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Correlations of cave levels, stream terraces and planation surfaces along the River Mur—Timing of landscape evolution along the eastern margin of the Alps

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ABSTRACT

The transition zone of the Eastern Alps to the Pannonian Basin provides one of the best sources of information on landscape evolution of the Eastern Alpine mountain range. The region was non-glaciated during the entire Pleistocene. Thus, direct influence of glacial carving as a landscape forming process can be excluded and relics of landforms are preserved that date back to at least the Late Neogene. In this study, we provide a correlation between various planation surfaces across the orogen-basin transition. In particular, we use stream terraces, planation surfaces and cave levels that cover a vertical spread of some 700 m. Our correlation is used to show that both sides of the transition zone uplifted together starting at least about 5 Ma ago. For our correlation we use recently published terrestrial cosmogenic nuclide (TCN) burial ages from cave sediments, new optically stimulated luminescence (OSL) ages of a stream terrace and U–Th ages from speleothems. Minimum age constraints of cave levels from burial ages of cave sediments covering the last ~4 Ma are used to place age constraints on surface features by parallelizing cave levels with planation surfaces. The OSL results for the top section of the type locality of the Helfbrunn terrace suggest an Early Würm development (80.5 ± 3.7 to 68.7 ± 4.0 ka). The terrace origin as a penultimate gravel deposit (in classical Alpine terminology Riss) is therefore questioned. U-series speleothem ages from caves nearby indicate formation during Marine Isotope Stages (MIS) 5c and 5a which are both interstadial warm periods. As OSL ages from the terrace also show a time of deposition during MIS 5a ending at the MIS 5/4 transition, this supports the idea of temperate climatic conditions at the time of deposition. In general, tectonic activity is interpreted to be the main driving force for the formation and evolution of these landforms, whilst climate change is suggested to be of minor importance. Obvious hiatuses in Miocene to Pleistocene sediments are related to ongoing erosion and re-excavation of an uplifting and rejuvenating landscape.

1. Introduction

The landscape evolution of the Alps since the Late Neogene is a subject of topical interest (e.g. Frisch et al., 2001; Dunkl et al., 2005; Kuhlemann, 2007; Champagnac et al., 2009; Willet, 2010). The transition zone between the Alpine orogen and the Pannonian Basin around the city of Graz, Austria is a key site for this subject, as it provides considerable information regarding the evolution of landforms over this time period and has never been glaciated. Glacial carving can thus be excluded as a landforming process (Fig. 1a, Van Husen, 2000). The Mur River is the main drainage dissecting this region (Fig. 1a). It drains the Eastern Alps from the eastern edge of the Tauern Window into the Pannonian Basin, crossing the orogen-basin transition zone near the city of Graz. The landscapes of the Styrian Basin and the Highland of Graz, respectively south and north of this transition zone, comprise numerous planation surfaces and stream terraces which can be grouped into several distinct levels that cover a vertical spread of some 700 m. Due to the presence of karstifiable rocks in the Highland of Graz, phreatic cave levels are also developed (e.g. Maurin and Benischke, 1992).

In this paper we discuss the landscape evolution of this region by presenting a correlation of various levels and planation surfaces north and south of the orogen-basin transition zone. A relative chronology of these levels has previously been established (e.g. Winkler-Hermaden, 1955, 1957), but numerical ages of these landforms remain poorly constrained by scarce cross-correlations using dated volcanic rocks (Balogh et al., 1994) and some paleontological evidence (e.g. Mottl, 1946). The main objective of this work is to use recently available

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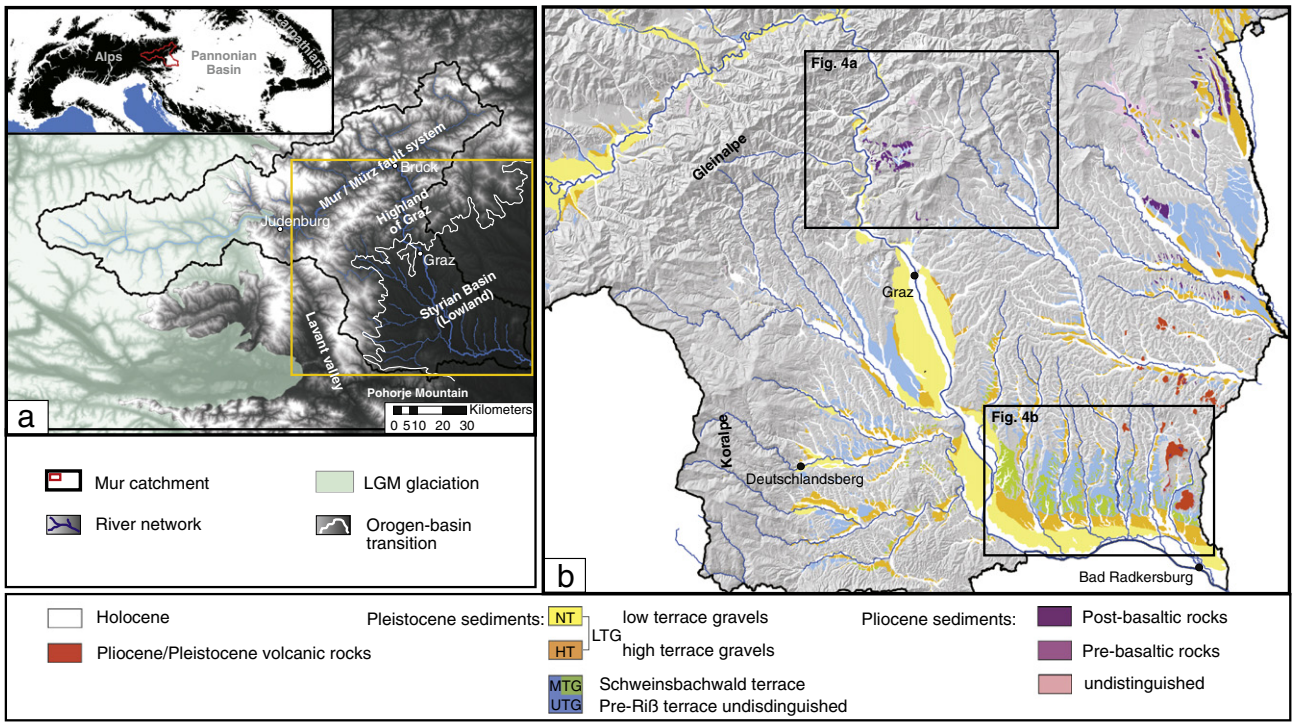

