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Speleothem deposition at the glaciation threshold — An attempt to constrain the age and paleoenvironmental significance of a detrital-rich flowstone sequence from Entrische Kirche Cave (Austria)

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ABSTRACT

Proxy records from high-altitude locations predating the Last Glacial Maximum are rare but could provide invaluable insights into the response of alpine catchments to the rapid climate fluctuations which characterized the last glacial period. Here we present a detrital-rich flowstone record from Entrische Kirche Cave, an inneralpine cave situated close to the accumulation area of the Pleistocene ice-stream network of the European Alps that expanded repeatedly into the lowlands during glacial maxima. U–Th dating of this calcite is challenging due to high detrital Th. However, petrographic and stable isotope analyses in conjunction with associated clastic cave sediments provide useful insights into the climatic boundary conditions during speleothem formation and into the paleoenvironmental processes which operated in the ~2000 m-high catchment above the cave.

Our data show that millennial-scale temperature fluctuations had a first-order control on the periglacial activity and vegetation in the catchment which strongly influenced the formation and infiltration of detritus into the karst aquifer. The brown laminated and brown dendritic fabrics that compose much of the detrital-rich flowstone succession reflect these environmental processes. The temperature-dependence of periglacial and permafrost processes allows to constrain the amount of cooling relative to the present-day mean annual air temperature that is required to initiate detrital-rich calcite formation in Entrische Kirche Cave, i.e. −2.5 °C (minimum) to −6 °C (maximum), respectively. White inclusion-poor calcite that is intercalated with the detrital-rich calcite indicates warm (interstadial) conditions and geomorphological stability in the catchment area. One such phase has been U–Th dated to 88.3 ± 6.9 ka (i.e. Greenland Interstadial 21 or 22).

1. Introduction

Reconstructing climate and paleoenvironmental change in (high) alpine environments is a challenging task because of the number and intensity of erosional processes that operate on such landscapes. A particularly well-studied example is the European Alps, where the repeated waxing and waning of ice-stream networks eroded most of the older paleoenvironmental archives during the Last Glacial Maximum (LGM; ca. 19–24 ka; Ivy-Ochs et al., 2008). As a consequence, archives in the Alps that pre-date the LGM are scarce and the detailed response of the alpine landscape to the complex succession of abrupt millennial-scale temperature fluctuations that characterised the middle and early parts of the last glacial cycle (i.e. the so-called Dansgaard–Oeschger (DO) events) remains largely elusive.

Speleothems allow us to gain "bottom-up" insights into the pre-LGM climate and paleoenvironmental evolution of the alpine realm. Protected from surface erosion speleothems can form continuously for many millennia and bear the great advantage of being precisely and accurately datable using U-series techniques (Henderson, 2006). Although formation of alpine speleothems preferentially occurs during warm interglacial and interstadial climatic conditions, speleothems also precipitate during cooler and less favourable climatic periods if the cave is situated in a low or intermediate altitude range, where cessation of calcite precipitation due to cave freezing occurs only during the most severe cold events (Holzkämper et al., 2005; Spötl et al., 2007).

For building U–Th chronologies using speleothems, clean calcite with low concentrations of detrital Th is preferable and in combination with stable oxygen isotope analysis the timing and duration of major isotope-defined climatic events can be constrained. This strategy results in atmospheric proxy signals ($\delta^{18}O$) that are accurately and precisely dated and can thus be supra-regionally correlated and compared (e.g. Wang, et al., 2008; Boch, et al., 2011). Cave calcites with a significant content of detrital material are usually avoided in speleothem studies, because of the need to correct for detrital ^{232}Th, which results in large age uncertainties (Richards and Dorale, 2003). Hence, limited research

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on detrital-rich calcite from caves has been undertaken so far (e.g., Labonne, et al., 2002).

Detrital components in karst sediments comprise particles and colloids that are produced by the weathering of host rock and soil and are washed into the karst system. Such clastic sediments range in grain size from gravel to clay (Sasowsky and Mylroie, 2004; Palmer, 2007) and form metre-thick accumulations in many caves. Fine-grained detritus can be transported by seepage flow and become incorporated into speleothems. Such detrital phases can be present in speleothems as macroscopically visible silt or mud layers (Niggemann et al., 2003; Jaillet et al., 2006) or, more common, as microscopic particles concentrated in individual layers of calcite (Railsback et al., 1999). In addition, the presence of detritus can also be reflected by a change in the calcite fabric (Ayalon et al., 1999; Turgeon and Lundberg, 2001) and by certain trace elements commonly bound to detrital particles and/or colloids, e.g. Fe, Mn, Zn, Th, and Rare Earth Elements (e.g. Ayalon et al., 1999; Zhou et al., 2008; Fairchild and Treble, 2009).

Recent studies demonstrate the potential of detrital proxies and sediments for paleoclimate and paleoenvironmental research and suggest that they can (i) provide insights into Earth-surface processes that operated in the infiltration area during the time of speleothem formation (in contrast to speleothem $\delta^{18}O$ records that primarily reflect atmospheric processes (Goede et al., 1998; Frumkin and Stein, 2004; Richter et al., 2004; Hu et al., 2005; Li et al., 2005; Zhou et al., 2008; Schimpf et al., 2011)), but (ii) can also improve our understanding of the paleohydrology (Niggemann et al., 2003; Jaillet et al., 2006; Forbes and Bestland, 2007; Sroubek et al., 2007).

