9000 years of human lakeside adaptation in the Ethiopian Afar: fisher-foragers and the first pastoralists in the Lake Abhe basin during the African Humid Period

Lamya Khalidi[1]*, Carlo Mologni[2], Clément Ménard[3], Lucie Coudert[4,5], Marzia Gabriele[1], Gourguen Davtian[1], Jessie Cauliez[4], Joséphine Lesur[5], Laurent Bruxelles[4,6,7], Lorène Chesnaux[4], Blade Engda Redae[8,9], Emily Hainsworth[3], Cécile Doubre[10], Marie Revel[2], Mathieu Schuster[10], Antoine Zazzo[5]

[1]* Université Côte d'Azur, Centre National de la Recherche Scientifique (CNRS), Cultures et Environnements. Préhistoire, Antiquité, Moyen Age (CEPAM) – UMR 7264, 24 av. des Diables Bleus 06300 Nice, France, lamya.khalidi@cepam.cnrs.fr, **corresponding author**. [Gabriele: marzia.gabriele@gmail.com; Davtian: gourguen.davtian@cepam.cnrs.fr]
[2] Université Côte d'Azur, Centre National de la Recherche Scientifique (CNRS), Observatoire de la Côte d'Azur (OCA), IRD, Géoazur, 250 rue Albert Einstein, 06905 Sophia Antipolis, France, [Mologni: Carlo.MOLOGNI@geoazur.unice.fr; Revel: revel@geoazur.unice.fr]
[3] Centre Français des Études Éthiopiennes (CFEE), P.O. Box 5554, Addis-Ababa, Ethiopia, [Ménard: clement.menard@cfee.cnrs.fr; Hainsworth: amy.hainsworth@gmail.com]
[4] Université Toulouse Jean Jaurès, Travaux et Recherches Archéologiques sur les Cultures, les Espaces et les Sociétés (TRACES) - UMR5608, Centre National de la Recherche Scientifique (CNRS), 5 allées Antonio Machado 31058 Toulouse, France, [Coudert: lcoudert@univ-tlse2.fr; Cauliez: jessie.cauliez@univ-tlse2.fr; Bruxelles: laurent.bruxelles@inrap.fr; Chesnaux: chesnauxlorene@yahoo.fr]
[5] Muséum National d'Histoire Naturelle (MNHN), Centre National de la Recherche Scientifique (CNRS), Archéozoologie et Archéobotanique - Sociétés, Pratiques et Environnements (AASPE) - UMR 7209, 55 rue Buffon 75005 Paris, France, [Lesur: jolesur@mnhn.fr; Zazzo: antoine.zazzo@mnhn.fr]
[6] School of Geography, Archaeology and Environmental Studies (GAES), University of the Witwatersrand, Johannesburg, South Africa
[7] Institut national de recherches archéologiques préventives (INRAP), France
[8] Université de Poitiers, Centre National de la Recherche Scientifique (CNRS), Paléontologie, Evolution, Paléoécosystèmes, Paléoprimatologie (PALEVOPRIM) - UMR 7262, 6 rue Michel Brunet 86073, Poitiers, France, bladenengda@gmail.com
[9] Authority for Research and Conservation of Cultural Heritage (ARCCH), National Museum, Yared St, Addis Ababa, Ethiopia
[10] Université de Strasbourg, Centre National de la Recherche Scientifique (CNRS), Institut de Physique du Globe de Strasbourg UMR 7516, Ecole et Observatoire des Sciences de la Terre UMS 830, 67084 Strasbourg, France, [Doubre: cecile.doubre@unistra.fr; Schuster: mschuster@unistra.fr

Abstract:

In this study, new approaches are developed for measuring and understanding the reactivity of East African amplifier lakes and the societies that occupied their margins to African monsoon related hydrological changes. Drawing on seven newly discovered archaeological sites in the Lower Awash valley, corresponding to the northern Abhe Lake basin, we present the first Holocene human occupation sequence in the Ethiopian Afar. We reconstitute fluctuating Abhe Lake levels in association with human settlement strategies through correlation of new archaeological and geomorphological data and 37 new radiocarbon dates. The sites cluster into three periods of human occupation of the lake margins separated by intervals that lack archaeological data. These occupation phases span two major humid-arid transitions of the African Humid Period (AHP) (including the Younger Dryas (YD, ~12.9-11.7 ka), 8.2 ka, and 4.2 ka arid events) during which Abhe Lake levels varied significantly, and the transition from Later Stone Age (LSA) hunter-gatherers to mixed herding-hunter-gatherer economies. Over a 9000 year period we observe continuity and ruptures in subsistence strategies and material culture techno-complexes and correlate these with sedimentary formation processes and changing paleo-shorelines. Our study reveals that flexible multiple resource economies were a human response to strongly fluctuating environments, even with the onset of herding and associated pottery traditions unique to the Abhe Lake basin, sometime between 4.8 and 3.3 ka cal. BP .

Thorough evaluation of littoral morpho-sedimentary data, well-dated human settlements and associated economic strategies suggests that major cultural and socio-economic changes of populations inhabiting Abhe paleolakeshores were distinctive ecological responses to transformations in the local environment and to fluctuating lake levels.

Keywords: *Africa; Holocene; Climate dynamics; Geomorphology, coastal;* Ethiopian Afar; African Humid Period; Paleolandscape evolution; Lake Abhe; Later Stone Age; Herding

1 - Introduction

The East African Rift region is renowned for vast exposed sedimentary formations hosting an exceptional hominin record. As a result it has attracted research programs focused on the recovery of our very ancient past at the expense of more recent prehistoric periods. During the Early to early Late Holocene (11.7-3 ka), global climate changes hosted different transitions from hunter-gathering to food production across the world that changed the course of humanity, and yet this period remains largely uninvestigated in the region. Previous studies have tended to suggest correlations between hydroclimatic change and the spread of agro-pastoralism from a center outward to explain these transitions (Ashley et al. 2011; Kuper & Kropelin 2006), rarely taking their inter- and intra-regional arhythmicity or local paleoecological considerations into account. Poor chrono-cultural, hydroclimatological and paleoecological resolution at the inter-regional scale are major obstacles to advancing our understanding of the complexity of the human trajectory – one that is marked by junctures during the Holocene when hundreds of thousands of years of hunting-gathering were replaced by domestication at different rhythms and in different ways (Lesur et al. 2014). This is certainly the case in the Horn of Africa, a region shaped by a mixture of its tropical latitude and the morpho-tectonic patterns of the East African Rift System into a complex mosaic of steep topography, variable soils, rainfall and vegetation patterns, and the resulting complex hydrography and sedimentation that characterize it. It is within this context that we find extremely varied tempos and types of transition to food production that have likely more to do with local paleoecology than with climate, human migration or cultural influence per se (Chritz et al. 2019).

In Ethiopia more specifically, the few Early to Late Holocene archaeological sites recovered have little in common and are chronologically and spatially dispersed, providing us with insufficient correlations with which to reconstruct a concrete regional Holocene sequence (Fig. 1.a). Interestingly some of the most comprehensive dated human occupation sequences spanning the Holocene can be found on paleomargins of large lake basins in the Main Ethiopian Rift (MER), namely Lakes Ziway-Shala and Abhe (Bon et al. 2013; Brandt 1980; Gutherz et al. 2017; Ménard & Bon 2015; Fig. 1.a). The exceptional sensitivity of water level fluctuations in rift environment lakes such as these to even moderate climate variation was recorded by Street (1980) and Street-Perrott and Harrison (1985) who coined the term *amplifier lakes* to distinguish them from lakes with less variable surface to volume ratios.

It has been hypothesized that these amplifier lakes may have had a principal role in human evolutionary trajectories in the East African Rift System (EARS) due to their amplified response to climatic variation (Maslin et al. 2014). This is explained by the geometry and topography of the EARS and the contrast between high rainfall in catchment zones and high evaporation rates in their associated lowland lake basins. Periods of extreme transgression and regression occurring in these lakes are suggested to have isolated populations and deferred migration along or across this natural corridor, while periods of stable lake levels encouraged dispersal and mixing (Maslin et al. 2014; Trauth et al. 2010). It has also been argued that without analysis of sequence stratigraphy of lacustrine deposits, climate variability can be overstated and its nuances overlooked (Nutz et al. 2017).

We often look to climate proxies to understand changes in human behavior, but are less likely to do the inverse. Moreover, studies rarely attempt to gauge the time lag between hydroclimatic change in catchment areas and its local effects (including tipping points) on watersheds making such hypotheses difficult to test. This study aims to demonstrate that correlation of morpho-sedimentary data, well-dated human settlements and associated economic strategies can function as an effective multi-proxy for understanding these important subtleties in local paleoecological transformations. This approach can lead to more accurate reconstructions of human and environmental responses to the nuances of climate change. The exceptional sensitivity of amplifier lakes can reflect nuances in climate variability and human adaptation to such fluctuating environments can better explain changes in human behavior than large scale climate-driven population diffusion models.

Major Late Quaternary transgressions and regressions of Lake Abhe, an amplifier lake located at the tripartite junction of the Nubian, Arabian and Somali tectonic plates in the Central Afar depression, were reconstituted and interpreted by F. Gasse in the 1970s (1977), mainly through study of diatoms. However, the low resolution of the resulting lake-level model has provided a lacunar framework for understanding the evolution of Abhe lake-level fluctuations (Fig. 1.c). Until archaeological work was conducted in the linked Gobaad basin in the Republic of Djibouti in the 1980s-90s (Gutherz et al. 1996; Joussaume 1995), no human occupation sequences were recovered in the context of this research. While archaeological work in Djibouti is ongoing and has provided a large corpus of mainly Middle Holocene sites (Gutherz et al. 2015, 2017), the Lower Awash River valley and the majority of the Abhe Lake basin can be found in Ethiopia, where archaeological work had been lacking prior to this study. Well-developed sedimentary sequences across this basin present an ideal context for the preservation of stratified Holocene sites that cover the period of economic transition from fishing-hunter-gatherers to the first herders. This makes it an exemplary watershed in which to begin to correlate human occupation sequences with Abhe lake-level fluctuations that occurred from the Early to Late Holocene humid to dry transition (corresponding to the AHP). In this study, new approaches are developed for measuring and understanding the reactivity of amplifier lakes and the societies that occupied their margins to African monsoon related hydrological changes.

