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1 **Hydrological study of Lyngmossen bog, Sweden: isotopic tracers (${}^3\text{H}$, $\delta^2\text{H}$ and $\delta^{18}\text{O}$) imply**
2 **three waters with different mobilities.**

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15

16

17 **Abstract**

18 The ${}^3\text{H}$ concentration and stable isotope ratio of hydrogen and oxygen, δD and $\delta^{18}\text{O}$,
19 of waters extracted from a *Sphagnum*-dominant raised bog in Lyngmossen, Sweden, were
20 measured in order to understand where the precipitation is retained and how mobile it is. Three
21 types of waters, which were defined by extractability, were collected from the peat. Two waters
22 were extracted by compressing samples with different pressures (SQW1 and SQW2). The other
23 water was obtained by distilling the compressed samples (DW). ${}^3\text{H}$ was detected in all types of
24 water from depths of 0-50 cm: the concentrations in SQW1, SQW2 and DW ranged 1.17-3.07
25 Bq/L, 0.98-2.03 Bq/L, and 1.02-1.54 Bq/L, respectively. The maximum ${}^3\text{H}$ concentrations of

26 SQW1, SQW2 and DW were all detected at a depth of around 15 cm, whose ^{14}C age covers the
27 year of the atomic bomb experiments. The ^3H results of SQW1/2 indicate that SQW consists of
28 at least two waters of different mobility, water flowing rapidly downward and immobile water.
29 *Sphagnum* hyaline cells may be responsible for the immobile water.

30 The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ relationship exhibited independent trends between SQW and DW.
31 The distinct difference observed between the two waters at the surface (0-5 cm) indicates that
32 the two waters may be supplied by precipitation at different times of the year, or alternatively
33 that DW comprises plant water taken in from hyaline cells. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of both
34 SQW and DW in the shallow layer increased with increasing depth, and in the layer around 30
35 cm depth, those of SQW showed a distinct decrease with depth. Isotope fractionation caused by
36 evaporation and/or plant utilization of water at the surface layer are considered to be the main
37 causes of such isotopic variation at the surface. Evaporation is likely to take place in much drier
38 conditions for DW than for SQW, probably through stems by capillary action. In SQW freezing
39 may be a possible cause for the decrease of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ around 30 cm depth. DW is
40 isotopically very well separated from two SQW1/2.

41 Integrating all isotopic information, we conclude the presence of three different
42 waters: least mobile water at shallow depth perhaps in hyaline cells, which can be extracted by
43 squeezing peat with low pressure; most mobile water in a deeper layer than 30 cm, extracted
44 also by squeezing peat; mobile but least extractable water, which is likely water inside plant
45 tissues.

46

47 **1. Introduction**

48 Since some peat bogs may accumulate organic matter more than 10,000 years, peat
49 bog organic layers have the potential to extract past climatic information (Heusser, 1990; White
50 et al., 1994; Akagi et al., 2004; Beerling et al., 2009; Yasuda et al., 2015). The isotopic
51 composition of hydrogen and oxygen of cellulose in peat has been utilized for extracting past
52 paleoenvironmental information, such as temperature, humidity, etc. (Brenninkmeijer, 1983;
53 Aucour et al., 1996; Hong et al., 2000; Pendall et al., 2001; Daley et al., 2010; Loader et al.,
54 2016). Those studies have introduced an implicit assumption that the water utilized by plants is
55 precipitation at that time of plant growth. This assumption was given a credit to some extent by
56 comparing the hydrogen and oxygen isotope ratios of cellulose of modern *Sphagnum* with those
57 of local precipitation (Daley et al., 2010) or water by the *Sphagnum* (Loader et al., 2016), but
58 there seems to remain unexplainable errors in the comparison. This basic assumption needs to
59 be examined for robust establishment of a *Sphagnum* isotope archive.

60 Peat may be exposed to a wide range of weather from wet to arid conditions.
61 *Sphagnum* species have developed water-storage organs called hyaline cells which store water
62 when water supply is abundant to avoid drying when it is limited (Watson, 1918; Kremer et al.,
63 2004). Hyaline cells are dead cells and the function of water storage is supposed to continue to
64 function after burial. Circulation of water cannot be simple considering the hyaline cells. We are
65 interested in the behavior of water in hyaline cells during accumulation of peat and how
66 strongly water can be retained in the cells. If it is strongly retained for a substantially long time,
67 the water in hyaline can be treated as “fossil water”, i.e., water supplied during *Sphagnum*
68 growth. To understand what hydrogen and oxygen isotopes represent, we have to understand the
69 hydrology of peat composed of *Sphagnum* accumulates.

70 Mažeika et al. (2009) investigated water circulation in peat bogs, simply applying
71 distillation to peat bogs, and reported that downward water flow in bogs is significant based on
72 ^3H vertical profiles. Although water in hyaline cells ought to comprise a significant portion in
73 peats, the role of hyaline cell water is unclear. To understand the hydrology of hyaline cells,
74 hyaline cell water needs to be separately extracted and examined.

75 In this study, we applied three methods to extract water from peat: compression at
76 two different pressures and distillation, in expectation of collecting water in hyaline cells as one
77 of three waters of different retention or extractability levels. We compared ^3H concentrations
78 and $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values among waters of different types to understand the hydrology of a peat
79 bog.

80

81 **2. Methods**

82 **2.1 Core sampling**

83 The study area, Lyngmossen bog, is located in southern Sweden
84 ($57^{\circ}24'\text{N}$, $12^{\circ}22'\text{E}$) (Fig. 1). Several lakes and marshes are scattered within a few kilometers
85 from the sampling point, with Stora Horredssjön Lake located 5 km to the south. Lyngmossen
86 bog is a raised bog and the dominant vegetation comprises *Sphagnum* species such as *S. fuscum*,
87 *S. magellanicum* and *S. rubellum*. Other vegetation includes *Calluna vulgaris*, *Eriophorum*
88 *vaginatum* and *Mylia anomala*. Lyngmossen bog is ombrotrophic and acidic, and precipitation
89 is the exclusive water source in this bog. The annual precipitation in Göteborg ($57^{\circ}42'\text{N}$,
90 $11^{\circ}58'\text{E}$), 50 km northwest of the Lyngmossen bog, is 820 mm/year from 1951 to 2009 based
91 on data from the European Climate Assessment & Dataset (n.d.). Approximately half of the

92 precipitation is in the form of rain and the rest□is snow. With respect to stratigraphy, Franzén
93 (2006) showed that there is high humification and high ash concentration around surface layers.
94 From dry bulk density Franzén (2006) showed the highest decomposition is around 10-20 cm
95 below the surface, a typical stratigraphic pattern of south Swedish raised bogs.

96 The core sample was collected from near the center of the bog on the plateau, where
97 the depth of the bog was approximately 6 m. We selected a site without distinct
98 micro-topographic features. The nearest hollow is more than five meters away at the time of
99 sampling. The acrotelm/catotelm boundary was observed in the 20-30 cm depth sections.

100 A core sample from the top was collected using a 5 cm diameter Russian corer in
101 May 2010. Peat was subdivided into 5 cm sections and water extracted from each section. Each
102 section was first compressed at a lower pressure (2.5×10^5 Pa or below) by hand using a juice
103 squeezer to obtain SQW1, and further compressed at a higher pressure (5×10^6 Pa or above) to
104 obtain SQW2 using a laboratory bench press. After wiping the compressed peat samples with
105 dry paper, water was further collected from the sections cryogenically under vacuum; this
106 distilled water was thus named DW. Some water flowed out during the sampling procedure, and
107 efforts were made to ensure the peat did not come into contact with this water. The reason we
108 sampled three waters of different extractabilities is to get rid of (or at least to evaluate) the
109 influence of such out-flow water (by comparing SQW1 and SQW2), and at the same time to
110 avoid cross-contamination of the least extractable and most extractable waters (thus the
111 “crossover” water is likely to be within SQW2). The pressures applied to squeeze samples were
112 determined as those which would either sample the most readily extractable water or would
113 extract as much as water extractable physically. The weight of SQW1, SQW2 and DW relative

114 to that of the original peat were typically about 50, 40 and 5%, respectively. The remaining 5%
115 was organic matter. For $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analysis, SQW1, SQW2 and DW were extracted from
116 sections every 5 cm between 0-50 cm depth and once every 1 metre at deeper levels between 1
117 to 6 m depth. The remaining organic components of the peat were used for ^{14}C dating.

118 For the ^3H measurement, a large volume of peat samples, greater than 10 kg, was
119 required from each depth to obtain enough amount of water (more than 500 ml) because of DW
120 water, which merely occupies 5% of the total weight. We sampled 30 peat cores separately
121 within one-meter distance from the first core. These 30 samples collected from 5 cm sections of
122 the same depth layer were combined. In each core, the acrotelm/catotelm boundary occurred
123 between 20-30 cm depth. DW samples of every two sections were further combined, because of
124 insufficient amount of each 5 cm DW (less than 500 ml).

125

126 **2.2 ^3H measurement**

127 The extracted water contains a high concentration of organic matters, which
128 interferes with the ^3H concentration measurement. Pretreatment of the water samples were
129 performed following the procedures of Momoshima et al. (2005) and Momoshima et al. (2008).
130 The SQW samples were filtered with membrane filters of 0.45 μm pore size. The filtered SQW
131 and DW were distilled with 0.1 g of sodium peroxide and 0.1 g of potassium permanganate to
132 remove organic matter by oxidation. The distillation was repeated twice. 1 L or 0.5 L of the
133 treated water samples were concentrated to 80 ml with an electrolytic enrichment system
134 (XZ001, Permelec electrode Ltd), into which emulsifier was added. The concentrated solutions
135 were subject to ^3H counting using a low background liquid scintillation counter (LSC LB-5,

136 Aloka Ltd.). For the SQW and DW samples of 1000 ml and 500 ml, precision of the
137 measurements was better than 0.03 and 0.06 Bq/l, respectively.

