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Tectonic and climatic control on terrace formation: Coupling in situ produced ^{10}Be depth profiles and luminescence approach, Danube River, Hungary, Central Europe

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ABSTRACT

The terrace sequence of the Hungarian part of the Danube valley preserves a record of varying tectonic uplift rates along the river course and throughout several climate stages. To establish the chronology of formation of these terraces, two different dating methods were used on alluvial terraces: exposure age dating using in situ produced cosmogenic ^{10}Be and luminescence dating. Using Monte Carlo approach to model the denudation rate-corrected exposure ages, in situ produced cosmogenic ^{10}Be samples originated from vertical depth profiles enabled the determination of both the exposure time and the denudation rate. Post-IR IRSL measurements were carried out on K-feldspar samples to obtain the ages of sedimentation.

The highest terrace horizon remnants of the study area provided a best estimate erosion-corrected minimum ^{10}Be exposure age of >700 ka. We propose that the abandonment of the highest terrace of the Hungarian Danube valley was triggered by the combined effect of the beginning tectonic uplift and the onset of major continental glaciations of Quaternary age (around MIS 22). For the lower terraces it was possible to reveal close correlation with MIS stages using IRSL ages. The new chronology enabled the distinction of tIIb (~90 ka; MIS 5b–c) and tIIIa (~140 ka; MIS 6) in the study area. Surface denudation rates were well constrained by the cosmogenic ^{10}Be depth profiles between 5.8 m/Ma and 10.0 m/Ma for all terraces. The calculated maximum incision rates of the Danube relevant for the above determined >700 ka time span were increasing from west (<0.06 mm/a) to east (<0.13 mm/a), toward the more elevated Transdanubian Range. Late Pleistocene incision rates derived from the age of the low terraces (~0.13–0.15 mm/a) may suggest a slight acceleration of uplift towards present.

1. Introduction

The age and position of a fluvial terrace with respect to a reference level provides a good approximation of the river incision rate. In certain occasions this is a valid time-averaged proxy for the surface uplift rate. On the other hand, climatically induced changes in river style can also lead to terrace formation (Bridgland, 2000; Peters and Van Balen, 2007; Bridgland and Westaway, 2008; Gibbard and Lewin, 2002, 2009; Warner, 2012). Incision/uplift rates calculated on the basis of age determination of river terraces in Europe mostly suggest values up to ~1 mm/a for middle and late Pleistocene times (Brocard et al., 2003; Peters and van Balen, 2007; Viveen et al., 2012; Necea et al., 2013; Rixhon et al., 2011, 2014) and

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exceptionally, in tectonically active regions, like the SE Carpathians (Necea et al., 2013) or for shorter periods (Antón et al., 2012) present higher rates. Burial age determination of cave sediments using cosmogenic ^{10}Be and ^{26}Al in Schwitzerland suggested an incision rate of 0.12 mm/a for the early Pleistocene, and a tenfold increase was suggested for middle to late Pleistocene times Häuselmann et al. (2007a). Applying the same method Wagner et al. (2010) calculated rather low average bedrock incision rates of 0.1 mm/a for the last 4 Ma with a decreasing trend towards present (Table 1). However, the decrease towards younger times was attributed to the rise of the base level due to sediment aggradation within the valley.

The uplift rate of 1.75 mm/a provided by geodetic measurements in the western and northern Alpine foreland (Ziegler and Dézes, 2007) represents the higher end of the uplift rates based on geochronological and geomorphological constraints (Table 1).

The combined application of cosmogenic ^{10}Be exposure dating and luminescence dating allows a more robust age determination than using either method separately, as it was demonstrated by some previous studies (Anders et al., 2005; Delong and Arnold, 2007; Guralnik et al., 2011; Viveen et al., 2012). Main objective of the present study is to provide age constraints to fluvial terraces of the Danube River in order to determine its incision rate. New constraints on vertical neotectonic deformation of the western Pannonian Basin and on the role of climate change in terrace evolution are presented. Denudation rates provided by ^{10}Be depth profiles will contribute to a better understanding of the pace of surface processes in the region.

2. Geological and geomorphological setting

2.1. Quaternary tectonics and drainage pattern evolution

The Pannonian Basin (Fig. 1) represents a back-arc basin formed by Miocene crustal thinning and subsequent “post-rift” thermal subsidence (Horváth and Royden, 1981; Horváth et al., 2015), which led to the formation of the several 100 m deep Lake Pannon. This lake was filled up during the late Miocene due to large sediment input (Magyar et al., 2007, 2013). The Western Pannonian Basin was subsequently occupied by a fluvio-lacustrine system, established in the latest Miocene (Uhrin et al., 2011), with paleo-rivers drained towards the south (Szádeczky-Kardoss, 1938, 1941; Pécsi, 1959; Gábris and Nádor, 2007). Neotectonic shortening and related uplift progressively shifted from SW (Slovenia) toward NE (Tari, 1994; Fodor et al., 2005). The deflection of the Alpine and Carpathian rivers (including the paleo-Danube) from their southerly flow towards the east, their current runoff direction, followed the propagation of the neotectonic deformation. As a result, the formation of a large alluvial fan in the Danube Basin was proposed during the early Pleistocene (Szádeczky-Kardoss, 1938, 1941) (Fig. 2), and the Danube was forced to find its way towards the east across the TR. The age of abandonment of the highest terrace of the Danube provides a good approximation of the age of the onset of fold-related uplift in the northeast part of the TR.

