Paleoclimate change in Ethiopia around the last interglacial derived from annually-resolved stalagmite evidence

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ABSTRACT

Oxygen and carbon ($\delta^{18}O/\delta^{13}C$) isotope, growth rate and trace element data are reported for a U-Th dated, annually-laminated stalagmite, GM1 from Goda Mea Cave, Ethiopia. The stalagmite grew intermittently around the last interglacial. The proxy records are used to

develop a conceptual growth model of the stalagmite and to assess its potential for revealing a climate signal in this climatically sensitive northeastern African region during an important period in the evolution of *Homo sapiens* and dispersal of Anatomically Modern Humans out of Africa. Speleothem deposition is of short-duration occurring at ~129 ka, ~120 ka, in an undated growth phase, and at ~108 ka; probably due to tectonic activity. $\delta^{18}O$ composition is very stable within growth phases (1σ variability < 0.76‰), as are Mg/Ca, Sr/Ca and Ba/Ca, all indicative of well-mixed source-waters. A shift to positive $\delta^{18}O$ values and increased variability in Mg/Ca, Sr/Ca and Ba/Ca prior to growth hiatuses is observed, indicating a loss of the well-mixed water source prior to growth cessation. Mean $\delta^{18}O$ composition (–3.82 to –7.77‰) is lower than published modern and Holocene stalagmites from the region. Geochemical data, statistical analyses, and a conceptual model of stalagmite growth, demonstrate that climatic conditions recorded by GM1 were wetter than the Holocene. The ~129 ka growth phase particularly presents an annual record of the relative Intertropical Convergence Zone (ITCZ) position. The GM1 record, the oldest high-resolution continental climate record from Ethiopia so far published, presents evidence that any early human migrations which occurred during MIS 5 are likely to have occurred during a wet event in northeast Africa.

Key words: Last interglacial; Northeast Africa; speleothem; oxygen isotopes; paleoclimate

1. Introduction

In Ethiopia, stalagmites provide high-resolution records of past climate and environment (Asrat et al., 2007; Baker et al., 2007; 2010). Fast-growing, annually-laminated stalagmites are ubiquitous, due to the strong seasonality of rainfall and the water balance in Ethiopia. Regular laminae, visible in hand section, can provide precise annual chronology. Annual

51 growth rates of these stalagmites, determined from the thickness of an annual lamina, is at the
52 upper range of those observed in stalagmites (typically ~0.5 mm/yr). This is due to the
53 optimal climatic conditions (high temperature and rainfall) for limestone dissolution and re-
54 precipitation. This rapid growth facilitates the high-resolution sampling of stalagmite calcite.
55 In Ethiopia, the real advantage of using speleothems to provide a paleoclimate proxy
56 record is that they contain information on past rainfall variability in the region. Several major
57 air streams and convergence zones influence the current climate pattern in northeast Africa,
58 whose effects are often compounded by such regional factors as topography and the
59 proximity to the oceans (e.g., Nicholson, 1996). The relatively dry north-easterly and south-
60 easterly monsoons and the humid and moisture-laden (rainfall generating), westerly and
61 south-westerly air flow of the Congo air stream, generally dominate the regional wind and
62 pressure patterns. The Intertropical Convergence Zone (ITCZ) and the Congo Air Boundary
63 (CAB) separate these major air streams. The passage of the ITCZ (Fig. 1a) dominantly
64 determines the rainy seasons in Ethiopia, while the topography (highland barriers separated
65 by a rift zone) modulates the local rainfall distribution. Accordingly, Ethiopian climate has
66 two rainy seasons, one from the northward passage of the ITCZ, called locally the 'big rains'
67 (between June and September), which is reliable and whose maxima migrates with the
68 position of the ITCZ. A second rainy season, the 'small rains', is less consistent and occurs
69 between March and May with maxima in April. Dryland farming, including subsistence
70 farming, leads to a high dependency on rains in both seasons. Failure of the 'small' rains is
71 common and has occurred in recent years in 2013/2014 and 2015/2016, particularly in the
72 southeastern Ethiopian lowlands bordering the current study area. The climate dynamical
73 cause of the failure of the 'small' rains, and how this varies over time, is still poorly
74 understood.

In addition, reliable, high-resolution climate records beyond the Holocene are scarce in the northeastern African region, one of the major candidates for the origin of *Homo sapiens* and a gateway to the "out of Africa" migration of our species during the late Pleistocene. The influence of climate on the dispersal of Anatomically Modern Humans from northeastern Africa particularly during the period ~120 to ~50 ka has been a subject of intense discussion (e.g., Tierney et al., 2017 and references therein; Lamb et al., 2018). Recent discovery of *Homo sapiens* fossils dated to 177 to 194 ka in the Misliya cave in Israel (Hershkovitz et al., 2018) indicates that the "out of Africa" migration episodes have started earlier than the previously thought period of migration (~120-50 ka). Discussions on influence of climate on human dispersal often rely on marine climate records from the Indian Ocean and Mediterranean Sea. The recently published Lake Tana record from the northwestern Ethiopian highland, largely covering the last ~150 ka (Lamb et al., 2018) is the only continental record available. In this paper, we present a high-resolution continental climate record from an Ethiopian stalagmite (GM1) that grew intermittently around the last interglacial, which is very pertinent to this discussion. Though it is not a continuous record over the whole period of the last interglacial, the growth phases of GM1 are dated at particularly important periods of the MIS 5. The GM1 record, the oldest high-resolution climate record so far published from Ethiopia and continental eastern Africa, is therefore very significant in an area where any kind of reliable continental climate records from this period are scarce.

