Martin H. Trauth, U Potsdam

together with the Chew Bahir Drilling Project Team

including Markus Fischer, Manfred Mudelsee & Norbert Marwan

Time Series Analysis

Photo: Annett Junginger

icdp

INTERNATIONAL CONTINENTAL
SCIENTIFIC DRILLING PROGRAM

The Hominin Sites and Paleolakes Drilling Project

Workshop Addis Ababa, Ethiopia Nov 17-21 2008

2009 Workshop Report

2022 Synthesis Paper

Workshop Reports

Understanding Paleoclimate and Human Evolution Through the Hominin Sites and Paleolakes Drilling Project

by Andrew Cohen, Ramon Arrowsmith, Anna K. Behrensmeyer, Christopher Campisano, Craig Feibel, Shimeles Fisseha, Roy Johnson, Zelalem Kubsa Bedaso, Charles Lockwood†, Emma Mbua, Daniel Olago, Richard Potts, Kaye Reed, Robin Renaut, Jean-Jacques Tiercelin, and Mohammed Umer

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Understanding the evolution of humans and our close relatives is one of the enduring scientific issues of modern times. Since the time of Charles Darwin, scientists have speculated on how and when we evolved and what conditions drove this evolutionary story. The detective work required to address these questions is necessarily interdisciplinary, involving research in anthropology, archaeology, human genetics and genomics, and the earth sciences. In addition to the difficult tasks of finding, describing, and interpreting hominin fossils (the taxonomic tribe which includes *Homo sapiens* and our close fossil relatives from the last 6 Ma), much of modern geological research associated with paleo-anthropology involves understanding the geochronologic and paleoenvironmental context of those fossils. When were they entombed in the sediments? What were the local and regional climatic conditions that early hominins experienced? How did local (watershed scale) and regional climate processes combine with regional tectonic boundary conditions to influence hominin food resources, foraging patterns, and demography? How and when did these conditions vary from humid to dry, or cool to warm? Can the history of those conditions (Vrba, 1988; Potts, 1996) be related to the evolution, diversification, stasis, or extinction of hominin species?

Most of the efforts to address these questions to date have centered on evidence from outcrops where the hominin fossils have been collected. Earth scientists have made great strides in understanding these contextual questions using fluvial, paleosol, and marginal lacustrine sediments associated with hominin fossils; however, this approach has its limitations. Outcrops, for example, cannot normally provide us with continuous, unweathered stratigraphic sections needed to address many questions relating events in hominin evolution and environmental change. The places where hominins actually lived (literally, above the water table) tend to have only discontinuous and relatively low resolution lithostratigraphic records of climate and other aspects of environmental change.

For these reasons the paleoanthropology community has turned to drill cores as a potential source of more highly resolved paleoenvironmental information. This concept is not new. Almost thirty years ago, the U.S. National Science Foundation (NSF) sponsored a workshop to examine the potential of recovering long sediment cores from the deepest and oldest of the modern African Rift Valley lakes, with a particular emphasis placed on how these records might inform our understanding of the environmental context of early hominin evolution (Lewin, 1981). In an influential paper, deMenocal (1995) demonstrated how northeastern African paleoclimate could be inferred from dust records encased in Deep Sea Drilling Project (DSDP) drill cores collected in the Gulf of Aden. This paper, as well as subsequent ones (deMenocal,

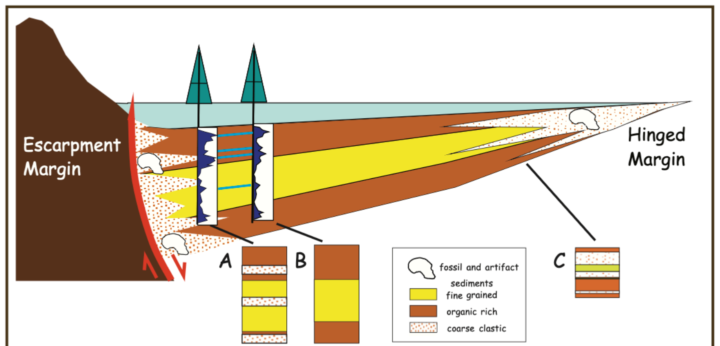

Figure 1. A conceptual model for drill site targeting in HSPDP (Hominin Sites and Paleolakes Drilling Project), using a half-graben rift basin depositional model. Note that a lake is shown in the diagrammatic cross section, although for the current phase of drilling we are targeting paleolake deposits where drilling from a barge can be avoided. The primary target (Drill Site B) would be far enough from the paleoshoreline to avoid most coarse clastic facies (pattern), with a relatively thick and highly resolved stratigraphic record. These types of offshore (fine-grained, organic rich) sediments (shown as yellow and brown solid colors) are most likely to yield the continuous paleoclimatic records useful for addressing current questions about hominin evolution/climate interactions. In contrast, a hinged margin site (C), even though potentially in close proximity to fossil and artifact localities, will yield a thinner and more discontinuous record, and one in which high stand lake deposits are over-represented. A more proximal target on the escarpment margin (A) will yield a dominantly coarse-grained stratigraphic record that is also less desirable for paleoclimate studies, although it may provide a useful secondary target for correlation into the hominin-bearing outcrops and/or records of tectonic uplift affecting the watershed.

ANNUAL REVIEWS

Annual Review of Earth and Planetary Sciences

Reconstructing the Environmental Context of Human Origins in Eastern Africa Through Scientific Drilling

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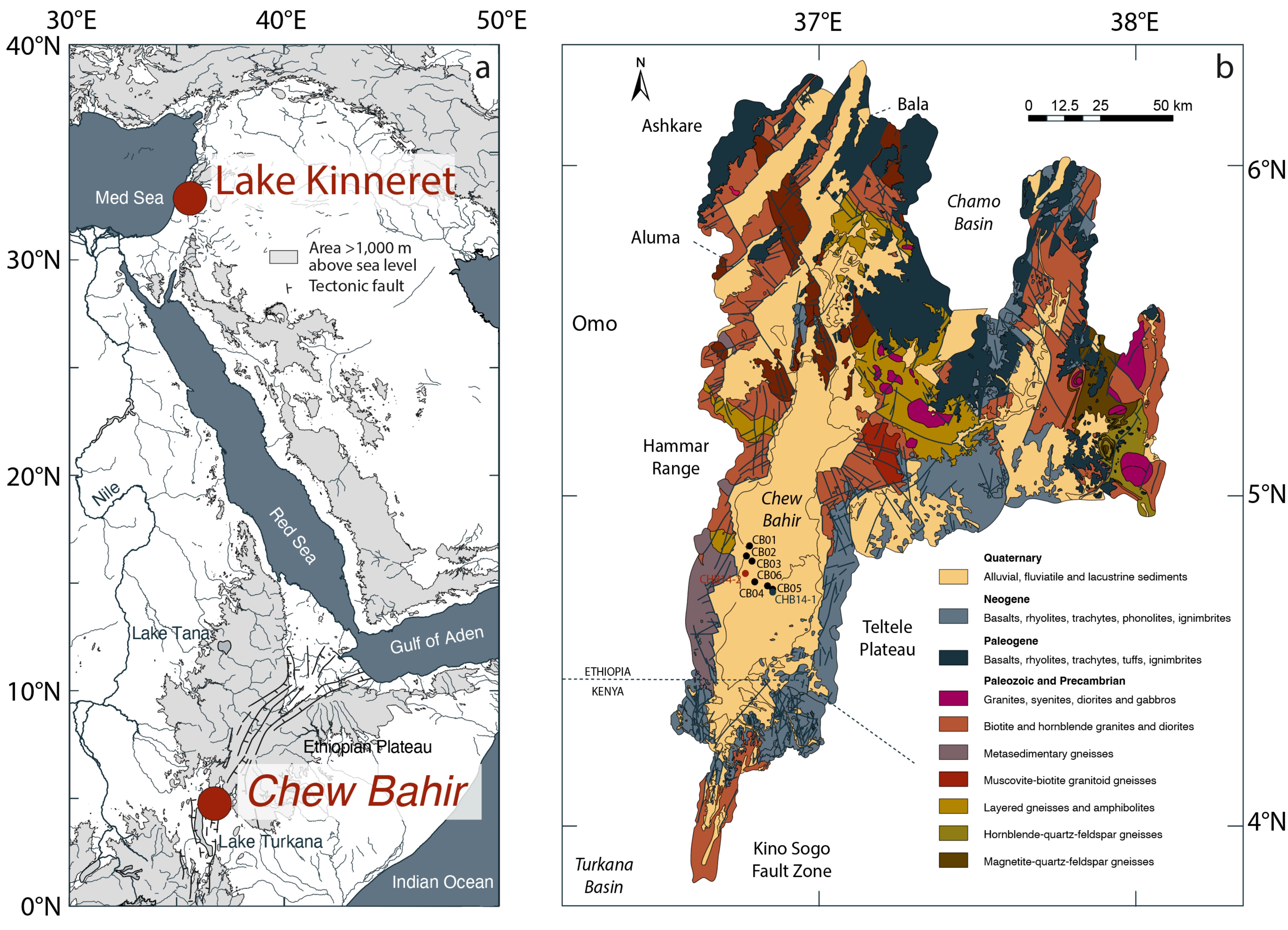
The Chew Bahir Coring / Drilling Project



