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The Last Glacial Maximum in the Tropics: Human Responses to Global Change, 30–10 ka

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Abstract

The world at 18,000 BP, published by Gamble and Soffer (The world at 18,000 BP. Vol. 2: low latitude, Unwin Hyman, 1990), represents the first, and so far the only, attempt at characterising and discussing the impact of the Last Glacial Maximum (LGM) on human societies on a global scale. At the time, they highlighted that research and data on the LGM in southern latitudes and the tropics in particular were scant. Since 1990, however, many sites dated to the LGM and located in tropical latitudes have been published. Many paradigms have changed regarding the peopling of the Americas, which allows the archaeology of this continent to be integrated into global scale studies of the LGM. The development of Pleistocene archaeology in tropical contexts, in parallel with methodological advances in cultural, geosciences and palaeoenvironmental studies have strongly reshaped what we know of the antiquity of human occupation in tropical regions and specific human–environment interactions. This article provides for the first time a pan-tropical perspective on the impact of the LGM on human groups living within the tropical latitudes, drawing from case studies in Southeast Asia, Africa and South America, specifically regions which have up until now never been discussed together. To this end, we focus on six different tropical regions between 30 and 10 ka. We present the archaeological and paleoenvironmental data available in these areas, along with proposed relationships for variations in these two records. Finally, we discuss at the regional scale the presence or absence of human changes (site density and techno-cultural change or continuity) before, during and immediately after the LGM.

Keywords Last Glacial Maximum · Tropics · Human evolution · Human–environment interactions

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Introduction

The Last Glacial Maximum (LGM) was a time of global climatic maximum often considered as a chronological marker, both as regards significant environmental changes, and in terms of impact on prehistoric populations. In their seminal publication *The world at 18,000 BP*, Gamble and Soffer assembled a number of contributions with the aim of examining the variability in hunter-gatherer adaptation during the LGM (Gamble & Soffer, 1990; Soffer & Gamble, 1990). They divided the publication into two volumes, the first one focusing on 'High Latitudes' and the second on 'Low Latitudes'. This division was in part chosen because it reflects perceived fundamental differences at the global scale between high and low latitudes in terms of the impact of the LGM on human behaviours. This impact is commonly considered to be greater in the northern latitudes than in the southern latitudes, both in terms of environmental change and significance for humans. The LGM is often seen as a turning point in the development of socio-cultural complexity during the Upper and Late Palaeolithic in Europe, with the generalisation of cultural paraphernalia (Gamble & Soffer, 1990) but also with respect to demography and biological anthropology (Maier et al., 2016; Posth et al., 2016). *The world at 18,000 BP* also underlined the different traditions and density of research characterising the northern and southern latitudes, revealing the sparsity or even complete absence of coverage for large areas of the world, and particularly for the tropics. The authors also pointed to perceptual differences of the terminal Pleistocene record in the two hemispheres, with a tendency to show more continuity across the Pleistocene and Holocene in the southern latitudes, while in the northern ones, 'disjunctions' are emphasised between the Upper/Late Palaeolithic and the Mesolithic (Gamble & Soffer, 1990, p. 19). Despite this, these volumes represent a fundamental step in highlighting the socio-cultural diversity and human complexity in hunter-gatherer societies during the LGM, beyond a simple dichotomy between northern and southern latitudes.

Critically, only four contributions to *The world at 18,000 BP* concerned regions located in the tropics (Bellwood, 1990 – Sundaland; Brooks & Robertshaw, 1990 – tropical Africa; Jones, 1990 – Australia; Walker, 1990 – Zimbabwe). These contributions showed that varied environmental conditions characterised tropical regions at the LGM, but that data were lacking for vast areas of those regions. Since the publication of *The world at 18,000 BP* more than 30 years ago, there has been a growing body of evidence documenting the period corresponding to the LGM in the tropical latitudes. Comprehensive syntheses of climatic and environmental data for the tropics at the LGM have been published (Adams & Faure, 1997; Farrera et al., 1999) and archaeological and palaeoenvironmental data around the LGM in diverse tropical areas of the world are now available: for Western Africa (Chevrier et al., 2018), Central Africa (Clist et al., 2023; Cornelissen, 2002), Eastern Africa (Foerster et al., 2015; Gasse, 2000, p. 200; Gasse et al., 2008; Leplongeon et al., 2020, 2023; Tryon, 2019), South(-East) Asia (Forestier et al., 2017; Ochoa et al., 2022; Wedage et al., 2019), and Australia (Williams et al., 2013), to name but a few. The date of the beginning of the peopling of the American continent, however, continues to be the subject of debate (Chatters et al., 2022; Coutouly, 2021, 2022; Politis & Prates, 2021; Potter et al., 2022 *versus* Ardelean et al., 2022; Becerra-Valdivia & Higham, 2020;

Boëda et al., 2022; Dillehay et al., 2021a, 2021b; Dillehay et al., 2021a, 2021b; Lourdeau, 2021). Since the 1980s, archaeological evidence that may go back to the LGM has been unearthed in South America: in Peru (MacNeish et al., 1980, 1981, 1983), Chile (Dillehay, 1997), and Brazil (Guidon & Delibrias, 1986; Parenti, 2001). These data have failed to convince the entire scientific community, whose most conservative members rely on the chronology proposed by geneticists (Moreno-Mayar et al., 2018; Raghavan et al., 2015; Skoglund & Reich, 2016) to invalidate any archaeological discovery prior to 16 ka cal. BP. Nevertheless, new studies reinforce the corpus of archaeological data prior to or contemporaneous to the LGM in South America (Boëda et al., 2013, 2016, 2021; Dillehay et al., 2015; Fariña et al., 2014; Lahaye et al., 2013; Vialou & Vilhena Vialou, 2022; Vialou et al., 2017). They are supported by data along similar lines in North America, and in particular the spectacular recent discovery of footprints at the site of White Sands (USA), dated to c. 23–21 ka cal. BP (Bennett et al., 2021; Pigati et al., 2023). The development of Pleistocene archaeology in South America thus appears as a major advancement to enable worldwide pan-tropical approaches in prehistoric archaeology.

Lastly, various recent contributions mark a milestone in the study of early human settlements in the tropics (Ben Arous et al., 2025; Braucher et al., 2022; Cornelissen, 2002, 2016; Dennell et al., 2014; Faulkner et al., 2021; Forestier, 2020; Ingicco et al., 2018; Levis et al., 2020; Mercader, 2002a, 2002b; Roberts, 2019; Roberts & Petraglia, 2015; Rostain, 2021; Scerri et al., 2022) and give rise to another perception of the tropics in archaeology and palaeosciences. While at the regional scale of study, researchers working in the tropics have been gradually contributing to a paradigm shift highlighting this diversity of human and environmental responses to the LGM, on a broader scale, the perception of the impact of the LGM on the tropics differs little from the conclusions of *The world at 18,000 BP*, namely a low impact on human populations.

New research in prehistory of the tropics has contributed to nuancing this view, but has developed a specific focus on rainforests, particularly with a view to evaluating their role in human evolution (Ben Arous et al., 2025; Bonilauri & Forestier, 2023; Cornelissen, 2016; Mercader, 2002a; Roberts, 2019; Roberts & Stewart, 2018; Roberts et al., 2017, 2018; Rostain, 2021; Scerri et al., 2022; Wedage et al., 2019; Xhauflair et al., 2023b).

There is no global updated synthesis of the tropical archaeological record that could provide a consistent perspective on the LGM in the various tropical regions and biomes. In this paper, we review some currently available palaeoenvironmental and archaeological data for the LGM in the tropics, taken in its broader geographical sense in order to discuss human–environment interactions during the LGM from a multi-scalar perspective: from the site scale to the regional and *pan*-tropical scales. We will then discuss the relevance of the use of the LGM as a milestone in tropical archaeology: can we observe a threshold in human cultural evolution associated with the LGM in the tropics?

We aim to embrace the environmental diversity of the tropical belt, covering not only moist and dry savannahs, and semi-desert and desert areas, but also higher altitude zones and coastal areas. In the following sub-section, we define the tropics and the LGM before presenting the data gathered for the following tropical regions: West

Africa, Central Africa, Horn of Africa, continental Southeast Asia and insular Southeast Asia, and finally Central Brazil.

What are the Tropics?

The tropics are geographically defined as the region of the Earth surrounding the Equator between the latitudes of the Tropics of Cancer and Capricorn at +/−23.5°. This defines a region, the (inter)tropical zone, where the sun reaches a sub-solar point (zenith) at least once a year. Outside the intertropical zone, the sun never reaches this position. This definition is used by the State of the Tropics project (State of the Tropics, 2014), which examines changes in the tropics over the years, with a particular interest in the impact of climate change on human populations.

Aside from a geographic definition, 'tropical' can also refer to a climate. Following the Koppen-Geiger climate classification, a tropical climate occurs in regions having no month with mean temperatures below 18°. However, while most regions with a tropical climate are within the tropics, this definition also excludes some areas within the tropics (e.g., mountains), and includes some outside the tropics. Another marker of tropical climate is the meteorological phenomenon known as the Intertropical Convergence Zone (ITCZ). The ITCZ refers to and explains a tropical climatic specificity, called by Hallé the 'marvel of summer rains' (Hallé, 2014, p. 54). This belt of several hundred kilometres from north to south is a moving strip around the geographical Equator, and is the place where anticyclonic warm and humid air masses meet, pushed from the tropics by the trade winds. Regions subject to the ITCZ are characterised by alternating dry and humid seasons (monsoon). The further one goes from the ITCZ line towards the tropics, the more pronounced the seasons are, divided into dry/warm/summer and humid/cold/winter phases. However, a climate-based definition of the tropics cannot be used in a long-term perspective, because of past climatic changes and the lack of available detailed data about paleotemperatures in most parts of the tropics. For these reasons, the geographic rather than the climatic definition of the tropics is used here. Any further reference to the tropics below will refer to the geographic tropics.

From an environmental perspective, the tropics are commonly referred to as a region hosting a great diversity of plants and animals and, as such, as areas particularly sensitive to climate change. It is however important to note, following Kellman and Tackaberry, that these are mostly located in tropical forested environments and that the tropics also include lower-diversity regions (Kellman & Tackaberry, 1997, p. 94). The tropics include two main plant formations: tropical forests and tropical savannahs (Kellman & Tackaberry, 1997). Nowadays, they form 40% and 60% of tropical environments respectively, with a tendency for tropical forests to become tropical savannahs under human action. There was always¸ however, a highly dynamic relation between these two types of plant formation in the Pleistocene (Kellman & Tackaberry, 1997, p. 164; White, 2001).

The tropics include several ecozones, characterised by a diversity of climates and environments (Schultz, 2005), namely: the dry tropics (semi-deserts and deserts); transition zones to more humid ecozones (thorn savannah with summer rain); the dry and moist savannahs in the tropics with summer rain; and the rainforest (evergreen tropical lowland forest) in the tropics with year-round rain.

Adopting a geographic definition of the tropics assists in questioning earlier historical assumptions stemming from an almost 'mythical' perception of the tropics often associated exclusively with the tropical rainforest environment (Gheerbrant, 2005; Thomas, 2018; Leroux et al., 2015; Marris, 2005; Martin-Granel, 2010; Mboukou, 2010). This imagined perception of tropical environments often saw them as 'fragile' but stable environments, while on the contrary tropical environments are often highly dynamic environments (Kellman & Tackaberry, 1997, pp. 9, 17). Rainforests, in particular, as biodiversity hotspots, have been the focus of many studies that aim to understand their sensitivity to climate change and the threat to biodiversity that their destruction represents (State of the Tropics, 2014). In parallel, rainforests have also long been viewed as areas that could not be inhabited by hunter-gatherers (Bahuchet et al., 1991; Bailey et al., 1989; Meggers, 1971; Sato et al., 2012), implying that human modifications of rainforests occurred only in the recent past (colonial and industrial eras). This, however, has been refuted by evidence of a long history of occupation of rainforests, sometimes associated with evidence of the human impact on tropical palaeoenvironments (Cruz-y-Cruz et al., 2022; Mercader, 2002b; Oslisly et al., 2013; Roberts et al., 2018; Roosevelt, 2013; Saulieu et al., 2018; Thompson et al., 2020, 2021; Wedage et al., 2019).

Last Glacial Maximum

The Last Glacial Maximum (LGM) generally refers to the maximum in global ice volume during the last glacial cycle, which corresponds to the largest minima in the marine isotope record, and associated global sea-level minimum. It was a major change in the Earth's climate system and the LGM is frequently associated with a series of other climatic oscillations occurring during the last glacial cycle. However, there is considerable debate on the age of this global event, depending on the dating methods or proxy used (Hughes et al., 2013). Dates vary from c. 18 ka to 21 ka cal. BP, or to the periods 23–18 ka or 24–19 ka cal. BP (see reviews in Hughes et al., 2013; Sanchez Goñi & Harrison, 2010). Most recent articles use 23–19 ka cal. BP (Waelbroeck et al., 2009) as dates for the 'global LGM' (e.g., Tierney et al., 2020). The 'global LGM' however does not always correlate with the timing of the maximum extent of continental ice sheets or mountain glaciers on a *regional* scale (Hughes et al., 2013, p. 201). This led to the concept of 'local LGM' (i.e., local glacial maxima that do not coincide with the 'global LGM').

In the framework of archaeological research, the LGM is traditionally apprehended in terms of its impact on human populations. While changes in sea levels and glacial extents at the LGM play a prominent role in studies of the distribution of human populations (Compton, 2011; Lambeck & Chappell, 2001; Pedoja et al., 2011; Stewart et al., 2012), indirect proxies such as those related to the reconstruction of temperature and precipitation estimates are also used in discussions of the LGM's impact on human populations. This often leads to a shift in the meaning of the LGM in archaeological research, where the LGM is often equated with temperature or precipitation minima in a given region at the end of the Pleistocene. From this perspective, in archaeological research, it becomes crucial to distinguish the 'global LGM' from the 'Local LGMs' due to the local scale of fieldwork and the broader scale of data contextualisation.

The significance of the LGM as a concept in archaeological research comes from the perception of the LGM as a tipping-point in human evolutionary history, with a pre-LGM and a post-LGM humanity, the latter characterised by dramatic growth in human population and expansion of hunter-gatherers, which led to the occupation of all regions and environments of the world (e.g., the Holocene filter in Mirazón Lahr, 2016). This is strongly linked to the concepts of ecological 'refugia' or genetic 'bottleneck' (Bennett & Provan, 2008; Hewitt, 1996, 2000). In the tropics, several authors argued that it represented a major change for human populations: for example, Mirazón Lahr (2016) suggested that 'where prehistoric records exist, the evidence suggests that all regional populations appear to have been affected, representing a moment of species-wide potentially significant loss of diversity'. Or again, Barham and Mitchell (2008, p. 265) argued that 'one dramatic consequence was the wholesale abandonment of some parts of the [African] continent, most obviously the Sahara'. Both examples illustrate the common assumption that the LGM had a major impact on human population demography, leading to a fragmentation of populations. Here we take a pan-tropical approach in order to evaluate the relevance of the concept of LGM in the archaeological record of the tropics. This is made possible by the steep increase in available archaeological data from the tropics in the last 30 years associated with the development of archaeological research in rainforests, deserts and other tropical environments in the world. We focus on the period between the beginning of MIS 2 and the beginning of the Holocene (c. 30–10 ka) in order to propose a dynamic perspective on a period encompassing the time range before, during and after the global LGM.

The Last Glacial Maximum in the Tropics: Some Consequences for the Preservation of Pleistocene Archaeological Sites

The development of prehistoric archaeology in tropical environments would not have been possible without recent methodological developments in geoarchaeology and geochronology. However, it remains challenging for paleosciences as some tropical environments limit the conservation of archaeological material, the latter being highly dependent on climatic conditions or soil processes (Herz & Garrison, 1998).

Archaeological soils are usually defined as mixtures of organic and lithic materials and several physical factors/parameters affect the preservation of archaeological and palaeoenvironmental deposits through time: bioturbation caused by animals or insects (burrows and tunnels) or by plants (roots), swelling and shrinking of clays, or circulation of water at local and regional scale or formation of specific minerals (salt, gypsum). Bioturbation (by roots or insects in anthills or holes made by wasps), for instance, can mix grains with different origins/histories and fundamentally affect the interpretation of the dating of archaeological assemblages (e.g. vertical movement of quartz grains). In some specific cases (West Africa, Yamé river deposits, Mali), these forms of bioturbation led to the development of a specific optically stimulated luminescence (OSL) dating methodology to discriminate mixed quartz grains (Soriano et al., 2010; Tribolo et al., 2010, 2015; see also references therein).

Hydrographic networks are also major features of the tropics (e.g., the Amazon or Congo basins), which may have impacted prehistoric occupation preservation. These two basins represent nowadays the highest flow rate of the world and are several thousand kilometres long. Erosion can be intense due to heavy rain and the tons of sediment remobilised, leading to the destruction of potential archaeological sites. In Ounjougou (Mali), for example, the post-Holocene system eroded most of the MIS 2 deposits (Rasse et al., 2012), of which no sediments remain today. In addition, changes in the behaviour of these fluvial systems led to sediment reworking and archaeological remains are often redeposited and found outside of their primary context.

The tropics are also marked by various biomes and vegetation types. In Western and Central Africa, in the Sahelian belt, sub-desert soils, which lack organic material, are prevalent. The driest areas are characterised by sand and pebbles and the upland soils are usually thin and stony. A similar type of soil is also observed in the Southern Hemisphere, along the coastal plain of Angola, before the boundary with the Namib Desert. In tropical environments, almost all organic material that reaches the soil surface decomposes rapidly, so the surface accumulation of soil organic matter is minimal.

