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Abstract

Climate change and hominin evolution are inextricably linked. Pleistocene climate variability, for example, is thought to have had major influences on hominin morphology, brain size, and diversity. However, clear cause-and-effect relationships between specific climatic events and major evolutionary occurrences are difficult to establish due to temporal and spatial gaps in paleoclimatic, paleoenvironmental, and archaeological records. A new branched GDGT paleotemperature record from the Lantian Basin of Central China (Lu et al., 2022), a location known for the earliest hominin presence in East Asia, illustrates warm land surface temperatures over a two-million-year period between 2.6 and 0.6 Ma, a critical time in human evolution. Warmer temperatures may have increased land-sea thermal contrast that facilitated the long-term intensification of the East Asian summer monsoon, and likely had serious ecological and biological implications for Pleistocene hominin lineages.

Key Points

- A new paleotemperature record from the Lingtai loess-paleosol sequence in Central China shows ~1.1 °C of warming between 2.6 and 0.6 Ma
- This is opposite to observed cooling trends based upon Pleistocene-aged ocean temperature proxy records from the same period
- This warm period may have had serious ecological and biological implications for Mid-Pleistocene hominin lineages as they dispersed across East Asia

Plain Language Summary

Until relatively recently, cross-disciplinary datasets in direct association with stratified archaeological and fossil assemblages were not specifically targeted when reconstructing hominin landscape environments. Lake and ocean cores have produced well-integrated, high-resolution reconstructions of the broad environmental context in which the genus *Homo* and its closest relatives evolved, adapted, and experimented with novel technologies. A recent work by Lu et al., (2022, doi:https://doi.org/10.1029/2022GL099520), presents a 3-million-year-long land surface temperature record from the Chinese Loess Plateau using brGDGTs (branched glycerol dialkyl glycerol tetraethers). This land surface temperature data comes from the Lantian Basin and is ~190 km from the Dali skull locality and the hominin sites of Gongwangling and Chenjiawo. The unique long-term warming trend over the Pleistocene is opposite to the trajectories of sea surface temperature records from the same period and indicates that more on- or near-site paleoclimatological data is needed for hominin fossil localities. This study presents much needed original land surface temperature data that support novel interpretations on a mechanism for important paleoclimate phenomenon in East Asia, with serious ecological and biological implications for Middle Pleistocene hominin lineages as they dispersed and settled across East Asia.

1. Introduction

The Pleistocene epoch is colloquially referred to as the *Ice Age* and evokes images of cold-tolerant megafauna, expansive ice sheets and glaciers, and the eventual appearance of *Homo sapiens* and closely related species that lived alongside us for much of our existence. This was a time of great climate variability, with ecological reorganization often being suggested as a driver for changes in hominin morphology, brain size, and diversity (deMenocal, 2011). In the Mid-to-Late Pleistocene, our genus withstood and adapted to various "extreme" environments and associated resource instability by exhibiting complex behavioral responses (Chen et al., 2019; Scerri et al., 2015; Stewart & Mitchell, 2018; Yuan, Huang, & Zhang, 2007). For example, a recent oxygen isotope study in Bulgaria indicates that a small population of *H. sapiens* experienced subarctic climates and far colder conditions than previously expected ~45,000 years ago (Pederzani et al., 2021). Linking hominin technological, morphological, or behavioral changes to landscape ecology and climate variability remains challenging, however, as clear cause-and-effect relationships between specific climatic events and major evolutionary occurrences are difficult to establish (Faith et al., 2021). One of the main challenges is that climate or environmental data are often derived from sources distal to hominin activity, thus representing systems that are in some way detached from actual human environments and experiences (Patalano & Roberts). Only by examining "on-site" can the importance of broader climatic phenomena, such as land surface temperatures (LST), be directly related to the lives of past plants, animals, and environments of explicit relevance to human evolution.

