



- 1 Bayesian age-depth modelling applied to varve and radiometric
- 2 dating to optimize the transfer of an existing high-resolution
- 3 chronology to a new composite sediment profile from Holzmaar
- 4 (West-Eifel Volcanic Field, Germany)
- 5 Stella Birlo<sup>1\*</sup>, Wojciech Tylmann<sup>2</sup>, Bernd Zolitschka<sup>1</sup>
- 6 1 University of Bremen, Institute of Geography, GEOPOLAR, Bremen, Germany
- 7 2 University of Gdańsk, Faculty of Oceanography and Geography, Gdańsk, Poland
- 8 \*Corresponding author: sbirlo@uni-bremen.de





# 9 Abstract

10 This study gives an overview of different varve integration methods with Bacon. These techniques 11 will become important for the future as technologies evolve with more sites being revisited for 12 the application of new and high-resolution scanning methods. Thus, the transfer of existing 13 chronologies will become necessary, because the recounting of varves will be too time consuming 14 and expensive to be funded.

15 We introduce new sediment cores from Holzmaar (West-Eifel Volcanic Field, Germany), a volcanic 16 maar lake with a well-studied varved record. Four different age-depth models (A-D) have been 17 calculated for the new composite sediment profile (HZM19) using Bayesian statistics with Bacon. 18 All models incorporate new Pb-210 and Cs-137 dates for the top of the record, the latest 19 calibration curve (IntCal20) for radiocarbon ages as well as the new age estimation for the Laacher 20 See Tephra. Model A is based on previously published radiocarbon measurements only, while 21 Models B-D integrate the previously published varve chronology (VT-99) with different 22 approaches. Model B rests upon radiocarbon data, while parameter settings are obtained from 23 sedimentation rates derived from VT-99. Model C is based on radiocarbon dates and on VT-99 as 24 several normal-distributed tie-points, while Model D is segmented into four sections: Sections 1 25 and 3 are based on VT-99 only, whereas Sections 2 and 4 rely on Bacon age-depth models 26 including additional information from VT-99. In terms of accuracy, the parameter-based 27 integration Model B shows little improvement over the non-integrated approach, whereas the tie 28 point-based integration Model C reflects the complex accumulation history of Holzmaar much 29 better. Only the segmented and parameter-based age-integration approach of Model D adapts and 30 improves VT-99 by replacing sections of higher counting errors with Bayesian modelling of 31 radiocarbon ages and thus efficiently makes available the best possible and precise age-depth 32 model for HZM19. This approach will value all ongoing and high-resolution investigations for a 33 better understanding of decadal-scale Holocene environmental and climatic variations.

Keywords: Lacustrine sediments, Varves, Bayesian age-depth modelling, Bacon, Radiometricdating





# **1. Introduction**

Terrestrial archives from lakes have the potential to provide information about climate and the human history of its catchment area beyond instrumental and historical data. In the late 1980s, piston coring and freeze coring techniques for lacustrine sediment records have improved tremendously allowing a better quality of sediments to be recovered from modern lakes. Since then, the new fields of limnogeology and paleolimnology flourished with increasing demand of societies for documentation of natural background data related to questions around acid rain, environmental pollution and more and more with a focus on global climate change.

44 To provide such information not only on local scales but also on larger regional to global scales, 45 investigations from different sites need to be compared and linked. However, such correlations 46 are only successful if the contributing archives are based on robust chronologies. Therefore, 47 precise and reliable age-depth models are the basis for sedimentary investigations and 48 reconstructions of environmental and climatic changes of the past, as they ensure intra-site 49 comparability and enable recognition of larger scale patterns. A reliable chronology should be 50 based on a combination of different dating techniques (multiple dating approach) such as 51 radiometric dating, well-known event layers (e.g., tephrochronology), historic data (e.g., flood 52 events) or varve counting. The term "varve" (Swedish: layer) was first introduced by De Geer 53 (1912) for outcrops with proglacial sediments and describes finely laminated sediment structures 54 with annual origin. The alternating pale and dark layers are driven by seasonal changes in 55 temperature and precipitation that cause different chemical and biological processes within the 56 lake and its catchment area. When anoxic conditions at the sediment-water-interface are given at 57 least seasonally, i.e. no bioturbation destroys laminations, varves are preserved and provide high-58 resolution and precise chronologies in calendar years (Zolitschka et al., 2015).

59 Until the 1980s, varve chronologies were the only option for calendar-year chronologies for 60 sediment records, while AMS radiocarbon dating was still in its infancy and calibration of 61 radiocarbon ages was restricted to the Middle and Late Holocene, if at all applied. First reviews 62 about methodological advances in the study of annually laminated sediments appeared at the 63 same time (Anderson and Dean, 1988; O'Sullivan, 1983; Saarnisto, 1986) and long varve-dated 64 reconstructions were published for Elk Lake, USA (Dean et al., 1984) and Lake Valkiajärvi, Finland 65 (Saarnisto, 1985). Meerfelder Maar and Holzmaar were the first varve-dated lacustrine records 66 covering the entire Holocene and the Late Glacial for Central Europe (Zolitschka, 1989, 1988), 67 followed by records concentrating on the Late Glacial to Holocene transition at Soppensee, Switzerland (Lotter, 1991) and at Lake Gosciaz, Poland (Goslar et al., 1993). As such, the Holzmaar 68 69 record became one of the best studied lacustrine records in Europe, if not world-wide. Since the 70 first coring campaign in 1984, several sediment records have been recovered from Holzmaar and





71 numerous studies were carried out with sedimentological, biological, geochemical and 72 geophysical methods (e.g. Zolitschka, 1989; Lottermoser et al., 1993; Hajdas et al., 1995; 73 Raubitschek et al., 1999; Leroy et al., 2000). However, the early sediment records from Holzmaar, 74 although counted and corrected multiple times, still contain sections of high counting uncertainty 75 and thus suffer from optimal core correlation as it is possible today by applying high-resolution 76 scanning techniques and digital line-scan images. Moreover, independent time control of varve 77 chronologies with AMS radiocarbon dating became available only in the 1990s (Hajdas-78 Skowronek, 1993), while Bayesian age-depth modelling established as a tool for optimizing dating 79 efforts only during the last decade (Ramsey, 2009) and sediment scanning revolutionized 80 limnogeology and paleolimnology over the last 20 years. Therefore, we revisited Holzmaar to 81 obtain fresh sediment cores for the conduction of innovative and high-resolution (sub-millimetre-82 scale) sediment scanning techniques to be based on an improved age-depth model.

As chronologies are always a "running target", especially as new scientific methods and approaches appear, it is no wonder that the varve chronology for Holzmaar sediments has developed from its first attempt as "Varve Time 1990" (VT-90) (Zolitschka, 1990) to VT-99 ten years later (Zolitschka et al., 2000). In the course of applying ultra-high (sub-mm-scaled) resolution scanning techniques to the new set of sediment cores from Holzmaar (HZM19), VT-99 was transferred to HZM19 making use of marker layers and radiocarbon ages for correlation as well as of Bayesian age-depth modelling for the creation of an updated varve chronology (VT-22).

90 Different to earlier studies, we make use of available radiocarbon dates from Holzmaar not only 91 to correct the varve chronology but to combine it with the independent radiocarbon chronology 92 using Bayesian modelling. This integration approach is not commonly used for lacustrine records. 93 Here we select three different methods to integrate varve and radiometric dating and apply it to 94 the Holzmaar data. We concentrate on approaches using the Bacon package for the R statistical 95 programming software (Blaauw and Christen, 2011), whereas literature also provides 96 comparable methods for alternative Bayesian age-depth modelling software, such as OxCal 97 (Martin-Puertas et al., 2021; Ramsey, 2008; Vandergoes et al., 2018), which was also used to 98 integrate varve counting and radiometric dating for the Holocene sediment record HZM96-4a,4b 99 from Holzmaar (Prasad and Baier, 2014).

In this study we discuss the possibilities to integrate and improve different chronologies by combining a varve chronology with modelling approaches. This is accomplished by testing and comparing integration methods with regard to accuracy and precision from the interpolated varve chronology itself and for a Bayesian model without any varve information. With this integration of all age information we produce the most reliable age estimations for the HZM19 record: VT-22. Based on the best model outcome, this master chronology serves as the chronological base for





- 106 ongoing and future biological, geochemical and geophysical investigations conducted on the new
- 107 Holzmaar sediment cores (e.g. García et al., 2022).

# 108 **2. Materials and Methods**

### 109 2.1 Regional Setting

The late Quaternary volcanic maar lake Holzmaar (425 m a.s.l., 50°7'8" N, 6°52' 45" E) is located 110 in the western central part of the Rhenish Massif in the West-Eifel Volcanic Field (WEVF; 111 112 Rhineland-Palatinate, Germany, Fig. 1). The WEVF consists of more than hundred volcanic cones 113 and maars, of which only nine are water-filled today (Meyer, 2013; Schmincke, 2014). The 114 volcanism in the Eifel region was caused by uplift of the Rhenish Shield since 700 - 800 ka, which 115 started in the NW near Ormont (Meyer and Stets, 2002; Schmincke, 2007). Volcanic activities reached a peak at ca 600 - 450 ka in the central WEVF and then decreased towards Bad Bertrich 116 in the SE (Schmincke, 2007). The uplift is responsible for many eruptive centres at NW-SE 117 118 trending tectonic faults, along which several phreatomagmatic maar explosions occurred (Büchel, 119 1993; Lorenz, 1984; Lorenz et al., 2020; Meyer, 1985). One of these eruptions formed the 120 Holzmaar system ca. 40 - 70 ka ago (Büchel, 1993) consisting of three maars with the maar lake 121 of Holzmaar, the raised bog of Dürres Maar and the dry Hetsche or Hitsche Maar (from SE to NW). 122 With 100 m in diameter, the latter is the smallest maar of the WEVF (Fig. 1).

The catchment area of Holzmaar (2.06 km<sup>2</sup>) includes the Sammetbach, a creek that flows in and out of the lake. Due to the low erosive energy of the stream no delta formed in the lake (Scharf, 1987; Zolitschka, 1998a). The geology in the catchment area consists of Devonian metamorphic slates, greywackes and quartzites as well as Quaternary loess and volcanic rocks related to eruptions of the Holzmaar system (Meyer, 2013). Holzmaar is located within a conservation area since 1975 protecting the surrounding beech forest (Fagus sylvatica L.), while ca. 60% of the catchment area is in agricultural use (Kienel et al., 2005).

130 Holzmaar has a diameter of 300 m (water surface: 58,000 m<sup>2</sup>) and with a maximum water depth 131 of 19-20 m shows a deep and steep-sided morphology typical for maar lakes. Only a small and 132 shallow embayment in the SW interrupts the nearly circular and 1100 m long shoreline. This 133 appendix-like bay developed due to an artificial damming in the late Middle Ages, which was 134 constructed to supply a downstream water mill (Zolitschka, 1998a). For the last glacial, 135 paleolimnological investigations indicate oligotrophic conditions, but eutrophication started 136 already at the onset of the Late Glacial (García et al., 2022). During the Holocene, water quality is affected by human activities, which started during the Neolithic (around 6500 cal. BP) according 137 to pollen analysis (Litt et al., 2009). Together with the inflow of the Sammetbach this caused a 138 139 steady but slow process of eutrophication and today leads to meso- to eutrophic conditions (Lücke





- 140 et al., 2003; Scharf and Oehms, 1992; Zolitschka, 1990). The lake is holo- and dimictic with an
- 141 anoxic hypolimnion during summer stratification (Scharf and Oehms, 1992). Altogether, this
- 142 caused a high potential for varves to be formed and preserved.