Some chemical factors, such as weathering (biochemical alteration) or the development of forest cover, also affect the preservation of archaeological deposits. The often thick laterites which cover about 25% of the land surface are generally predominant in the tropics and subtropics (Tardy, 1993). These covers are composed mainly of quartz and heavy minerals, with secondary constituents consisting mainly of kaolinite and iron and aluminium oxides. They are related to the extensive weathering processes largely predominant in tropical areas (Fritsch, 2005). Archaeology conducted in tropical ecosystems faces similar challenges due to mostly poor preservation conditions and rapid soil formation. Heavy forests under intense biochemical alteration due to water, carbonic gas and humid acid favour the development of ferritic soils. Tropical environments in general have a big impact on the preservation of archaeological sites and by extension, the organic materials, limiting geochronological applications, ancient DNA preservation or isotopic analyses. For example, for the period of interest here (30–10 ka), radiocarbon or the U-series dating of bones can rarely be used because of the absence of appropriate materials.

While open-air sites are overrepresented in archaeological tropical research, their conservation is sometimes questioned because of the possible reworked sediments leading to a secondary position of the archaeological material. Caves and rock shelters, in contrast, are traps that allow the conservation of archaeological archives; they are still poorly investigated, however. Biological activity, such as that of bats, leading to guano deposits is often present in archaeological caves but in the humid period, these deposits can be thick and abundant and widely developed (Queffelec et al., 2018) and alter the later archaeological deposits as at Tabon cave (Philippines, Choa et al., 2016). Chemical processes are also frequent in cave sites. For example, intense humidity coupled with the dissolution of limestone is responsible for the formation of carbonate minerals (mostly calcite), while bio-organism activities linked to insects and guano deposits by birds or bats, for instance, favour the formation of phosphoric acid which reacts with bones to implement the neo-formation of phosphate minerals. In contrast, faunal remains have been preserved in very few rock shelters in tropical humid forests—an exception is Iho Eleru (Nigeria, Cerasoni et al., 2023; Shaw & Daniels, 1984)—because they were burnt.

The variability of geological factors as well as the physicochemical alteration processes encountered in tropical areas impact the implementation of dating methods. The difficulties encountered are related to the environmental context. The acidic soil conditions rarely allow the preservation of organic matter beyond the end of the Pleistocene. Consequently, the well-established dating methods used in other regions to build chronological benchmarks, such as the U-series, electron spin resonance (ESR) on tooth enamel, or radiocarbon dating, are rarely usable for open-air sites. Quartz mineral is a good geochronometer and also a good material for paleodosimetric dating applications, especially for luminescence applications, since the signal is dominated by the fast component and shows high sensitivity. However, the fluvial context or reworking by colluviation may have led to partial bleaching of the grains. In addition, past termite activity induces bioturbation that can then lead to mixtures of grains deposited at different periods (Tribolo et al., 2010, 2015).

A Qualitative Approach to Track the Last Glacial Maximum in the Tropics

The use of statistical models for environmental reconstruction and/or prediction is necessary for a better understanding of world-scale phenomena (e.g., Bartlein et al., 2011; Chevalier et al., 2020; Crucifix, 2012; Sugita, 2007a, 2007b) but has shown limitations, particularly for tropical regions. These limitations include the unequal coverage of palaeoenvironmental data (Izumi et al., 2023), the extensive use of pollen as the main proxy for palaeoenvironmental reconstructions despite the under-representation of certain plant species in a pollinic spectrum (Lézine et al., 2021) or the high dependency on statistical models (Izumi et al., 2023). Multiregional approaches to the archaeological record are subject to similar limitations. Studies of human–environment interactions on a wide scale often make use of paleodemographic estimates based on the number and distribution of sites, but with the caveat that the number of dated sites is often too small to allow statistical analyses, even for regions where archaeological research has been particularly intensive for decades (e.g., Clist et al., 2023; Maier et al., 2016). The development of computational and integrated approaches in the archaeology of climate change (Burke et al., 2021) is an important contribution to the study of human–environment interactions. However, in these models, lithic data are often integrated as a way to measure types of mobility/land-use (e.g., with measures of retouch intensity as a proxy for land-use strategies), while data regarding the variability of technological behaviours are rarely taken into account (Barton & Riel-Salvatore, 2014; Padilla-Iglesias et al., 2022). The need to quantify technological data in order to integrate them into these studies sometimes results in their transformation into binary variables (presence or absence of core or tool types; e.g., Blinkhorn & Grove, 2021; Padilla-Iglesias et al., 2024; Timbrell et al., 2022; Tryon & Faith, 2013), reducing the variability and diversity of human behaviour. In addition, these studies often rely strongly on climatic and environmental modelling predicting suitable environmental conditions for human occupation, and are therefore subject to limitations in the resolution of these data (Banks, 2017). Only a few studies take into account a large number of technological traits in multivariate quantitative analyses (e.g., Scerri et al., 2014; Tostevin, 2012), but these are also subject to the representativity of the archaeological data available in the study zone.

Several of the regions considered in this paper present only sparse data from environments that are challenging for geoarchaeological sciences and with a low possibility of inter-site comparisons at a micro-scale. Consequently, these corpora require careful scrutiny in order to assess to what extent and in which context these data can be exploited, particularly with our aim of developing a 'Pan-tropical approach', since many biases internal to the site formation process or to the historiographical context can explain the data sets available. For example, to what extent has the total absence of archaeological data from South America for decades impacted the statistical models that have been established? To what extent can the intensity of research, current population density, or land cover, explain the site distribution in a region? A recent overview of the dated archaeological record in the last 50,000 years in Central Africa, for instance, identified 24 research biases affecting the interpretation of archaeological data (Clist et al., 2023).

To address this problem, we chose to apply a qualitative approach to critically examine the available data from tropical regions. This paper focuses on five tropical regions, which are the subject of the authors' investigations (fieldwork and/or collection studies): Western Africa, Central Africa, Eastern Africa (Horn of Africa), Insular and Mainland Southeast Asia, and South America (central Brazil) (Fig. 1). Even though not all tropical areas are discussed here, our data encompass different tropical environments: tropical forests, desert areas as well as savannahs, coastal and inland sites across three continents. We acknowledge, however, that other tropical regions such as the Andean Mountain range, southern Arabia, or India, for which a growing body of data are becoming available, may offer a complementary perspective on the tropics at the LGM.

The main research question addressed in this review is: do the existing data show evidence of a significant impact of the ('global' and/or 'local') LGM on human populations in the tropics? In particular, we aim to explore, for each region for the period 30–10 ka:

1. to what extent the period is associated with archaeological data, and when it is not, whether this may be due to the absence of human occupation, or biases in the data such as the absence of research, or taphonomic biases;
2. current evidence of climatic and environmental fluctuations recorded at archaeological and non-archaeological locations;
3. changes in the archaeological record and to what extent they may represent specific responses to environmental changes.

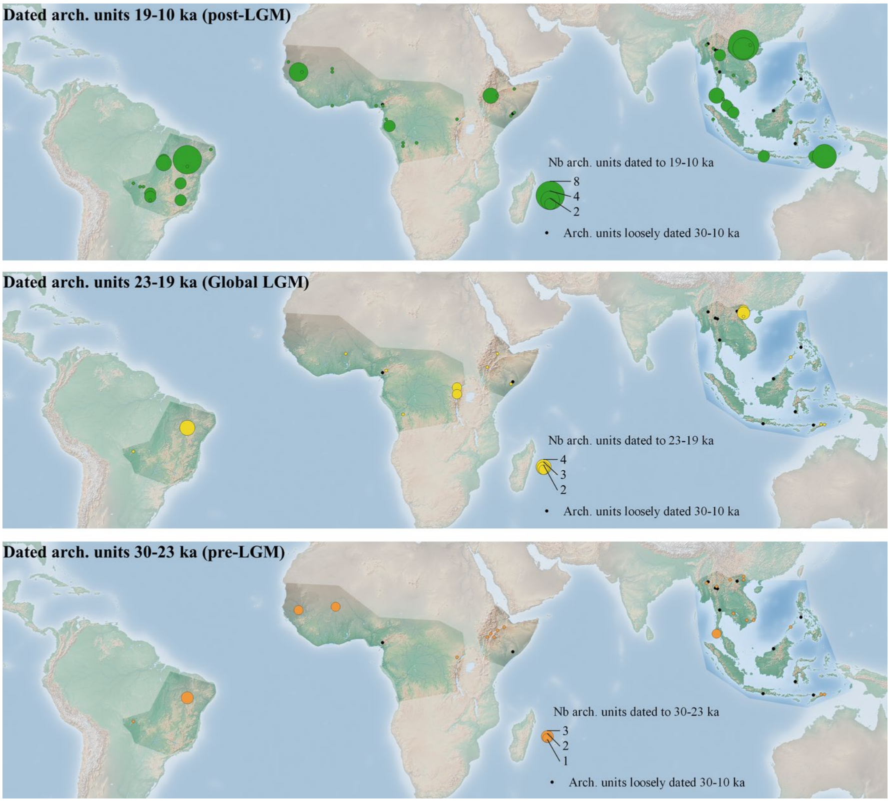

Fig. 1 Map showing the location of the sites dated to the period 30–10 ka for the regions considered and grouped under three main chronological periods: pre-LGM, LGM and post-LGM. Counts of sites were made on a grid of 100*100 km. Created using QGIS 3.28.10 and Natural Earth Data

In order to discuss these points, and to enhance the comparability between regions that have been characterised by very different research histories and heterogenous data types or resolution, data for each region were collected using the same criteria and then compiled in an Excel database (see suppl. Table 1). Our base unit for the data set is the archaeological layer/geological unit, which makes it possible to consider the presence of potential archaeologically sterile units and sedimentological hiatuses. This facilitates discussion on possible evidence for the absence of human occupation at a particular site. For each layer/unit, the data were compiled according to three factors: environmental data, nature of the archaeological material, and chronology, when available. Only layers/units from sites associated with at least one chronometric date were considered (see Table 1). These data were then compared to the regional palaeoenvironmental record, in order to provide, for each region, a critical review of the LGM and its impact on human populations, paying specific attention to the limitations of the available data (research and taphonomic biases, methodological difficulties, etc.).

Table 1 Number of dated archaeological layers considered in the study per tropical region

	WestAfrica	CentralAfrica	HornAfrica	MainlandSEA	IslandSEA	CentralBrazil	Total
Before the LGM (30–23 ka)	4	1	5	10	3	4	27
During the LGM (23–19 ka)	1	5	3	7	3	5	24
After the LGM (19–10 ka)	10	8	8	34	13	29	102
30–10 ka*		1	1	5	12		19
Total	15	15	17	56	31	38	172

*Dated archaeological units, but which cannot confidently be attributed to one of the chronological phases above

Regional Overviews

West Africa (c. 6 million km^2)

Delimited by the coastal countries of the northern Gulf of Guinea to the Niger river basin and the Sahelian lands, West Africa is divided into five main biomes from the north to the south (the Saharan, Sahelian, Sudanian, Sudanian-Guinean and Guinea: White, 1983), distributed in parallel bands of vegetation zones from the southern Guinean coast with distributed rainfall to zones of increasingly drier vegetation until the Sahara Desert is reached in the north (White, 1983).

Archaeological Assemblages Dated to the Period 30–10 ka

Currently, the archaeological assemblages dated chronometrically between 30 and 10 ka are scattered at the West African scale over about fourteen sites unequally distributed throughout the region (Fig. 1): most of them are located in Sahelian Acacia savannah ecoregions at Ounjougou (Mali), in the Falémé valley (Senegal) or at isolated sites within the Guinea forest-savannah mosaic. Critically, compared to other tropical regions detailed in Sect. 'Regional overviews', known archaeological sites in West Africa are single-level sites and very few are truly displaying several stratified levels containing stone tools (e.g., Ben Arous et al., 2025).

The West African Middle Stone Age (MSA) is characterised by elements found in the MSA from other African regions (Clark, 1988; Mcbrearty & Brooks, 2000; Scerri & Will, 2023), such as the Levallois, discoidal, unidirectional and blade debitages (Chevrier et al., 2016, 2018, 2020; Soriano et al., 2010). The period between 30 and 10 ka in particular witnessed the end of the MSA, with assemblages showing evidence of bifacial shaping, which persisted until the beginning of the MIS 2 as shown by the bifacial points made using pressure flaking of Toumboura III (dated between 40 ± 3 ka and 30 ± 3 ka) (Lebrun et al., 2016; Schmid et al., 2022). Elsewhere in West Africa, the end of the MSA is dated to 24 ± 3 ka in Birimi (Quickert et al., 2003), where Levallois debitage is associated with discoid cores and bifacial points, while in other Senegalese sites, at Ndiayène Pendao, Laminia or Saxomonya (Scerri, 2017; Scerri et al., 2021), the lithic assemblages show generic MSA affinity (mainly Levallois and discoid debitage) c. 10 ka. In the Falémé valley, several MIS 2 archaeological assemblages partly fill the sedimentary and cultural hiatus observed ~ 22–12 ka at the Ounjougou site complex in Mali (Chevrier et al., 2018; Fig. 2). This hiatus is attributed to a hyper-arid episode at the beginning of the Holocene (Lespez et al., 2008), eroding the MIS 2 sedimentary deposits.

The transition from MIS 3 to MIS 2 thus coincides with the end of bifacial debitage and also with the emergence of industries presenting unelaborate debitage as observed for the Toumboura II and Ravin des Guépiers sites (Chevrier et al., 2018), dated respectively with the OSL dating method at 33 ± 3 ka (Lebrun et al., 2016) and 18 ± 1 ka (younger age for the site, Lebrun, 2018). These assemblages are on quartz and siliceous limestone and the aspect of lithic production appears simpler, compared to MIS 3 assemblages. Unelaborate debitage predominates during the MIS 2 as shown in Ravin des Guépiers, raising many questions regarding this 'loss of

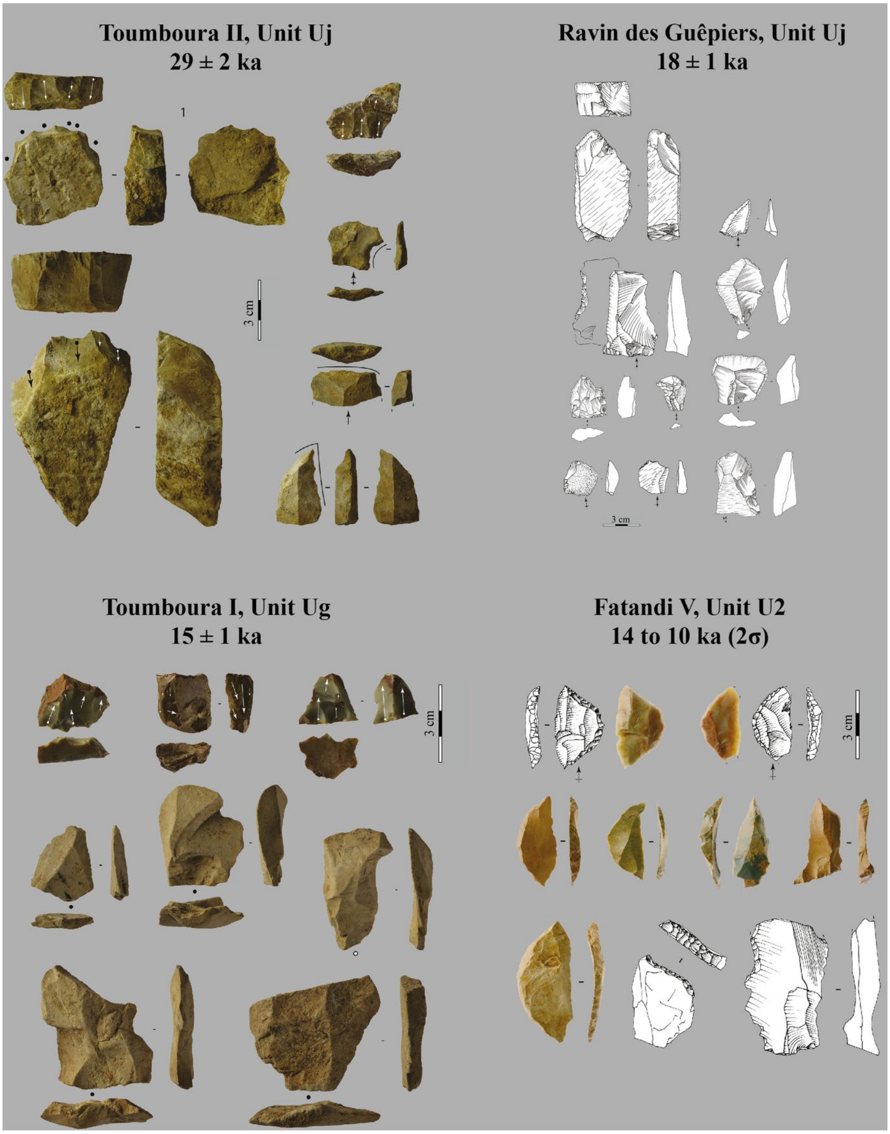

Fig. 2 Selected lithic artefacts from several sites from the Falémé valley (Senegal) for the period 30–10 ka, after Chevrier et al. (2016, 2020)

technical knowledge during an intensely arid climatic episode' already pointed out by Chevrier et al. (2016). These unelaborate debitages are then followed by more complex industries, characterised by microlithic and geometric microlithic tools including lamino-lamellar debitage as documented in the Fatandi V site and Toumboura I (Chevrier et al., 2020; Huysecom et al., 2009). The revised chronology of Fatandi V (using Bayesian and OSL chronologies) places the occupations between 11.2 and 13.3 ka for the upper boundary and between 10.3 and 14.3 for the lower boundary

(Chevrier et al., 2020). Interestingly, two other sites with a chronology similar or close to Fatandi V, namely Ravin Sansandé (dated between 13 ± 1 ka and 12 ± 1.1 ka) and Toumboura I-2017 (dated between 17 ± 1 and 16 ± 1 ka), exhibit completely different toolkits dominated by segments (Ndiaye et al., 2024) (Fig. 2).