138

139 **2.3 $\delta^{18}\text{O}$ measurement**

140 $\delta^{18}\text{O}$ values were determined by equilibrating water samples with CO₂ (Epstein and
141 Mayeda, 1953). 2 ml of water sample and CO₂ gas were introduced into flat-bottomed vials and
142 they were allowed to equilibrate for 4 hours at a constant temperature of 26.3 °C. The
143 equilibrated CO₂ was analyzed by a stable isotopic ratio mass spectrometer in dual-inlet mode
144 (VG, SIRA-10, U.K.). A laboratory standard was measured every 5 samples. The analytical
145 uncertainty for $\delta^{18}\text{O}$ was better than 0.05 ‰, after calibrating the laboratory standard against
146 VSMOW and SLAP. Reproducibility of the measurement without standard correction was
147 0.06‰.

148

149 **2.4 $\delta^2\text{H}$ measurement**

150 $\delta^2\text{H}$ values were determined using a Cr reduction system modified from Itai and
151 Kusakabe (2004). 1 µl of water was injected into a Cr reactor at 800°C and was converted to
152 hydrogen gas over 25 mins, which was then admitted to the mass spectrometer (VG, SIRA-10,
153 U.K.). The laboratory standard was measured every ten samples. The analytical uncertainty for
154 $\delta^2\text{H}$ was typically 0.5 ‰, after calibrating the laboratory standard against VSMOW and SLAP.
155 Reproducibility of the measurement without standard correction was 0.7‰. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$
156 results are expressed relative to V-SMOW.

157

158 **2.5 ^{14}C dating**

159 We separated *Sphagnum* for dating, as the presence of long-rooted plants could
160 confound the dates. The remnant of *Sphagnum* was carefully separated with a pair of tweezers
161 from the final peat samples. Collected *Sphagnum* was pulverized with an agate mortar to pass
162 through a 63 μm mesh sieve. From the powdered *Sphagnum*, waxes and oils were removed with
163 a mixture solvent of 100 ml benzene and 50 ml ethanol by soxhlet extraction over 6 hours. 5 mg
164 of the prepared samples were converted to CO_2 and then were reduced to graphite with H_2 . $\Delta^{14}\text{C}$
165 values of the graphite samples were determined by AMS in MALT (Micro Analysis Laboratory,
166 Tandem Accelerator) in Tokyo University, Japan, and the calibrated ages were calculated by
167 using CALIB, the Radiocarbon Calibration Program Rev. 6.0 (Stuiver and Reimer, 1993) before
168 the atomic bomb experiments (ABEs). After the ABEs, the ^{14}C data reported by Hua et al.
169 (2013) were averaged to cover the age range each section represents, and an accumulation year
170 range was determined to consistently explain the accumulation depth. Age determination using
171 the CALIBomb Program (Reimer and Reimer, 2011), often adopted in dendrochronology,
172 assumes one-year coverage for each ^{14}C datum and gave erroneously younger ages. Precision of
173 $\Delta^{14}\text{C}$ measurement of NIST oxalic acid standard (SRM 4990C) was better than 20‰.

174

175 **3. Results**

176 **3.1. Depth-age relationship of the core**

177 The ages determined from the $\Delta^{14}\text{C}$ values of peat samples (Table 1) are shown in the
178 depth-age relationship (Fig. 2). There is an age hiatus at the depth of 20-30 cm. Above this
179 hiatus the peat accumulation rate exponentially changes from 4 to 18 cm/year and below the

180 hiatus the rate is about 8 cm/ year.

181

182 **3.2 Vertical profiles of ^3H concentration of SQW and DW**

183 The results of ^3H concentration are summarized in Table 2 and its vertical profiles are
184 shown in Fig. 3. The ^3H concentration of both SQW1 and 2 exhibited a maximum at the depth
185 of 15-20 cm from the surface, whose $\Delta^{14}\text{C}$ value corresponds to AD1957, and estimated age
186 range includes years of ABEs (Table 1), and the ^3H concentration decreased gradually below 20
187 cm depth. The peak of SQW2 was lower than that of SQW1 and the peak of SQW2 tailed to the
188 deeper layer. The ^3H concentration of DW had a similar variation to those of SQWs, whose
189 maximum appeared at the depth of 10-20 cm and the ^3H concentration was decreased gradually
190 below 20 cm depth. The ^3H concentration of DW is substantially lower than that of SQW, even
191 considering the lower resolution of DW, except for the first 0-10 cm sample. The peaks tail to
192 the deeper layers of 45-50 cm depth in SQW, where the ^{14}C age corresponds to AD 1152 yr
193 (Table 1).

194

195 **3.3 $\delta^2\text{H}$ and $\delta^{18}\text{O}$ profiles**

196 The results of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are summarized in Table 3. The depth profiles of $\delta^2\text{H}$
197 and $\delta^{18}\text{O}$ are shown in Figs. 4a and 4b, respectively. The $\delta^{18}\text{O}$ profiles showed almost no
198 systematic difference among the two SQW samples (SQW1 and 2) for each section. The $\delta^{18}\text{O}$
199 values increased with increasing depth in the layers shallower than 25 cm. The $\delta^{18}\text{O}$ slightly
200 decreases with increasing depth between 20 and 45 cm depths, except for the 30-35 cm sections.
201 $\delta^{18}\text{O}$ values changed only marginally below 1 m depth. A similar trend was also observed in the

202 $\delta^2\text{H}$ profile. The $\delta^2\text{H}$ values of the two SQW samples are again almost identical and also
203 showed a conspicuous variation in the shallow layer, a decrease between 20-40 cm depth and
204 slight increase in the deeper layer, with increasing depth. The DW samples displayed a different
205 profile from that of SQW: $\delta^{18}\text{O}$ values of DW were higher than that of SQW except for the
206 surface sample, while the $\delta^2\text{H}$ values of DW were always lower than that of SQW.

207 The relationship between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ is shown in Fig. 5. Because systematic
208 differences were not seen among two SQWs in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for most depths, the averages of
209 both data are plotted as SQW. As a general trend of SQW, the plots of the shallow layer from
210 surface to 50 cm depth move along a line of a slope of about 6, which is lower than 8 - the
211 Global Meteoric Water Line (GMWL). In detail, the values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ increase gradually
212 from the surface to 25 cm and decrease slightly from 25 cm to 45 cm along a line with a slope
213 of about 6. The data of the deeper layer (depth > 1 m) are plotted to the right of the data of the
214 shallower layer collectively. A closer look discloses two small changes just greater than the limit
215 of accuracy: increase in both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (1-3 m depth); small decrease in $\delta^{18}\text{O}$ and increase in
216 $\delta^2\text{H}$ (4-6 m depth).

217 The data of DW plot separately from those of SQW to the right and downward in the
218 $\delta^{18}\text{O}$ - $\delta^2\text{H}$ diagram except for the 0-5 cm sample, which is plotted far away from the other DW
219 samples. The plot of 0-5 cm ($\delta^{18}\text{O} = -11.20\text{\textperthousand}$, $\delta^2\text{H} = -72.2\text{\textperthousand}$) falls relatively near the Local
220 Meteoric Water Line (LMWL), which was drawn to pass through the seven data of local
221 precipitation (Table 4). However, the next sample of 5-10 cm section is plotted below the
222 LMWL ($\delta^{18}\text{O} = -7.04\text{\textperthousand}$, $\delta^2\text{H} = -60.4\text{\textperthousand}$) and far from the 0-5 cm sample. Plots of other deeper
223 samples scatter around the area of $-7.84\text{\textperthousand} < \delta^{18}\text{O} < -5.60\text{\textperthousand}$ and $-60.4\text{\textperthousand} < \delta^2\text{H} < -51.4\text{\textperthousand}$.

224

225 **4. Discussion**

226 **4.1. How much ${}^3\text{H}$ was supplied to the Lyngmossen bog and how much remains?**

227 A huge spike of ${}^3\text{H}$ was added to the Earth's surface during ABEs. In nature ${}^3\text{H}$ is
228 generated in the atmosphere by nuclear reaction of ${}^{14}\text{N}$ in the atmosphere with fast neutrons in
229 cosmic rays (Radiation Information Network, n.d.). This constitutes the background ${}^3\text{H}$ level of
230 precipitation. This background level depends on latitude and is the higher in the higher
231 latitudinal areas. ${}^3\text{H}$ decays with a half life of 12.32 years and, therefore, in the closed
232 environment, without further supply of ${}^3\text{H}$, the nuclides become almost extinct within 100 years.

233 A good coincidence among the ${}^3\text{H}$ peaks for the three water samples and the $\Delta {}^{14}\text{C}$
234 peaks in organic matter (Fig. 3 and Table 1) indicates that the influence of the ABEs exists at the
235 depth of 15-20 cm, which covers the 1960s, and that the hydrology of the 30 peat cores within
236 one metre are relatively similar to each other. Detection of ${}^3\text{H}$ at the 45-50 section (Fig. 3)
237 implies immigration of recent water to this older layer, since the original ${}^3\text{H}$ in water of the age
238 of the layer (AD1152 yr, Table 1) should have decayed to a negligible level. The discussion on
239 water retention in the layer will strongly depend on the total amount of ${}^3\text{H}$ supplied to the
240 studied bog, whose estimation is made hereafter.

241 It is considered that the ${}^3\text{H}$ level of precipitation has decreased to the natural ${}^3\text{H}$
242 concentration for the last 30 years (Koster et al., 1989; Stimson et al., 1996). The natural ${}^3\text{H}$
243 level is governed by latitude (Weiss and Roether, 1980). For instance, at $60^\circ 18' \text{N}$ in Finland, the
244 ${}^3\text{H}$ concentration of the precipitation in 2009 is 1.26 Bq/L and at $51^\circ 55' \text{N}$ in Ireland it is 0.3
245 Bq/L based on data from Water Isotope System for Data Analysis, Visualization and Electronic

246 Retrieval (WISER) (n.d.). We considered that the natural ${}^3\text{H}$ concentration of the precipitation to
247 Lyngmossen bog ($57^\circ 24\text{N}$) is represented by that of the surface SQW and is 1.1-1.2 Bq/L.