Figure 1: ESRI Satellite image of the Holzmaar volcanic system and its catchment area (indicated by a white dashed line)
with Holzmaar, Dürres Maar, Hetsche Maar and Sammetbach (blue line, flow direction indicated by arrows). Upper left
insert: Location of Holzmaar in Germany (red star). Upper right insert: Bathymetric map with isobaths in meter and coring
locations (HZM19-07, -08, -10 and -11) marked by red stars.

#### 148 **2.2 Sediment core collection**

In August 2019 Holzmaar was revisited and four parallel cores (HZM19-07, HZM19-08, HZM19-10, HZM19-11) have been retrieved from the centre of the lake in 19 m water depth (Fig. 1) using a UWITEC piston-corer with a diameter of 90 mm (HZM19-07, -08, -10) and 60 mm (HZM19-11) from a coring platform. The water-sediment interface was perfectly recovered with HZM19-07-01 as the piston stopped 15 cm above the sediment surface. At the GEOPOLAR lab (University of Bremen) the cores have been split in halves lengthwise, photographed and visually described using a Munsell colour chart and according to the description guide line by Schnurrenberger et al.





(2003). Cross correlation of all sediment-core sections was conducted macroscopically usingdistinct layers.

#### 158 2.3 Chronology

#### 159 **2.3.1 Evolution of the Holzmaar varve chronology**

First varve counts and documentation of the annual origin for the finely laminated sediments 160 161 preserved in the Holzmaar record were carried out in the late 1980's (Zolitschka, 1990, 1991, 1992), presenting the initial Holocene and Late Glacial varve chronology VT-90. Varve Time (VT) 162 refers to varve (calendar) years before 1950 CE (Common Era), which is equivalent to the 163 commonly used reference timescale for radiocarbon dates provided in cal. BP (calibrated years 164 before present, i.e. 1950 CE). The chronology of VT-90 was elaborated for the HZM84-B/C 165 166 composite record recovered in 1984 and was counted back to the onset of the Late Glacial, i.e. to 12,794 VT-90. This varve chronology was subsequently extended by counting the deeper, 167 168 periglacial section back to the Last Glacial Maximum, i.e. to an age of 22,500 VT-90 (Brauer, 1994; 169 Brauer et al., 1994).

By including the new sediment cores of HZM90-E/-F/-H, VT-90 was modified resulting in VT-94. 170 171 These overlapping sediment-core series as well as all other mentioned cores have been recovered 172 from the deepest part of Holzmaar, i.e. from within the 20-m isobath (Fig. 1). This recounting 173 revealed an underestimation of the youngest 5000 years, for which 555 years have been added. This initial underestimation was mainly caused by sections with very thin varves difficult to count 174 175 (Zolitschka, 1998b). Another discrepancy occurred within the sediments of the Younger Dryas 176 (YD), for which 245 years had to be added. Altogether, the difference from VT-90 to VT-94 177 comprises an addition of 800 years, shifting the basal age of the Late Glacial back to 13,594 VT-94 178 (Zolitschka, 1998b).

179 To crosscheck the varve chronology with an independent dating method, 41 samples of terrestrial 180 macrofossils along the entire profile (Tab. A2) have been analysed using the AMS (Accelerator 181 Mass Spectroscopy) radiocarbon method (Hajdas et al., 1995 and one unpublished radiocarbon 182 date). A comparison between VT-94 and the calibrated radiocarbon chronology shows a discrepancy of +346 years between 3500 and 4500 VT-94 (Hajdas et al., 1995; Hajdas-Skowronek, 183 1993). This correction factor was estimated by Chi<sup>2</sup>-minimization and added by linear 184 interpolation between 3500 and 4500 VT-94. The outcome was VT-95, which consists of three 185 186 segments. Segment I is covered by an "absolute" chronology until 3500 VT-95, while segment II 187 (3500 - 4846 VT-95) was extended based on the discrepancy detected between varve and 188 calibrated radiocarbon chronologies. Segment III covers sediments from 4846 - 13,940 VT-95 and 189 is considered as a floating chronology (Hajdas et al., 1995; Zolitschka, 1998b).





190 In 1996 new sediment cores (HZM96-4a, -4b) have been obtained from Holzmaar and VT-95 was 191 transferred to this new record using 26 distinct marker layers with their related VT and error. The 192 age-depth model was subsequently obtained by linear interpolation (Baier et al., 2004). At the 193 same time, novel varve counts for the Meerfelder Maar sediment record established 1880 varve 194 years between the two isochrones of Laacher See Tephra (LST, eruption ca 40 km NE from 195 Holzmaar) and Ulmener Maar Tephra (UMT, eruption ca 13 km NE from Holzmaar) (Brauer et al., 196 1999), which both are also archived in the Holzmaar sediment record. However, this well-197 constrained time interval was only 1560 years long for the Holzmaar record. The obviously 198 missing 320 years have been positioned and added to VT-95 based on pollen data from Holzmaar 199 (Leroy et al., 2000), assuming a hiatus for the middle part of the YD biozone at 12,025 VT-95. This 200 results in the latest version (VT-99) of the Holzmaar varve chronology (Zolitschka et al., 2000) 201 with a basal age of 14,260 VT-99 for the Late Glacial.

202 Varve quality and error estimations were first discussed and described based on multiple counts 203 of selected and representative thin sections (Zolitschka, 1991). Later, different varve quality 204 classes have been described in more detail for VT-90 (Zolitschka et al., 1992) and for VT-95 205 (Zolitschka, 1998b) with error estimations in the  $1\sigma$  range (Table A1). Similar error margins were 206 confirmed by counting more recent sediment profiles (HZM96-4a, 4b) from Holzmaar (Prasad and 207 Baier, 2014). In this study, the uppermost part was discussed as showing even higher counting 208 uncertainties. However, no alternative error margins were provided for this section. Thus, we use 209 the data of Table A1 for further evaluations.

210 **2.3.2 Transfer of VT-99 to HZM19** 

211 The varve chronology VT-99 (Zolitschka et al., 2000) was transferred to HZM19 by using 43 212 predefined marker layers and 41 radiocarbon sampling positions analysed by Hajdas et al. (1995, 213 2000) with their specific VT-99 ages and errors (Tables A1, A2). Both, marker layers and 214 radiocarbon sampling positions have been identified and justified by comparison with documents 215 describing the samples as well as core photographies from previous studies and sediment profiles, such as HZM90-E, -F, -H and HZM96-4a, 4b. All marker layers cover an age range from 141 to 216 217 14,158 VT-99. After assignment, the ages of the marker layers have been linearly interpolated and cumulative counting errors were calculated based on the  $1\sigma$  errors provided with Table A1. 218

219 2.3.3 Pb-210 and Cs-137 dating

The isotopes Pb-210 and Cs-137 have been used to radiometrically date the uppermost part of HZM19 at the University of Gdansk. In total, 61 samples were taken with a thickness of 2 cm. The activity of Cs-137 was determined directly by gamma-ray spectrometry from freeze-dried and homogenized samples. Gamma measurements were carried out using a HPGe well-type detector (GCW 2021) with a relative efficiency of 27% and full width at half maximum (FWHM) of 1.9 at





the energy of 1333 keV (Canberra). Energy and efficiency calibration were done using reference

226 material CBSS-2 (Eurostandard CZ) in the same measurement geometry like the samples. The

227 counting time for each sediment sample was 24 hours.

228 Activity of total Pb-210 was determined indirectly by measuring Po-210 using alpha 229 spectrometry. Dry and homogenized sediment samples of 0.2 g were spiked with a Po-209 yield 230 tracer and digested with concentrated HNO<sub>3</sub>, HClO<sub>4</sub> and HF at a temperature of 100 °C using a CEM 231 Mars 6 microwave digestion system. The solution obtained was evaporated with 6M HCl to 232 dryness and then dissolved in 0.5M HCl. Polonium isotopes were spontaneously deposited within 233 four hours on silver discs. Activities were measured using a 7200-04 APEX Alpha Analyst 234 integrated alpha-spectroscopy system (Canberra) equipped with PIPS A450-18AM detectors. 235 Samples were counted for 24 hours. A certified mixed alpha source (U-234, U-238, Pu-239 and 236 Am-241; SRS 73833-121, Analytics, Atlanta, USA) was used to check the detector counting 237 efficiencies.

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#### 2.3.4 Bayesian age-depth modelling

239 To produce the chronology for HZM19 we test and compare different methods integrating varve 240 counts with radiometric measurements using Bayesian age-depth modelling. The advantage of 241 any modelling approach is that all possible calendar ages of calibrated radiocarbon dates and their 242 probability density functions (PDFs) will be tested by using a repeated random sampling method (Blaauw, 2010; Telford et al., 2004). In addition, using the Bayes theorem allows to incorporate 243 244 information of the accumulation history known prior to modelling. Thus, calendar ages, which are 245 monotonic with depth and with positive accumulation rates in yr cm<sup>-1</sup> (in sedimentological terms, 246 accumulation rates as they are used for Bayesian age-depth modelling are equivalent to 247 "sedimentation rates", as corroborated by the units used) are calculated (Lacourse and Gajewski, 248 2020; Trachsel and Telford, 2017). This is different if compared to the "CLassical Age-depth 249 Modelling" carried out by CLAM (Blaauw, 2010).

250 Currently established programs that use Bayesian statistics are Oxcal (Ramsey, 2008), BChron 251 (Haslett and Parnell, 2008) and Bacon (Blaauw and Christen, 2011), all of which differ in terms of 252 parameter settings and handling of outliers. In this study, we focus on varve counting integration 253 methods using Bacon (rBacon version 2.5.7; Blaauw et al., 2021; Blaauw and Christen, 2011) for 254 the R programming language (version 4.1.1; R Core Team, 2021). Bacon uses a Markov Chain 255 Monte Carlo (MCMC) sampling strategy to model the accumulation history piecewise using a 256 gamma autoregressive semi-parametric model (Blaauw and Christen, 2011). The accumulation 257 rate of each segment depends on the accumulation rate of the previous segment. Dates are treated 258 using a student's t-distribution. Although Bacon provides default values, the accumulation rate is 259 controlled by two adjustable prior distributions (prior model), the accumulation rate as a gamma





distribution and the memory, which describes the dependence of accumulation rates between
neighbouring depths as a beta distribution. Both latter parameters are defined by a shape and a
strength prior, respectively, in addition to a mean prior. Furthermore, we make use of the number
of segments (thick-parameter) recommended by Bacon. The program also allows to incorporate
information about hiati and slump events in the profile.

- Only few studies use the Bayesian approach that integrates varve counting information with radiocarbon dates. We extracted three different methods and for comparison include one model only with radiocarbon data, i.e. excluding any VT-99 information. Thus, four different age-depth models (A-D) are compared and discussed:
- A) Model based only on radiocarbon dates.

