

1 **A varved lake sediment record of the ^{10}Be solar activity proxy for the**
2 **Lateglacial-Holocene transition**

3 Markus Czymzik^{a,*}, Florian Adolphi^a, Raimund Muscheler^a, Florian Mekhaldi^a, Celia Martin-
4 Puertas^b, Ala Aldahan^c, Göran Possnert^d, Achim Brauer^b

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6 ^a Department of Geology, Quaternary Sciences, Lund University, 22362 Lund, Sweden

7 ^b GFZ-German Research Centre for Geosciences, Section 5.2 Climate Dynamics and Landscape
8 Evolution, 14473 Potsdam, Germany

9 ^c Department of Geology, United Arab Emirates University, 15551 Al Ain, UAR

10 ^d Tandem Laboratory, Uppsala University, 75120 Uppsala, Sweden

11 *Corresponding author. Tel.: 0046 46 222 1729. Email address: markus.czymzik@geol.lu.se (M.
12 Czymzik).

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14 **Keywords:** ^{10}Be , varved lake sediments, solar activity, time-scales

15 **Highlights:**

16 ^{10}Be record from varved lake sediments covering the Lateglacial-Holocene transition

17 New approach quantifies environmental influences on ^{10}Be deposition

18 Indicates potential of ^{10}Be in varved lake sediments for solar activity reconstruction

19 Indicates potential of ^{10}Be in varved lake sediments as synchronization tool

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25 **Abstract**

26 Solar modulated variations in cosmogenic radionuclide production provide both information on
27 past changes in the activity of the Sun and a global synchronization tool. However, to date the
28 use of cosmogenic radionuclides for these applications is almost exclusively based on ^{10}Be
29 records from ice cores and ^{14}C time-series from tree rings, all including archive-specific
30 limitations. We present the first ^{10}Be record from annually laminated (varved) lake sediments for
31 the Lateglacial-Holocene transition from Meerfelder Maar. We quantify environmental
32 influences on the catchment and, consequently, ^{10}Be deposition using a new approach based on
33 regression analyses between our ^{10}Be record and environmental proxy time-series from the same
34 archive. Our analyses suggest that environmental influences contribute to up to 37 % of the
35 variability in our ^{10}Be record, but cannot be the main explanation for major ^{10}Be excursions.
36 Corrected for these environmental influences, our ^{10}Be record is interpreted to dominantly reflect
37 changes in solar modulated cosmogenic radionuclide production. The preservation of a solar
38 production signal in ^{10}Be from varved lake sediments highlights the largely unexplored potential
39 of these archives for solar activity reconstruction, as global synchronization tool and, thus, for
40 more robust paleoclimate studies.

41

42 **1. Introduction**

43 Changes in solar activity have been suggested to influence past and modern climates (Gray et al.,
44 2010). An accurate knowledge of changes in the activity of the Sun is crucial for understanding
45 solar influences on climate (Gray et al., 2010). Before satellite measurements of solar irradiation
46 and the observation of sunspots, cosmogenic radionuclides like ^{10}Be in polar ice cores and ^{14}C in
47 tree rings provide key information on changes in solar activity (Beer et al., 1990; Muscheler et
48 al., 2007; Vonmoos et al., 2006). ^{10}Be is produced in the upper atmosphere (about $\frac{2}{3}$ in the
49 stratosphere and $\frac{1}{3}$ in the troposphere) as by-product of cascades of nuclear reactions induced by
50 incident high-energy galactic cosmic rays (Lal and Peters, 1967). The flux of these galactic
51 cosmic rays towards the atmosphere is modulated by solar activity variations through varying
52 heliomagnetic shielding (Lal and Peters, 1967). During periods of higher solar activity and
53 stronger heliomagnetic shielding, less galactic cosmic rays reach the atmosphere and less ^{10}Be is

54 produced. Further ^{10}Be production rate changes introduced by the varying geomagnetic field
55 strength become most likely significant only on >500-year time-scales (Snowball and Muscheler,
56 2007).

57 In addition to the atmospheric production, available cosmogenic radionuclide records are to a
58 varying degree affected by archive-specific so-called system effects: Changing exchange rates
59 between Earth's carbon reservoirs add non-production variations to the atmospheric ^{14}C record
60 (Muscheler et al., 2004). Theoretically, this effect can be accounted for by using a carbon cycle
61 model to calculate the atmospheric ^{14}C production. However, past exchanges between carbon
62 reservoirs are difficult to quantify, particularly in times of abrupt climate changes (Köhler et al.,
63 2006). While ^{10}Be is in comparison to ^{14}C geochemically more stable and thus in principle a
64 more direct indicator of the production rate, inhomogeneous tropospheric mixing and
65 precipitation during the short about 1 to 2-year atmospheric residence time (Raisbeck et al.,
66 1981) cause spatially varying ^{10}Be deposition patterns (Heikkilä et al., 2013; Pedro et al., 2012).
67 Further uncertainties in available ice core ^{10}Be records arise from the assumed depositional
68 mode. In case of wet deposition ^{10}Be concentrations, and in case of dry deposition ^{10}Be fluxes
69 would best reflect the atmospheric production signal (Alley et al., 1995; Delaygue and Bard,
70 2011). However, no single depositional mode correctly reflects reality and the dominant mode of
71 deposition can change over time (Alley et al., 1995). Exploring the potential of ^{10}Be in new
72 archives like varved lake sediments offers a complementary approach for tracking the
73 atmospheric ^{10}Be production signal and, thereby, could improve our knowledge on past changes
74 in solar activity.

75 To date, the potential of ^{10}Be in varved lake sediments is largely unexplored. Chronologies based
76 on varve counting enable the establishment of ^{10}Be records at a chronological precision that is
77 comparable to that for ice cores or tree rings. First calibration studies of annually resolved ^{10}Be
78 time-series from three varved lake sediment archives yielded a correlation between changes in
79 ^{10}Be and solar activity during the 11-year solar 'Schwabe' cycle (Berggren et al., 2010; Czymzik
80 et al., 2015). However, further correspondences with proxy time-series also suggest that
81 environmental factors like e.g. varying organic matter contents and sediment redeposition may
82 influence ^{10}Be deposition in these lakes (Czymzik et al., 2015). Therefore, more detailed
83 investigations are needed to improve the use of ^{10}Be in varved lake sediments as indicator of the

84 atmospheric production rate and, thereby, solar activity. In addition, detecting the common
85 atmospheric radionuclide production signal in varved lake sediments provides the opportunity
86 for continuous climate-independent synchronizations to cosmogenic radionuclide records
87 worldwide. Such a synchronization could e.g. contribute to the discussion on the unresolved
88 rapid chronological shift between the GICC05 ice core and ^{14}C time-scales around the Younger
89 Dryas (Adolphi and Muscheler, 2016; Muscheler et al., 2014).

90 The varved Meerfelder Maar (MFM) lake sediment record is a well-established
91 paleoenvironmental archive, particularly for the Lateglacial-Holocene transition (Brauer et al.,
92 2008, 1999; Engels et al., 2015; Lane et al., 2015; Lücke and Brauer, 2004; Rach et al., 2014).
93 Increased ^{10}Be accumulation rates coinciding with an interval of thicker varves enabled the
94 linkage of a grand solar minimum about 2800 years ago with a synchronous change in regional
95 atmospheric circulation in times of moderate climate variations (Martin-Puertas et al., 2012b).
96 Here, we present the first lake sediment record of ^{10}Be concentrations ($^{10}\text{Be}_{\text{con}}$) at ~20-year
97 resolution covering the Lateglacial-Holocene transition (11310 to 13130 varve a BP; i.e. before
98 AD 1950) from MFM. A novel methodological approach based on complementary
99 environmental proxy time-series from the same archive allows us to systematically investigate
100 the depositional mechanisms and, thereby, track solar induced changes in the atmospheric ^{10}Be
101 production rate. Spanning the early Holocene, Younger Dryas and late Allerød, our record
102 enables us to test the robustness of our results on ^{10}Be deposition in MFM sediments under
103 varying sedimentary regimes and climatic boundary conditions.

104

105 **2. Study site**

106 Meerfelder Maar is situated within the Westeifel Volcanic field (50°6'N, 6°45'E), at an elevation
107 of 334 m a.s.l. (Fig. 1). The contemporary lake has a depth of 18 m and a surface area of 0.25
108 km², covering about 1/3 of the about 150 m deep crater surface (Fig. 1). Meerfelder Maar
109 sediments are continuously varved between ~1500 and 14230 varve a BP (Brauer et al., 2000).
110 Varves during the Holocene comprise couples of diatom and detrital sub-layers. Within the
111 Lateglacial, snowmelt varves (late Younger Dryas), clastic-organic varves (early Younger Dryas)
112 and Fe-rich siderite varves (late Allerød) have been formed (Brauer et al., 1999; Martin-Puertas

113 et al., 2012a). Varve formation in MFM is sensitive to North Atlantic climate variations (Brauer
114 et al., 2008; Martin-Puertas et al., 2012b)

115

116 **3. Methods**

117 *3.1. Sediment sub-sampling*

118 Bulk sediment samples for ^{10}Be measurements were extracted from composite profile MFM09
119 (Lane et al., 2015; Martin-Puertas et al., 2012a) at about 20-year resolution, excluding the
120 Laacher See Tephra. Upper and lower sample boundaries were determined using macroscopic
121 varved dated marker layers (Brauer et al., 2000; Lane et al., 2015).