These annual-resolution records of $\delta^{18}O$, $\delta^{13}C$, trace elements and growth rate are from the Goda Mea Cave in Ethiopia (Fig. 1b). A combination of U-Th dates and lamina counting are used to identify the timing of the growth phases. Samples milled at annual resolution were analysed for $\delta^{18}O$ and $\delta^{13}C$, and at decadal resolution for trace elements. Variogram, autocorrelation and spectral analyses of the geochemical and growth rate time series are used

100 to develop a conceptual model for the hydrology of the waters feeding the speleothem. The
101 time series of $\delta^{18}O$, $\delta^{13}C$, trace elements and annual growth rate are then interpreted, with
102 comparison to the published modern and Holocene stalagmites from the region and globally.
103 Such high resolution, multi-proxy approach has been proved useful in reconstructing annual,
104 in some cases seasonal, rainfall (e.g., Johnson et al., 2006).
105
106 **2. Methodology**
107 *2.1. Site Description*
108 Goda Mea Cave was explored and surveyed in 2007 and a full description can be found in
109 Gunn et al. (2009). The cave is entered from a collapse doline and after about 30 m there is a
110 large flowstone deposit that almost fills the passage. A crawl beneath opens into a NE-SW
111 oriented rift passage that is initially some 5 m wide by 1 m high but increases downstream to
112 10-15 m by 7 m. The cave ends in a 90 m x 40 m x 20 m high chamber formed by upwards
113 stoping as evidenced by abundant breakdown. Above the chamber there is ~25 m of sandy
114 limestone intercalated with some thin marl and mudstone layers towards the top, overlain by
115 a ~20 m thick calcareous sandstone, silt, carbonate rich shale and marl intercalation, which
116 extends to ~1 m of soil at the surface. The limestone and sandstone-shale-marl units above
117 the cave form a continuous hydrogeological unit, connected by network of fractures.
118 There are numerous speleothems in the chamber including stalactites, stalagmites and a
119 central column that is over 10 m high and 6 m diameter. The speleothems are mostly relict
120 with some evidence of re-solution and many of the stalagmites are fractured, most likely by
121 tectonic activity (Fig. 1c and d). Speleothem growth is generally focused along some aligned
122 zones below major fracture systems/brecciated fault traces crossing the hydrogeological unit
123 all the way up to the surface.

Some modern monitoring data (e.g., drip water chemistry) for the cave is presented in Asrat et al. (2008). Drip water Ca^{2+} and Mg^{2+} concentrations in all analysed drip water samples from this cave are 2.57±0.65 mmol/L and 1.54±1.12 mmol/L, respectively. The drip water Ca^{2+} concentration in this cave is high as compared to the range of Ca^{2+} in the Mechara caves (2.63±2.36 mmol/L) and falls within the range of values expected for "open system" evolution (Baker et al., 2016). The high Ca^{2+} concentration can be attributed to the open system calcareous sandstone/shale, marl and limestone hydrogeological unit, with the calcite-cemented sandstones, carbonate rich shale, marl and limestone all contributing Ca^{2+} ions to the drip waters.

2.2. Sample description

GM1 is a large broken stalagmite found in the cave chamber. The 591 mm long stalagmite was sectioned into two halves, and one half polished for lamina counting (Fig. 2). The polished half shows continuous laminations, alternating between dense and porous/white calcite, as well as visually recognizable growth hiatuses, marked by shifts in growth axis and the stalagmite morphology. The other half of GM1 was milled using a hand held dental driller for oxygen and carbon isotopes at ~0.6 mm resolution (966 samples), and trace element analysis at ~5.5 mm resolution (103 samples). 38 samples for U-Th dating were similarly drilled using a dental driller, with samples located either side of possible growth hiatuses, and regularly spaced within growth phases.

2.3. Geochemical analyses

U-Th analyses were undertaken by ICP-MS at the University of Melbourne, Australia, following the method of Hellstrom (2003). Samples were dissolved in concentrated HNO_3 and equilibrated with a mixed ^{229}Th–^{233}U–^{236}U tracer. U and Th were extracted in a single

149 solution using Eichrom TRU resin before introduction to a Nu Plasma multi-collector ICP-
150 MS, where isotope ratios of both elements were measured simultaneously. The decay
151 constants of Cheng et al. (2013) were used, and detritally-corrected ages calculated using eqn.
152 1 of Hellstrom (2006) with an assumed initial [$^{230}Th/^{232}Th$] of 1.5 ± 1.5. Age-depth modelling
153 combined floating annual laminae chronologies and U-Th analyses were as described in
154 section 3.1.

155 Oxygen and carbon isotopes were analysed at the Stable Isotope Laboratory (SILLA),
156 University of Birmingham, UK. The calcite samples were reacted with phosphoric acid and
157 analysed using an Isoprime continuous flow mass spectrometer. By comparison with a
158 laboratory marble standard, the sample $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios are reported as $\delta^{18}O$ and
159 $\delta^{13}C$ values in per mil (‰) versus VPDB. Analytical precisions are 0.07‰ for $\delta^{18}O$ and
160 0.04‰ for $\delta^{13}C$ on the standard marble (KCM).

161 Trace elements powders were analysed at University of New South Wales, Sydney.
162 Samples of approximately 0.05 g each were weighed directly into polypropylene vials. One
163 mL of 1-1 hydrochloric acid was added to each vial. The samples were sonicated for 15
164 minutes to ensure complete dissolution. The solutions were diluted to 10.0 mL with ASTM®
165 Type I water (Millipore® filtration system, Millipore® Corporation, Billerica, Massachusetts,
166 USA).

167 Diluted samples were analysed for Ca (317.933 nm) and Mg (285.213 nm) using the
168 PerkinElmer Optima™ 7300DV ICP-OES (PerkinElmer, Shelton, USA). Ba and Sr were
169 analysed by PerkinElmer NexION 300D ICP-MS (PerkinElmer, Shelton, USA). Both
170 instruments were coupled with an ESI SC4 FAST sample introduction system (Elemental
171 Scientific, Inc., Omaha, USA) to minimise sample carryover.

172 The ICP-OES and ICP-MS were calibrated using certified multi-element standards in a
173 matrix of 2% HCl. Wavelength and analytical mass selection took into consideration spectral

interferences as well as sensitivities. Internal standards were added on-line via injection valve to correct for physical interferences. Quality control check standards were run at selected intervals in an unattended automatic analysis run, to ensure that the instrument performance remained consistent over the length of analysis.