B) This parameter-based varve integration method introduced by Vandergoes et al. (2018) compares several varve integration techniques for sediments from Lake Ohau (New Zealand) using both OxCal and Bacon. Here, we select the integration approach with Bacon, where the "varve counts function" is the source for the prior-parameter of mean accumulation rate. Major changes in accumulation history recorded by the varve data are derived by using the R package "segmented" (Muggeo, 2022). It dissects the sediment sequence and for each resulting segment an individual mean accumulation-rate prior is defined.

C) The tie point-based integration used by Shanahan et al. (2012) integrates the varve chronology from Lake Bosumtwi (Ghana) based on certain tie points with normally distributed age uncertainties of the cumulative error. They address the problem of integrating all individual varve counts, as they cannot be considered as independent chronological datapoints. Thus, they would be weighted too strongly in the model. The compromise we have chosen for this study, is placing one varve tie-point every 100 years. As there is no varve counting available for HZM19 but VT-99 ages based on marker layers, we implement them with cumulative errors as tie points instead.

284 D) The segmented and parameter-based integration introduced by Bonk et al. (2021) provides 285 the most complex method for varve integration. The problem of not or poorly varved sections in 286 the sediment profile of Lake Gosciaz (Poland) is compensated by dividing the profile into three 287 sections and interpolating the section with low-quality varves using Bayesian modelling. For the 288 Holzmaar record, we define four sections: sections 2 and 4 are based on Bayesian modelling, while 289 sections 1 and 3 rely on VT-99. Section 3 is treated as a floating chronology and placed based on 290 the sum of calibrated radiocarbon probabilities lying within this section. To tighten the two 291 Bayesian modelled sections to the following varved sections, an anchor tie-point based on the 292 oldest age of the younger sections is implemented.





For each model we use the calibration curve IntCal20 (Reimer et al., 2020) and make use of the default accumulation strength and memory priors. We also implement a surface age of -69 +- 1 cal. BP as tie point with a normal distributed error to anchor the chronology to present-day.

# **3. Results and Interpretation**

# 297 **3.1 Lithology**

The four parallel cores HZM19-07, -08, -10 and -11 were aligned and correlated to form the composite profile HZM19 (Fig. 2), which includes 24 core sections and reaches to a basal depth of 14.64 m (Table A3). One technical sediment gap exists at a composite depth of 10.90 m. To determine the precise length of this gap, we use core photographies from a previous Holzmaar core (HZM90-H5u) and determined the technical gap with a length of 12.9 cm (Fig. A1).

- 303 The lithological description of HZM19 follows the characterization of Zolitschka (1998a, 1998b), dividing the HZM84-B/C profile into 12 lithozones (H1 – H12). Except H1, all lithozones cover 304 305 finely-laminated diatomaceous gyttja with varying minerogenic and organic content and colour. All lithozone depths are summarized in Table A4. The transition from light greenish grey (10Y 306 307 8/1) and greyish brown (2.5Y 5/2) minerogenic, finely laminated, weakly carbonaceous silts and 308 clays in H1 (12.9 – 14.6 m) to carbonaceous laminated gyttja in light olive brown (2.5Y 5/3), black 309 (10YR 2/1) and light-yellow brown (2.5Y 6/3) with slightly higher organic content in H2 (11.3 – 310 12.9 m) indicates the transition from the Pleniglacial to the Late Glacial. 311 Within H2, the distinct and almost 20 cm thick coarse-grained tephra from the Laacher See 312 eruption (LST, 11.5 – 11.7 m) is deposited, a well-dated isochrone (Reinig et al., 2021) of European
- 312 lake sediments. The following lithozone H3 (10.9 11.3 m) shows a high minerogenic content
- and almost no organic components with colours of light greenish grey (5GY 7/1) and grey brown
- 315 (10YR 5/2), representing the YD at the end of the Pleistocene. Unfortunately, almost one third
- 316 (12.9 cm) of the YD lithozone H3 is missing due to a technical gap.







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Figure 2: Composite profile of HZM19 with (from left to right) lithozones H1 to H12 (cf., Table A4), lithological description,
 core photographies taken immediately after core splitting, positions of marker layers and radiometric samples (cf., Tables)

320 A2, A5) and core sections used for the composite profile (cf., Table A3).

The Holocene sediment shows a periodic change from sections with higher organic content in black (2.5Y 2.5/1) and light olive brown (2.5Y 5/3) (H4: 10.7 – 10.9 m, H6: 9.9 – 10.0 m) to sections with high organic and clastic content in slightly brighter colours like grey (10YR 5/1) (H5: 10.0 – 10.7 m, H7: 9.3 – 9.9 m). The tephra of the Ulmener Maar eruption (UMT, ca. 3 mm thick) occurs in H5 at 10.24 m. The longest lithozone H8 (5.5 – 9.3 m) contains distinctly varved dark reddish brown (5YR 3/2) sediments with high organic content changing towards the top to very dark





greyish brown (10YR 3/2) and brown (10YR 4/3) with several up to 5 mm thick lenses of
authigenic vivianite. Also, a low carbonate content was recognized. Furthermore, turbidites are
observed more frequently from H8 to the top of HZM19.

330 Above H8, the clastic content increases and brightens up to light olive brown (2.5 Y 5/3) and 331 greyish brown (2.5Y 5/2) hues in H9 (4.3 – 5.5 m). In H10 (3.1 – 4.3 m) colours change to darker 332 hues, e.g. olive grey (5Y 4/2) and black (5Y 2.5/2), while the organic content remains high and 333 terrestrial macrofossils like pieces of wood or leave remains occur more frequently towards the 334 top. The organic content is decreasing slightly in H11 (1.1 - 3.1 m), which also contains clastic components and terrestrial plant material as well as turbidites with paler colours, e.g. olive brown 335 336 (2.5Y 5/3) and grey (2.5Y 5/1). The uppermost lithozone H12 (1.1 m to the top of HZM19) shows 337 unconsolidated organic sediment with a homogenous blackish (5Y 2.5/1) colour for the lower part and brighter dark olive grey (5Y 3/2) sediment at the very top. 338

# 339 **3.2 Chronology**

# 340 3.2.1 Pb-210 and Cs-137 dating

341 The profile of unsupported Pb-210 activity concentration shows a gradual rather than an 342 exponential decrease within the first meter of HZM19 (Fig. 3). Additionally, a plateau from 8 to 30 cm is interpreted as a section with rapid deposition of homogenous material and will be 343 344 treated for further analyses as a slump event. Despite this irregularity, the gradual decrease in 345 unsupported Pb-210 activity with depth indicates high sedimentation rates. We use the CFCS 346 (Constant Flux Constant Sedimentation) model to estimate mean sedimentation rates of 1.09±0.13 cm yr<sup>-1</sup>. This value should be treated with caution but suggests that the uppermost 347 348 meter (including a 22 cm-thick slump) was deposited in ca. 70 years.







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Figure 3: Results of unsupported Pb-210 (left) and Cs-137 (right) measurements with error bars for the uppermost 110 cm
of HZM19. Shaded areas indicate the plateau shown by Pb-210 data, black arrows mark peaks assigned to
radiochronological events (given numbers are ages in years CE).

354 The variability of Cs-137 activity concentrations delivers potentially three historical markers 355 (Fig. 3). The Cs-137 profile is smooth lacking sharp peaks due to high sedimentation rates and 356 likely sediment focusing. First traces of Cs-137 are recognizable at 101.2 cm and indicate atomic 357 bomb testing in the early 1950's. At 89.2 cm, there is a significant increase signalling 358 atmospheric fallout in the early 1960's in response to peak atomic bomb testing. Finally, at 69.2 359 cm a strong increase in Cs-137 documents the 1986 Chernobyl accident (Fig. 3, Table A5). This 360 interpretation is generally in line with the results of Pb-210 dating. The shape of the Cs-137 record also corresponds nicely to the results of Sirocko et al. (2013), who measured Cs-137 on 361 362 sediments from Schalkenmehrener Maar and Ulmener Maar (both WEVF). For both of these 363 cases, the 1986 Chernobyl peak is also much larger than the one related to the start of atomic 364 bomb tests in 1963.

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# 3.2.2 Varve time and independent radiocarbon chronology

The varve chronology VT-99 was transferred to HZM19 using 84 marker layers of which 41 are
radiocarbon dating positions. These marker layers distribute in HZM19 from 1.16 - 12.93 m and
cover the VT-99 age range from 141 to 14,158 VT-99 (Table A2). During the transfer of marker
layers to HZM19 and comparison between HZM19 and previous Holzmaar sediment cores
(HZM84-B/C, HZM92-E/-F/-H, HZM96-4a/4b) differences in position of the lowermost marker





- layers occurred. All records show differences in distances between marker layers (ML) 1 (14,156
  VT-99), ML-2 (14,152 VT-99) and ML-3 (13,646 VT-99) making a clear assignment of these layers
  difficult. Thus, we excluded these three marker layers for the transfer of VT-99 to HZM19. The
  lowermost applied marker layer is therefore ML-4 with a varve age of 13,087 VT-99 at a depth of
  11.86 m. Because of inconsistencies in documentation, we excluded two more VT-99 ages, i.e.
  those related to the radiocarbon ages HZM-46 and HZM-10.1 (Table A2).
- The marker layer density reaches a mean value of 5.5 dpm (dates per millennium) being most frequent before 10,000 and after 6000 cal. BP (Fig. 4). We use a linear interpolation to receive an age-depth model based only on VT-99 with a resulting accuracy of 282 years as a mean age range and a maximum age range of 744 years (Table A6).
- The radiocarbon dating density of HZM reaches an overall mean value of 2.7 dpm (Fig. 4), which is 35% higher than the 2 dpm recommended for Bayesian modelling by Blaauw et al. (2018). However, their distribution is uneven. Radiocarbon dates are most frequent for ages >10,000 cal. BP with 3-7 dpm (mean: 5 dpm) (Fig. 4). A minimum density of radiocarbon dates (0-1 dpm) is obtained from 10,000-6000 cal. BP (mean: 0.5 dpm). Therefore, a chronology based on the available radiocarbon data within this section should be interpreted with caution. Dating density for the uppermost 6000 years is higher and varies between 1 and 4 dpm (mean: 2.2 dpm).
- When we compare VT-99 with radiocarbon ages calibrated with the latest calibration curve IntCal20 (Reimer et al., 2020), an overall agreement with marker layers is observed. Only for the lowermost part below approximately 10.64 m at radiocarbon sample HZM-46 (Table A2), we observe an increasing underestimation of VT-99 in relation to IntCal20 calibrated radiocarbon ages (Fig. A2, Table A2). This was already observed by Hajdas et al. (2000) in comparison to Intcal98 but has not been corrected yet.





395



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Figure 4: Number of dating points per millennium (dpm) of HZM19 for marker layers (n: 84, mean: 5.5 dpm) and
radiocarbon dates (n: 41, mean: 2.7 dpm). Red dotted line marks the recommended threshold of 2 dpm for Bayesian
modelling suggested by Blaauw et al. (2018). Surface age and three ages estimated by Cs-137 are excluded.