Lithic assemblages of the LSA are also present at Bingerville Highway in Côte d'Ivoire around 16–15 ka cal. BP (Chenorkian, 1983) or Iwo Eleru in Nigeria as supported by the terminal Pleistocene–Early Holocene U-Th chronology for human burial between 15 and 11 ka (Harvati et al., 2011) and by the initial radiocarbon dating results (Shaw & Daniels, 1984). From the end of the Pleistocene, the Ravin de la Mouche site in Mali presents assemblages post-dating MIS 2 with a majority of geometric microliths, bipolar and blade debitage, but which, contrary to Fatandi V and Toumboura I, are also associated with ceramics around 10–9 ka (Huysecom et al., 2009). Overall, in West Africa the available LSA sites are chronologically constrained to the MIS 3–MIS 2 transition. They are contemporaneous with typical MSA technologies in Senegal dated to at least the Pleistocene–Holocene transition, which shows that complex cultural processes—still poorly understood—occurred during the Final Pleistocene in West Africa (Fig. 3).

Palaeoenvironmental Data for the Period 30–10 ka

Understanding the cultural trend in different ecozones is challenging as few sites are available, and their numerical dates are sometimes unreliable, preventing a good understanding of the impact of paleoenvironments and paleoclimates on human settlements. This is the case for the period spanning 30–10 ka. In West Africa, the age of the local LGM varies. In Mauritania, the period around the LGM (25–15 ka) corresponds to a period of high eolian activity and the development of sand seas leading to sand dune formations (Lancaster, 2002). In Senegal, arid conditions are documented in the Senegal and Gambia river basins between 20 and 12 ka (Michel, 1973), while arid environments (and the transformation of forested environments into savannahs) are observed between 21 and 18 ka, based on a few lacustrine cores (Bosumtwi, Shum Laka W-10 Barombi Mbo, Ngamakala) situated in tropical Africa (Assi-Kaud-

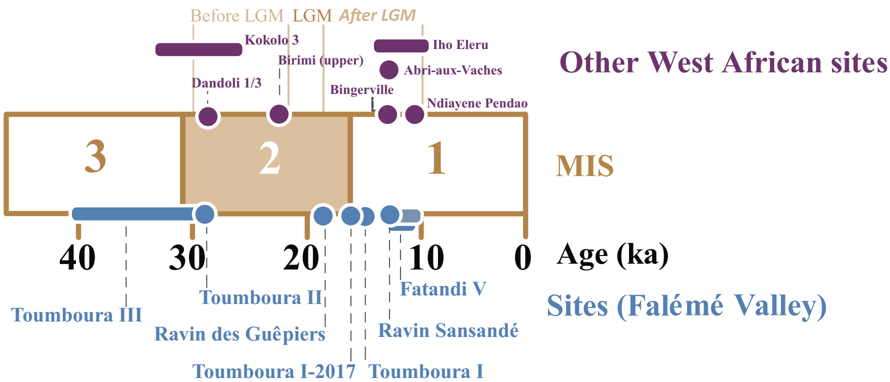

Fig. 3 Chronological distribution of West African sites for the period 30–10 ka. CAD: Eslem Ben Arous

jhis et al., 2010; Miller & Gosling, 2014; Miller et al., 2016) and unequally spread between West and Central Africa. For example, the core of Bosumtwi (Ghana) is the only one located in West Africa covering the time range 30–10 ka (Miller & Gosling, 2014; Miller et al., 2016). Wetter periods are observed at Lake Bosumtwi between 21.5 and 18.5 ka but also between 17 and 15 ka and between 11.5 and 10.5 ka (Gasse, 2000). These scattered data show that the LGM was characterised by intense aridity from 21–18 ka, which resulted in a generalised drop of lake levels (Gasse, 2000), an expansion of savannah environments at low altitudes and, locally, by a decrease in the upper limit of trees at high altitudes (Assi-Kaudjhis et al., 2010). Drier conditions characterised the period from 20 to 15 ka, relating to the extension of the Sahara to the south (Maley, 2004) and over a distance of more than 700 km, in correlation with intense aeolian activity in the Niger delta (Makaske, 1998).

The period between 16 and 12 ka is marked by cool and wet conditions (Gasse, 2000; Lézine et al., 2005) related to the reactivation of the monsoon at the beginning of the African Humid Period in Sudanian-Sahelian Africa. During the African Humid Optimum, the so-called ‘Green Sahara’ was characterised by savannah environments with many rivers and permanent lakes (Ozainne, 2014), the dense Guinean-Congolian forest expanded in the plains and the Afromontane forest covered larger areas in the highlands (Assi-kaudjhis et al., 2010). The timing of this clear trend towards a return to wetter conditions is broadly placed between 12 and 5 ka (deMenocal et al., 2000). Globally, during the LGM, the rainforest mixed with intrusive Afromontane elements was strongly reduced during this period to the benefit of the expansion of open herbaceous environments (Elenga et al., 2004).

Human–Environment Interactions in the Period 30–10 ka in West Africa

Only a few sites present a clear association with local palaeoenvironmental data and a reliable chronological context. Simultaneous geomorphological, sedimentary and cultural studies from newly excavated West African sites allow the paleoclimatic recontextualisation of archaeological sites. For example, the sites in the Falémé valley have benefited for more than a decade now from in-depth geomorphological studies that have made it possible to link the chrono-sedimentary framework to the hydrographic regimes of the Falémé river during the MSA (Davidoux et al., 2018; Lespez et al., 2008). Phytolith analyses can also be used to combine cultural and environmental studies, as was the case for the Ravin Blanc I site (Douze et al., 2021), but remain sparse. Analyses of plant wax biomarkers on sediment (Patalano et al., 2021) are currently being developed and have produced successful results that match the pollen and phytoliths results from the Bété I site (Ben Arous et al., 2025). For the archaeological sites of the late Pleistocene–Holocene, recent faunal and isotopic analyses from Iho Eleru have shown that a mixed tropical forest-savannah ecotonal landscape persisted during the late Pleistocene and late Holocene (Cerasoni et al., 2023).

The scarcity of data means that a detailed synthesis of the region during the LGM cannot be proposed but suggests nonetheless complex population dynamics at the local scale from the late Pleistocene onwards. This period seems to correspond to the end of the MSA and the emergence of the LSA. In Ounjoungou and the Falémé valley, the end of the MSA appears to coincide with the humid period documented in tropical and equatorial Africa around 28–26 ka (Lézine & Cazet, 2005). Data from this area suggest that human groups with different technical traditions repeatedly succeeded one another in this region and were highly mobile at the end of the Pleistocene (Chevrier et al., 2016, 2018). This in turn leads to the hypothesis that the diversity in the lithic assemblages documented in this area more likely results from populations with different traditions rather than a single population evolving in situ (Chevrier et al., 2018; Soriano et al., 2010). The presence of archaeological sites in the Falémé valley during MIS 2, compared to their absence in Ounjougou, raises the question of the presence of a local environmental refugium in the Falémé (Chevrier et al., 2018, p. 20). In other areas of Senegal, the evidence points to a persistence of the MSA until the beginning of the Holocene (Scerri et al., 2021). If confirmed at other sites, this may suggest a certain continuity in technical behaviours across the environmental changes of the LGM and the early Holocene.

The appearance of the LSA in the forested region of eastern and central West Africa correlates with an expansion of forests during the later Pleistocene, around 15 ka (Miller & Gosling, 2014). It remains unclear whether the cultural data from 30–10 ka represent West Africa as a whole for the period, or regional epiphenomena related to specific environments.

Central Africa (Congo Basin: c. 3.8 Million km^2)

Central Africa extends from the African Great Lake region to the Atlantic coast and is mainly encompassed by the Congo river system (Runge, 2007) and the Congolian biogeographic region (Linder et al., 2012). The Congo river (4 700 km) system is characterised by a diversity of environments including different types of forests: evergreen rainforests mainly concentrated in the central part of the basin, semi-deciduous forests and Afromontane forests (Runge, 2007; White, 1983). The oceanic parameters and altitudinal gradient also have a significant impact on the environmental and climatic variability in the region (Izumi et al., 2023). In addition, several types of secondary forests, woodlands and savannahs are present partially due to human activities (e.g. slash and burn practices). Historically, and until recently, these environmental conditions were seen as having acted as a barrier for hunter-gatherers. Nevertheless, the archaeological record of the late Pleistocene and especially MIS 2 is well documented in the region in comparison with older time periods.

Cultural Diversification in Central Africa from c. 40 ka

Genetic studies and archaeological data both suggest demographic and techno-cultural changes at the end of the Pleistocene. First, DNA analysis conducted on modern groups of Central African hunter-gatherers points toward different events of genetic diversification during the late Pleistocene and Holocene (Batini et al., 2011; Lipson et al., 2020; Patin et al., 2009; Perry et al., 2014; Verdu et al., 2009), among which is a specific differentiation between western and eastern populations of the Congo basin, which may be contemporaneous with the LGM (c. 20 ka) (Batini et al., 2011). Second, using a statistical model based on paleoclimatic, ethnographic and genetic data, Padilla-Iglesias et al. (2022) suggested that there was less inter-connectivity between eastern and western hunter-gatherer populations during the late Pleistocene. Third, based on the archaeological record, different cultural and technological trajectories are suggested, particularly between the western and eastern parts of the Congo basin during the Final Pleistocene (Cornelissen, 2002), with a further diversification from the Early Holocene (Clist, 2006). Sites from the period 30–10 ka in Central Africa are attributed to the end of the MSA or to the LSA.

The Central African MSA, the 'Lupemban' industry, remains poorly understood with discussion around its definition and chronological range (Mesfin et al., 2020; Taylor, 2011, 2016). The Lupemban seems to have developed during the Middle Pleistocene both in eastern and western Central Africa up to the end of the Pleistocene (Barham & Smart, 1996; Cornelissen, 2016; Ervedosa, 1980) although the frequent vertical disturbance of MSA industries makes the few dates available so far within Central Africa unreliable (Mercader et al., 2002; Taylor, 2016). Contrary to MSA sites, LSA sites seem to document different types of lithic industries within the Congo basin, with for example the Tshitolian industry mainly documented in the western part of Central Africa, whereas quartz flake industries, some microlithic, are well represented in the eastern part of Central Africa. However, it remains unclear to what extent the archaeological diversity observed between eastern and western LSA Central African sites compared to the MSA is due to a better archaeological resolution for the Final Pleistocene or whether it reflects consistent evidence of regional diversification.

In eastern Democratic Republic of Congo, sites are mainly located in valley bottoms, which led Cornelissen (2016) to suggest that rivers acted as corridors for mobility. An informal LSA quartz microlithic industry characterised by the bipolar technique for the production of bladelets and microliths is dominant in this region, as in Matupi cave and Makubasi Southeast. In Matupicave, the middle levels are contemporaneous with the LGM and range from 26 to 13 ka cal. BP. They have provided examples of bipolar microlithic cores, with a few geometrics (e.g., Fig. 5c) associated with environmental proxies indicating a mixed environment with savannahs and gallery-forests (Van Neer, 1984). At Makubasi Southeast a radiocarbon date gave an age of 23–22 ka cal. BP, associated with a lithic assemblage of quartz microliths and proxies indicating a rainforest environment (Mercader & Brooks, 2001). Quartz microlithic assemblages seem to prevail during the Final Pleistocene in the extreme eastern margin of the Congo basin and especially in the Ituri region. In North-Kivu, another local singular technology has been described at Ishango (Brooks & Smith, 1987). The site presents two layers ranging between 25 and 20 ka cal. BP in a palaeoenvironment potentially similar to the present-day environment, that is, an undifferentiated Afromontane vegetation (White, 1986). Subsistence strategies based on aquatic resources are suggested by a toolkit composed of bone tools presumably used in fishing activities (Yellen, 1998). The lithic assemblage is quartz-based with few microliths but grinding stones are well represented. Ishango is the only site to have delivered human remains for the MIS2 in Central Africa. Analysis of infra-cranial bones suggests lower terrestrial mobility compared with other late Pleistocene and Holocene foragers, and is consistent with a greater investment in aquatic mobility such as paddling or swimming (Crevecoeur et al., 2016).

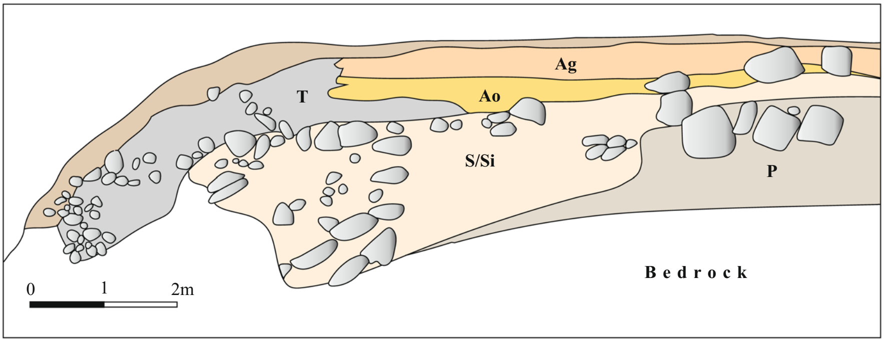

Fig. 4 Stratigraphic section from Shum Laka (Cameroon), after Lavachery et al. (1996); Note that S deposit is contemporaneous with the LGM

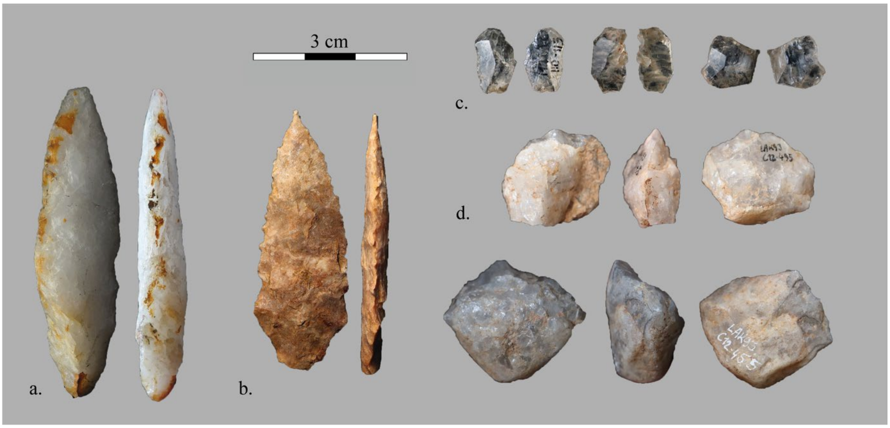

Fig. 5 Selected artefacts from Central Africa for the period 30–10 ka; **a** bipoint in vein quartz from Maboué 5, Layer 3, Gabon; **b** point from Mitshikala port, Democratic Republic of Congo; **c** microliths on crystal quartz from Matupi, Democratic Republic of Gabon; **d** microlithic cores from Shum Laka, Cameroon. Photos and CAD: Isis Mesfin

In western Central Africa, an unstandardised microlithic quartz industry has also been identified among several assemblages that are potentially contemporaneous with the LGM. However, the sites present a large chronological range and an absence of finely stratified deposits for this precise time period. This is the case at Njuinye (Layer 3: 41–21 ka cal. BP), at Maboué 5 (Layer 3: 45–15 ka cal. BP), and at Shum Laka rockshelter (S Deposit: 38–15 ka cal. BP; Fig. 4) (Cornelissen, 2003). All present a quartz industry with microlithic (e.g., Fig. 5a, d) and unstandardised tool types. As for the eastern Central African corpus, quartz-based assemblages seem to be present in a broad spectrum of landscapes ranging from savannah to rainforest. The lack of inter-site comparison hampers our vision of the homogeneity/diversity of this late Pleistocene technical phenomenon in western Central Africa.

