

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

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19 **Abstract**

20 Here we present the results of a first application of a “Combined Vacuum Crushing and Sieving
21 (CVCS)” system to determine past (cave / soil) temperatures from dissolved noble gas concentrations
22 in stalagmite samples grown under ‘cold’ climatic conditions (e.g. close to freezing point of water)
23 during the last glacial-interglacial transition. To establish noble gas temperatures (NGTs) also for stal-
24 agmites grown in cold regions, we applied the CVCS system to samples from stalagmite M2 precipitated
25 in the Milandre Cave, located in the Swiss Jura Mountains. The investigated stalagmite M2 covers the
26 Allerød – Younger Dryas – Holocene transitions. Noble gas temperatures are determined by using a new
27 algorithm based on noble gas and water abundances and not from concentrations. Noble gas results
28 indicate annual mean temperatures in the Milandre Cave were 2.2 ± 1.8 °C during the late stages of the
29 Allerød, then dropping to 0 $\left(\begin{smallmatrix} + \\ - \end{smallmatrix}\right)$ 2.6 °C at the onset of the Younger Dryas. Such temperatures indicate
30 conditions near to the freezing point of water during the first part of the Younger Dryas. During the last
31 part of the Younger Dryas, the temperature increased to 6.3 ± 2.3 °C. No early Holocene temperature
32 could be determined due the non-detectable water abundances in these samples, however one late Hol-
33 ocene sample indicates a cave temperature of 8.7 ± 2.7 °C which is close to the present day annual mean
34 temperature. NGTs estimated for the Allerød – Younger Dryas – Holocene are in good agreement with
35 paleo-temperature reconstructions from geochemical and biological proxies in lake sediments. The ob-
36 served deviations between the different paleo-temperature reconstructions are minor if the according
37 temperatures are rescaled to annual mean temperatures and are primarily attributed to the chronological
38 tuning of the different records. As in other stalagmites, NGT reconstructions of the recently precipitated
39 stalagmite (‘young’) samples again are biased, most likely due to diffusive gas loss during sample pro-
40 cessing. We speculate that a reduced retentivity of noble gases during experimental sample processing
41 is a general feature of recently precipitated stalagmite fabrics. Therefore, the recently precipitated stal-
42 agmite samples do not allow the reliable NGT determination given the currently available experimental
43 methods. Nevertheless, this study makes the case that noble gas thermometry can be applied to stalag-
44 mites for physically based paleo-temperature reconstruction, also for stalagmites grown during cold cli-
45 matic conditions.

46 Keywords: Noble gas thermometry, Stalagmite, Fluid inclusion, Younger Dryas, Allerød.

47 **1. Introduction**

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

65 With the development of a combined vacuum crushing and sieving system (CVCS; Vogel et al., 2013a),
66 it has become possible to determine paleo-temperatures from the noble gases dissolved in minute
67 amounts of water in speleothem inclusions. The concept of this so-called noble gas temperature (NGT)
68 is based on the temperature, pressure, and salinity-dependent solubility of atmospheric noble gases in
69 water, whereby the concentrations of noble gases are constant in air on a scale of up to about 10^6 a
70 (Brennwald et al., 2013b). Although the method is routinely applied to 'large' water samples from lakes
71 and groundwaters, i.e. $\sim 20 - 50$ g (Kipfer et al., 2002), the application of noble gas thermometry to
72 stalagmites is experimentally challenging, as the amounts of stalagmite water and the associated noble
73 gas abundances are very small (water ≤ 1 mg and noble gas abundance $\leq n$ Mol) and thus difficult to

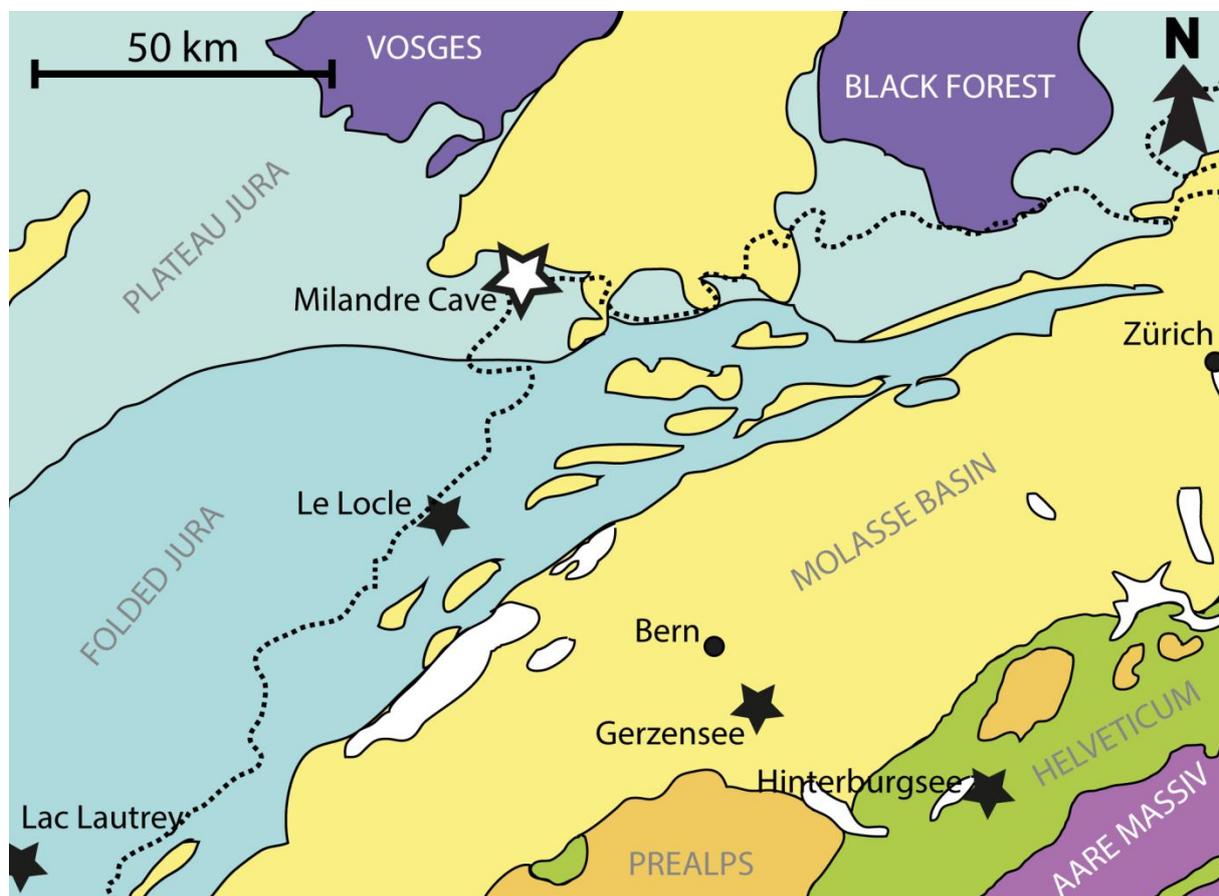
74 analyze (e.g. Brennwald et al., 2013a). Furthermore, noble gases of water-filled inclusions convey in-
75 formation on paleo-temperatures whereas the noble gases in air-filled inclusions do not contain any
76 information because such inclusions host only unfractionated noble gases in atmospheric abundance.
77 Since noble gas abundances in stalagmites are commonly dominated by noble gases from air inclusions
78 (Kluge et al., 2008; Scheidegger et al. 2010; Brennwald et al 2013a), air-filled inclusions pose severe
79 experimental and conceptual problems to reconstruct cave temperatures. The separation of water inclu-
80 sions from air inclusions is therefore a prerequisite for reconstructing paleo-temperatures (Brennwald et
81 al., 2013a; Kluge et al., 2008; Scheidegger et al., 2010; Scheidegger et al., 2011; Vogel et al., 2013a).
82 The CVCS system reduces the amount of air in calcite samples and therefore delivers meaningful paleo-
83 temperature estimates. It also allows to obtain hydrological information by measuring the water and
84 noble gas amounts extracted from the crushed stalagmite samples. The new CVCS system was success-
85 fully applied on samples from tropical stalagmites from Yemen (Vogel et al., 2013a) and Borneo (Meck-
86 ler et al., 2015). But up to now, the CVCS crushing method has never been applied on stalagmites which
87 grew under ‘cold’ climatic conditions (e.g. close to freezing point of water) such as the Pleistocene-
88 Holocene transition. We consider this study as a critical methodological analysis to assess and validate
89 noble gas thermometry on stalagmite that formed under cold climate conditions.