Archaeological work conducted since 2014 in the Lower Awash River valley and northern Abhe Lake basin in the Ethiopian Afar (Fig. 1.a, b) has brought to light 9000 years of well-preserved prehistoric human occupation sequences. These have allowed us to construct a local chronology and to begin exploring human, landscape and environmental responses to a fluctuating amplifier lake in one of the most arid parts of the world.

Of 40 sites documented in the area (Fig. 1.b), 34 have major prehistoric components that range in period from the Late Pleistocene to the advent of herding in the Middle Holocene. 37 radiocarbon dates from 7 excavated/sounded sites and associated sedimentary records provide the most robust chronological sequence to date for late prehistoric occupation in Ethiopia, and are the first major evidence for semi-continuous LSA to *Neolithic* occupation in the Ethiopian Afar.

2 – Regional setting

2.1 – Geological and tectonic control of Abhe Lake basin formation

The Abhe Lake Basin is located along the axis of the Tendaho-Gobaad graben (NE-SW), corresponding to a subsided floor of basalts from the stratoid series (4.4-2.5 Ma; Varet 1978, 2018) covered by a thick sedimentary series between numerous faults associated with extensional tectonics (Barberi & Varet 1977; Manighetti et al. 1998, 2001). Plio-Pleistocene basaltic fissure flows and alkaline rhyolitic flows from axial ranges partially cover the stratoid series. This igneous palimpsest represents the base bedrock for the Late Pleistocene to Holocene sedimentary fillings concerning this study. The lacustrine sedimentary sequence accumulation began during the Early Pleistocene (Gasse 1990), while the sedimentary synthem of the Abhe basin developed within a topography similar to that of today starting around 130 ka. The greater part of the sedimentary accumulation seems concentrated in the eastern sector of the Lower Awash plain and rests on the Gamari and Afambo faults which were probably tectonically active until the Middle Holocene (Gasse 1975; Fig. 1.b). The Lower Awash Plain is tectonically tilted toward the eastern graben faults with a 30 m vertical offset over a length of 30 km (Acoccella et al. 2008). This tectonic activity, coupled with volcanic phenomena localized to the north of the rhyolitic Borawli Mountain, probably caused the deviation of the Awash River and the formations of Gamari and Afambo fault pits (Fig. 1.b; Gasse 1975). The final hydrological tracing of the Awash River (and associated residual lakes) is the consequence of Holocene tectonic movements and response to magmatic intrusions below the basin axis (Gasse 1975). A similar phenomenon (6 ka) was also detected almost 80 km away from the Lower Awash valley, at the Asal Lake (Afar, Djibouti), with a 70 m tectonic subsidence of the axial valley (Abdallah et al. 1979; Ruegg & Briole 1990). The genesis and evolution of the Abhe Lake basin system is thus the result of ancient (Early Pliocene) to recent (Holocene) volcano-tectonic activity, which, coupled with climatic control triggered the current morpho-sedimentary and geomorphological patterns.

2.2 - Hydro-climatological control of Abhe Lake basin formation

The increase in magnitude of precession-driven insolation in the Northern Hemisphere between 14.8 and 5.5 ka appears to be at the origin of the northward migration of the rainfall belt associated with the Inter Tropical Convergence Zone (ITCZ) (Collins et al. 2017; deMenocal et al. 2000; Gasse 2000; Kutzbach & Street-Perrott 1985; Mohtadi et al. 2016; Skonieczny et al. 2019). These changes in convergence zone patterns led to enhanced precipitation in the tropics which expanded symmetrically in both hemispheres (Costa et al. 2014; Tierney & deMenocal 2013; Tierney & Pausata 2017). This can be correlated to a northward spread of vegetation cover (Hopcroft et al. 2017), and to the massive extension of African lakes (Gasse 2000; Junginger et al. 2014) such as Lake Abhe. This continental African Late Pleistocene to Holocene pluvial period is known as the 'African Humid Period' (AHP; Shanahan et al. 2015).

Three main lacustrine sedimentary sequences covering the period between 130 and 3 ka and corresponding to the Late Quaternary ITCZ oscillations, were first distinguished in the Lake Abhe basin by Gasse (1977): ~100-70 ka (Abhe I), 60-18 ka (Abhe II - Abhe III), and 10-4 ka (Abhe IV - Abhe V; Fig. 1.c). During the Holocene, Abhe Lake, currently reduced to a small (~350 km^2) and shallow (<30 m depth) waterbody was part of a large freshwater filling which generated the last highstand phases in response to the AHP hydrological regime: Abhe IV (10-8 ka; Fig. 1.c), Abhe V (7.5- 4.5 ka) and Abhe VI and VII (0-2.5 ka). Its maximum water surface extent at the height of the AHP was estimated by Gasse (1975, 1977) to be around 6000 km^2.

The Central Afar region receives allochthonous freshwater supplies generated by African monsoon precipitation in the Ethiopian Highlands during the rainy season from June to September (200 mm/month; Tsidu 2012). Thus, the African monsoon is responsible for the majority of solid discharge material transported by the Awash River and which constitutes the Late Pleistocene-Holocene sedimentary synthems of the Abhe lake basin. In particular, the Abhe Lake system receives its water catchment from the Awash River (Fig. 1a), which is joined by many affluent rivers as it descends the Ethiopian Highlands, until it meets the Lower Awash Plain (4000 km^2) where it continues without freshwater supply until it reaches its final destination, endorheic Lake Abhe (Fig. 1.b; 230 m a.s.l.).

Our study area coincides with this last and arid part of the Awash River course, characterized by 200 mm/yr precipitation, with an evaporation rate of 3500 mm/yr (Rognon & Gasse 1973; Gasse 1990; Varet 2018). This plain, including Tendaho (400 m a.s.l.), Gamari and Afambo Lakes (339 m a.s.l.) is limited by the Gamari escarpment to the east (1300 m a.s.l.) and Magenta escarpment to the west (400 m a.s.l.; Fig. 1.b).

The dynamics of regression and transgression of the Abhe Holocene lakes played a substantial role in paleolandscape evolution, on soil development and on paleo-ecological patterns of the basin surroundings, likely influencing peopling dynamics. In the 1970s, geomorphological research in the Central Afar region was focused on deep (offshore or distal) lacustrine deposits (Faure et al. 1976; Gasse 1975, 1977; Rognon & Gasse 1973) with an almost absent regard for a wide range of peri-lacustrine depositional environments and processes (e.g. gilbert-deltas, pedological horizons, gravity-induced deposits and fluvial or fluvio-lacustrine deposits).

Since 2014, our current work on Late Quaternary sedimentary systems of the Abhe Lake paleobasin is focused on pedo-stratigraphical and geochronological investigation of new archaeological sequences linked to past transgression-regression lake dynamics. This approach aims to correlate sedimentary formation processes of human occupation layers with paleolandscape evolution to arrive at a more holistic understanding of the relationship between climate-change forcing and Holocene human settlement strategies in the Lake Abhe basin.

2.3 – Prior research on Holocene human occupation in the Abhe Lake basin

Since the 1980s archaeological investigations in the Gobaad basin in Djibouti (Joussaume 1995) have provided evidence of several late LSA sites characterized mainly by graves with human and wild faunal remains, and several sites with cattle and caprine domestication in association with developed impressed pottery and complex built funerary traditions dated today to as early as 4.8 ka BP (Cauliez et al. in press; Lesur et al. 2014). Several Middle-Late Holocene periods are represented and characterized by chronologically distinct impressed pottery traditions, and more generally, grinding and pounding equipment, cobble-lined hearths and a lithic tradition of obsidian backed geometrics associated with *pièces esquillées* tools made almost exclusively from obsidian (see Gutherz (ed.) 2017; Gutherz et al. 2015). The eastern Abhe lakeshore has provided the earliest confirmed dates for the onset of herding in the Horn of Africa region, contemporary with those at the Lothagam North Pillar Site in the region of Lake Turkana (Cauliez et al. in press; Hildebrand et al. 2018; see Asa Koma & Lothagam Fig. 1.a).

Aside from geomorphological and geological studies carried out in the 1970s (Gasse 1977; Varet 2018; Varet & Gasse 1978), the northern Abhe Lake basin lacked archaeological investigation prior to our work save for a briefly mentioned locality found in the Logiya region in the 1970s (Faure et al. 1976). Since 2014, the VAPOR-Afar program has investigated the remaining paleoshorelines of Abhe Lake in the Ethiopian Afar and confirmed the presence of an equally large number of prehistoric occupations. Some of these sites present nuanced regional and chronological variation in relation to the eastern shores of the same lake basin in Djibouti and permit a more holistic understanding of the entire basin's formation, evolution and its occupation by humans. While Abhe Lake highstands were recorded in the 1970s, relationships between human occupations and lake fluctuations had never been investigated in this region prior to our work. This makes Abhe Lake an exceptional case-study that allows us to evaluate human adaptation to changing lacustrine landscapes and environments over 9000 years.

The Abhe Lake basin represents an important region for our understanding of the northeast African late prehistoric record, and our current work provides a register of new dated sites that contribute to filling gaps in the local and regional chrono-cultural sequence within the context of hydroclimatic and paleoshoreline fluctuations.