122 *3.2. ^{10}Be extraction and AMS measurements*

123 After drying and homogenizing, 0.5 mg ^9Be carrier was added to 0.5 g sediment material and Be
124 leached overnight with 7.5 ml 8 M HCl at 60°C. The solution was subsequently filtered to
125 remove the undissolved fractions. Further addition of NH_3 , EDTA and H_2SO_4 induced the
126 precipitation of metal hydroxides, other metals and silicates which were again separated from the
127 solution by filtering (Berggren et al., 2010). The remaining solution was then passed through ion
128 exchange columns (Bio-Rad Polyprep Prefilled Chromatography Columns, 100-200 mesh,
129 hydrogen form) in which Be was retained (Berggren et al., 2010). Be was extracted from the
130 columns through the addition of 7 ml 4 M HCl, and $\text{Be}(\text{OH})_2$ precipitated in a warm water bath
131 using NH_3 (25 %, Suprapur). The samples were washed and dehydrated three times with warm 2
132 % NH_4NO_3 and oxidized to BeO by heating to 600°C. Finally, the samples were mixed with Nb
133 and pressed into sample holders. AMS measurements of BeO were performed at the Uppsala
134 Tandem Laboratory using the reference standard NIST SRM 4325 ($^{10}\text{Be}/^9\text{Be} = 2.68 \cdot 10^{-11}$)
135 (Berggren et al., 2010).

136 *3.3. Environmental proxy time-series*

137 Geochemical, total organic carbon (TOC) and sediment accumulation rate (SAR) datasets at the
138 about 20-year resolution of the ^{10}Be data were constructed from available higher resolution time-
139 series. The element composition was measured on cleaned sediment core halves at 200 μm

140 resolution using an ITRAX X-ray fluorescence (μ -XRF) scanner (Martin-Puertas et al., 2012a).
141 Measured element intensities were centered log-ratio (clr) transformed to minimize the effects of
142 varying sediment properties (Weltje and Tjallingii, 2008). TOC contents of a continuous series
143 of sediment samples were determined from 4 mg decalcified sample aliquots in Ag-capsules
144 using an EA3000-CHNS elemental analyzer. The SAR ($\text{g cm}^{-2} \text{ year}^{-1}$) is the product of varve
145 thickness (cm year^{-1}) and dry density (g cm^{-3}), reflecting a mixture of changes in the deposited
146 sediment volume and composition (Zolitschka, 1998). Microscopic varve thickness
147 measurements were performed on series of overlapping petrographic thin-sections (Brauer et al.,
148 2000; Lane et al., 2015; Martin-Puertas et al., 2012a). Dry density was determined by weighing
149 freeze-dried 1 cm^3 sediment samples.

150 *3.4. Chronology*

151 All investigated time-series are on the MFM2015 time-scale, established by means of varve
152 counting and fixed to the absolute time-scale using tephrochronology and radiocarbon dating (for
153 details see: Brauer et al., 2000, 1999; Lane et al., 2015; Martin-Puertas et al., 2012a). The Vedde
154 Ash in the MFM2015 (12140 ± 40 varve a BP) (Lane et al., 2013) and GICC05 time-scales
155 (12121 ± 114 a BP) (Rasmussen et al., 2006), located about midway through the investigated
156 MFM sediment interval, provides an independent tie-point for a comparison of the MFM ^{10}Be
157 record to those from the GRIP and GISP2 ice cores.

158 *3.5. Statistical significance*

159 Statistical significances of correlations between the $^{10}\text{Be}_{\text{con}}$ record and environmental proxy time-
160 series were assessed using a non-parametric random-phase test (Ebisuzaki, 1997). The test takes
161 into account the effects of autocorrelation present in the time-series (Ebisuzaki, 1997). First,
162 10000 versions of the $^{10}\text{Be}_{\text{con}}$ record were computed that have an identical frequency spectrum as
163 the original record, but randomly differ in the phase of each frequency. The statistical
164 significances of the correlations between the ^{10}Be record and the environmental proxy time-
165 series were then determined by replacing the original $^{10}\text{Be}_{\text{con}}$ record with its phase shifted
166 surrogates and calculating the probability distribution of the correlations that occur by chance.

167

168 **4. Results**

169 $^{10}\text{Be}_{\text{con}}$ were measured in 96 sediment samples from a 158 cm long section (725 to 882 cm
170 composite depth) of composite profile MFM09 (Lane et al., 2015; Martin-Puertas et al., 2012a)
171 (Fig. 2). Mean $^{10}\text{Be}_{\text{con}}$ is $2.7 \cdot 10^8$ atoms g^{-1} . $^{10}\text{Be}_{\text{con}}$ vary distinctly between 2 and $4.7 \cdot 10^8$ atoms
172 g^{-1} (mean $3 \cdot 10^8$ atoms g^{-1}) from 820 to 882 cm composite depth and depict smaller variability
173 between 1.8 and $3.3 \cdot 10^8$ atoms g^{-1} (mean $2.5 \cdot 10^8$ atoms g^{-1}) from 725 to 817 cm composite
174 depth (Fig. 2). Mean AMS measuring uncertainty is $0.1 \cdot 10^8$ atoms g^{-1} . A series of 6 MFM
175 sediment samples yielded $^{10}\text{Be}_{\text{con}}$ up to $45.9 \cdot 10^8$ atoms g^{-1} , distinguished from the remaining
176 record by their exceptionally high ^{10}Be concentrations (up to a factor of 17 higher than the mean
177 of the remaining $^{10}\text{Be}_{\text{con}}$ record). Since (i) we did not observe coinciding distinct changes in
178 sediment accumulation or composition and, (ii) more importantly, these anomalous high values
179 were not replicated by ^{10}Be measurements in sediment samples from the same core position,
180 these six data points were treated as measurement outliers and excluded from the analyses. Due
181 to the 1.387 ± 0.012 Ma long half-life of ^{10}Be (Korschinek et al., 2010) the effect of radioactive
182 decay is negligible in our about 2000-year long ^{10}Be record from the Lateglacial-Holocene
183 transition.

184

185 **5. Discussion**

186 *5.1. Environmental effects on $^{10}\text{Be}_{\text{con}}$ deposition*

187 Regional environmental variations during the Lateglacial-Holocene transition modify catchment
188 processes and might, therefore, bias the atmospheric ^{10}Be production signal in lake sediment
189 archives. Comparing the MFM $^{10}\text{Be}_{\text{con}}$ record to sedimentological and geochemical proxy time-
190 series from the same archive allows us to evaluate these effects.

191 Changing sediment accumulation rates (SAR) might influence $^{10}\text{Be}_{\text{con}}$ in MFM sediments by
192 diluting them more (higher SAR) or less (lower SAR) (Berggren et al., 2010). This is potentially
193 reflected by a significant negative correlation between $^{10}\text{Be}_{\text{con}}$ and SAR ($r=-0.39$, $p<0.01$) (Figs.
194 2 and 3). However, despite this correlation, major changes in SAR (e.g. around 750, 800 and 851
195 cm composite depth) are not reflected by the MFM $^{10}\text{Be}_{\text{con}}$ record (Fig. 2).

196 Relationships with $^{10}\text{Be}_{\text{con}}$ are further noticeable for the element Ti and the Si/Ti ratio, reflecting
197 main sediment components in MFM during the Lateglacial-Holocene transition (Brauer et al.,
198 1999) (Figs. 2 and 3). Ti is indicative of detrital material transported from the catchment into the
199 lake (Martin-Puertas et al., 2012a) and exhibits a significant negative correlation with $^{10}\text{Be}_{\text{con}}$
200 ($r=-0.39$, $p<0.01$) (Fig. 2). However, neither major rises (e.g. at 802 cm composite depth) nor
201 drops in Ti (e.g. at 748 cm composite depth) are paralleled by major shifts in the $^{10}\text{Be}_{\text{con}}$ record
202 (Fig. 2). The Si/Ti ratio is interpreted as an indicator of diatom abundances since Si in MFM
203 sediments represents both detrital input and diatom deposition, while Ti is related to detrital
204 influx only (Martin-Puertas et al., 2012a) (Fig. 2). Like Ti, the Si/Ti ratio is significantly
205 correlated with $^{10}\text{Be}_{\text{con}}$ ($r=0.17$, $p=0.07$), but major shifts in this proxy (e.g. around 728 and 802
206 cm composite depth) do not correspond to major changes in $^{10}\text{Be}_{\text{con}}$ (Fig. 2).