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

99 **2. Experimental methods**

100 **2.1. The study area and sample description**

101 Stalagmite M2 was collected in 2007 and found actively growing (fresh calcite was forming on top of
102 the sample) from the Galerie des Fistuleuses in the Milandre cave (400 m a.s.l.) in Switzerland (47°29'
103 N, 07°01' E). The Milandre cave (Fig. 1) extends for more than 10 km total and is embedded in the St.
104 Ursanne Limestone Formation in the Swiss Plateau Jura (Braillard, 2006). Continuous temperature
105 measured between 2008 and 2010 at four locations within the cave show stable temperatures, which
106 were hardly influenced by seasonal variations and remain constant at around 9.56 ± 0.15 °C (Schmass-
107 mann, 2010; Spadin et al., 2015). Additional cave air temperature measurements conducted between
108 2012 and 2013 in close proximity to the M2 sampling site are around 9.8 ± 0.2 °C (Affolter et al., 2015).
109 During the same time interval (2008 - 2010), the annual mean air temperature at the meteorological
110 station of Fahy (596 m a.s.l., ~ 10 km SW from Milandre) is around 9.0 °C. Using the mean annual lapse
111 rate of 0.5 °C / 100 m obtained from forty stations in Switzerland between 1991 and 2013 (data source
112 Meteo Schweiz, <http://www.meteoschweiz.admin.ch>), this translates into a mean annual air temperature
113 outside Milandre Cave of around 10 °C. Therefore, within half a degree the current Milandre cave air
114 temperatures are in good agreement with the annual mean temperature of the region outside of the cave.



115

116 **Fig. 1.** Simplified geological map of NW Switzerland. The dashed line delineates the NW border of Switzerland. Stars indicate
117 other locations in Switzerland (Le Locle, Gerzensee, Hinterburgsee) and France (Lac Lautrey) where paleo-climatic infor-
118 mation is available and to which our NGT reconstructions are compared.

119 The 256 mm long stalagmite M2 is composed of columnar calcite and shows several clay layers in its
120 upper 140 mm (Fig. 2a). The Allerød – Younger Dryas – early Holocene transitions are covered in the
121 lower part of M2, between 154 and 195 mm depth, and are well visible in the oxygen isotope record.
122 Isotopic shifts of 2.2 ‰ and 3.5 ‰ VPDB were measured at the transition between Allerød – Younger
123 Dryas and Younger Dryas – early Holocene, respectively. The shift of oxygen isotopes in Milandre cave
124 is interpreted as an indicator of temperature changes at the cave, with a positive shift indicating warmer
125 temperatures (Schmassmann, 2010; Häuselmann, 2015). The sampling locations of the calcite used for
126 U / Th dating are indicated by the black arrows in Fig. 2b. The results of the U / Th dating of M2 calcite
127 are presented in Table 1 and Fig. 2b. Schmassmann (2010) dates the calcite precipitated at 128 mm in
128 M2 stalagmite (8.1 ± 0.5 ka BP, BP = 1950). For the calcite precipitated between 151 and 265 mm
129 depth, an age model was built using the COPRA algorithm (Breitenbach et al., 2012), and for the calcite
130 precipitated between 0 and 144 mm depth we used linear age interpolation (0 mm: 0 a, 144 mm: $9.31 \pm$
131 0.15 ka BP). Unfortunately, the use of interpolation and the presence of multiple hiati do not allow us
132 to build a strong age model for the top 151 mm of sample , although the age measured by Schmassmann
133 (2010) agrees well with our rather rough age model. The calcite precipitated at a growth rate between
134 0.026 and 0.051 mm / a between 14.39 ka BP and 11.32 ka BP. After 9.31 ka BP we estimate a mean
135 growth rate of ~ 0.015 mm / a.

136

Table 1

137

U / Th dating results of stalagmite M2.

Sample Number	Depth (mm)	²³⁸ U (ppb)	²³² Th (ppt)	²³⁰ Th / ²³² Th ($\times 10^{-6}$)	$\delta^{234}\text{U}$ * (measured)	²³⁰ Th / ²³⁸ U (Bq / Bq)	²³⁰ Th Age (a) (uncorrected)	²³⁰ Th Age (a) (corrected)	$\delta^{234}\text{U}_{\text{initial}}$ ** (corrected)	²³⁰ Th Age (a BP)*** (corrected)
M2-B	147	73.5 \pm 0.1	668 \pm 13	191 \pm 4	245 \pm 1	0.1050 \pm 0.0005	9582 \pm 51	9371 \pm 158	251 \pm 1	9311 \pm 158
M2-C	162	72.5 \pm 0.1	194 \pm 4	792 \pm 16	248 \pm 2	0.1289 \pm 0.0005	11854 \pm 52	11792 \pm 68	256 \pm 2	11732 \pm 68
M2-D	197	112.3 \pm 0.1	235 \pm 5	1092 \pm 22	225 \pm 2	0.1384 \pm 0.0004	13020 \pm 43	12971 \pm 56	234 \pm 2	12911 \pm 56
M2-E	253	145.4 \pm 0.1	2525 \pm 51	169 \pm 3	398 \pm 2	0.1779 \pm 0.0005	14747 \pm 45	14389 \pm 257	414 \pm 2	14329 \pm 257

138

U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10} \text{ a}^{-1}$ (Jaffey et al., 1971) and $\lambda_{234} = 2.82206 \times 10^{-6} \text{ a}^{-1}$ (Cheng et al., 2013). Th decay constant: $\lambda_{230} = 9.1705 \times 10^{-6} \text{ a}^{-1}$ (Cheng et al., 2013). * $\delta^{234}\text{U} = ([^{234}\text{U} /$

139

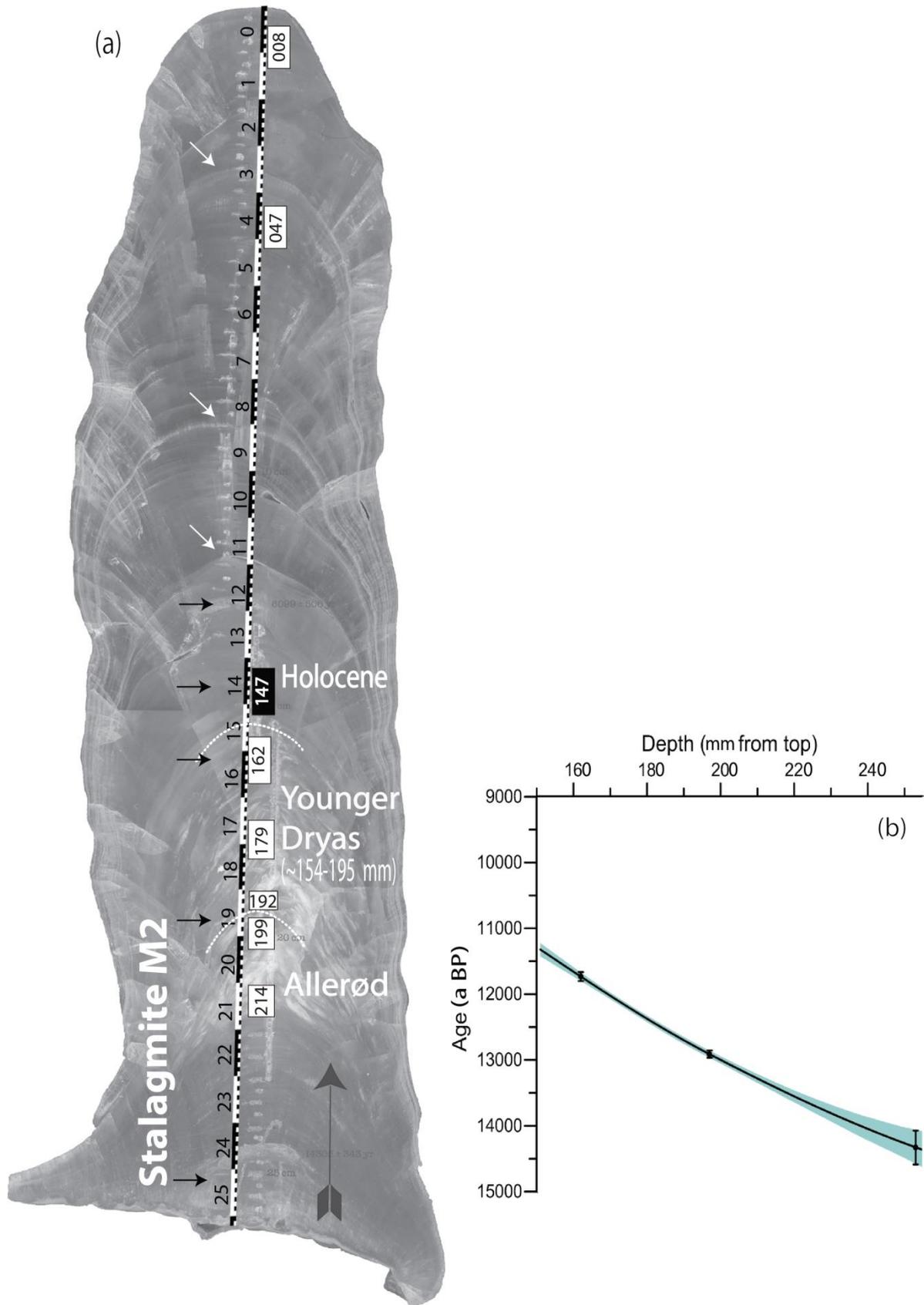
 $^{238}\text{U}]_{\text{activity}} - 1) \times 1000$. ** $\delta^{234}\text{U}_{\text{initial}}$ was calculated based on ²³⁰Th age (T), i.e. $\delta^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{\lambda_{234} \times T}$. ***Corrected ²³⁰Th ages assume the initial ²³⁰Th / ²³²Th isotopic ratio of 4.4 ± 2.2