In this study we describe a brown, detrital-rich flowstone sequence from the inneralpine Entrische Kirche Cave (hereafter abbreviated as EKC) that was deposited intermittently during the middle and early parts of the last glacial cycle (Fig. 1). This calcite sequence is remarkable because it reveals a distinct isotopic and petrographic signature suggestive of extreme environmental change in the high-alpine infiltration area during speleothem formation (i.e. the mean annual air temperature in the infiltration area was just high enough to maintain an ice-free catchment and liquid water in the karst aquifer). Here we explore depositional and paleoenvironmental models to explain the formation of this unusual calcite sequence.

2. Geologic and geomorphologic settings

EKC is situated in the central Austrian Alps in close proximity to some of the highest summits of the main crests of the orogen (e.g., Großglockner 3798 m, Sonnblick 3105 m, Fig. 1). The distance from the cave to the northern rim of the Alps is ca. 55 km. The host rock is composed of calcite mylonite (Klammkalk; Exner, 1979). The entrance to the cave system is in the flank of the steep Gastein valley at an elevation of 1040 m asl and from there the cave extends into easterly direction for ~270 m (Fig. 2A). The total length of the cave is 1.6 km and the passages (elliptical tunnels which alternate with partly collapsed halls) are arranged in two sub-horizontal levels that are connected via shafts (Fig. 2B; Klappacher, 1992). A perennial stream with a peak discharge of ca. 10 L/s drains the lower cave level.

The small catchment area of the cave (~3 km^2) reaches up to 2119 m in elevation and rock overburden above the presently explored cave network is thus ≥900 m. Conifer forests cover the valley slopes up to ~1800–1900 m (i.e. the altitude of the regional timberline today) and alpine mats and shrubs constitute the vegetation in the infiltration area directly above the cave (Fig. 2C). The intensively folded host rock also controls the morphology in the catchment area, where anticlines form the backbone of mountain ridges and synclines host high-alpine lakes. Two such lakes are directly situated above EKC (Paar lakes, at 1856 and 1949 m, respectively), and are surrounded by steep slopes (Figs. 2A and C). Tracer experiments demonstrated a direct connection between a ponor on the northern shore of one of the lakes and the cave stream in the lower level of EKC (transit time 1 to 3 days, horizontal distance 1.8 km; Ganahl, 1991).

3. Chemical and clastic cave sediments

EKC hosts active and fossil flowstones, stalagmites, stalactites and soda straws, as well as clastic sediments. The latter comprise fine-grained gravel, sand and abundant silt and clay, attaining a thickness of up to 1.6 m (Fig. 2B). Gravel and sand are only present in the lowermost cave level, close to the modern stream. Grey silt and clay are widespread also in the higher levels of the cave. These fine-grained sediments were probably deposited during the LGM when the alpine ice-stream network (reaching an elevation of ~2000–2100 m in the study area — van Husen,

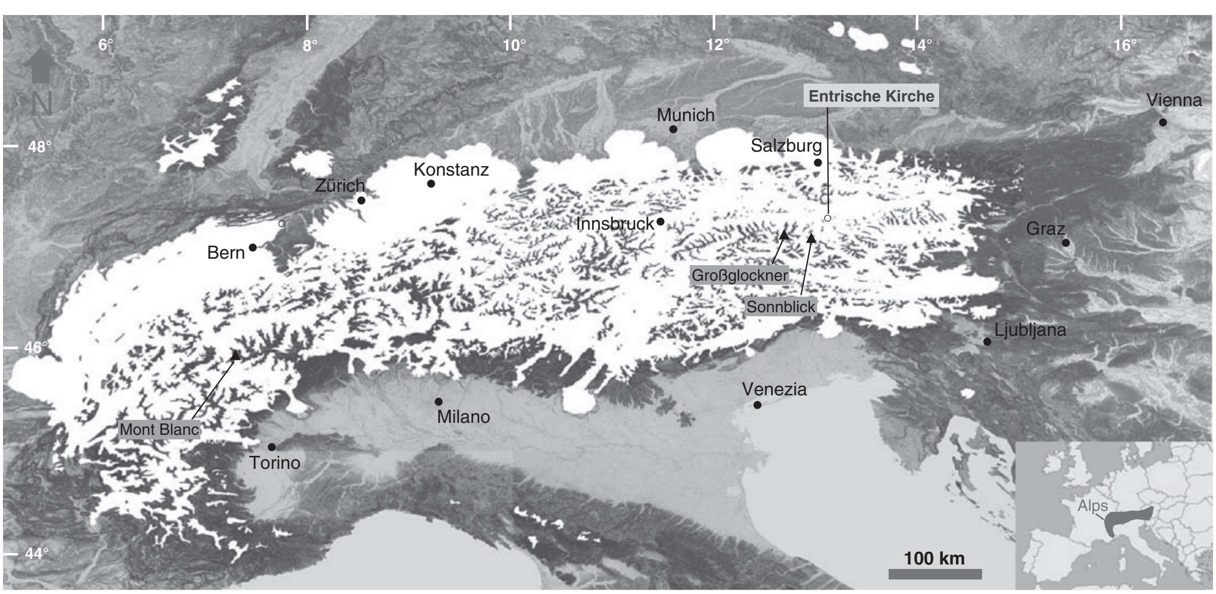

Fig. 1. The European Alps during the Last Glacial Maximum and position of the investigation area. Digital elevation model from Jarvis et al. (2008). Ice extent after Ehlers and Gibbard (2004).