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# Revealing the pace of river landscape evolution during the Quaternary: recent developments in numerical dating methods

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A B S T R A C T

During the last twenty years, several technical developments have considerably intensified the use of numerical dating methods for the Quaternary. The study of fluvial archives has greatly benefited from these enhancements, opening new dating horizons for a range of archives at distinct time scales and thereby providing new insights into previously unanswered questions. In this contribution, we separately present the state of the art of five numerical dating methods that are frequently used in the fluvial context: radiocarbon, Luminescence, Electron Spin Resonance (ESR), $^{230}Th/U$ and terrestrial cosmogenic nuclides (TCN) dating. We focus on the major recent developments for each technique that are most relevant for new dating applications in diverse fluvial environments and on explaining these for non-specialists. Therefore, essential information and precautions about sampling strategies in the field and/or laboratory procedures are provided. For each method, new and important implications for chronological reconstructions of Quaternary fluvial landscapes are discussed and, where necessary, exemplified by key case studies. A clear statement of the current technical limitations of these methods is included and forthcoming developments, which might possibly open new horizons for dating fluvial archives in the near future, are summarised.



## 1. Introduction

Unravelling processes and rates of long-term landscape evolution, focusing on the evolution of river drainage systems, has been a core topic in the earth surface sciences since Davis's (1899) pioneering work more than a century ago. Since then, river terrace sequences and/or related landforms have thus been extensively used as geomorphic markers across the world. However, assigning chronologies to these sequences and related river sediments or landforms has constantly been challenging. Until the late 20th century, this goal was often achieved using diverse methods that provide relative age information on Quaternary fluvial deposits. Such methods included: correlation with the alpine glacial chronology (e.g. Brunnacker et al., 1982), soil chronosequences (e.g. Engel et al., 1996), palaeomagnetism (e.g. Jacobson et al., 1988), clast seismic velocity (e.g. Crook, 1986), weathering rind analysis (e.g. Colman and Pierce, 1981), obsidian hydration (e.g. Adams et al., 1992), amino-acid racemization of terrestrial molluscs (e.g. Bates, 1994) or correlation to Marine Isotope Stages (MIS) via mammalian (e.g. Schreve, 2001) and molluscan (e.g. Preece, 1999) biostratigraphy. Combining these methods often yielded insightful relative chronologies for Quaternary terrace flights (e.g. Knuepfer, 1988; Schreve et al., 2007).

Whilst methodological improvements to some of these techniques have since been achieved (e.g. Penkman et al., 2007 for amino-acid racemization), in most instances, relative dating methods have been progressively supplemented by dating methods delivering absolute numerical ages over the last two or three decades. With the exception of radiocarbon dating, which has been applied since Libby's seminal paper (Libby et al., 1949), the

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development of most of these geochronometers occurred in relation to major theoretical and/or technical improvements in the late 20th century. For instance, although cosmic rays were discovered in 1912 by the Nobel laureate Victor Hess, only the development of accelerator mass spectrometers (AMS) in the 1980s enabled measurements of cosmogenic nuclide concentrations (e.g. Klein et al., 1982) and thus their use as a geochronometer (e.g. Nishiizumi et al., 1986). Likewise, Electron Spin Resonance (ESR) spectroscopy, already outlined in the mid 1930s (Gorter, 1936), was first successfully applied as a dating tool only 40 years later (Ikeya, 1975).

In the framework of this FLAG (Fluvial Archives Goup) special issue, we present and discuss the recent major dating advances offered by modern numerical methods in diverse fluvial environments. Five methods are discussed: radiocarbon, Luminescence, Electron Spin Resonance, $^{230}$Th/U and terrestrial cosmogenic nuclide (TCN) dating. They were specifically selected amongst the array of Quaternary dating methods because (i) they are commonly used in the fluvial context, (ii) they have all experienced major theoretical and/or technical developments during recent decades, (iii) they require different dateable material and thereby may also yield information about a wide range of fluvial processes and environments, (iv) they have different time ranges of application, but altogether, span the last million years (Fig. 1). Detailing all theoretical principles of the individual techniques is beyond the scope of this contribution. Instead, the focus is on relevant major technical developments and how these enabled new dating applications for different kinds of fluvial archives in distinct settings. The pathways of dateable material within fluvial systems are detailed in Fig. 2. Fundamental information and precautions about sampling strategies in the field and/or laboratory procedures are also provided. Whilst these are well known by geochronologists, they have not often been published and need therefore to be clarified to non-specialists who intent to collect samples for dating. For each method, new and important implications for chronological reconstructions of Quaternary fluvial landscapes are also discussed and, if necessary, exemplified. Case studies published in outputs related to former FLAG activities and using one (or more) of these dating method(s) are listed in Table 1. Current technical limitations and probable forthcoming developments are also addressed.