2.4. Time series analysis

Statistical analysis on the annual growth rate time series followed the approach of Mariethoz et al. (2012), which included the analysis of the first derivative of growth rate (growth acceleration) to determine the flickering parameter (f), which is the magnitude of the anti-correlation at lag 1. Flickering ranges between –0.5 and 0, the more negative *f* values indicating stronger flickering. Negative values of *f* are indicative of a karst store filling and draining, as opposed to a climate forcing, and helps identify climatically sensitive speleothems. In addition, variogram analysis of the growth rate time series permits the derivation of the information content (*IC*) and range (*r*) in the growth rate data, which helps identify the signal: noise ratio in the data and the time over which useful information might be expected. Stable isotope and annual growth rate time series data were also analysed for their autocorrelation and spectral properties. As the data was evenly spaced in time, spectral analysis was performed using discrete Fourier transforms, using the FFTW library within Microcal Origin. Five windows were used (Bartlett, Hanning, Rectangular, Welsh and Triangular) in order to investigate the extent of signal leakage.

3. Results

3.1. GM-1 Chronology

3.1.1. Lamina

199 Lamina were counted (in duplicate) and a total of 1356 lamina were identified with a
200 mean lamina thickness of 0.44±0.14 mm (ranging between 0.19 and 1.12 mm). This lamina
201 thickness compares well to those reported for stalagmites in previous studies in the region
202 (Ach-1, mean = 0.53±0.26 mm, Bero-1 = 0.45±0.23 mm, Asfa-3 = 0.32±0.11 mm; Merc-1 =
203 0.29±0.04 mm; Asrat et al., 2007; Baker et al., 2007; Baker et al., 2010). In these stalagmites,
204 the visible laminae have been demonstrated to be annual by comparison to the radiometric
205 dates. The GM1 laminae are similar in their appearance and thickness to these other
206 stalagmites. Examination of thick sections of GM1 at various levels of the growth phases
207 (Fig. 2) show continuous and regular visible laminae with alternating brownish calcite (Dark
208 Compact Laminae, DCL) and thinner white calcite (White Porous Laminae, WPL) as defined
209 by Genty & Quinif (1996) and Genty et al. (1997). The presence of fine sediments on the
210 white porous calcite, and some dissolution features at the top of the DCL, suggests some
211 seasonal infiltration variability (*cf*. Borsato et al., 2007). Overall, the regularly alternating
212 DCL/WPL laminae sequence, even without more obvious structures from infiltration
213 variability, indicate deposition under a seasonal hydroclimate regime (e.g. changes in drip
214 water supersaturation or cave air CO_2 concentration), where recharge was sufficient to
215 maintain continuous dripping to the stalagmite.
216
217 *3.1.2. Growth hiatuses*
218 There are three major growth hiatuses based on the U-Th chronology (see below), and
219 other possible minor growth hiatuses have been recognized by changes in the growth axis
220 within the growth phases (Fig. 2). Visual examination of the three major growth hiatuses on
221 the polished stalagmite and the thick sections show that the hiatuses between the four major
222 growth phases are all marked by accumulation of fine detritus and brownish material on the

top 2 mm sections, with no indications of dissolution. Such textural features are typical of the ceasing of growth due to cessation of the drip source (Railsback et al., 2013).

3.1.3. Stalagmite morphology

The morphology of the stalagmite changes from candle stick shaped, with regular nearly horizontal lamina on and off the growth axis for most of the first growth phase to upwards-thinning, laterally less extensive layers with laminae rapidly changing to sub-vertical angle, off the growth axis, just below the first hiatus (Fig. 2). The second growth phase above the first hiatus then gets broader at its axis with rapid flowing/dripping down the sides of the stalagmite forming nearly vertical lamina. The third growth phase shows similar morphology to the second though it rapidly thins towards the top below the third major hiatus. The last growth phase has relatively broader shape with significant deposition along its axis. The morphology of the stalagmite changing with the hiatus position is a clear demonstration of the changing amount and concentration of calcite in the dripping water. It shows a general drying out of the drip source towards the tops of the three older growth phases, while the last growth phase is marked by an increased drip rate throughout the growth period.

3.1.4. U-Th dates and annual growth rate

The 38 U-Th dates on the sample (Fig. 3, Table 1) demonstrate 4 periods of growth and confirm the presence of 3 hiatuses. Several age inversions are present, and one short growth phase containing 37 laminae was undated.

The U-Th ages were used to constrain a chronology based on the annual laminae. Firstly, the longest phase of speleothem growth (from ~127 mm from the top, to the base at 591 mm) contained 29 very similar U-Th ages (a mean and standard deviation of 130.0 ± 3.5 ka, with an average uncertainty on individual analyses of 1.3 ka), providing further evidence that the

1087 laminae present in this growth phase are likely to be annual. Secondly, following established methods (Asrat et al., 2007; Dominguez-Villars et al., 2012; Baker et al., 2015), we compared two approaches to tie the lamina chronology to the U-Th ages. The first approach was as follows: within each growth phase, each U-Th age was adjusted by using its relative laminae age to obtain an equivalent U-Th age for the date of the start of each growth phase. Taking the mean and standard deviation, this yielded growth phases starting at 129.3±2.7 ka, 120.7±1.7 ka, and 108.3±0.2 ka. We compared this approach to that calculated from linear regression applied to conventional age-depth plots. In this case, we used only the U-Th ages with a [^{230}Th/^{232}Th]>1000, presuming they would be the most accurate. This approach yielded a date for the start of deposition for two of the four growth phases of 129.2±1.7 ka and 120.6±0.3 ka. The two approaches therefore give consistent dates for the start of deposition that agree with the analytical error of individual analyses.

GM1 deposition periods are therefore ascribed to four phases: 1087 years commencing 129.3±2.7 ka, 54 years of deposition at 120.7±1.7 ka, a 37-yr long undated growth phase, and 176 years of deposition from 108.4±0.3 ka. The ~129.3 ka growth phase occurs, within dating uncertainty, at Termination II or the early part of the last interglacial (Cheng et al., 2009), and the 120.7 ka deposition immediately post-dates the full interglacial. The growth phase at 108.5-108.3 ka falls within the isotope stage 5c interglacial.

The annual growth rate for GM1, determined from the annual lamina thickness, is presented in Figure 4. Mean growth rate does not vary between growth phases: 0.43±0.14 mm/yr (129.3 ka), 0.41±0.17 mm/yr (120.7 ka), 0.53±0.15 (undated), and 0.47±0.14 mm/yr (108.4 ka).