140

 $\times 10^{-6}$. Those are the values for a material at secular equilibrium, with the bulk earth ²³²Th / ²³⁸U value of 3.8. The errors are arbitrarily assumed to be 50% (2 σ). Samples for NGT analysis were

141

taken close to locations where U / Th ages were available.



142

143 **Fig. 2.** Sampling of stalagmite M2 (a). Samples were cut out of the stalagmite as ‘cubes’ with a microsaw and prepared for
 144 NGT analysis (see Table 2). Boxes represent samples taken for NGT measurements. Numbers in boxes indicate the mean
 145 distance of each sample to the top of the stalagmite in millimeters. White dashed lines mark to the approximate position of the
 146 ‘Allerød – Younger Dryas’ and ‘Younger Dryas – Holocene’ transitions as estimated by the oxygen isotope record (Schmass-
 147 mann, 2010, Häuselmann, 2015). White arrows indicate clay layers, which might point to growth hiatus. Black arrows show

148 samples dated by U / Th. The gray arrow indicates the growth direction of calcite in the stalagmite M2. The sample at 147 mm
149 from the top (in the black box) did not contain enough water for a reasonable noble gas analysis and it thus excluded from
150 further discussion. Individual depth-age model of 'older' section of stalagmite M2 (b). The outer shaded zones define the 95%
151 uncertainties.

152 **2.2. Sampling procedure for NGT analysis**

153 In total, eight samples for NGT analysis were cut along the growth axis of stalagmite M2 (Fig. 2). Only
154 one early Holocene sample (at 147 mm from the top) did not contain enough water for noble gas analy-
155 sis, therefore, it is excluded from further discussion. Most samples were taken from the transitions of
156 the Late Glacial into the early Holocene, but two samples younger than 8.1 ka BP were also prepared
157 for noble gas analysis.

158 **2.3. Water and noble gas measurements for NGT determination**

159 A detailed description of the sample processing using the CVCS system, the gas purification and subse-
160 quent noble gas and water content measurements is given in Vogel et al. (2013a) and Scheidegger et al.
161 (2010, 2011). Briefly, each stalagmite sample is crushed in a vacuum to a manually pre-set grain size of
162 ~ 0.8 – 1.2 mm and is then sieved into three grain size fractions of > 0.5 mm, 0.5 – 0.3 mm and < 0.3
163 mm, which are collected in three glass fingers. Of these, solely the coarsest fraction was used for sub-
164 sequent water and noble gas extraction, because that fraction commonly shows the highest water / air
165 inclusion ratios (Vogel et al. 2013a). Water and noble gases were extracted from the separated fractions
166 by heating the respective glass finger for one hour at 260 °C. The extracted water (and the condensable
167 fluid species) were concentrated cryogenically in a well-defined volume, which was subsequently heated
168 to ~ 50 °C to prevent water from condensating and to allow the H₂O gas pressure to be determined by a
169 high precision manometer (Scheidegger et al., 2010). The mass of the extracted water can be calculated
170 from the water gas pressure in combination with known volume and temperature. In a next step, the
171 extracted noble gases were purified, cryogenically separated into a He-Ne and an Ar-Kr-Xe fraction,
172 and quantitatively analyzed in two consecutive steps (He, Ne and Ar, Kr, Xe steps) by static vacuum
173 (noble gas) mass spectrometry (e.g. Beyerle et al., 2000). In contrast to the pure atmospheric noble gases
174 (Ne-Xe), most of the extracted ⁴He does not stem from the sample, but is released from the glass into
175 the system when the crushed sample is heated in the glass finger (Vogel et al., 2013a) – therefore, ⁴He
176 is not discussed. After extraction, the grain separate is heated for a second time ('re-extraction') using

177 the same extraction parameters as for the initial extraction. The water and noble gas amounts released
178 from the according re-extractions were used for ‘blank’ correction of the respective ‘sample’ extraction.
179 ^{22}Ne blank correction was large and very variable (< 60%), whereby the highest values were associated
180 with the two youngest samples M2-047 and -008. Blank corrections of ^{40}Ar , ^{86}Kr , and ^{136}Xe were smaller
181 and considerably uniform (~ 5%, ^{136}Xe in M2-008: 20%). Blank corrections of the water amounts were
182 < 3%. ^{22}Ne signals were corrected (< 3%) for interference of CO_2^{++} on mass 22 by monitoring the CO_2^+
183 signal and applying an experimentally determined $\text{CO}_2^{++} / \text{CO}_2^+$ ratio. The noble gas amounts were
184 determined by normalization to the analyses of calibration gas (known aliquots of air) before or after
185 each sample extraction step (Beyerle et al., 2000). The calibration gas is processed using the same ana-
186 lytical procedure as the sample gas.

187 **2.4. NGT determination**

188 Although the CVCS technique reduced the fraction of air-related noble gases of the analyzed stalagmite
189 samples significantly by about 1–2 orders of magnitude (Scheidegger et al. 2010, 2011), the determined
190 noble gas amounts still represent mixtures of noble gases from air and air-saturated water (ASW). To
191 estimate NGTs, the measured amounts of water and noble gases are thus conceptually interpreted as a
192 binary mixture of air released from the air inclusions and of air-saturated water (i.e. noble gases origi-
193 nally dissolved in the water inclusions). The applied mixing model to separate the noble gas concentra-
194 tions component depends on the following model parameters: the noble gas temperature (*NGT*, i.e. the
195 temperature at which the fluid inclusion was captured), the amount of air per unit mass of water (*A*), and
196 the mass of water (*M*). Such models were originally developed to determine recharge temperatures in
197 (ground)waters from dissolved noble gas concentrations (Mazor , 1972; Kipfer et al., 2002; Jung et al.,
198 2013). For determination of NGTs, a similar regression method is used as is commonly applied in
199 groundwater studies (Aeschbach-Hertig et al., 1999; Ballentine and Hall, 1999) in order to determine
200 the best-fit values of the model variables (NGT, *A*, and *M*) through minimizing the sum of the squared
201 error-weighted residuals between the modeled and the measured data (χ^2 – optimization). This method
202 quantifies the model variables NGT, *A* and *M* by regression from the measured noble gas concentrations
203 in a statistically sound manner, thus, delivering the paleo-temperature at the time when the calcite was

204 deposited. If the assumed model of noble gas partitioning is consistent with the data, the expected χ^2
205 value obtained from the fit is similar to the number of degrees of freedom (DF) of the fit (Press et al.,
206 1986). The number of degrees of freedom of the fit is the difference between the number of measured
207 parameters (noble gas and water amounts) and the number of the fitted model parameters (NGT, A and
208 M).

209 We note that the commonly used regression methods (Aeschbach-Hertig et al., 1999) implicitly assume
210 that the error of the amount of water of a given sample is negligibly small and, hence, does not affect
211 the calculation of the total error of the noble gas concentrations. This is a valid assumption for water
212 samples larger than 1g as it is the case for (ground) water in the classical approach. In the case of stal-
213 agmites, however, the error of the minute amount of water extracted from a calcite sample contributes
214 significantly to the total error of the determined atmospheric noble gas concentrations. Thus, ignoring
215 the error of the extracted water mass principally undermines the basic assumption of statistically uncor-
216 related errors which is fundamental for any χ^2 based regression method. To avoid the correlation of
217 errors, we did not fit noble gas concentrations, but treated noble gas abundances and water amounts
218 determined in each sample as independent parameters to be fitted. To this end, we developed a new,
219 more flexible regression tool, which is also based on the χ^2 minimization technique (please see more
220 details: <http://brennmat.github.io/noblefit/>). This new tool allows a statistically sound assessment of the
221 quality of the fit based on the resulting χ^2 -value also in the case of stalagmite samples as the error for
222 the water mass determination is explicitly accounted for. Like other codes (Aeschbach-Hertig et al.,
223 1999), the new tool also provides statistically sound estimates of the uncertainties of the fitted parame-
224 ters by propagating the analytical errors of the noble gas and water amounts.