207 Further uncertainties in ^{10}Be production time-series from lake sediments could be caused through
208 the preferential binding of ^{10}Be to a particular sediment fraction. It was suggested that Fe and
209 organic matter are favorable carriers of ^{10}Be (Mann et al., 2012; Willenbring and von
210 Blanckenburg, 2010). High Fe values from 857 to 877 cm composite depth reflect the deposition
211 of siderite varves in MFM, indicative of anoxic bottom water conditions (Fig. 2) (Brauer et al.,
212 2008). $^{10}\text{Be}_{\text{con}}$ and Fe exhibit a significant correlation in the investigated sediments ($r=0.32$,
213 $p<0.01$) (Figs. 2 and 3). However, even though the major drop in Fe at 855 cm composite depth
214 coincides with a distinct decrease in $^{10}\text{Be}_{\text{con}}$, other shifts in Fe (e.g. at 740, 760 and 832 cm
215 composite depth) are not reflected in the $^{10}\text{Be}_{\text{con}}$ record (Fig. 2). These results suggest that the
216 amplitudes of the variations in our $^{10}\text{Be}_{\text{con}}$ record caused by a potential preferential binding to Fe
217 are likely small. One possible reason for this small influence might be that iron cycling in lakes
218 occurs predominantly at the water-sediment interface (Davison, 1993), while ^{10}Be scavenging
219 likely takes place throughout the entire water column.

220 Positive correlations point to a preferential binding of ^{10}Be to organic material in previously
221 measured annually resolved ^{10}Be time-series from recent varved sediments of two central
222 European lakes (Czymzik et al., 2015). While mean TOC concentrations in these two lake
223 sediments are about 10 %, they are generally lower in the investigated MFM sediments (mean
224 4.5 %), with only one short peak reaching about 10 % at 855 cm composite depth (Fig. 2).
225 Nevertheless, $^{10}\text{Be}_{\text{con}}$ and TOC are significantly correlated in the investigated MFM sediment

226 record ($r=0.44$, $p<0.01$) (Fig. 2). However, except for the mentioned peak around 855 cm
227 composite depth, other major shifts in TOC (e.g. at 748 and 798 cm composite depth) do not
228 correspond to distinct changes in the $^{10}\text{Be}_{\text{con}}$ record (Fig. 2). Therefore, potential effects of a
229 preferential binding to TOC likely introduce minor variations and do not obscure major
230 excursions in our $^{10}\text{Be}_{\text{con}}$ record. A reason for this weak linkage to $^{10}\text{Be}_{\text{con}}$ might be the low TOC
231 concentrations in the investigated MFM sediment interval (Fig. 2). Small effects of a preferential
232 binding of ^{10}Be to TOC and Fe are in agreement with a review study concluding that no single
233 constituent dominates the distribution of ^{10}Be in soils (Graly et al., 2010).

234 Mean $^{10}\text{Be}_{\text{con}}$ are about 10 % higher during the early Holocene ($2.8 \cdot 10^8$ atoms g^{-1}) and about 20
235 % higher during the late Allerød ($3 \cdot 10^8$ atoms g^{-1}), compared to the Younger Dryas ($2.5 \cdot 10^8$
236 atoms g^{-1}) (Fig. 2). Varying mean $^{10}\text{Be}_{\text{con}}$ during the three climate periods could be explained by
237 changes in tropospheric mixing and precipitation (Heikkilä et al., 2013) and catchment processes
238 (Czymzik et al., 2015), but also by different atmospheric ^{10}Be production rates, all potentially
239 modifying ^{10}Be deposition at MFM. However, mean $^{10}\text{Be}_{\text{con}}$ changes during these three climate
240 periods do not exceed 20 %, compared to the about 90 % variations during major $^{10}\text{Be}_{\text{con}}$
241 excursions (Fig. 2).

242 To summarize, comparing the MFM $^{10}\text{Be}_{\text{con}}$ record to proxy time-series from the same archive
243 suggests that environmental influences on the catchment cannot be the main explanation for
244 major $^{10}\text{Be}_{\text{con}}$ excursions in the investigated MFM sediments (e.g. around 750, 820, 855 and 875
245 cm composite depth) (Fig. 2). Nevertheless, significant correlations between $^{10}\text{Be}_{\text{con}}$ and SAR,
246 Ti, Si/Ti ratio, TOC and Fe point to influences of varying catchment conditions on $^{10}\text{Be}_{\text{con}}$
247 deposition in our archive (Figs. 2 and 3). In the following section we aim at quantifying and
248 correcting for these influences on $^{10}\text{Be}_{\text{con}}$ deposition in order to extract a regional atmospheric
249 input signal.

250 *5.2. Regional atmospheric ^{10}Be input*

251 In an attempt to extract a regional atmospheric input signal ($^{10}\text{Be}_{\text{con}}$ corrected for the effects of
252 environmental influences on catchment conditions and ^{10}Be deposition), a two-step procedure
253 was applied to the MFM $^{10}\text{Be}_{\text{con}}$ record. First, simple linear regressions were calculated between
254 the MFM $^{10}\text{Be}_{\text{con}}$ record and the significantly correlated proxy time-series SAR, Ti, Si/Ti ratio,

255 TOC and Fe separately, to determine the likely environmental bias ($^{10}\text{Be}_{\text{bias}}$). Second, the
256 resulting $^{10}\text{Be}_{\text{bias}}$ time-series were subtracted from the original MFM $^{10}\text{Be}_{\text{con}}$ record to
257 approximate the regional atmospheric ^{10}Be input ($^{10}\text{Be}_{\text{atmosphere}}$) (Fig. 4a). The equations are as
258 follows:

259 (1) $^{10}\text{Be}_{\text{bias}} = a + x * \text{proxy}$

260 (2) $^{10}\text{Be}_{\text{atmosphere}} = (^{10}\text{Be}_{\text{con}} - ^{10}\text{Be}_{\text{bias}} + \text{mean}(^{10}\text{Be}_{\text{con}})) / \text{mean}(^{10}\text{Be}_{\text{con}})$

261 For evaluating the possibly largest environmental bias on ^{10}Be deposition, we further calculated a
262 $^{10}\text{Be}_{\text{atmosphere}}$ time-series performing a multiple regression analysis between our $^{10}\text{Be}_{\text{con}}$ record and
263 all proxy time-series with a significant correlation (Fig. 4a). The final $^{10}\text{Be}_{\text{atmosphere}}$ curve includes
264 only corrections from proxy time-series with a significant contribution (>90 % level: Si/Ti ratio,
265 TOC) to the final multiple regression (Table 1).

266 All six calculated $^{10}\text{Be}_{\text{atmosphere}}$ time-series depict similar multi-decadal variability and trends,
267 compared to the original MFM $^{10}\text{Be}_{\text{con}}$ record (Fig. 4a). Changing environmental conditions
268 ($^{10}\text{Be}_{\text{bias}}$) explain between 8 and 29 % (mean 18 %) of the variance when the $^{10}\text{Be}_{\text{con}}$ record is
269 corrected using the individual SAR, Ti, Si/Ti ratio, TOC and Fe time-series (Table 1). Corrected
270 using all significantly correlated proxy time-series, $^{10}\text{Be}_{\text{bias}}$ explains 37 % of the variations in the
271 $^{10}\text{Be}_{\text{con}}$ record (Fig. 4a, Table 1). The amplitude of the older part of the $^{10}\text{Be}_{\text{con}}$ peak from 12670
272 to 12770 varve a BP is broadly unchanged when $^{10}\text{Be}_{\text{atmosphere}}$ is calculated using SAR, Ti, Si/Ti
273 ratio and Fe, but reduced by about 30 % when $^{10}\text{Be}_{\text{atmosphere}}$ is calculated using TOC and all
274 significantly correlated proxy time-series (Fig. 4a).

275 To test the robustness of these corrections, we calculated the six $^{10}\text{Be}_{\text{atmosphere}}$ time-series
276 separately for the early Holocene, Younger Dryas and late Allerød (Fig. 4b). The calculated
277 $^{10}\text{Be}_{\text{atmosphere}}$ time-series for the individual climate periods resemble those for the complete record
278 (Fig. 4). This test illustrates that the corrections of the $^{10}\text{Be}_{\text{con}}$ record are not influenced by
279 varying environmental conditions and sedimentary regimes connected to the three climate
280 periods.

281 To conclude, in our analyses environmental influences on catchment conditions account for up to
282 37 % of the variability in the MFM $^{10}\text{Be}_{\text{con}}$ record. Corrected for these influences, the resulting
283 $^{10}\text{Be}_{\text{atmosphere}}$ time-series likely reflect a regional atmospheric input signal. In the following

284 section we will discuss connections between the MFM $^{10}\text{Be}_{\text{atmosphere}}$ time-series and changes in
285 solar activity inferred from other cosmogenic radionuclide records as well as the effects of
286 inhomogeneous tropospheric mixing and precipitation, which are presumably not recorded by the
287 MFM proxy time-series.