248 We estimated the amount of ${}^3\text{H}$ in local precipitation at Lyngmossen using data
249 reported elsewhere. The nearest observatory is in Göteborg, 50 km northwest of the
250 Lyngmossen bog, but the length of observation time of ${}^3\text{H}$ is very limited (from year 1961 to
251 year 1967). We compared the data in Göteborg ($57^\circ 42\text{N}$, $11^\circ 58\text{E}$) with those in Valentia
252 ($51^\circ 55\text{N}$, $11^\circ 45\text{W}$), Ireland (WISER, n.d.). We found that the correlation was fairly good
253 ($r^2=0.944$) between the monthly ${}^3\text{H}$ concentration raw data in Göteborg and those in Valentia
254 (Fig. 6a). The correlation became better ($r^2=0.978$) when precipitation-weighted annual ${}^3\text{H}$
255 concentrations were compared between Göteborg and Valentia using precipitation data of
256 Göteborg for those of Valentia (Fig. 6b), in which the weighted annual ${}^3\text{H}$ concentrations (wH)
257 in both sites were calculated using the following equation.

258
$$wH = 1/p \sum (p_t \times {}^3\text{H}_t),$$

259 where p represents the annual precipitation; p_t and ${}^3\text{H}_t$ are rainfall amounts and ${}^3\text{H}$ concentration,
260 respectively, for each month. We reconstructed the annual ${}^3\text{H}$ concentration in Göteborg from
261 Valentia ${}^3\text{H}$ concentration data using the relationship shown in Fig. 6b, which is formulated as

262
$$wH_{\text{Göteborg}} = wH_{\text{Valentia}} \times 1.7993.$$

263 We then estimate the accumulated ${}^3\text{H}$ concentration at Lyngmossen in the year of 2010, when
264 we made the ${}^3\text{H}$ measurement, using the reconstructed Göteborg ${}^3\text{H}$ concentration and
265 considering ${}^3\text{H}$ half-life.

266 This calculation is dependent on the length of year the sampled sections represent.
267 The depth-age relationship demonstrates a hiatus around 20-30 cm depth, above and below

which 1 cm section represents about 4-18 and 8 years, respectively (Fig. 2). Because of the presence of this layer of uncertain age, the lengths of time for the 15-20 cm section (for SQW) is similarly unconstrained. The exponential interpretation shown in Fig.2 gives about 90 years coverage for the section. Our calculation shows that, for a 20-year span, water between 1958 and 1977 gives the highest ${}^3\text{H}$ concentration of only 2.7 Bq/L by 2010. The concentration decreases with increasing year coverage. This figure of 2.7 Bq/L is lower than the observed ${}^3\text{H}$ concentration of SQW1 for the 15-20 cm section (3.07 Bq/L) and indicates that the length of time the 15-20 cm section represents should be shorter than 20 years and also that the original water should have been firmly retained in the 15-20 cm section. Paradoxically, this 20 year estimate is considerably shorter than that estimated by the ${}^{14}\text{C}$ data of 90 years. This discrepancy of the time periods given by ${}^3\text{H}$ and ${}^{14}\text{C}$ calculations is mitigated to some extent by the possible bias in the age estimation based on the $\Delta{}^{14}\text{C}$ profile, which sometimes tends to give older than the true ages due to the CO₂ released from deeper peat (Jungner et al., 1995). Nevertheless, this calculation indicates that most of the water supplied during the ABEs should have remained in SQW within the depth of 50 cm. If SQW1 is taken as the standard water that retains ${}^3\text{H}$ in the layer of depth 0-50 cm, SQW2 and DW is considered to have lost a portion and about a half of the water, respectively, although some uncertainty accompanies this calculation due to the unknown baseline profile. If SQW did not migrate in the sampling, the possibility of which will be discussed later, the tailing seen in SQW2 implies that water has moved downwards, but the direction of tailing is not clear in the case of DW.

288

289 **4.2. Indication for strong water retention by hyaline cells**

290 The ${}^3\text{H}$ concentration indicates that SQW1 retains ${}^3\text{H}$ more than SQW2 and that
291 SQW2 retains more ${}^3\text{H}$ than DW, implying that the SQW1 waters are less mobile than SQW2
292 and that SQW2 is less mobile than DW. This means that water of higher extractability is less
293 mobile, which is counterintuitive. Considering the ${}^3\text{H}$ concentration of the present precipitation
294 in Lyngmossen to be 1.1-1.2 Bq/L, to explain the high ${}^3\text{H}$ concentration in SQW at the depth of
295 40 to 50 cm, the SQW should flow there within a few years. However, this fast flow would have
296 washed down most of the ${}^3\text{H}$ from the ABEs in SQW, which is apparently not the case (see
297 Section 4.1). Thus there are incompatible observations which require explanation.

298 Is this extraordinary observation simply a result of analytical artifacts? Sampling of
299 peat cores with a Russian corer includes pressing peat and exuding water, and such water may
300 be re-absorbed by the peat, eventually exchanging the original water with the water of other
301 depths. If this is the case, SQW1 is most vulnerable to this “exchange”, and this “exchange” is
302 more likely to act to diffuse the ABE ${}^3\text{H}$. However, as in Fig. 3, SQW1 showed the
303 sharpest/highest distribution of ${}^3\text{H}$, and its profile tails less than that of SQW2. Also, the
304 unexpected results of the lowest ${}^3\text{H}$ concentration of DW cannot be explained by the exchange
305 with SQW. If detection of ${}^3\text{H}$ in SQW from 40-50 cm depth is a result of the sampling artifacts,
306 the nearly identical concentration of ${}^3\text{H}$ in both SQW1 and SQW2 at that depth (${}^3\text{H}$
307 concentration in SQW1 is even slightly smaller than in SQW2) is difficult to explain. One
308 cannot rule out the possibility of water exchange during sampling, but it does not readily
309 explain any observation. One possible interpretation is that water once squeezed out from peat
310 (probably in hyaline cells as mentioned later) is not re-absorbed by the peat. We judged that
311 sampling artifacts did not seriously affect the results.

312 *Sphagnum* can store a great amount of water in hyaline cells (Bold, 1967; Clymo and
313 Hayward, 1982; Sakaguchi, 1989). The cells are dead cells and may function even following
314 burial of *Sphagnum*. The water in the hyaline cells may be responsible for the presence of the
315 distinct ABE water in the bog. In water-logged conditions, there could be a narrow passage
316 outside hyaline cells in the layer. Further, in dry weather the depth of the water table can
317 decrease as low as 20 cm (Quinty and Rochefort, 2003; Allan et al., 2013), providing a temporal
318 cavity for direct water passage to the deeper layer. We can then assume that there are two waters
319 of contrasting mobility, outside and inside hyaline cells. The water in hyaline cells can be
320 extracted by applying a relatively low pressure (the most typically as SQW1). If the hyaline
321 cells continue to retain water, SQW in the depth of 40-50 cm should have a ^3H concentration as
322 low as zero. The fact that it has a similar ^3H concentration of the SQW to that of the surface
323 layer, however, implies that the hyaline cells have lost their ability to retain water, perhaps by
324 cell degradation, which enabled the rapid exchange of flowing water and static water in the cells.
325 The age hiatus observed in the 20-30 section (Fig. 2) implies a sudden aging of peat at the depth
326 of 20-30 cm perhaps being accompanied with an increasing extent of degradation. The
327 acrotelm/catotelm boundary was observed at the depth of 20-30 cm. It is likely the hyaline cells
328 are intact in the acrotelm layer, where the water retention is physiologically important to
329 *Sphagnum*.

330 Regarding the lower ^3H concentration of DW than that of SQW, approximately half
331 the original water has to flow out from the layer of 0-50 cm depth. The observed difference in
332 ^3H concentration between SQW and DW in the layer of 20-30 cm depth indicates that the
333 exchange of water between the two waters is fairly restricted. This consideration is endorsed by

334 the apparently independent/different $\delta^2\text{H}$ and $\delta^{18}\text{O}$ distribution between SQW and DW in Fig. 5.

335 A considerably lower ${}^3\text{H}$ concentration in DW than that of SQW necessitates the replacement

336 of ABE water by non-ABE water, either *downwardly* or *upwardly*. It is considered that

337 *Sphagnum* stems act as conduits for water to flow through by capillary action, with water in

338 stems being well-separated from SQW. Most capillary action is considered to work externally,

339 outside *Sphagnum* cells (perhaps this explains the mobility of SQW below 40 cm depth in this

340 study), and only 1/100 of the capillary action is reported to work through stems (Proctor, 1982).

341 The growth of upper branches precedes extension of lower stems, which is clearly seen in the

342 outphased variation of $\delta^{13}\text{C}$ variation (Yasuda et al., 2015). It is likely that the water can

343 sometimes flow *upwardly* through *Sphagnum* stems to supply water to elongating stems and

344 capitulum, growth points, especially in dry weather (Fig. 7). This water is likely to be deep, old

345 water with a lower ${}^3\text{H}$ concentration and constitutes a portion of DW in order to explain the

346 lower concentration of ${}^3\text{H}$ in the DW of the 10-20 cm layer than that of SQW at corresponding

347 depth. The somewhat higher ${}^3\text{H}$ concentration in the surface DW than that of lower layer (depth

348 >20 cm) may be explained by small tailing of ${}^3\text{H}$ from the major DW peak (10-20 cm). This

349 interpretation will later be supported by the discussion of $\delta^2\text{H}$ and $\delta^{18}\text{O}$, which suggests

350 intensive evaporation of DW (see Section 4.4).