This quartz industry appears to be contemporaneous with a specific regional facies, the ‘Tshitolian’. The Tshitolian was initially described by H. Breuil from the Tshitolo Plateau assemblage (Breuil, 1944). It is characterised by 'miniaturised' Lupemban tool types and marked by the appearance of arrowheads and some types of microliths (Assoko Ndong et al., 1999; Bequaert & Mortelmans, 1955; Clark, 1963; Cornelissen, 2002; de Bayle des Hermens, 1981; Miller, 2001). The geographical extent of the Tshitolian corresponds mainly to the Lower Congo, Téké Plateau, Kinshasa Plain, Niari Valley and northern Angola (Cornelissen, 2002). Most of the sites are Holocene in age (Cornelissen, 2002; Lanfranchi & Lanfranchi-Salvi, 1986; Van Neer & Lanfranchi, 1985) but some Tshitolian hallmarks have been identified at Maboué 5—Layer 3 in Gabon (small-size lanceolates and the small 'tranchets') (Mesfin et al., 2021) and shaped arrowheads, associated with microlithic production; small shaped tools have also been reported at the neighbouring site of Lopé 2 and dated to 13–12 ka cal. BP (Oslisly et al., 1996). This depicts a possible association of Tshitolian techno-typological patterns and quartz microlithism. Shaped arrowheads have also been reported at Loukoko II in the Batéké Plateau associated with *Landolphia* sp. remains dated to 18–15 ka cal. BP (Pinçon, 1991), a plant known for its use as a glue or as a poison (Van Neer & Lanfranchi, 1986). The small and fine Tshitolian shaped tool component is often associated with flaking strategies usually described for the older MSA facies such as discoidal and Levallois flake production, even though most of the radiocarbon dates are Holocene (Cahen & Mortelmans, 1973; De Maret et al., 1977; Mesfin et al., 2021; Miller, 2001; Oslisly et al., 1996; Van Neer & Lanfranchi, 1985).

In the northeastern part of the distribution area of the Tshitolian Industry, several sites have been discovered and/or re-examined, with radiocarbon dates on charcoal of c. 24 ka cal. BP for the open-air site of Bagata (Cornelissen et al., 2025), c. 16–15 ka cal. BP and 15–14 ka cal. BP for the open-air site of Mitshakila (Coutros et al., 2025; Fig. 3:b), and various ^{14}C ages ranging between 12 and 15 ka cal. BP for the Mukila open-air sequence (Jungnickel et al., 2024). These three localities provide new information on the southwestern margins of the Congolese *cuvette* in environments that are nowadays mosaic-like due to significant human impact, but the palaeoenvironments remain unknown. At this stage, these sites indicate the use of polymorphic sandstone and blade production, as well as *chaînes opératoires* of shaped tools, which position these sites within the perimeter of the Lupembian and Tshitolian industries during the LGM.

Nevertheless, the archaeological record suggests that both eastern and western Central African sites at the very end of the Pleistocene are marked by the preference for quartz and microlithisation. Informal/unstandardised quartz microlithic assemblages, also called 'miniaturized quartz assemblages' (Cornelissen, 2018), are encountered in several types of environments. The emergence of these LSA industries remains poorly understood but seems to be a gradual process beginning before the LGM (Cornelissen, 2003, 2016; Mesfin et al., 2021; Van Noten, 1977). Surprisingly, at a local scale, archaeological sequences do not exhibit significant technological changes before/during/after the LGM. This is shown for example at Shum Laka rockshelter (Cornelissen, 2003; Fig. 4), Matupi cave (Van Noten, 1977) or Maboué 5 (Oslisly et al., 2006). Similarly, in the Ituri, a diachronic approach conducted on pre- and post-LGM sites did not highlight any significant technological changes (Mercader & Brooks, 2001). In western Central Africa, microlithic quartz assemblages have also been reported for the Holocene record (Lupo et al., 2021; Oslisly et al., 1996). This may reflect the fact that quartz microlithic technology is more flexible, resilient and adapted to several types of environments in Central Africa (Cornelissen, 2016; Pargeter & Shea, 2019). However, the lack of inter-site comparisons for the quartz microlithic LSA industries hampers our understanding of microlithisation emergence and diffusion processes within the Congo basin since the Final Pleistocene.

Asynchronous Environmental Changes During the Last Glacial Maximum Across Central Africa

During MIS2, the forest cover is believed to have been fragmented into different types of environments ranging from herbaceous savannahs to rainforests (Beyer et al., 2020; Leal, 2004). Beyond the large trend of a cooler and drier climate impacting the regression/extension of the equatorial forest cover, terrestrial sequences assumed much more complex and diversified scenarios at local scales (Cornelissen, 2016; Elenga & Vincens, 1990; Giresse et al., 1994; Izumi et al., 2023; Leal, 2004; Lebamba et al., 2012; Stager, 1999; White, 2001). Several terrestrial sequences show that environmental aridification (expansion of savannah environments or 'savannisation') occurred before the LGM and continued after the LGM (Cornelissen, 2016; Oslisly et al., 1996), while forest cover was already extending in other parts of Central Africa (Runge, 2001). In addition, the synthesis provided by Runge (2001) showed that the impacts differed between north and south of the Equator and that differences also depended on altitudinal gradients. Consequently, one can assume that there is no homogeneous impact of the LGM savannisation in Central Africa, whether from an environmental or from a chronological point of view.

Although sites combining archaeological and palaeoenvironmental sequences are rare, the record shows that it is important to develop local studies because environmental and techno-cultural changes are not synchronous with the global LGM in all regions of Central Africa.

Finally, the data provide evidence for: (1) techno-cultural diversification in Central Africa slightly prior to the LGM; and (2) the fact that the observed technological shifts cannot be clearly correlated to LGM climatic or environmental changes. This is evidenced by the persistence of MSA-like or Lupemban industries up to the end of the Pleistocene and by the fact that the quartz microlithic/miniaturisation phenomenon is documented across the LGM chronological boundaries and in different ecological niches. Central African environments appear to have remained attractive to hunter-gatherers during the LGM, as suggested by the relatively high number of sites known. We can also mention the current development of several on-going studies which contribute to enlarging the number of sites contemporaneous with the LGM such as at Mabewele in Equatorial Guinea (Cruz-y-Cruz et al., 2022), Youmbidi cave (Angue Zogo et al., 2023) and Aloumbé in Gabon (Oslisly, pers. Comm.), or Mitshakila Port in Democratic Republic of Congo (Coutros et al., 2022). These sites are likely to shed light on new aspects of the regional lithic variability between 30 and 10 ka.

The central *cuvette* of the Congo basin—where only surface collections have been made (Fiedler & Preuss, 1985; Menghin, 1925)—appears to be a geographical hiatus in our knowledge of population dynamics during the LGM, although recently published studies show the potential of this area for stratified deposits dating to the end of the Pleistocene (Cornelissen et al., 2025; Coutros et al., 2025; Jungnickel et al., 2024). Until some preserved sites are discovered or researched in this part of Central Africa, it will not be possible to investigate further the west/east differences among populations of the Congo basin and to determine whether the western and eastern parts represent a single or a multiple phenomenon.

Horn of Africa (c. 1.8 million km^2)

The Horn of Africa refers to the Eastern African region comprising what are now Ethiopia, Eritrea, Somalia, Somaliland and Djibouti. It is characterised by great climatic and environmental diversity, which is also related to the high elevation gradient (from –125 m in the Danakil depression to more than 4500 m asl in the Simien Mountains) and the precipitation brought by the Intertropical Convergence Zone and the Indian Ocean (Gasse et al., 2008). Environments range from tropical lowland rainforests or woodlands to semi-desert grasslands.

This great environmental diversity must have played a role in the distribution and preservation of human occupations over time. In particular, environmental factors may have played a role in the nature/type of the sites (open-air sites in the lowlands, rock shelters in the Rift margins and the highlands) or organic preservation due to their geological environment (sediment acidity, environmental conditions). The distribution of archaeological sites in this region may therefore result from the differential preservation or visibility of sites in these various environmental conditions as well as different settlement dynamics (movements between different ecological zones) over time. This may be particularly true during MIS 2 when some very drastic environmental changes are documented in the region.

Site Distribution in Light of Regional Environmental Diversity

Very few archaeological sites are dated for the period between 30 and 10 ka in the Horn of Africa (Fig. 6, Table 1). Until recently, most dates falling into that time range were questionable (old radiocarbon dates on combined charcoal or ostrich eggshell fragments), or the archaeological contexts for the dates were poorly elucidated, such as an unclear association between cultural material and dated material, or evidence of stratigraphic disturbance and possible mixing of different levels (see review in Leplongeon et al., 2020, pp. 274–276). In addition, recent investigations at two sites with long sequences spanning the Upper Pleistocene and Holocene document gaps in their sedimentological sequences, broadly corresponding to MIS 2 (Figs. 7, 8). These sites are Goda Buticha (~1380 m asl, Fig. 6), a cave located in the limestone formations to the southeast of the Ethiopian Rift (Pleurdeau et al., 2014, 2023; Tribolo et al., 2017), and Mochena Borago (~2200 m asl), a rock shelter formed within the volcanic rock formations on the flank of Mount Damota, a volcano located at the boundary between the Southwest Ethiopian highlands to the west and the southern Main Ethiopian Rift Valley to the east (Brandt et al., 2012, 2017, 2023). Similarly, the important lacustrine sequences in the Ziway-Shala Basin also seem to show a gap in human occupation

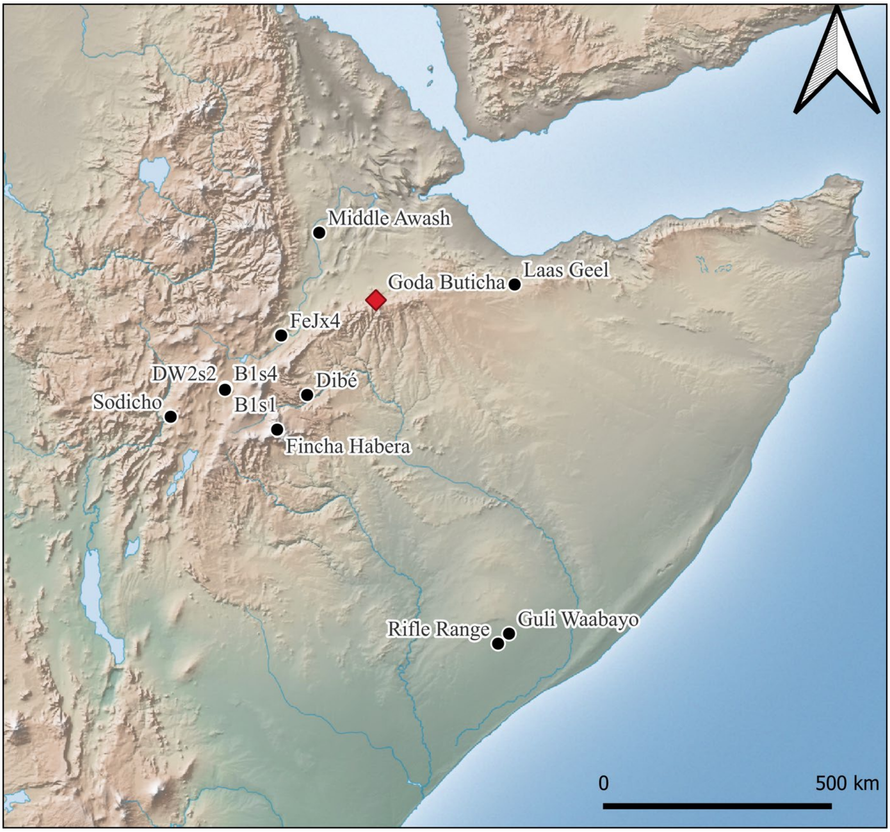

Fig. 6 The Horn of Africa between 30 and 10 ka. Map showing the location of sites mentioned in the text and the location of Goda Buticha in red. Created using QGIS 3.28.10 and Natural Earth Data

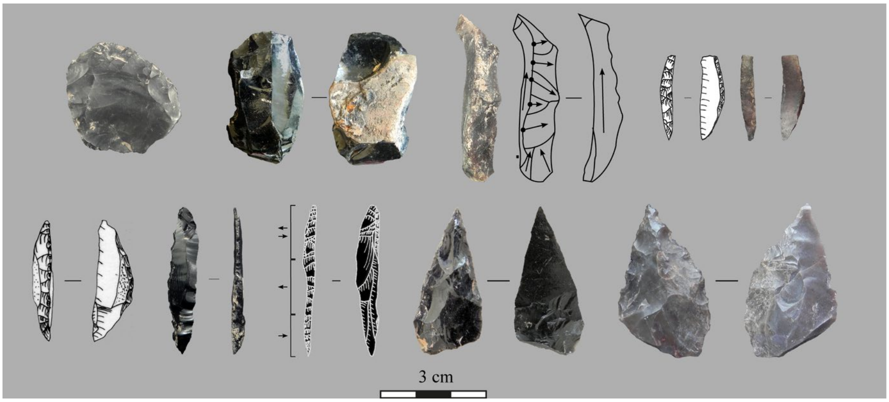

Fig. 7 Goda Buticha, mid-Holocene layer IIC: selection of artefacts

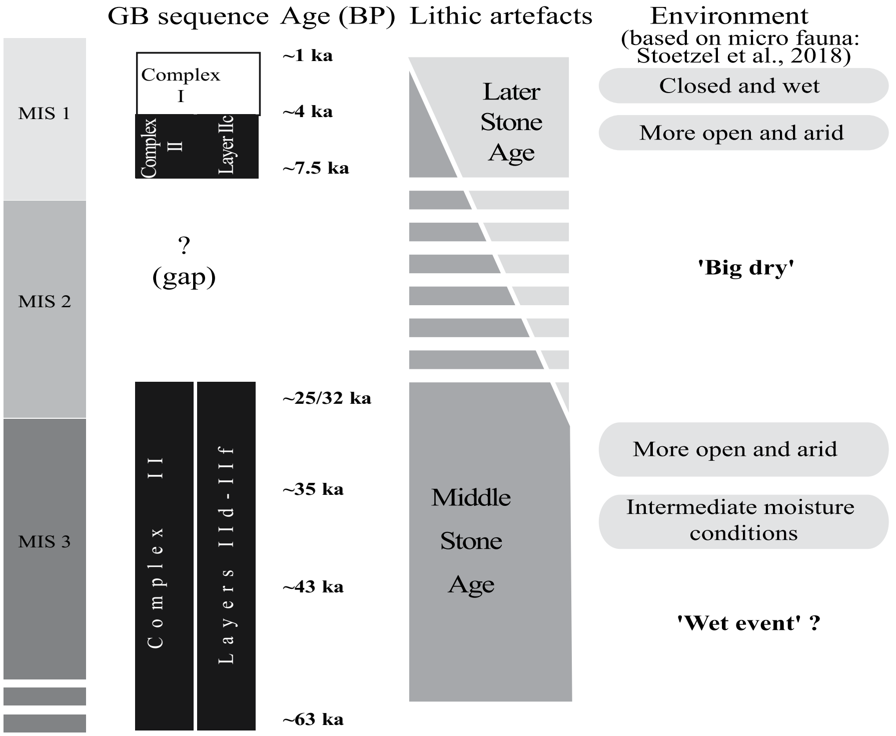

Fig. 8 Goda Buticha (GB). Schematic representation of co-occurrence of archaeological and environmental data at the site, after Stoetzel et al. (2018)

during MIS 2, either because human occupation of the area was hampered (volcanic eruptions, submerged basin) or because of preservation biases (Bon et al., 2013; Ménard & Bon, 2015, 2023). This potential evidence for lack of human occupation during MIS 2 led to the formulation of the hypothesis that environmental conditions were too arid to enable human occupation in the Horn of Africa during part or all of MIS 2, or at least corresponded to much lower densities of human populations (Leplongeon et al., 2017, 2020; Pleurdeau et al., 2014).

Most palaeoenvironmental records indeed indicate generally dry conditions with lower temperatures in tropical Africa, including the Horn of Africa during MIS 2, even if extremes in temperature or precipitation were rarely coeval with the LGM (Gasse, 2000; Gasse et al., 2008; Umer et al., 2004). Reconstructed vegetation models indicate a reduction of around 25% annual precipitation in tropical Africa, and changes in temperature in mountainous environments led to as much as a 1000 m lowering of the Afro-alpine vegetation zone (Anhuf, 2000; Fischer et al., 2020, 2021). Few high-resolution environmental records are available for this period in the region (see review in Umer et al., 2004). Lacustrine records show evidence of increased aridity, significant contractions of the extent of the lakes or even desiccation (lack of lacustrine sedimentation and formation of a palaeosol) during MIS 2, such as at Lake Chew Bahir (Foerster et al., 2012), in the Ziway-Shala Basin (Gasse & Street, 1978), at Lake Dendi (Wagner et al., 2016), at Lake Tana (Lamb et al.,

2007) or at Lake Abhe (Gasse, 2000; Khalidi et al., 2020), sometimes persisting until the Early Holocene c. 12 ka (e.g., Khalidi et al., 2020; Wagner et al., 2018), with a peak of aridity coeval with Henrich 1 (H1, 16.8 ka). The climate record at Chew Bahir in particular documents rapid wet–dry–wet fluctuations before 15 ka that correlate with Dansgaard-Oeschger cycles, which may have been challenging for human groups living in the area (Foerster et al., 2012, 2015; Trauth et al., 2018). Other types of continental records are rare. Speleothem records are only available for the Last Interglacial (Asrat et al., 2018) and the Holocene (Asrat et al., 2008). Pleistocene glaciations are recorded in several Ethiopian mountains (Umer et al., 2004). In the Bale Mountains in particular, the most recent glacial advance precedes the global LGM (Umer et al., 2004) and has been recently dated to c. 45 ka (Ossendorf et al., 2019).

This brief overview of palaeoenvironmental records available for the period shows that the late Pleistocene in the Horn of Africa was a generally arid period, even if the most arid episodes were not necessarily coeval with the LGM but may have been earlier or later (in particular, around H1). What the few available data suggest is that there were complex relationships between local and regional environmental responses to global climatic changes. Even if available data do suggest a general trend towards a greater aridity at the end of the Pleistocene, the greater aridity does not take place only during the global LGM and it is necessary to approach human–environment interactions in the Horn of Africa at the end of the Pleistocene on multiple scales (local and regional), as well as across a wider chronological range, encompassing but not restricted to the global LGM.

