 10 ka after ice recession (Church and Slaymaker, 1989). The response time depends on catchment size.

In this study we present the first attempt to date fluvial terrace sequences in the Ariège River catchment, a major tributary of the Garonne River in the northern Pyrenees, using terrestrial cosmogenic nuclide (TCN) inventories obtained from depth profiles in fill terrace (Fig. 1). The results provide an updated chronostratigraphic reference frame for the north-Pyrenean piedmont, which thus far had only benefited from constraints provided by relative chronology (Alimen, 1964; Icole, 1973; Hubschman, 1973, 1975a,b,c). Firstly, this new chronology sets constraints on the sediment weathering scale and associated soil chronosequence that developed during and after the Middle Pleistocene on the tread of each successive terrace. Secondly, the geochronological constraints also provide scope for discussing the drivers of glaciofluvial terrace aggradation and incision during the last glacial cycle. In order to test the range of hypothetical conditions understood to control glaciofluvial aggradation (see above), we integrate the TCN chronology