351

352 **4.3. The mechanism controlling $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in SQW**

353 Three different stages in the variation of $\delta^2\text{H}$, $\delta^{18}\text{O}$ can be identified in SQW (Figs.

354 4a, 4b and 5): 1) Steady increase in both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ with increasing depth (depth 0-25 cm);

355 2) Decrease in both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ with increasing depth (depth 25-45 cm); 3) Decoupled change

356 in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (depth >1 m). In following the three changes are discussed separately.

357 1) Steady increase in both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ with increasing depth (depth 0-25 cm)

358 If the isotope composition of the shallower SQW is explained by the precipitation, the
359 monotonous decrease roughly in parallel with the LMWL ($\Delta\delta^{18}\text{O}$ and $\Delta\delta^2\text{H}$ of about 2.3‰ and
360 14‰) during the last several years (Fig. 5) could correspond to a decrease in temperature of
361 1.5-1.6°C (Dansgaard, 1964; Rozanski et al., 1992). This monotonous temperature change,
362 however, has not been observed in the data from Koninklijk Netterlands Meteorologisch
363 Instituut (KNMI) Climate Explorer (n.d.).

364 Based on the ${}^3\text{H}$ profiles and $\delta^2\text{H}$ - $\delta^{18}\text{O}$ relationship between SQW and DW, the two waters,
365 especially shallower than 25 cm, are isotopically separate (Fig. 5). Therefore, the influence of
366 DW is likely too small to explain the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data of SQW. Some SQW water may be
367 located in hyaline cells and the water should have firmly retained the original ${}^3\text{H}$ supplied by
368 precipitation, in other words, movement of water from a hyaline cell to another seems to be
369 prohibited. The three possible ways to explain both the $\delta^2\text{H}$ - $\delta^{18}\text{O}$ relationship of SQW as well as
370 ${}^3\text{H}$ retention are:

371 a) Evaporation: Remaining water following evaporation is enriched in the heavier isotopes due
372 to kinetic fractionation. During evaporation $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of water change following
373 $\Delta\delta^2\text{H}/\Delta\delta^{18}\text{O} < 8$, depending on humidity. The water in deeper hyaline cells may have
374 experienced more intensive evaporation.

375 b) *Sphagnum* water utilization: When *Sphagnum* use water in metabolic reactions, it is likely
376 that lighter water molecules are more favorably utilized, leaving a residue of heavier water.
377 The extent of water utilization may be greater with the time of burial.

378 c) Varying contribution of hyaline water to SQW: Water in hyaline cells may be supplied in
379 relatively cold weather (when $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are relatively low) and that in outside hyaline
380 cells are supplied in a warm and wet weather (when $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are relatively high). The
381 contribution of water in hyaline cells decreases with deterioration of the cells at increasing
382 depths by being diluted with flowing water.

383 The distinct ${}^3\text{H}$ profile of SQW requires that the most of this water is preserved in
384 hyaline cells in the section of 15-20 cm depth. Thus, a steady increase in both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in a
385 layer shallower than 20 cm seems incompatible with the third interpretation (c). Both the other
386 two interpretations (a) and (b) seem to explain the observation. In evaporation processes,
387 $\Delta\delta^2\text{H}/\Delta\delta^{18}\text{O}$ depends on humidity. The slope seen in the variation in the 0-15 cm layer is around
388 6 (Fig. 5), implying that the process might have proceeded in rather humid conditions (Kendall
389 and Coldwell, 1998). Regarding the second interpretation (b), water in hyaline cells should be
390 absorbed through the cell walls, which are dead, only passively by diffusion along a moisture
391 gradient and then are likely transported to the capitulum through stems. The difference between
392 DW (likely in stems) in the top layer and SQW (likely in hyaline cells) in the shallow layer is
393 explainable by the water utilization as indicated by the arrow in Fig. 5.

394 2) Decrease in both $\delta^2\text{H}$, $\delta^{18}\text{O}$ with depth increase (depth 20-45 cm)

395 The Lyngmossen bog experiences surface freezing every year. The equilibrium
396 fractionation of $\Delta\delta^{18}\text{O}$ and $\Delta\delta^2\text{H}$ observed experimentally between ice and water are
397 $2.91 \pm 0.03\text{\textperthousand}$ and $21.2 \pm 0.4\text{\textperthousand}$, respectively (Lehmann and Siegenthaler, 1991). This
398 experimental $\Delta\delta^2\text{H}/\Delta\delta^{18}\text{O}$ ratio (7.3) is close to that observed for the first 25 cm layer (approx. 6,
399 Fig. 5) to a certain degree, but the freezing process cannot be the main mechanism for change of

400 the the 0-25 cm layer considering strong immobility inferred from the ${}^3\text{H}$ profile of SQW. One
401 of the authors, L. F., observed that the depth of freezing is around 20-30 cm. The $\delta^{18}\text{O}$ and $\delta^2\text{H}$
402 values of SQW from the depth of 25-30 cm are slightly lower than that of the depth of 20-25 cm
403 (Figs. 4 and 5). This may be caused by the enrichment of ${}^{18}\text{O}$ and ${}^2\text{H}$ in ice in the section at the
404 depth of 20-25 cm against the unfrozen water in the section of 25-30 cm or lower. This
405 interpretation requires that the water in hyaline cells in the layer deeper than 25 cm is mobile. It
406 is compatible with our discussion based on ${}^3\text{H}$ profile of SQW that hyaline cells are considered
407 to lose high water retention at depths greater than 20 cm. (Section 4.2). Incidentally it is
408 interesting to note that freezing must not have reduced the water retention capacity of hyaline
409 cells.

410 3) Decoupled $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (depth > 1 m)

411 Only small changes observed at this depth imply that there are no influential
412 processes which would modify the isotopic composition of water. A closer look at the variation
413 in Figs. 4a, b and 5 identifies two small variations: increase in both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (depth = < 3
414 m); increase in $\delta^2\text{H}$ and decrease in $\delta^{18}\text{O}$ (depth > 4 m). Regarding these variations, three
415 possible causes can be proposed: a) Exchange of oxygen with silicate minerals; b)
416 decomposition of organic matter modifying the $\delta^{18}\text{O}$ of water; c) free movement between DW
417 and SQW. The first and second interpretations (a and b) would explain the shift of plots to the
418 right in Fig. 5. The second interpretation (b) may be very unique to long lasting water in peat
419 bogs. Organic matter can be decomposed through glycolysis and the TCA cycle under aerobic
420 conditions or processes of glycolysis and acetic acid formation under anaerobic conditions.
421 During glycolysis, water molecules are produced using oxygen from the organic substrates,

422 which typically have much higher $\delta^{18}\text{O}$ from 20 to 30‰ (Kahmen et al., 2011). Hydrogen in the
423 water is likely from phosphoric acids. This mechanism may explain the decoupled behavior of
424 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of SQW. Around 1/10 of SQW water produced by these processes may explain the
425 observed shift in $\delta^{18}\text{O}$. Regarding the last possible interpretation (c), during decomposition of
426 plant tissues, the water of DW may be able to mix with SQW. However, if this were the case,
427 the observed steady increase in $\delta^2\text{H}$ is difficult to explain. Also SQW water is about 20 times the
428 volume of DW, so any effects caused by mixing with DW will be minor. Due to the paucity of
429 relevant information some of this discussion is rather speculative.

430 **4.4. The mechanism of controlling $\delta^{18}\text{O}$ and δD in DW**

431 The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of surface DW are located near a lower position
432 along the meteoric line than that of the surface SQW (Fig. 5) and indicate that the original DW
433 may have been supplied at lower temperatures than SQW. In this case, *Sphagnum* might have
434 grown in wet conditions with snow-melt water of low temperature origin (both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ are
435 low) when the temperature becomes higher in spring. Water utilization of lighter water by plants
436 is an alternative interpretation. In this case, water in subsurface hyaline cells rather than water in
437 stems may be regarded as a residue of the originally supplied water, considering $\Delta\delta^2\text{H}/\Delta\delta^{18}\text{O}$ of
438 water utilization (Fig. 5). For deeper and older peat layers, the independent distribution of DW
439 from that of SQW indicates that negligible exchange has occurred between SQW and DW.

440 $\Delta\delta^2\text{H}/\Delta\delta^{18}\text{O}$ during the evaporation of water is reported to be less than 8 and this
441 ratio depends on humidity during evaporation (Kendall and Caldwell, of 1998; McGuire and
442 McDonnell, 2007). The marked change observed in the isotopic composition of DW of
443 subsurface layer compared with the immediate surface is considered to be due to evaporation,

444 since the slope of the change is smaller than 5. A slope lower than 5 implies that the evaporation
445 may have proceeded in very low humidity as low as 20% (McGuire and McDonnell, 2007).
446 This humidity is much lower than that experienced by SQW. It is likely that DW experienced
447 intensive evaporation at very low but fluctuating levels of humidity to explain the scattered data.
448 Stems support the capitulum of *Sphagnum*, which is the growth point and usually higher than
449 the peat layer. This structural feature may explain the lower humidity DW has experienced. The
450 ^3H study implies that DW may have flowed upwardly at times. Intensive evaporation may be
451 favorable for upward flow.

452 DW water may also be subject to $\delta^{18}\text{O}$ modification due to decomposition of organic
453 matter similarly to SQW, but its effect might not be evident due to the rather scattered $\delta^2\text{H}$ and
454 $\delta^{18}\text{O}$ values of DW.

455

456 **Conclusions and implications for paleoclimatic studies**

457 Three waters of different of levels of mobility and perhaps flow direction were
458 identified using ^3H , $\delta^2\text{H}$ and $\delta^{18}\text{O}$. The least mobile water in the peat was that obtained by
459 compressing peat with a hand squeezer (SQW1). Water stored in hyaline cells was likely to be
460 extracted by compressing peat samples with a relatively low pressure. This water still records
461 the high ^3H activity released to the atmosphere by the atomic bomb experiments. However, the
462 same process of squeezing extracted rather mobile water in deeper layers. It is likely that
463 hyaline cells lose their retentive properties during burial. The application of squeezing to obtain
464 pristine fossil water in hyaline cells seems therefore to be valid only in shallow layers, but the
465 isotopic composition of the water in hyaline cells seem to have altered by evaporation and/or

466 plant utilization.

