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Timing of European fluvial terrace formation and incision rates constrained by cosmogenic nuclide dating

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ABSTRACT

Age constraints of late Cenozoic fluvial terraces are important for addressing surface process questions related to the incision rates of rivers, or tectonic and climate controls on denudation and sedimentation. Unfortunately, absolute age constraints of fluvial terraces are not always possible, and many previous studies have often dated terraces with relative age constraints that do not allow for robust interpretations of incision rates and timing of terrace formation. However, in situ-produced cosmogenic nuclides allow absolute age determination, and hence incision rates, of fluvial deposits back to 5 Ma. Here we present, cosmogenic depth profile dating and isochron burial dating of four different river systems in Europe spanning 12° of latitude. We do this to determine river incision rates and spatial variations in the timing of terrace formation. Isochron burial age constraints of four selected terraces from the Vltava river (Czech Republic) range between 1.00 ± 0.21 to 1.99 ± 0.45 Ma. An isochron burial age derived for the Allier river (Central France) is 2.00 ± 0.17 Ma. Five terrace levels from the Esla river (NW Spain) were dated between $0.08 + 0.04/-0.01$ Ma and $0.59 + 0.13/-0.20$ Ma with depth profile dating. The latter age agrees with an isochron burial age of 0.52 ± 0.20 Ma. Two terrace levels from the Guadalquivir river (SW Spain) were dated by depth profile dating to $0.09 + 0.03/-0.02$ Ma and $0.09 + 0.04/-0.03$ Ma. The one terrace level from the Guadalquivir river dated by isochron burial dating resulted in an age of 1.79 ± 0.18 Ma. Results indicate that the cosmogenic nuclide-based ages are generally older than ages derived from previous relative age constraints leading to a factor 2–3 lower incision rates than previous work. Furthermore, the timing of terrace formation over this latitudinal range is somewhat obscured by uncertainties associated with dating older terraces and not clearly synchronous with global climate variations.

1. Introduction

Quaternary fluvial terraces can be used to address geomorphic questions related to climate and tectonic interactions with the Earth's surface (e.g., Pratt et al., 2002; Repka et al., 1997; Schaller and Ehlers, 2006; Schaller et al., 2002; Scherler et al., 2015). In this study we investigate four European catchments in tectonically quiescent and latitudinally diverse settings that have Quaternary river terrace sequences. We do this to address the questions of: (1) if terrace formation ages at different latitudes can be determined sufficiently well to compare to events of global climate change, and (2) are temporal variations in fluvial incision rates evident? Before addressing these questions, the formation ages of fluvial terraces must be known. However, determination of terrace formation ages can be problematic. For example, previous work on terraces of the Meuse river in the Maastricht area (The Netherlands), have relative dates from paleomagnetic techniques as old as ∼2.0 Ma (van den Berg and van Hoof, 2001; and references therein). One of these terraces (Terrace Geertruid-2) determined to be 1.09 Ma by paleomagnetics was dated by (absolute) simple burial dating with cosmogenic nuclides to an age of 1.72 ± 0.22 Ma (Schaller et al., 2004). This example highlights that discrepancies in terrace ages are a crucial problem that needs to be resolved before

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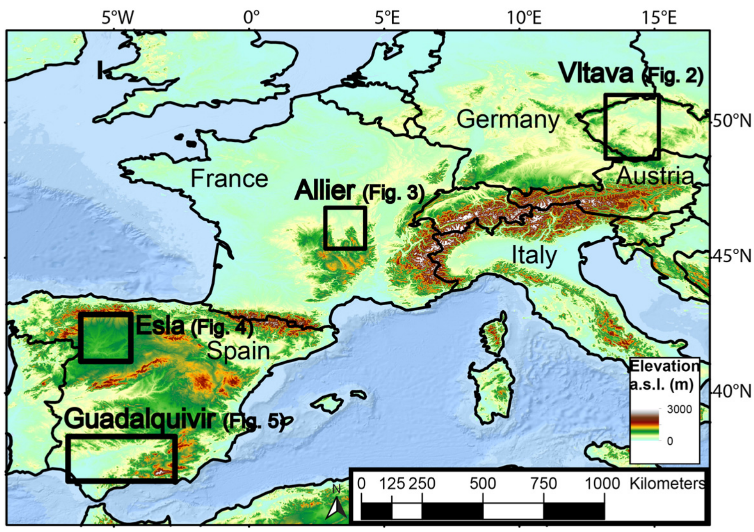

Fig. 1. Location overview of the four European terrace sequences dated with cosmogenic nuclide techniques: the Vltava river (Czech Republic), the Allier river (Central France), the Esla river (NW Spain), and the Guadalquivir river (SW Spain).

the impact of past climate or tectonic events on fluvial systems can be evaluated.

