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Thesis abstract

Paleoclimate reconstruction using biomarker and stable isotope analyses of lake sediments in the Bale Mountains, Ethiopia

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Climate change and global warming extensively affect eastern Africa. However, the driving mechanisms of the spatially and temporarily complex climatic changes of the past, especially over the last 15 000 years, are insufficiently understood. While several paleoclimatic studies have reconstructed temperature and hydrological changes, the understanding of atmospheric circulation changes and teleconnections is limited due to (i) the lack of long, high-quality records of environmental change, especially in the Horn of Africa region; (ii) the lack of high-altitude records; and (ii) insufficiently studied regions like eastern Ethiopia and Somalia.

This thesis aims to overcome these limitations and create a better understanding of the complex climatic history of eastern Africa. The Bale Mountains encompass the continent's largest area above 4000 m a.s.l. High-elevation areas yield valuable archives for paleoclimate and environmental reconstructions. High-altitude perennial lakes in particular have the advantage of continuous sedimentation, recording climatic and environmental changes without anthropogenic disturbance. Such a high-altitude archive is the only perennial lake in the Bale Mountains, known as the Garba Guracha. Situated at 3950 m a.s.l., the Garba Guracha has yielded a continuous sedimentary record since the last deglaciation at ~ 16 ka.

In this dissertation, the results of applied new, innovative proxies, e.g., $\delta^{18}O_{\mathrm{diatom}}$, $\delta^{18}O_{\mathrm{fucose}}$, $\delta^{2}H_{\mathrm{n-alkane}}$, and branched glycerol dialkyl glycerol tetraethers (brGDGTs), broaden paleoclimatic knowledge by producing quantitative temperature and hydrological data of the Bale Mountains. The interpretation of these proxy results requires a deeper understanding of the chronology, sedimentology, and the source of the organic matter of the 2017-retrieved sediment cores of the Garba Guracha.

We produced a high-resolution and robust chronology by applying several different dating methods and compounds (^{210}Pb dating, radiocarbon dating of bulk sedimentary organic matter (OM), compound class-specific *n*-alkanes, and charcoal) with an external age control based on the geochemical correlation of tephra layers in the Garba Guracha sediments to dated tephra layers of the region. The chronology yields a basal age of ~ 16 ka cal BP, marking the minimum deglaciation age (Bittner et al., 2020; Groos et al., 2021; Ossendorf et al., 2019). The high-resolution chronology of Garba Guracha is one of the most robust chronologies of eastern Africa.

We analyzed TOC, N, $\delta^{13}C$, n-alkanes, and sugar biomarkers to determine the origin of OM. Predominant autochthonous organic matter production is indicated by relatively low TOC/N ratios and relatively positive $\delta^{13}C$ values in the Garba Guracha record. The missing offset between n-alkane and bulk sediment radiocarbon ages points to short residence times and/or high aquatic productivity. Additionally, sugar biomarker ratios point to a predominant production of aquatic sugars.

We analyzed the isotopic composition of oxygen in the sugar biomarkers to reconstruct hydrological changes. The similar ranges of the $\delta^{18}O_{fucose}$ record in comparison with the pure aquatic $\delta^{18}O_{diatom}$ record (7.9 ‰ and 7.1 ‰, respectively) further support the aquatic origin. The high correlation between $\delta^{18}O_{diatom}$ and $\delta^{18}O_{fucose}$ results underlines the potential of $\delta^{18}O_{sugar}$ analyses in paleoclimatic studies for reconstructing climatic and environmental conditions. Moreover, in the case of the Garba Guracha, the methodological comparison confirms that the $\delta^{18}O_{fucose}$ record reflects $\delta^{18}O_{lakewater}$. Therefore, while the influence of the "amount effect" and the "source effect" should not be excluded, the record primarily reflects the precipitation-to-evaporation ratio (P/E) (Bittner et al., 2021).

We analyzed brGDGTs to reconstruct temperature changes in the past. The MBT'$_{5ME}$ calibration (Russell et al., 2018) was modified due to uncommon isomer distributions in surface sediments by adding 6-methyl brGDGT IIIa' (resulting in the MBT'$_{5ME}$-Bale Mountain index, $r^2 = 0.93$, $p < 0.05$) (Bittner et al., 2022).

The hydrology reconstruction shows that regional and Northern Hemisphere climatic changes are recorded in the Garba Guracha archive. At the onset of the Holocene, a phase of increased precipitation and an overflowing lake lasted between ~10 and ~7 ka cal BP, corresponding to the African Humid Period (AHP). The comparison with other eastern African records shows that equatorial and northern Africa experienced a spatially complex humid phase between 15–5 ka, driven by the interplay of Intertropical Convergence Zone movement and enhanced West African monsoon (WAM) (Costa et al., 2014; Garelick et al., 2021; Gasse, 2000; Jaeschke et al., 2020; Junginger et al., 2014). While the recorded hydrological changes of eastern Africa seem to be driven by meridional climatic processes, the easterly situated Bale Mountains and likely regions further to the east are more influenced by the East African monsoon (EAM) activity and show similarities to reconstructed monsoonal changes in Oman. The humid phase in the Bale Mountains ends around 7 ka cal BP, with a gradual shift towards drier conditions in present times.

In monsoonal regions, the hydrology is closely connected to insolation forcing and associated temperature variations. Therefore, insolation-driven temperature changes are visible in the Garba Guracha record and further modified by supraregional climatic changes like the AHP, as well as local anomalies like catchment deglaciation and hydrology. After the catchment deglaciation, cold temperatures prevailed until the Holocene onset. A significant warming (3.0 °C in less than 600 years) occurred around 10.5 ka cal BP, followed by a thermal maximum lasting until 6 ka cal BP. The thermal maximum coincides with the reconstructed humid conditions, and the same is true for a temperature decrease during the aridity trend until 1.4 ka cal BP.

The findings of this dissertation reveal regional and global driving mechanisms of climate change in the Bale Mountains and thus expand the paleoclimatic understanding of the Horn of Africa. The innovative methodological approach of this work demonstrates the potential of $\delta^{18}O$-sugar analyses and n-alkane dating. In addition, the results emphasize the demand for basic research such as local brGDGT calibration studies to further develop and refine existing scientific concepts.

Data availability. For the data supporting this study, see the thesis in the link at the start of this paper and Bittner et al. (2020, 2021, 2022).

Competing interests. The contact author has declared that none of the authors has any competing interests.

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