467 The water extracted from the squeezed peat by distillation (DW) is isotopically very
468 different from the water obtained by squeezing (SQW). DW water is different from SQW in
469 terms of temperature of precipitation and in the conditions of evaporation. DW seems to have
470 experienced the most intensive evaporation among the three waters based on the $\delta^2\text{H}$ and $\delta^{18}\text{O}$
471 relationship.

472 In total three different waters are identified in peat (Fig. 7), implying a more
473 complicated hydrology in peat than previously considered. Hyaline cells are major reservoirs of
474 peat water in the layers < 20 cm and should represent more than 90% of water in the peat. The
475 cells hold water very firmly for more than 50 years without exchanging free water, while the
476 hyaline cell walls are intact. The cells lose high water retentivity in deeper layers probably
477 beneath the acrotelm/catotelm boundary at the depth of 20-30 cm. The water beneath the
478 boundary can be supplied directly from precipitation and move downwards and thus may
479 sometimes be newer than overlying water. The water most likely utilized by *Sphagnum* at the
480 top can be supplied through stems, to which water stored in deeper hyaline cells may be
481 supplied by diffusion and/or even deeper water beneath the acrotelm/catotelm boundary by
482 capillary action. The water seems to be disconnected from water outside the plants. The
483 circulation of the water in a shallow peat seems rather complicated following our investigation,
484 and it can be significantly older than the newly-supplied water via precipitation. If the water is
485 supplied by capillary action from the deeper water pools of relatively heavier isotopes, the
486 isotope signature of water utilized by *Sphagnum* should depend on the humidity of the
487 environment. This consideration would lead to the increase in $\delta^2\text{H}$ and $\delta^{18}\text{O}$ at high temperature

488 and low humidity. Physiologically high temperature increases growth rates (Yasuda et al., 2015),
489 resulting in lesser discrimination for lighter isotopes and low humidity is believed to suppress
490 diffusion of water again resulting in lesser discrimination (Rice and Giles, 1996). Therefore, our
491 interpretation may work as an exaggeration of physiological control, which is in a good
492 agreement with recent observation using modern *Sphagnum* (Loader et al., 2016).

493 DW water in peat is a possible candidate for a paleoclimate archive. The isotope
494 ratios of DW may likely record the extent of evaporation in the past and the record can be
495 protected from the exchange of flowing water. However, extra caution and further study are
496 required in using isotopes for climatic information in the past, as the water used by plants may
497 not be the water directly supplied by precipitation.

498

499 **Acknowledgement**

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501

502 **Footnote**

503 This study was implemented in search for fossil water, the water supplied by
504 precipitation at the time of *Sphagnum* growth. This idea was hatched by Lars Franzén, who has
505 passed away during the preparation of manuscript. We would like to dedicate this paper to L.F.

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606 Figure and Table Captions

607 Fig. 1 A map of the study site, Lyngmossen peatland in Sweden and the position of Valentia in
608 Ireland, where the reference data of ${}^3\text{H}$ in precipitation is available.

Fig. 2 Depth-age relationship of the studied peat core. The right figure is the magnified relationship of the upmost 50 cm layer. The broken line represents the linear relationships for the deeper (30-615cm) layers. The broken curve is the exponential interpretation of the peat accumulation rate in the shallow layer (0-25cm), which gave the rate of 15 cm/year at the depth of 17.5 cm.

614 Fig. 3 Vertical ${}^3\text{H}$ profile among each sample type. Circles, squares and crosses represent
615 SQW1, SQW2 and DW, respectively.

616 Fig. 4 The depth profile of $\delta^2\text{H}$ (a) and $\delta^{18}\text{O}$ (b) for SQW1 (open circles), SQW2 (closed circles)
 617 and DW (crosses).

618 Fig. 5 The $\delta^{18}\text{O}$ - $\delta^2\text{H}$ relationship of average SQW (circles), DW (crosses), precipitation
 619 (diamonds) and surface water (triangle). Solid line indicates LMWL defined by
 620 precipitation (a). Fig. 5(b) represents a magnified portion of Fig. 5(a). Solid and broken
 621 arrows are evaporation and utilization lines, respectively.

622 Fig. 6 Comparison of ${}^3\text{H}$ concentration of precipitation between Valentia and Göteborg. (a)
623 Correlation of the monthly ${}^3\text{H}$ concentration raw data in Valentia and Göteborg. Units
624 are TU (Tritium Units). (b) Relationship between the estimated annual ${}^3\text{H}$ concentration
625 in Valentia and Göteborg. Note that annual precipitation data of Göteborg were used for
626 Valentia as well.

627 Fig. 7 Illustration showing the presence of three types of water with different mobilities in peat

628 bog, inferred from this study (a). 1) Water in hyaline cells explains extremely immobile
629 water above 20 cm depth. It was extracted as SQW. 2) Rapidly flowing water comprises
630 of a part of SQW. This water is likely to be outside of hyaline cells. 3) Water inside
631 plant tissues extracted as DW. This water is more mobile than water in hyaline cells and
632 sometimes flows upwardly in dry conditions probably through *Sphagnum* stems. We
633 consider that water 2) is introduced to a peat layer at a time of low water table (b),
634 where *Sphagnum* individuals are vertically prolonged due to the removal of a burden of
635 water.

636

Table 1 $\Delta^{14}\text{C}$ and calibrated ^{14}C age of peat core.

Depth (cm)	$\Delta^{14}\text{C}$ (‰)	Calibrated year (yr)
0-5	33±11	AD 2007-2009 (AD 2008 ± 1)
5-10	84±11	AD 1996-2007 (AD 2002 ± 3)
10-15	223±13	AD 1975-1995 (AD 1984 ± 1)
15-20	114±12	AD 1900-1975 (AD 1957 ± 1)
20-25	-29±10	AD 1800 ± 150
25-30	-28±10	AD 1802 ± 148
30-35	-72±10	AD 1375 ± 67
35-40	-92±10	AD 1268 ± 49
40-45	-104±14	AD 1162 ± 120
45-50	-108±10	AD 1152 ± 104
100-105	-146±18	AD 823 ± 158
150-155	-206±4	AD 259 ± 82
200-205	-249±8	BC 300 ± 96
270-275	-276±4	BC 672 ± 117
500-505	-383±7	BC 2299 ± 156
570-575	-414±7	BC 2780 ± 141
610-615	-425±6	BC 3108 ± 204

Before the ABEs, the ages are calculated using the Radiocarbon Calibration Program (Stuiver et al., 2017).

After the ABEs, the ages are shown for the year ranges to give the mean ^{14}C activity that is consistent with peat accumulation. The ages calculated using the CALIBomb Program (Reimer and Reimer, 2011) are also shown in brackets and are erroneously young (see text).

Table 2 ${}^3\text{H}$ concentration of water of peat core in shallow layer (< 50 cm). Unit: Bq/L

Depth (cm)	SQW1	SQW2	DW
0-5	1.20	1.14	
5-10	1.17	1.13	
10-15	1.17	0.98	
15-20	3.07	2.03	
20-25	2.16	1.67	
25-30	1.50	1.75	
30-35	1.41	1.70	
35-40	1.39	1.48	
40-45	1.35	1.42	
45-50	1.33	1.41	
0-10			1.12
10-20			1.54
20-30			1.02
30-40			0.95
40-50			1.02

Uncertainty of ${}^3\text{H}$ concentration is 0.03 Bq/L for SQW and 0.06 Bq/L for DW.

Table 3 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of SQW and DW.

Depth (cm)	SQW1		SQW2		DW	
	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)
0-5	-9.54	-53.94	-9.52	-54.11	-11.20	-72.25
5-10	-8.53	-48.90	-8.12	-46.99	-7.04	-60.41
10-15	-8.30	-45.31	-8.20	-45.52	-7.84	-57.95
15-20	-7.88	-43.31	-7.83	-43.35	-6.69	-52.17
20-25	-7.24	-41.35	-7.37	-41.53	-6.77	-50.52
25-30	-7.60	-43.15	-7.52	-43.25	-6.79	-52.18
30-35	-7.31	-43.81	-7.12	-44.68	-6.80	-55.10
35-40	-7.57	-44.35	-7.63	-44.25	-7.50	-53.88
40-45	-7.69	-44.52	-7.69	-44.67	-6.95	-46.05
45-50	-7.68	-43.89	-7.67	-44.57	-7.27	-56.57
100-105	-7.00	-43.18	-7.28	-43.58	-6.50	-44.11
200-205	-6.12	-43.57	-6.87	-42.98	-5.76	-50.52
300-305	-6.75	-42.22	-6.68	-43.18	-5.60	-57.07
400-405	-6.89	-42.17	-7.01	-42.80	-6.47	-55.26
500-505	-6.95	-42.47	-7.00	-41.96	-5.95	-51.47
600-605	-6.94	-40.84	-6.93	-42.22	-7.06	-51.64

Table 4 $\delta^{18}\text{O}$ and δD of precipitation in 2010 and surface water.

Sample Name	$\delta^{18}\text{O}$ (‰)	δD (‰)
Precipitation (June)	-7.63	-40.79
Precipitation (July)	-3.86	-23.83
Precipitation (August)	-5.86	-41.69
Precipitation (September)	-9.01	-51.79
Precipitation (October)	-4.20	-17.51
Precipitation (November)	-5.92	-26.18
Precipitation (December)	-19.66	-108.97
Surface water 1	-8.91	-48.76
Surface water 2	-9.55	-52.88
Surface water 3	-8.88	-48.53

Precipitation in December is snow. The other precipitation samples are rain.