# 400 **3.2.3 Age-depth modelling**

401 Four different Bayesian age-depth models are calculated, of which three include varve ages 402 (Model B-D) and one only radiocarbon ages (Model A). In common for all model runs are the 403 default memory priors and the use of the IntCal20 calibration curve (Reimer et al., 2020). 404 Furthermore, based on the Pb-210 and Cs-137 dating analysis, a slump at a composite depth of 8-405 30 cm was implemented, as well as the LST from 11.52 - 11.71 m. As known from previous varve 406 and pollen studies of the Holzmaar record (Brauer et al., 1999; Leroy et al., 2000), 320 years are 407 missing during the YD and have been included into VT-99 at 12,025 VT-99. Based on the study of 408 Leroy et al. (2000), we were able to locate the position of the YD hiatus to a depth of 11.09 m, 409 which we implemented for each model with a maximum duration of 320 years. In addition to marker layers and radiocarbon dates, we included the surface age of -69 +- 1 cal. BP and three 410 events dated by Cs-137 (Table A5). 411

Preliminary test runs reveal two necessary changes to be made for the calculations: 1) The default 412 413 number of iterations is too low to produce a robust model for the entire HZM19 sediment 414 sequence. Thus, we use the Baconvergance()-function of Bacon to estimate the number of 415 iterations needed. This function repeats the calculations and tests if the MCMC mixing of the core results in a robust model by calculating the "Gelman and Rubin Reduction Factor" (Brooks and 416 Gelman, 1998). Good mixing is indicated by a threshold of <1.05, which in our case was reached 417 418 after three iterations when the number of iterations was increased to 40,000. This results in a 419 better mix of MCMC iterations but also in long calculation times (> 5 hours). 2) For each test run, 420 Bacon predicted ages consistently too old for the LST, which is probably caused by slightly too old





- 421 ages of the surrounding radiocarbon dates (Table A2). To gain a better comparability with studies
- from other sites, we decided to include the latest LST age of 13,006 +- 9 cal. BP (Reinig et al., 2021,
- 423 Table A5).
- In addition, we extended the age-depth model to a maximum depth of 14.64 m, as ongoing
  analyses exceed the lowermost dated level. However, in the following chapters we only discuss
  the model output between the first (ML36/1) and the last (HZM-19) marker layer at 12.93 m
  (Table A2) and compare it with the interpolated varve chronology (VT-99).
- 428 After each calculation and if the Bacon output indicates a highly variable log of objectives or MCMC
  429 iterations, we made use of the scissor()-command to achieve a better mixing of the output. All
  430 Bacon model outputs with their settings and additional information are shown in Fig. A3 and
  431 related ages are listed in Table A6.
- 432 The model without varve integration (Model A) is based on the year of sediment recovery
- 433 (surface age), three dates estimated by Cs-137 analyses, the age for the LST (Reinig et al., 2021)
- 434 and 41 calibrated radiocarbon probability density functions (Fig. A3A). Different to Hajdas et al.
- 435 (1995), this model includes the outlier of HZM-23, but excludes HZM-24 and other described
- 436 outliers (Table A2).
- Model A results in an age of 14,615 [minimum: 14,339, maximum: 14,926] cal. BP at the
  lowermost dated depth of 12.93 m with a mean age uncertainty of 468 yrs. The maximum age
  uncertainty of approx. 1056 years occurs at a depth of 8.86 m within lithozone H8 (Table A6),
  where radiocarbon dating density is <1 dpm (Fig. 4).</li>
- The parameter-based integration (Model B) integrates VT-99 using all dates as in Model A and 441 442 adjusts the prior information given for the calculation based on the varve accumulation-history. 443 We follow the procedure presented by Vandergoes et al. (2018) and calculate a breakpoint based 444 on ages and depths of the marker layers at 4.43 m, i.e. at 1312 VT-99 (Fig. A3B). This boundary is 445 implemented as an additional hiatus to the Bacon code with a duration of 1 year. The accumulation 446 rate prior is set based on published sedimentation rates (Zolitschka et al., 2000). We calculate 447 with a mean of 0.49 yr/mm for the uppermost part (71-1312 VT-99), with 1.30 yr/mm from 1312 to the YD hiatus at 12,025 VT-99 and with 0.76 yr/mm from the YD hiatus to the lowermost age 448 449 of 14,158 VT-99. Model B is calculated using the same parameters as for Model A and with the 450 same treatment of outliers.
- The resulting posterior model shows similarities to Model A, having a maximum mean age of 14,456 [min.: 14,236, max.: 14,749] cal. BP at a depth of 12.93 m and a mean 95% confidence interval of 456 years with a maximum of 1064 years at 8.78 m, i.e. within the period of lowest radiocarbon dating density (Fig. 4).





The **tie point-based integration (Model C)** is based on the approach used by Shanahan et al. (2012). We include 43 marker layers with related VT-99 ages and cumulative errors as normal distributed tie points into the model, which adds to the dates used in Models A and B and sums up to 89 dates. This approach increases the amount of chronological information and fills areas with larger gaps between radiocarbon dates. The model was run with default settings provided by Bacon (Fig. A3C). Bacon recognizes the outliers in the same way as by previously described models.

462 Model C results in a maximum age of 14,614 [min.: 14,332, max.: 14,919] cal. BP (at 12.93 m) with 463 a mean 95% confidence interval of 329 years, which is better than for Models A and B. A maximum 464 age range of 749 years is given at a depth of 9.18 m, which is also slightly better than for previously 465 presented models. However, Model C produced MCMC iterations with highest noise and it was 466 difficult to cut out a well-mixed section (Fig. A3C, upper left panel).

467 The segmented and parameter-based integration (Model D) is a more complex method of 468 varve integration used by Bonk et al. (2021) and was adapted for the HZM19 profile by dividing 469 the varve chronology of VT-99 into four sections. This separation is based on variations of 470 counting uncertainty, radiocarbon sampling density and an increasing offset of VT-99 to the latest 471 calibration curve IntCal20 (Fig. A2).

472 Section 1 (0 – 5.98 m) and Section 3 (6.70 – 9.90 m) are transferred and interpolated based on VT-473 99 marker layers, as they are consistent with calibrated radiocarbon data (Section 1) and have 474 well-preserved varves with small counting errors of  $\pm 0.7\%$  (Section 3). Section 2 (5.98 – 6.70 m) 475 and Section 4 (9.9 – 14.6 m) are reported as showing higher counting uncertainties (Section 2) or 476 increasing differences between VT-99 and the calibration curve (Section 4). Thus, we replace the 477 varve chronology in Sections 2 and 4 with Bayesian age-depth modelling (Fig. A3D). Section 4 also 478 contains very dense radiocarbon dates (Hajdas et al., 2000), which increase the predictability of 479 Bacon (Fig. 4).

480 Section 1 is based on linear interpolation for ages of the sediment surface (-69 ± 1 cal. BP), three
481 dates derived by Cs-137 analyses (Table A5) and 25 ages of marker layers with a basal age of 3704
482 ± 134 cal. BP at the position of HZM-25 (Table A2).

The modelled Section 2, previously identified as a section with sedimentation rates >2.86 yr/mm and therefore a source of high counting uncertainties and underestimation of varve ages (Zolitschka et al., 2000), consists of five radiocarbon dates (Table A2) and the basal age of Section 1 (3704 ± 134 cal. BP) as anchor point for Section 2. To reduce the resulting gap between first and second sections, we reduce the error estimation for the anchor point to ±70 years (+-0.5 $\sigma$ ). As there is a major change in sedimentation rates within this section, we calculated a boundary





- similar as in Model B using the marker layers of this section (Fig. A3D). This allows defining a
  boundary at the depth of 6.29 m with adjusted accumulation means of 3.33 yr/mm above (5.98 –
  6.29 m) and 1.59 yr/mm below (6.29 6.70 m), using published sedimentation rate data
  (Zolitschka et al., 2000). Based on suggestions by the software, the "thick"-parameter was set to 4
  mm. The resulting model covers and age range from 3709 [min.: 3591, max.: 3825] to 5419 [min.:
  5220 max.: 5548] col. BB (Fig. A2D partian 2)
- 494 5329, max.: 5548] cal. BP (Fig. A3D section 2).
- 495 Section 3 interpolates 16 marker layers (Table A2), which are treated as a floating chronology.
- 496 The placement of the anchor point relates to the basal age of the lowermost calibrated
- 497 radiocarbon date (HZM-4.3) in Section 2 (Table A2) and the maximum sum of the four calibrated
- 498 radiocarbon PDFs within this part with a summed probability of 0.076 at 5450 ± 165 cal. BP (Fig.
- 499 A4 A).







500

Figure 5: Age-depth model for HZM19 based on Model D with Sections 1 and 3 based on VT-99 (section numbers at the
 right) and Sections 2 and 4 based on Bayesian modelling (shaded).

In comparison to the original VT-99 this approach results in a shift of +65 years for all marker
layers within Section 3 (Fig. A4 B). Thus, a basal age of 10,619 ± 213 cal. BP is obtained for Section
3.

The basal age of Section 3 is implemented as the anchor tie-point for the Bacon calculation of Section 4 with a reduced error of 100 years to tighten both sections closer to each other. In





addition to the difficulties based on missing sediment within the YD, this section is the source of
highest counting uncertainties for VT-99. Section 4 is based on 25 radiocarbon dates and the latest
age estimation for the LST (Table A2). As in Section 2, we adjusted the sedimentation rate prior
(= 0.94 yr/mm) based on VT-99 accumulation rate data (Zolitschka et al., 2000). The Bacon
software suggests a segment length of 30 mm that we applied. The resulting model covers an age
range from 10,663 [min.: 10,457, max.: 10,864] to 14,485 [min.: 14,287, max.: 14,721] cal. BP at
12.93 m (Fig. A3D, Section 4).

515 If all sections are merged, the continuous age-depth relationship forming Model D (Fig. 5) consists 516 of 63% VT-99 ages and 37% Bacon modelled ages with in total 80 missing years between the 517 sections, as it is not possible to determine the exact start and end age of the models. This 518 segmented and parameter-based integration model results in a maximum age of 14,485 [min.: 519 14,287, max.: 14,721] cal. BP (at 12.93 m) with a mean age uncertainty of 229 years, which is the 520 smallest of all four tested models. The maximum age range is 447 years at 11.09 m depth and thus 521 considerably smaller compared to those of Models A to C (Table A6).

#### 522 **3.2.4 Comparison of model output with the isochrones UMT and**

#### 523

#### LST and the YD biozone

The tephra layers of UMT and LST have been identified for sediments from Holzmaar and Meerfelder Maar (Brauer et al., 1999). The varve age of 11,000 VT-99 for UMT was derived from the Holzmaar chronology (Zolitschka, 1998b), while the YD hiatus of this site did not allow any calendar-year estimation for LST. As no such hiatus exists between these two isochrones at Meerfelder Maar, the age for the LST was derived as 1880 varve years older than UMT, i.e. as 12,880 VT-99. A recent study presents a new and 126 years older age for the LST (Reinig et al., 2021). This age of 13,006 cal. BP was implemented for the calculation of Models A-D.

When we compare all models, the age estimations for UMT and LST are close to the published ages
with the UMT dated ca. 20-50 years earlier and thus matches well within the 95% confidence
interval (Table A6). Due to the new age of LST, the distances between both isochrones vary from
2030 (Model D) to 2057 (Model C) years, which is 150-177 years more than counted for
Meerfelder Maar.