Modified after Trauth et al. Nat. Commun. 2024


Photo: Verena Förster


Photo: Asfawossen Asrat

The Chew Bahir Cores 2009–2014

Core ID	Location	Latitude	Longitude	Length	Total Depth	Coring Date	Core Recovery
CB01	Margin	N 04°50.6’	E 36°46.8’	22 m	19 m	Dec 2009	81%
CB02	Margin	N 04°48.7’	E 36°46.2’	10 m	9 m	Nov 2010	97%
CB03	Intermediate	N 04°47.9’	E 36°47.2’	11 m	11 m	Nov 2010	98%
CB04	Centre	N 04°43.3’	E 36°50.2’	10 m	10 m	Nov 2010	99.5 %
CB05	Centre	N 04°42.8’	E 36°51.3’	10 m	10 m	Nov 2010	97%
CB06	Centre	N 04°44.1’	E 36°47.9’	10 m	10 m	Nov 2010	97%
CB01–06		**Composite Core**			**19 m**		**~95%**
CHB14-1	**Center**	**N 4°42.4'**	**E 36°51.1'**		**~40 m**		
CHB14-2A	Margin	N 4°45.7'	E 36°46.1'		278.58 m	Nov/Dec 2014	
CHB14-2B	Margin	N 4°45.7'	E 36°46.2'		266.38 m	Nov/Dec 2014	
CHB14-2		**Composite Core**			**292.87 m**		**~90%**

Trauth et al. Nat. Commun. 2024

The climate proxy forming process

2018

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Towards an understanding of climate proxy formation in the Chew Bahir basin, southern Ethiopian Rift

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ABSTRACT

Deciphering paleoclimate from lake sediments is a challenge due to the complex relationship between climate parameters and sediment composition. Here we show the links between potassium (K) concentrations in the sediments of the Chew Bahir basin in the Southern Ethiopian Rift and fluctuations in the catchment precipitation/evaporation balance. Our micro-X-ray fluorescence and X-ray diffraction results suggest that the most likely process linking climate with potassium concentrations is the authigenic illitization of smectites during episodes of higher alkalinity and salinity in the closed-basin lake, due to a drier climate. Whole-rock and clay size fraction analyses suggest that illitization of the Chew Bahir clay minerals with increasing evaporation is enhanced by octahedral Al-to-Mg substitution in the clay minerals, with the resulting layer charge increase facilitating potassium-fixation. Linking mineralogy with geochemistry shows the links between hydroclimatic control, process and formation of the Chew Bahir K patterns, in the context of well-known and widely documented eastern African climate fluctuations over the last 45,000 years. These results indicate characteristic mineral alteration patterns associated with orbitally controlled wet-dry cycles such as the African Humid Period (~15–5 ka) or high-latitude controlled climate events such as the Younger Dryas (~12.8–11.6 ka) chronozone. Determining the impact of authigenic mineral alteration on the Chew Bahir records enables the interpretation of the previously established µXRF-derived aridity proxy K and provides a better paleohydrological understanding of complex climate proxy formation.

1. Introduction

The relationship between climate and sediment composition in lake cores is nonlinear due to differential and incongruent weathering and to variations in the erosion and dissolution, transport, sedimentation, and precipitation of minerals within the catchment (Muhs et al., 2001; Phillips, 2006; Porter et al., 2007; Carré et al., 2012). The complexity of this relationship makes it difficult to decipher climatic information in sediment cores as it may result in different time-lags between the responses of different climate proxies. However, these differences provide valuable information on the dynamics of the source-to-sink sedimentation system and its controlling factors. For example, differential weathering of less resistant and more resistant minerals in magmatic source-rocks is dependent on the local climatic conditions of the source area and may therefore in itself be useful as a climate proxy (Nesbitt and Young, 1984; Muhs et al., 2001; Navarre-Sitchler and Brantley, 2007; Moses et al., 2014).

The increasing availability of micro-X-ray fluorescence (µXRF) scanners has led to an increase in the use of major and trace element concentrations (often without any quantitative calibration) as climate proxies (Peterson et al., 2000; Jaccard et al., 2005; Yancheva et al., 2007; Martínez-Garcia et al., 2010; Foerster et al., 2012, 2014). The physicochemical processes linking climate with element concentrations, however, are not sufficiently well understood. Investigations on

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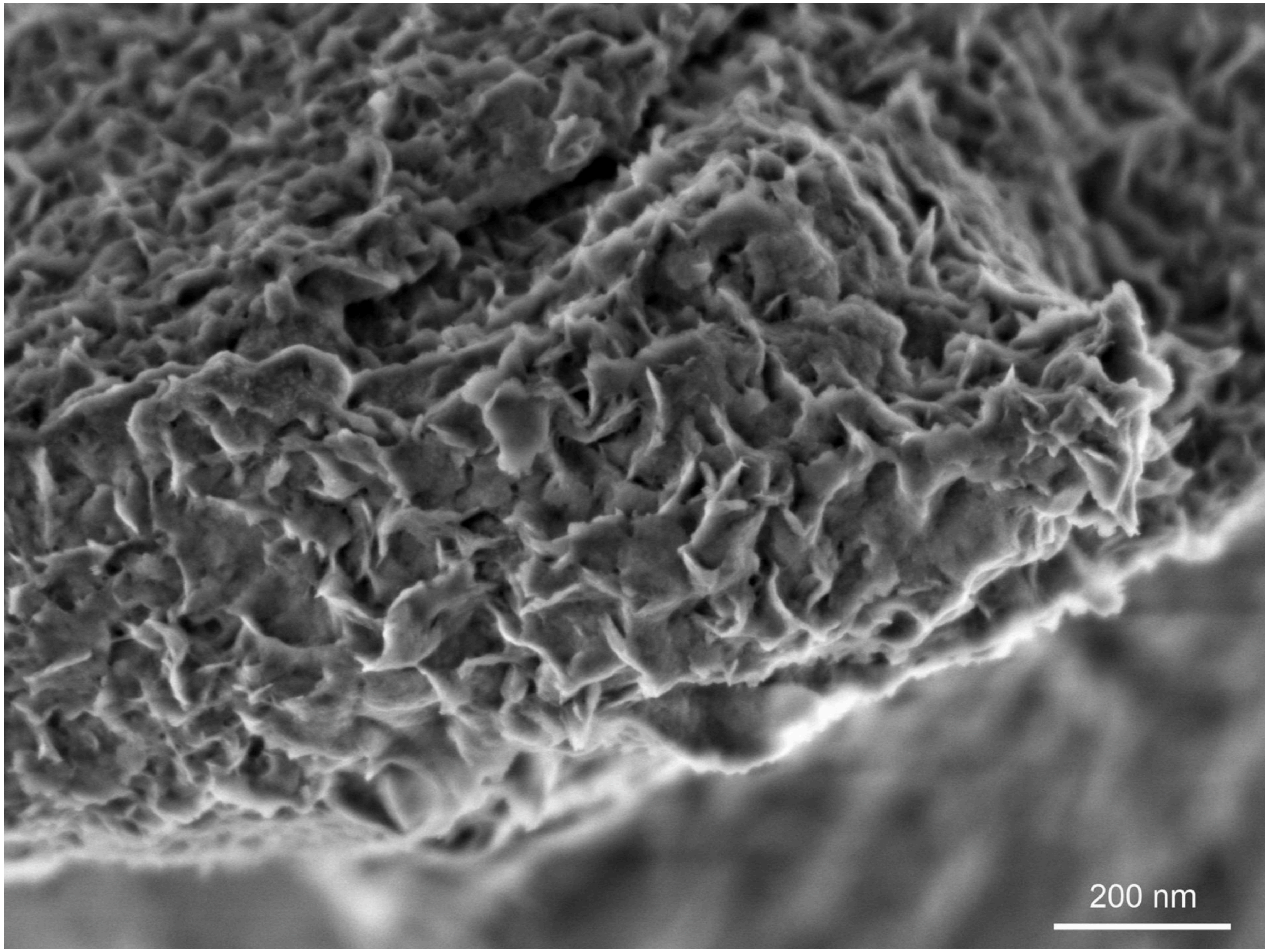
Natrium, Calcium