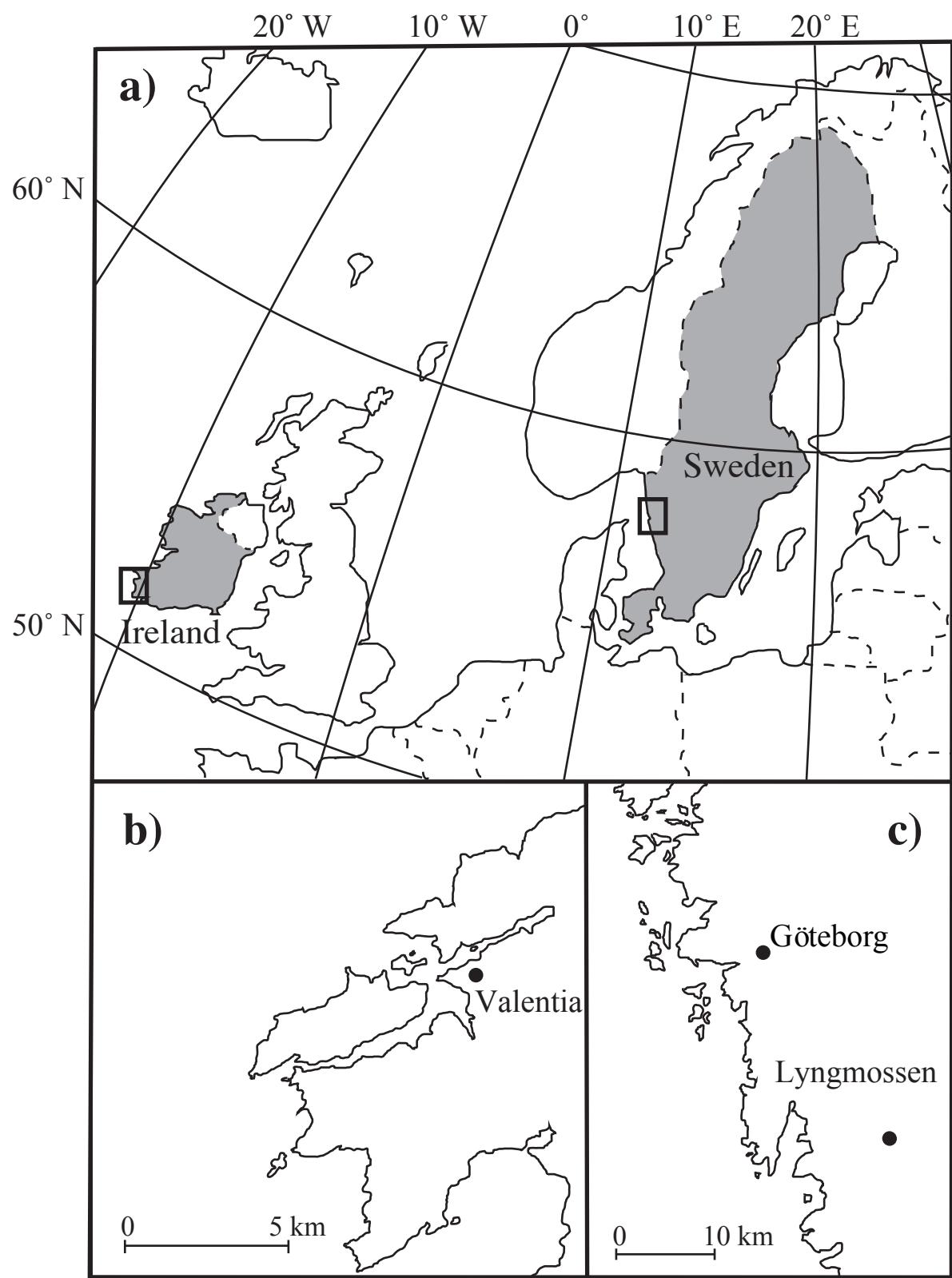


Fig. 1 Ooki et al.

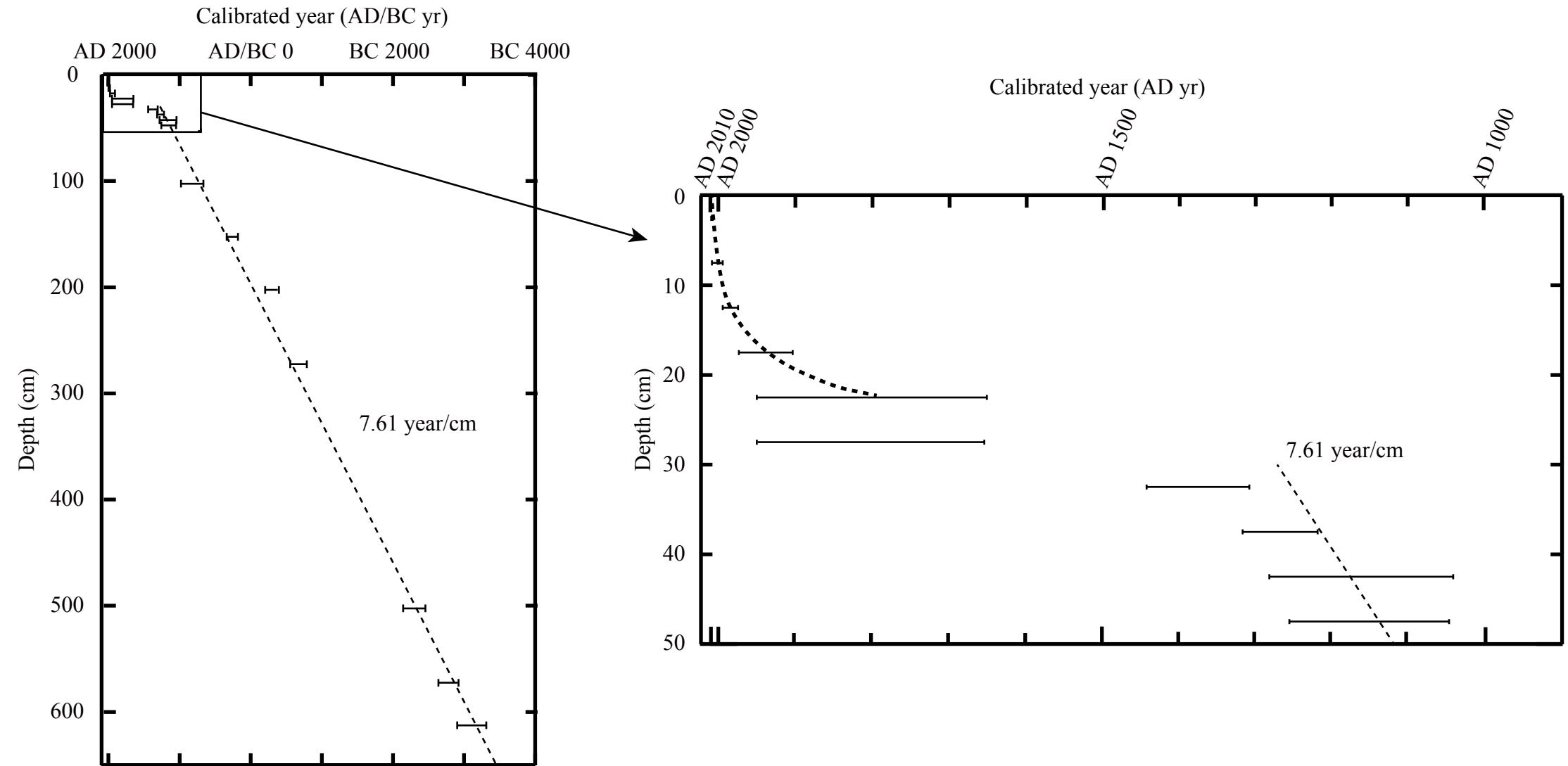


Fig. 2 Ooki et al.