The main differences occur in prediction of the end of the YD that defines the transition to the Holocene. The rapid cooling and subsequent warming left behind easy to recognize traces in many European lake records increasing the comparability between sites. The entire YD is not covered by HZM19 due to a technical gap. Nevertheless, we are able to estimate depth and time range based on detailed pollen investigations (Leroy et al., 2000). Using VT-99, Leroy et al. (2000) date the onset of the YD, i.e. the Allerød/Younger Dryas transition (AL/YD) to 12,606 VT-99 and the





- Younger Dryas/Preboreal (YD/PB) transition to 11,632 VT-99 with a 320 years hiatus at 12,025
  VT-99. For HZM19 these boundaries occur at 10.88 m (YD/PB), at 11.26 m (AL/YD) and the hiatus
  at 11.11 m (Fig. 6).
- All model runs predict a YD duration in the range of 1012 (Model C) to 1073 (Model D) years, which is longer than the 974 years given by VT-99 (Table A6). However, the predicted times are closer to its duration counted for Meerfelder Maar (1080 years) (Brauer et al., 1999) or the even longer time spans detected for Lake Gosciaz (1150 years) (Bonk et al., 2021)..
- Moreover, the YD transition has been predicted within the 95% confidence interval comparable 549 550 to VT-99 (Table A6) and to the Meerfelder Maar record. Only the AL/YD transition varies between 551 12,694 (Model C) and 12,737 (Model B) cal. BP and, thus, is predicted earlier than for VT-99 552 (12,606 VT-99). However, this age range still covers the age estimations from Lake Gosciaz 553 (12,620 [min.: 12,389, max.: 12,753] cal. BP) and Meerfelder Maar (12,680 [min.: 12,640, max.: 12,720] cal. BP). In difference, the YD/PB transition varies between 11,655 (Model D) and 11,723 554 555 (Model B) cal. BP, which is slightly earlier than estimated by Meerfelder Maar (11,600 [min.: 11,570, max.: 11,630] cal. BP) and much earlier than the age estimation for Lake Gosciaz (11,470 556 [min.: 11,264, max.: 11,596] cal. BP). These discrepancies between the boundaries of the YD 557 biozone obtained by VT-99 and those obtained by the model runs are probably related to the new 558 559 and 126-year older age for the LST, which is included with all models. Thus, age discrepancies are attenuating towards the UMT with 110 years at the AL/YD transition and 57 years at the YD/PB 560 561 transition.

# 3.2.5 Comparison of model output with VT-99

The comparison of all presented models differs in means and accuracies of predicted ages along 563 the core (Fig. 6A1; B1; C1; D1), which becomes more evident in comparison with VT-99 (Fig. 564 565 6A2,3; B2,3; C2,3; D2,3). These differences in mean modelled age and mean VT-99 age vary in direction and amplitude (Fig. 6A2; B2; C2; D2). The largest age differences during the Holocene 566 occur in Model A and B with up to 300 years between 4 and 6 m depth (Fig. 6A2; B2). The defined 567 boundary in Model B results in large differences within the boundary area, predicting much 568 569 younger ages than VT-99. Due to the small cumulative counting uncertainty of VT-99 in the upper part of the profile, the mean of Model B outranges the VT-99 error in most sections above 6 m (Fig. 570 571 6B2).





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Figure 6: Results of Models A, B, C, D plotted against composite depth (1), compared to VT-99 as the difference of mean ages
(Model mean – VT-99 mean) (2) and plotted vs. VT-99 confidence intervals (CI) (3).

The approach used for Model C reduces the difference between VT-99 and the model, probably a
result of increased dating density (Fig. 6C2). This approach also leads to less over- and
underestimations of the model's mean age and the VT-99 age range (Fig. 6C2). Only the segmented
insertion of VT-99 in model D results in comparable ages during the Holocene (Fig. 6D2)

In the Late Glacial part below 11 m, all models produce ages constantly older than VT-99 (Fig. 6A2, B2, C2, D2). The age differences are even higher (up to 477 years), when the Bacon prior for accumulation rates was not adjusted to VT-99 (Fig. 6A2, C2). In the other cases the maximum age differences are 369 and 354 years for Model B and D, respectively (Fig. 6B2, D2). Hajdas et al. (2000) already observed a shift between the varve ages of radiocarbon dated samples and calibrated ages using the INTCAL98 calibration curve (Stuiver et al., 1998) and discuss the





difference using the LST age estimation from Meerfelder Maar (12,880 VT). However, no adjustment has been made to fit the VT-99 ages to the calibration curve. With the LST dated to 13,006 +-9 cal. BP (Reinig et al., 2021) and the use of the INTCAL20 calibration curve, an underestimation of VT-99 compared to the calibration curve is still existing (Fig. A2). Therefore, a correction of ages older than 12,800 cal. BP is needed to ensure comparability of HZM19 to other sites.

591 In order to find the best method to transfer VT-99 to HZM19 and to improve the chronology by 592 using Bayesian modelling, a closer look to each model's accuracy is necessary (Fig. 6A3, B3, C3, D3). In comparison to the cumulative VT-99 counting error, Models A and B show maximum 593 594 differences in age uncertainties up to +655 and +665 years, respectively (Table A6). Especially below 9.82 m, both models predict ages with larger uncertainties than the estimated counting 595 error for VT-99, particularly with increasing distance to radiocarbon dated levels. Therefore, no 596 597 improvement in accuracy of age estimations is observed when using the parameter-based 598 approach (Model B).

599 The tie point-based Model C also predicts larger uncertainties than VT-99 below 9.82 m (Fig. 6C), 600 whereas the overall difference of the age range is reduced to a mean of 47 years with a maximum 601 of +401 years (Table A6). Only the segmented and parameter-based Model D shows no 602 significantly enlarged age uncertainties and an overall improved mean age range as it adapts the 603 cumulative error of the varve chronology in Sections 1 and 3 (Table A6). The overall improvement 604 occurs in Sections 2 and 4, which is the result of more detailed prior settings for the model run. 605 However, all age models result in more accurate age estimations in the Late Glacial part, where 606 the cumulative counting error is higher and radiocarbon dating sampling is dense. But still we see 607 that Models C and D perform best within this section, as they predict ages with constantly lower 608 uncertainty ranges than VT-99. This is in contrast to the other models, which show increased and 609 therefore larger uncertainties at a depth of ca. 11 m. As we calculate this section in Model D with 610 the same data like for Model A and B, we assume that the better adjustment of the sedimentation 611 rate mean prior of Model D influences the model's accuracy. In terms of accuracy, there are no 612 general improvements in calculating a single model for the entire record, but improvements are 613 realised by adjusting the priors in a more detailed way.

# **4. Evaluation of the different varve integration techniques**

All models predict convincing age estimations for the isochrones of LST and UMT, whereas the
prediction of the YD between both isochrones remains somewhat ambiguous, due to a
documented hiatus and too few radiocarbon ages being available for this biozone.





In terms of accuracy and precision, the varve-integration technique applied in Model D, introduced by Bonk et al. (2021), results in most convincing age estimations for HZM19. Especially in terms of accuracy, none of the completely Bayesian modelled age-depth relationships improved the small age uncertainties of VT-99 in the upper part. Only in sections with markedly higher radiocarbon sampling density or in sections with high varve counting uncertainty the Bacon models perform better and result in more accurate age estimations than VT-99.

624 In comparison, Model B shows nearly no improvement over the approach without varve 625 integration (Model A). The reason is probably the low-resolution definition of sedimentation rate 626 changes (boundaries) for HZM19, which does not reflect the complex accumulation history. Also 627 Vandergoes et al. (2018) reject this integration model. We suggest that this form of varve 628 integration is more useful for less complex and for shorter sediment profiles.

629 Better results are observed applying Model C, which is actually the easiest to apply. The accuracy 630 is improved compared to Models A and B as the dating density increases significantly. Based on 631 the Bayesian approach, this leads to smaller age ranges as higher uncertainties occur with increasing distances to dated levels. The resulting mean age is more constrained by VT-99. The 632 633 accuracy might be improved by additional adjustments of the sedimentation-rate prior (here: 634 based on VT-99). However, varve ages inserted as tie points are included with normal distribution. 635 Therefore, they should not be interpreted as independent measurements with non-normal distributed PDFs. Bayesian statistics could weight tie points too much when they are included too 636 densely. Therefore, this approach should be interpreted with care. 637

- The best result in precision and especially accuracy is achieved by the segmented and parameterbased Model D. This approach is the most challenging, but makes advantage of both, the high accuracy of varve counting and the Bayesian approach for densely radiocarbon dated sections. The main difference to the other models is that Model D replaces the sections of lower dating accuracy with modelled ages that incorporate varve information and radiocarbon measurements, which result in a much better performance.
- For upcoming geochemical and geophysical studies of the HZM19 record, we will use Model D. As
  parts of VT-99 (63%) are included in the new chronology, we will refer to it as chronology "VT22", which delivers highly accurate age estimations for each depth of the sediment profile HZM19.
  Altogether, this will improve the comparability of the Holzmaar record with other sites.

# 648 **5. Conclusion**

As limnogeological and varve studies proceed, new techniques for sediment analysis develop.
Thus, previous studies can be improved by reinvestigation. However, many of the previously
studied sediment cores are not available for analysis anymore. We expect such cases to happen





652 more frequently in the future. Rarely, the rather time-consuming and expensive chronological 653 studies, especially if the counting of varves is involved, will be funded a second time. This 654 increases the need for finding best ways to adapt varve chronologies obtained during previous 655 studies and to transfer them efficiently and precisely to new sediment cores.

- For the well-dated Holzmaar record, we tested three different approaches for the integration of varve counting and radiocarbon dating using Bayesian modelling and applied them to the new composite profile from Holzmaar (HZM19). We conclude that all models result in accurate and precise age estimations. However, with higher dating density and more prior settings used to adjust the Bacon model runs, the model output is enhanced. This is confirmed by results of Model D, which improved and corrected the age estimations considerably. In contrast, Models B and C show nearly no improvement over VT-99 just like the output of Model A without varve integration.
- Multiple varve counting is still one of the best approaches of building a reliable chronology for
  lacustrine sediment archives. However, the occurrence of hiati or errors in varve counts lead to
  larger uncertainties with increasing depth that need to be corrected by using independent dating
  techniques. Therefore, if varve and radiocarbon data are available, like it is the case for Holzmaar,
  the transfer of both to form a new and integrating chronology is the best option.
- For this study of varve integration, we use Bacon. The parameter adjustment of Bacon is complex
  and especially beginners have problems to understand each single parameter and the effect it has
  on model results. We compare different models and settings, which helps to decide selecting the
  best suited approach. and to consider the parameters that have to be adjusted. Afterall, we suggest
  to increase the independent dating density and to adjust prior settings as detailed as possible to
  gain a more precise chronology for the varve-integration attempt.
- 674 Optimizing the Holzmaar chronology is the first step in order to provide a precise and robust age-
- 675 depth model for upcoming and high-resolution multi-proxy investigations to unveil all the
- 676 environmental details recorded by the varved sediment archive of Holzmaar.







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679 Figure A1: Determination of the technical gap for HZM19 during the YD. This gap exists between sections HZM19-10-07

680 and HZM19-08-10 and is bridged by section HZM90-H5u from an earlier coring campaign.