225 **3. Results**

226 **3.1. Elemental ratios**

227 Before estimating NGTs to study the temperature evolution of the Milandre site during the last 15 ka,
228 we check if the measured noble gas amounts (Table 2) can conceptually be described by binary mixing
229 model of unfractionated air and ASW. In a three-element plot (Fig. 3), any such mixture falls on a
230 straight line connecting the two endmember compositions. Fitting algorithms yield statistically robust

231 temperature estimates for such ‘simple’ mixtures. Instead of mixing lines for particular (water) temper-
 232 atures, Fig. 3 shows expected mixing areas covering ASW compositions between 0 and 15 °C and air.

233 **Table 2**
 234 Measured water and noble gas amounts in stalagmite M2 from the Milandre cave.

Sample	Water amounts [$\times 10^{-5}$ g]	Ne [$\times 10^{-12}$]	Ar [$\times 10^{-10}$]	Kr [$\times 10^{-12}$]	Xe [$\times 10^{-12}$]
M2-214	20.0 \pm 0.8	479 \pm 8	3318 \pm 47	49.3 \pm 0.6	5.8 \pm 0.3
M2-199	14.4 \pm 1.1	226 \pm 5	1704 \pm 24	27 \pm 0.3	3.5 \pm 0.1
M2-192	11.1 \pm 0.8	203 \pm 5	1596 \pm 23	24.5 \pm 0.3	3 \pm 0.1
M2-179	7.2 \pm 0.9	66 \pm 5	719 \pm 10	13.1 \pm 0.2	1.8 \pm 0.2
M2-162	8.9 \pm 0.8	73 \pm 3	643 \pm 9	11.8 \pm 0.6	1.6 \pm 0.1
M2-047	6.5 \pm 0.6	31 \pm 2	285 \pm 4	4.8 \pm 0.1	0.9 \pm 0.04
M2-008	3.3 \pm 0.7	10 \pm 2	94 \pm 1	1.9 \pm 0.04	0.4 \pm 0.02

235 Noble gas amounts are in cm³STP (1 mole = 22414 cm³ STP). Uncertainties of water and gas amounts are given at the 1 σ level.
 236 Uncertainties of the water amounts include the error of the manometric pressure reading to determine the water vapor pressure,
 237 the error of the temperature of the water basin keeping the calibration volume at a constant and uniform temperature, and the
 238 error of the calibration volume for the pressure determination to which the noble gases and water were expanded. The overall
 239 uncertainty also accounts for the systematic error associated with the correction for a small fraction of water that interacts with
 240 the inner walls of the extraction line (see Vogel et al., 2013a). Uncertainties of noble gas amounts include errors associated
 241 with ion counting statistics, interference and blank corrections, and errors related to absolute noble gas calibration (for the
 242 details see Beyerle et al., 2000; Vogel et al., 2013a). Ne, Ar, Kr, and Xe amounts were calculated from the measured ²²Ne,
 243 ⁴⁰Ar, ⁸⁶Kr, and ¹³⁶Xe abundances using the respective atmospheric isotopic compositions (Kipfer et al., 2002, and references
 244 therein).

245
 246 In all three panels of Fig. 3, the composition of sample M2-162 falls on the mixing area within 1 σ
 247 uncertainties, indicating four atmospheric noble gases are consistent with the interpretation of binary
 248 mixtures of air and ASW. Thus, all atmospheric noble gas concentrations can be consistently translated
 249 into common NGT values (Table 3).

250 The composition of all other samples show offsets from the mixing areas in at least one of the 3 ele-
 251 mental-ratio panels: Samples M2-214, -199, and -192 show a moderate, samples M2-047 and M2-008
 252 show substantial deviations from the mixing area in Ar / Kr and Xe / Kr ratios (Fig. 3a). A much better
 253 match with the expected mixing area of ASW and air is found for samples M2-214, -199, and -192 for
 254 Ne / Kr and Xe / Kr ratios (Fig. 3b). In fact, Ne, Kr, and Xe can conceptually much better be interpreted
 255 as binary mixing of ASW and air than Ar, Kr, Xe compositions. These observations point to a singular
 256 excess of Ar in these samples. We note that Ar enrichment relative to the other atmospheric noble gases
 257 is only observed during the first extraction ('sample', see section 2.3.) whereas the re-extraction is not
 258 affected ('blank'). Because the re-extractions, which are used for blank correction, hardly contain any
 259 water or any other extractable fluid, thus Ar excess is not ‘produced’. As a result, the blank corrections
 260 become inadequate. In concert with inherent analytical constraints (Vogel et al., 2013a, see section 3.3.1)

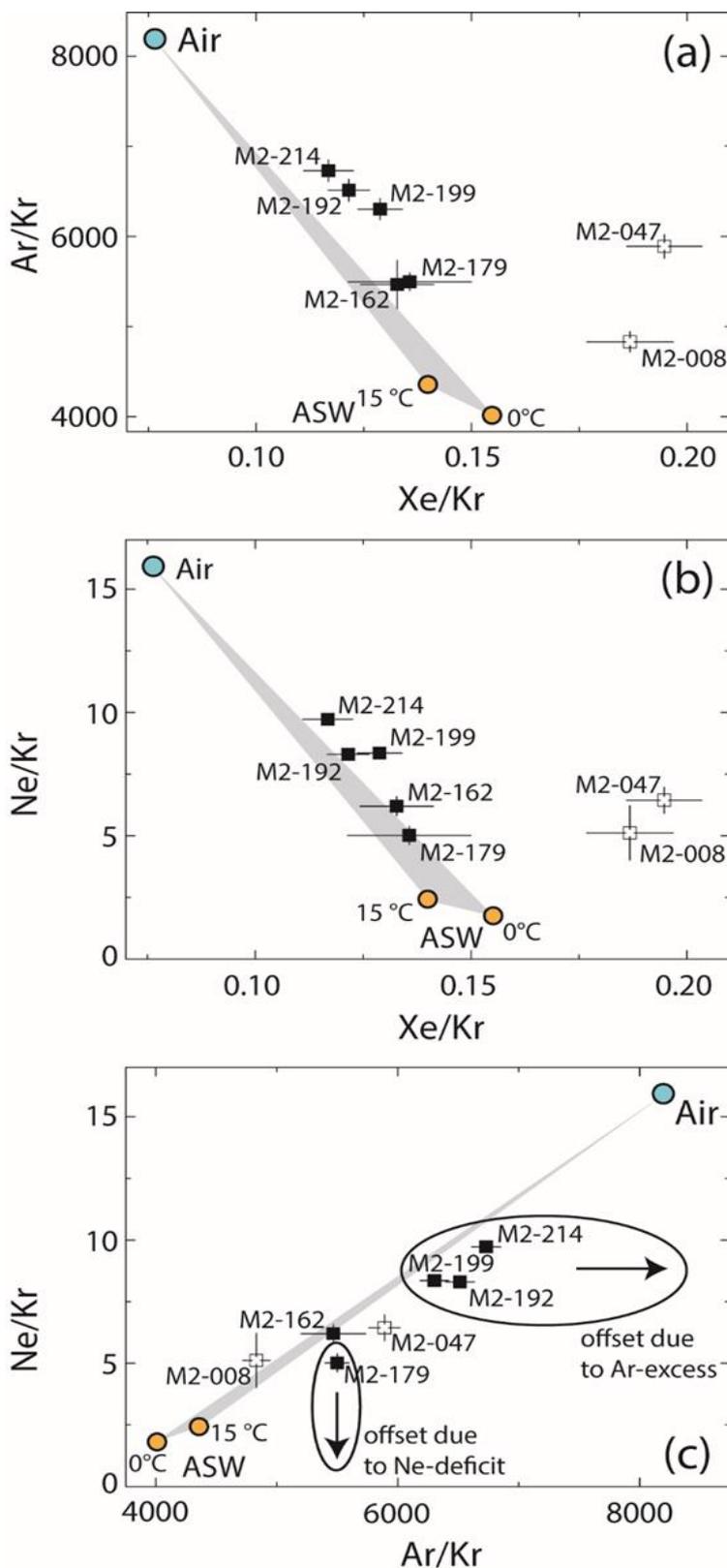
261 it is thus concluded that the observed Ar excess is not related to any kind of external process (e.g. leak),
262 but is due to an internal process which is only operational if extracted gases and water interact with the
263 interior surface of the extraction line ('memory effect'). Most likely - we hypothesize - Ar is liberated
264 from the interior surface of the extraction line in a kind exchange reaction. The extracted water and
265 gases of the first extraction adsorb to metal surfaces and displace the Ar previously sitting at the same
266 position (e.g. due to air calibration or venting of the system, etc.) as the reactive species bind signifi-
267 cantly stronger than the non-reactive Ar.

