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Noble gas based temperature reconstruction on a Swiss stalagmite from the last glacial–interglacial transition and its comparison with other climate records

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ABSTRACT

Here we present the results of a first application of a "Combined Vacuum Crushing and Sieving (CVCS)" system to determine past (cave/soil) temperatures from dissolved noble gas concentrations in stalagmite samples grown under 'cold' climatic conditions (e.g. close to freezing point of water) during the last glacial–interglacial transition. To establish noble gas temperatures (NGTs) also for stalagmites grown in cold regions, we applied the CVCS system to samples from stalagmite M2 precipitated in the Milandre Cave, located in the Swiss Jura Mountains. The investigated stalagmite M2 covers the Allerød–Younger Dryas–Holocene transitions. Noble gas temperatures are determined by using a new algorithm based on noble gas and water abundances and not from concentrations. Noble gas results indicate annual mean temperatures in the Milandre Cave were $2.2 \pm 1.8\,°C$ during the late stages of the Allerød, then dropping to $0\ ^{+}_{(-)}\ 2.6\,°C$ at the onset of the Younger Dryas. Such temperatures indicate conditions near to the freezing point of water during the first part of the Younger Dryas. During the last part of the Younger Dryas, the temperature increased to $6.3 \pm 2.3\,°C$. No early Holocene temperature could be determined due the non-detectable water abundances in these samples, however one late Holocene sample indicates a cave temperature of $8.7 \pm 2.7\,°C$ which is close to the present day annual mean temperature. NGTs estimated for the Allerød–Younger Dryas–Holocene are in good agreement with paleo-temperature reconstructions from geochemical and biological proxies in lake sediments. The observed deviations between the different paleo-temperature reconstructions are minor if the according temperatures are rescaled to annual mean temperatures and are primarily attributed to the chronological tuning of the different records. As in other stalagmites, NGT reconstructions of the recently precipitated stalagmite ('young') samples again are biased, most likely due to diffusive gas loss during sample processing. We speculate that a reduced retentivity of noble gases during experimental sample processing is a general feature of recently precipitated stalagmite fabrics. Therefore, the recently precipitated stalagmite samples do not allow the reliable NGT determination given the currently available experimental methods. Nevertheless, this study makes the case that noble gas thermometry can be applied to stalagmites for paleo-temperature reconstruction based on a physical method including stalagmites that grew during cold climatic conditions.

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1. Introduction

Stalagmites are recognized to represent excellent climate archives, which cover long time periods of up to 10^6 a and can be dated with high precision (Fairchild and Baker, 2012). A wide range of analytical methods – mainly stable isotope analyses – are routinely applied to deduce direct or indirect information about climatic and environmental conditions. These commonly applied methods have been compiled in comprehensive papers (e.g. Fairchild and Baker, 2012; Meckler et al., 2015). Recently, novel methods have been developed and applied to obtain temperatures from stalagmites, such as clumped isotope thermometry (Affek et al., 2008), D/H ratios of water inclusion in stalagmite (Zhang et al., 2008; Affolter et al., 2014), liquid–vapor homogenization of stalagmite fluid inclusions (Krüger et al., 2011) and noble gas temperature determination of fluid inclusions (Kluge et al., 2008; Vogel et al., 2013a; Meckler et al., 2015). Such temperature estimates are of particular importance, because cave temperatures are usually not affected by seasonal temperature variations and correspond to mean annual air temperatures (Fairchild et al., 2006; Kluge et al., 2008). Therefore, noble gas analysis (e.g. noble gas thermometry) permit to reconstruct the annual mean temperature (Brennwald et al., 2013a), complementing many seasonal temperature reconstructions derived from other terrestrial climate archives. Likewise, noble gas thermometry allows to disentangle temperature from other environmental processes that also affect the calcite precipitated during stalagmite growth, e.g. hydrological signals are being recorded in the stalagmites' stable isotope composition (Vogel et al., 2013b; Affolter et al., 2015).