3.2. Oxygen and carbon isotopes

272 The oxygen and carbon isotope ($\delta^{18}O$ and $\delta^{13}C$) data were ascribed to an annual lamina
273 and are presented in Figures 4. Scatter plots of $\delta^{18}O$ and $\delta^{13}C$, including the analysis of the
274 isotopes along a lamina (the 'Hendy test') are shown in Figure S1.
275 $\delta^{18}O$ varies significantly between growth phases (–7.77±0.57‰ (129.3 ka), –
276 3.82±0.61‰ (120.7 ka), –6.05±0.76‰ (undated), and –6.31±0.59‰ (108.4 ka). Within each
277 growth phase, $\delta^{18}O$ can be described as having long periods of relatively invariant
278 composition (e.g., ±0.33‰ for the first 1000 years of the 129.3 ka deposition period, and
279 ±0.23‰ in the first 150 years of the 108.4 ka deposition period), as well as periods of rapid
280 change. For example, $\delta^{18}O$ increased from –7.8‰ to –5.3‰ in four years (and to –4.5‰ after
281 13 years) at the end of the 129.3 ka growth phase, and from –6.2‰ to –4.4‰ in nine years at
282 the end of the 108.4 ka growth period.
283 $\delta^{13}C$ is characterised by low inter-sample variability, with the presence of long-term
284 trends. For example, in the 129.3 ka growth phase, the standard deviation of $\delta^{13}C$ over any
285 50-year period is between 0.1‰ and 0.3‰, but over the whole 1087 years of deposition, $\delta^{13}C$
286 trends from –1‰ to –4‰. This 3‰ change in $\delta^{13}C$ with the growth phase is as great as the
287 variability between growth phases.
288 Figure S1 shows the relationship between $\delta^{18}O$ and $\delta^{13}C$, both throughout the time series
289 as well as along growth layers ('Hendy tests'). The Hendy tests suggest a 1‰ increase or
290 decrease in isotope composition is possible along a growth layer, which is greater than the
291 inter-annual variability of $\delta^{13}C$ and $\delta^{18}O$. For stalagmite GM1, there is no evidence for near-
292 equilibrium deposition: modern and Holocene stalagmites demonstrate isotope fractionation
293 of 1-2‰ (Asrat et al., 2007; Baker et al., 2007; 2010), and similar deposition conditions
294 appear to apply to stalagmite GM1. Based on these works, we have quantified these
295 fractionation processes and confirmed that they operate in the same direction as the climate
296 forcing, which has also been observed by other works (e.g., Dorale and Liu, 2009).

297

298 *3.3. Trace elements*

299 Ba/Ca, Mg/Ca and Sr/Ca show similar patterns to $\delta^{13}C$ and $\delta^{18}O$, although sampled at a
300 lower temporal resolution. A long-term trend to lower ratios in the 129.3 ka growth phase
301 matches that observed in $\delta^{13}C$. Significant short-term changes in trace element composition
302 occurs at the same time as the increases in $\delta^{18}O$ and $\delta^{13}C$ at the end of the 129.3 ka growth
303 phase, and within the 120.7 ka growth period. At the end of the 129.3 ka growth phase, a
304 change in gradient of Mg/Ca, Sr/Ca and Ba/Ca lasted for ~170 years, indicative of a drying
305 trend. This was followed by the $\delta^{18}O$ increase of 2.2‰ that occurred over 4 years, and then
306 an increased variability in Sr/Ca, Mg/Ca and Ba/Ca (Mg/Ca increases, Mg/Ca and Ba/Ca
307 decrease) until growth stops 28 years later. In contrast, the trace element response at the time
308 of a 2‰ increase in $\delta^{18}O$ at the end of the 108.4 ka growth phase is muted and trends to lower
309 values. The greatest range in trace elements occurs in the 120.7 ka growth phase, where Sr/Ca
310 increases, and Mg/Ca and Ba/Ca have opposing increasing and decreasing trends.

311

312 *3.4. Time series analysis on stable isotope and growth rate time-series*

313 Following Mariethoz et al. (2012), and as described in section 2.4, the growth rate time
314 series variogram properties was investigated. Due to the short duration of several of the
315 growth phases, only the longest time series at 129.3 ka was analysed. The results are plotted
316 in Figure 5a, where variogram analysis on stalagmite GM1 is compared to previous published
317 stalagmite statistics on growth rate series. The autocorrelation and spectral properties of the
318 growth rate, $\delta^{18}O$ and $\delta^{13}C$ series were also investigated (Figs 5b and c).

319 Stalagmite GM1 growth at 129.3 ka has evidence of 'flickering' (f=–0.33), that is a
320 growth acceleration that flickers around a mean value (Mariethoz et al., 2012). 'Flickering'
321 has been explained as growth rate sensitivity to the filling and draining of a karst store, which

322 is trying to reach a dynamic equilibrium, with reported values between –0.24 (low flickering,
323 potential climate signal) and –0.39 (high flickering, potential karst hydrology signal).
324 Variogram analysis shows that the stalagmite has low range (*r*, 20.5 years) in the growth
325 rate record. Growth rate therefore has no 'memory' of previous growth rates longer than this
326 timescale, indicative that the karst store(s) that feed the stalagmite are relatively small. The
327 GM1 range is the lowest reported to date for an annually laminated speleothem. The
328 Information Content (*IC*) of growth rate, which is the balance of the signal in the variogram
329 and the noise, is 56%, indicating that the stalagmite growth rate record contains a greater
330 proportion of signal than noise. In comparison to previously published records (Fig. 5a),
331 stalagmite growth rate statistical properties lie in region A, with stalagmites that have a high
332 information content, relatively low flickering and range, and where growth rate has proven
333 useful in paleoclimate reconstruction.
334 Autocorrelation of growth rate, $\delta^{13}C$ and $\delta^{18}O$ time series are presented in Figure 5b for
335 the three longest growth phases (~129, ~120 and ~108 ka). Significant autocorrelation can be
336 observed for $\delta^{13}C$ and $\delta^{18}O$ for the ~129 and ~108 ka growth phases, with autocorrelation
337 >0.6 at 15-year lag. Autocorrelation for $\delta^{13}C$ is stronger than for $\delta^{18}O$, indicative of
338 additional smoothing of the $\delta^{13}C$, likely from the soil carbon store. Growth rate has very low
339 autocorrelation (<0.4 after 4 years lag), in agreement with the observed flickering of growth
340 rate. The ~120 ka growth phase has lower autocorrelation of $\delta^{18}O$ and $\delta^{13}C$ than the other two
341 growth phases, suggesting limited mixing or smoothing of these proxies during this short
342 growth phase. Low autocorrelation would agree with the observed highest variability in trace
343 elements at this time.
344 Spectral analysis was also undertaken (Fig. 5c) for the longest continuous growth phase at
345 ~129 ka. Bartlett, Hanning, Rectangular, Welsh and Triangular windows were used to
346 explore the spectral properties for $\delta^{18}O$ and growth rate time series. Growth rate has a 17-18