## 2. Radiocarbon dating of fluvial deposits

Radiocarbon dating has been a common method applied to fluvial deposits in those settings where organic material is readily preserved within sequences, i.e. partially or fully waterlogged parts of the floodplain system, including channels and overbank deposits (Fig. 2). As a technique it has contributed significantly to understanding key questions, both about palaeoenvironmental information contained within fluvial deposits (e.g. Kasse et al., 1995) and about periods of river activity (e.g. Macklin et al., 2005). The accuracy with which age estimates can be gained from ever smaller samples has improved significantly over the 60–70 years since the first development of the technique. This is partly due to the increasingly routine use of accelerator mass spectrometry (AMS) measurements of smaller samples (~1 mg in some cases, Ruff et al., 2010, but more robustly 5–6 mg, Brock et al., 2010). Another important development has been the significant international cooperation involved in calibrating radiocarbon measurements against independent annually-resolved records to account for natural variability in the concentration of atmospheric $^{14}$C, culminating most recently in the IntCal13 dataset (Reimer et al., 2013).

The $^{14}$C dating method can be applied to any material that contains carbon. This includes: cellulose-containing materials (wood, seeds, plant remains), charcoal and charred material, carbonates (including corals, foraminifera, shells), collagen-containing materials (bone, tooth, antler, ivory), hair, and bulk sediment. Many of these are found within fluvial deposits in more temperate environments, where preservation conditions are favourable, but not all are *in situ* (Fig. 2). Therefore, when considering the radiocarbon dating of fluvial deposits, we need to consider the issue of provenance and reworking. In addition, calibration, reservoir effects and appropriate pretreatments are also relevant to fluvial archives in lakes, but reviewed elsewhere (Brauer et al., 2014).

All present-day carbon-bearing material contains three naturally occurring carbon isotopes. Of these, $^{14}$C is radioactive, with a half life of 5730 ± 40 years (Godwin, 1962). The source of this $^{14}$C is cosmic ray activity in the atmosphere. This enters the global carbon cycle when it is oxidised to $CO_2$, and concentrations are very low compared to $^{12}$C and $^{13}$C. Conventional radiocarbon ages are calculated from measured concentrations of $^{14}$C, using either beta counting methods or, meanwhile more commonly, AMS. To allow consistency with earlier analyses, these are reported using the original Libby half life of 5568 years (e.g. Stuiver and Polach, 1977; Reimer et al., 2004). They are also corrected for fractionation processes that occur during measurement, as described by Brauer et al. (2014). Because of the multiple stages at which differences can occur within the calculation of a radiocarbon age, they should be reported in detail according to the conventions described by Millard (2014).

### 2.1. Provenance and reworking of radiocarbon samples in the fluvial environment

A feature of fluvial systems is the wide range of depositional

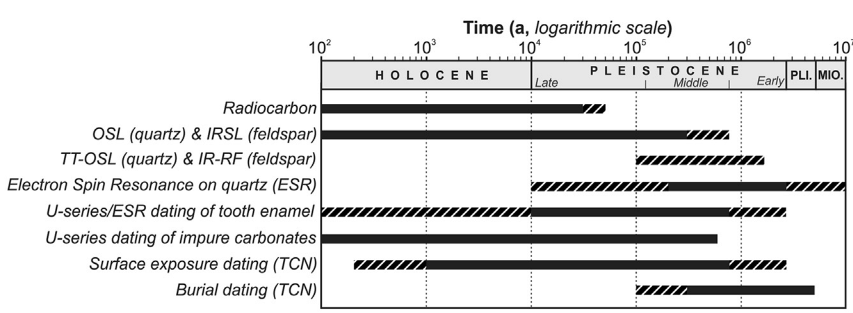


**Fig. 1.** Dateable ranges of the five numerical dating methods detailed in this contribution. Black rectangles refer to time spans within which the methods usually provide reliable results; dashed rectangles represent challenging time periods. Luminescence methods are divided into two rows: the first row represents the routinely applied techniques (OSL: optically stimulated; IRSL: infrared stimulated, including pIRIR) and the second row the techniques currently under development (TT: thermally transferred; RF: radiofluorescence). ESR dating on quartz and U-series/ESR dating of tooth enamel as well as surface exposure dating and burial dating with terrestrial cosmogenic nuclides (TCN) are also divided because of the different dating principles.

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