268 Notably, samples with higher water yields (Table 2) seem to be subject to higher Ar enrichment than
269 samples with less water - an observation which adds some support to the idea that the observed Ar
270 enrichment might indeed be result of an internal exchange process. Although caution needs to be exer-
271 cised in drawing final conclusions we are tempted to identify the Ar source in some of the used getter
272 material as these alloys were produced under a protecting Ar atmosphere. In conclusion, Ar in samples
273 M2-214, -199, and -192 originates from three and not from two different components (Air, ASW and
274 from the internal extraction processes). Therefore, Ar for these samples cannot be interpreted in terms
275 of a binary mixture of air and ASW. Thus, NGTs in the samples M2-214, -199, and -192 can only be
276 determined from Ne, Kr, and Xe concentrations.

277 Sample M2-179 seems to be depleted in Ne (Fig. 3c) whereas Ar, Kr, and Xe concentrations are the
278 results of binary mixing of ASW and air (Fig. 3a). A potential reason for the observed Ne-deficit is an
279 inappropriately large blank correction (30%). Heating experiments using empty glass fingers show that
280 the glass does not only become permeable for He (Vogel et al., 2013a), but also for Ne, but to a much
281 smaller extent. Thus, blank corrections especially for samples with very low noble gas abundance (M2-
282 179) might become inadequate. However, Ar, Kr, and Xe appear to be unaffected (Fig. 3a and caption
283 of Table 3) and thus these concentrations can be converted into NGT.

284 The two youngest samples M2-047 and M2-008 show strongly fractionated element patterns in the Ar /
285 Kr vs. Xe / Kr and the Ne / Kr vs. Xe / Kr plots (Figs. 3a and 3b). These shifts are most probably due to
286 Xe enrichment in these samples as Ne, Ar, and Kr can reasonably be understood as binary mixtures of

287 ASW and air (Fig. 3c). The possible causes for the relative Xe enrichment in these samples will be
 288 discussed in detail in section 3.2.2.



289
 290 **Fig. 3.** Three element plots Ar / Kr vs. Xe / Kr (a), Ne / Kr vs. Xe / Kr (b), and Ne / Kr vs. Ar / Kr (c). Errors are reported at
 291 1σ level. It is also shown the light gray mixing areas between the endmember compositions of air and air-saturated water
 292 (ASW). The salinity of drip water entering the cave is typically very low and, thus, it has a very minor effect on noble gas

293 solubilities. Therefore, ASW compositions are calculated for freshwater with temperatures between 0 and 15 °C taking into
294 account the elevation of Milandre Cave of 400 m a.s.l. and using suitable noble gas solubility data (Kipfer et al., 2002 and
295 references therein). The empty squares show the recently precipitated stalagmite ('young') samples which cannot be interpreted
296 in paleo-temperature terms.

297 **3.2. Stalagmite M2 noble gas temperatures**

298 We used two different sets of atmospheric noble gases to evaluate NGTs (Table 3): NGT_1 estimated
299 from the water amounts and the abundance of all four atmospheric noble gases (Ne, Ar, Kr, and Xe) and
300 NGT_2 from the water amounts and those three atmospheric noble gases (e.g. only using Ne, Kr, and Xe)
301 of the particular samples which are in good agreement with the model of a binary mixture of air and
302 ASW. Except for the two youngest samples (M2-008 and M2-047), the NGT_1 and NGT_2 agree within
303 their 1σ uncertainties. However, as expected, the χ^2 -values of the NGT_2 fits (e.g. only using Ne, Kr, Xe)
304 are much closer to the respective values of DF than those associated with NGT_1 (i.e. fitting all atmos-
305 pheric noble gases Ne, Ar, Kr and Xe). For sample M2-162 Ne, Ar, Kr and Xe can be interpreted as
306 binary mixtures of air and ASW, thus NGT_1 and NGT_2 are identical and χ^2 values in either case match
307 the number of degree of freedom.

308 **3.2.1. Allerød and Younger Dryas samples**

309 At the end of the Allerød (samples M2-214, and -199), the reconstructed annual mean temperature in
310 Milandre Cave are 1.8 ± 1.5 and 2.6 ± 2.2 °C. At the onset of the Younger Dryas the cave temperature
311 dropped down to a temperature close to zero degree (M2-192 and M2-179). Cave temperatures below 0
312 °C are not captured by stalagmites due to the possible lack of liquid water and the resulting reduction of
313 stalagmite growth rate. A cave / soil temperature of 0 °C is regarded as maximum temperature estimate.
314 NGTs increase considerably towards the end of the Younger Dryas, reaching 6.3 ± 2.6 °C (M2-162). At
315 the end of the Younger Dryas, noble gas data indicates an annual mean temperature at the Milandre
316 Cave of 6.3 ± 2.6 °C. The given error of this temperature accounts for the age uncertainty as a single
317 calcite samples ($1 \times 1 \times 1$ cm³) integrates over a considerable time interval. Taking into account the large
318 error (e.g. related to sample preparation and dating), to our point of view the temperature of this sample
319 most likely marks the transition into the Holocene. This interpretation is in good agreement with in-
320 creasing $\delta^{18}O$ at the early Holocene in Fig. 4. As noted earlier, a NGT could not be determined for the
321 early Holocene as these samples did not contain enough extractable water.

322 3.2.2. *Late Holocene samples (M2-047 and M2-008)*

323 NGT₂ of the two youngest samples M2-047 and M2-008 are significantly higher than 20 °C. Such high
324 temperatures at the cave site are impossible because the recent annual mean temperature in Milandre
325 Cave does not exceed 10 °C and given the recent climate evolution it appears reasonable to assume that
326 past cave temperatures were never higher during the past few thousand years. Therefore, we conclude
327 that these recently precipitated stalagmite ('young') samples (i.e. being close to growing zone) must
328 have been affected by a process that depleted the atmospheric noble gas concentrations and fractionated
329 the according elemental ratios in the water-filled inclusions after the stalagmite M2 was cut and prepared
330 for noble gas analysis in the laboratory. The recently precipitated stalagmite ('young') samples M2-047
331 and M2-008 show significantly lower noble gas and water abundances in comparison with the old part
332 of the stalagmite that crystallized a long time age (see Table 2). Further, the low water and noble gas
333 amounts and the fractionated noble gas ratios point towards some gas loss which depleted noble gases
334 concentrations in the water filled inclusions whereby Ne, Ar and Kr were more affected than Xe (Table
335 2, Figs. 3a and 3b). The observed elemental fractionation indicates that the assumed gas loss might be
336 controlled by solubility or molecular diffusion which are known in aquatic systems to deplete Ne, Ar
337 and Kr with regard to Xe as Xe has the lowest Henry coefficient (i.e. is most soluble) and smallest
338 diffusion coefficient among noble gases in water (Jähne et al., 1987; Kipfer et al., 2002; Tyroller et al.,
339 2016; de Magalhães et al., 2017).

340 Similar noble gas depletion and fractionation were also reported from a comprehensive study comparing
341 different methods to reconstruct past temperatures from stalagmites from Borneo (Meckler et al., 2015).
342 This study also reported gas loss in the recently precipitated stalagmite samples (i.e. showing unreason-
343 ably high NGTs) but also showed that some of the emerging novel methods to retrieve environmental
344 information for stalagmites (e.g. homogeneous temperatures of fluid inclusion) have limitations if being
345 applied to recently precipitated calcites. In contrast, the 'old' samples were found to be unaffected and
346 the respective noble gas concentrations were successfully converted into more meaningful cave temper-
347 atures (Meckler et al., 2015).