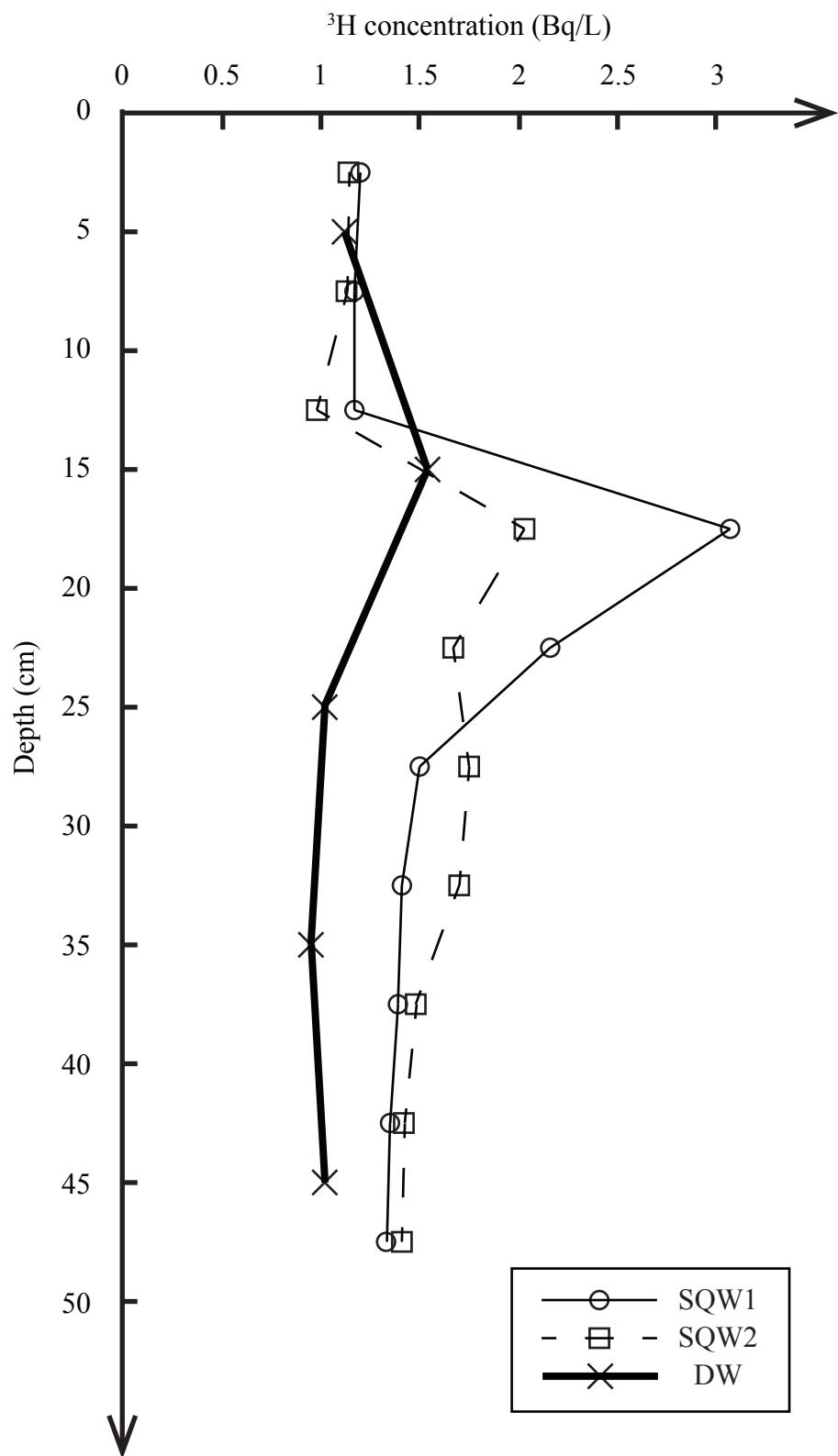


Fig. 3 Ooki et al.

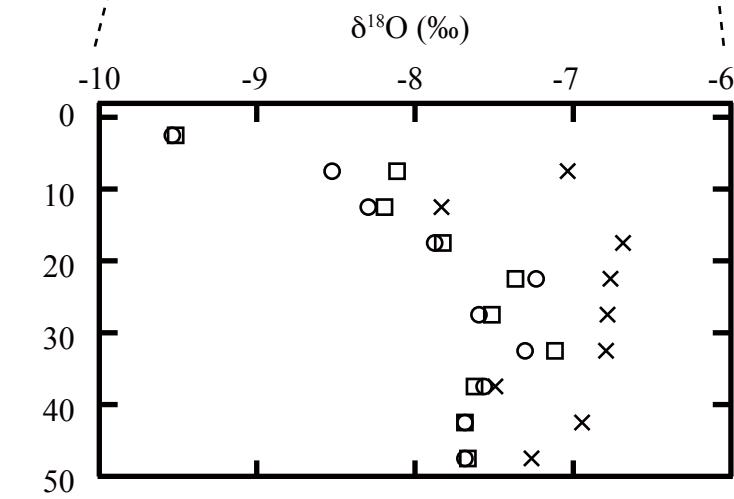
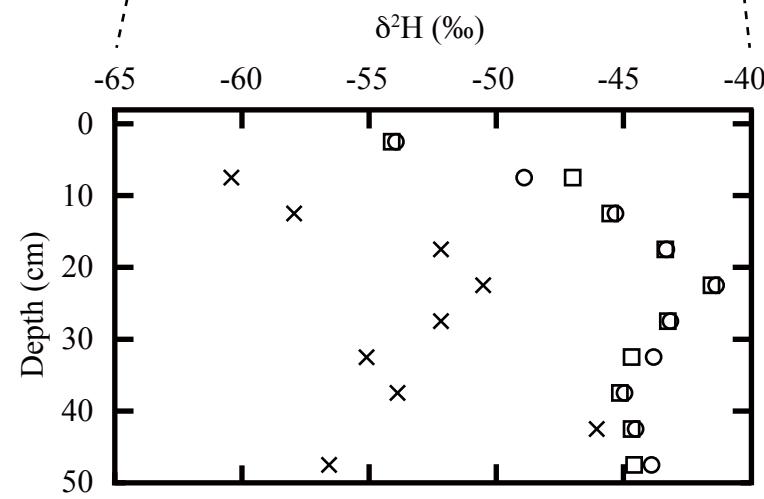
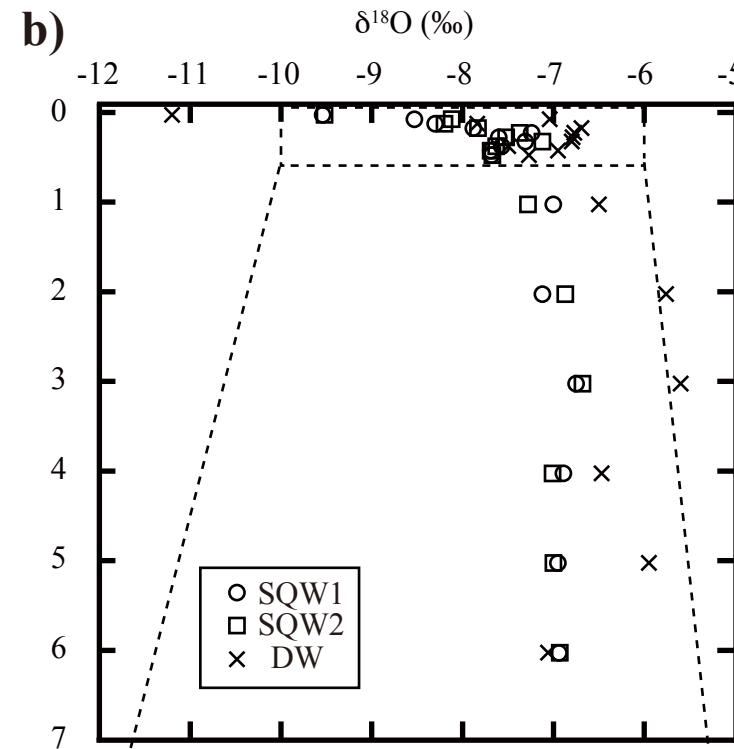
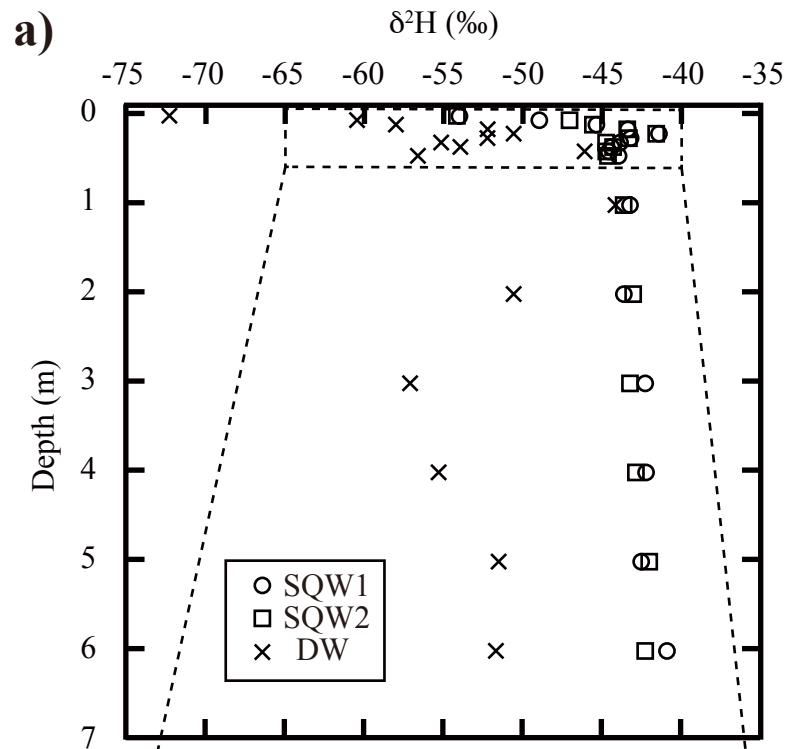


Fig. 4 Ooki et al.