Previous work by Bridgland and Westaway (2008a, and references therein) provides a comprehensive compilation of terrace sequences worldwide. Many of these terrace sequences have been considered to be Quaternary in age, and often late Quaternary (e.g., Gibbard and Lewin, 2009). However, the age of clastic sedimentary deposits is not always easy to constrain. Deposits that are ~500 ka and younger can be dated using ^{14}C in organic material (e.g., Tebbens, 1999), thermoluminescence (e.g., Straffin et al., 1999), Optically Stimulated Luminescence, U–Th in secondary calcite, calcrete nodules or travertine (e.g., Veldkamp et al., 2004), as well as in situ-produced cosmogenic nuclides measured from depth profiles (e.g., Hidy et al., 2010) or cosmogenic surface exposure dating of boulders (e.g., Ivy-Ochs et al., 1996). If deposits are >100 ka they can be dated by magnetostratigraphy and biostratigraphy techniques, or through absolute dating techniques such as Ar/Ar or U–Pb (e.g., Pastre, 2005; Pickering et al., 2010), in situ-produced cosmogenic depth profiles (e.g., Granger and Smith, 2000; Akcar et al., 2014), cosmogenic simple burial dating (e.g., Granger et al., 1997), and more recently using the method of cosmogenic isochron burial dating (e.g., Balco and Rovey II, 2008; Erlanger et al., 2012).

A promising variation of the isochron burial dating method based on sand from different depths (Balco and Rovey II, 2008) is the method of isochron burial dating based on multiple clasts from the same depth (e.g., Erlanger et al., 2012). The clast approach uses in situ-produced ^{26}Al and ^{10}Be concentrations in five to six quartz bearing clasts from the same sampling depth. This approach has been successfully applied in a terrace sequence of the Sundays river in South Africa (Erlanger et al., 2012) where a sequence of terrace ages ranging from 0.26 ± 0.15 to 4.26 ± 0.68 Ma were determined. However, few other applications of this technique have been published (with exceptions being, for example, Balco et al., 2013; Ciner et al., 2015; Bender et al., 2016). One reason for this is that the isochron burial method is labor and cost intensive.

In this study, we complement previous work by applying the methods of both cosmogenic depth profile dating and isochron burial dating on terrace sequences preserved in four European catchments (Fig. 1). The catchments investigated include the Vltava (Czech Republic), Allier (Central France), Esla (NW Spain), and Guadalquivir (SW Spain) rivers. Ages derived from cosmogenic nuclide dating are compared to previous age constraints from relative dating techniques including biostratigraphy, paleomagnetics, as well as archaeological findings. The geochronological age constraints from our four study areas are, with the exception of one catchment, generally older than previous age constraints. We use our absolute age constraints to evaluate spatial and temporal variations in the timing of terrace formation, as well as to determine Quaternary fluvial incision rates.

2. Study areas and sample selection

In this study, we build upon four previously investigated study areas that have estimated terraces ages that met the following criteria: First, geographically diverse locations were needed to evaluate if latitudinal differences in the timing of terrace formation could be detected. Second, multiple terrace sequences were needed that span the Quaternary. Third, well preserved terraces with minimal visible post-depositional denudation needed to be present. Related to the last point, the terrace preservation was a key factor in determining which individual terraces were sampled. Detailed information about each terrace sequence and their known age constraints follow below. Additional details are provided in the on-line supplemental information 1 (Sample locations), 2 (Sample preparation and parameters used in this study), and 3 (Figures and Tables).

2.1. Vltava river (Czech Republic)

At several locations, the Vltava river and the Labe (Elbe) river have fluvial deposits (e.g., Zaruba et al., 1977; Tyracek et al., 2004). It is not clear what the fluvial depositional conditions are in some cases (e.g., fluvial fans or terraces). However, for simplicity the fluvial deposits in the Vltava and Labe catchments are called terraces in this study. The terraces near the confluence of Vltava and Labe river at Melnik (North of Prague) were sampled (Fig. 2; Table 1). A suite of seven main terrace levels (I to VII) with several sublevels have been recognized (e.g., Tyracek, 2001; Tyracek et al., 2004; Tyracek and Havlicek, 2009). Terrace level I at Krabcice is situated ~110 m above the river and is correlated to Oxygen Isotope Stage (OIS) 18/16 (Tyracek et al., 2004). This correlation puts the terrace level I in the Melnik area to ~0.7 Ma (Table 1). In contrast, terrace level I is considered to be almost 1 Ma by Zaruba et al. (1977). Terrace level Ledcice 1 (IIa) at ~90 m above river is considered to be formed at ~0.55 Ma. The Straskov terrace (IIIb) situated ~70 m above the river is attributed to OIS 12 (~0.45 Ma) by mammal and Archeological findings overlying the deposit. At this time the river course was still situated further to the West than at present.