288 5.3. Solar modulated ^{10}Be production

289 For deciphering solar modulated changes in ^{10}Be production, we compare a composite (to reduce
290 noise) of the six MFM $^{10}\text{Be}_{\text{atmosphere}}$ time-series to ^{10}Be fluxes from the GRIP (Adolphi et al.,
291 2014) and GISP2 ice cores (Finkel and Nishiizumi, 1997) and ^{14}C production rates derived from
292 tree rings (Muscheler et al., 2014) (Fig. 5). A 500-year high-pass filter was applied to the time-
293 series to minimize the effects of the varying geomagnetic field on cosmogenic radionuclide
294 production (Snowball and Muscheler, 2007). This filter also reduces system effects that are
295 potentially present in the ^{10}Be and ^{14}C records (Adolphi and Muscheler, 2016). The shared
296 variance of the radionuclide records can be considered as an indicator of the solar modulated
297 cosmogenic radionuclide production rate (Muscheler et al., 2007). Maximum differences
298 between the individual $^{10}\text{Be}_{\text{atmosphere}}$ time-series at each point were used as uncertainty ranges
299 (Fig. 5). In addition, bandpass filtering was applied to the cosmogenic radionuclide records to
300 focus on the frequency ranges of the solar Gleissberg (frequencies between $1/75$ and $1/100$ years⁻¹)
301 and De Vries (frequencies between $1/180$ and $1/230$ years⁻¹) cycles (Fig. 6). The Vedde Ash
302 dated to 12140 ± 40 varve a BP in the MFM2015 and 12121 ± 114 a BP in the GICC05 time-
303 scale (Lane et al., 2013; Rasmussen et al., 2006) indicates no age-scale difference between the
304 MFM and GRIP/GISP2 ice core records, within the dating uncertainties (Fig. 5).

305 Most distinctive features of the MFM $^{10}\text{Be}_{\text{atmosphere}}$ composite are three peaks centered at 12400,
306 12750 and 13050 varve a BP and a minimum around 11650 varve a BP (Fig. 5). All these
307 features are also visible in the ^{14}C production rate and GRIP and GISP2 ^{10}Be flux records
308 suggesting that they are related to common solar modulated radionuclide production changes
309 (Fig. 5). Differences between the ^{10}Be records from MFM and the ice cores might be explained
310 by inhomogeneous tropospheric mixing and precipitation causing differing ^{10}Be deposition
311 patterns at the sites of MFM and the ice cores (McHargue and Damon, 1991). Differences
312 between the MFM $^{10}\text{Be}_{\text{con}}$ record and the ^{14}C production rate could be further due to uncorrected
313 carbon cycle influences on the ^{14}C production record (McHargue and Damon, 1991; Siegenthaler

314 et al., 1980). After the production, ^{14}C oxidizes to $^{14}\text{CO}_2$ and enters the global carbon cycle while
315 ^{10}Be attaches to aerosols (McHargue and Damon, 1991; Siegenthaler et al., 1980). Temporal
316 offsets between the MFM and ice core ^{10}Be records might be explained by time-scale differences
317 within the dating uncertainties (Fig. 5).

318 In the frequency range of the solar Gleissberg cycle, the MFM $^{10}\text{Be}_{\text{atmosphere}}$ composite reveals a
319 good agreement with ^{10}Be fluxes in the GRIP ice core and ^{14}C production rates (Fig. 6). The
320 different phase relationship around 12800 a BP might be caused by inhomogeneous tropospheric
321 mixing and precipitation, uncorrected carbon cycle influences, time-scale differences within the
322 dating uncertainties (see the paragraph above for details) and/or a single data point with high/low
323 values that can lead to the inclusion or exclusion of a cycle in the narrowly filtered time-series
324 (Fig. 6). The about 50-year resolution of the GISP2 ^{10}Be flux record inhibits investigating
325 variations in the Gleissberg cycle frequency range.

326 All four cosmogenic radionuclide records reveal notable variability within the frequency range of
327 the solar De Vries cycle (Fig. 6). However, while these variations in the $^{10}\text{Be}_{\text{atmosphere}}$ composite
328 are in-phase with those in the GRIP ^{10}Be flux and ^{14}C production rate records from 11310 to
329 about 12500 a BP, they reveal different relationships and amplitudes from about 12520 to 13310
330 a BP (Fig. 6). Again, the most likely explanation for these differences might be inhomogeneous
331 tropospheric mixing and precipitation, uncorrected carbon cycle influences, time-scale
332 differences within dating uncertainties (see the paragraph above for details) and single outlying
333 data points. The same reasons could explain the phase shift between the MFM $^{10}\text{Be}_{\text{atmosphere}}$
334 composite and the GISP2 ^{10}Be flux record (Fig. 6).

335 To summarize, similarities with the reconstructed ^{14}C production rate and ^{10}Be fluxes in the
336 GRIP and GISP2 ice cores suggest the preservation of the solar production signal in the MFM
337 $^{10}\text{Be}_{\text{atmosphere}}$ composite. Remaining differences between the MFM $^{10}\text{Be}_{\text{atmosphere}}$ composite and
338 the other cosmogenic radionuclide time-series point to inhomogeneous tropospheric mixing and
339 precipitation, uncorrected carbon cycle influences and/or time-scale differences within the dating
340 uncertainties.

341 *5.4. Mechanisms of ^{10}Be deposition*

342 The preservation of the solar modulated production signal in MFM $^{10}\text{Be}_{\text{atmosphere}}$ allows us to
343 draw conclusions about the depositional mechanisms: (i) Increased sediment flux through the
344 water column tends to increase ^{10}Be scavenging and, thereby, does not distinctly influence ^{10}Be
345 concentrations in the sediments (major excursions in SAR are not mirrored by $^{10}\text{Be}_{\text{con}}$ changes of
346 opposite sign (Fig. 2) and ^{10}Be availability does not seem to be a limiting factor in our study) and
347 (ii) higher ^{10}Be concentrations in the lake water increase the amount of ^{10}Be atoms deposited by
348 each sediment particle. In combination, these two effects are comparable to the proposed ^{10}Be
349 wet deposition in ice cores (Alley et al., 1995) and supported by sediment trap studies on ^7Be and
350 ^{10}Be deposition in Lakes Constance and Zurich (Schuler et al., 1991; Vogler et al., 1996). Both
351 sediment trap studies suggest that Be deposition in the lakes is controlled by the particle flux
352 through the water column and atmospheric ^{10}Be input (Schuler et al., 1991; Vogler et al., 1996).
353 Results on ^7Be can be transferred to those from ^{10}Be since both isotopes behave chemically
354 identical (Aldahan et al., 1999).

355 On multi-decadal to centennial scales, ^{10}Be fluxes in the GRIP and GISP2 ice cores during the
356 Holocene vary by about 50 % (Muscheler and Heikkilä, 2011). These variations are in agreement
357 with estimates of solar induced ^{10}Be production rate changes on such time-scales (Masarik and
358 Beer, 1999; Muscheler and Heikkilä, 2011). However, $^{10}\text{Be}_{\text{con}}$ in the investigated MFM
359 sediments shows up to 90 % variability (Fig. 2). Therefore, ^{10}Be flux from the catchment into the
360 lake by surface runoff is likely to contribute to the larger variability in the MFM $^{10}\text{Be}_{\text{con}}$ record.

361

362 **6. Conclusions**

363 We present the first ^{10}Be record from varved lake sediments for the Lateglacial-Holocene
364 transition from Meerfelder Maar. We attempt to quantify regional environmental influences on
365 catchment conditions and ^{10}Be deposition based on regression analyses between our ^{10}Be record
366 and proxy time-series from the same archive. Regional environmental influences contribute to up
367 to 37 % of the variability in our ^{10}Be record, but cannot explain major ^{10}Be excursions. Corrected
368 for environmental influences, our ^{10}Be record is interpreted to dominantly reflect changes in solar
369 modulated cosmogenic radionuclide production. The preservation of the solar production signal
370 indicates the large potential of ^{10}Be in varved lake sediments for solar activity reconstruction and
371 as global synchronization tool. However, our results also indicate the importance of a mechanistic

372 understanding of, partly site-specific, environmental effects on ^{10}Be deposition in lake sediment
373 archives. Therefore, more studies of ^{10}Be in varved sediments from lakes with different
374 lake/catchment characteristics can help to further improve the application of this proxy as
375 indicator of the atmospheric cosmogenic radionuclide production rate.

376

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383 samples and Oliver Rach for measuring TOC contents. ^{10}Be data are available at the PANGAEA
384 data library. We thank two anonymous reviewers for their constructive comments.