Montmorillonit

$(Na,Ca)_{0,3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$

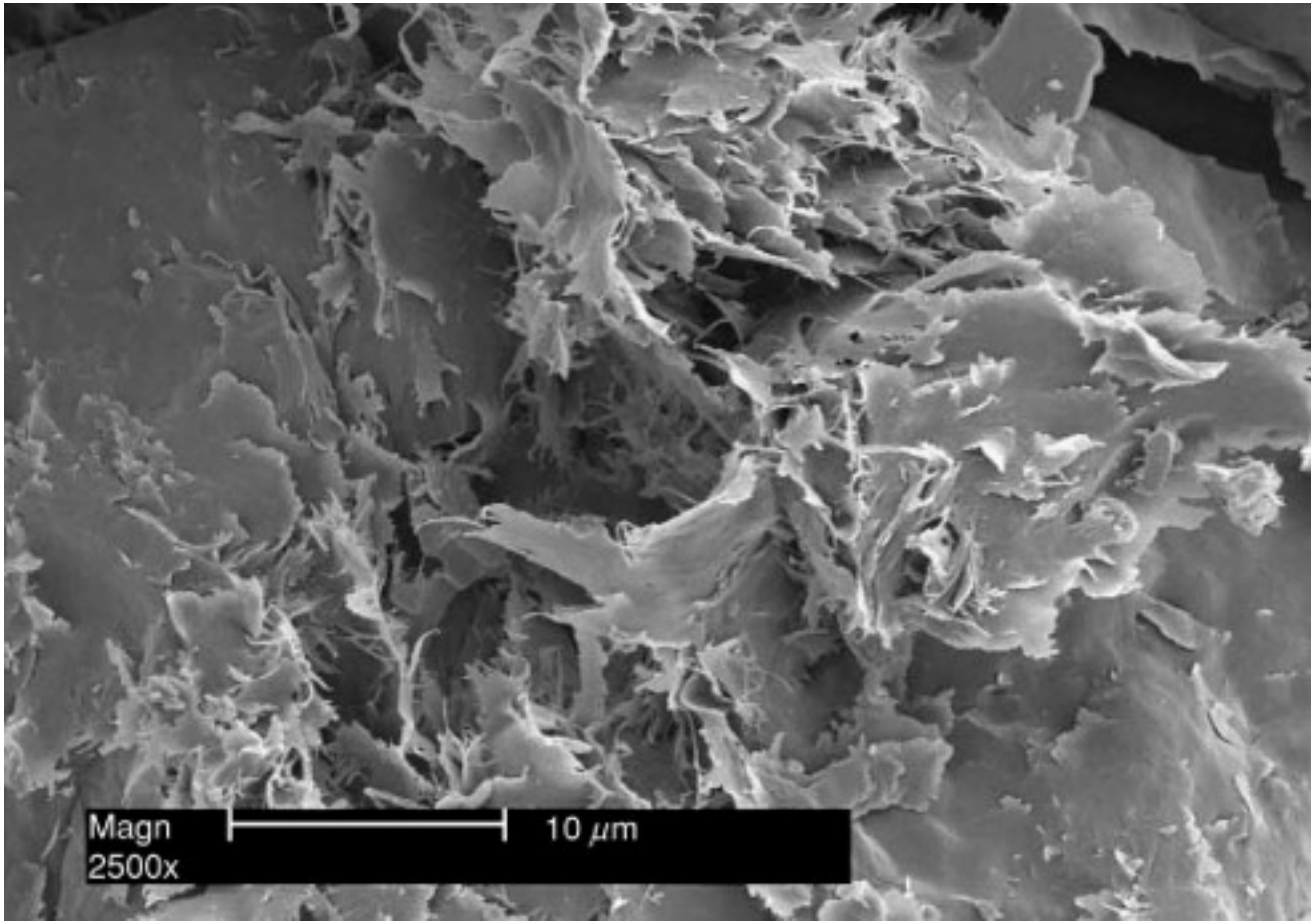


ZEISS

Kalium

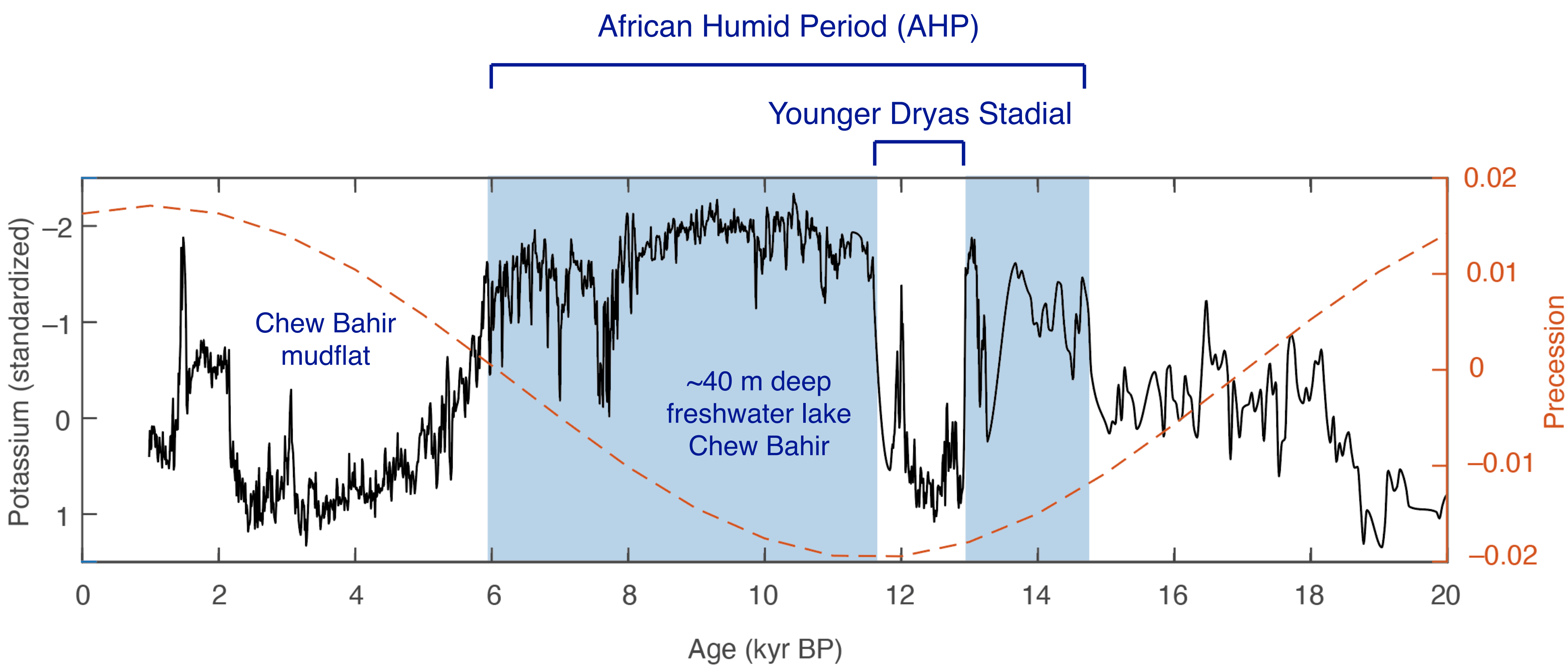
Illit

$K_{0,65}Al_{2,0}Al_{0,65}Si_{3,35}O_{10}(OH)_2$



Developments in Clay Science, 2013

The Chew Bahir potassium record



Foerster et al., Quat Int 2012, Trauth et al., J Hum Evol 2015

The Chew Bahir age model

2021

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Invited Paper

Using multiple chronometers to establish a long, directly-dated lacustrine record: Constraining >600,000 years of environmental change at Chew Bahir, Ethiopia

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ABSTRACT

Despite eastern Africa being a key location in the emergence of *Homo sapiens* and their subsequent dispersal out of Africa, there is a paucity of long, well-dated climate records in the region to contextualize this history. To address this issue, we dated a ~293 m long composite sediment core from Chew Bahir, south Ethiopia, using three independent chronometers (radiocarbon, $^{40}Ar/^{39}Ar$, and optically stimulated luminescence) combined with geochemical correlation to a known-age tephra. The site is located in a climatically sensitive region, and is close to Omo Kibish, the earliest documented *Homo sapiens* fossil site in eastern Africa, and to the proposed dispersal routes for *H. sapiens* out of Africa. The 30 ages generated by the various techniques are internally consistent, stratigraphically coherent, and span the full range of the core depth. A Bayesian age-depth model developed using these ages results in a chronology that forms one of the longest independently dated, high-resolution lacustrine sediment records from eastern Africa. The chronology illustrates that any record of environmental change preserved in the composite sediment core from Chew Bahir would span the entire timescale of modern human evolution and dispersal, encompassing the time period of the transition from Acheulean to Middle Stone Age (MSA), and subsequently to Later Stone Age (LSA) technology, making the core well-placed to address questions regarding environmental change and hominin evolutionary adaptation. The benefits to such studies of direct dating and the use of multiple independent chronometers are discussed.

1. Introduction

The impact of climate and environmental change on hominin evolution, adaptation and dispersal in Africa has been the subject of much debate in recent years. Some of the dramatic events of the last half-million years include megadroughts (e.g. Scholz et al., 2007), faunal change and extinctions, the emergence of *Homo sapiens* (e.g. Hublin et al., 2017; McDougall et al., 2008; Brown et al., 2012; Potts et al., 2018), major transitions in tool technologies (e.g. MSA and LSA; Morgan and Renne, 2008; Gliganic et al., 2012;

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Combining orbital tuning and direct dating approaches to age-depth model development for Chew Bahir, Ethiopia

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ABSTRACT

The directly dated *RRMarch2021* age model (Roberts et al., 2021) for the ~293 m long composite core from Chew Bahir, southern Ethiopia, has provided a valuable chronology for long-term climate changes in northeastern Africa. However, the age model has limitations on shorter time scales (less than 1–2 precession cycles), especially in the time range <20 kyr BP (kiloyears before present or thousand years before 1950) and between ~155 and 428 kyr BP. To address those constraints we developed a partially orbitally tuned age model. A comparison with the ODP Site 967 record of the wetness index from the eastern Mediterranean, 3300 km away but connected to the Ethiopian plateau via the River Nile, suggests that the partially orbitally tuned age model offers some advantages compared to the exclusively directly dated age model, with the limitation of the reduced significance of (cross) spectral analysis results of tuned age models in cause-effect studies. The availability of this more detailed age model is a prerequisite for further detailed spatiotemporal correlations of climate variability and its potential impact on the exchange of different populations of *Homo sapiens* in the region.