A recent study by Lu et al., in *Geophysical Research Letters* (Lu et al., 2022), constructed a long-term, three-million-year LST record for the Chinese Loess Plateau of Lingtai, which is located near to numerous East Asian paleoanthropological sites in the Lantian Basin (Fig. 1a). The new temperature data derived from loess microbial organic geochemistry records, assuming regional climatic signals are representatives of the larger Asian continent, runs opposite to observed cooling trends based upon Pleistocene-aged ocean temperature proxy records. The authors found that average temperature recorded in the Lingtai loess-paleosol sequence increased by ~1.1 °C in central China between 2.6 and 0.6 Ma (Fig. 1b), whereas the average sea surface temperature at similar latitudes decreased by ~2.2 °C. In addition to the warming stage, the temperature proxy showed a rapid cooling event that happened between 3.0 and 2.6 Ma, and a high-amplitude, 100-thousand-year glacial-interglacial phase that began 0.6 Ma and aligns with other global and regional geochemical proxies for this time.

2. Branched GDGTs Paleo-Temperature Proxy

Lu and co-authors used brGDGTs (branched glycerol dialkyl glycerol tetraethers), bacterial cell membrane lipids that are ubiquitous and dominant in soils, and when preserved in sedimentary archives like loess, act as a proxy for continental mean annual soil temperature (MAST) and soil pH (Weijers, Schouten, van den Donker, Hopmans, & Sinninghe Damsté, 2007). Newly applied in archaeology (Kielhofer et al., 2023), brGDGTs offer a novel approach to quantitatively measuring terrestrial paleotemperatures closely associated with human environments. Although factors like precipitation may affect the distribution of brGDGTs, the GDGT-based temperature reconstructions from loess sections mainly reflect *in situ* LST during the growth season of microorganisms. On one hand, the Lingati record exhibits relatively distinct glacial-interglacial