385

386

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528 **Table 1.** Statistics for the linear regressions between the Meerfelder Maar $^{10}\text{Be}_{\text{con}}$ record and
529 significantly correlated proxy time-series. **(a)** For simple linear regressions between $^{10}\text{Be}_{\text{con}}$ and
530 SAR, Ti, Si/Ti ratio, TOC and Fe separately. **(b)** For the multiple linear regression between
531 $^{10}\text{Be}_{\text{con}}$ and all five significantly correlated proxy time-series. Only proxy time-series with a
532 significant contribution (90 % level) were included in the final regression.

533

534 **Fig. 1.** Lake-catchment setting of Meerfelder Maar. Geographical position of Meerfelder Maar in
535 western Europe. Topography of the Meerfelder Maar crater and bathymetry of the lake with
536 location of composite sediment profile MFM09.

537

538 **Fig. 2.** Meerfelder Maar ^{10}Be concentrations ($^{10}\text{Be}_{\text{con}}$) and environmental proxy time-series from
539 the same archive. $^{10}\text{Be}_{\text{con}}$ compared with sediment accumulation rate (SAR), Ti, Si/Ti ratio, total
540 organic carbon (TOC) and Fe. The Laacher See Tephra was excluded from the analyses. Gray
541 bars indicate $^{10}\text{Be}_{\text{con}}$ measurement uncertainties. Colored numbers indicate mean $^{10}\text{Be}_{\text{con}}$ for the
542 early Holocene, Younger Dryas and late Allerød. Significance levels of correlations between
543 $^{10}\text{Be}_{\text{con}}$ and proxy time-series were calculated using a random phase test (Ebisuzaki, 1997). Onset
544 (12679 varve a BP) and termination (11590 varve a BP) of the Younger Dryas were defined from
545 Meerfelder Maar sediments (Brauer et al., 2008; Martin-Puertas et al., 2012a).

546

547 **Fig. 3.** Correlation analyses of ^{10}Be concentrations ($^{10}\text{Be}_{\text{con}}$) and environmental proxy time-series
548 from the investigated Meerfelder Maar sediments. $^{10}\text{Be}_{\text{con}}$ plotted against sediment accumulation
549 rate (SAR), Ti, Si/Ti ratio, total organic carbon (TOC) and Fe. All datasets were normalized by
550 dividing by the mean.

551

552 **Fig. 4.** Meerfelder Maar ^{10}Be concentrations ($^{10}\text{Be}_{\text{con}}$) corrected for the effects of varying
553 environmental conditions. $^{10}\text{Be}_{\text{con}}$ corrected for changes in the environment ($^{10}\text{Be}_{\text{atmosphere}}$) as
554 reflected by variations in sediment accumulation rates (SAR), Ti, Si/Ti ratio, total organic carbon
555 (TOC) and Fe. The corrections were calculated using the individual environmental proxy time-
556 series and all significantly correlated proxy time-series, to evaluate the largest possible
557 environmental effects on $^{10}\text{Be}_{\text{con}}$ deposition (the final regression only includes the Si/Ti ratio and
558 TOC proxies with a significant (90 % level) contribution). **(a)** $^{10}\text{Be}_{\text{con}}$ and calculated $^{10}\text{Be}_{\text{atmosphere}}$
559 time-series for the complete record from 11310 to 13130 varve a BP. **(b)** Same as **(a)**, but
560 calculated separately for the early Holocene (11310-11570 varve a BP), Younger Dryas (11610-
561 12670 varve a BP) and late Allerød (12690-13130 varve a BP). Before the analysis, all datasets
562 were resampled to a 20-year resolution and normalized by dividing by the mean.

563

564 **Fig. 5.** 500-year high-pass filtered cosmogenic radionuclide records. The black line represents
565 the Meerfelder Maar $^{10}\text{Be}_{\text{atmosphere}}$ composite (mean of the six $^{10}\text{Be}_{\text{atmosphere}}$ time-series for the
566 period 11310 to 13130 varve a BP). Gray bands indicate the uncertainty ranges of the
567 $^{10}\text{Be}_{\text{atmosphere}}$ composite expressed as the maximum differences between the individual
568 $^{10}\text{Be}_{\text{atmosphere}}$ time-series. The red line depicts the reconstructed ^{14}C production rate (Muscheler et
569 al., 2014). The blue line shows ^{10}Be flux in the GRIP ice core (Adolphi et al., 2014). The green
570 line shows ^{10}Be flux in the GISP2 ice core (Finkel and Nishiizumi, 1997). Both ice core ^{10}Be
571 records are on the GICC05 time-scale. The age of the Vedde Ash was determined to 12140 ± 40
572 varve a BP in the MFM2015 time-scale (Lane et al., 2013) and 12121 ± 114 a BP in the GICC05
573 time-scale of the GRIP/GISP2 ice cores (Rasmussen et al., 2006).

574

575 **Fig. 6.** Comparison of the Meerfelder Maar $^{10}\text{Be}_{\text{atmosphere}}$ composite with other cosmogenic
576 radionuclide records. $^{10}\text{Be}_{\text{atmosphere}}$ composite and reconstructed ^{14}C production rate (Muscheler et
577 al., 2014), ^{10}Be flux from the GRIP ice core (Adolphi et al., 2014) and ^{10}Be flux from the GISP2
578 ice core (Finkel and Nishiizumi, 1997) after high and bandpass filtering. Both ice core records
579 are on the GICC05 time-scale. **(left)** 500-year high pass filtered time-series. **(middle)** Solar
580 Gleissberg cycle (frequencies between $1/75$ and $1/100$ years $^{-1}$). **(right)** Solar De Vries cycle
581 (frequencies between $1/180$ and $1/230$ years $^{-1}$). Gleissberg cycle variations cannot be
582 investigated for the GISP2 ^{10}Be flux time-series due to the on average 50-year resolution of the
583 record.

Table 1

(a) ^{10}Be corrected using single sig. proxy records
$^{10}\text{Be}_{\text{atmosphere}}$ (SAR)
$^{10}\text{Be}_{\text{atmosphere}}$ (Ti)
$^{10}\text{Be}_{\text{atmosphere}}$ (Si/Ti ratio)
$^{10}\text{Be}_{\text{atmosphere}}$ (TOC)
$^{10}\text{Be}_{\text{atmosphere}}$ (Fe)
(b) ^{10}Be corrected using all sig. proxy records
$^{10}\text{Be}_{\text{atmosphere}}$ (Si/Ti ratio + TOC; not significant at 90% level: SAR, Ti, Fe)

Figure 1

[Click here to download high resolution image](#)