1. Introduction

The Chew Bahir Drilling Project (CBDP), initiated in November 2008, was part of the Hominin Sites and Paleolakes Drilling Project (HSPDP), aiming to provide continuous, high-resolution records of environmental change which span critical intervals of human evolution, dispersion, and cultural innovation (Cohen et al., 2016, 2022; Foerster et al., 2012, 2022; Schaebitz et al., 2021; Trauth et al., 2024; Fischer et al., 2024). In 2009 and 2010, we recovered several short cores CB01–06 along a ~20 km long NW–SE transect across the southern part of the basin, up to 18.8 m long and spanning the last ~47 kyrs (Foerster et al., 2012, 2015; Trauth et al., 2018) (Table 1, Fig. 1). In May 2014, a ~40 m long core CHB14-1 was collected from the central part of the southern Chew Bahir basin covering the last ~120 kyrs (Viehberg et al., 2018). During a 35-day coring campaign in Nov–Dec 2014, two ~280 m long parallel cores CHB14-2A and 2B were collected that were subsequently merged to a ~293 m long composite core CHB14-2 (Foerster et al., 2022). The age models of the short cores CB01–06 and the intermediate core CHB14-1 that cover the younger sedimentary deposits were discussed in separate publications (e.g., Foerster et al., 2012, 2015; Viehberg et al., 2018; Trauth et al., 2018, 2019, 2024). The age model of CHB14-2 named RRMarch2021 followed a direct-dating approach and was presented in Roberts et al. (2021) providing a reliable first chronology for the Chew Bahir composite core spanning the last ~620 kyrs. The RRMarch2021 age model has been used in several studies related to different topical foci in paleoclimate dynamics reconstructed from the long composite core CHB14-2 (e.g., Schaebitz et al., 2021; Trauth et al., 2021; Foerster et al., 2022).

The RRMarch2021 age model works well when looking at climate changes on time scales longer than that of climate precession (~23 kyr), but larger uncertainties become evident when analyzing high-frequency climate fluctuations; this applies in particular in sections of the core younger than ~20 kyr BP and between 155 and 428 kyr BP (Roberts et al., 2021). Uncertainties in the younger section (<20 kyr BP) of the

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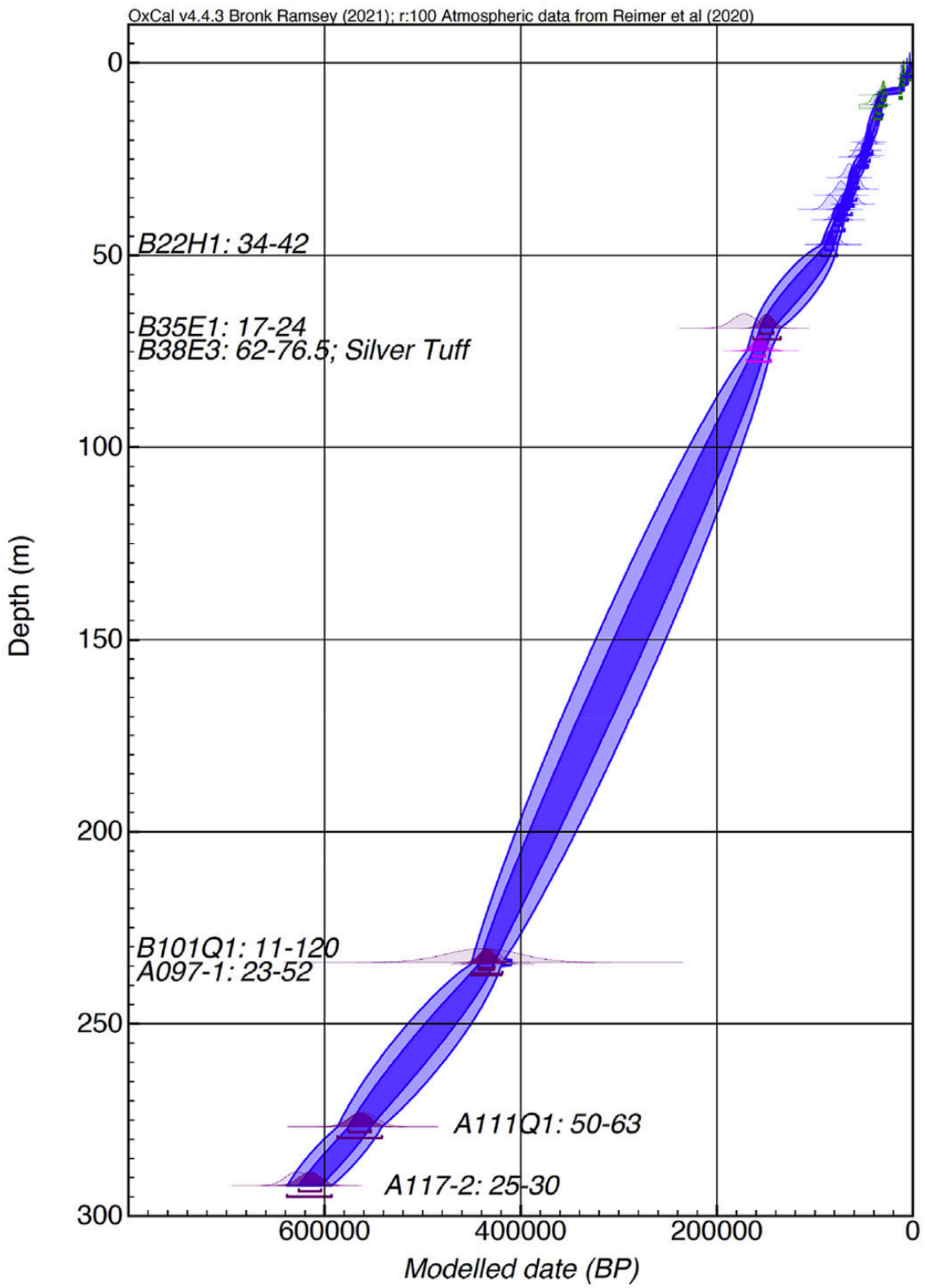
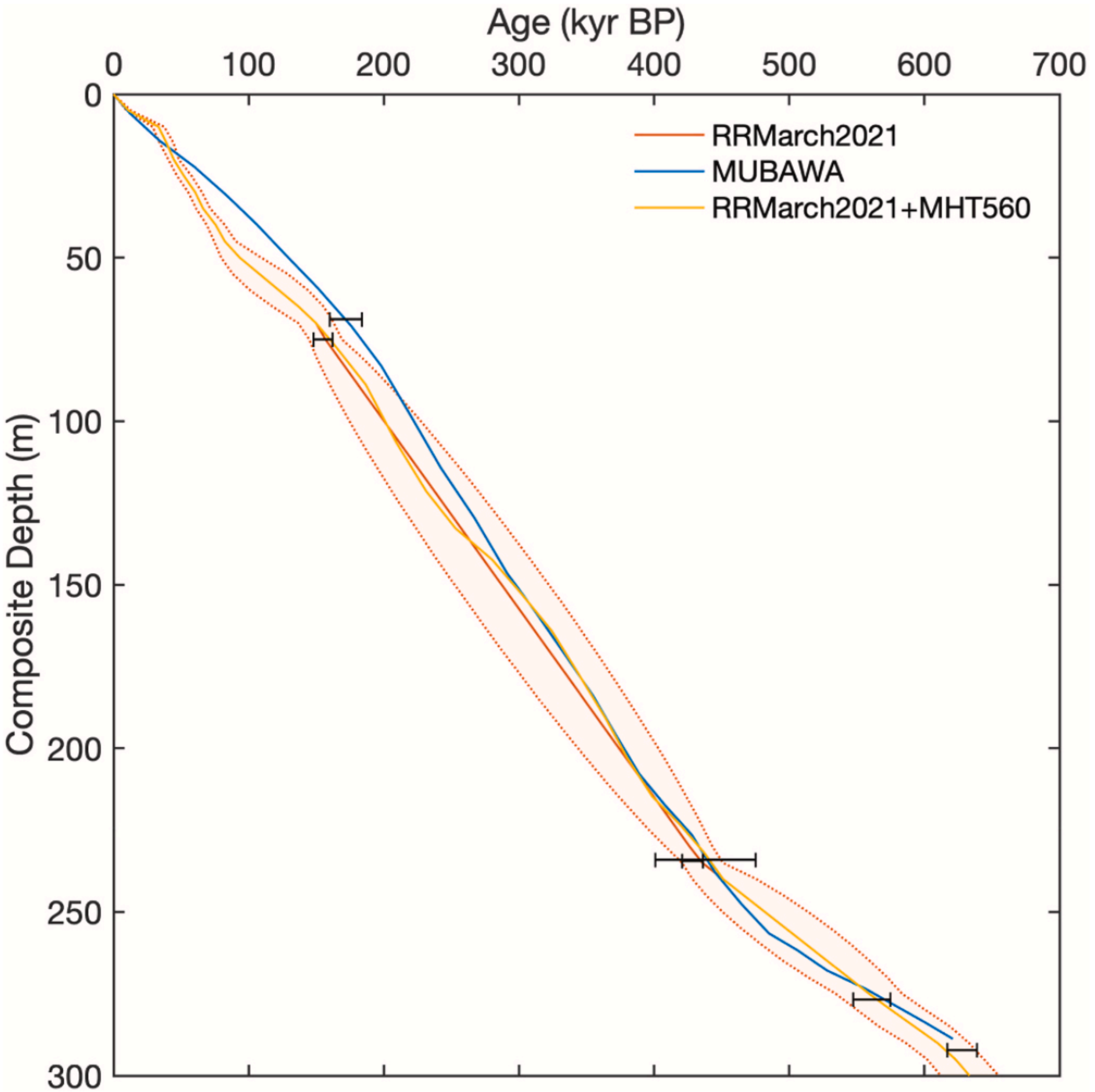
The Chew Bahir age models