Human–Environment Interaction at the Local Scale

Diverse intensities of environmental changes are thus to be expected in the different ecological settings characterising the Horn of Africa over the period between 30 and 10 ka. These are likely to have impacted human populations. Two main hypotheses can be considered: movements towards refuge areas or specific adaptations to a changing environment.

One main refugium area mentioned for this period in the Horn of Africa is the Southwestern Ethiopian Highlands (Brandt, 1986; Brandt et al., 2012; Fischer et al., 2020, 2021; Foerster et al., 2012; Hensel et al., 2021; Vogelsang, 2023; Vogelsang & Wendt, 2018). Support for this hypothesis comes from palaeoenvironmental and archaeological data, as well as from palaeovegetation and palaeolake modelling, suggesting that human groups may have avoided the Afro-alpine vegetation belt (above 2000 m asl), preferring to live in grassland environments at lower altitudes (Fischer et al., 2020, 2021). Specific archaeological support for this hypothesis comes from the Sodicho rock shelter (~1930 m asl) located in the Southwestern Ethiopian highlands, on the southern slopes of Mount Sodicho a few kilometres to the north of Mount Damota, and just below the reconstructed Afro-alpine vegetation belt during MIS 2. The lower units (Units IX–VII) are dated to between 27 and 16 ka cal. BP, with a main phase of occupation dated to between 27 and 22 ka cal. BP and possibly a short gap in human occupation (deposition of tephra unit VIII) before the deposition of an anthropogenic layer dated to between ~17 16 ka cal. BP. The associated cultural materials remain unpublished but are briefly described as showing an obsidian bladelet industry, which *could* fit with an attribution to the Later Stone Age (Hensel et al., 2021; Vogelsang, 2023).

The sites of Guli Waabayo (Buur Heybe, ~610 m asl) and Rifle Range (Buur Hakaba, ~290 m asl), located in the lowlands of the inter-riverine regions of southern Somalia, between the Shebele and Jubba rivers (Jones & Brandt, 2022; Jones et al., 2018, 2021; Reid et al., 2019), may provide evidence for the second hypothesis, that is, specific adaptations to a changing environment. These sites have been recently re-dated. Guli Waabayo (Jones et al., 2021; Reid et al., 2019) shows a repeated use of the rock shelter between 26 and 6 ka cal. BP. The earliest layers are associated with the Eibian industry, dated to MIS 2. Chronological gaps are apparent in the sequence at ~23–19.5 ka cal. BP, ~17.5–15 ka cal. BP, ~12.9–11 ka cal. BP and 11–9 ka cal. BP. At the Rifle Range site (Jones et al., 2018), a single AMS date on ostrich eggshell at ~20 ka cal. BP is associated with the Eibian industry and local palaeoenvironmental data are consistent with an arid climate and environment. This may document a continuous, albeit low, presence of human groups in the inter-riverine region of southern Somalia that might have impacted their archaeological visibility (Jones et al., 2021).

Another few sites document MIS 2 occupations in several areas of the Horn of Africa. Aga Dima Site 2 (ADS2, c. 1630 m asl) is located in the Ethiopian Rift Valley (Habte Endalew, 2020; Ménard & Bon, 2023). It is a sedimentary trap with the lowest layers dating to ~33–26 ka cal. BP, with a lithic assemblage characterised by a volumetric blade production showing continuity with the blade production systems documented in the latest MSA sites of the Ziway-Shala basin (Ménard et al., 2014) and associated with retouched points and backed pieces. Assemblages dated to ~24–21.5 ka cal. BP are also contained in the Oulen Dorwa Beds of the Halibee Member in the Middle Awash and bear characteristics that are consistent with an attribution to the LSA (Niespolo et al., 2021). Their detailed study is still ongoing. Information is lacking to discuss how these occupations can testify to specific adaptations to a changing environment.

These recently excavated or re-dated sites thus contribute to filling an important gap and may suggest that despite the general aridity of the period, human occupation of certain areas in the Horn of Africa may still have been possible. These occupations may show evidence for the contraction of populations towards refugium areas (e.g., at Sodicho), or an adaptation to arid environments (e.g., at the Somalian sites).

Discussion

The low number of sites dated to MIS 2 contrasts with the numerous sites known in the Horn of Africa for the beginning of MIS 1 (15–12 ka) and the beginning of the Holocene (12–11 ka) (Ashkenazy & Sahle, 2021; Bon et al., 2013; Finneran et al., 2000; Ménard et al., 2014), even if phases where no sites are known correlate with the arid Younger Dryas (Ménard & Bon, 2015; Ménard et al., 2014).

Different hypotheses are proposed to explain this low number of sites during MIS 2 in the Horn of Africa:

- Low population densities, leading to a low archaeological visibility

- Population movements towards environmental refugia
- Preservation biases (e.g., lack of sedimentation, erosion, etc.)
- Research biases

This brief overview seems to indicate, however, that a simple model equating general arid conditions with lack of human occupation can be rejected. Beyond the question of possible impacts of environmental changes on the distribution of human occupations in the Horn of Africa, another question arises, that of its possible correlations with changes in human behaviours. Before MIS 2, all lithic assemblages in the Horn of Africa may be attributed to the MSA, with some indications of a higher variability and processes of technological change towards what would later be characteristic of Later Stone Age technologies towards the end of MIS 3 (Leplongeon et al., 2023). After MIS 2, all lithic assemblages dated to between 15 and 10 ka are attributed to the Later Stone Age, albeit showing a great variability in their technological characteristics (Ménard et al., 2014). Except for the MIS 2 industries from southern Somalia, attributed to a distinct LSA industry, the Eibian, the lithic assemblages from the other sites dated to MIS 2 are only partially published. As a result, it is not yet possible to discuss the nature of changes from MSA towards LSA technologies in the Horn of Africa and their possible correlations with environmental changes. In any case, this brief overview invites caution in proposing explanations at the regional level based on the absence of evidence and highlights the importance of the increase in archaeological and environmental data on a local scale.

Mainland Southeast Asia (c. 2.5 million km^2)

During the Last Glacial Maximum (LGM) and up to about 11,000 years BP, populations of modern humans had longer periods of time to move on dry land between mainland Southeast Asia and Indonesia when the Java Sea was a plain. When the Sunda Plateau became dry land because of lowered sea levels, the marine valleys of the South China and Java Seas were exposed and became large rivers, respectively the Sunda river and Java river (Molengraaff, 1921). With the LGM marine regression, Sundaland became a continental extension of Southeast Asia of about 2.5 million km^2 linking the mainland to the Malay Peninsula and the islands of Sumatra, Java and Borneo. During the LGM Sundaland is considered to have become a large 'savannah corridor' as shown by various data from palynology and fauna data (Heaney, 1991). This corridor thus separated the plateau into two geographical areas with Sumatra and Java on one side (west and south) and Borneo on the other (Bird et al., 2005).

The prehistory of mainland Southeast Asia has the particularity of referring to a single technocomplex during the migrations of *Homo sapiens* between MIS 3 and MIS 1: the Hoabinhian (Fig. 9). The term comes from the eponymous Hoa-Binh-karst province in North Vietnam (Colani, 1927, 1932; Forestier et al., 2023). Despite some regional variations, this chrono-cultural episode, with a longevity of almost 40,000 years, is mainly made up of heavy tools on oblong pebbles that are massive and unifacially shaped, but also choppers, chopping tools and split pebbles. Nevertheless, during the Hoabinhian period, hunter-gatherer populations developed techno-economic strategies for mobility and the supply of raw materials, as at the Tràng An

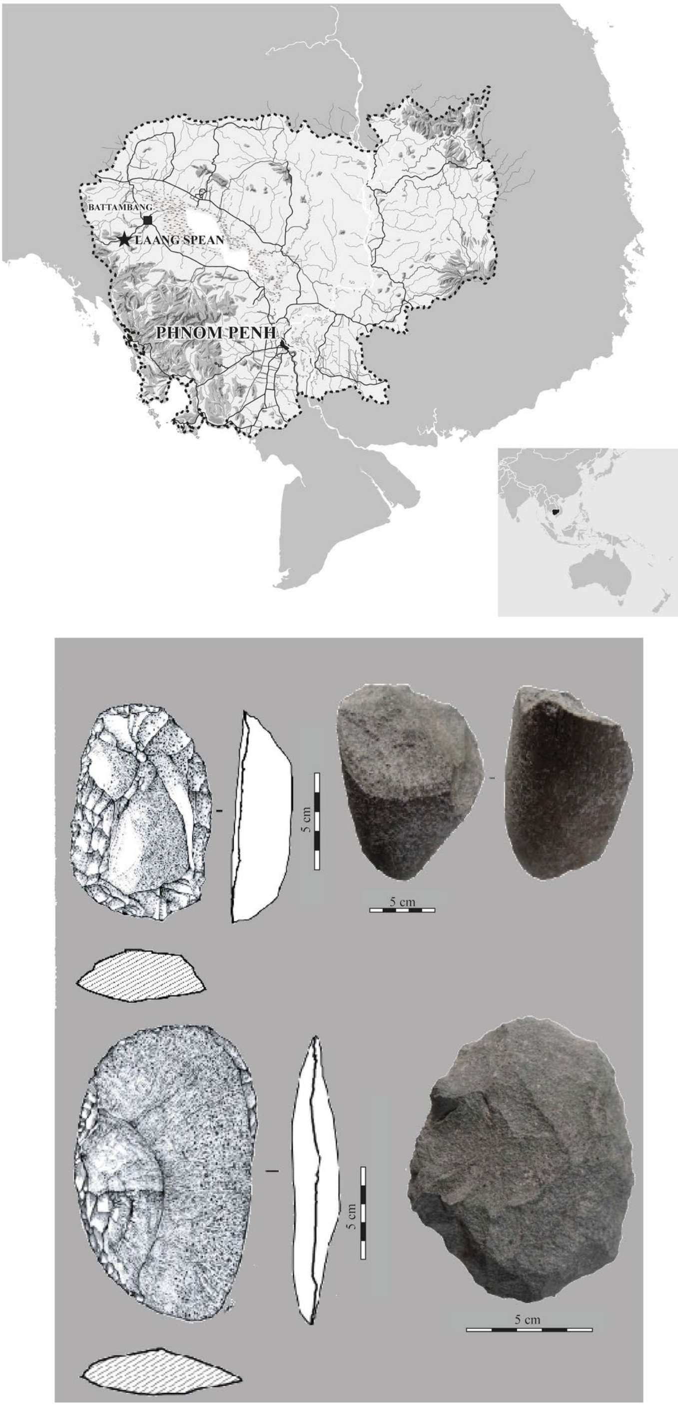

Fig. 9 Laang Spean, Cambodia. Top: Map showing the location of Laang Spean, Battambang Province, North-West Cambodia. Bottom: Examples of typical Hoabinian unifacial pebble tools from Laan Spean (11 ka)

site in Northern Vietnam (Utting, 2022). In this region of c. 2.5 million km^2 with nearly a hundred cave and shelter sites, only four sites are known to date back to the pre-LGM: Tham Lod in Northern Thailand (Chitkament et al., 2016; Marwick, 2008; Shoocongdej, 2006); Hang Cho (Yi et al., 2008), Hang Trong (Rabett et al., 2017) in North Vietnam and Tham Khuong (Nguyen, 1991). Recent excavation data agree that the massive arrival of human groups preferentially took place after the LGM, at the Pleistocene/Holocene transition or even at the very beginning of the Holocene, as shown by the filling of caves such as Laang Spean (11 ka–5 ka) in Cambodia (Forestier et al., 2015; Fig. 5), Hiem cave (8–8.3 ka) in Vietnam (Masojć et al., 2023), or Moh Khiew (11–9 ka) in southern Thailand (Auetrakulvit et al., 2012). Late Upper Pleistocene hunter-gatherers inhabited these monsoonal forest regions, settling in the tropical environment which explains the 'archaic' nature of Hoabinhian tools. One cannot therefore speak strictly of a 'Stone Age', but rather of a 'forest civilisation'.

By measuring the oxygen and carbon isotope ratios (^{18}O et ^{13}C) along a marine core, Gingele et al. (2002) reconstructed the magnitude of marine currents since 75 ka, in relation to eustatic changes. Between 35 and 20 ka, the climate was relatively humid and dominated by the winter monsoon. The study of sedimentary records in the South China Sea (Wang et al., 1999) shows, however, that Heinrich Event 4 (c. 32 ka BP) was characterised by a significant drying and cooling of temperatures.

During the Pleistocene–Holocene transition around 11 ka and the beginning of the sea-level rise, the land area gradually decreased by at least one third (Voris, 2000). Sumatra became an island isolated from the Malay Peninsula and Borneo around 6 ka (Hanebuth et al., 2011; Sathiamunthy & Voris, 2006; Voris, 2000).

Sun et al. (2000) consider that in Southeast Asia, a maximum temperature decrease of 2 °C to 7 °C occurred, and even as much as 10 °C at high altitudes in Papua New Guinea (Flenley, 1996). The response of the Southeast Asian environment to different climatic forcings is debated, however, with some authors arguing for a moisture-dominated vegetation with an increase in tropical rainforest *sensu stricto,* based on pollen records in the northern Sunda Plateau (Hope et al., 2004; Sun et al., 2002).

In view of these climatic and environmental data, what may have been the impact from a cultural point of view? Was there a notable change in lithic production between the LGM and Early Holocene industries? As far as Mainland Southeast Asia is concerned, the Hoabinhian technocomplex as observed in most of the sites of this period does not present major technical changes over the period, with the persistence of a generalised pebble tool industry. In these lithic assemblages, the main tools are heavy, robust and made on pebbles or blocks and are present until the mid Holocene before giving way to an 'Asian Neolithic' rapidly replaced by the Metal Age. In order to illustrate the few diachronic cultural changes observed over the period, the sequence of the site of Laang Spean is detailed below.

The Example of One Cave in Cambodia: Laang Spean

The Laang Spean cave site (Battambang province, North-West Cambodia) is a key site presenting a long, 13 m deep stratigraphical sequence including a Hoabinhian level in the upper part of the sequence (Forestier et al., 2015; Figs. 9, 10). The partial collapse of the vault of the cavity has created skylights and a giant arch (Fig. 10). Due

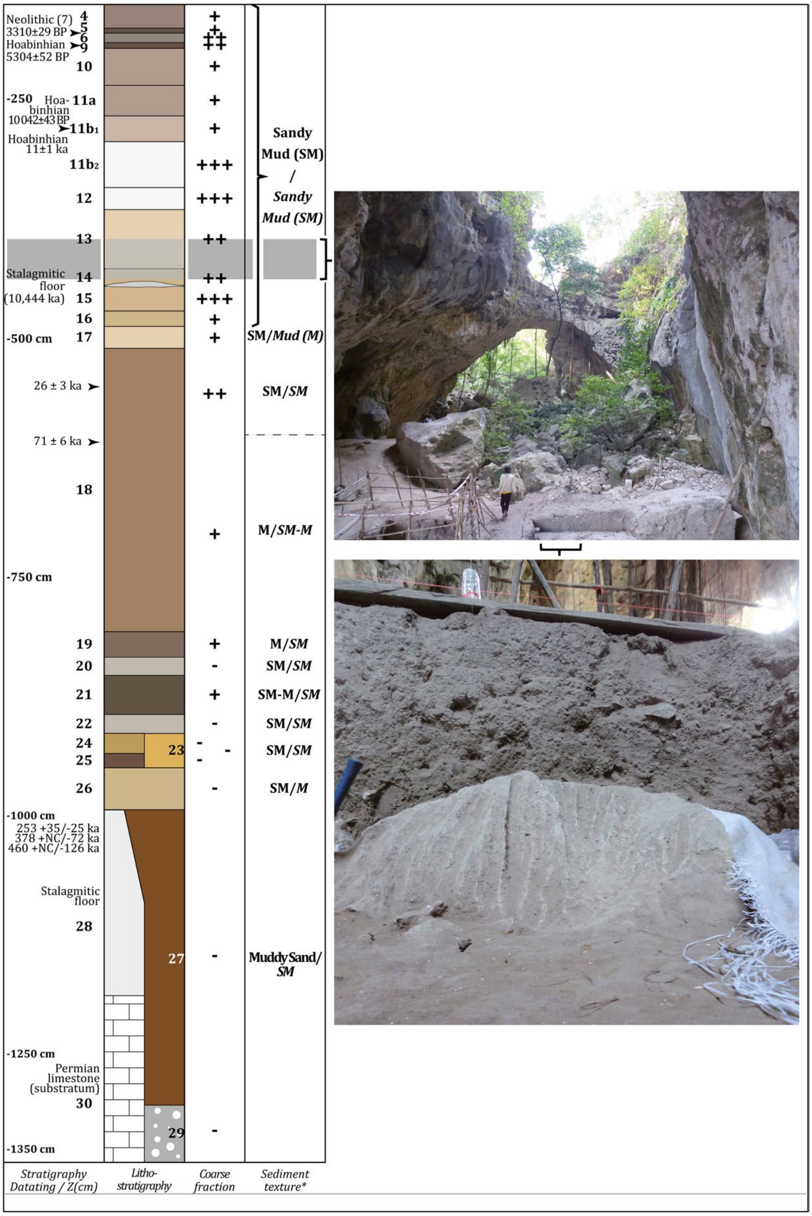

Fig. 10 Laang Spean, Cambodia. Left: Stratigraphical sequence. Coarse fraction:—rare (0 ≤ % ≤ 5%), + present (5 ≤ % ≤ 25%, + + abundant (25 ≤ % ≤ 50%), + + + very abundant (50 ≤ % ≤ 100%). Sediment texture: 63 µm ≤ Sand ≤ 2 mm and Mud < 63 µm (**bold**: raw sediment / ***bold italic***: decarbonated sediment). Top right: View of the accumulation of limestone blocks from the entrance of the site. We can see the opening of the vault of Room 2, the bridge and the collapse of the bottom of the cave. Bottom right: Limestone block from the collapse of the ceiling of Room 2. Its surface bears traces of dissolution. These are flutes (*rillenkarren*)

to its volume, Laang Spean is a large empty underground cave whose cavities are the result of phases of equilibrium and disequilibrium. In most cases, these cavities tend towards a state of equilibrium, usually adopting a rounded vault.