With the development of a combined vacuum crushing and sieving system (CVCS; Vogel et al., 2013a), it has become possible to determine paleo-temperatures from the noble gases dissolved in minute amounts of water in speleothem inclusions. The concept of this so-called noble gas temperature (NGT) is based on the temperature, pressure, and salinity-dependent solubility of atmospheric noble gases in water, whereby the concentrations of noble gases are constant in air on a scale of up to about 10^6 a (Brennwald et al., 2013b). Although the method is routinely applied to 'large' water samples from lakes and groundwaters, i.e. ∼20–50 g (Kipfer et al., 2002), the application of noble gas thermometry to stalagmites is experimentally challenging, as the amounts of stalagmite water and the associated noble gas abundances are very small (water ≤1 mg and noble gas abundance ≤n Mol) and thus difficult to analyze (e.g. Brennwald et al., 2013a). Furthermore, noble gases of water-filled inclusions convey information on paleo-temperatures whereas the noble gases in air-filled inclusions do not contain any information because such inclusions host only unfractionated noble gases in atmospheric abundance. Since noble gas abundances in stalagmites are commonly dominated by noble gases from air inclusions (Kluge et al., 2008; Scheidegger et al., 2010; Brennwald et al., 2013a), air-filled inclusions pose severe experimental and conceptual problems to reconstruct cave temperatures. The separation of water inclusions from air inclusions is therefore a prerequisite for reconstructing paleo-temperatures (Brennwald et al., 2013a; Kluge et al., 2008; Scheidegger et al., 2010, 2011; Vogel et al., 2013a). The CVCS system reduces the amount of air in calcite samples and therefore delivers meaningful paleo-temperature estimates. It also allows to obtain hydrological information by measuring the water and noble gas amounts extracted from the crushed stalagmite samples. The new CVCS system was successfully applied on samples from tropical stalagmites from Yemen (Vogel et al., 2013a) and Borneo (Meckler et al., 2015). But up to now, the CVCS crushing method has never been applied on stalagmites which grew under 'cold' climatic conditions (e.g. close to freezing point of water) such as the Pleistocene–Holocene transition. We consider this study as a critical methodological analysis to assess and validate noble gas thermometry on stalagmite that formed under cold climate conditions.

Here we present the application of the CVCS technique to determine noble gas concentrations and water content for stalagmite M2, a specimen that grew under cold climate conditions in the Milandre Cave (Jura Mountains, Switzerland) during the time period from the end of the last glacial to the present (Table 1). The determined NGTs are *directly* calculated from the deduced noble gas and water abundances and compared to other independent temperature estimates from lake sediments derived *indirectly* from other proxies. We make the case that the NGTs generally agree with the other indirect temperature reconstructions which for the time being is the only possible approach to compare temperature reconstruction from different methodologies and we then discuss potential causes for the observed temperature deviations.

2. Experimental methods

2.1. The study area and sample description

Stalagmite M2 was collected in 2007 and found actively growing (fresh calcite was forming on top of the sample) from the Galerie des Fistuleusses in the Milandre cave (400 m a.s.l.) in Switzerland (47°29′N, 07°01′E). The Milandre cave (Fig. 1) extends for more than 10 km total and is embedded in the St. Ursanne Limestone Formation in the Swiss Plateau Jura (Braillard, 2006). Continuous temperature measured between 2008 and 2010 at four locations within the cave show stable temperatures, which were hardly influenced by seasonal variations and remain constant at around $9.56 \pm 0.15\,°C$ (Schmassmann, 2010; Spadin et al., 2015). Additional cave air temperature measurements conducted between 2012 and 2013 in close proximity to the M2 sampling site are around $9.8 \pm 0.2\,°C$ (Affolter et al., 2015). During the same time interval (2008–2010), the annual mean air temperature at the meteorological station of Fahy (596 m a.s.l., ∼10 km SW from Milandre) is around 9.0 °C. Using the mean annual lapse rate of 0.5 °C/100 m obtained from forty stations in Switzerland between 1991 and 2013 (data source Meteo Schweiz, http://www.meteoschweiz.admin.ch), this translates into a mean annual air temperature outside Milandre Cave of around 10 °C. Therefore, within half a degree the current Milandre cave air temperatures are in good agreement with the annual mean temperature of the region outside of the cave.

The 256 mm long stalagmite M2 is composed of columnar calcite and shows several clay layers in its upper 140 mm (Fig. 2a). The Allerød–Younger Dryas–early Holocene transitions are covered in the lower part of M2, between 154 and 195 mm depth, and are well visible in the oxygen isotope record. Isotopic shifts of 2.2‰ and 3.5‰ VPDB were measured at the transition between Allerød–Younger Dryas and Younger Dryas–early Holocene, respectively. The shift of oxygen isotopes in Milandre cave is interpreted as an indicator of temperature changes at the cave, with a positive shift indicating warmer temperatures (Schmassmann, 2010; Häuselmann, 2015). The sampling locations of the calcite used for U/Th dating are indicated by the black arrows in Fig. 2b. The results of the U/Th dating of M2 calcite are presented in Table 1 and Fig. 2b. Schmassmann (2010) dates the calcite precipitated at 128 mm in M2 stalagmite (8.1 ± 0.5 ka BP, BP = 1950). For the calcite precipitated between 151 and 265 mm depth, an age model was built using the COPRA algorithm (Breitenbach et al., 2012), and for the calcite precipitated between 0 and 144 mm depth we used linear age interpolation (0 mm: 0 a, 144 mm: 9.31 ± 0.15 ka BP). Unfortunately, the use of interpolation and the presence of multiple hiati do not allow us to build a strong age model for the top 151 mm of sample, although the age measured by Schmassmann (2010) agrees well with our rather rough age model. The calcite