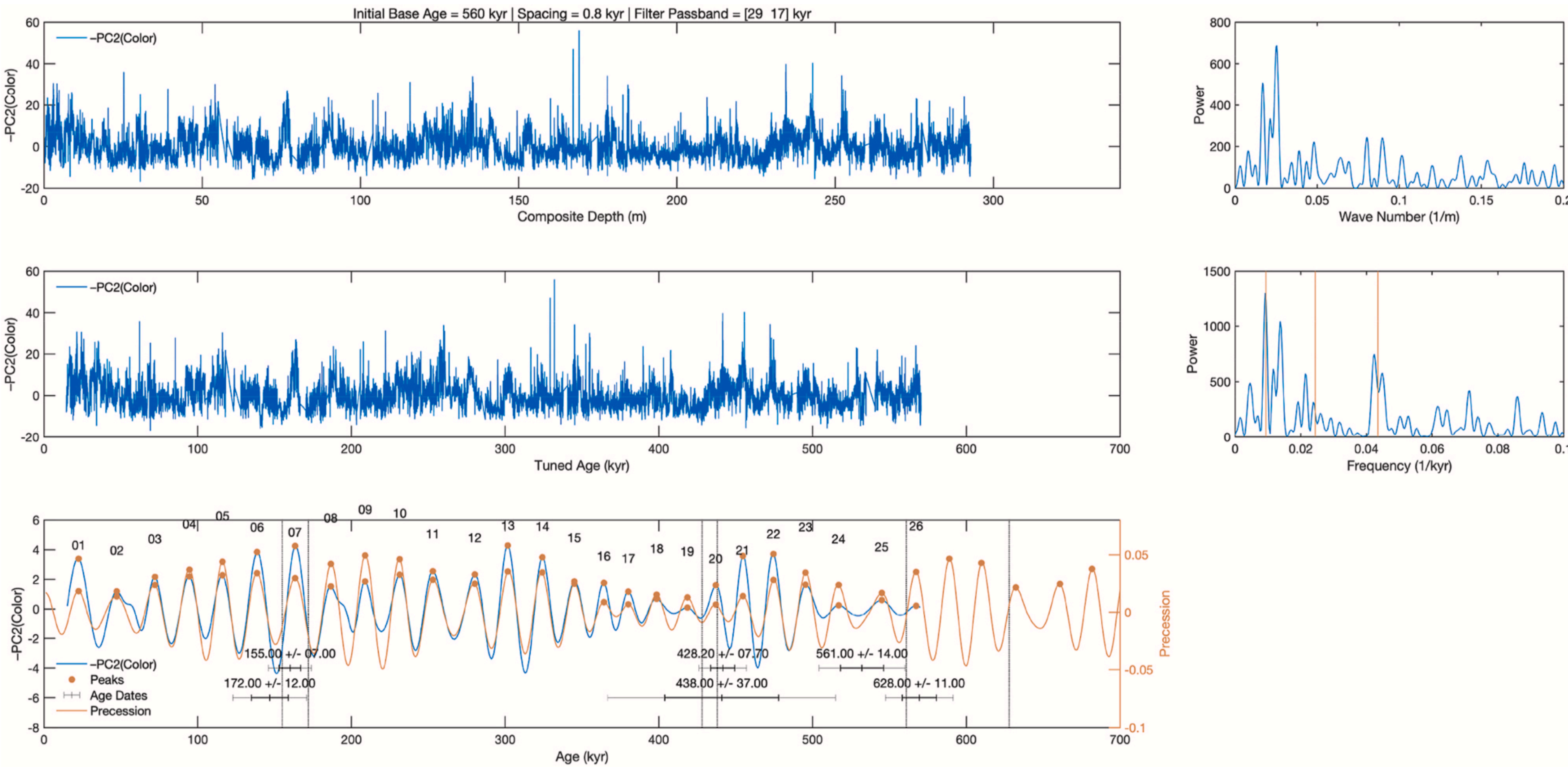




Roberts et al. QSR 2021

Trauth et al. QSR 2024

The Chew Bahir Age Model



Introducing the long Chew Bahir records

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Pleistocene climate variability in eastern Africa influenced hominin evolution

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Check for updates

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Despite more than half a century of hominin fossil discoveries in eastern Africa, the regional environmental context of hominin evolution and dispersal is not well established due to the lack of continuous palaeoenvironmental records from one of the proven habitats of early human populations, particularly for the Pleistocene epoch. Here we present a 620,000-year environmental record from Chew Bahir, southern Ethiopia, which is proximal to key fossil sites. Our record documents the potential influence of different episodes of climatic variability on hominin biological and cultural transformation. The appearance of high anatomical diversity in hominin groups coincides with long-lasting and relatively stable humid conditions from ~620,000 to 275,000 years BP (episodes 1–6), interrupted by several abrupt and extreme hydroclimate perturbations. A pattern of pronounced climatic cyclicity transformed habitats during episodes 7–9 (~275,000–60,000 years BP), a crucial phase encompassing the gradual transition from Acheulean to Middle Stone Age technologies, the emergence of *Homo sapiens* in eastern Africa and key human social and cultural innovations. Those accumulative innovations plus the alignment of humid pulses between northeastern Africa and the eastern Mediterranean during high-frequency climate oscillations of episodes 10–12 (~60,000–10,000 years BP) could have facilitated the global dispersal of *H. sapiens*.

Eastern Africa during the Middle–Late Pleistocene offered a wide range of habitats, and deposits of this age are rich in human fossils and archaeological remains[1–4]. Hypotheses seeking to explain links between climate and human origins are difficult to test because both climate records and traces of early human populations are often incomplete or poorly dated[3–5]. Encouraged by discussion of possible climate-evolution linkages, the Hominin Sites and Paleolakes Drilling Project (HSPDP) was established in 2008, with deep drilling campaigns in 2013–2014[6]. One component of HSPDP, the Chew Bahir Drilling Project (CBDP), collected two ~280-m-long cores from Chew Bahir (CHB), a playa lake in southern Ethiopia (4° 45' 40.5″ N, 36° 46' 1.0″ E) (Fig. 1)[7,8], covering the past ~620,000 years (620 kyr)[9], which includes the time frame of the emergence of *H. sapiens* in Africa[6,10,11]. While there is a general consensus that the physical, cognitive and cultural evolution of *H. sapiens* in Africa developed multiregionally[11,12], the CHB record provides an environmental window with which to view the eastern African part of this history[6]. The CHB coring site is situated near key archaeological and palaeoanthropological sites, such as the Omo-Kibish (~90 km west