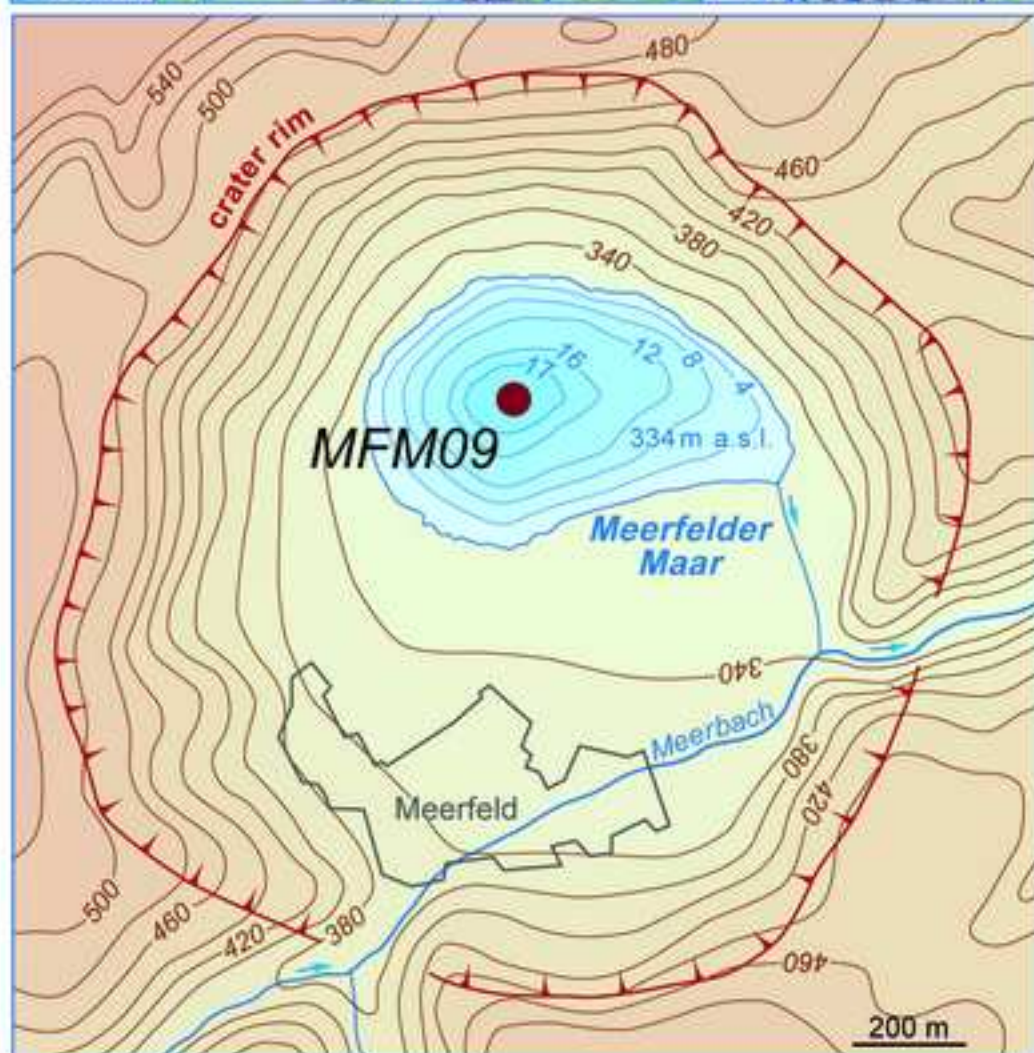


Figure 2

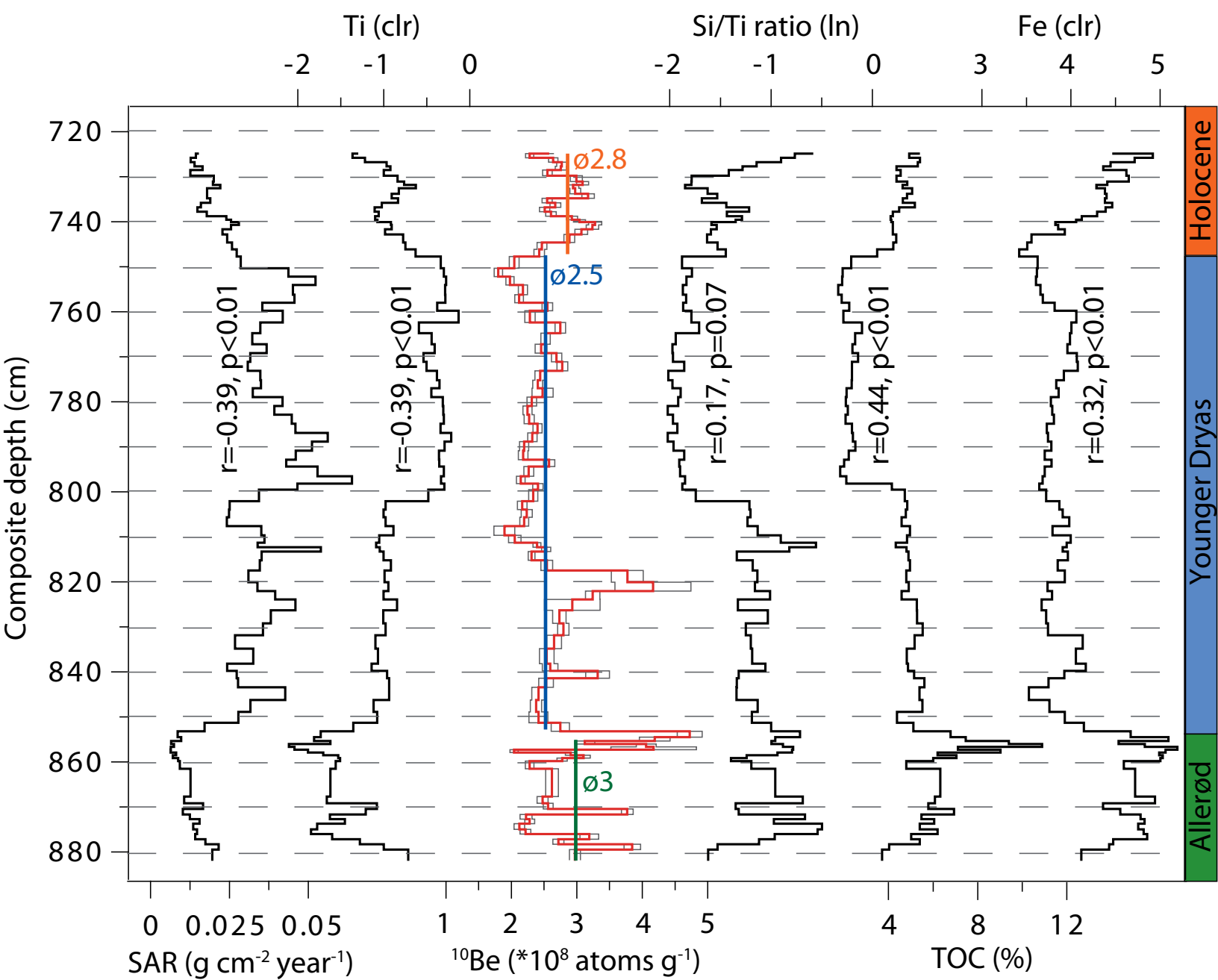


Figure 3