4 – Methodology and materials

4.1 – Survey, excavation and sampling strategies

Since 2014, a combination of remote sensing, geomorphological and archaeological survey was carried out from the lowlands to the fault margin slopes over the totality of the Lake Abhe basin, with a particular regard for littoral morphologies and sedimentary complexes. The building of a revised lake-level curve permitted us to localize the paleo-shorelines of the Holocene Abhe Lake during fieldwork, and facilitated identification of peri-lacustrine deposits associated with archaeological occupation layers.

18 test pits ranging from 1 to 1.3 m^2 area were excavated during fieldwork. The richest archaeological levels were investigated over more extensive surfaces dimensionally adapted to each site following a 1 m grid system. Fine excavation methods were used and all sediment was sieved using a 2 mm mesh. Levels with archaeological materials were sieved in their totality. All archaeological artifacts >2 cm were geolocalized and assigned a unique number. Field pedo-sedimentary sequence description and systematic bulk sampling were carried out in each Sedimentary Unit (SU), while selective sampling in controlled undisturbed contexts was employed for dating material.

4.2 – Cartography and GIS analysis

The project Geographical Information System was constructed using the Esri ArcGIS10.7.1® and the Clark University TerrSet® programs. All sample locations and maps presented here are expressed in a geographic coordinate system (WGS84).

Using an altimetry survey, a high-resolution (1 m) Digital Terrain Model (DTM) was created for our study region which enabled us to carry out different mapping operations and to create precise 3D (X, Y, Z) geographic information using a Trimble® Differential Geographic Positioning System (DGPS) Geo7XT. With a differential correction, artifact coordinates were mapped with a precision of 1-2 cm. The use of a DGPS not only allowed us to record archaeological data but also to georectify the cartographic database created for the project.

Regional and micro-regional cartographic modelling (eg. lake-level modelling) was carried out using a 12 m resolution DTM (Tandemx) and LandSAT® (28.5 m resolution, https://landsat.usgs.gov) satellite images.

4.3 - ^{14}C dating and calibration

The age model of the archaeological sequences is based on 35 Accelerator Mass Spectrometry (AMS) ^{14}C measures obtained on charcoal, bone bioapatite, stromatolites and aquatic/terrestrial mollusk shells (Table 1, 2). Where organic or biogenic carbonate macroremains were absent, ^{14}C dating was performed on sediment bulk organic carbon (OC > 1%).

Dating on bone bioapatite was performed on two faunal remains from the site of Det Bahari-01 (Betba-1291, Betba-11, Table 2). Bioapatite gives minimum ages due to the possible exchange with dissolved carbonates (Zazzo 2014; Zazzo & Saliège 2011). The age shift is usually quite low for samples younger than 5000 BP, especially in arid environments like those found in the Afar.

The ^{14}C reservoir effect on lacustrine carbonates can be extremely variable in continental contexts depending on the periods and water bodies, notably with regards to the water-depth and the content of dissolved ancient calcium carbonates in the water (eg. Bronk Ramsey 2008; Cohen 2003; Geyh et al. 2005). The reservoir effect in the Awash-Abhe hydrological system has not been estimated to date. However, two new dates on charcoal and shell samples recovered from the same sedimentary unit (Logiya_1A, Logiya_1B, Table 1) indicate a ~100 year reservoir effect. To our knowledge, these are the only dated samples today that allow us to discuss the existence of a reservoir effect in this hydrological system. Although these samples are isolated, they enable us to suppose that the reservoir effect is very low if not non-existent in this area. It is therefore on the basis of this assumption that we do not apply a reservoir correction value on lacustrine carbonate ages and that the data below are presented.

New and previous ranges and Median ages were calibrated with the Oxcal 4.3 program (Bronk Ramsey 2001) and IntCal13 curve (Reimer et al. 2013). The ages were considered here using 95.4% ranges and are reported in cal. BP or cal. ka BP (calibrated year or kilo annum before 1950). Holocene subdivisions used follow those formally ratified by the International Union of Geological Sciences (Walker et al. 2018).

5 – Results

5.1 – Revised Age Model of Holocene Abhe paleo-lake level phases

The revision of the age model of Holocene Abhe paleo-lake water levels is based on the calibration and the re-calculated elevation of ^{14}C ages on littoral lacustrine carbonates published by Gasse (1975, 1977; A.1), and on new radiocarbon dates on stromatolites (Table 1).

25 previous ages were selected according to the following criteria (A.1): **a)** only ages from littoral lacustrine material from Abhe basin were considered; **b)** using stratigraphic information provided by Gasse (1975), inversed ages or ages from reworked sediments were rejected ; **c)**

ages from shores of residual lakes were not considered (ex: Gamari or Gargori residual lakes); **d)** ages with incomplete geographic localization (partial GPS points) do not allow proper correlation with DEM data and were not used for model building; **e)** ages on anthropic material.

Stromatolites from African lakes are well known markers of littoral and stable lacustrine paleoenvironments (Casanova 1991; Hillaire-Marcel et al. 1986; Lisker et al. 2009). These are an accurate proxy of shallow waters and can complement and confirm lake level models. 14 new ^{14}C ages on stromatolites sampled and mapped during fieldwork were compared with previous revised data with the aim of confirming and refining the paleo-lake level model (for subsequent new age references, refer to Table 1, Fig. 2).

The first Early Holocene lake highstand is localized at 359 m a.s.l. in the north of the basin. A stromatolite newly dated to 11210-10805 cal. BP (Strom_20-SU5) allows us to push back the onset of this lake transgression (Abhe-IV phase) to ~1000 years earlier than the data presented in Gasse's (1977) original lake-level model (Fig. 1.c, 2). After a slight drop in level (342 m a.s.l.; 11086-10253 cal. BP; Gasse_96, A.1), the lake level rose again between 10660-10404 and 10565-10295 cal. BP (Strom_20-SU4, Strom_20-SU1). This phase of lacustrine highstand was maintained until 10.2-9.8 ka cal. BP (Logiya_1A; Gasse_94, 90, A.1) with a maximal elevation of ~420 m a.s.l. and a surface extension of ~6000 km^2. From 9.8 ka cal. BP Abhe Lake levels appear to have dropped ~50 m (~370 m a.s.l.), persisting at this level until 8.4 ka cal. BP (Gasse_85, 82, 80, 76, 64, 63, 62, A.1; Strom_10b, 31). This result permits us to add a second lake highstand of phase Abhe-IV, with respect to Gasse's original (1977) model (Fig. 2.b). At 8 ka cal. BP a rapid decrease of the water table is recorded with a lowstand level of 238-236 m a.s.l. (Gasse_57, A.1). The resurgence of rising lake levels is recorded at 7498-6448 cal. BP (Gasse_35, A.1; 327 m a.s.l.) followed by lake level stabilization (~360-370 m a.s.l.) which marks the onset of phase Abhe-V (Fig. 2.b). Between ~8 and ~7 ka cal. BP water-level modelling was not possible due to an absence of data from lacustrine carbonates. However, an *in situ* archaeological site located at 378.4 m a.s.l. and dated to 7564-7424 cal. BP indicates that during this period the lake could not have attained this elevation (sample SP-01_US2_001, Table 2). The last high waters of the Middle Holocene lake are dated on a stromatolite to 5712-5591 cal. BP (Stromatolis-SU1), which is followed by a slight regression event until 4874-4297 cal. BP (Gasse_16, A.1). Low lake-levels probably occur between ~4.5 and ~3 ka cal. BP, however the lack of data does not allow lake level modelling during this period. During the Late Holocene, from 3172-2490 cal. BP (Gasse_13, A.1) a new rise in lake levels corresponds to phase Abhe-VI which continued until ~1.4 ka cal. BP.

5.2 - The Abhe basin archaeological sequences: material culture, radiocarbon dating and pedo-sedimentary description

Of the 40 archaeological sites identified in our research area (Fig. 1.b), the archaeological sequences presented here are derived from 16 test pits conducted on nine sites. Six of these are stratified and were radiocarbon dated on in situ materials in undisturbed contexts. With the addition of the Det Bahari-01 surface site, seven dated archaeological sites are presented in chronological order, from the oldest to the youngest with a brief pedo-stratigraphic description and diagnostic material culture presentation.

5.2.1 - Lakora-03

Sounding 1 (S1) measuring 1.5x2 m^2 was excavated at the site of Lakora-03 (Fig. 3.c) located on the slopes of a stratoid series basalt ridge NW of the rhyolitic Borawli volcano (Fig. 1.b).

Over the basaltic bedrock, a saprolitic layer developed (SU7) presenting a whitish-brown silty-clayey matrix packing a large amount of weathered basaltic gravels mixed with reworked calcareous crusts. The following layer (SU6) shows the development of a granular structure of dark-brown well sorted silts containing few terrestrial shells and rare obsidian artifacts. SU5 and 4 represent two sedimentary phases of the main human occupation level characterized by a very dark-brown, well to moderately sorted silt with a loose granular structure, containing a small hearth, charcoal, and a large amount of fish remains and obsidian artifacts (Fig. 3.b, d). SU5 represents the base of a stone line composed of decametric sub-angular basaltic blocks which are capped at the top by a stromatolitic crust (SU3). Several worked lithics in SU5 were also capped by the stromatolitic crust SU3. Charcoal recovered in SU5 was radiocarbon dated to 11164-10737 cal. BP; Table 2).

Archaeological materials from SU5 and 4 included abundant faunal remains, namely fish (Table 3), worked obsidian, charcoal, and a single round flat ostrich eggshell bead recovered from the hearth.

The excavation of S1 provided a relatively rich sample of lithic material (n=132) with one refit (Fig. 4). The lithic materials from the sounding were compared with surface collections of materials localized quasi-exclusively within a 40x15 m^2 area along the eastern edge and downslope of the basalt outcrop. Surface collections included both systematic collection of all artifacts in a 1 m^2 area where there was the highest density of materials and a random collection of cores and shaped tools from the entire surface area (Fig. 4.a-c). Lithic materials from the sounding were comparable to surface collections from a technological and typological point of view and are generally very altered, both mechanically and chemically (Fig. 4.d-f). The materials collected at the site indicate dominant production of large bladelets from cores belonging to distinct operative schemes. Very few shaped tools were present in both the surface and excavated collections. These are mostly burins and endscrapers (Fig. 4f). Interestingly, not a single backed piece was collected or observed at the site.