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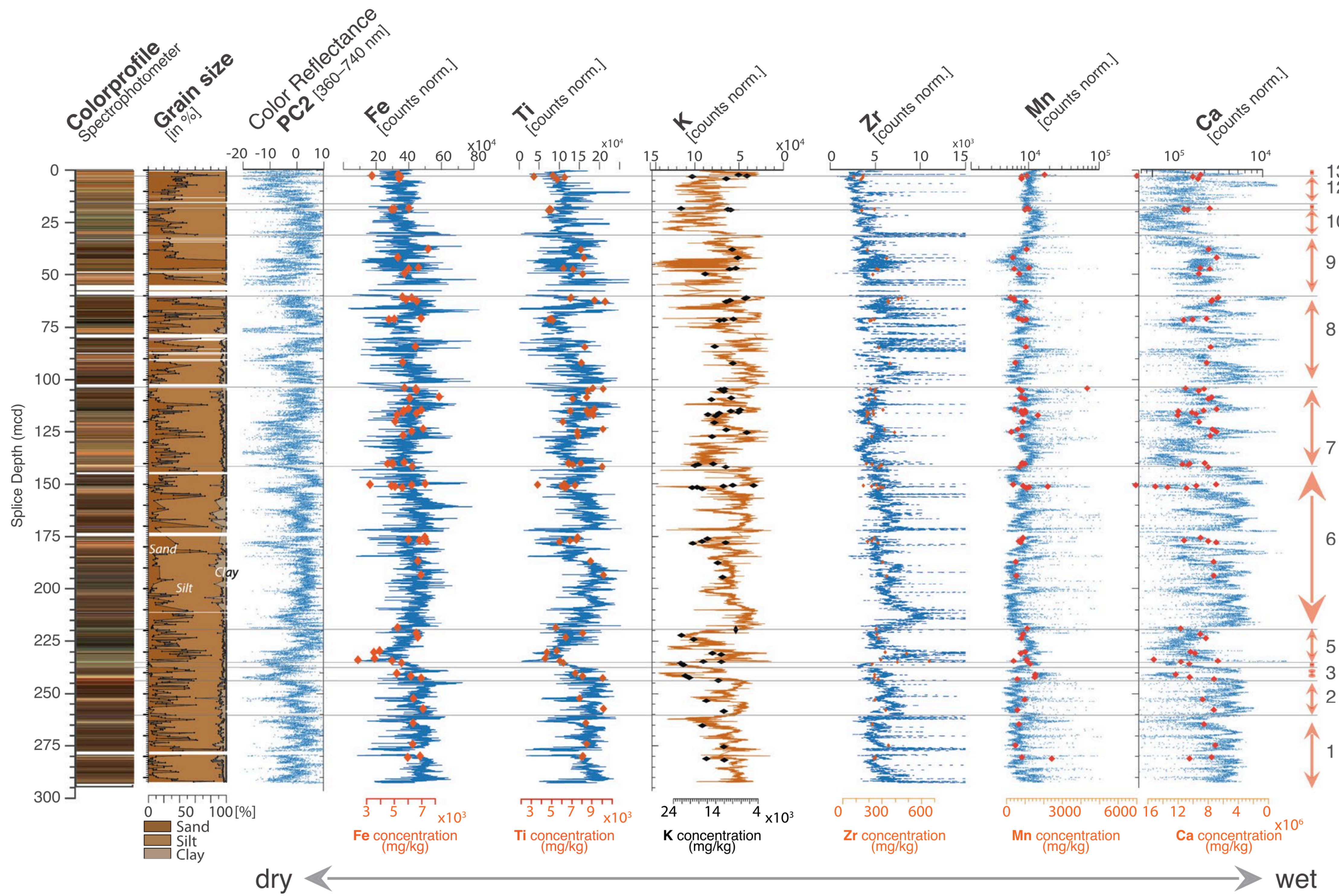

Extended Data Fig. 2 | Summary stratigraphy of composite core HSPDP-CHB14-2 and results of chemical and physical sediment analyses. Columns from left to right: Core color profile (MSCL- spectrophotometer), grain sizes in %, PC2 of the color reflectance (ref. [15]) and scanning XRF results (5 mm resolution) in normalized counts report to the upper x-axis (blue plots and red curve) and are compared to results of quantitative XRF analyses (concentrations in mg/kg) that report to the lower x-axis (red and black squares). Elemental variations from left to right: iron (Fe), titanium (Ti), potassium (K) (note inverted scale), zirconium (Zr), manganese (Mn), calcium (Ca) (note inverted scale). Episodes on the right axis correspond to environmental episodes in Fig. 2. Proxy values oriented to the right indicate wet conditions; proxy values oriented to the left are indicative for dry conditions.

Foerster et al. Nat. Geosci. 2021

Tipping points and early warning signals

Time Series Analysis

Extreme component

Periodic component

Variable function

$$x(t_k) = x_p(t_k) + x_{tr}(t_k) + x_e(t_k) + s(t_k) \cdot x_{ns}(t_k)$$

Random noise

Trends, transitions,
change points …

Mudelsee 2020, Trauth 2024, 2025

2024

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Early warning signals of the termination of the African Humid Period(s)

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Check for updates

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The transition from a humid green Sahara to today's hyperarid conditions in northern Africa ~5.5 thousand years ago shows the dramatic environmental change to which human societies were exposed and had to adapt to. In this work, we show that in the 620,000-year environmental record from the Chew Bahir basin in the southern Ethiopian Rift, with its decadal resolution, this one thousand year long transition is particularly well documented, along with 20–80 year long droughts, recurring every ~160 years, as possible early warnings. Together with events of extreme wetness at the end of the transition, these droughts form a pronounced climate "flickering", which can be simulated in climate models and is also present in earlier climate transitions in the Chew Bahir environmental record, indicating that transitions with flickering are characteristic of this region.

The mid-Holocene climate transition from predominantly wet to dry conditions in tropical and subtropical northern Africa is the most dramatic example of a climate tipping point during the present interglacial. Climate tipping points occur when small perturbations in the forcing mechanism trigger a large, nonlinear response from the system, moving climate to a different future state generally accompanied by dramatic consequences for the biosphere[1–4]. The mid-Holocene climate transition underscores that the much-touted stability of the Holocene climate and its beneficial effects on the evolution of human societies do not hold true, at least not for the low latitudes. In fact, the transition from the African Humid Period (AHP), and with it the so-called Green Sahara phase, 15–5 kiloyears before present (kyr BP) to pronounced aridity after ~5 kyr BP led to significant changes in human environments in large areas of northern Africa[3,5–7].

The mid-Holocene climate transition was caused by the decrease in solar radiation in the Northern Hemisphere driven by the Earth's climate precession[3,8]. This change occurred slowly, as the sinusoidal period of precession is ~23 kyrs, whereas the more rapid quasilinear change in solar irradiance occurred during a quarter period of precession (~6 kyrs) between 9 and 3 kyr BP[9]. The response of the climate system to the 7–8% decrease in solar irradiance within 6 kyrs was much more rapid, perhaps faster than ~200 years in western Africa, but up to 1000 years in eastern Africa[3,7–9]. The main reason suggested for the rapid termination of the AHP is the positive feedback between the monsoon and vegetation that amplifies the comparatively small changes in external forcing[5].

These rapid environmental changes had a strong impact on humans in northern Africa, as their preferred habitats of grasslands, open forests, and lakes disappeared[10]. They responded to increasing

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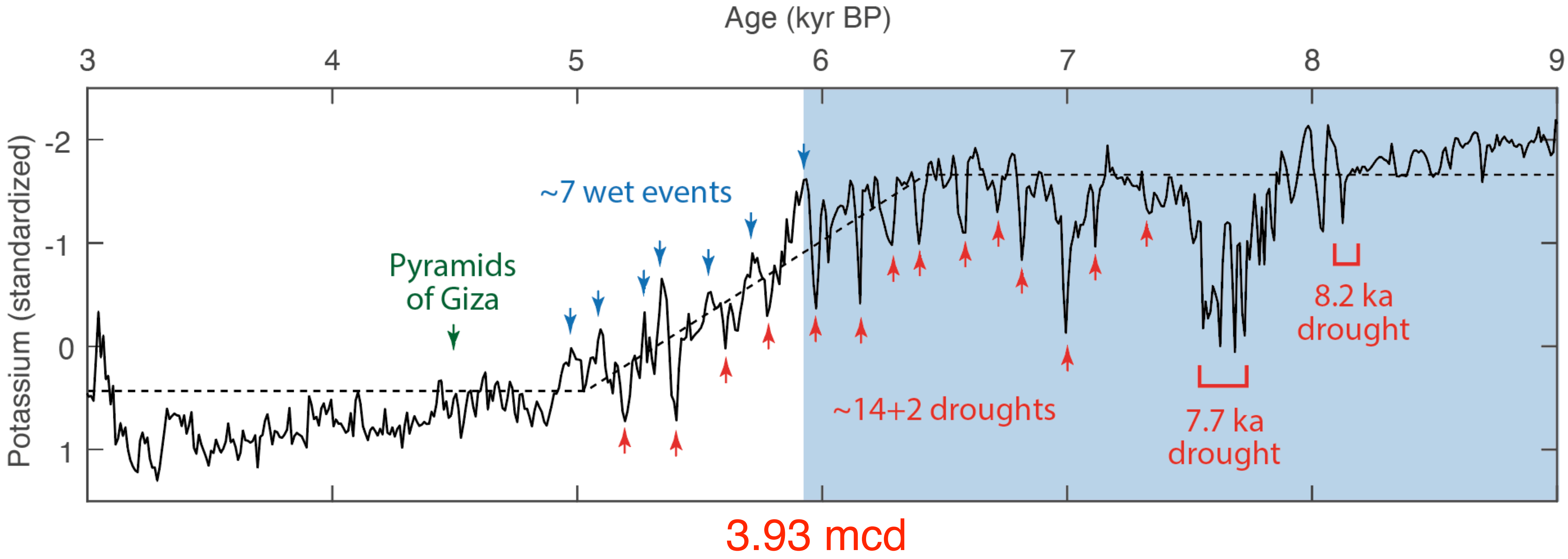