348 According to our experimental CVCS protocols to process stalagmite samples, prior to crushing stalag-
349 mite samples are stored in the CVCS chamber for about 1 to 2 days at around 40 °C when the glass

350 fingers were heated up to 350 °C to reduce operational blanks during the later thermal gas extraction.
351 The ‘clean’ glass fingers were used later for thermal gas extraction. After crushing to the pre-set grain
352 size, the crushed and separated stalagmite samples are stored in their respective glass fingers at room
353 temperature. During that time, they are pumped for several hours to remove the noble gases from the
354 air-filled inclusions which were preferentially cracked open by the crushing procedure (for details, see
355 Vogel et al., 2013a). In either case (e.g. during storage as uncrushed pre-heated samples or during stor-
356 age and pumping of the crushed samples), stalagmite samples can be subject to gas and water loss as
357 they are exposed to lower pressure and higher temperatures (e.g. room temperature or higher) than in
358 the cave. Based on our still limited dataset, we postulate that the currently available experimental pro-
359 tocols yield systematically too low water and noble gas abundances for very recently precipitated stal-
360 agmite (‘young’) samples as such samples seem to be susceptible to gas loss under vacuum conditions.
361 In support of our hypothesis, we refer to Thompson (1973) who also reported significant water loss (<
362 20 %) when recently precipitated stalagmite sample was heated to 60 °C.
363 As Xe, due to its low diffusivity and large solubility, is less subject to gas loss, we tried to use the Xe
364 abundances to roughly estimate NGT for the recently precipitated stalagmite samples. Assuming that all
365 remaining Xe in M2-047 and M2-008 originated from the ASW component, we derived temperatures
366 of around 6 °C and 14 °C, respectively. Although a fraction of the Ne has obviously been lost, Ne might
367 still be used for a tentative air correction for Xe. Doing so, a NGT of 8.7 ± 2.7 °C is determined for M2-
368 047 and 15.6 ± 6.7 °C for M2-008. At least in case for M2-047, the roughly scaled NGT agrees reason-
369 ably well with the modern temperature of the Milandre cave. The true NGT originally captured by the
370 recently precipitated stalagmite samples might well have been lower (Xe loss due to baking, see above),
371 but certainly cannot have been higher than these values (Table 3).

372
373

Table 3
NGTs of Stalagmite M2.

Sample	Age (time interval ka)	M [mg]	Fits with complete set of tracers (Ne, Ar, Kr, Xe)					Fits with reduced set of tracers				Tracer set used for fitting
			NGT ₁ [°C]	A ₁ [cm ³ STP / g]	χ ₁ ²	#DF ₁	NGT ₂ [°C]	A ₂ [cm ³ STP / g]	χ ₂ ²	#DF ₂		
Old samples	M2-214	13.4 (13.2 - 13.5)	0.199 ± 0.008	2.2 ± 1.5	0.123 ± 0.006	11.7	2	1.8 ± 1.5	0.121 ± 0.006	1.2	1	Ne, Kr, Xe
	M2-199	12.95 (12.8 - 13)	0.139 ± 0.011	3.7 ± 2.3	0.077 ± 0.007	13.3	2	2.6 ± 2.2	0.077 ± 0.007	4.6	1	Ne, Kr, Xe
	M2-192	12.76 (12.7 - 12.8)	0.113 ± 0.008	1.2 ± 2	0.093 ± 0.007	23.5	2	0 ₍₋₎ ⁺ 2*	0.087 ± 0.007	0.3	1	Ne, Kr, Xe
	M2-179	12.3 (12.2 - 12.5)	0.072 ± 0.009	0 ± 3	0.045 ± 0.007	16.1	2	0 ₍₋₎ ⁺ 3.2*	0.057 ± 0.009	0.4	1	Ar, Kr, Xe
	M2-162 ^a	11.7 (11.5 - 11.9)	0.089 ± 0.008	6.3 ± 2.6	0.034 ± 0.004	0.4	2	6.3 ± 2.6	0.034 ± 0.004	0.4	2	Ne, Ar, Kr, Xe
Young Samples	M2-047	2.94 (2.6 - 3.2)	0.066 ± 0.006	(20.9 ± 3.3)	0.019 ± 0.003	84.3	2	(31 ± 3.8)	0.020 ± 0.003	2.6	1	Ne, Ar, Kr
	M2-008	0.34 (-0.02 - 0.71)	0.031 ± 0.007	(-4.5 ± 9.4)	0.018 ± 0.013	28.0	2	(25.8 ± 8.1)	0.004 ± 0.004	1.5	1	Ne, Ar, Kr

374 NGT₁, NGT₂ and amounts of air per unit mass of water (A₁, A₂) determined for stalagmite M2. NGT₁, A₁, χ₁², and #DF₁ were determined using the complete set of measured noble gases Ne, Ar, Kr,
375 and Xe abundances. NGT₂, A₂, χ₂² and #DF₂ were determined using a reduced set of noble gases, which agree best with the model assumption of a binary mixture of air and ASW. M: fitted water
376 mass. The regression method and fit statistics (χ², #DF) are explained in section 2.4. All uncertainties are given at 1σ level. Ages represent mean ages of the sampled interval based on the age models
377 of each sample. * A calculated temperature below the freezing point of water is the result of the mathematical error propagation and has no paleo-climatic meaning. ^a For sample M2-162 Ne, Ar, Kr
378 and Xe can be interpreted as binary mixtures of air and ASW, thus NGT₁ and NGT₂ are identical and χ₂² values, in either case match the number of degree of freedom. (-): Unrealistic temperature
379 estimations due to different structure compared to other samples. Therefore, no meaningful temperature could be determined for recently precipitated stalagmite samples.

380 4. Discussion

381 4.1. Independent paleo-temperature information for the Milandre Cave area

382 In the following section, we compare our stalagmite-based NGTs with other temperature reconstructions
383 from four locations in Northwestern Switzerland: Gerzensee, 603 m a.s.l. (Lotter et al., 2000), Hinter-
384 burgsee, 1515 m a.s.l. (Heiri et al., 2003), Le Locle, 915 m a.s.l. (Magny et al., 2001), and Eastern
385 France: Lac Lautrey, 788 m a.s.l. (Heiri and Millet, 2005). These locations are within a radius of ~ 120
386 km from the Milandre Cave (Fig. 1). However, these paleo-temperature records are based on pollen,
387 cladoceran, and chironomid assemblages and, therefore, are seasonally biased towards summer temper-
388 atures (June, July, and August).

389 Table 4 summarizes available paleo-temperature information from four close-by locations in Northwest-
390 ern Switzerland and Eastern France that have different altitudes. We note that these estimates are based
391 on different methods that strictly speaking reconstructed different temperatures (e.g. annual mean tem-
392 perature (Magny et al., 2001), summer temperature (Lotter et al., 2000), and July temperature (Heiri et
393 al., 2003; Heiri and Milet, 2005, see Table 4 for details).

394 **Table 4**
395 **Independent paleo-temperature information from four locations in Northwestern Switzerland and Eastern France**

Location	Le Locle	Gerzensee	Hinterburgsee	Lac Lautrey
	915 m	603 m	1515 m	788 m
Intervals	Pollen	Pollen & Cladoceran	Chironomid	Chironomid
	Annual mean temperature	Summer temperature	July temperature	July temperature
End of Bølling	n.d.	n.d.	n.d.	16
Allerød	n.d.	11 – 13	n.d.	16.5 – 17
Allerød – Younger Dryas	3 – 5.5	9 – 10	n.d.	15
Younger Dryas – Holocene	3.5 – 6.5	11.5 – 12	10.4 – 10.9	14
Early – Middle Holocene	8 – 10	14 – 15	11.9 – 12.8	16.5
Late Holocene	n.d.	n.d.	11.5 – 12	n.d.

396 Temperatures in °C, altitude in meters a.s.l.. The paleo-temperature information is derived from pollen (Lotter et al., 2000;
397 Magny et al., 2001), chironomid (Heiri et al., 2003; Heiri and Millet et al., 2005) and cladoceran (Lotter et al., 2000) assem-
398 blages from sediment cores of lakes. Investigated sites are located within a 120 km radius from the Milandre cave (n.d. = no
399 data).