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683 Figure A2: Radiocarbon ages vs. Intcal98 and Intcal20 calibrated ages between 10,000 and 15,000 cal BP. Black circles

show radiocarbon ages from Holzmaar vs. VT-99 age. An underestimation of these ages occurs after 12,500 cal BP, where
VT-99 seems to be too young.







Figure A3: Bacon output for Model A, B, C and D (sections 2 and 4. Each output with indicator panels from top left to right:
MCMC iterations, prior (green) and posterior (grey) for accumulation rate distribution, memory and hiatus with defined
settings in red. Main panel: model with calibrated radiocarbon date probabilities (blue), tie-points with normal distribution
(orange) and the posterior age-depth model with mean (red dotted line) and 95% confidence intervals (gray dotted line).
Vertical gray lines (from left to right): slump event, defined hiatus and Laacher See Tephra. In additional panels of Models
B and D2 boundaries indicating major changes in accumulation rate are provided as vertical dotted lines.







Figure A4: Calculations for the floating VT-99 chronology of Model D, section 3. A: Calculation of shift based on calibrated
probability density functions of each radiocarbon sample within this section. The maximum summed probability occurs at
5450 cal BP. B: Original VT-99 (black) vs. floating VT-99 (+65 years, red dotted) with calibrated radiocarbon samples
plotted vs. depth.





Table A1: Error (1 sigma) estimations for different varve quality periods for the Holzmaar record (Zolitschka, 1998b),
 updated from VT-95 to VT-99.

Varve quality period	VT-99 (duration in years)	Error
Α	0 – 2800	±4.0 %
В	2800 - 5300	±2.6 %
С	5300 - 11,600	±0.7 %
D	11,600 - 14,158	±5.9 %
Entire record	0 - 14,158	±2.5 %

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705 Table A2: Marker layers (in italics) and radiocarbon dates (Hajdas et al., 2000, 1995 plus one unpublished radiocarbon 706 707 date) vs. composite depth of HZM19. The calibrated median <sup>14</sup>C age is calculated using OxCal with the IntCal20 calibration

curve. Inconsistent calibrated ages are shown in brackets.

Marker layer	HZM19	VT-99 Age	VT-99 cumulative	14C ago (BD)	<sup>14</sup> C ±1σ error	Calibrated	<sup>14</sup> C ±1σ
<sup>14</sup> C sample ID	depth (m)	(cal BP)	±1σ error	- Cage (DP)	(yrs)	age (cal BP)	(yrs)
	1.10	1.4.1	(yrs)				
ML-36/1	1.10	141	D				
ML-36	1.45	209	8				
ML-35/1	1.81	334	13				
ML-35	2.12	442	18				
ML-34	2.44	572	23				
ML-33/2	2.62	657	26				
ML-33/1	2.69	685	27				
HZM-1.1	2.90	796	32	685	40	644	41
HZM-1.2	2.91	802	32	795	40	708	29
HZM-1.3	2.93	810	32	975	90	869	94
ML-33	2.94	819	33				
ML-32	3.29	985	39				
ML-31/1	3.54	1248	50				
HZM-2.2+3	4.01	1569	63	1565	55	1451	57
ML-31	4.17	1710	68				
ML-30	4.29	1789	72				
ML-29	4.59	1984	79				
ML-28	4.91	2219	89				
HZM-3.1	5.16	2433	97	2405	60	2469	112
ML-27	5.17	2449	98				
HZM-3.3*	5.19	2450	98	2750	60	(2850)	66
ML-26	5.43	2593	104				
HZM-23*	5.45	2595	104	2720	60	(2826)	58
HZM-24	5.61	2754	110	2620	65	2743	101
ML-25/1	5.77	3147	121				
HZM-25	5.97	3704	136	3465	70	3730	96
ML-25	6.11	3992	143				
ML-24	6.21	4420	154				
HZM-26*	6.23	4616	159	4100	90	4624	127
ML-23	6.51	5083	171				
ML-22	6.68	5286	177				
HZM-4.1	6.69	5334	177	4575	65	5243	131
HZM-4.2	6.70	5359	177	4730	70	5462	85
HZM-4.3	6.71	5385	178	4675	70	5409	95
ML-21	6.78	5520	179				
ML-20	6.84	5619	179				
ML-19	7.05	5977	182				
ML-18/2	7.51	6328	184				
ML-18/1	7.70	6590	186				
ML-18	8.06	7274	191				
HZM-5.3	8.13	7428	192	6455	70	7363	68
ML-17/3	8.42	7870	195				
ML-17/2	8.72	8338	198				





ML-17/1	9.03	8943	203				
HZM-6.1	9.33	9649	207	8800	95	9851	170
ML-17	9.40	9746	208				
ML-16	9.66	10169	211				
HZM-7	9.92	10464**	213	9465	45	10705	130
ML-15	9.92	10554	214				
ML-14	10.03	10681	215				
HZM-8	10.07	10708	215	9495	55	10773	148
ML-13	10.24	10999	217				
HZM-9 (UMT)	10.25	11008	217	9560	49	10923	121
HZM-40	10.27	11048	217	9550	80	10901	148
HZM-41	10.33	11109	218	9665	100	10998	154
HZM-42	10.38	11145	218	9565	100	10912	160
HZM-43	10.46	11226	219	9830	100	11264	178
ML-12	10.48	11232	219				
HZM-44	10.52	11267	219	9805	190	11243	329
HZM-45	10.59	11322	219	9905	80	11357	138
HZM-46	10.64	11357**	219	10060	80	11584	159
HZM-10.1	10.67	11339**	219	10085	80	11630	165
HZM-47	10.70	11400	220	10110	110	11680	231
ML-11	10.73	11453	220				
HZM-48	10.78	11534	221	11040	140	(12959)	120
HZM-50	10.99	11942	241	10080	110	11628	214
ML-9	11.02	11943	241				
HZM-12	11.10	12354	266	10520	90	12509	181
HZM-51	11.14	12530	276	10350	90	12203	194
ML-8	11.20	12578	279				
HZM-13*	11.38	12769	290	11295	85	(13197)	74
ML-7	11.41	12778	291				
HZM-14*	11.48	12861	296	11780	100	(13647)	112
ML-6	11.56	12880	297				
ML-5	11.70	12880	297				
HZM-30	11.74	12925	299	11250	110	13158	109
ML-4	11.86	13087	309				
HZM-16*	12.03	13130	311	13140	140	(15766)	212
HZM-32	12.19	13445	330	11770	135	13642	150
HZM-17	12.26	13472	332	12100	110	13984	183
ML-3	12.40	13646**	339				
HZM-35	12.78	13985	362	12570	130	14858	286
ML-2	12.86	14152**	369				
HZM-18	12.90	14156	372	12430	110	14586	249
ML-1	12.90	14156**	372				
HZM-100***	12.92	14157	372	12380	85	14492	228
HZM-19	12.93	14158	372	12555	80	14879	221

708

\* Dates described to contain reworked organic material or being fractionated during graphitization (see Hajdas et al.,

710 1995).

711 *\*\* VT-99 dates excluded from modelling due to inconsistencies in documentation.* 

712 \*\*\* unpublished radiocarbon age (KIA-1460)





Core section	From	То	Length	Composite core section end
	[mm]	[mm]	[mm]	depth [mm]
HZM19_07_01	138	800	662	662
HZM19_08_01	305	755	451	1113
HZM19_07_02	243	924	681	1794
HZM19_08_02	380	839	459	2254
HZM19_07_03	229	912	683	2936
HZM19_08_03	375	714	339	3275
HZM19_07_04	243	800	557	3833
HZM19_08_04	235	994	759	4592
HZM19_10_01	90	913	823	5415
HZM19_08_05	630	930	299	5715
HZM19_10_02	183	877	693	6409
HZM19_08_06	596	957	361	6770
HZM19_10_03	87	827	740	7510
HZM19_08_07	562	971	409	7919
HZM19_10_04	179	870	691	8611
HZM19_08_08	641	967	326	8937
HZM19_10_05	137	859	722	9659
HZM19_11_06	395	655	260	9919
HZM19_08_10	35	974	939	10859
Technical gap			129	10988
HZM19_10_07	30	810	780	11768
HZM19_11_07	710	1012	302	12071
HZM19_10_08	72	902	830	12902
HZM19_11_08	326	1245	919	13822
HZM19_07_17	100	920	820	14643

714 Table A3: Core section depths of the composite profile HZM19 with resulting composite end depths for each core.

715 716





	Human phase	Last century	Middle Ages / Little Ice Age	Migration Period / Early Middle Ages	Iron Age / Roman Period								
	Biozone	Subatlantic	Subatlantic	Subatlantic	Subatlantic	Subboreal/Atlantic	Boreal	Preboreal	Preboreal	Preboreal	Younger Dryas	Bölling/Alleröd	Pleniclacial (Late Weichselian)
	Composite depth [mm]	1057	3081	4308	5535	9280	9852	10025	10745	10855	11258	12859	14643
To	Section depth [mm]	700	520	710	750	480	588	140	860	970	300	859	920
	Section	HZM19_08_01	HZM19_08_03	HZM19_08_04	HZM19_08_05	HZM19_10_05	HZM19_11_06	HZM19_08_10	HZM19_08_10	HZM19_08_10	HZM19_10_07	HZM19_10_08	HZM19_07_17
	Composite depth [mm]	11	1058	3081	4308	5535	9280	9852	10025	10745	10855	11258	12860
From	Section depth [mm]	138	700	520	710	750	480	588	140	860	026	300	860
	Section	HZM19_07_01	HZM19_08_01	HZM19_08_03	HZM19_08_04	HZM19_08_05	HZM19_10_05	HZM19_11_06	HZM19_08_10	HZM19_08_10	HZM19_08_10	HZM19_10_07	HZM19_10_08
	Lithozone	H12	H11	H10	태	88	H7	9H	H5	H4	Ħ3	H2	Ħ

### 718 Table A4: Core section and composite depths of lithozones H1 to H12 for HZM19





719	Table A5: Additional dates for the HZM19 chronology with composite depths, ages (cal. BP) and errors used for Bacon
720	calculations. LST age with error is from Reinig et al. (2020).

Event	HZM19 comp. depth (cm)	Age (cal. BP)	error
Sediment surface	0.00	-69	1
Chernobyl accident	47.20*	-36	1
Maximum atomic bomb tests	67.20*	-13	1
First atomic bomb tests	79.20*	0	1
Laacher See Tephra	1160.00	13,006	9

721 \* 22 cm subtracted due to slump event documented by Pb-210 data.





- 723 Table A6: Age estimations for VT-99 and Models A-D with their 95% confidence intervals in brackets for Ulmener Maar
- 724 Tephra (UMT), Younger Dryas/Preboreal-transition (YD/PB), YD duration, Allerød/Younger Dryas-transition (AL/YD),
- 725 predicted YD hiatus with duration and position, Laacher See Tephra (LST), Maximum model age at 12.93 m with its mean
- 726 and maximum age ranges and position of the maximum age range and maximum difference between VT-99 and each of
- the model ranges.