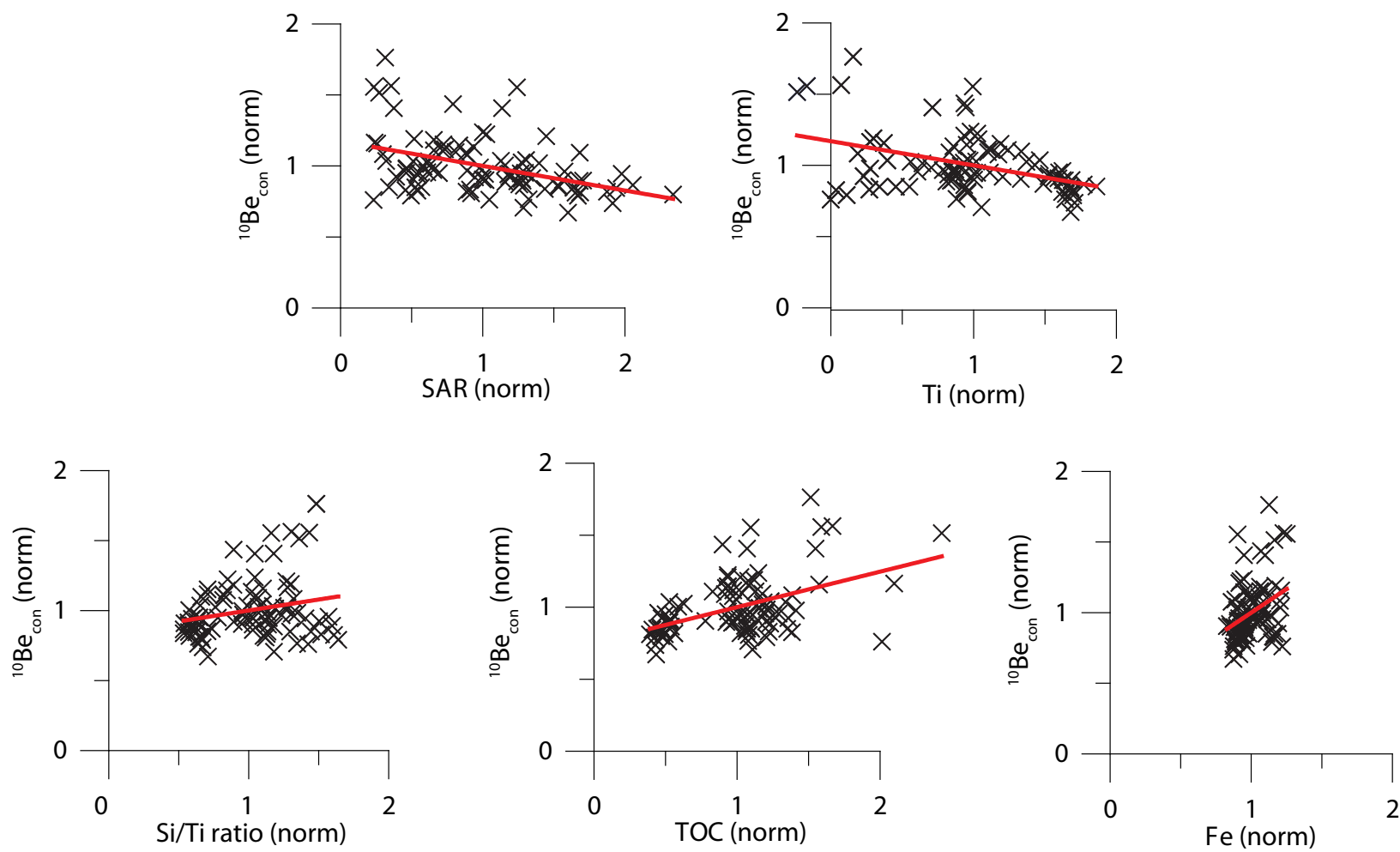


Figure 4

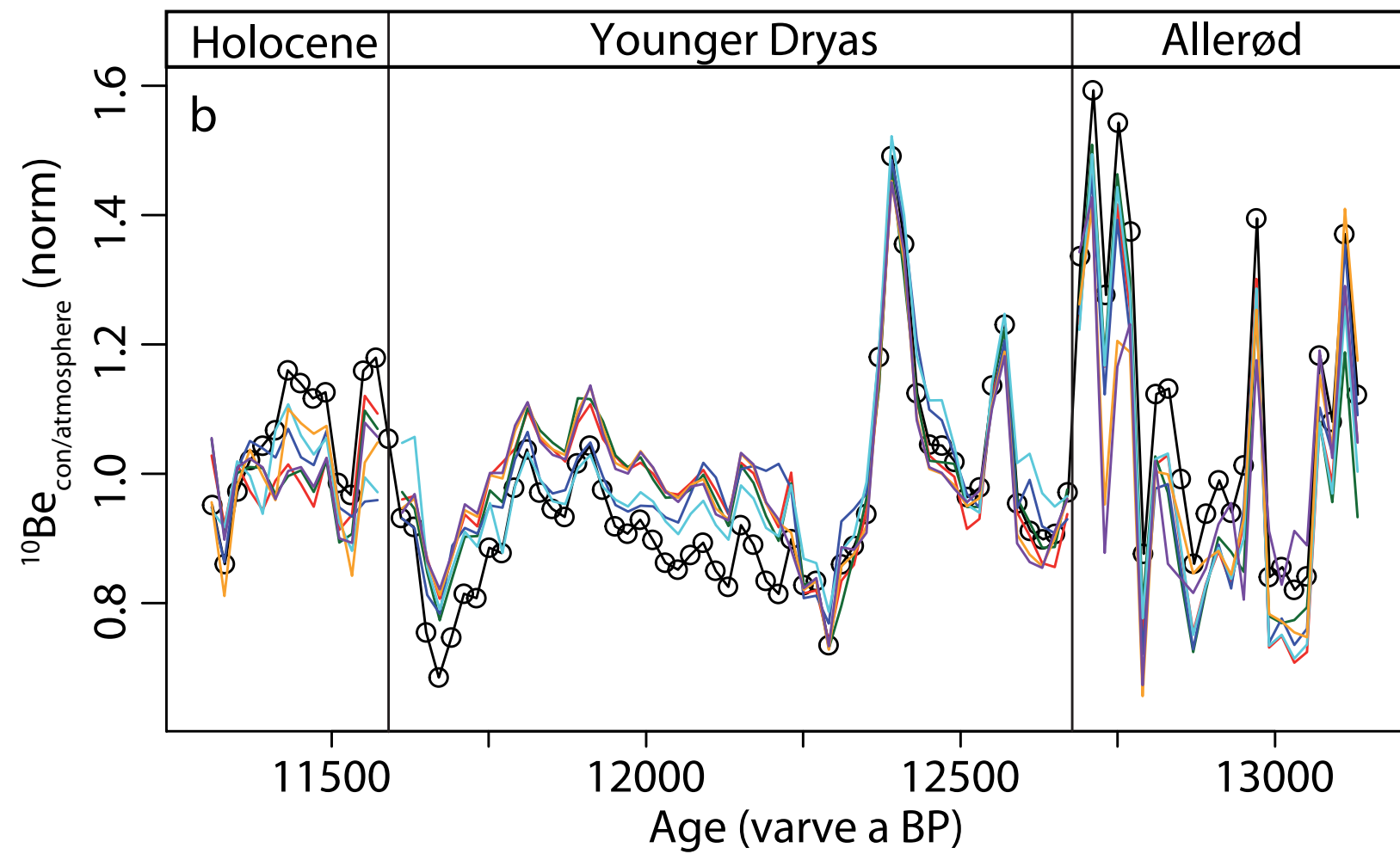
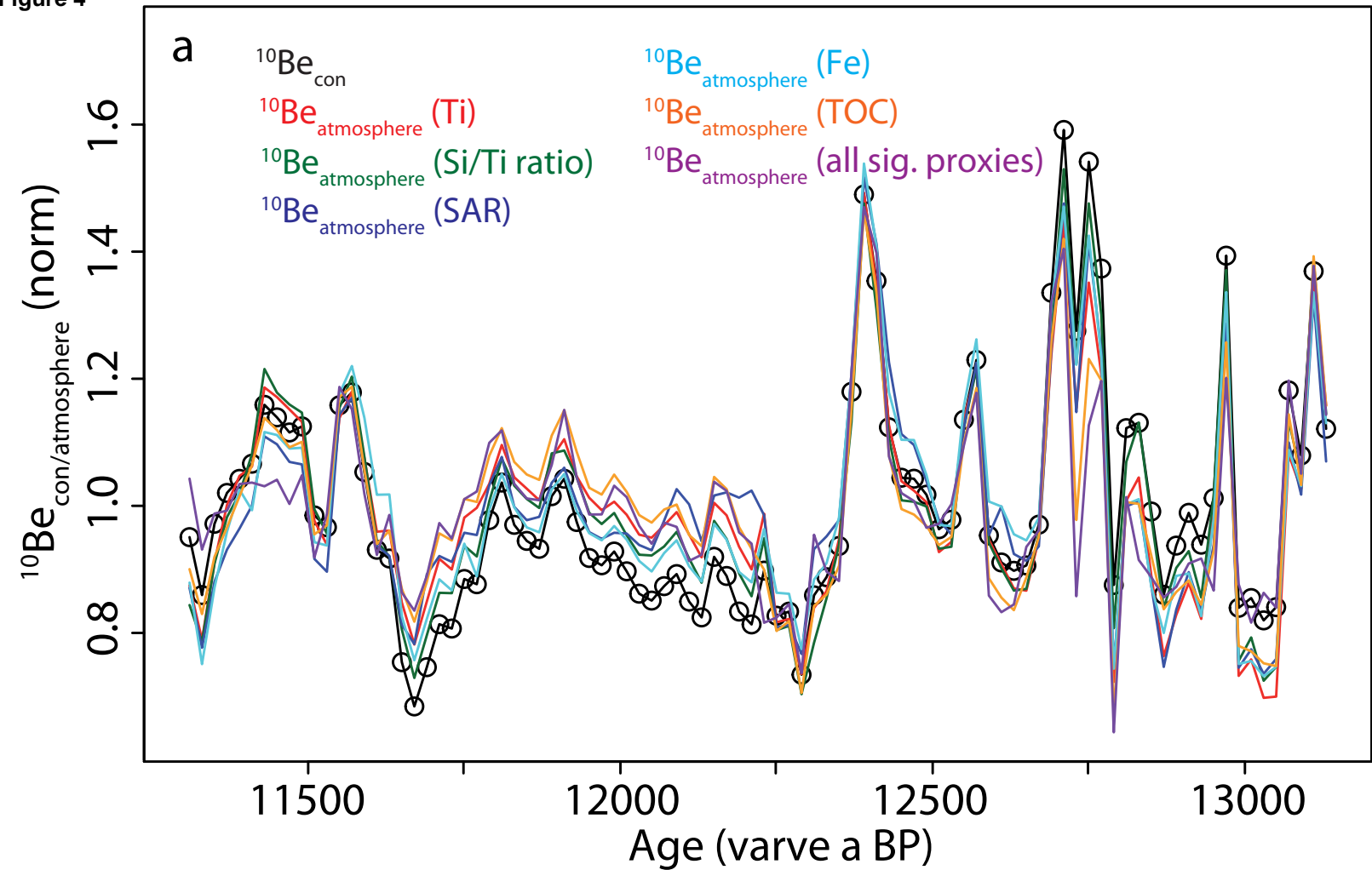