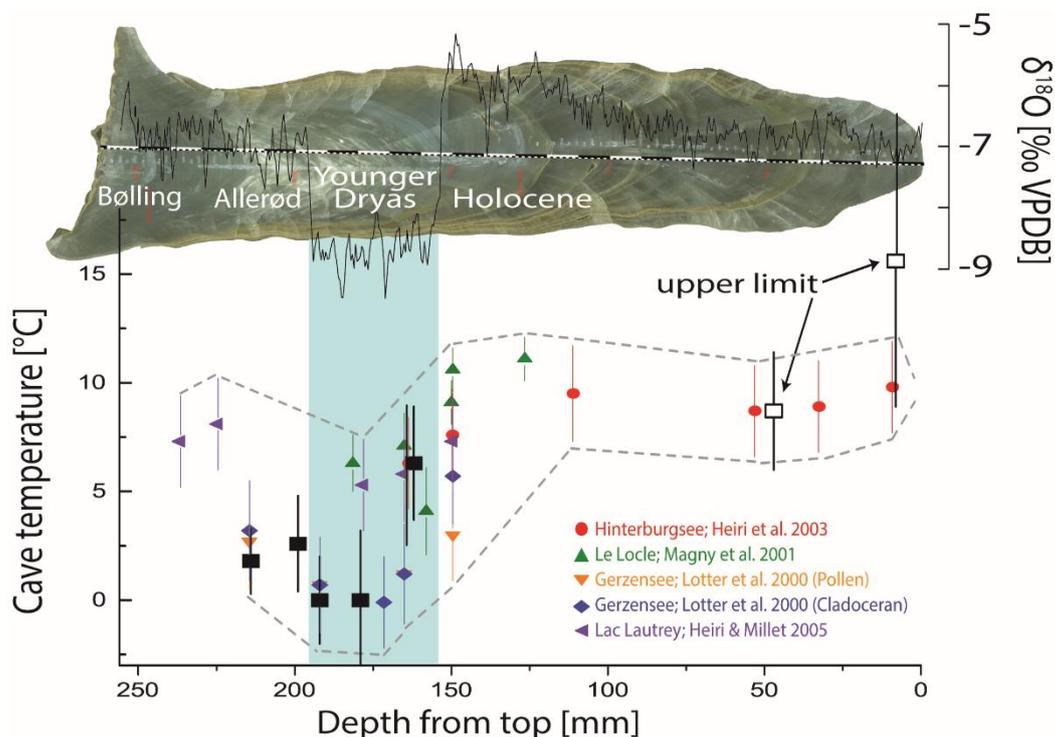
400 4.2. Comparison of NGTs with published paleo-temperature information for the Milandre Cave

401 In order to compare these various temperature reconstructions with each other and with our stalagmite
402 M2 NGTs, all records need to be rescaled to the elevation of the Milandre Cave (400 m a.s.l.). This
403 scaling is done by correcting the local reconstructed atmospheric temperature (e.g. summer and mean

404 temperature) of each site according to the respective present-day atmospheric lapse rate (summer: 0.6 °C
405 / 100 m, e.g. Livingstone et al., 1999, and the annual mean lapse rate: 0.5 °C / 100 m, e.g. Magny et al.,
406 2001). We also account for the slight difference between cave temperature and the temperature outside
407 the cave at the Milandre site (0.5 °C, see below). Next and most importantly, the scaled summer and
408 July temperatures have to be converted to annual mean temperatures; i.e. to those temperatures recorded
409 by the noble gases in stalagmites. To carry out this transformation, we compared long term instrumental
410 temperature records from Zürich (Switzerland: 1935-1993), Basel (Switzerland: 1849-1998), and Fahy
411 (Switzerland: 1985-2011), which show a stable temperature difference (ΔT) of about 8 °C between sum-
412 mer and annual mean temperatures, and a difference of 9 °C between the July and annual mean temper-
413 atures. However, the climate in Middle Europe at the end of the last glacial is generally assumed to have
414 been more continental than today, i.e. being characterized by a larger annual temperature amplitude
415 (Wick, 2000). Therefore, present day ΔT s were also analyzed for locations which either show summer
416 temperatures similar to the ones most probably prevailing at the Milandre site during the Allerød –
417 Younger Dryas – Holocene (e.g. Helsinki, Stockholm, Uppsala, Oslo, Umea, Östersund, Trondheim,
418 Selbu, Oulu, Kemi), or which lie at a similar geographical latitude as Milandre, but in a more continental
419 climate setting (Vienna, Budapest, Bishkek, Astana). Resulting ΔT s are found to be indeed higher (~ 11
420 °C difference between summer and annual mean temperature, and 12 °C between July and annual mean
421 temperature). We therefore decide to use the mean of the two ΔT estimates for converting summer / July
422 temperatures to annual mean temperatures (summer temperature → annual mean temperature: 9.5 °C,
423 July temperature → annual mean temperature: 10.5 °C). These mean ΔT values are used to convert the
424 Late Glacial and early Holocene samples ('continental climate'), but for younger samples the present
425 day temperature lag is applied ('recent climate'). We are aware that the seasonal variation can affect the
426 conversion from summer temperature to mean annual temperature and a long summer season can dom-
427 inate over the winter season and vice versa. However, there is no data available to allow us to estimate
428 this effect. Further, our calcite samples have a length of ~ 10 mm and integrate climatic evolution over
429 rather long time periods (e.g. ~ 1 ka) and, thus, cannot catch short-term variations. Therefore, the NGTs
430 capture only temporarily integrated temperature signals.

431 We assign uncertainties of ± 2.1 °C (e.g. standard deviations between the four different ΔT estimates)
 432 to the conversion of July / summer temperatures to annual mean temperatures. We explicitly note that
 433 the assigned uncertainty is not related to the original temperature estimations – in fact most studies do
 434 not quote any errors - but it is related to the conversion of the determined temperature (e.g. summer or
 435 July temperature) to the annual mean temperature.

436 Fig. 4 summarizes our stalagmite-derived NGTs and the converted annual mean temperatures for Milan-
 437 dre Cave inferred from the literature temperatures being scaled to annual mean temperature as described.



438

439 **Fig. 4.** Reconstructed NGTs (solid and open black squares) in comparison with temperature reconstructions from other studies
 440 (colored non-square symbols) scaled to the climatic conditions at the Milan-dre Cave. The error bars of the literature data
 441 represent the combined uncertainties from the small errors (if available) in the original publication and, except for the annual
 442 mean temperatures reported by Magny et al. (2001), from the large uncertainties introduced by scaling of the summer / July
 443 temperatures to annual mean temperature. Dashed lines delineate the upper and lower temperature limits derived from literature
 444 values. The Younger Dryas is visualized by the blue area and is also clearly visible in the sharp negative excursion of $\delta^{18}\text{O}$ in
 445 the M2 stalagmite (Schmassmann, 2010; Häuselmann, 2015). The magnitude of the variation of the $\delta^{18}\text{O}$ record is in agreement
 446 with data from Lake Ammersee (south Germany, von Grafenstein et al., 1998). Open squares represent best NGT guess esti-
 447 mated from Ne and Xe only (see text for further information).

448 The data in Fig. 4 makes the case that all determined NGTs agree with the range of the converted annual
 449 mean temperatures derived from pollen, cladoceran, and from chironomid assemblages in lake sedi-
 450 ments. The Lac Lautrey records (Heiri and Millet, 2005) of the chironomid-based temperature at the end
 451 of Bølling show high temperatures which cannot be compared to our NGTs reconstruction because only
 452 samples of younger age are included (depth < 225 mm, Fig. 4). Our NGTs indicate for the Allerød and

453 the earlier part of the Younger Dryas annual mean temperatures at the lower margin of the converted
454 published temperature estimates, i.e. 1.8 ± 1.5 to 2.6 ± 2.2 °C during the Allerød and 0 (\pm) 2 °C at the
455 onset of the Younger Dryas. While the temperature difference at the transition Allerød – Younger Dryas
456 corroborates previous results, the absolute temperatures reconstructed from noble gases are systemati-
457 cally lower than annual mean temperatures derived from pollen data from Le Locle (Magny et al., 2001).
458 However, both pollen and cladoceran assemblages from Gerzensee (Lotter et al., 2000) indicate the
459 same low annual mean temperatures as our NGTs (for the Allerød – Younger Dryas transition). At the
460 end of the Younger Dryas, noble gas data indicates an annual mean temperature at the Milandre Cave
461 of 6.3 ± 2.6 °C, identical to temperature estimates derived from Le Locle, Lac Lautrey, and Hinter-
462 burgsee data (Magny et al., 2001; Heiri et al., 2003; Heiri and Millet, 2005). The respective temperature
463 increase reconstructed from the sediments of Gerzensee is observed somewhat later, just after the onset
464 of the Holocene. The relatively warm early Holocene temperatures, as seen in the Le Locle record
465 (Magny et al., 2001), stabilized through most of the Holocene at somewhat lower temperatures of around
466 8 °C (with some brief excursions toward lower temperatures, e.g. Heiri et al., 2003). This average Hol-
467 ocene temperature is well reproduced by our maximum temperature estimate from sample M2-047 (8.7
468 ± 2.7 °C at around 2.9 ka BP). This agreement suggests that Xe was completely retained in this sample
469 despite considerable loss of the lighter noble gases. In contrast, the maximum temperature estimate for
470 the most recent sample M2-008 is, with 15.6 ± 6.7 °C, considerably higher (but not outside of 1σ un-
471 certainties) than the annual mean temperature of Late Holocene reported from Hinterburgsee (around
472 10 °C; Heiri et al., 2003). However, the NGT of M2-008 also exceeds temperature measurements in
473 Milandre Cave between 2008 and 2010. Therefore, it must be assumed that M2-008 has not only signif-
474 icantly lost Ne, Ar, and Kr, but was also subject to substantial Xe loss.