The breakdown of this equilibrium occurs when the cavities widen or under the effect of stress variations within the limestone formation (Gili, 1986). At Laang Spean, evidence of the collapse of the roof of Room 2 has been fossilised in the sedimentary fill of the site. Slump blocks from this event can be recognised in the stratigraphy where they are included in part of and above Layer 14 (Fig. 10). They are visible in particular in the cross-section of the central deep testpit at around 400 cm below datum, as well as in the cross-section (band 32 from M to S).

From a chronological point of view, dating was carried out on different materials on either side of the layer that fossilised the falling blocks. Thus, below Layer 14, the sediments of Layer 18 were dated by OSL to 26 ± 3 ka (CLES 2). Above Layer 14, Layer 11b1 was dated by OSL (sediment) at 11 ± 1 ka (CLES 4) and the base of Layer 11a (^{14}C on charcoal) at 10 042 ± 43 BP (Wk-38610) (Fig. 10).

According to Gili (1986), the destabilisation of the walls and the vault occurs when sudden changes affect the karst formation in which the cavity is dug. Post-glacial periods appear to be favourable to this type of event with the melting of mountain glaciers (e.g. in the Himalayas where the Mekong river rises), releasing masses of water that incise the limestone massifs of the valleys and create small limestone hills or *phnom* such as Laang Spean. These karsts in Kampot and Western Cambodia are 200 million years old (Permian) and were then reworked, i.e. opened up, but are in no way native to the Quaternary (Demangeot, 1999). Nevertheless, when conditions become wetter, the surface karstification mechanism resumes by sculpting the *phnom* limestone into lace shapes called 'mogotes formation'. With the lowering of the base level, the residual reliefs rise, leaving the sides and the surface of these reliefs to decompress. This relaxation is the cause of the block slides that affected the *phnom* where the Laang Spean cave is located. The decompression of the walls continues to a lesser extent even today, with a process of desquamation of the cavity resulting in the fall of thin calcareous elements or 'onion skins'. Given the chronology of the site, it seems plausible to consider that the destabilisation phase of the cavity and the block collapse of its vault coincided with the LGM. At this time, the climate tended to become cooler and less humid, resulting in less rainfall and less humidity in the Indochinese peninsula (Chabangborn et al., 2014; Maloney, 1983).

The Hoabinhian fauna of Laang Spean (11–5 ka) only provides information on the Pleistocene/Holocene transition in the past environment, which is mainly composed of large mammal taxa typical of the Indochinese peninsula. The vast majority are Bovines (*Bos javanicus* and to a lesser extent *Bos frontalis/sauveli, Bubalis arnee*) and in second place, Cervids (*Rucervus eldii*, *Rusa unicolor* and *Muntiacus sp.).* There is also the presence of *Rhinoceros sondaicus* and *Sus scrofa* and a few Primates (*Macaca sp., Trachipithecus sp.*), with some carnivores (*Panthera tigris, Panthera pardus*). This faunal association, characteristic of a tropical rainforest, interspersed with clearings, suggests an open forest cover rather than a dense forest for the Holocene period.

The mixing of faunas from open and closed forest contexts is reported in different regional sites such as Tham Hang or Nam Lot in Laos (Bacon, 2012) or Tham Lod in

Thailand (Shoocongdej, 2006), but it is not possible to determine whether this mixing is due to the existence of a mosaic of synchronous landscapes or to a succession of faunas from different biotopes that changed over time.

At Lang Rongrien (Krabi Province), Mudar and Anderson (2007) noted the disappearance of *Elephas* and the arrival of the Bearded Boar, *Axis porcinus* and Rhinoceros (Sumatra) at the LGM. However, their interpretation, which lacks many key sites, mentions that a 'little open forest' was replaced by the coexistence of grasslands and more open forest after the LGM.

At Laang Spean, a cooler and drier climate than the present one was introduced, which had some bio-environmental implications (Fig. 10) implying a drop in temperature of 5 °C on average during the last pleniglacial period and even a drop of around 10 °C as indicated by palynological results (Maloney & McCormac, 1995).

Regional Human–Environment Interactions Around the Last Glacial Maximum in Mainland Southeast Asia

The vegetation cover in Mainland Southeast Asia during the Pleistocene could have seen three ecozones vary under the effect of changes in temperature and rainfall (more or less annual monsoon): (i) a dipterocarp forest in the coastal zone, (ii) a dipterocarp forest in the highland humid tropics, (iii) savannah or deciduous forest between the two (Sinitsyn, 1962; Van Tan, 1976).

The situation at the LGM had the direct effect of depressing the highland vegetation zones, especially in the mountains, with a generalised cooling of a few degrees Celsius, which in the tropics is expressed as greater aridity, if not a drought, with fewer rainy episodes. This must certainly have led to a reduction or displacement of the rainforest in refuge areas in favour of a more extensive savannah area: 'fossil pollen records demonstrate that Southeast Asian vegetation during the Last Glacial Maximum (c. 18 000 BP) differed substantially from that of today with an increase in the extent of montane vegetation and savannah and a decline in rain forest' (Heaney, 1991, p. 33; see also Kellman & Tackaberry, 1997).

Palynological studies in Asia–Pacific (Pickett et al., 2004) or more regionally in the north and northeast of Thailand in a peat-swamp context, have shown changes in vegetation over the last c. 40 ka, which consisted mainly of fagaceous-coniferous forest with a peak during the LGM about 20 ka (Penny & Kealhofer, 2005). As climatic conditions became colder and drier than those experienced in Thailand today, there was a replacement of the forest cover by a tropical broad-leaf deciduous forest at the Pleistocene/Holocene transition (Penny, 2001). With the Holocene and the return of climatic improvement, there was a resumption of rapid biogeographic development during this period with the return of a relatively humid climate until a floral stability identical to modern vegetation was reached at approximately 6.3 ka (Penny, 2001). In the Holocene, the return of rainfall and the monsoon resulted in changes in vegetation and lake conditions up to the present day as shown by the study of pollen taken from permanent, closed-basin, volcanic lakes in Ratanakiri Province, northeastern Cambodia (Maxwell, 2001). Furthermore, the paleoclimatological and paleohydrological data obtained from lake samples show a clear 'monsoon variability' and sea-level fluctuations during the Holocene (Penny, 2006).

In conclusion, the colder and drier climatic conditions at the LGM that affected northern East Asia and the whole of northern Eurasia must also have strongly disrupted the climatic equilibrium of the tropics, especially at the position of the Inter-Tropical Convergence Zone (ITCZ). The displacement of the ITCZ could explain some climate disturbances such as the decrease in annual precipitation during the Pleistocene with a 30% drop in rainfall compared to that in a monsoon regime (Urushibara-Yoshino & Yoshino, 1997). According to Rabett and colleagues, ‘the effects on moisture-laden systems travelling over the continental landmass of Sundaland, coupled with resultant changes in the positioning of the atmospheric (ITCZ) and this drop in air and sea temperature, combined to exert great influence over Southeast Asian climate’ (Rabett et al., 2017, pp. 101–102). Since the Final Pleistocene, there have therefore been phases of dense forest, as during most of the Holocene, and phases of savannah vs. dense forest, between which there were 'unstable' episodes or transitions between the two phases. To this must be added disturbances in the general hydrology, i.e. the activity of the large rivers and their tributaries that cut through continental Southeast Asia from north to south.

Insular Southeast Asia (c. 2 million km^2)

Insular Southeast Asia is composed mainly by the Philippine and Indonesian Archipelagos, limited on the west side by continental Asia and on the east side by Australia. This region is characterised by three phenomena: volcanism, tectonic activity and eustasy. The subduction of the Australian and Philippine Sea Plates under the Eurasian Plate led to changes in the islands’ morphology in time and space.

In Insular Southeast Asia, during the Quaternary period and successive glacial cycles, land bridges (glacial) linking the continent and the archipelagos periodically formed. During these periods, the drier and cooler climatic conditions led to the regression of the rainforest and the extension of dry seasons (Anshari et al., 2001; Dam et al., 2001; Forestier et al., 2005; Haberle et al., 2001; Hope, 2001; Stuijts, 1984; Stuijts et al., 1988; Suparan et al., 2001; van der Kaars, 1998; van Zeist et al., 1979).

The land bridges and the opening of the forest allowed the diffusion of faunas and humans. While the present climatic conditions (interglacial) allow the development of forests, the high level of human disturbance alters the landscapes at low and medium altitudes.

However, during the period considered (30–10 ka), a climatic improvement began around 15 ka (Sémah et al., 2004a, 2004b) and although evidence of deforestation can be observed in Sumatra for instance (Flenley & Butler, 2001) during the Holocene, there is no evidence of human modification of the environment during the Pleistocene.

A specific focus on three South-East Asian sites (Song Terus cave and Ambarawa basin on Java island, Indonesia, and Tabon cave on Palawan island, Philippines) affords some insight into the Southeast Asian LGM (Figs. 11 and 12).

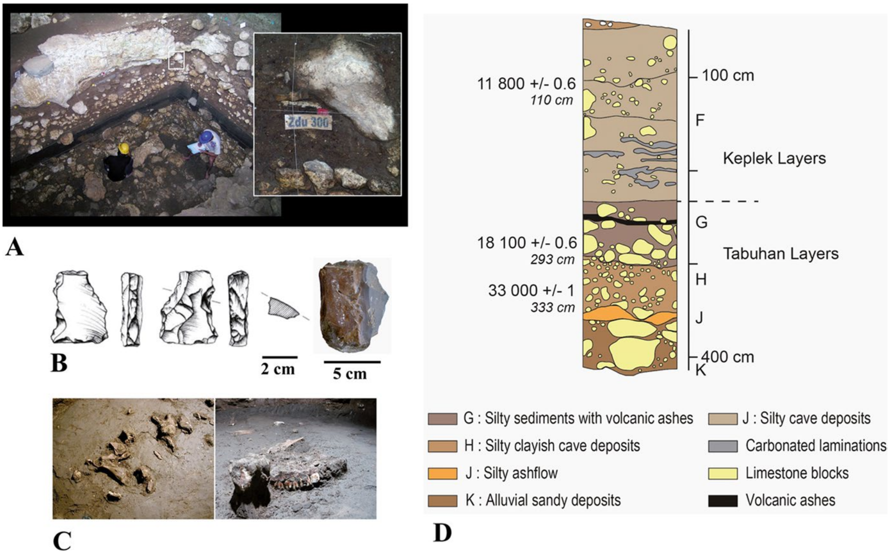

Fig. 11 Song Terus Cave, Indonesia. **A** Last Glacial Maximum levels showing bones in the section (AM Sémah); **B** Lithic artefacts (H. Forestier); **C** Fauna (Cervidae) (Semananjung); **D** Stratigraphy of Song Terus (X. Gallet, AM Sémah)

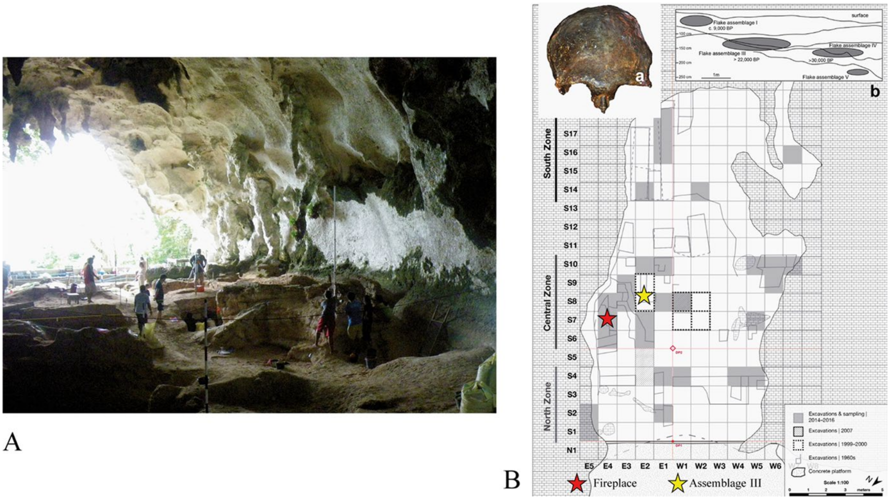

Fig. 12 Tabon Cave, Philippines. **A** View of Tabon Cave (AM Sémah); **B**-(a) Tabon Cave human frontal skull cap (16.5 ka) and (b) Map of excavations at Tabon Cave showing the distribution of archaeological horizons (After Dizon et al., 2002; Choa, 2018)

Significance of Song Terus Cave (Central Java, Indonesia)

Song Terus cave, located on the southern coast of central Java near the Indian ocean, has been excavated since 1994 and presents extensive stratified deposits from the Middle Pleistocene up until the Holocene (Gallet, 2004; Hameau, 2004; Sémah et al., 2004a, 2004b) (Fig. 11). During this long chronological sequence, the last 40 ka, which cover the LGM, are well documented thanks to sediment deposits, palynological analysis, faunal remains and chronometric dates.

From 30 to 40 ka, the climate was mostly dry: sedimentation is marked by aeolian deposits and volcanic ashes, and there are few traces of karstic activity (no speleothems or calcite crystallisation). The environment is open, as indicated by palynological data (*Poaceae, Arecaceae, Moraceae*) and fauna (Bovidae and Cervidae). Human presence is confirmed by the so-called Tabuhan flake industry on chert.

From 30 to 12 ka, the lower part of this chronological sequence clearly presents a humid period, as shown by the karst reactivation (speleothem growth, rock falls). Pollen data indicate a change of environment with rain forest vegetation, confirmed by the presence of related fauna (*Rhinoceros*, *Elephas*, *Macaca* and *Presbitys-Cercipithecus*). There are few—if any—traces of human occupation at this period. The middle part of this sequence shows proxies of a drier environment, mostly limited by traces of aeolian deposits and the absence of karstic influences. There is a hiatus in human occupation at this period.

The upper part of the sequence, just before 12 ka, presents further changes and the return to more humid conditions, with rain forest pollen, forest fauna and karst reactivation as pinpointed by carbonate laminations and speleothem growth. There is, however, still no trace of human activities inside the cave at this time.

Song Terus cave clearly presents a good example of environmental changes during the LGM, at least for an area which varied from insular to continental.

Ambarawa

The Ambarawa basin (Sémah et al., 2004a, 2004b) is located in central Java, in Indonesia, at an altitude of c. 460 m. The lowest part of the depression is occupied by a shallow swamp, the *Rawa Pening*, where floating islands of peat are intensively exploited by local people. Because of the monsoon system, it is a place of alternating dry and rainy seasons.

The Pojoksari G core (41 m deep) is divided into two parts: a detrital basal series (between 4100 and 2600 cm) and an organic upper series (from 2600 cm to the top), and gives a continuous palaeoenvironmental record of pollen and sediments covering the last 20,000 years.

Between 21 and 15 ka, a major climatic oscillation resulted in cooler conditions, increased aridity, and extension of grasslands vulnerable to soil erosion. Lower altitude forest cover was limited to refugial stands including taxa now found at higher altitudes, consistent with a downward shift of vegetation zones.

From 15 until 10.5 ka, increased precipitation during the rainy season led to the development of swamp conditions in the basin. The Rawa Pening was covered by a dense swamp forest, which reached its maximum extension between 9 and 7 ka during an almost 'everwet' period.

Even though this area is not directly linked with archaeological discoveries, it provides a useful model of palaeoclimatic change over the last 20,000 years.

Significance of Tabon Cave (Palawan Island, the Philippines)

Palawan island is part of the Philippines archipelago and remained insular during the LGM: even with the 120 m sea-level drop, it has never been attached to Borneo (the nearest continental mass).

Tabon cave is located in the western part of Palawan, in a limestone formation opening onto the present-day China Sea. This cave is famous for containing the oldest modern human remains in the archipelago (Fox, 1970) (Fig. 12). Although direct dating is limited, isotopic and mineralogical data (Choa, 2018) have recorded climatic and environmental variations from 40 to 33 ka. Before 40 ka, there was a humid environment around the cave with an active karst, guano deposits and neoformation of phosphate minerals. No clear evidence of human occupation is associated with this phase.

Between 40 and 33 ka, human occupation of the cave (Assemblage III) was contemporaneous with a drier environment with little karst activity and limited geochemical alteration. Use-wear patterns on stone artefacts from Assemblage III are consistent with an early use of fibre technology, perhaps in link with rope/basket making (Xhauflair et al., 2023a). This was followed by another humid period characterised by thick guano deposits, speleothem formation, intense geochemical alteration and the neoformation of phosphate minerals, with no evidence of human occupation. Around 33 ka, a fireplace presents evidence for another occupation of the cave in a drier environment.