The faunal material is dominated by fish, represented mainly by catfish remains, but also by one tilapia and one Cyprinidae bone. The rest of the fauna includes remains of large mammals, including bovids. Some shell and ostrich eggshell are also present (Table 3).

5.2.2 - Raso-02

A step Sounding 2 (S2) measuring 1.5x2 m^2 was excavated along an exposed section at the site of Raso-02 (Fig 3.a) located at the base of a stratoid basalt ridge on the NW edge of the Manda Gargori volcano-tectonic segment (Fig 1.b).

From bottom to top (Fig. 3.a) the sounding included a saprolitic layer (SU9) that formed over the basaltic bedrock; a dark-brown muddy sediment rich in secondary carbonate nodules (SU8); a silty-clayey horizon (SU7 and 6) with a polyhedral structure where secondary carbonates are reduced and replace the intrapedal porosity as infillings. A channel-morphology erosional surface marks the end of the lower pedogenic complex. The channel bottom is characterized by few sub-angular and rounded basaltic blocks packed in the gravely-clayey SU5d and gravely-sandy SU5c which fill the fluvial channel body. SU5b and 5a represent the main archaeological level which is characterized by common fauna, including a large mammal long bone fragment, charcoal and obsidian artifacts, packed in a gravely-sandy matrix (SU5b) and massive medium sand (SU5a). The top of the archaeological level is marked by an erosional surface and by the installation of massive fine-sand/silty texture patterns (SU4b and 4a), with abundant lacustrine shell inclusions (SU3). An oncolite layer (SU2) is packed in a brown muddy matrix rich in lacustrine *in situ* shells, while the SU2/1b interface contains few obsidian lithic artifacts, charcoal and fish remains. This is followed by a pedogenic event with well-developed clay granular structure (SU1b), affected in its upper part (SU1a) by desiccation cracks filled by reworked surface material.

Charcoal from the base of SU5a was dated to 10744-10418 cal. BP (Raso-02-Sond2-SU5, Table 2), while the oncolite layer gives an age range of 5913-5746 cal. BP (Raso-02_Strom, Table 1). In addition, some faunal remains (mammals and fish; n=9) were recovered from SU5a and abundant fish remains (n=1328) from SU2. Materials collected on the surface of the site include noticeably large blades and bladelet cores (which produced relatively large blanks). The extensive surface collection from 1 m^2 area provides similar kinds of materials but shows heavy mechanic alterations, and particularly double-patina breaks and retouch-like damage. Only a very limited archaeological sample was recovered from the sounding (n=36), where materials are also heavily altered. The few illustrative but undiagnostic artifacts are limited to a distal fragment of a retouched bladelet in SU1, and a large blade and two flake cores (including one Levallois) in SU5. SU5 is richer and could correspond to material found on the surface but a larger sample is needed to confirm this and to propose a proper technological or typological description. Besides these limitations regarding sample size, Raso-02 materials do not seem very different from the Lakora-03 ones.

5.2.3 - Det Bahari-01

Det Bahari-01 is an open-air site preserved as a residual artifact-rich surface on a low oval mound located on the eastern edge of the Det Bahari sand plain SW of the town of Dubti (Fig. 6.c). The site dated on hippopotamus remains to 7956-7761 and 7674-7523 cal. BP (Betba-1291, Betba-11, Table 2) overlies a palustrine deposit dated on *in situ* bivalve shells to 10415-10245 and 10230-10170 cal. BP (Betba01log2A, Betba01log2B, Table 2).

The good state of preservation of fauna, lithics and basalt groundstone fragments, and evident refits within the residual archaeological level localized in a ~70x45 m^2 area led us to collect the totality of surface materials (Fig. 5.a). 1438 artifacts were collected including ~550 knapped obsidian (90%) and chalcedony (10%) artifacts, and ~750 other mineral items (mostly igneous rocks). The igneous material can be subdivided in two groups: the largest one is composed of heavily fragmented mafic rocks (mostly vesicular basalt(?)) with no apparent sign of anthropic transformation; the second is represented by several artifacts interpreted as pounding stone fragments (grinding stones?, hammers?) providing functional clues. An important number of refits were made on materials from this group (60 refit groups, of which 12 groups include 3 or more artifacts, and 4 groups between 5 or 6 artifacts, or 103 conjoins) (Fig. 5.a). If some of these refits correspond to natural fragmentation (taphonomic alteration of the most fragile stones, particularly the vesicular basalts), some refits may indicate intra-site artifact circulation (as an indication, distance between conjoined artifacts are greater than 3 m in 26 cases, and greater than 10 m in 6 cases). A second category corresponds to small size pebbles of various materials. Most of them do not feature any sign of use and could have been present in alluvial deposits in the direct vicinity of the site, or perhaps in a dismantled overlying stratigraphic unit. The association between mafic rocks and cobbles remains uncertain but their overlapping distribution at the site and complete absence in the direct vicinity of the site could be an indication of contemporaneous occupation of a single site of limited extent.

Another component of the lithic material was composed of knapped artifacts (obsidian and chalcedony, both similarly treated) (Fig. 7). Systematic attempts to find conjoins between all flake fragments were unfortunately unsuccessful. There was an intense re-use of various products and particularly of cores which were almost systematically fragmented and reduced to very small proportions, often by bipolar percussion. Nevertheless, numerous blades and bladelets (some of them used as blanks for shaped and modified tools) were recovered and are an indirect indication of the importance of these productions (Fig. 7.a-b). It remains unclear what proportion of pieces showing bipolar percussion stigmas are core and intermediary tools (*pièces esquillées*) but some of them are of very reduced dimensions and could not have been cores for the blanks recovered, at least in their last exploitation stages. Relatively few shaped tools (n=45) were recovered at the site, however, most of those that were are curved backed bladelets (n=27, Fig. 7.d-f), associated with few endscrapers (Fig. 7.c), thick truncations, and simple burins (angle burins on break, mostly). In addition to these, numerous blanks show irregular modifications of various extent.

The fauna totaled 98 specimens including hippopotamus and crocodile, middle sized bovids and 33 fish remains. The dominance of aquatic fauna suggests the presence of a lakeside settlement with an economy based on fishing of tilapia and catfish and the hunting of mainly aquatic prey (Table 3).

5.2.4 - Stromatolis

The site of Stromatolis is located between the SE slopes of the late quaternary basalt flows of Kurub volcano (Fig 6.c). The archaeological findings consist of a small dry wall circular structure ~150 cm in diameter constructed from naturally sub-angular basalt blocks (SU2; Fig. 5.c). The blocks were laid on a continuous formation of columnar structure stromatolite domes (SU5) as well as on two thin overlying levels of a clayey silt with terrestrial shell (SU4) and an aeolian fine to medium cross-laminated sand deposited prior to its construction (SU3) (Fig. 5.b). The anthropic structure is capped by a second generation of stromatolitic crust (SU1) presenting laminar structure and ripple marks on their surface. The underlying stromatolite generation (SU5) was dated to 8978-8598 cal. BP, and SU4 to 8593-8419 cal. BP (Stromatolis_SU4, Table 2, Strom_31, Table 1, Fig. 5.b), while the overlying laminar stromatolite generation (SU1) was dated to 5712-5591 cal. BP (Stromatolis_SU1, Table 1, Fig. 5.b). No artifact was found in association with the structure.

5.2.5 - MS-01/02

Two soundings (01 and 02) were conducted at the site MS located in an active sand dune field in the Kurub Bahari plain ~2 km due north of the current Awash River bed (Fig. 6.c). These soundings reveal alternating aeolian layers and pedogenic horizons to a depth of ~200 cm (Fig.

6.b). The MS-01 sequence is composed of 20 SU. From bottom to top, SU1 is composed of clayey-fine silty material with a polyhedral to prismatic structure where several obsidian artifacts were recovered. This first pedogenic horizon is capped by alternating fine-silty and clayey bed layers (SU2) containing a discontinuous horizontally oriented line of Fe-Mg oxide nodules in its uppermost matrix. The archaeological evidence and the similarity of pedological characteristics of SU1 and 2 allow us to propose a stratigraphic correlation with SU3 and 4 of the MS-02 sounding (Fig. 6.b). Along the upper part of the MS-01/02 sequences three types of alternating layers are defined: thin silty-clayey pedological horizons with prismatic to polyhedric structure (MS-01_SU4, 6, 8, 10, 18; MS-02_SU6, 8), silty horizontally laminated layers (MS-01_SU7, 9, 11, 13, 15, 17; MS-02_SU7, 9), and fine to medium sand cross-laminated layers (MS-01_SU3, 5, 12, 14, 16, 19, 20; MS-02_SU2, 5). Discontinuous beds of silicic nodules are commonly present in the silty and sandy layers. Archaeological layer MS-01_SU1/MS-02_SU3 was dated to 8190-8000 cal. BP (MS1_US1_001, Table 2, Fig. 6.b).

5.2.6 - SP-01

Site SP-01 is located at 380 m a.s.l. on the stratoid basalt outcrop on the NW ridges of the rhyolitic Borawli volcano (Fig. 6.a). A 1 m^2 test pit revealed preserved sedimentary deposits trapped within the parallel NNW-SSE oriented fissure flows of the stratoid series formation and topographically localized above the Holocene lacustrine wave-cut terrace and littoral lacustrine sedimentary deposits (Fig. 6.a). From bottom to top, we observed a massive silty-clayey layer with abundant gravel inclusions (SU5), a prismatic structure pedologic horizon containing occasional knapped obsidian artifacts (SU4), and a massive fine-sand ensemble (SU3, 2, 1). A date on bulk organic carbon from the base of SU4 gives an age of 7519-7424 cal. BP (SP-

01_US2_001, Table 2). Obsidian artifacts recovered from the sounding were limited to small undiagnostic chips, however the small and selective surface collection recovered on the adjacent outcrop edge, and probably belonging to the eroded pedologic horizon (SU4) correspond to the production of large bladelets. The only shaped tools collected at the site are curved backed bladelets of relatively large dimensions.