475 **4.3. The significance of temperature ranges at given times in the past**

476 Generally, the different paleo-temperature records in Fig. 4 agree well, both in absolute temperature
477 values as well as in temperature variations between different time periods. However, the various tem-
478 perature estimates at specific times in the past cover a considerable range. For instance, the estimated
479 annual mean Allerød temperature in the studied area range between 1 and 8 °C. At the transition Younger

480 Dryas – Holocene, the observed temperature spread is even larger. We are tempted to argue that the
481 observed temperature range / scatter neither has a paleo-climatic meaning, nor does it indicate any sys-
482 tematic problem with one or other method to reconstruct past temperatures. Instead we emphasize that
483 the systematic uncertainties associated with the applied temperature scaling (e.g. conversion of summer
484 / July temperature to annual mean temperature) cannot be properly quantified and might, therefore, ac-
485 count for the observed temperature spread. Possible causes of these uncertainties are discussed in the
486 following paragraphs.

487 A major uncertainty is introduced if different ‘types of temperatures’ (i.e. July or summer temperatures)
488 are converted to annual mean temperatures (or vice versa) as was required to directly compare that
489 different data sets. Due to the lack of robust estimates of the difference of summer / July temperature
490 and the respective annual mean temperature (ΔT , see above), the ΔT s used in our study are estimated
491 from the present situation in Switzerland or from more continental regions showing a larger annual
492 temperature variation (see section 4.2.). Although the associated error of the applied temperature scaling
493 is large, small-scale regional or temporal variability of the paleo- ΔT might still not fully cover the pre-
494 vailing ΔT in the past.

495 A similar argument holds for the applied summer and annual mean adiabatic lapse rates of 0.6 and 0.5
496 °C / 100 m, which we used to scale the temperature estimates to the same altitude, i.e. that of the Milan-
497 dre Cave. We assume that these present-day lapse rates were not markedly different from those in the
498 past, i.e. that they are insensitive with respect to different climatic studies of the past. This assumption
499 is supported with results of a recently comprehensive study (Mauri et al., 2015), which used the present-
500 day topographic lapse rate to reconstruct past climate on different landscapes. However, the uncertainty
501 introduced by this assumption cannot be easily quantified and is, therefore, not accounted for by our
502 applied scaling exercise.

503 Another well-known difficulty is to properly tune different records in terms of chronology. Most studies
504 do not explicitly give information on different records (sediment cores, stalagmites), different time res-
505 olutions and age uncertainties. Neither, the numbers of tie points where absolute ages are available is

506 essential for the accuracy of the respective age model, were not available. In addition, methods to re-
507 construct past temperatures require different amounts of sample material, i.e. each sample integrates
508 over a different time range, which constrains the direct comparability of different data. Therefore, in our
509 point of view, the large deviation of the observed temperature estimates for the Younger Dryas – Holo-
510 cene transition simply reflects an irregular temporal trend of the past temperature increase towards the
511 early Holocene resulting from comparing different climatic records.

512 **4.4. Loss of noble gases from recently precipitated stalagmite samples**

513 As discussed above, the youngest sample (M2-008) has experienced substantial loss of noble gases from
514 its water inclusions. A more moderate loss of noble gases is also observed for the second youngest
515 sample (M2-047). As discussed in section 3.2.2., noble gas loss most likely occurs during sample pro-
516 cessing under vacuum conditions. In contrast, samples older than 10'000 years BP have completely
517 retained water and noble gases in their inclusions and thus yield reliable NGTs. A similar observation
518 has been made earlier on a large NGT data set of very old and recently precipitated stalagmite samples
519 from Borneo (Meckler et al., 2013, 2015). Therefore, we hypothesize that a reduced retentivity for noble
520 gases in recent stalagmite samples during sample processing is a general feature of recent calcite pre-
521 cipitates. In spite of the fact that the available NGT data set on recent stalagmite samples is still very
522 small, we conclude that some kind of secondary diagenetic process occurring later than the original
523 trapping of the fluid inclusion strengthen (e.g. by progressive cementation) the crystal fabric of the stal-
524 agmite with increasing time. However, because such a secondary process is not yet operational for the
525 most recent part of the stalagmite, the calcite structure of the recently precipitated stalagmite is still
526 weak and thus is prone to gas (and water) loss during noble gas extraction by the CVCS technique. Frisia
527 et al. (2018) add some evidence to our hypothesis that early diagenetic processes operate within the first
528 few centimeters below the active growth layer. In this uppermost zone, fluid can circulates within spe-
529 leothems and change the properties of the original calcite fabrics (see more details: Frisia et al., 2018).
530 This early diagenetic processes seem to influence the growth of the calcite, and thus might have pro-
531 found effects on preservation of the initial crystal structure. Therefore, we speculate that such calcite

532 structure seems not to ‘strong / rigid’ enough to preserve the original noble gases signature within fluid
533 inclusions.

534 **5. Summary**

535 We have applied for the first time our CVCS technique to determine noble gas temperatures in a stalag-
536 mite grown under cold climatic conditions. Determination of past cave temperatures based on noble gas
537 concentrations in speleothem fluid inclusions by using the CVCS system has so far only been shown to
538 be reliable for stalagmites grown under warm / hot climatic conditions. The investigated stalagmite M2
539 indicates annual mean temperatures in the Milandre Cave (Swiss Jura Mountains) of 2.2 ± 1.8 °C (av-
540 erage of M2-214 and -199) at the end of the Allerød Interstadial and drop to 0 (\pm) 2.6 °C (average of
541 M2-192 and -179) in the early part of the Younger Dryas. These temperatures indicate conditions near
542 to the freezing point of water during the first part of the Younger Dryas with reduced stalagmite growth.
543 The mean annual temperature increases towards the Younger Dryas – Holocene transition to 6.3 ± 2.3
544 °C, and a temperature of around 8.7 ± 2.7 °C is inferred from a late Holocene sample, very similar to
545 modern cave air temperatures of 9.56 ± 0.15 °C at the sampling site of stalagmite M2. Our determined
546 NGTs agree very well with (scaled) annual mean temperatures derived from pollen, chironomid, and
547 cladoceran assemblages from sediment cores of lakes and from sites located within a 120 km radius
548 from the Milandre Cave. Differences between the various temperature reconstructions are mainly at-
549 tributed to the difficulty of converting the published paleo-temperatures to annual mean temperatures,
550 and to the difficulty of arranging the temperatures from various paleo-climate records in accurate chron-
551 ological order. However, we note that the rescaling exercise is only used to validate our temperature
552 reconstruction of noble gases with other temperature reconstructions. We are well aware that the details
553 of rescaling different temperature reconstruction techniques to a common basis (e.g. summer tempera-
554 ture to annual mean temperature) calls for further investigation. Gas losses observed in two recently
555 precipitated stalagmite samples are most likely experimentally caused during sample processing. The
556 depletion is too substantial to derive meaningful temperature information from the resulting noble gas
557 data. Reduced retentivity for noble gases in recently precipitated stalagmite samples is not only observed
558 in the investigated stalagmite M2, but also in stalagmites from Borneo (Meckler et al., 2015). Thus, this

559 phenomena seems to be an inherent feature of recently precipitated stalagmite samples. We hypothesize
560 that the underlying cause might be related to an incomplete diagenetic processes that stabilizes or seals
561 the structure of the calcite fabric during stalagmite growth. This observation calls for further investiga-
562 tion to clarify this issue in order to evaluate if such constraint not only limits NGT determination, but
563 also affects other methods being used to retrieve past climate information from fluid inclusion of stal-
564 agmites (e.g. δD analysis in water inclusions).

565 With the exception of the recently precipitated stalagmite samples, with this study we have now estab-
566 lished noble gas thermometry as a valid and operational tool to reconstruct paleo-temperatures for stal-
567 agmites grown under a large range of climatic conditions from hot – arid (Vogel et al., 2013a) over hot
568 – humid (Meckler et al., 2013, 2015) to cold environmental conditions (this study).

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