Figure 5

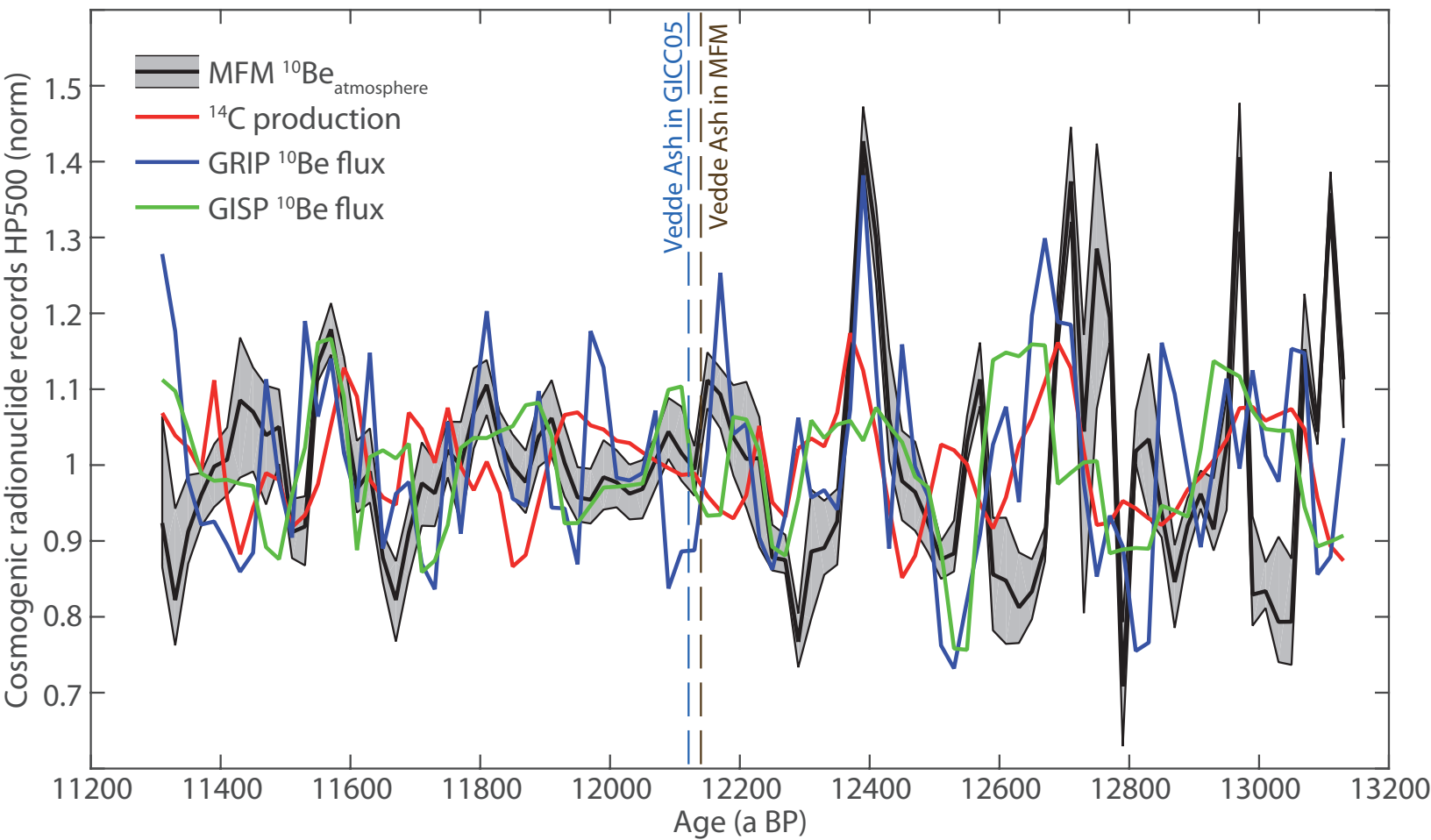
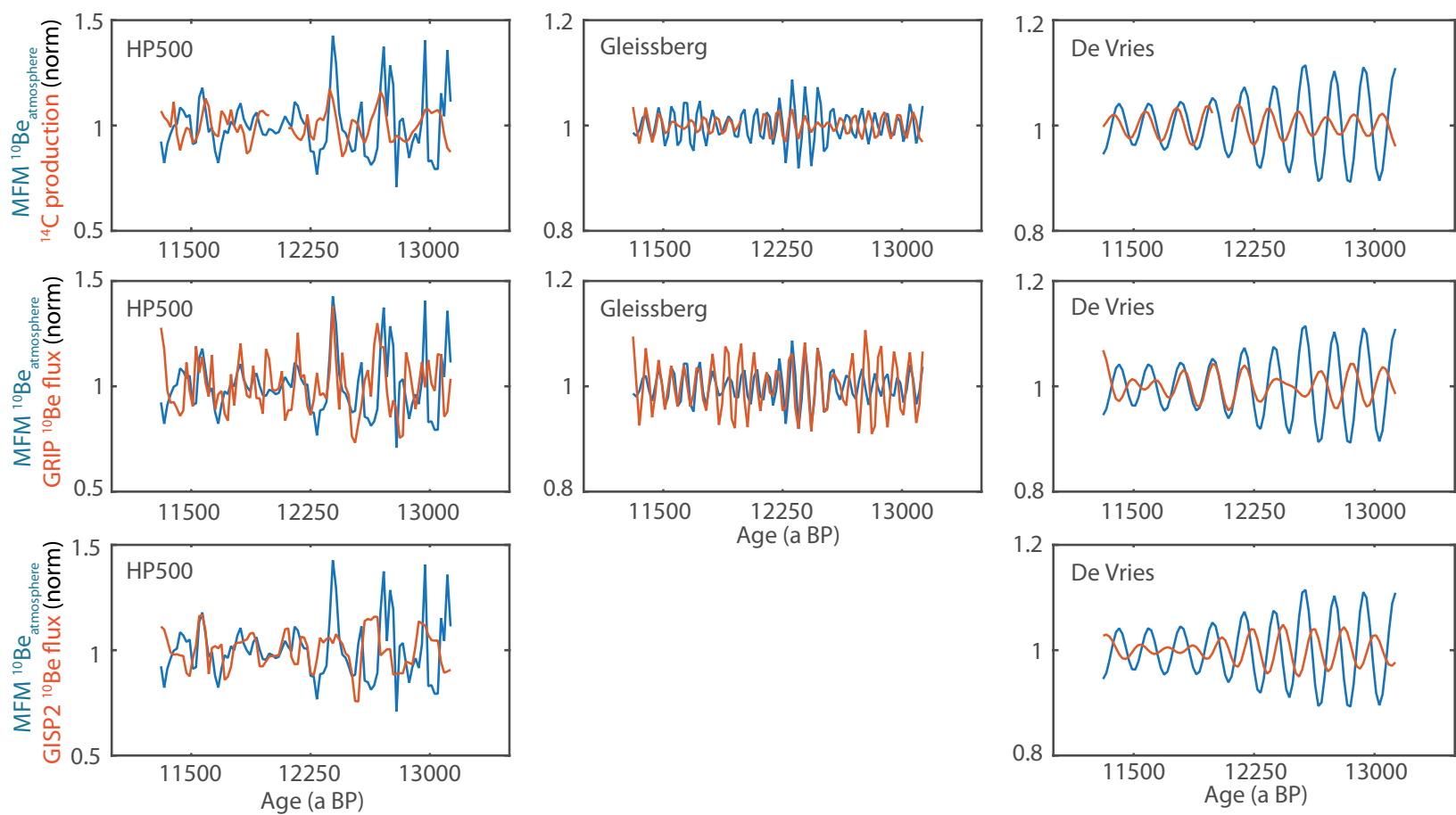


Figure 6



Highlights:

^{10}Be record from varved lake sediments covering the Lateglacial-Holocene transition

New approach quantifies environmental influences on ^{10}Be deposition

Indicates potential of ^{10}Be in varved lake sediments for solar activity reconstruction

Indicates potential of ^{10}Be in varved lake sediments as synchronization tool

1 Response to the reviewer's comments

2 We thank the reviewer for the constructive comments, which helped to further improve our
3 manuscript.

4 Reviewer #2: The manuscript has been improved in response to my initial comments. I list several points below
5 that still require some revisions. With these revisions addressed I think the manuscript is suitable for publication. I
6 do not need to see the manuscript again.

7
8 1). The authors modified the title in response to my initial comments but maintain the claim in the abstract and
9 conclusion that they are presenting a "record of solar activity variations". Records of solar activity are directly used
10 (and sometimes misused) in forcing paleoclimate model runs. If they think their record is something that is suitable
11 to be used as such a forcing then they might persist with this claim. Otherwise I would suggest to back it off as in
12 the title or, at the very least, add some qualification on this point.

13
14 2). From the abstract line 35: "Our data suggest that environmental influences on the catchment do not
15 substantially bias major ^{10}Be excursions on multi-decadal scales, but contribute to up to 37 % of variability".
16 This sentence does not make sense. The review response distinguished between correlation and 'multi-decadal
17 ^{10}Be excursions'. A couple of sentences are needed here to state the results of your regression analysis
18 (environmental influences contribute up to 37% of the variance: $r = 0.63$ is not minor!) and separately state your
19 point about also seeing major shifts in ^{10}Be that are not mirrored by changes in these environmental variables.
20 This two points are different and this must be explained clearly.

21
22 3) Abstract line 36: "The ^{10}Be record dominantly reflects changes in solar activity".
23 Given that the environment-corrected ^{10}Be record is not quantitatively tested against other more established
24 records of solar activity this statement should be qualified. e.g. "We interpret that the ^{10}Be record dominantly
25 reflects...". The same point applies in the Discussion and Conclusion.

26
27 4) Line 343: "(i) Increased sediment flux through the water column tends to increase ^{10}Be scavenging and,
28 thereby, does not distinctly influence ^{10}Be concentrations in the sediments".
29 This statement assumes that the available ^{10}Be store in the water column is never a limiting factor. This may be
30 the case, but please add a couple of sentences to acknowledge the assumption and explain why it is reasonable.

31
32 Minor point:

33 Line 65: Its not a case of 'might'; ^{10}Be deposition *is* spatially variable.

34 We modified our manuscript according to the reviewer's suggestions.

Appendix 1

[Click here to download Supplementary Data: Czymzik et al. Appendix 1.xls](#)