5.2.7 – Kurub-07

The site of Kurub-07 was excavated over a 34 m^2 surface area (Fig. 8.a.3). This open-air site is exposed on the slopes of a large dune complex in the SW of the Kurub Bahari plain and several kilometers north of the current Awash River delta (Fig. 1.b, Fig. 8.b). 43 SU were described during three seasons of fieldwork on the basis of excavation and pedo-stratigraphic observations from site sections. We present here only the SU observed on the K_trench section, which is representative of the stratigraphic and site formation processes and of the main archaeological layers (Fig. 8.a.1).

SU18 represents the continuous sedimentary basement of the sequence characterized by dark-brown prismatic structured clays rich in authigenic gypsum which has been interpreted as a palustrine pedogenised deposit. This layer is dated on bulk organic carbon to 7587-6174 cal. BP (Kur-07-K15-US18-1488, Table 2). A paleodune complex represented by SU41 and 13 composed of cross-laminated and well sorted fine sand follows. At the interface between SU41 and 13 we find a phase of occupation characterized by few lithic artifacts, faunal remains and small charcoal. The following archaeological level SU15 is dated between 3914-3647 and 3830-3587 cal. BP (Kur-07-K14-US15-1203, Kur-07-L16-US15-1283, Table 2). SU15 is a silty-clayey polyhedral structured layer rich in secondary carbonate nodules with abundant flat-lying broken ceramics, semi-articulated faunal remains, charcoal and lithics. SU12, marked by a more structured matrix, by the lack of secondary carbonates and the persistence of anthropic material is dated between 3638-3477 and 3568-3407 cal. BP (Kur-07-US12-591, Kur-07-US12-2459, Table 2). SU9/14 are composed of consolidated or non-consolidated aeolian sand and produced some pottery fragments, wild and domestic fauna, charcoal, lithics and groundstone, namely on or just below the surface, and cap the underlying pedogenic horizons. The most recent anthropic layer is a polymorphous oven structure (ST1, Fig. 8.a.2) cutting into SU12, 42, 43 and 18 in the south end of the site (K-L/10-9; Fig. 8.a.1). The oven, which is the first of its kind for the period and region has been dated on charcoal to between 3600 and 3300 cal. BP (Kur-07-US10-667, Kur-07-US10-1136, Table 2).

Faunal material from the site is dominated by domesticates (sheep, goat and cattle) which are present in SU15, 12, 10, and the surface of 9/14. Wild fauna includes mainly middle to small sized bovids, among which only the Dorcas gazelle could be identified. The rest of the fauna includes rodents, reptiles and fish remains (Siluriform and tilapia), as well as ostrich eggshell (Table 3).

At least two ceramic technological traditions corresponding to two phases of occupation can be distinguished. Few artifacts are affiliated with the first phase (SU15 and contemporary SU16-17, Fig. 8.a.1, 9.a-c). These are characterized by at least two well-differentiated and refitted vessels with incised or impressed decorations, simple forms and medium volumetric capacities. Decoration includes the use of a blunt point and comb impressions on one of the pots (Fig. 9.a), pivoting impressions using a flat spatula on the second (Fig. 9.b), and simple impressions by means of oblique lines in horizontal bands on a third pot (Fig. 9.c).

The second phase corresponds to the use of the oven feature (ST1, SU10, SU12, Fig. 8.a.1, 9.d-k). From a morpho-metrical standpoint, the containers are of average volumetric capacity and of simple contour like in the preceding phase, but sometimes present rectified edges (Fig. 9.d). Just as in the previous phase, decoration includes simple impressions with a comb (Fig. 9.g) or pivoting impressions with a comb or shell (Fig. 9.h, i). However, this phase also presents few roulette impressions (Fig. 9.f). The compositions are always very airy and do not cover the entire surface, but are distinguished from the first phase by use of more diverse motifs combined on the same vessel or the association of two decorative techniques (Fig. 9.e, j). The presence of few sherd fragments with a red slip applied before firing, testify to the application of colorants on certain pottery vessels in these levels (Fig. 9.k).

In addition, the ongoing study of ceramic raw materials allows us to distinguish between two cultural phases. The older one (SU15) is mostly characterized by ceramic pastes with inclusions made of shell tests (e.g. entire gastropods, e.g. *Melanoides*), charcoal and bones. The more recent phase appears to be mostly characterized by inclusions made of rounded volcanic sand and by other distinctive features such as vegetal remains, grog and diatoms.

The lithic material is mainly composed of worked obsidian with an inclination towards flake debitage, though irregular blades and bladelets are also present. The majority of cores studied are flake or *pièces esquillées* cores and were fragmented or reduced to small proportions, often by bipolar percussion on anvil. A number of blanks show irregular modifications of various extent, while very few shaped tools (scrapers, perforators and curved backed pieces) were recovered from excavations. The presence of rounded and rolled neo-cortex on some obsidian lithics attests to a partial selection of small obsidian cobbles by populations. While the study is ongoing, there are similar production tendencies across occupation levels pertaining to potter pastoralist populations (SU15, 12, 10, 9/14), while lithic material from the earlier SU41 was rare and therefore difficult to compare.

6 – Discussion

14 new ages on littoral lacustrine carbonates combined with re-calibrated ages and recalculated elevations taken from Gasse (1975) allow us to estimate fluctuating paleoshoreline levels of Abhe Lake and its relationship with other lakes in Ethiopia over the last 12000 years (Fig. 10). 23 radiocarbon dates from 7 excavated sites and associated sedimentary records (Table 2) provide the most robust chronological sequence to date for late prehistoric occupation in Ethiopia, and are the first major evidence for semi-continuous LSA to potter-pastoralist settlement in the Ethiopian Afar.

Paleo-lake level reconstruction combined with pedo-stratigraphic sounding results allow us to propose a semi-continuous Holocene chronostratigraphy of peri-lacustrine landscapes in relation to changes in human settlement, economy and culture across the Abhe Lake basin (Table 4) and to discuss these results in relation to pertinent patterns observed across northeast Africa.

6.1 – Early Holocene (~11.7 to ~8.2 ka)

6.1.1 – The Paleolandscape context

Our new dates and geomorphological results show a lack of sedimentary deposits concerning the Marine isotope stage (MIS)2 to early MIS1 periods (~29-12 ka) in accordance with the lack of regional lacustrine and continental sedimentation (Beck et al. 2019; Gasse 1977; Gasse & Street 1978; Gillepsie et al. 1983; Lamb et al. 2018; Wagner et al. 2018).

At the beginning of the Holocene (~11.1 and ~10.6 ka cal. BP; Fig. 10.d) the water-level of Abhe Lake was relatively low, oscillating between 340-360 m a.s.l. During this period, dated SU from two sequences indicate the development of a pedogenic event at the edges of the Awash alluvial plain in which the oldest preserved anthropic settlements occur (Lakora-03_SU4-5). Soil development is followed by a fluvial event dated to ~10.5 ka cal. BP (Raso-02_SU5), suggesting the re-activation of the hydrological system leading to the rise of lake-levels at the beginning of the Abhe-IV transgressive phase (Raso-02_SU5). Between ~10.3 and ~9.8 ka cal. BP the lake attained its maximal water-level (~410-420 m a.s.l.) occupying the totality of the Lower Awash plain. This Early Holocene highstand demonstrates the centennial scale reactivity of the Awash hydrological system to monsoon magnitude variations associated with the northward migration of the ITCZ (Fig. 10.d). This period coincides with the highest Holocene precipitation values recorded in the Ethiopian highlands (Bastian et al. 2017; Costa et al. 2014) and with the maximal insolation values (corresponding to precession minima) occurring at this latitude (~11°N; Berger & Loutre 1991; Fig. 10.a, b).

The Early Holocene period comes to an end with a reduced stable lake-level (~370-380 m a.s.l.) until ~8.2 ka (Fig. 10.d), during which contemporary peri-lacustrine sedimentary deposits likely developed. After this period, lake levels did not rise above 380 m a.s.l. probably as a consequence of channel incision that evacuated water towards the Hanle semi-graben. One channel incision, which is a likely candidate but requires ground verification was identified using remote sensing and DEM modelling around Serdo town (Fig. 1.b). The absence of sedimentary and archaeological data corresponding to Early Holocene high lake stands is likely a result of an extreme post-lacustrine erosional rate on high basaltic outcrops and by difficult to access elevated regions during fieldwork (above 400 m a.s.l.).

6.1.2 – Human adaptation to rising lake levels in the Later Stone Age

The rarity of sedimentary deposits during the YD period (12.9- 11.7 ka; Rasmussen et al. 2014) is echoed by the lack of sites recovered for this period. Sites recovered immediately after the YD concern lakeside settlements as the lake was rising and had reached ~ 360 m a.s.l. of the 430 m a.s.l. it would progressively attain one millennium later. The first evidence of Holocene occupation at Lakora-03_SU4-5 and Raso-02_SU5 occurred as climatic conditions became more humid after the YD arid event (Foerster et al. 2012). SU5a at Raso-02 dated to 10744-10418 cal. BP is slightly younger than SU4-5 at the site of Lakora-03. The Raso-02 uppermost layers (SU 1a-1b) may have been redeposited from eroded older levels that can be found preserved under large stromatolite domes slightly uphill of the studied section. This has been observed from study of the top sedimentary units at this site which appear reshuffled, and from a radiocarbon determination on charcoal from the transition between SU1b-2 which provides an inverted age slightly older and closer in age to the Lakora-03 archaeological level, than the distinctly underlying SU5.