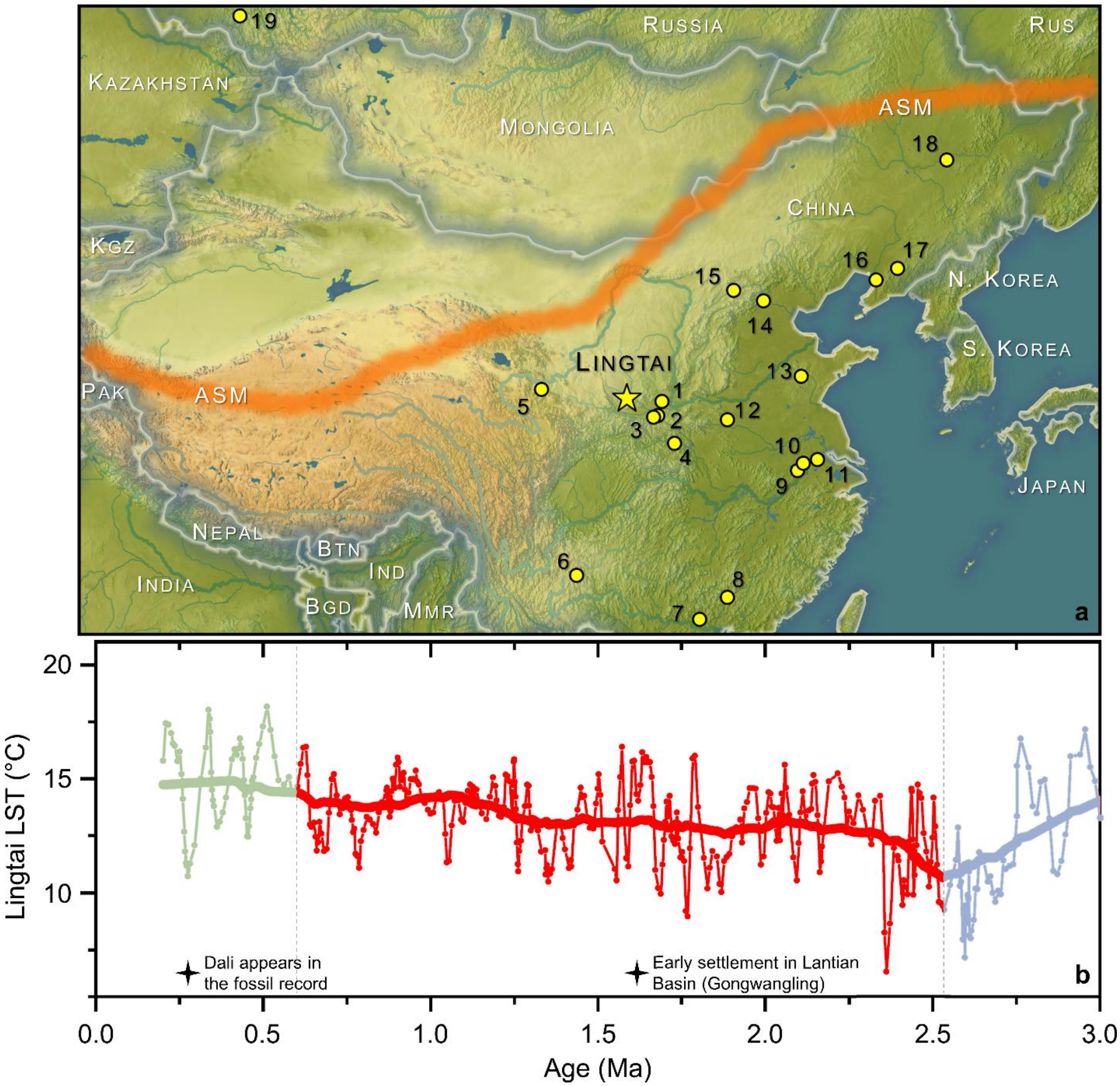

Figure 1. Lingtai brGDGT temperature record from the center of the Chinese Loess Plateau. a. Location of the Lingtai loess profile and hominin sites in East Asia: 1. Dali. 2. Gongwangling. 3. Chenjiawo. 4. Bailong Cave. 5. Baishiya Karst Cave. 6. Panxian Dadong. 7. Panlong Cave. 8 Shaoguan. 9. Chaoxian. 10. Hexian. 11. Tangshan. 12. Lingjin. 13. Yiyuan. 14. Zhoukoudian. 15. Xujiayao. 16. Jinniushan. 17. Miaohoushan. 18. Harbin. 19. Denisova Cave. Northern limit of the modern Asian Summer Monsoon (ASM-orange). **b.** Lingtai land surface temperature 3-point-moving average record based on brGDGTs showing the cooling period (right-blue), warming trend (center-red), and high-amplitude glacial-interglacial phase (left-green). Modified from Lu et al., 2022. Map created using ArcGIS Pro desktop GIS software developed by Esri.

cyclicity that is broadly synchronized with marine $\delta^{18}O$ records, suggesting that overall, the data agrees with global climate changes. On the other hand, the brGDGTs indicate that warming in LSTs may have increased land-sea thermal contrast that facilitated the long-term intensification of the East Asian summer monsoon, and likely had serious ecological and biological implications for Middle Pleistocene hominin lineages (Ni et al., 2021) and their living environments.

3. Evolutionary Implications

The 2.6 to 0.6 Ma period was a critical time in human evolution, as it saw the onset of the Pleistocene and the appearance and diversification of the genus *Homo* as well as hominin dispersals within and beyond Africa. Additionally, this timeframe encompasses the onset of the Early-Middle Pleistocene Transition (also known as the Mid-Pleistocene Transition) that occurred roughly between 1.2 and 0.8 Ma and marked the prolongation and intensification of glacial-interglacial cycles that are hypothesized to have resulted in a significantly colder and drier climate of the interior of Eurasia (White et al., 2010). It is also toward the end of this transition that greater encephalization and the differentiation of geographic groups (Roksandic, Radović, Wu, & Bae, 2022) come to characterize *Homo*. The Lingtai record covers both the earliest presence of hominins in East Asia (i.e., *H. erectus* at Gongwangling ~1.65 Ma (Zhu et al., 2015)) as well as the possible (local) appearance of archaic *H. sapiens* and other species (i.e., the Dali skull ~260 ka (Athreya & Wu, 2017)).