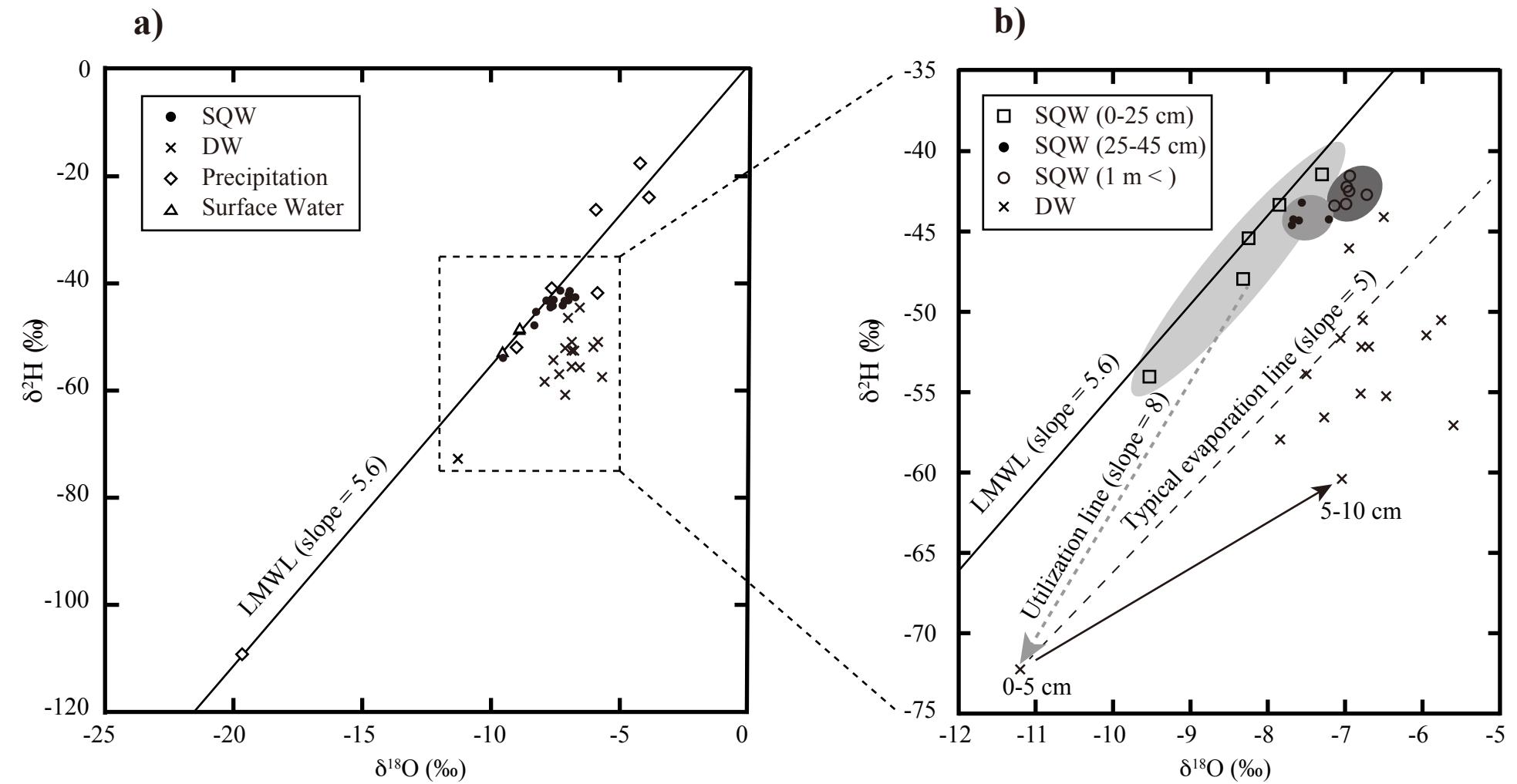


Fig. 5 Ooki et al.

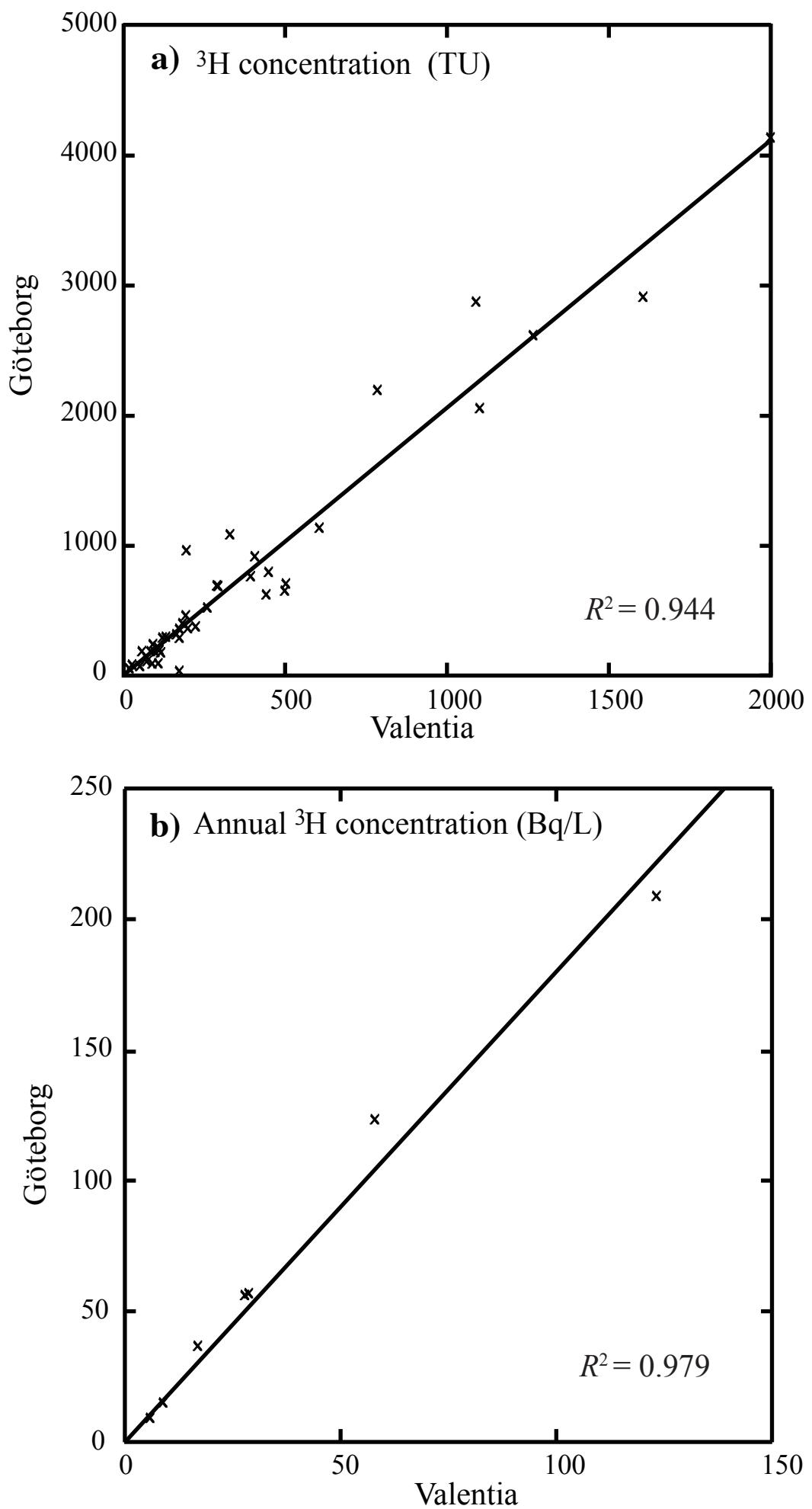


Fig. 6 Ooki et al.

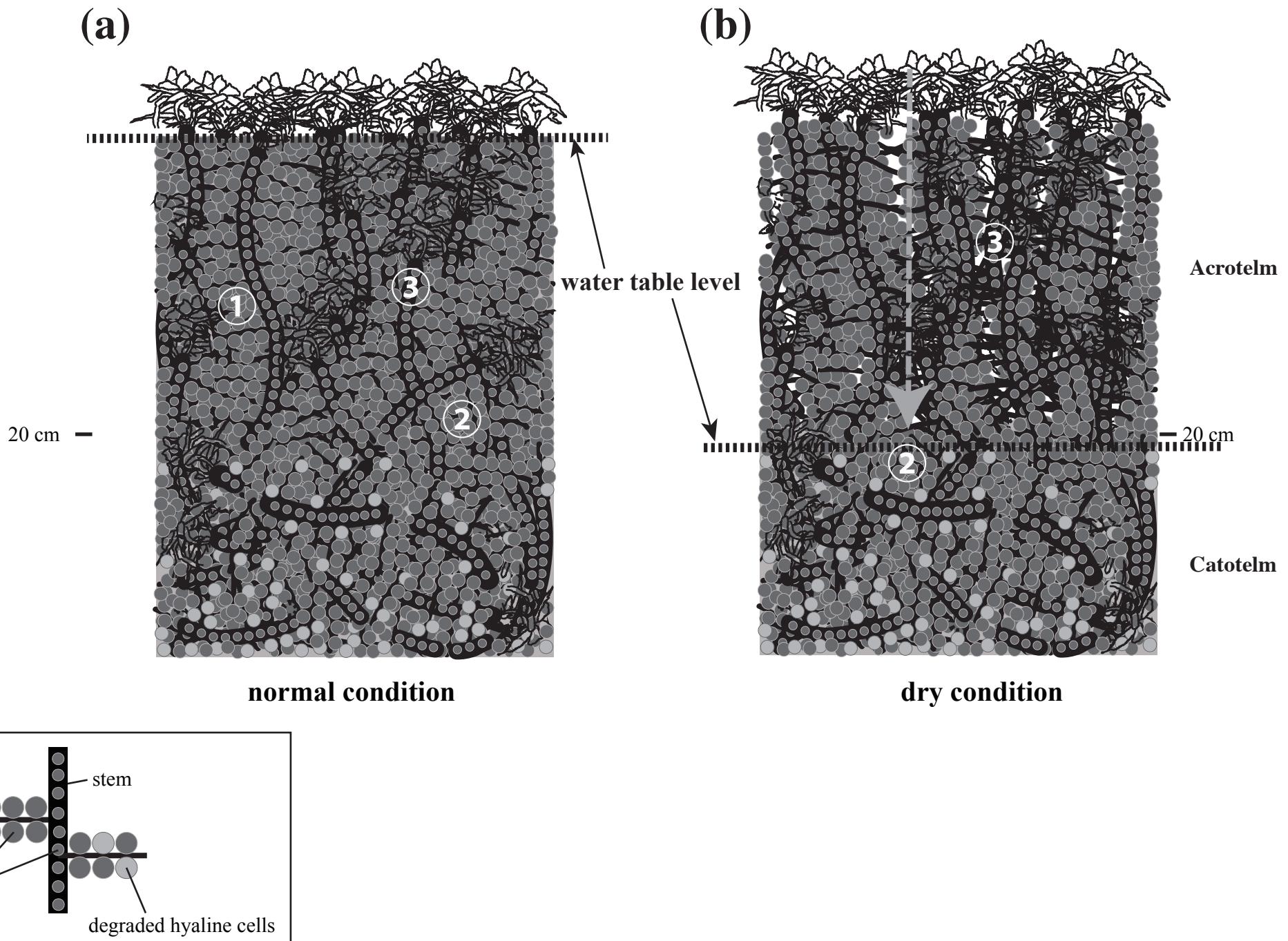


Fig. 7 Ooki et al.