The archaeological levels at these two sites present fish and other faunal remains, lithic material exclusively knapped on obsidian and an anthropogenic feature (hearth at Lakora-03). During this period the lakeshore was located several kilometers from Raso-02 and at the foot of the Lakora-03 site. The abundance of fish remains (including burnt) at Lakora-03 confirms that populations were temporarily settled near the lake edge and that fishing constituted a major activity and the source of an important part of their diet. The obsidian lithic assemblage has few shaped tools and is technologically similar on both sites.

The Lakora-03 settlement indicates intensive fishing from a slightly elevated basalt promontory or islet. The faunal assemblage at Raso-02 includes 3 wild mammal remains and one fish remain and is too small to draw any conclusions. However, comparison with Lakora-03 where fish remains are abundant and dominate the assemblage may reflect the slight age difference between these occupations and their respective proximity to the lake edge (Fig. 3.c). Judging by the exponential rise in lake levels over one millennium, it is likely that these populations adapted to significant centennial if not generational-scale landscape modifications, following lake edges as they rose all the while benefitting from the rich and readily available lacustrine resources. Lithic materials from both sites have features reminiscent of slightly older sites (~14-13.5 ka cal. BP) from the Ziway-Shala basin (Ménard et al. 2014), with dominant production of blades and bladelets, few shaped tools and a possible absence of backed pieces. There is unfortunately no synchronous assemblage in the region to make comparisons with but material collected at Lakora-03 and Raso-02 could indicate a late persistence of a Late Glacial (if not older) tradition.

6.2 – Middle Holocene (~8.2 to ~4.2 ka)

6.2.1 – The paleolandscape context

The Middle Holocene onset period is marked around 8.2 ka cal. BP by rapid decrease (centennial scale average) of the Abhe Lake water-level (Fig. 10.d), which was in phase with an abrupt (300 to 100 year) Holocene cold event at 8.2 ka recorded from Greenland ice cores (Thomas et al. 2007) and recently revisited by the General Circulation Model (Matero et al. 2017). A similarly abrupt transition from D-depleted to D-enriched waxes in Lake Tana is dated around 8.5-8 ka cal. BP and is attributed to a reduction of moisture derived from westerly sources (Congo basin, Atlantic ocean; Costa et al. 2014; Marshall et al. 2011; Fig. 10.b). At the scale of tropical Africa, the first manifestation of less humid conditions which began around 8.4 ka cal. BP is documented almost everywhere in Africa (Gasse 2000) and is particularly well documented and dated from large catchment areas such as the Nile and Congo deltaic-fan sediments (Ménot et al. 2020).

This latter paleoclimatic scenario is confirmed by the Stromatolis_SU4 palustrine layer, which covers a stromatolitic formation and indicates a slight lake regression that began around ~8.5 ka cal. BP. This corresponds to an average drop in lake-levels of 4 cm/yr between ~8.5 and ~8.2 ka cal. BP. Lacustrine regression accelerated abruptly between ~8.2 and ~8 ka cal. BP with an average drop in lake-levels of ~70 cm/yr. This is evidenced by a paleosoil that developed at 8190-8000 cal. BP (355 m a.s.l.; MS-01_SU1; Fig. 6.b) in the southern part of the Kurub Bahari plain, while the installation of the ensuing drying environmental patterns is observed in a thick paleodune sequence at MS-01 and by aeolian sands in the Stromatolis site sequence (Fig. 6.b, 5.b).

A resurgence of wet conditions may be suggested namely by two hippopotamus bones directly dated to around ~7.8 and ~7.6 ka cal. BP, and a large aquatic faunal assemblage at the Det Bahari-01 site (370 m a.s.l.). A pedogenic event is observed and dated to 7519-7424 cal. BP (SP-01_SU4; Fig. 6.a) suggesting the reduction of aeolian sediment transport dynamics and the availability of water supplies. These results are in accordance with rainfall and terrigenous input increase recorded at Lake Tana starting ~7.7 ka cal. BP (Costa et al. 2014; Marshall et al. 2011; Fig. 10.b) and from the Nile deep-sea fan archive (Ménot et al. 2020).

Across the Abhe basin, rising lake levels were detected on dated stromatolites at ~7 ka cal. BP (~330 m a.s.l.; Fig. 10.d), reaching a stable level between ~6.6 and ~5.6 ka cal. BP (360-370 m a.s.l.). From ~5.6-4.6 ka cal. BP we observe a decrease in lake levels at a rate of ~1.5 cm/yr.

6.2.2 – Adaptation of Later Stone Age fisher-hunter-gatherers to a fluctuating lacustrine environment

A window into the period leading up to and after the 8.2 ka event is visible at the site of Stromatolis characterized by the first LSA built structure known to date. The sediments that accumulated during the use of the anthropic circular structure were partially deflated by aeolian action after its abandonment and prior to the lake submerging the area. Given this *terminus ante quem* for the structure's use, it is, to our knowledge, the oldest possibly non-funerary anthropic structure in the Horn of Africa, and was likely used during the 8.2 ka arid event.

Human occupation at MS-01/MS-02 corresponds to a period of continued low lake levels following the 8.2 ka event, and suggests that human groups were extremely reactive to rapid lake level oscillations during this period, moving along with the lakeshore.

The site of Det Bahari-01, occupied between 7.9 and 7.5 ka cal. BP falls within a period where lake levels are not documented. While the site is a relict surface site, dated faunal remains, lithic refits, and the homogeneity of the assemblage suggest it belongs to a single or to multiple occupation events that occurred over a short time. Directly dated hippopotamus bone, and dominant aquatic fauna suggest the Det Bahari plain was partially submerged at this time and that the site itself was near the water's edge. This would suppose that an undocumented transgressive lacustrine phase occurred during the occupation of Det Bahari-01. Lithic traditions observed at Det Bahari-01 (lamino-lamellar debitage, curved backed pieces) and the presence of some aquatic fauna on the surface of site SP-01 (~7.5-7.4 ka cal. BP) further support the continuity of shoreline settlement over the course of ~500 years of oscillating lake-levels.

Our results establish that the Lower Awash plain which makes up the northern shore of the Early to early Middle Holocene Lake Abhe was settled before, during and after the 8.2 ka arid event. Between ~8.1 and ~7.4 ka cal. BP another phase of settlement is identified in the area. These archaeological sites and their associated aquatic fauna suggest at least one low lake stand before the Abhe-V stable lake transgression. This period differs markedly from the period prior to 8.2 ka in that while fish remain a staple, there is significantly less than at earlier sites, and more large aquatic fauna such as crocodile and hippopotamus, notably on sites like Det Bahari-01. While fishing remained a common practice, the presence of larger quantities of wild aquatic fauna may suggest new technical innovations in hunting and fishing equipment. Use-wear study on a select number of curved backed pieces show diagnostic impact fractures that suggest their use as composite projectile points (barbs and axial points likely set into wood or bone shafts) to act as arrows, spears or harpoons for hunting and/or fishing. Unfortunately the lack of preserved plant material in the deposits limits our understanding of these populations' relationships with wild plants and whether or how they may have been used for shelter, food and craft production. The presence of groundstone implements, and debitage oriented towards the production of bladelet blanks for composite backed pieces are also departures from traditions observed in the previous settlement period identified.

6.3 – early Late Holocene (~4.2 to ~3 ka BP)

6.3.1 – Paleolandscape context

The Late Holocene period is marked by a decrease of lake levels around ~4.5 ka cal. BP and the spread of arid conditions across the Abhe basin (Fig. 10.d). This change in hydrological patterns corresponds to the reduction of the African monsoon rainfall regime, which marks the end of the AHP (Gasse 2000; Shanahan et al. 2015).

This period likely corresponds to the renowned 4.2 ka event (Kaniewski et al. 2019; Rousseau et al. 2019) characterized by a rapid (centennial scale average) decrease in precipitation in tropical Africa that led to the spread of hyperarid conditions. In the Abhe basin, the installation of the first Middle to Late Holocene aeolian accumulations fall in the range between ~4.5 and ~3.7 ka cal. BP (Kurub-07_SU41 and SU13). At the Kurub-07 site we observe alternations between paleodune layers and aridisols between ~3.7 and ~3.2 ka cal. BP, confirming the persistence of arid conditions. Considering the low altitude of human settlements and the similarity in low precipitation values during the YD and the 4.2 event in the Ethiopian Highlands (Costa et al. 2014; Fig. 10.b, c), this Late Holocene arid event led to a drastic reduction of Abhe Lake levels like those recorded during the 8.2 ka event.

6.3.2 – Multi-resource economies and the transition to herding in the Middle to Late Holocene transition

Lower lake-levels and more arid conditions began at ~5.5 ka cal. BP and took hold around ~4.5 ka cal. BP though there is a general lack of lake-level data for this period (Fig. 10.d). The earliest evidence of herding in the region is attested around 4.8 ka cal. BP on the eastern shores of Lake Abhe (Cauliez et al. in press; Coudert et al. 2018; Lesur et al. 2014), while we have yet to date a pottery herding site of this period in the Ethiopian Afar.

The site of Kurub-07 is exceptional for the region for its discontinuous roughly two-millennia long human occupation sequence and for the preservation of remains of the first potter pastoralists who inhabited the area. The site features an older level of human occupation (SU41) thus far devoid of ceramics or animal domesticates. Three radiocarbon dates from this level are inverted and have therefore been rejected (Kur_07_ST6_655, Kur_07_Spit8_661, Kur-07-K15-Spit8-663B, Table 2). However, we can bracket this archaeological level between dates for the last lake transgression ~4.5 ka cal. BP and the following anthropic level (SU15) radiocarbon dated to ~3.9-3.6 ka cal. BP.