Periodic component

Extreme component

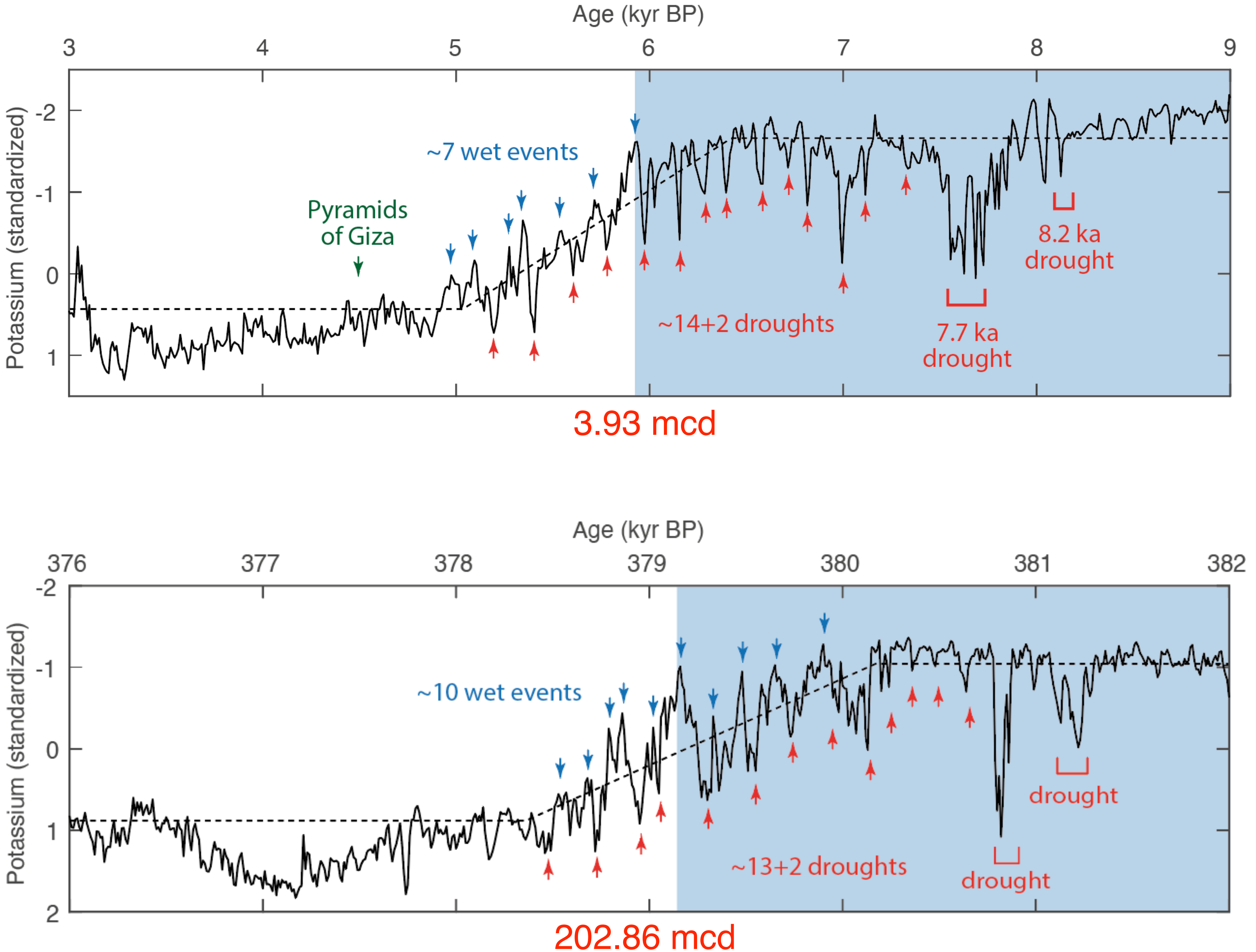
Variable function

$$x(t_k) = x_p(t_k) + x_{tr}(t_k) + x_e(t_k) + s(t_k) \cdot x_{ns}(t_k)$$

Trends, transitions, change points …

Random noise

Trauth et al. Nat. Commun. 2024



Trauth et al. Nat. Commun. 2024

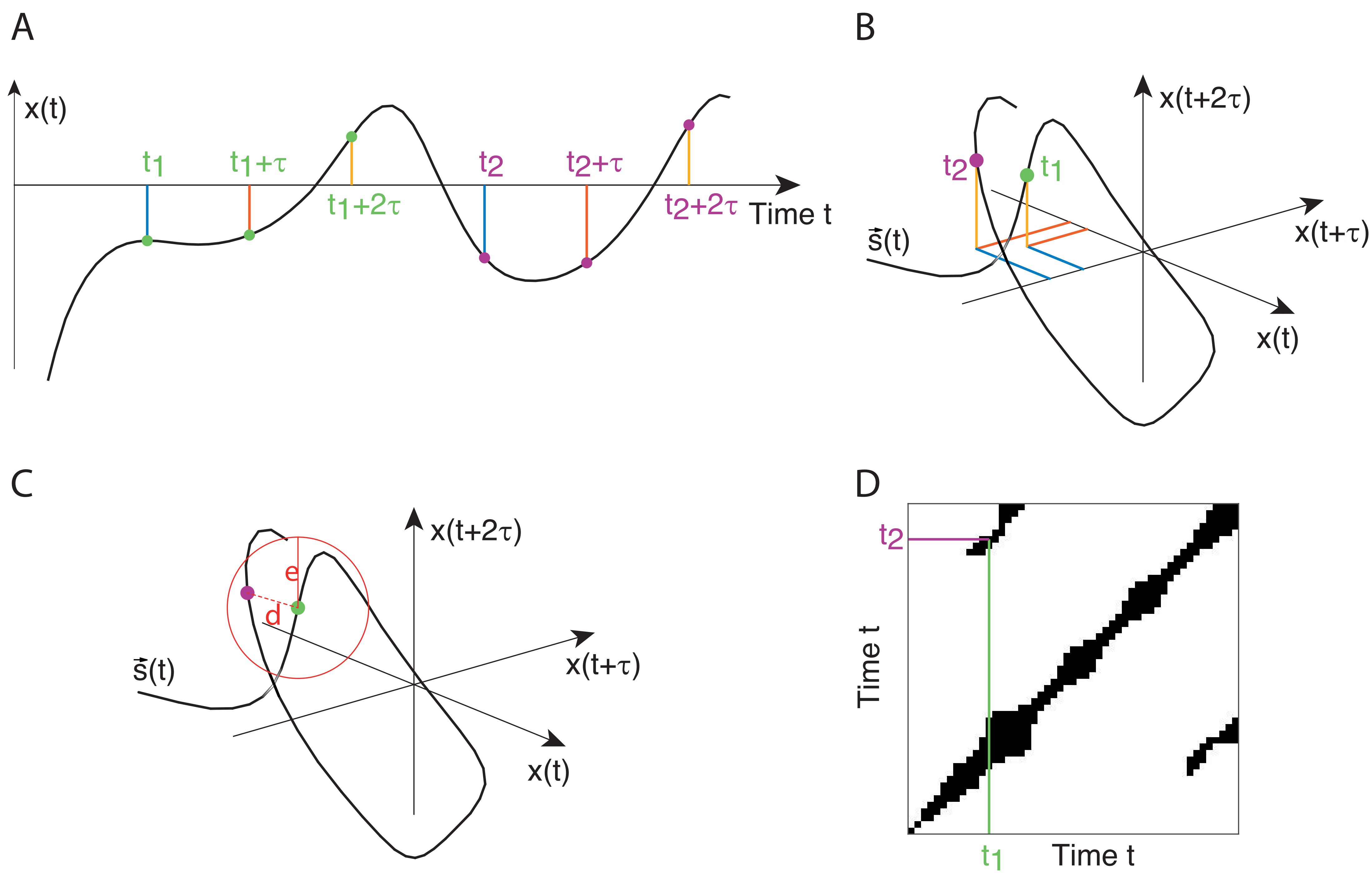
Recurrence Plots

A recurrence plot (RP) is a graphical display of such recurring states of the system that is calculated from the distance (e.g., the Euclidean distance) between all pairs of phase space vectors $\vec{y}(t)$ within a threshold value ε