Discussion

During the LGM, the decrease in sea level had a particular impact on the island context. Coastal morphology and coastal sites underwent strong changes and sites that nowadays are coastal were inland during the LGM. This is the case for Tabon cave as well as Pilanduk cave (Philippines), for example (Ochoa et al., 2022). Palaeoenvironmental data show that the drier conditions during the LGM were followed during the late Pleistocene and the Holocene by a wet environment and the development of a closed forest. For the sites presented here, it is important to note that the LGM corresponds to a partial hiatus of sedimentation and to levels that were seldom, or never, occupied. The same holds for many other sites, such as Bubob I in the Philippines (Boulanger et al., 2019), and Gua Mapkan in Alor Island (Indonesia) (Kealy et al., 2020).

Central Brazil (c. 2 million km^2)

The selected area corresponds to central Brazil in the broad sense, which includes the central plateau and northeast Brazil, bounded to the north by the Amazon basin, to the south by the southern plateau, to the west by the Pantanal depression and to the east by the narrow strip of plain of the Atlantic coast. It represents an area of about 2,000 × 1,000 km, or an approximate area of 2 million km^2 (Fig. 1). The choice of this region is justified by the wealth of archaeological data available for the chronological range of 30–10 ka, which is the focus of this article. Almost all known sites are rock shelters, mainly in sandstone or limestone contexts.

The relief of the region is of moderate altitude (mainly between 200 and 1,000 m). The current climate is sub-humid to semi-arid. The natural vegetation that predominates today is that of a wooded savannah (*cerrado*) and shrub (*caatinga*, in the northeast, more arid) (IBGE, 2010).

The palaeoenvironmental information available for central Brazil comes mainly from palynological studies and speleothem analysis. According to these data, at the end of MIS 3 the region was covered by an overall more open vegetation, such as grassland, and the climate was cooler than the current one. Dry/wet alternations have been identified corresponding to instabilities related to Heinrich and Dansgaard-Hoeschger events (Lee et al., 2009; Mayle et al., 2009; Novello et al., 2017; Wainer et al., 2005).

The earliest settlements of central Brazil took place during this period. Before 15 ka, evidence of human presence is debated. There is a controversy over fully Pleistocene occupations, linked to the predominant model about the peopling of the Americas (for a summary, see Sutter, 2021). Yet, despite the absence of human remains for this period throughout the continent, archaeological data are ever more numerous and more accurate. We therefore integrate them here into our discussion.

For the period 30–10 ka, a total of 27 sites have been documented in the region (Table 1). Among them, four sites (corresponding to five archaeological levels) are dated to the LGM (23–19 ka), 4 sites (4 archaeological levels) to the period immediately preceding the LGM, and 27 sites (29 archaeological levels) to the period immediately following the LGM.

The data older than 15,000 years are distributed irregularly over the territory and are isolated. They come mainly from two points in this vast space: the site of Santa Elina, in the state of Mato Grosso, in the west of the area in question (Vialou et al., 2017) (Fig. 13); and the Serra da Capivara region in the northeastern state of Piauí (Boëda et al., 2013; Parenti, 2001). The latter constitutes a concentration of several sites, including Pedra Furada, Sitio do Meio, Vale da Pedra Furada and Tira-Peia. With the exception of Vale da Pedra Furada, all deposits are shelters, either in sandstone environments (Pedra Furada and Sitio do Meio) or in limestone environments (Tira-Peia and Santa Elina).

Occupations prior to 15 ka can be divided into two successive periods. The first is between the end of MIS 3 and the LGM (about 30 to 20 ka). In Santa Elina, in the centre of the South American continent, the oldest archaeological level, dated around 27 ka cal. BP, has delivered lithic remains flaked on limestone blocks and small chert plates (Fig. 14:A) associated with the bone remains of a giant sloth (*Glossotherium*). The limestone slabs are flaked or marginally retouched. No cut mark has been identified on the bones, but human–fauna interaction is attested by the presence of small osteoderms of *Glossotherium* bearing traces of modification, some having been pierced (Pansani et al., 2023; Vialou & Vilhena Vialou, 2022; Vialou et al.,

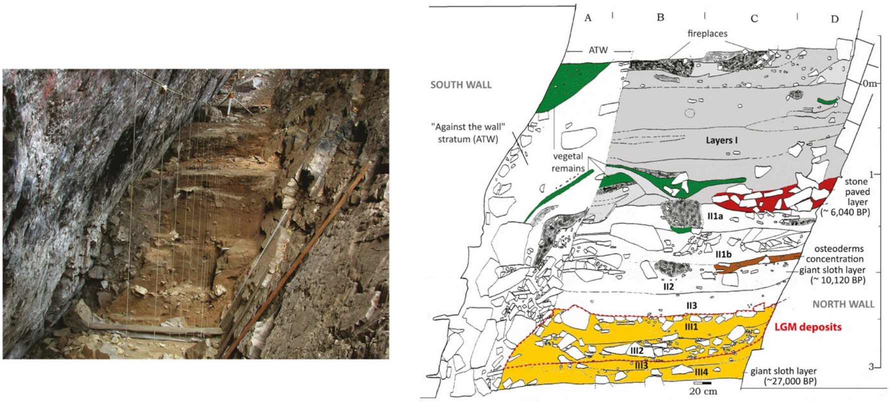

Fig. 13 Santa Elina, Central Brazil. Left: View of the main cross section of the shelter (after Vilhena Vialou, 2005; Right: Drawing of the main cross section (after Vilhena Vialou, 2005)

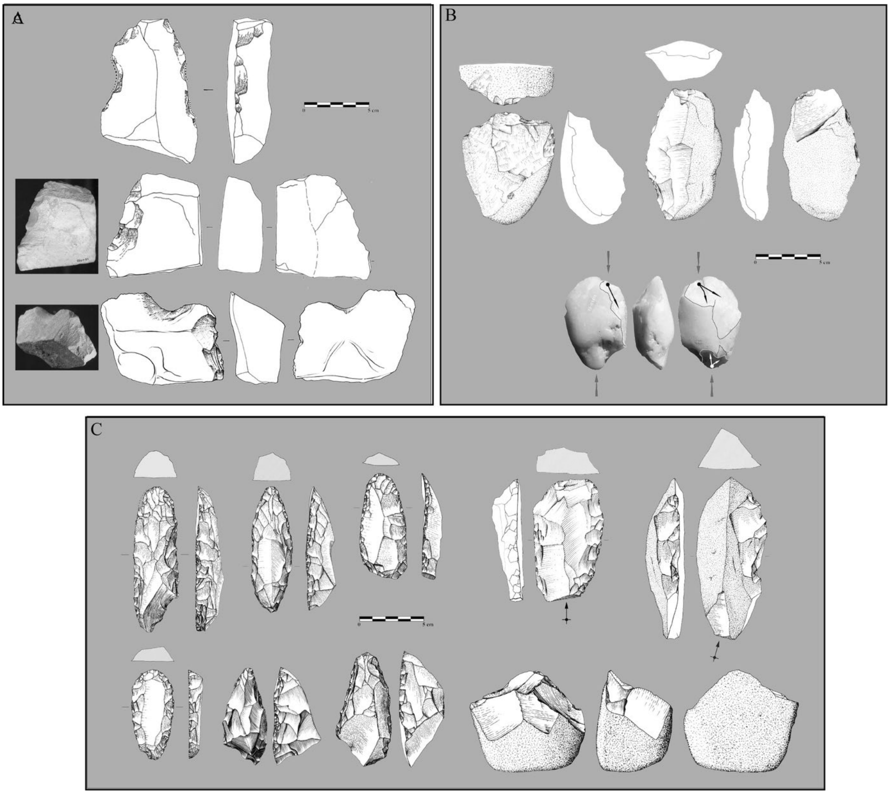

Fig. 14 Central Brazil, selected artefacts. **A** Pre-LGM lithic artefacts (after Vilhena Vialou, 2005); **B** Serra da Capivara. Pre-LGM lithic artefacts (from Pedra Furada) (after Lourdeau, 2014a); **C** Post-LGM lithic artefacts (Itaparica technocomplex) from GO-JA-01 (cobble tool is from Pedra Furada) (after Lourdeau, 2014a, 2014b, 2016)

2017; Vilhena Vialou, 2003, 2005). At the same time, in the Serra da Capivara, there was a lithic industry on quartz and quartzite pebbles (Fig. 14:B). Massive tools with various types of cutting edges were obtained on pebbles or large flakes, while lighter tools were produced on retouched flakes or small pebbles. Concentrations of stones and charcoal suggest the presence of fireplaces at some sites (Boëda et al., 2013, 2014, 2016, 2021; Parenti, 2001).

During the LGM *sensu stricto*, between 20 and 18 ka, an archaeological hiatus is recorded for the region. It corresponds, in terms of climate, to a strengthening of the cold and dry conditions that had started in the previous period. After the LGM, temperatures and precipitation gradually increased, until the beginning of the Holocene. The climate remained cooler but was wetter than the current one, and forest areas developed in central Brazil (Ledru, 2022).

The archaeological data of the terminal Pleistocene, between 18 and 15 ka, do not show profound differences with those of the earlier period. In Santa Elina, a level dated to c. 19 ka, less dense than the previous one, still presents an industry based on limestone blocks. Similarly, in the Serra da Capivara, the almost exclusive use of quartz and quartzite pebbles as tool blanks or for obtaining flakes continued. However, some discrete changes are noticeable, such as a beginning of diversification of raw materials and a more marked development of the production of shaped tools (Lourdeau, 2019).

This continuity of techniques suggests that the observed hiatus between 20 and 18 ka corresponds to a lack of records or discoveries rather than to a total desertion of the area by prehistoric populations during the LGM *sensu stricto*.

Between about 15 and 13 ka, a second archaeological hiatus is observed, followed rapidly by a great multiplication of evidence of human occupations. Before 13 ka, the data remain dispersed and discontinuous from the geographical point of view, confined mainly to the two regions mentioned above. For the period between 13 and 10 ka, however, 24 archaeological sites are listed, with a relatively homogeneous spatial distribution (see Table 1). This rapid increase in the number of archaeological sites seems to be linked to a demographic development corresponding to the first conspicuous settlement of central Brazil (Bueno et al., 2013, 2020).

Associated with this phenomenon, a major technological change took place: in most sites, an industry associated with the Itaparica technocomplex appeared (Bueno & Isnardis, 2017) (Fig. 14C). The latter is characterised by the production of unifacially shaped, elongated and symmetrical pieces, and relatively standardised retouched flake tools. The functional potential of these two categories of tools is complementary (Lourdeau, 2015). Raw materials became more varied. The use of silicified sandstone was widespread, and the presence of chert more marked, but quartz and quartzite continued to be widely used, including in the form of pebbles. While subsistence data available in the literature are still scarce, they point to the widespread hunting of all types of game (extinct megafauna being attested only in Santa Elina), and the exploitation of a wide range of plant resources.

Archaeological, paleoanthropological and genetic evidence is still lacking to determine whether the emergence of the Itaparica technocomplex was the result of a development of local populations present since the Final Pleistocene or rather the consequence of migration. In any case, because of their contemporaneity, it is not unreasonable to propose a correlation between the appearance and development of this new technical system and the demographic increase highlighted by the clear increase in the number of archaeological sites.

Focus on the Stratigraphic Sequence of Santa Elina

Santa Elina is a large limestone shelter located in the state of Mato Grosso, right in the centre of South America (Vialou & Vilhena Vialou, 2022; Vialou et al., 2017; Vilhena Vialou, 2003, 2005) (Fig. 13). The deepest layers (450–350 cm deep) are composed of very sandy sediments of fairly bright colour containing blocks and highly altered carbonate pebbles (Fig. 13).

Layer III 4–3, dated using radiocarbon and OSL dating between 27 ka cal. BP and 25 ka, is distinguished by its archaeological content: bones of megafauna (*Glossotherium*) and retouched fragments and plates. The lower part III4 (between 340 and 310 cm deep) is sandy-silty and formed by rather heterogeneous sediments. Decalcification clays are present throughout the layer. Its upper part III3 (between 310 and 280 cm deep) is generally brown in colour. It contains stones with rather blunt or angular edges. In this layer there is a distinctive level of very rich organic matter probably due to the development of a forest soil in the vicinity. It also presents illuviation phenomena in the form of small concentrations of decalcification clays.

Layer II3, dated around 19 ka, is rich in small nodules of whitish clays from illuviation, attesting to the transfer of particles by internal circulation of water from the upper levels. The layers of this stratigraphic set are very sandy, fairly uniform, relatively thick and have the appearance of sediments deposited *en masse* after a short transport. The human presence, attested by lithic pieces, changed the structure of these deposits slightly.

Layer II2, dated between 15 and 12 ka cal. BP, has a sandy and silty sedimentation. The eastern part of the rock shelter is much richer in limestone blocks and contains a poorly developed calcitic floor, testifying to a rather short, humid and temperate climatic episode. This Layer II2 is distinguished by its richness in osteoderms and bone fragments of *Glossotherium* dated to c. 15 ka cal. BP. This sandy layer, which produced lithic material, has a greyish coloration due to the presence of ash and charcoal. This attests to the presence of humans and megafauna in the same layer.

The upper part of Layer II is formed mainly of ash and charcoal, silt, and coarse carbonate fraction and has a lithic industry on siliceous material. It contains fireplaces dated from 10 to 9 ka. The nature and establishment of this layer are intimately linked to human presence in the site.

In summary, for the archaeological sequence of central Brazil, the period of 30 to 10 ka is fundamental because it corresponds to the very first moments of occupation, very gradually at the beginning, and then with more rapid consolidation of settlement from the Pleistocene–Holocene transition. The impact of the LGM *sensu stricto* on human occupations is seldom mentioned, due to the scarcity of data available before the Pleistocene/Holocene transition. In general, the archaeological evidence is quite similar before and after the LGM in quantitative and qualitative terms. Rather, it is from the Pleistocene–Holocene transition that the most profound change took place.

Discussion

The alignment of 'geological events', with social, cultural or demographic changes is a recurrent debate; an important and frequent question is to what extent this alignment of geological event and human change is really 'global' (Bicho & Cascalheira, 2018; Broecker, 2001; Waters et al., 2022). Concurrently, the palaeoenvironmental and archaeological data for the northern hemisphere are denser than for the tropics and for a long time formed the grounds for the prevalence of a European-centred perception of these major changes, observed concomitantly in Earth Sciences and in archaeological sciences.

The recent epistemological shift in the archaeology of tropical zones, including several major changes in our perception of resilience and adaptation to environments, antiquity of early human dispersal, environmental diversity and tropical ecology, and human–environment relationships, calls into question the relevance of some concepts used in both European and extra-European archaeology such as the global LGM. Even if our starting point was a common definition for the LGM, it becomes apparent that different perceptions of the LGM exist depending on the regions, and that these perceptions are strongly rooted in the history of research in the different tropical areas.

Different Types of Last Glacial Maximum Archaeological Data in the Tropics

In Africa, the question of refugia in particular, intrinsically linked to the LGM (Bennett & Provan, 2008; Stewart & Stringer, 2012), has guided research on human–environment interactions in the late Pleistocene (e.g., see Blinkhorn et al., 2022 for a recent review and reassessment of the concept of refugia in late Pleistocene Africa). However, our review of three African regions located in the tropics (West and Central Africa, and the Horn of Africa) shows that past interpretations related to the impact of the LGM in tropical Africa have often suffered from a lack of nuance, reflecting the lack of data, whereas recent research in these regions tends towards the building of new narratives. For example, the apparent gap in human occupation during the LGM in Ounjoungou (Mali) is not present in the Falémé valley (Senegal) for which detailed evidence of continuity in human occupations is recorded with a marked cultural diversity from 30 to 10 ka. Additionally, it is still difficult to assess the degree of local variability in the palaeoenvironmental record or its impact on the habitability of different zones because data of the required resolution remains scarce. Similarly, the gaps documented at several rock shelters in the Horn of Africa could suggest an absence of human occupation during the LGM, but newly excavated and re-dated sites are starting to fill out this gap in other areas of the Horn (such as at the Sodicho rock shelter) (Hensel et al., 2021). By contrast, Central Africa, which perhaps more than other African regions has been pointed out as a region where continuity of human occupation was possible even during arid periods, does show evidence of specific demographic changes at the end of the Pleistocene, compared to earlier periods. Careful evaluation of the palaeoenvironmental settings of these occupations shows no association of human occupation with a specific type of environment, and the increase in the number of known sites is not coeval with environmental changes.

What is apparent from our review is that the period between 30 and 10 ka shows increasing evidence of cultural diversification in the archaeological record, and although this variability may echo the diversity of ecological settings present in these regions, this does not appear to be directly linked to environmental changes, at local or regional scales (see Table 2).

In Southeast Asia, a direct impact of the LGM is the lowering of the sea levels, leading to a vast submerged area, the Sundaland. As a consequence, it is possible that a large part of the LGM archaeological record of this region is now under water. The LGM is also broadly associated there with more arid conditions leading to the cessation of karstic activity. Several sites show evidence of occupation of cave environments in mild humid conditions preceding the period between 30 to 10 ka, but show no evidence of human occupation during the driest and most humid moments, which seem to correlate with rockfalls and intense karstic activity. Given that most archaeological sites documented in Southeast Asia are caves or rock shelters, and that very few archaeological occupations of Southeast Asia are dated to the LGM (23–19 ka), this raises important questions related to whether the region was sparsely occupied during the LGM or whether settlement strategies were very different compared to earlier or later ones, perhaps related to environmental conditions. Among the few cave sites occupied during the LGM are sites that would have been relatively far from the coast during the LGM and which show specialised hunting activities (Ochoa et al., 2022), while others are on tectonically uplifted coastlines with steep offshore drop-offs and show intensive exploitation of marine resources (O'Connor & Aplin, 2007).