After a period of abandonment of the site (SU13), several continuous well-preserved levels of occupation by potter herders that cover the period from ~3.9 to ~3.3 ka cal. BP follow. Remains of domesticates including cattle, sheep and goat confirm the presence of a herding economy. Although small, the spectrum attests to the importance of livestock in the diet. However, the large numbers of small wild fauna, particularly suited to open and arid plains, and some fish remains attest to the persistence of hunting and fishing probably carried out in the vicinity of the site while also suggesting the presence of drier conditions (semi-arid environment).

In addition to the introduction of small domestic herds during this period, we observe major changes in technical traditions with the appearance of pottery for storage, built structures such as ovens, and bipolar percussion on anvil on small obsidian nodules mainly for flake and to a lesser degree bladelet production. While few shaped tools were recovered, geometric backed pieces, *pièces esquillées* and few scrapers and perforators were recovered from excavations. This diverges from LSA lamino-lamellar debitage traditions but the production of curved backed composite tools on bladelet blanks is reminiscent of what was identified at Det Bahari-01 (Fig. 7.d-f) and dated to the Middle Holocene.

Particularly unique to the Abhe Lake region are the impressed pottery traditions (Fig. 9). The Kurub-07 ceramic assemblage is lacking in the regional sequence and the site presents an important milestone that contributes to our understanding of the socio-cultural landscape of this sector. Ceramics from the first and second phase of occupation of this site show some similarities to well-defined potter traditions east of Abhe Lake, in particular with the Asa Koma / Wakrita facies identified on several sites dating to between ~4.8 and ~4 ka cal. BP in the Gobaad Basin in

Djibouti (Cauliez et al. 2008; 2017; in press; Gutherz et al. 2015). The analogies are based on the exclusivity of simple forms in the assemblage and medium sized formats, the absence of elements in relief, both decorative and for handling, the airy aspect of the compositions, the diversity of techniques and their combinations, and the place granted to herringbone or diamond compositions and to pivot impressions. These similarities may suggest that ceramic features dated to the earliest attestations of herding on the eastern shores of Lake Abhe may have persisted on the northern and western shores of the same lake between ~4-3.4 ka cal. BP. However, we see more distinctions than parallels between these traditions, namely with regard to more diverse decorative motifs on eastern shore sites. It is therefore not yet possible to directly associate the two phases of Kurub-07 with this tradition.

A few rare isolated body sherd fragments testify to the practice of applying a red slip to undecorated surfaces on pottery vessel walls before firing in the more recent occupation phase at the site of Kurub-07 as well as on other surface sites in the area (Fig. 9.k). This practice has also been attested at several sites in the eastern sector of Abhe Lake (Cauliez et al. 2016).

6.4 – Situating Holocene settlement in the Abhe paleolake basin in the context of Northeast Africa

From a wider inter-regional perspective, fishing, hunting and foraging of aquatic resources characterize many Early Holocene sites in the Saharan belt and the Sahel, at a time when paleolakes and vegetation flourished in today's arid zones as a result of the mesic conditions of the AHP. In these regions, populations drawn to the abundant aquatic resources available in surrounding lakes probably had low residential mobility, judging by the presence of cemeteries, storage vessels and local raw material exploitation (Nash et al. 2011). These lakeside communities once termed *aqualithic* (Sutton 1974) are commonly grouped in association with bone harpoons and developed impressed pottery traditions that can first be found as early as ~12-10 ka cal. BP in the Sahara and Sahel, and as far south as Lake Turkana in Kenya (Beyin et al. 2017; Goldstein et al. 2017; Sereno et al. 2008; Wright et al. 2015; Fig. 1.a). Elsewhere in the Horn of Africa, namely the Ziway-Shala and Abhe lake basins, aquatic resources played an important role in the economy while pottery and bone harpoon traditions were entirely absent (Coudert et al. 2018; Ménard et al. 2014).

Through this wide angle, the transition to herding of Mesolithic or LSA fisher-hunter-gatherers was extremely variable, complementing enduring aquatic economies. The earliest evidence of herding in adjacent regions can be found in South Arabia between 9-8 ka cal. BP (Martin et al. 2009; Fedele 2008), several millennia after its northern Near Eastern neighbors adopted farming. In both cases these Neolithic societies remain aceramic for millennia. In northeast Africa, herding, in association with regionally specific ceramic traditions appeared before farming. This is evidenced first in the Eastern Sahara and Nile Valley (Honneger 2011; Linseele et al. 2016) around 9-8 ka cal. BP, then in Lakes Turkana and Abhe around 4.8 ka cal. BP (Cauliez et al. in press; Chritz et al. 2019; Coudert et al. 2018), only becoming common during or after ~3 ka cal. BP in Southwest Ethiopia, the Kenyan Rift and Lake Victoria region (Ambrose 1998; Gifford-Gonzalez 2000; Hildebrand et al. 2010; Lesur et al. 2014: 51; Prendergast 2010; Fig. 1.a).

The arid climatic conditions that took hold at the end of the AHP (~4.5-4.2 ka) are thought to have had a role in the southern spread of herding into East Africa following the retreating monsoon belt (Kuper & Kropelin 2006). It has been argued that mobility associated with herding may have supported its spread, both through interaction and exchange of livestock with foragers, and through social networks that enabled them to thrive faced with growing aridity (Marshall et al. 2011). It has also been suggested that maritime mobility across the Red Sea, confirmed through obsidian sourcing studies (Khalidi et al. 2018, Oppenheimer et al. 2019) may have played a role in the spread of herding by means of coastal fisher-herding communities from southern Arabia (Gutherz et al. 2017; Lesur et al. 2014). However, the current study provides new data that suggest traditions in the Abhe Lake basin had few to no parallels with those in surrounding regions across the three periods of settlement documented in the region. Parallels that can be drawn with adjacent regions are limited to certain lithic traditions, though these have a large and persistent chrono-regional scope on the African continent and beyond, and to the domestic sheep and goat populations that were integrated into multi-resource economies sometime between 4.8 and 3.9 ka cal. BP in the Afar, but which are similar in all neighboring Neolithic contexts. The unique Abhe traditions are neither in line with Early Holocene harpoon potters and Mid-Holocene potter herders of the Sahara and Nile corridor, nor with Early Holocene Epipaleolithic hunter-gatherers and Mid-Holocene aceramic herders of Arabia.

Today, the most robust chrono-cultural sequence outside of the Abhe and Ziway-Shala regions can be found in the Lake Turkana and Victoria basins in Kenya (Ashley et al. 2011; Beyin et al. 2017; Hildebrand et al. 2018; Mirazon Lahr et al. 2016; Owen et al. 1982; Prendergast 2010; Robertshaw 1991; Robertshaw et al. 2010; Wright et al. 2015). A recent study comparing these two basins has demonstrated very distinct ecological responses to climatic changes in each, as well as establishing the complexity of relations between these responses and early herding (Chritz et al. 2019: 129).

Similarly, correlation with lake-level proxies, human settlement pattern and archaeomaterial data demonstrate that over 9000 years, major socio-economic changes of populations inhabiting Abhe paleolakeshores were distinctive ecological responses to transformations in the local environment and to fluctuating lake levels.

7 - Conclusion

Through cross-examination of morpho-sedimentary and archaeological datasets we provide a preliminary reconstruction of the evolution of the Abhe paleolandscape and the lifeways of its Holocene populations as the lacustrine environment significantly transformed over 9000 years.

We present the first Holocene chrono-cultural sequence for the Ethiopian Afar including 23 ^{14}C dates on archaeological levels ranging between ~11 and ~3.5 ka cal. BP. These cluster into three periods during which we find preserved human settlement along shifting Abhe paleolakeshores. These three periods fall within the AHP, which is interrupted by and terminates with two sedimentologically documented hyperarid events (8.2 and 4.2 ka) hosting human occupations. Although human occupation levels are not continuous, these windows of site preservation offer insight into continuities and ruptures in techno-economic traditions of Abhe societies, which we interpret as ecological responses to local amplifier lake behavior in one of the most arid regions of the world.

Our results provide a revised Early to Late Holocene model of lake-level fluctuations linked to dynamic peri-lacustrine landform evolution. The centennial-scale reactivity of this amplifier lake to climatic forcing is echoed in the variability of settlement location and strategy, and in the flexible multiple resource economies of its populations over time. Most interestingly, our data suggest that the Abhe Lake basin hosted populations with local techno-economic traditions who relied on aquatic resources even with the introduction of domestic herds. As we have yet to find continuity in human occupation over 9000 years, it is possible that different populations settled the area over time, and that stable lake levels attracted more groups to the area, while extreme lake level rise and fall forced groups to move to higher altitudes or towards isolated oases and refugia as has been suggested for amplifier lakescapes (Maslin et al. 2014; Trauth et al. 2010), and more generally for arid environments (see Purdue et al. (eds.) 2018). Throughout the periods represented, our data are consistent with populations adapted to lakeshore fluctuations, and populations with continuity in traditions between hyperarid events.

This local multi-scalar and multi-proxy approach allows a preliminary diachronic restitution of human ecological responses to local landscape transformation that would normally have been overlooked and overshadowed by correlations with regional and global climate proxies. These results provide the first data available on Early to Late Holocene human occupations in the Ethiopian Afar and on the transformation and resilience of prehistoric human societies in the context of the dynamic and arid landscape they occupied.

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Figure captions

Figure 1. a) Regional map (after GMTED2010, SRTM) with the location of the VAPOR-Afar project area, sites mentioned in the text, and a schematic representation of the earliest attestations of herding in the Horn of Africa; **b**) Satellite image (LANDSAT) of the Lower Awash valley in the Ethiopian Afar with the location of VAPOR-Afar archaeological sites and modelling of the Abhe Lake highstand between 10.2-9.8 ka cal. BP; c) Abhe Lake level phases after Gasse & Street (1978).