1

Chronology	VT-99	Α	В	C	D
Age of	10999	10961	10965	10952	10981
UMT	[10782, 11216]	782, 11216] [10784, 11090] [10787, 11093]		[10788, 11067]	[10829, 11088]
YD/PB	11622	11674	11723	11682	11655
transition	11052	[11461, 11965]	[11486, 12070]	[11494, 11913]	[11499, 11845]
YD duration	974	1038	1014	1012	1073
AL/YD		12712	12737	12694	12728
transition	12606	[12517, 12880]	[12562, 12880]	[12475, 12869]	[12595, 12838]
Duration of YD hiatus	320	320 623 603		583	686
End of YD hiatus	12025	11863	11952	11901	11854
	12025	[11571, 12269]	[11623, 12502]	[11646, 12207]	[11651, 12098]
Age of	12880	13010	13010	13009	13011
LST	[12583, 13177]	[12984, 13042]	[12985, 13043]	[12984, 13037]	[12984, 13043]
Maximum model age	14158	14615	14456	14614	14485
(at 12.93 m)	[13786, 14530]	[14339, 14926]	[14236, 14749]	[14332, 14919]	[14287, 14721]
Mean	282	468	456	329	229
age range	202	400	-50	525	
Maximum age range	744	1056	1064	749	447
Max. age range position (m)	12.93	8.86	8.78	9.18	11.09
Maximum difference to VT-99 age range	0	655	665	401	0

728





# 730 Data Availability

- The results of the different age-depth models carried out for the lacustrine sediment record
- 732 from Holzmaar are accessible via the PANGAEA data archiving and publication system at
- 733 https://doi.org/10.1594/PANGAEA.xxxxx.

# 734 Author contributions

- 735 SB and BZ conducted the fieldwork and conceptualized the study. SB described and sampled the
- race sediment, modified and run the Bayesian age-depth models, visualized the data and drafted the
- 737 first version of the manuscript. WT measured and interpreted lead and cesium data. All authors
- contributed to the writing and to revising of the manuscript.

# 739 **Competing interests**

740 The contact author declares that neither she nor her co-authors have any competing interests.

# 741 Disclaimer

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# 747 **References**

- Anderson, R. Y. and Dean, W. E.: Lacustrine varve formation through time, Palaeogeogr. Palaeocl.,
  62, 215–235, https://doi.org/10.1016/0031-0182(88)90055-7, 1988.
- 750 Baier, J., Lücke, A., Negendank, J. F. W., Schleser, G.-H., and Zolitschka, B.: Diatom and
- 751 geochemical evidence of mid- to late Holocene climatic changes at Lake Holzmaar, West-Eifel
- 752 (Germany), Quatern. Int., 113, 81–96, https://doi.org/10.1016/S1040-6182(03)00081-8, 2004.
- 753 Blaauw, M.: Methods and code for 'classical' age-modelling of radiocarbon sequences, Quat.
- 754 Geochronol., 5, 512–518, https://doi.org/10.1016/j.quageo.2010.01.002, 2010.
- Blaauw, M. and Christen, J. A.: Flexible paleoclimate age-depth models using an autoregressive
  gamma process, Bayesian Anal., 6, 457–474, https://doi.org/10.1214/11-BA618, 2011.
- 757 Blaauw, M., Christen, J. A., Bennett, K. D., and Reimer, P. J.: Double the dates and go for Bayes —
- 758 Impacts of model choice, dating density and quality on chronologies, Quaternary Sci. Rev., 188,
- 759 58–66, https://doi.org/10.1016/j.quascirev.2018.03.032, 2018.





- 760 Blaauw, M., Christen, J. A., Lopez, M. A. A., Vazquez, J. E., V, O. M. G., Belding, T., Theiler, J., Gough,
- 761 B., and Karney, C.: rbacon: Age-Depth Modelling using Bayesian Statistics, CRAN [code], 2021.
- 762 Bonk, A., Müller, D., Ramisch, A., Kramkowski, M. A., Noryśkiewicz, A. M., Sekudewicz, I.,
- 763 Gąsiorowski, M., Luberda-Durnaś, K., Słowiński, M., Schwab, M., Tjallingii, R., Brauer, A., and
- 764 Błaszkiewicz, M.: Varve microfacies and chronology from a new sediment record of Lake Gościąż
- (Poland), Quaternary Sci. Rev., 251, 106715, https://doi.org/10.1016/j.quascirev.2020.106715,
   2021.
- 767 Brauer, A.: Weichselzeitliche Seesedimente des Holzmaars Warvenchronologie des
- Hochglazials und Nachweis von Klimaschwankungen, Ph.D. thesis, Universität Trier, Documenta
   naturae, 85, 1–210, 1994.
- 770 Brauer, A., Hajdas, I., Negendank, J. F. W., Rein, B., Vos, H., and Zolitschka, B.: Warvenchronologie
- eine Methode zur absoluten Datierung und Rekonstruktion kurzer und mittlerer solarer
- Periodizitäten, Geowissenschaften, 12, 325–332, 1994.
- 773 Brauer, A., Endres, C., Günter, C., Litt, T., Stebich, M., and Negendank, J. F. W.: High resolution
- 774 sediment and vegetation responses to Younger Dryas climate change in varved lake sediments
- from Meerfelder Maar, Germany, Quaternary Sci. Rev., 18, 321–329,
- 776 https://doi.org/10.1016/S0277-3791(98)00084-5, 1999.
- 777 Brooks, S. P. and Gelman, A.: General Methods for Monitoring Convergence of Iterative
- 778 Simulations, J. Comput. Graph. Stat., 7, 434–455,
- 779 https://doi.org/10.1080/10618600.1998.10474787, 1998.
- 780 Büchel, G.: Maars of the Westeifel, Germany, in: Paleolimnology of European Maar Lakes, edited
- 781 by: Negendank, J. F. W. and Zolitschka, B., Springer, Berlin, Heidelberg, 1–13,
- 782 https://doi.org/10.1007/BFb0117585, 1993.
- De Geer, G.: A geochronology of the last 12,000 years., Eleventh International Geological
  Congress, Stockholom, 1, 241–253, 1912.
- 785 Dean, W. E., Bradbury, J. P., Anderson, R. Y., and Barnosky, C. W.: The Variability of Holocene
- 786 Climate Change: Evidence from Varved Lake Sediments, Science, 226, 1191–1194,
- 787 https://doi.org/10.1126/science.226.4679.1191, 1984.
- 788 García, M. L., Birlo, S., and Zolitschka, B.: Paleoenvironmental changes of the last 16,000 years
- 789 based on diatom and geochemical stratigraphies from Holzmaar (West-Eifel Volcanic Field,
- 790 Germany), Quaternary Sci. Rev., accepted manuscript,
- 791 https://doi.org/10.1016/j.quascirev.2022.107691, 2022.
- 792 Goslar, T., Kuc, T., Ralska-Jasiewiczowa, M., Rózánski, K., Arnold, M., Bard, E., van Geel, B., Pazdur,
- 793 M., Szeroczyńska, K., Wicik, B., Więckowski, K., and Walanus, A.: High-resolution lacustrine
- record of the late glacial/holocene transition in central Europe, Quaternary Sci. Rev., 12, 287–
  294, https://doi.org/10.1016/0277-3791(93)90037-M, 1993.
- Hajdas, I., Zolitschka, B., Ivy-Ochs, S. D., Beer, J., Bonani, G., Leroy, S. A. G., Negendank, J. W.,
- 797 Ramrath, M., and Suter, M.: AMS radiocarbon dating of annually laminated sediments from lake
- Holzmaar, Germany, Quaternary Sci. Rev., 14, 137–143, https://doi.org/10.1016/0277 3791(94)00123-S, 1995.
- 800 Hajdas, I., Bonani, G., and Zolitschka, B.: Radiocarbon Dating of Varve Chronologies: Soppensee
- and Holzmaar Lakes after Ten Years, Radiocarbon, 42, 349–353,
- 802 https://doi.org/10.1017/S0033822200030290, 2000.





- 803 Hajdas-Skowronek, I.: Extension of the radiocarbon calibration curve by AMS dating of
- laminated sediments of Lake Soppensee and Lake Holzmaar, Ph. D thesis, ETH Zurich,
   https://doi.org/10.3929/ETHZ-A-000916163, 1993.
- 805 https://doi.org/10.3929/ETHZ-A-000916163, 1993.
- Haslett, J. and Parnell, A.: A simple monotone process with application to radiocarbon-dated
  depth chronologies, J. R. Stat. Soc. C.-Appl., 57, 399–418, https://doi.org/10.1111/j.1467-
- 808 9876.2008.00623.x, 2008.
- 809 Kienel, U., Schwab, M. J., and Schettler, G.: Distinguishing climatic from direct anthropogenic
- 810 influences during the past 400 years in varved sediments from Lake Holzmaar (Eifel, Germany),
- 811 J. Paleolimnol., 33, 327–347, https://doi.org/10.1007/s10933-004-6311-z, 2005.
- Lacourse, T. and Gajewski, K.: Current practices in building and reporting age-depth models,
  Quaternary Res., 96, 28–38, https://doi.org/10.1017/qua.2020.47, 2020.
- Leroy, S. A. G., Zolitschka, B., Negendank, J. F. W., and Seret, G.: Palynological analyses in the
  laminated sediment of Lake Holzmaar (Eifel, Germany): duration of Lateglacial and Preboreal
  biozones, Boreas, 29, 52–71, https://doi.org/10.1111/j.1502-3885.2000.tb01200.x, 2000.
- Litt, T., Schölzel, C., Kühl, N., and Brauer, A.: Vegetation and climate history in the Westeifel
  Volcanic Field (Germany) during the past 11 000 years based on annually laminated lacustrine
  maar sediments, Boreas, 38, 679–690, https://doi.org/10.1111/j.1502-3885.2009.00096.x,
  2009.
- Lorenz, V.: Explosive Volcanism of the West Eifel Volcanic Field/Germany, in: Developments in
  Petrology, vol. 11, edited by: Kornprobst, J., Elsevier, 299–307, https://doi.org/10.1016/B978-0444-42273-6.50026-2, 1984.
- 824 Lorenz, V., Lange, T., and Büchel, G.: Die Vulkane der Westeifel, Jahresberichte und Mitteilungen
- 825 des Oberrheinischen Geologischen Vereins, 102, 379–411,
- 826 https://doi.org/10.1127/jmogv/102/0022, 2020.
- Lotter, A. F.: Absolute Dating of the Late-Glacial Period in Switzerland Using Annually Laminated
  Sediments, Quaternary Res., 35, 321–330, https://doi.org/10.1016/0033-5894(91)90048-A,
  1991.
- 830 Lottermoser, B. G., Oberhänsli, R., Zolitschka, B., Negendank, J. F. W., Schütz, U., and Boenecke, J.:
- 831 Environmental geology and geochemistry of lake sediments (Holzmaar, Eifwl, Germany), in:
- 832 Paleolimnology of European Maar Lakes, vol. 49, edited by: Negendank, J. F. W. and Zolitschka,
- 833 B., Springer Berlin Heidelberg, Berlin, Heidelberg, 305–316,
- 834 https://doi.org/10.1007/BFb0117603, 1993.
- Lücke, A., Schleser, G. H., Zolitschka, B., and Negendank, J. F. W.: A Lateglacial and Holocene
  organic carbon isotope record of lacustrine palaeoproductivity and climatic change derived from
  varved lake sediments of Lake Holzmaar, Germany, Quaternary Sci. Rev., 22, 569–580,
- 838 https://doi.org/10.1016/S0277-3791(02)00187-7, 2003.
- 839 Martin-Puertas, C., Walsh, A. A., Blockley, S. P. E., Harding, P., Biddulph, G. E., Palmer, A., Ramisch,
- 840 A., and Brauer, A.: The first Holocene varve chronology for the UK: Based on the integration of
- 841 varve counting, radiocarbon dating and tephrostratigraphy from Diss Mere (UK), Quat.
- 842 Geochronol., 61, 101134, https://doi.org/10.1016/j.quageo.2020.101134, 2021.
- 843 Meyer, W.: Zur Entstehung der Maare in der Eifel, Z. Dtsch. Ges. Geowiss., 141–155,
- 844 https://doi.org/10.1127/zdgg/136/1985/141, 1985.