In central Brazil, and more broadly, in Southern America, the slow and not yet fully agreed paradigm change regarding the chronology of the earliest human occupations in the Americas has led to a discussion of the archaeological record prior to 15 ka mostly in terms of presence or absence of human occupation. As a result, human–environment interaction is a topic that remains little explored for these earlier periods.

The general overviews of the six main tropical regions considered here (West Africa, Central Africa, Horn of Africa, Mainland and Island Southeast Asia, central Brazil) around the LGM highlight the high heterogeneity of the data available. The coverage of archaeological research in these regions remains overall low and unequal, constrained by difficulties of access (e.g., in the rainforest, or underwater), specific site formation processes, or epistemological barriers (resistance to the idea of sites dating to the LGM).

A Changing Environment at the Last Glacial Maximum in the Tropics?

Archaeological sites from the six regions considered here are located in a wide array of environmental settings (in five of the 14 modern ecoregional biomes defined in Olson et al., [2001, p. 20]), and consist of both open-air sites and caves or shelters (see Table 2).

Because of the diversity of their environmental settings, archaeological and palaeoenvironmental sites from the six tropical regions do show evidence for environmental change across the global LGM but the evidence varies between sites, within and between regions. All regions evidence a generally cooler and drier climate around the LGM (although more often than not it does not correspond to the local peak of aridity), but with significant local variations depending on the location of the sites, which determines which aspects of environmental changes will have the greatest impact. For example, sites along the coast would have been more impacted by sea-level changes, sites in the mountains by changes of temperature – which would have affected the local vegetation, sites in forested areas by changes in the types of forests, while at sites in savannah settings changes in precipitation would have been critical for the survival of certain species (both plant and animal, including human). Human responses to the global LGM in tropical areas are thus expected to vary.

Low Sea Levels and Palaeolandscapes of Continental Shelves in the Tropics at the Last Glacial Maximum

Low sea levels led to changes in the landscape of the coastlines worldwide, including in the tropics (Bailey et al., 2017; Evans et al., 2014; Flemming et al., 2017). However, these changes vary locally and regionally, with the interplay of the rate of the sea-level change and local or regional topography of coastlines leading to different consequences in terms of the extent of emerged lands, or the velocity of the sea regression/transgression (Chiocci et al., 2017). During the LGM, at least 20 million km^2 of additional land—now submerged—were available at the global scale. In northern North America, northern Eurasia or Southeast Asia, this corresponded to up to a 40–100% increase of emerged land (Bailey et al., 2017a; Harff et al., 2016; Sturt et al., 2018). These newly emerged areas may have been particularly attractive to hunter-gatherer groups, representing ecologically and topographically diverse areas (Bailey et al., 2017a; Harff et al., 2016), which may have played an important role in the mobility and dispersals of populations (Bailey et al., 2017b). Faure et al. (2002) propose a model according to which emerged continental shelves likely contained abundant resources, including coastal freshwater springs resulting from increased groundwater flow to the sea due to the lowering of the sea level. Newly emerged coastal plains could therefore have been favourable environments during the LGM, particularly in tropical and subtropical arid lands in Africa, where coastal areas would have formed refugia ('coastal oases') compared with the drier hinterlands (Faure et al., 2002).

However, the archaeology of now-submerged coastal plains remains largely understudied in the tropics and, as a result, not a single archaeological site dated to the LGM is known from these settings in the tropics (Flemming, 2017). This may, however, reflect the state of the research, more than an archaeological reality. In South America, one submerged LGM site was excavated on the Pacific Coast of Chile (López et al., 2016), and the low-sloping eastern continental shelf in Brazil presents a high potential for the preservation of archaeological sites (Sturt et al., 2018). However, while the continental shelf is around 100 and up to 200 km wide in southeastern Brazil, it is only between a few and a dozen km wide in the northeastern part of the country (Sturt et al., 2018). No Pleistocene archaeological site is known from the coast of Brazil (on the coast or submerged). The earliest known human occupations in the area are shell middens (*Sambaquis*), all dated to after 10 ka, with

Table 2 Synthetic table showing main characteristics of archaeological and palaeoenvironmental data for the period between 30 and 10 ka for each tropical region considered in this paper

Region	Area of the region considered in this study	Main site type	No. of archaeological layers dated to between 30 and 10 ka	Modern biomes of archaeological sites 30–10 ka	Global LGM (23–19 ka) impact	Evidence for change in patterns of human occupation before/during/after the global LGM (23–19 ka)	Evidence for cultural change before/during/after the global LGM (23–19 ka)
West Africa	> 6 million km^2	Open Air; few caves/ rock shelters	15	Tropical & Subtropical Grasslands, Savannahs & Shrublands and Tropical & Subtropical Moist Broadleaf Forests	Intense aridity between 21 and 18 ka, wetter periods before and after, dry conditions between 20 and 15 ka	Low number of sites overall; lower number of sites during the LGM compared to before, and especially after the LGM	MSA assemblages throughout the period; unelaborate industries emerge during the LGM; segments and microlithic lamellar industries only after the LGM
Central Africa	> 6 million km^2	Both Open Air and caves/ rock shelters	13	Tropical & Subtropical Moist Broadleaf Forests, Tropical & Subtropical Grasslands, Savannahs & Shrublands, Mangroves	Forest cover fragmentation during the period 30–10 ka, but not synchronous in the whole region. Very diversified environments ranging from herbaceous savannahs to rainforests ('mosaic landscape')	Low number of sites overall; higher number of sites during the LGM compared to immediately before. In general, gradual increase in the number of sites over the period 30–10 ka	Development of LSA industries and microlithism and technical diversification occur slightly before the LGM and are still present after the LGM
Horn of Africa	c. 2 million km^2	Caves/ rock shelters; few open air sites	17	Montane Grasslands & Shrublands, Tropical & Subtropical Grasslands, Savannahs & Shrublands, Deserts & Xeric Shrublands	Lacustrine records show increased aridity around the global LGM with a peak of aridity afterwards, with up to 1000 m lowering of the Afro-alpine vegetation in mountain areas	Low number of sites overall; lower number of sites during the LGM, but low number before the LGM as well	Most of the rare assemblages dated to the period 30–10 ka are still unpublished; data point towards a gradual transition from the MSA to the LSA starting before the LGM, with the development of fully-fledged bladelet industries during the LGM

Table 2 (continued)

Region	Area of the region considered in this study	Main site type	No. of archaeological layers dated to between 30 and 10 ka	Modern biomes of archaeological sites 30–10 ka	Global LGM (23–19 ka) impact	Evidence for change in patterns of human occupation before/during/after the global LGM (23–19 ka)	Evidence for cultural change before/during/after the global LGM (23–19 ka)
Mainland Southeast Asia	c. 2 million km^2	Caves/rockshelters; rare open air sites	55	Tropical Clearance Forest	Northern part of the region shows a relatively stable environment and vegetation types changing from tropical to more temperate forests; southern part more affected by changing climate and lower sea levels	Low number of sites during the LGM, but also true for the period before the LGM. Significant increase in the number of sites after the LGM	Hoabinhian technocomplex throughout the period
Island Southeast Asia	c. 2.8 million km^2	Cave/rockshelters	32	Tropical & Subtropical Moist Broadleaf Forests	Lower sea levels; regression of rainforest, expansion of savannahs	Low number of sites during the LGM, but also true for the period before the LGM. Increase in the number of sites after the LGM	Flakes and blades technocomplex during the period. Technical change with the appearance of flint arrow head and microlith point only during the mid-Holocene
Central Brazil	c. 1.8 million km^2	Cave/rockshelters; few open air sites	38	Tropical & Subtropical Grasslands, Savannahs, Shrublands & Dry Broadleaf Forests	Generally colder and drier, but with large local variations	Low number of sites during the LGM, but also true for the period before the LGM. Significant increase in the number of sites after the LGM, especially after 13 ka	Lithic industries relatively stable throughout the period (tools on pebbles and blocks, simple debitage of small flakes, made from quartz, quartzite and limestone. Significant change after 13 ka with the Itaparica technocomplex

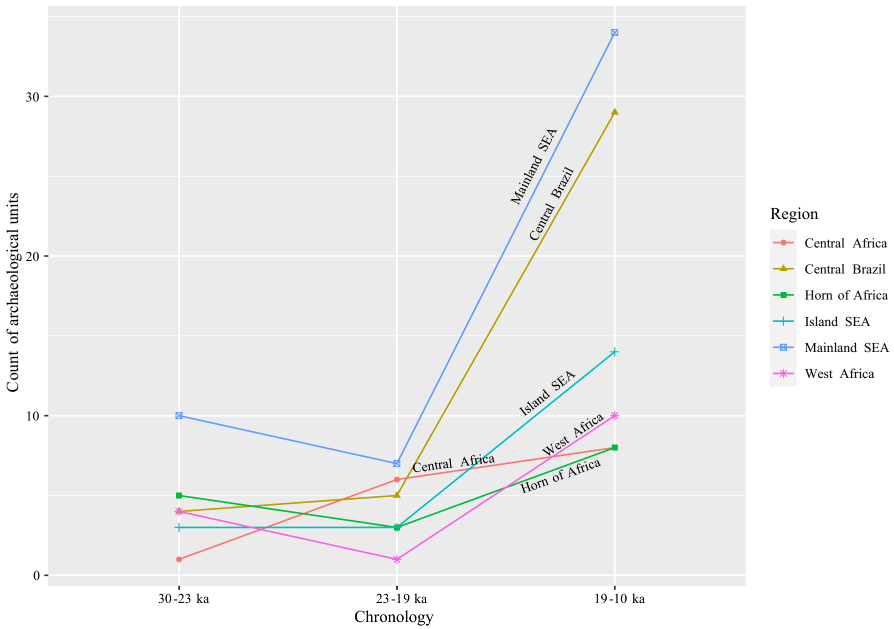

Fig. 15 Graph showing changes in numbers of archaeological units dated to before, during and after the global LGM for each tropical region considered in the study. Created using RStudio 2025.05.0, R 4.2.1 and the ggplot2 package; based on data from Table 1

a major development phase around the 4th millenium BP (DeBlasis et al., 2021). In West Africa, there is evidence for the presence of refugia for terrestrial vegetation on the coast of Senegal (Faure et al., 2002; Lézine, 1987), which may indicate the potential of future research in this area focusing on late Pleistocene archaeology. In Central Africa, research points toward large exposure of the Congo river fan during the LGM, suggesting that many sites could now be underwater (e.g. at Pointe-Noire, lithic material have been found underwater by Giresse: Giresse & Kouyoumontzakis, 1971).

Besides the potential of submerged continental shelves, it is worth noting that several LGM archaeological sites are known on tectonically uplifted coastlines, such as in Timor, in Southeast Asia (O'Connor & Aplin, 2007), suggesting that late Pleistocene uplifted beaches may also have the potential for LGM archaeological site preservation. Wherever uplifted beaches have been characterised and dated in Central and Eastern Africa for instance (Abuodha, 2004; Brook et al., 1996; Walker et al., 2016), however, no archaeological sites have been reported between 30 and 10 ka, but this may represent a promising field of investigation.

Site Distribution over the Period 30–10 ka

Few sites are documented for the period 30–10 ka, and this is particularly true of the period corresponding to the global LGM (23–19 ka) (See Tables 1, 2 and Fig. 15). Many of the archaeological layers dated to the period 30–10 ka are in fact dated to the post-LGM phase (terminal Pleistocene). This raises the question of the representativity of the archaeological data available for these regions during the LGM and invites caution towards interpretations of the data in terms of demographic trends and responses to environmental changes around the LGM, given that even fewer sites combine evidence of human occupation during the LGM with palaeoenvironmental data (see Table 2).

Based on the available data, for most regions, the number of layers dated to the global LGM, however, consistently appears to be lower than for preceding and especially succeeding periods, with the notable exceptions of Central Africa and central Brazil. When the period from 30 to 10 ka is considered, the number of dated sites remains low for all regions. This is less the case for the tropical regions of central Brazil, and Insular and Mainland Southeast Asia, but this is due to the steep increase in sites dated to the beginning of the Holocene in these regions. In central Brazil, this increase in sites occurs after a chronological gap between 15 and 13 ka where no human occupation is documented. In Island and Mainland Southeast Asia, the situation is less clear but many dated layers have low chronological resolution. In any case, the contrast between the number of sites during and after the LGM suggests that the low number of sites observed during the LGM in these regions may reflect lower population densities. The picture is more ambiguous for African tropical regions. It is unclear whether the low number of sites throughout the period is due to a lack of research, taphonomic processes or true low densities of the archaeological record. For example, in Central and West Africa, sites tend to be more and more numerous over time, which may be linked to issues of preservation of the archaeological record.

Cultural Changes over the Period 30–10 ka

Regarding cultural changes over the period 30–10 ka, the currently available data do not make it possible to suggest a correlation between cultural changes and the LGM. In Central Africa and Mainland Southeast Asia, three broad techno-complexes (microlithic quartz industries, Tshitolian, and Hoabinhian) appear to emerge before the LGM and show little change throughout the period, despite evidence of environmental changes in these regions. In West Africa, there is some evidence of continuity throughout the period 30–10 ka (with the persistence of Middle Stone Age characteristics until the Holocene), as well as evidence of an increase in lithic variability (such as in the Falémé valley). In the Horn of Africa as in Insular Southeast Asia, available data for LGM human occupation are particularly sparse. Archaeological sequences at single sites suggest discontinuities in human occupation on a local and perhaps regional scale, while a few other sites suggest the presence of a relatively rich archaeological record, at times in relation to specific environmental settings and some forms of specialization (deer hunting in Palawan, Philippines; small mammal exploitation in Somalia). It is in the Horn of Africa that technological change in relation to environmental changes around the LGM appears to receive the most support, with the transition to microlithic Later Stone Age industries seemingly taking place around the beginning of MIS 2. In central Brazil, among the few archaeological layers documented for the period prior to 15 ka, even if none coincide with the LGM *sensu stricto*, several layers are dated to immediately before or after the LGM, and the absence of abrupt changes in the lithic technology suggests cultural continuity of human occupation throughout the period 30–15 ka. An abrupt change in lithic technology is documented after a short gap between 15 and 13 ka with the emergence of a radically different lithic industry, perhaps connected with the arrival of new human groups in the area.

Overall, the Pleistocene–Holocene transition appears as a more important milestone in terms of number of sites or technical changes than the LGM. In Mainland and Island Southeast Asia and central Brazil, the number of sites increased massively after 15–13 ka, and was accompanied by a technical change in central Brazil. In West Africa, the beginning of the Holocene saw the emergence of the first societies producing ceramics, while in Central Africa, major technical diversification is also reported from the very Early Holocene along with an increase in the number of sites. In the Horn of Africa, diversification and specialisation in technical characteristics and subsistence strategies are also documented at the Pleistocene/Holocene transition.

Some Conclusions

Based on the available evidence, the LGM does not appear as a turning point in the evolutionary history of our species in the tropics, whether from a cultural or a demographic perspective. This notion of the LGM as a 'turning point' is rooted in the concept of environmental refugia (i.e., locations considered to have kept favourable environmental conditions for a given species across an Interglacial/Glacial cycle). To what extent is it useful to consider the concept of refugia in tropical regions? Our review shows that contrary to early assumptions, tropical regions were as prone to dynamic environmental changes in response to climatic variations as regions located in different latitudes. However, these environmental changes may not have affected the *inhabitability* of these regions for human populations. A recent review of refugia in late Pleistocene Africa showed that broad refugia areas (defined as regions receiving between 127 and 3286 mm total precipitation per annum throughout the late Pleistocene, based on data from climate modelling) covered up to 68% of Africa, and most of these broad refugia areas are located in the tropics (Blinkhorn et al., 2022, fig. 1). The corollary of refugia is that areas around refugia are assumed to have become unsuitable for human occupation, that is, to have turned into extreme environments, *sensu* Gómez (2011). This may have been the case locally in the Horn of Africa for example, but in most of the regions considered here, evidence for human occupation is present—albeit rare—across the period 30–10 ka. Data from other tropical regions not discussed here may provide key information to discuss human response to the LGM in the tropics.

In Western Europe, the LGM has been the focus of recent research, especially its potential correlation with the emergence of the Solutrean technocomplex. Recent palaeoenvironmental and archaeological research in the Iberian Peninsula in particular has contributed to the questioning of some of the paradigms linked to this period (in terms of presence/absence of human occupation as well as local and regional responses to the global LGM). Recent data, while not questioning the broad palaeoanthropological significance of the LGM in Western Europe, has warned against simple models of human responses to environmental changes that derive from assumptions based on absence of evidence (e.g., Cascalheira et al., 2021).

Archaeological data from the tropics are typically sparse, making these areas prone to the pitfalls of interpretations based on absence of evidence. In addition, due to their sparsity, these data are often not suitable for quantitative and model-based assessments of demographic changes and human–environment interactions. We argue here that a qualitative approach to the archaeological record allows careful evaluation of the different biases that affect the data, which in turn permits cautious interpretations on human–environment interactions. This paper highlights that the different tropical regions considered all present specific and local patterns that must be taken into account when considering the impact of the LGM on a global scale.

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