The question arises as to what evolutionary pressure, if any, this land warming trend might have had on hominin populations of the Lantian Basin, especially if it represents a regional phenomenon, as proposed by Lu et al., or rather has a global implication. Gradual land warming may have played a consequential role in the development of Pleistocene refugia and perhaps the diversification or migration of Mid-Pleistocene hominins (Bae, Li, Cheng, Wang, & Hong, 2018). A recent statistical analysis of the effect of climate warming on brain size (Stibel, 2023), found that brain size in *Homo* averaged significantly lower during warm periods compared to cooler periods over the last 50,000 years. Yet, this correlation does not extend over the past ~1.0 Ma (Will, Krapp, Stock, & Manica, 2021) and, although larger body sizes are consistently found in colder regions, there does not appear to be an association between temperature and brain size. Interestingly, there is a possible correlation with larger brain sizes occurring in more stable rainfall environments across all studied *Homo* taxa with brain size being found to decrease with increasing levels of long-term rainfall variability (Will et al., 2021).

In both above-mentioned studies (Stibel, 2023; Will et al., 2021), the climate datasets are "off-site" estimates based on global climate reconstructions using the European Project for Ice Coring in Antarctica (EPICA) at Dome C record with additional surface temperature data derived from a sediment core from Lake Malawi. The advantage of the Lingati brGDGT record is that the site is only ~190 km from both the Dali skull locality and the hominin sites of Gongwangling and Chenjiawo. The loess dataset is also chronologically well-constrained and is a source of well-preserved paleoenvironmental biomarkers. Though the brGDGT data show that LSTs were not as cold or extreme as recorded in ocean records, it indicates that warming temperatures increased land-sea thermal contrast that facilitated the long-term intensification of the East Asian summer monsoon. Perhaps this intensification created refugial conditions correlated with more-predictable rainfall that allowed some populations to remain in certain geographic regions for extended periods of time. This may help explain the long-term archaeological record of famous paleoanthropological sites like those in the Nihewan Basin or perhaps the early settlement at Gongwangling ~1.65 Ma.

4. Unanswered Questions and Future Outlook

The association between temperature change and human evolution does raise additional questions on the ways in which both temperature and precipitation contributed to the mosaic combinations of features present in Middle and Late Pleistocene East Asian lineages. For example, did the Dali lineage only emerge after 0.6 when climate returned to high-amplitude 100-Kyr oscillations? The older Gongwangling cranium, with a cranial capacity of 780 cm^3, and the Chenjiawo mandible have been assigned to *H. erectus* (Aigner & Laughlin, 1973). Conversely, the Dali cranium is often seen as contentious because it possesses mixed morphology; it is not comfortably allocated to *H. erectus* but rather is commonly assigned to "archaic" *H. sapiens* based on the skull's large endocranial volume of 1120 cm^3 and cranial morphology (Wu & Athreya, 2013). More recently, however, it has been considered to be the fossil evidence for Denisovans (Stringer, 2012) or part of the Harbin-*H. sapiens* clade (Ni et al., 2021). Therefore, was it only after the two-million-year warming trend that we begin to observe major morphological changes to East Asian hominin populations? Can these changes be due to sympatric isolation of small populations? Perhaps, within the Lantian Basin, the Dali lineage underwent a speciation event that gave rise to a daughter lineage due to geography, time, intragroup variation (Rightmire, 2015), or climate forcing. Whether this is due to cooler temperatures or changes in rainfall needs to be investigated further.

The brGDGT technique used by Lu and colleagues, which produced direct land surface temperature records closely associated with the earliest hominin occupation in East Asia, should elicit new questions and future research into the evolutionary implications of Pleistocene LSTs on hominin paleobiology. The morphological distinction between earlier *H. erectus*, later *H. sapiens*, and Dali, for example, may correspond to changing LSTs, the strengthening/weaking of the East Asian Monsoon, and the reorganization of local environments and resources. The study of Lu et al., therefore, underscores the potential of chronologically well-constrained paleo-archives for studying potential evolution and speciation events and anagenetic or cladistic branching. Some uncertainties remain, however, as to whether this warming event is restricted to the southern part of the Loess Plateau or if it can be confirmed in collaborative data from other parts of the Asian continent. Although the precise warming mechanism is not clear, the Lantian Basin is nevertheless under-studied in the context of tracking the ecological adaptability of *Homo*. Thus, there is great potential in using brGDGTs for generating high-resolution, multi-proxy datasets for understanding the impact of terrestrial ecosystem changes on both morphological diversification and the history of human dispersal and distribution across Asia.

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