347 year peak that is not statistically significant at 95% confidence, and two other peaks (31-33
348 and 53-59 years), which are longer than the range (r, 20.5 years) and are likely to be
349 harmonics of the 17-18 year frequency. $\delta^{18}O$ also has only weak and insignificant spectral
350 power, not surprising given the low variability in the $\delta^{18}O$ data.
351
352 **4. Discussion**
353
354 *4.1. Holocene stalagmite records*
355 Previous cave research in Ethiopia has included limited cave drip water and climate
356 monitoring during sampling expeditions to the Mechara region of Ethiopia between 2004 and
357 2008 (Asrat et al., 2008) (Fig. 1), and the analysis of modern and Holocene stalagmite
358 samples. Modern calibration studies of stalagmite $\delta^{18}O$ of carbonate shows evidence of
359 climate sensitivity, despite deposition out-of-equilibrium (Baker et al. 2007; 2010). The latter
360 is potentially due to both rapid degassing and evaporation. $\delta^{18}O$ and growth rate correlations
361 with climate are sample-specific. Drip-specific flow-paths determine whether a stalagmite
362 has a proxy which is sensitive to the 'big' rains, or to the relative amount of rain in the 'big'
363 and 'small' rain seasons, or neither. For example, modern stalagmite $\delta^{18}O$ and growth rate
364 records were reported from two stalagmites from Rukiesa Cave (Baker et al., 2007). The
365 annual nature of the laminae was confirmed by ^{14}C analyses and comparison to the modern
366 atmospheric bomb carbon peak. In these samples $\delta^{18}O$ and growth rate were shown to have a
367 correlation with the ratio of 'small' to 'big' rainfall and total summer rainfall, respectively. A
368 sample specific climate sensitivity of $\delta^{18}O$ and growth rate was observed, which probably
369 reflects the karst hydrogeology and its effect on individual water flow-paths. A loss of
370 climate correlation was also observed in one sample during a period of high growth rates.

371 $\delta^{18}O$ and growth rate time-series both exhibit multi-decadal variability in two stalagmite
372 samples deposited in the Holocene. Such variability may be an amplification of extremes in
373 hydroclimate (e.g., drought years) or rainfall isotopic composition, due to the non-linear
374 replenishment or drainage of karst stores (Baker et al., 2013). A mid-Holocene record from
375 Achere Cave (sample Ach-1) had laminae that were demonstrated to be annual by
376 comparison to U-Th dates (Asrat et al., 2007). In this stalagmite a 18-21 yr periodicity in
377 growth rate and $\delta^{18}O$ occur. $\delta^{18}O$ has a greater variability than $\delta^{13}C$, indicative of the
378 variability being driven by variations in the extent of evaporative enrichment of $\delta^{18}O$. A
379 discontinuous Holocene record from Bero Cave had six growth phases over the last 7800
380 years (Baker et al., 2010). Mean stalagmite $\delta^{18}O$ is 1.2‰ higher than that predicted by
381 forward modelling, and a multi-decadal variability in $\delta^{18}O$ and growth rate was again
382 observed (Baker et al., 2010). $\delta^{18}O$ from this stalagmite was indicative of both rapid
383 degassing and the additional enrichment, probably due to evaporation.
384 Stalagmite growth phases are relatively short (10^3-10^4 years) due to the tectonically active
385 nature of the region, which can change water flow paths. This is observed in stalagmites from
386 all three caves, and has been explained by changes in flow regime or to the relative position
387 of a growing stalagmite caused by tectonic activity related to the East African Rift (Asrat,
388 2012). Physically anomalous laminae within an otherwise regular and visible annual laminae
389 sequence, frequent deviations from vertical growth axis, and abrupt changes in stalagmite
390 morphology, as well as the tectonically-controlled formation of the larger cave system,
391 further confirm the influence of tectonics and recorded earthquakes in the region (see Fig. 1a)
392 on the length of the growth phases (Asrat et al., 2008; Asrat, 2012).
393
394 *4.2.Conceptual growth model*

395 The combination of stable isotope and trace element geochemistry, growth rate, statistical
396 analyses, and observations of the laminae types and stalagmite shape, allow us to build a
397 conceptual model for stalagmite GM1 (Fig. 6).

398 Firstly, the stalagmite probably had continuous deposition for more than 1000 years, and
399 during this period isotope and trace element composition has low variability and high
400 autocorrelation. This homogeneity of $\delta^{13}C$, $\delta^{18}O$ and trace elements suggests a drip water
401 source which is well mixed, enough to obscure any annual to decadal scale variability in $\delta^{18}O$
402 and maintain dripping. The continuous deposition of the laminae and the candle-stick shape
403 of the stalagmite before it narrows down towards the tip of this growth phase (the last few
404 years of growth) supports a continuous drip source. We propose this water comes from
405 matrix flow of the porous sandstone and sandy limestone, which was channelled to the drip
406 source by a network of small fractures. The annual laminae are driven by this flow regime,
407 which provides the necessary seasonal variability in drip water hydro-geochemistry.
408 Combined with the evidence from flickering, we infer the variations in lamina thickness are
409 driven by the karst hydrology and not by the cave environment. In the ~129 ka growth phase,
410 these would have to maintain high levels of saturation for the initial ~1000 years of
411 deposition.