Fig. 1. The area of investigation. (a) The present catchment area of the Mur River, the river course and its tributaries, and the extent of the last glacial maximum (LGM) (Van Husen, 2000) on top of a DEM. Inset shows the Alpine–Carpathian–Pannonian realm (black above 600 m, white below) and the Mur catchment upstream of Bad Radkersburg in red color. Extent of (b) indicated by the orange box. (b) Pliocene, Pleistocene and Holocene sediment distribution (sediment covered planation surfaces and stream terraces) and Pliocene/Pleistocene volcanic rocks. Pleistocene sediments are subdivided into the low terrace gravels (NT, "Niederterrasse" or Würm terrace), the high terrace gravels (HT, "Hochterrasse", which can be further split into a Riss (penultimate) glacial terrace and the Helfbrunn interglacial terrace) and terraces that are pre-Riss (older than the previous ones). In the latter, the so-called Schweinsbachwald terrace is distinguished as the youngest subunit in the lowland, especially in the Grabenland, where this is morphologically feasible (and likely related to the lateral (southward) shift of the Mur River in the area). Further upstream such a differentiation was no longer possible as absolute age constraints are not available. The same holds true for the few Pliocene sediments in the region. Where possible, pre- and post-basaltic gravels are distinguished. LTG = lower terrace group, MTG = middle terrace group and UTG = upper terrace group. The detailed study areas shown in Fig. 4a (the Central Styrian Karst in the Highland) and Fig. 4b (the Grabenland region in the Lowland) are indicated by black rectangles.

geochronological data on the timing of these geomorphic markers (Wagner et al., 2010), to complement these with new OSL and U–Th ages and to propose a model for the topographic evolution across the orogen-basin transition including both the Styrian Basin and the Highland of Graz. Our correlation allows further understanding of the morphological evolution on the eastern margin of the Alps in general.

2. The study area—the Styrian Block and the River Mur

The Styrian Block is the subject of this study and is defined here as a region that consists of the Styrian Basin and the surrounding basement. The block is delineated by the Mur–Mürz fault zone in the north, the Lavanttal fault zone in the west, the Pohorje Mountain in the south and the Pannonian Basin (excluding the Styrian Basin) to the east (Fig. 1). It comprises three major tectonic units that have distinct landforms and different geological histories: (i) The Austroalpine crystalline basement south of the Mur–Mürz fault zone and east of the Lavanttal fault zone; (ii) The Paleozoic of Graz forming the Highland of Graz in the orogen basin transition zone near Graz and (iii) the Styrian Basin, being the westernmost lobe of the Pannonian Basin. These three parts of the Styrian Block all have their characteristic features. The *crystalline basement* comprises mountainous landscape of high grade metamorphic rocks with elevations more than 2000 m a.s.l. with rounded and flat summits and deeply incised valleys characteristic of a non-glaciated landscape. It forms a presumably slowly exhuming region as fission track ages in the range of 35–50 Ma are preserved (Neubauer et al., 1995; Hejl, 1997; Dunkl and Frisch, 2002). These data suggest a small amount of Neogene denudation. However, Hejl (1997) showed that increased exhumation within the last 5–10 Ma is likely. The Koralpe is an area of relics of Miocene relief; although breaks along the hillslopes of headward migrating tributaries of the Mur River with high stream power point toward geomorphic disequilibrium (Winkler-Hermaden, 1957; Robl et al., 2008a). The *Paleozoic of Graz* contains a highly karstified region of Paleozoic carbonates and schists called the Central Styrian Karst where peaks reach up to 1700 ma.s.l. No low temperature thermochronological data are available from within the Paleozoic of Graz. Finally, the *Styrian Basin* forms an undulating lowland (henceforth termed the Lowland of Graz) comprising Neogene sediments with elevations between 200 and 600 ma.s.l. Despite the topographic and morphological differences between the three different regions of the block, the Styrian Block appeared to have behaved as a single tectonic unit since the end of the Miocene (Wagner, 2010) and it will be the purpose of this study to demonstrate this.

The most important tectonic event related to the onset of the morphological evolution of the region is the formation of the Pannonian Basin east of the Alps (e.g. Dunkl et al., 2005). Major subsidence in the early to mid Miocene caused the onset of lateral extrusion (Ratschbacher et al., 1989) and initiated the formation of the Styrian Basin. This coincides with the development of the W–E directed drainage system typical for the Eastern Alps and related pull-apart basins along the major strike-slip zones, e.g. the Mur-Mürz fault system (Ebner and Sachsenhofer, 1995). In the Styrian Basin, a fully marine sedimentary pile developed between ~18 and 11 Ma, punctuated by volcanic activity around 15 Ma. According to Ebner and Sachsenhofer (1995), the basin has inverted since about 5–6 Ma causing the end of its aquatic evolution and the beginning of its uplift history. A second phase of volcanic activity