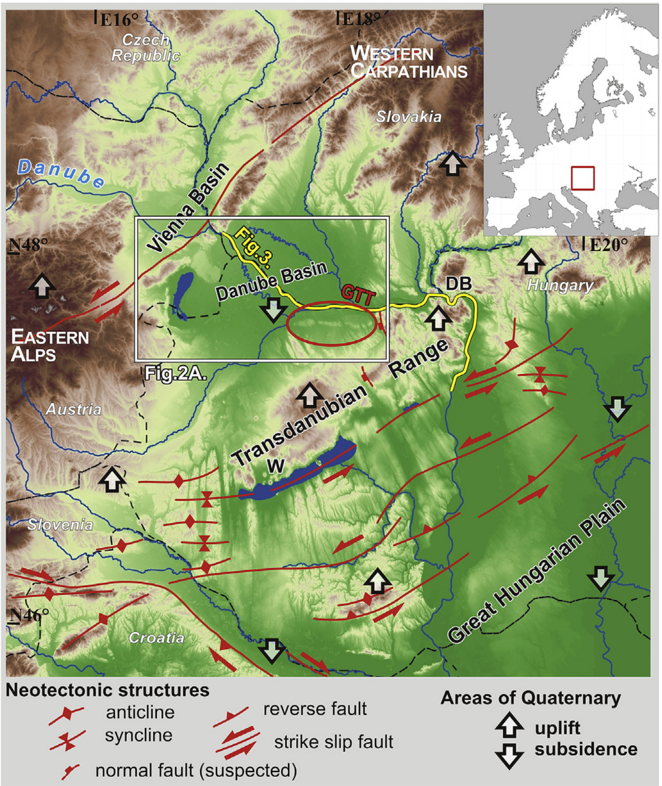

Fig. 1. SRTM-based digital elevation model of the Western Pannonian Basin and schematic pattern of neotectonic deformation structures (after Fodor et al., 2005; Bada et al., 2007; Dombrádi et al., 2010; Ruszkiczay-Rüdiger et al., 2007). DB: Danube Bend; GTT: Győr-Tata terrace region, W: location of ^{10}Be exposure age dated, 1.56 ± 0.09 Ma old wind polished landforms (Ruszkiczay-Rüdiger et al., 2011).

Table 1
Some incision/uplift rates derived from terrace studies and geodetic data in Europe.

	Incision/uplift rate (mm/a)	Dated landform	Method	Location	Timespan (ka)
Antón et al. (2012)	2.0–3.0	Strath terraces	Cosmogenic ^{10}Be, ^{21}Ne	Duero Basin	100–0
Brocard et al. (2003)	0.8	Alluvial terraces	Cosmogenic ^{10}Be	French Western Alps	190–0
Giachetta et al. (2015)	0.25–0.55	–	Numerical modelling	Iberian Chain	3000–0
Häuselmann et al. (2007a)	~0.12	Cave sediments	Cosmogenic ^{10}Be, ^{26}Al	Switzerland	>800
	~1.2				800–0
Necea et al. (2013)	0.1–2.2	Alluvial terraces	IRSL	SE Carpathians	780–0
Peters and van Balen (2007)	0.01–0.16	Alluvial terraces	Correlation, relative chronology	Upper Rhine Graben	800–0
Rixhon et al. (2011, 2014)	0.08–0.14[a]	Alluvial terraces	Cosmogenic ^{10}Be	NE Ardennes	725–0
Viveen et al. (2012)	0.07–0.08	Alluvial terraces	Cosmogenic ^{10}Be, OSL, IRSL	Miño River, Iberia	650–0
Wagner et al. (2010)	0.1	Cave sediments	Cosmogenic ^{10}Be, ^{26}Al	Eastern Alps	4000–0
Ziegler-Dézes (2007)	1.75	–	Geodetic data	Variscan Massifs in the Alpine foreland	2600–0
this study[b]	<0.06–0.13 (up to 0.33[c])	Alluvial terraces	Cosmogenic ^{10}Be	Danube River	>700–0
this study	0.13–0.15	Alluvial terraces	post-IR IRSL	Danube River	140–0

[a] The incision/uplift rate was calculated by this study based on the data published by Rixhon et al. (2011, 2014).
[b] The exposure ages are minimum ages therefore the incision/uplift rates are maximum rates.
[c] Incision/uplift rate inferred by data extrapolation along the valley.