412 Secondly, the four growth phases of GM1 reflect the changing karst hydrologic regime
413 above the cave. The ~129 ka growth phase is marked by the dominance of a continuous
414 supply of water from 'matrix' flow for most of its growth period, which rapidly dried out a
415 few tens of years before the hiatus. In contrast, the ~120 ka growth phase reflects a rapid
416 'fracture' flow, following a possible tectonic event, which did not maintain growth for a long
417 time before it abruptly shut off as marked by the rapid increase in trace element ratios and
418 $\delta^{18}O$. The third, undated growth phase shows similar features to that of the second, only the
419 growth period was shorter suggesting a rapid start to dripping and subsequent exhaustion

420 from a ‘fracture’ source, as marked by the nearly vertical laminae down the sides of the
421 stalagmite and the abrupt narrowing towards its top. The ~108 ka growth phase is again
422 marked by a more ‘porous’ matrix flow which maintained growth for longer period, attested
423 by the regular laminae, broad stalagmite shape, generally low variability trace element ratios
424 and depleted $\delta^{18}O$.

425 Thirdly, growth rate varies annually, shows evidence of flickering, and has a range of ~20
426 years and a spectral peak at 17-18 years. Given the relative homogeneity of the stable isotope
427 and trace element signals, the growth rate variability has to occur subsequent to the mixing of
428 the water. Dissolutionally-enlarged fractures or a network of small conduits would allow
429 limited water storage, permitting degassing of karst water and prior calcite precipitation
430 (PCP) as well as drip rate variations, both affecting growth rate variability. We conceive this
431 store to have a proportional volume of approximately 20 years of recharge (see later). In
432 drying conditions, water from this store could maintain dripping and deposition for short time
433 periods.

434 Fourth, a pre-existing fracture zone/brecciated fault trace which might have been
435 reactivated during subsequent tectonic activities, extending from the surface, through to the
436 store and the cave roof, permits fracture flow to stalagmite GM1. This would permit short-
437 duration recharge, probably after high magnitude / frequency rainfall events, in the absence
438 of saturated porous sandstone and limestone aquifer. This would explain the short duration,
439 high geochemical variability, ~120 ka growth phase. The absence of ‘stored’ water and
440 subsequently rapid exhaustion of the fracture flow/drip source is supported by the nearly
441 vertical lamina depositing down the sides of the stalagmite, high variability/rapid increase in
442 the $\delta^{18}O$ and trace element ratios and low autocorrelation in $\delta^{13}C$ and $\delta^{18}O$.

443 The varying trends between the $\delta^{18}O$ and $\delta^{13}C$, and trace element ratios from one growth
444 phase to the other suggests that a single kinetic fractionation process does not dominate our

445 proxy records, rather we infer a hydrological control based on climatic and tectonic
446 processes.

447 Our conceptual model explains other features of GM1 geochemistry and growth rate. The
448 geochemistry at the end of the 129.3 ka growth phase can be interpreted as a decline in the
449 saturation or water level in the porous media, leading to an increase in $\delta^{18}O$ and trace
450 elements as dripping is maintained just from the smaller store. Before growth stops, a change
451 in gradient of Mg/Ca, Sr/Ca and Ba/Ca indicates a drying trend which lasts for ~170 years,
452 followed by a $\delta^{18}O$ increase of 2.2‰ that occurred over 4 years, and then increased
453 variability in Sr/Ca, Mg/Ca and Ba/Ca until deposition stops 28 years later. Many of the
454 previously studied stalagmites from Ethiopia such as Ach-1 (Asrat et al., 2007) show similar
455 features, which could be attributed to the specific geological setting of the region where
456 earthquake/tectonics play a strong role in shifting the relative position or the extent of the
457 major 'fracture' flow routes for such short-phased growths, leading to growth maintained for
458 short time longer from the smaller 'matrix' flow.

459 The similarity in values for the range *r* (20.5 yrs), the spectral frequency f (17-18 yrs),
460 and the observation that it takes 24 yrs for the stalagmite to stop growing, all suggest the
461 presence of a water store that can hold ~20 years of recharged water. The multi-decadal
462 growth rate frequency of 17-18 yrs, although insignificant, is in agreement with that observed
463 from Holocene stalagmites in the region (Ach-1, Bero-1; Baker et al., 2010), and similar to
464 observed variability in the modern rainfall pattern and subsequent flow at the upper Blue Nile
465 (Taye and Willems, 2012). Plausible climatic forcing over this timescale includes changes in
466 Atlantic and Indian Ocean sea surface temperature and variability in the movement and
467 intensity of the ITCZ and its effect on Ethiopian rainfall (Degefu et al., 2017). However, the
468 similarity of f and *r* suggests that any climate forcing in GM1 growth rate variability may be

amplified by the size of karst water store, or be karstic rather than climatic, the latter something previously observed in forward modelling studies (Baker et al., 2013).

Finally, the shift to higher isotope values within a growth phase can be explained by our conceptual model as a change from porous flow being the dominant water source to a dominance of fracture flow. It suggests that the observed 2‰ shift could be indicative of a water that has undergone additional kinetic or evaporative isotope fractionation. Both fractionation processes had been previously inferred as occurring in both Modern and Holocene Ethiopian speleothems, and from 'Hendy tests' on GM1, to a similar extent (up to 1‰). The implication for the climatic interpretation of stalagmite $\delta^{18}O$ is that variability of up to 2‰ cannot be directly ascribed to climatic forcing, but larger changes cannot be explained by fractionation processes. Similar rapid shifts in $\delta^{18}O$ of +2‰ within a period of 6 years have been identified in the Hulu cave speleothems (Treble et al., 2007).