- 845 Meyer, W.: Geologie der Eifel, 4th ed., Schweizerbart Science Publishers, Stuttgart, Germany,
  846 2013.
- 847 Meyer, W. and Stets, J.: Pleistocene to Recent tectonics in the Rhenish Massif (Germany), Neth. J.
- 848 Geosci., 81, 217–221, https://doi.org/10.1017/S0016774600022460, 2002.
- 849 Muggeo, V. M. R.: segmented: Regression Models with Break-Points / Change-Points Estimation,
   850 CRAN [code], 2022.
- 851 O'Sullivan, P. E.: Annually-laminated lake sediments and the study of Quaternary environmental
- 852 changes a review, Quaternary Sci. Rev., 1, 245–313, https://doi.org/10.1016/0277-
- 853 3791(83)90008-2, 1983.
- 854 Prasad, S. and Baier, J.: Tracking the impact of mid- to late Holocene climate change and
- 855 anthropogenic activities on Lake Holzmaar using an updated Holocene chronology, Global
- 856 Planet. Change, 122, 251–264, https://doi.org/10.1016/j.gloplacha.2014.08.020, 2014.
- 857 R Core Team: R: A Language and Environment for Statistical Computing, 2021.
- Ramsey, C. B.: Deposition models for chronological records, Quaternary Sci. Rev., 27, 42–60,
  https://doi.org/10.1016/j.quascirev.2007.01.019, 2008.
- Ramsey, C. B.: Bayesian Analysis of Radiocarbon Dates, Radiocarbon, 51, 337–360,
  https://doi.org/10.1017/S0033822200033865, 2009.
- 862 Raubitschek, S., Lücke, A., and Schleser, G. H.: Sedimentation patterns of diatoms in Lake
- Holzmaar, Germany (on the transfer of climate signals to biogenic silica oxygen isotope
   proxies), J. Paleolimnol., 21, 437–448, 1999.
- Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Bronk Ramsey, C., Butzin, M.,
  Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J.,
- 867 Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., Palmer, J. G., Pearson, C., van
- der Plicht, J., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Turney, C. S. M., Wacker, L.,
- Adolphi, F., Büntgen, U., Capano, M., Fahrni, S. M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P.,
- 870 Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., and Talamo, S.: The
- 871 INTCAL20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP),
- 872 Radiocarbon, 62, 725–757, https://doi.org/10.1017/RDC.2020.41, 2020.
- 873 Reinig, F., Wacker, L., Jöris, O., Oppenheimer, C., Guidobaldi, G., Nievergelt, D., Adolphi, F.,
- 874 Cherubini, P., Engels, S., Esper, J., Land, A., Lane, C., Pfanz, H., Remmele, S., Sigl, M., Sookdeo, A.,
- and Büntgen, U.: Precise date for the Laacher See eruption synchronizes the Younger Dryas,
- 876 Nature, 595, 66–69, https://doi.org/10.1038/s41586-021-03608-x, 2021.
- 877 Saarnisto, M.: Long varve series in Finland, Boreas, 14, 133–137,
- 878 https://doi.org/10.1111/j.1502-3885.1985.tb00905.x, 1985.
- Saarnisto, M.: Annually laminated lake sediments, in: Handbook of Holocene palaeoecology and
  palaeohydrology, edited by: Berglund, B. E., John Wiley and Sons Ltd, Chichester, 343–370, 1986.
- 881 Scharf, B.: Limnologische Beschreibung, Nutzung und Unterhaltung von Eifelmaaren,
- 882 Ministerium für Umwelt und Gesundheit Rheinland-Pfalz, Mainz, 1987.
- 883 Scharf, B. W. and Oehms, M.: Physical and chemical characteristics, in: Limnology of Eifel maar
- lakes. Ergebnisse der Limnologie, vol. 38, edited by: Scharf, B. W. and Björk, S., E. Schweizerbart,
   Stuttgart, 63–83, 1992.





- 886 Schmincke, H.-U.: The Quaternary Volcanic Fields of the East and West Eifel (Germany), in:
- 887 Mantle Plumes: A Multidisciplinary Approach, edited by: Ritter, J. R. R. and Christensen, U. R.,
- 888 Springer, Berlin, Heidelberg, 241–322, https://doi.org/10.1007/978-3-540-68046-8\_8, 2007.
- 889 Schmincke, H.-U.: Vulkane der Eifel, 2nd ed., Springer, Berlin, Heidelberg, 2014.
- 890 Schnurrenberger, D., Russell, J., and Kelts, K.: Classification of lacustrine sediments based on
- 891 sedimentary components, J. Paleolimnol., 29, 141–154,
- 892 https://doi.org/10.1023/A:1023270324800, 2003.
- 893 Shanahan, T. M., Beck, J. W., Overpeck, J. T., McKay, N. P., Pigati, J. S., Peck, J. A., Scholz, C. A., Heil,
- 894 C. W., and King, J.: Late Quaternary sedimentological and climate changes at Lake Bosumtwi
- 895 Ghana: New constraints from laminae analysis and radiocarbon age modeling, Palaeogeogr.
- 896 Palaeocl., 361–362, 49–60, https://doi.org/10.1016/j.palaeo.2012.08.001, 2012.
- 897 Sirocko, F., Dietrich, S., Veres, D., Grootes, P. M., Schaber-Mohr, K., Seelos, K., Nadeau, M.-J.,
- 898 Kromer, B., Rothacker, L., Röhner, M., Krbetschek, M., Appleby, P., Hambach, U., Rolf, C., Sudo, M.,

and Grim, S.: Multi-proxy dating of Holocene maar lakes and Pleistocene dry maar sediments in

- 900 the Eifel, Germany, Quaternary Sci. Rev., 62, 56–76,
- 901 https://doi.org/10.1016/j.quascirev.2012.09.011, 2013.
- 902 Stuiver, M., Reimer, P. J., Bard, E., Beck, J. W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, G.,
- 903 Van Der Plicht, J., and Spurk, M.: INTCAL98 Radiocarbon Age Calibration, 24,000–0 cal BP,
- 904 Radiocarbon, 40, 1041–1083, https://doi.org/10.1017/S0033822200019123, 1998.
- Telford, R., Heegaard, E., and Birks, H.: All age-depth models are wrong: but how badly?,
  Quaternary Sci. Rev., 23, 1–5, https://doi.org/10.1016/j.quascirev.2003.11.003, 2004.
- 907 Trachsel, M. and Telford, R. J.: All age-depth models are wrong, but are getting better, Holocene,
  908 27, 860-869, https://doi.org/10.1177/0959683616675939, 2017.
- 909 Vandergoes, M. J., Howarth, J. D., Dunbar, G. B., Turnbull, J. C., Roop, H. A., Levy, R. H., Li, X., Prior,
- 910 C., Norris, M., Keller, L. D., Baisden, W. T., Ditchburn, R., Fitzsimons, S. J., and Bronk Ramsey, C.:
- 911 Integrating chronological uncertainties for annually laminated lake sediments using layer
- counting, independent chronologies and Bayesian age modelling (Lake Ohau, South Island, New
   Zealand), Quaternary Sci. Rev., 188, 104–120, https://doi.org/10.1016/j.quascirev.2018.03.015,
- 914 2018.
- 915 Zolitschka, B.: Spätquartäre Sedimentationsgeschichte des Meerfelder Maares (Westeifel).
- 916 Mikrostratigraphie jahreszeitlich geschichteter Seesedimente, E&G Quaternary Sci. J., 38, 87–93,
- 917 https://doi.org/10.3285/eg.38.1.08, 1988.
- Zolitschka, B.: Jahreszeitlich geschichtete Seesedimente aus dem Holzmaar und dem Meerfelder
  Maar, Z. Dtsch. Ges. Geowiss., 25–33, https://doi.org/10.1127/zdgg/140/1989/25, 1989.
- 920 Zolitschka, B.: Jahreszeitlich geschichtete Seesedimente ausgewählter Eifelmaare -
- 921 paläolimnologische Untersuchung als Beitrag zur spät- und postglazialen Klima- und
- 922 Besiedlungsgeschichte, Ph.D. thesis, Universität Trier, Documenta naturae, 60, 226, 1990.
- Zolitschka, B.: Absolute dating of late Quaternary Lacustrine sediments by high resolution varve
   chronology, 214, 59–61, https://doi.org/10.1007/BF00050932, 1991.
- 925 Zolitschka, B.: Climatic change evidence and lacustrine varves from maar lakes, Germany, Clim.
- 926 Dynam., 6, 229–232, https://doi.org/10.1007/BF00193535, 1992.





- 927 Zolitschka, B.: A 14,000 year sediment yield record from western Germany based on annually
- 928 laminated lake sediments, Geomorphology, 22, 1–17, https://doi.org/10.1016/S0169-
- 929 555X(97)00051-2, 1998a.
- 930 Zolitschka, B.: Paläoklimatische Bedeutung laminierter Sedimente: Holzmaar (Eifel,
- 931 Deutschland), Lake C2 (Northwest-Territorien, Kanada) und Lago Grande di Monticchio
- 932 (Basilicata, Italien), Habil. thesis, Universität Potsdam, Relief Boden Paläoklima, 13, 176, 1998b.
- 933 Zolitschka, B., Haverkamp, B., and Negendank, J. F. W.: Younger Dryas Oscillation Varve Dated
- 934 Microstratigraphic, Palynological and Palaeomagnetic Records from Lake Holzmaar, Germany,
- 935 in: The Last Deglaciation: Absolute and Radiocarbon Chronologies, edited by: Bard, E. and
- 936 Broecker, W. S., Springer Berlin Heidelberg, Berlin, Heidelberg, 81–101,
- 937 https://doi.org/10.1007/978-3-642-76059-4\_6, 1992.
- 938 Zolitschka, B., Brauer, A., Negendank, J. F. W., Stockhausen, H., and Lang, A.: Annually dated late
- 939 Weichselian continental paleoclimate record from the Eifel, Germany, Geology, 28, 783–786,
- 940 https://doi.org/10.1130/0091-7613(2000)28<783:ADLWCP>2.0.CO;2, 2000.
- 941 Zolitschka, B., Francus, P., Ojala, A. E. K., and Schimmelmann, A.: Varves in lake sediments a
- 942 review, Quaternary Sci. Rev., 117, 1–41, https://doi.org/10.1016/j.quascirev.2015.03.019, 2015.