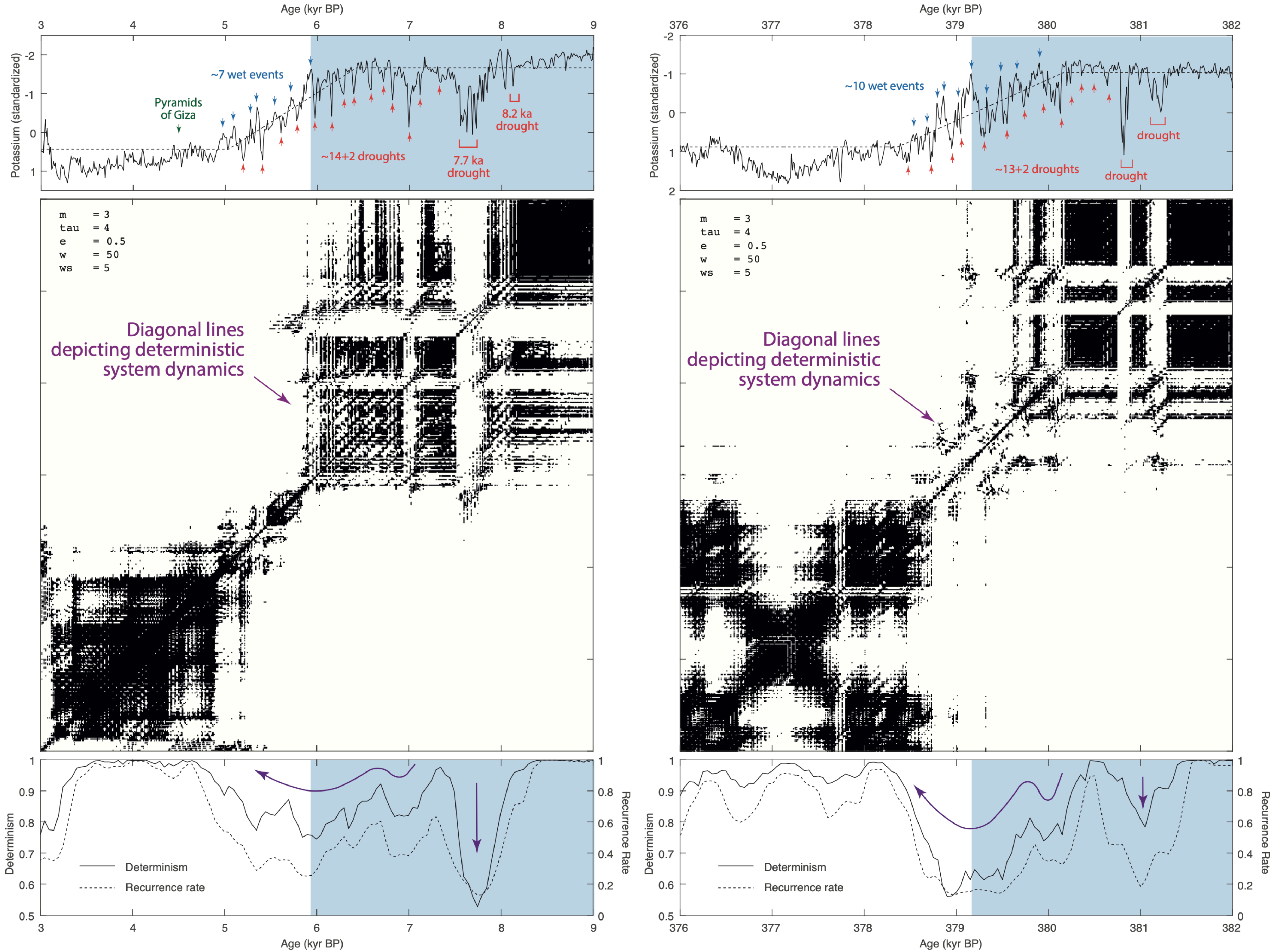
$$R_{i,j} = \begin{cases} 0, & \|x_i - x_j\| > \varepsilon \\ 1, & \|x_i - x_j\| \leq \varepsilon \end{cases}$$

If the distance between two states at times i and j is smaller than a given threshold ε, the value of the recurrence matrix R is one; otherwise, it is zero

Recurrence Plots



Trauth et al. QSR 2019



Marwan et al. QSR 2021, Trauth et al. Nature Communications 2024

Periodic component

Extreme component

Variable function

$$x(t_k) = x_p(t_k) + x_{tr}(t_k) + x_e(t_k) + s(t_k) \cdot x_{ns}(t_k)$$

Trends, transitions, change points …

Random noise

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Spectral analysis in Quaternary sciences

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ABSTRACT

Spectral analysis is a technique of time-series analysis that decomposes signals into linear combinations of harmonic components. Rooted in the 19th century, spectral analysis gained popularity in palaeoclimatology since the early 1980s. This was partly due to the availability of long time series of past climates, but also the development of new, partly adapted methods and the increasing spread of affordable personal computers. This paper reviews the most important methods of spectral analysis for palaeoclimate time series and discusses the prerequisites for their application as well as advantages and disadvantages. The paper also offers an overview of suitable software, as well as computer code for using the methods on synthetic examples.

1. Introduction

The prediction of future climate change requires an understanding of the external driving forces and the interactions that are internal to the earth's climate system (Köppen and Wegener, 1924; Broecker and van Donk, 1970; Berger, 1973; Imbrie and Imbrie, 1979; Berger, 1988, 2013; Ruddiman, 2013). The understanding of these interrelationships can be gained through the analysis of current, historical, and, increasingly, more ancient climate data (Hays et al., 1976; Shackleton and Opdyke, 1977; Pisias et al., 1984; Zachos et al., 2001). To this end, quantitative indicators of past climate conditions have been measured since the 1960s, first on marine sediment cores and in the following decades on other climate archives such as lake sediment cores, ice cores, tree rings, speleothems, and corals (e.g. Broecker and van Donk, 1970; Rossignol-Strick, 1983; Martinson et al., 1987; Winograd et al., 1992; Tiedemann et al., 1994; Wagner et al., 2019).

The description of recurring patterns and the correlation of climate records from different times and different places are supported by modern methods of statistics, including spectral analysis (Hays et al., 1976; Schwarzacher, 1993; Muller and MacDonald, 2000; Schulz and Mudelsee, 2002; Mudelsee, 2014; Trauth, 2021a). The use of these techniques helps to establish quantitative relationships between forcing and climate change, as well as complex interactions, teleconnections and feedbacks within the climate system (Croll, 1864a, b, 1875; Milankovitch, 1941; Berger and Loutre, 1991; Trauth et al., 2009; Berger, 2021; Trauth et al., submitted). Since the mid-1960s, increasingly since the early 1980er, new methodological developments help to address typical challenges in spectral analysis of palaeoclimate records, such as irregular sampling, dating uncertainties, or hidden couplings and transitions (e.g. Scargle, 1981; Park and Herbert, 1987; Schulz and Stattegger, 1997; Mudelsee et al., 2009; Rehfeld et al., 2011; Sinnesael et al., 2018).

The following review paper first analyzes the history of the use of spectral analysis methods and their application in palaeoclimate reconstructions. In the second part of the paper, the most popular methods are discussed and the requirements, advantages, and disadvantages of each method are described. The electronic supplementary material of the paper comprises a MATLAB script for each method using synthetic data. The methods section of this paper contains text that has been previously published in Trauth (2021a): parts of the introduction, the description of the Blackman-Tukey method, the periodogram, and the Lomb-Scargle algorithm.

2. History of spectral analysis applications in studies of past climate change

The roots of the description of the Quaternary glaciations and their interpretation go back well into the 18th century. In 1744 the

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Nonlinear time series analysis of palaeoclimate proxy records

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ABSTRACT

Identifying and characterising dynamical regime shifts, critical transitions or potential tipping points in palaeoclimate time series is relevant for improving the understanding of often highly nonlinear Earth system dynamics. Beyond linear changes in time series properties such as mean, variance, or trend, these nonlinear regime shifts can manifest as changes in signal predictability, regularity, complexity, or higher-order stochastic properties such as multi-stability. In recent years, several classes of methods have been put forward to study these critical transitions in time series data that are based on concepts from nonlinear dynamics, complex systems science, information theory, and stochastic analysis. These include approaches such as phase space-based recurrence plots and recurrence networks, visibility graphs, order pattern-based entropies, and stochastic modelling. Here, we review and compare in detail several prominent methods from these fields by applying them to the same set of marine palaeoclimate proxy records of African climate variations during the past 5 million years. Applying these methods, we observe notable nonlinear transitions in palaeoclimate dynamics in these marine proxy records and discuss them in the context of important climate events and regimes such as phases of intensified Walker circulation, marine isotope stage M2, the onset of northern hemisphere glaciation and the mid-Pleistocene transition. We find that the studied approaches complement each other by allowing us to point out distinct aspects of dynamical regime shifts in palaeoclimate time series. We also detect significant correlations of these nonlinear regime shift indicators with variations of Earth's orbit, suggesting the latter as potential triggers of nonlinear transitions in palaeoclimate. Overall, the presented study underlines the potentials of nonlinear time series analysis approaches to provide complementary information on dynamical regime shifts in palaeoclimate and their driving processes that cannot be revealed by linear statistics or eyeball inspection of the data alone.

1. Introduction

Past climate conditions, variability, and transitions are essential to understand current and future climate changes. In particular, the Plio-Pleistocene can be used as an analogue of future greenhouse climate and how and which regime shifts in large-scale atmospheric and ocean circulation can be expected in a warming world (Burke et al., 2018; Steffen et al., 2018). Moreover, it has been a period of important steps in human evolution, where significant climate regime shifts have most likely influenced the evolution and the migration of human ancestors (deMenocal, 1995; Potts, 1996; DeMenocal, 2004; Trauth, 2005; Staubwasser and Weiss, 2006; Donges et al., 2011b). A better understanding of abrupt climate changes, the pattern of variations, long-distance interrelationships, feedback loops, or the type of dynamics can further help to build our picture of the world and improve corresponding modelling approaches.

The last decades have shown an increasing availability and progress of quantitative approaches in geosciences, ranging from provenance analysis, over rock magnetic measurements, X-ray fluorescence analysis, to isotope geochemistry. Such quantitative approaches have enriched the qualitative studies significantly and

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