4.2. The climate record

We can compare the $\delta^{18}O$ composition for each GM1 growth phase with published Holocene stalagmite data from Ethiopia (Asrat et al., 2007; Baker et al., 2007; 2010), as well as the modelled solar insolation for 15°N (Laskar et al., 2004), and other archived speleothem $\delta^{18}O$ records along the monsoon path and the "downstream" countries (China, Cheng et al., 2017; Israel, Bar Matthews et al., 1999; 2003). This comparison is shown in Figure 7. In GM-1 the $\delta^{18}O$ composition (–7.77±0.57‰ (129.3 ka), –3.82±0.61‰ (120.7 ka), –6.05±0.76‰ (undated), and –6.31±0.59‰ (108.4 ka)) is generally isotopically more negative compared to both modern (Merc-1: –1.22±0.31‰; Asfa-3: –1.37±0.37‰; Baker et al. 2007), and Holocene (Bero-1: –3.42±1.45‰, Baker et al., 2010; Ach-1: –3.20±0.35‰, Asrat et al., 2007) samples from the region. Even allowing for kinetic fractionation and non-equilibrium deposition of up to 2‰ in all samples, GM1 $\delta^{18}O$ composition at 129.3 ka, 108.4 ka, and an

494 undated growth phase, is more negative than any Holocene stalagmites from the region.
495 Combined with our conceptual understanding of GM1 deposition, we can be certain that
496 these growth phases and lower isotope composition are indicative of wetter conditions and
497 sustained recharge.

498 The GM1 record is the first high-resolution last interglacial continental climate record
499 and among the few climate records of any resolution from Ethiopia so far published. A deep
500 seismic and near-continuous core record of the last 150,000 years from Lake Tana on the
501 Northwestern Ethiopian highlands used geochemical proxies (sediment Ca/Ti ratio) for
502 climate-driven lake level fluctuations (Lamb et al., 2018). The oldest cave sediment records
503 from the Southeastern Ethiopian highlands goes back only to 63±7 ka (Tribolo et al., 2017).

504 The four phases of the GM1 record are dated at particularly important periods of the last
505 interglacial. Noting the quantified age uncertainties (see section 3.1.4), they provide high
506 resolution snapshots from some critical time-windows. The two long growth phases at ~129
507 ka and ~108 ka, which we conceptualise as being dominated by a sustained porous/matrix
508 flow regime, match maximum summer insolation at 15°N. This suggests that though internal
509 growth variability may be dominated by karst hydrology above the cave, the GM1 growth as
510 a whole and the geochemical proxies were responding to climate forcing.

511 Comparison of the GM1 $\delta^{18}O$ record with the China composite $\delta^{18}O$ record (Hulu and
512 Dongge caves; Cheng et al., 2016), the Soreq cave (Israel) $\delta^{18}O$ record (Bar-Mathews et al.,
513 1999; 2003) (Fig. 7) suggests a similar relationship for all three sites, with wet conditions
514 (lower $\delta^{18}O$ and peak summer insolation) during the ~108 ka growth period, and dry or
515 drying conditions (higher $\delta^{18}O$ and low summer insolation) at the ~120 ka growth period.
516 The Soreq cave $\delta^{18}O$ record from central Israel in the Levant has been shown to indicate
517 enhanced rainfall (Bar-Mathews et al., 1999) and could be a "downstream" indicator of a
518 stronger northeast African monsoon (Tierney et al., 1999). At ~129 ka, the lower $\delta^{18}O$ and

519 wetter conditions in Ethiopia occur at the summer insolation maxima, but may occur before
520 the isotope response observed in Israel and China. Dating uncertainty in the GM1 record
521 prevents a more precise interpretation, but it does raise the possibility of the intensification of
522 the East African Monsoon before other northern hemisphere monsoon systems at the start of
523 the last interglacial. The Lake Tana (Northwestern Ethiopian highlands) sediment Ca/Ti
524 record (Fig. 7) indicates an abrupt increase in moisture even earlier at ~132 ka, leading to
525 stable high lake level conditions during the period ~132 ka to ~95 ka, with some brief dry
526 episodes (Lamb et al., 2018). This period is defined by a generally flat trend of Ca/Ti,
527 truncated by very brief high Ca/Ti excursions. The major wet conditions during the ~129 ka
528 and 108 ka growth phases of GM1 are generally consistent with this predominantly high lake
529 level phase, although they do not particularly correspond to the lowest values of Ca/Ti.
530 As speleothem records of the Holocene from the region (Fleitmann et al., 2007) show,
531 decreasing $\delta^{18}O$ values during the early Holocene indicate a rapid northward migration of the
532 summer ITCZ and intensification of the rain belt of the Indian Summer Monsoon. On the
533 other hand, the southward migration of the ITCZ during the middle to late Holocene, marked
534 by increasing $\delta^{18}O$ values in speleothems, led to weakening of the associated summer
535 monsoon. Similar studies from Madagascar (e.g., Voarintsoa et al., 2017) have also shown
536 the link between speleothem $\delta^{18}O$ values and the ITCZ migration. The ~129 ka growth phase
537 of GM1 could therefore be effectively considered as an annual record of relative ITCZ
538 position ~129 ka BP.
539 Ethiopia/northeast Africa has been considered as the origin of Anatomically Modern
540 Humans (White et al., 2003; McDougall et al., 2005) and possibly the region out of which
541 Anatomically Modern Humans dispersed during MIS 5-3 or during earlier migration episodes
542 (*cf*. Hershkovitz et al., 2018). Considering the significant debate about the role climate
543 variability played in human evolution and dispersal of Anatomically Modern Humans "Out of

544 Africa" (e.g., Tierney et al. 2017 and references therein; Lamb et al., 2018), high-resolution
545 speleothem records from Ethiopia and northeastern Africa such as those of GM1 can shed
546 light on this debate. The GM1 record for instance shows that the earliest human migration
547 during MIS 5, confirmed by the presence of ~110-80 ka old Anatomically Modern Human
548 fossils in Israel (Grün et al., 2005), occurred during a major wet event in northeast Africa.
549 The Tana Lake record confirms that the northwestern Ethiopian highlands experienced
550 relatively stable moist climate during MIS 5c-e (Lamb et al., 2018). This supports earlier
551 conclusions that human migration occurred during humid conditions, as such conditions
552 provided humans "green corridors" to overcome inhospitable deserts (e.g., Timmerman and
553 Friedrich, 2016). However, the major episode of human migration occurred during 50-75 ka
554 (Nielsen et al., 2017), and marine records from the Gulf of Aden show that this migration
555 event occurred during a sustained dry condition in northeast Africa (Tierney et al., 2017),
556 while the Lake Tana record shows more complex climate variability during this period (Lamb
557 et al., 2018). Future research is required on the speleothems from Goda Mea and Aynage
558 caves, some of which have been dated to the critical period of 120-50 ka.
559
560 **5. Conclusions**
561 Stalagmite GM1 was deposited discontinuously around the time of the last interglacial, at
562 ~129 ka, 120 ka, an undated growth phase, and ~108 ka. Variogram analysis of growth rate
563 shows a low range (20.5 years), some flickering (–0.33) and good information content (56%),
564 indicative of a stalagmite fed by a karst water store of limited volume. Oxygen and carbon
565 isotopes and trace elements generally have low variability, indicative of a second, well-mixed
566 water source feeding the stalagmite. Stalagmite GM1 provides a high-resolution insight into
567 stalagmite hydrogeochemical responses to environmental change prior to growth hiatuses.
568 Multi-decadal variability of frequency 17-18 years, though statistically not significant at 95%

569 confidence, is present, but only in the growth rate time series, and is slightly less than the
570 range in the growth rate record. A climatic or karstic forcing of this spectral frequency cannot
571 be determined.

572 Our conceptual model for the stable isotope, trace element and growth rate records in
573 GM1 allows the interpretation of the stalagmite geochemical time series. Importantly, all
574 three proxies were necessary to adequately understand the processes forcing them, and
575 whether they contained a climatic or karstic signal. Only through this approach were we able
576 to confirm that low $\delta^{18}O$ at ~129 ka and ~108 ka can be attributed to wetter climatic
577 conditions. These two growth phases occur at the same time as solar insolation maxima for
578 15°N, and suggest a direct solar forcing on rainfall in Ethiopia at these times, influencing the
579 northward migration of the ITCZ and the associated rain belt of the Indian Summer
580 Monsoon, of potential relevance for early modern human migration out of the region.

581

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http://www1.ncdc.noaa.gov/pub/data/paleo/speleothem/asia/china/cheng2016composite.txt
ftp://ftp.ncdc.noaa.gov/pub/data/paleo/speleothem/israel/soreq_peqiin_2003.txt

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723

Table Caption

Table 1. U and Th isotope data and age determinations (in depth order) for stalagmite GM1. Square brackets indicate activity ratios. Ages shown are corrected for an initial [$^{230}Th/^{232}Th$] of 1.5 and a 100% uncertainty, which is incorporated into the age uncertainty.

Figure Captions

Fig. 1. (a) Regional structural setting of Ethiopia showing the location of Mechara. Lake Tana, and the epicentres of the major earthquakes in the Main Ethiopian Rift and the adjoining highlands are marked (Note that earthquake epicentres in the northern Afar depression are not represented). Insets show the mean position of the ITCZ in July (Boreal summer) and January (winter) over Africa; and the mean monthly rainfall (mm) and mean monthly temperature of the Mechara region, at the Bedesa Meteorological Station (1994-2014 data from the Ethiopian Meteorological Agency). Location of (b) is marked by a broken triangle around the location of Mechara (modified from Asrat et al., 2008); (b) The topography, geology, structure and drainage system of the Mechara karst area and locations of the entrances to the caves mentioned in the text; (c) Goda Mea cave (surveyed according to BCRA Grade 3 using tape, compass and clinometer); (d) a photograph of the main chamber of the Goda Mea cave interior showing the collapse chamber on which grew several speleothems following a major fracture system (photograph by J. Gunn). Figures (a) and (b) modified from Asrat et al., 2008; Fig. (c) modified from Gunn et al., 2009.

748 Fig. 2. GM1 hand-section in both scanned image (left) and sketch (middle), showing the four
749 major growth phases, locations of the major and minor growth hiatuses, and sampling for
750 isotopes, trace elements and U-Th analyses. Right: photomicrographs of thick sections
751 from across the major growth hiatuses showing a clear evidence of growth stoppage with
752 no apparent dissolution.
753 Fig. 3. U-Th data for stalagmite GM1. (a) Corrected U-Th ages vs depth for all analyses. (b)
754 ^{238}U concentration vs depth (c) [$^{230}Th/^{232}Th$] vs depth (d) Initial [$^{234}U/^{238}U$] vs depth (e)
755 U-Th ages vs depth for samples with [$^{230}Th/^{232}Th$] >1000. In all plots, the three major
756 hiatuses are shown as vertical dashed lines.
757 Fig. 4. GM1 times series for the geochemical proxies. From top: growth rate, $\delta^{13}C$, $\delta^{18}O$,
758 Sr/Ca, Mg/Ca, Ba, Ca. Note the axis breaks on the x-axis, which permit equal scaling of
759 data on the time axis.
760 Fig. 5. (a) Scatterplot of variogram parameters range, information content and flickering for
761 the 129.3 ka growth phase; (b) Autocorrelation of growth rate, $\delta^{13}C$ and $\delta^{18}O$ time series
762 for the three U-Th dated growth phases; (c) Spectral analysis on the growth rate and $\delta^{18}O$
763 times series for the 129.3 ka growth phase. The 17-18 years peak, though statistically not
764 significant is marked.
765 Fig. 6. Conceptual model for the deposition of stalagmite GM1.
766 Fig. 7. Comparison of climate proxy records. (a) Insolation at 15°N (Laskar et al., 2004); (b)
767 Chinese composite stalagmite $\delta^{18}O$ record (Cheng et al., 2016); (c) Soreq Cave $\delta^{18}O$
768 record (Bar-Matthews et al., 1999; 2003); (d) Lake Tana sediment Ca/Ti record (Lamb et
769 al., 2018); (e) Ethiopian stalagmite $\delta^{18}O$ composite. Box-plots show median, inter-
770 quartile range and range for each stalagmite; shading represents different caves (grey –
771 Bero Cave; Green – Rukiesa Cave; Orange – Achere Cave; Cyan – Goda Mea Cave).

772 Note the x-axis break; vertical shading aligns the Ethiopian records to the other time
773 series.
774 Fig. S1. Scatter plot of $\delta^{13}C$ vs $\delta^{18}O$ for all growth phases. 'Hendy tests' along growth
775 laminae are shown in colour (Lines 1-7): their location is shown in Fig. 2 (HL1-HL7).
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