Figure 2. a) Multi-plot of calibrated ages from archaeological and palustrine layers, and littoral lacustrine carbonates (OxCal v4.3.2 Bronk Ramsey (2017); r:5 IntCal13 atmospheric curve (Reimer et al. 2013); **b)** Abhe paleolake level curve calculated from calibrated ages and recalculated elevations taken from Gasse (1975) and from new ages on littoral lacustrine carbonates.

Figure 3. a) Raso-02 archaeological site sequence with calibrated ages; **b**) Lakora-03 archaeological site sequence with calibrated ages; **c**) Satellite image (LANDSAT) with locations of Raso-02 and Lakora-03 sites, dated littoral lacustrine carbonates (this study) and dated littoral lacustrine markers (Gasse 1975) and modelling of Early Holocene Abhe Lake highstand ~10.6 ka cal. BP; **d**) Photogrammetry and point plotted artifacts from the main archaeological layer of the Lakora-03 site.

Figure 4. Lakora-03 obsidian lithic artifacts: a-c) surface collection, d-f) Sounding 1 (S1); **a)** blade core, **b)** bladelet core on dorsal surface of truncated blade ("Kostienki knife" core), **c)** re-

oriented bladelet core, **d)** notched(?) bladelet, **e)** bladelet, **f)** endscraper on retouched blade (possibly used as intermediary piece).

Figure 5. a) DEM (1 m resolution) of the site of Det Bahari-01 with point plotted surface artifacts, calibrated ages, and lithic conjoins; **b**) Stromatolis archaeological sequence with calibrated ages; **c)** Photogrammetry of the Stromatolis site.

Figure 6. a) SP-01 archaeological sequence with calibrated ages and a schematic morpho-sedimentary model of the littoral lacustrine profile of Abhe Lake; **b**) MS-01/02 archaeological sequence with calibrated ages; **c**) Satellite image (LANDSAT) with locations of SP-01, MS-01/-02, Det Bahari-01 and Stromatolis sites and modelling of Abhe Lake highstand between 9.8 and 8.2 ka cal. BP.

Figure 7. Det Bahari-01 obsidian lithic artifacts: **a**) technical blade (neocrest), **b)** retouched blade fragment, **c)** double-endscraper on blade, **d-f)** backed pieces, **g-h)** splintered pieces.

Figure 8. a.1) Kurub-07 western section of the K-trench archaeological sequence with location of calibrated ages; **a.2**) Orthophotograph of anthropic structure (ST1, oven) excavated at the Kurub-07 site with locations of calibrated ages; **a.3**) Aerial kite photograph of excavations at Kurub-07 draped with point-plotted artifacts; **b**) Satellite image (LANDSAT) with the location of the Kurub-07 site with modelling of the Abhe Lake regression phase between 5.5-4.6 ka cal. BP.

Figure 9. Decorated ceramics from the site of Kurub-07. ***Phase 1:*** **a)** Refitted vessel with combination incision / simple impression: a line incised with a blunt point under which there is a strip composed of multiple tooth comb impressed oblique lines. **b)** Refitted vessel with flat rim adorned with oblique lines and chevron pendant followed by pivoting impressions on body. **c)** Refitted vessel with simple impressions by means of oblique lines in horizontal band. ***Phase 2*** is characterized by decorated flat or externally beveled rims and diverse motifs combined on the same vessel **d)**: Vessel with band of oblique comb impressed lines under which parallel horizontal dotted lines frame comb impressed lozenges decorated with comb impressed motifs or herringbone motifs made with comb impressed oblique lines. **e)** Body sherd with combination of incision / simple impression and impressed oblique lines applied with a spatula on the rim. **f)** Two body sherds with roulette impressions. **g)** Rim sherd with simple comb impressions. **h-i)** Body sherds with pivoting impressions with a comb or shell. **j)** Body sherd with decorations that associate two impression techniques: a simple impression with a triangular tipped awl and a pivoting impression with a shell or a comb. **k)** Body sherd with red slip applied before firing, testifying to the application of colorants on certain pottery vessels.

Figure 10. Holocene paleovariations of **a**) June insolation at 15°N (Berger & Loutre 1991); **b**) δD WAX (‰; Costa et al. 2014) and Ti (mg/g; Marshall et al. 2011), Tana Lake; **c**) planktonic diatoms (%; Chalié & Gasse 2002) and lake levels (Gillespie et al. 1983), Ziway-Shala basin. **d**) Abhe paleolake level curve calculated from calibrated ages and recalculated elevations taken from Gasse (1975) and from new ages on littoral lacustrine carbonates with plotted calibrated dates and elevations of dated archaeological sites of the VAPOR-Afar project sites presented in

this study. e) Regional map (after GMTED2010, SRTM) with localization of Tana, Ziway-Shala and Abhe Lakes.

Tables

Table 1. Radiocarbon ages and elevations from littoral lacustrine carbonates from Abhe paleolake in Ethiopia. * rejected ages.

Table 2. Radiocarbon ages and elevations from archaeological sites (VAPOR-Afar project, Ethiopia) and associated palustrine layers. * rejected ages. The site of Det Bahari-01 (correct local name) was originally named Bet Bahari-01 based on appellation of the area on a map of the region (hence the Betba-01 site label). All samples have retained the old site label.

Table 3. Preliminary faunal spectrum from Kurub-07, Det Bahari-01 and Lakora-03 according to the NISP (Number of Identified Specimens Parts).

Table 4. Aspects of subsistence and technology according to period and Abhe Lake maximum highstand.

Appendices

A.1. Conventional and calibrated radiocarbon ages selected from Gasse (1975) with recalculated elevations based on a DEM (TanDEMx at 12 m resolution).

Sample Name	Material	Lab Code	Conventional yr BP	yr cal BP 2σ (range, 95.4 %)	Median yr cal BP	Elevation (DEM ± 12 m)
Strom_20-SU5	Stromatolite	SacA58238	9689 ± 40	11210-10805	11125 ± 113	359
Strom_20-SU4	Stromatolite	SacA58239	9320 ± 40	10660-10404	10530 ± 64	359
Strom_20-SU1	Stromatolite	SacA58240	9265 ± 40	10565-10295	10447 ± 73	359
Logiya_1A	Lacustrine Shell	Beta 446441	9180 ± 30	10477-10245	10241 ± 27	401
Logiya_1B	Charcoal	Beta 446442	9100 ± 30	10477-10245	10330 ± 55	401

Strom_10a	Stromatolite	SacA55608	8790 ± 30	10112-9679	9807 ± 81	366.8
Strom_10b	Stromatolite	SacA55609	8075 ± 35	9123-8785	9008 ± 70	366.8
Srom_31	Stromatolite	Poz-113925	7910 ± 50	8978-8598	8743 ± 109	371.7
Strom_13	Stromatolite	SacA55611	5919 ± 30	6829-6666	6738 ± 40	359
Raso-02_Strom	Stromatolite	Poz-113843	5085 ± 35	5913-5746	5815 ± 51	366
Strom_7	Stromatolite	SacA55610	5005 ± 30	5889-5653	5732 ± 69	361,5
Stromatolis-SU1	Stromatolite	Poz-113841	4910 ± 30	5712-5591	5632 ± 29	371.7
Strom_17A*	Stromatolite	Poz-113842	3310 ± 30	3610-3458	3529 ± 40	368
Strom_32*	Stromatolite	Poz-116164	1045 ± 30	1050-921	953 ± 31	406

Table 1

Sample Name	Site	SU	Material	Lab Code	Conventional yr BP	yr cal BP 2σ (range, 95.4 %)	Median yr cal BP	Elevation (DEM ± 12 m)
Lak3-T1-SU5-101	Lakora- 03	5	charcoal	Poz-111634	9590 ± 60	11164-10737	10939 ± 121	365.4
Raso-02-Sond2-SU2*	Raso-02	2	charcoal	Poz-111635	9430 ± 50	11057-10515	10662 ± 92	366
Raso-02-Sond2-SU5	Raso-02	5	charcoal	Poz-111496	9370 ± 60	10744-10418	10595 ± 89	366
MS1_US1_001	MS-01	1	organic sediment	Poz-105343	7290 ± 50	8190-8000	8100 ± 55	355.8
Betba-1291	Det Bahari-01	1	hippo bone	UBA34899	7031 ± 43	7956-7761	7872 ± 49	372.5
Betba-11	Det Bahari-01	1	hippo bone	UBA34900	6749 ± 40	7674-7523	7609 ± 32	372.5
SP-01_US2_001	SP-01	2	organic sediment	Poz-105340	6570 ± 40	7564-7424	7472 ± 37	378.4
Kur-07-K15-Spit4-558	Kurub-07	15	organic sediment	Beta-446445	4920 ± 30	5715-5596	5638 ± 32	352.8
Kur-07-K14-US15-1203	Kurub-07	15	charcoal	LTL17832A	3520 ± 45	3914-3647	3788 ± 64	352.8
Kur-07-L16-US15-1283	Kurub-07	15	charcoal	LTL17833A	3434 ± 45	3830-3587	3692 ± 68	352.8
Kur-07-K10-Spit2-591	Kurub-07	12	charcoal	Beta-446443	3330 ± 30	3638-3477	3565 ± 46	352.8
Kur-07-US29-2443	Kurub-07	29	organic sediment	Poz-116280	3325 ± 30	3636-3476	3556 ± 45	352.8
Kur_07_ST6_655*	Kurub-07	41	charcoal	Poz-116049	3305 ± 30	3607-3455	3526 ± 39	352.8
Kur-07-L10-US10-1136	Kurub-07	10	charcoal	Poz-107746	3300 ± 35	3611-3450	3524 ± 43	352.8
Kur_07_Spit8_661*	Kurub-07	41	charcoal	Poz-117158	3295 ± 30	3588-3451	3520 ± 37	352.8
Kur-07-US26-2383	Kurub-07	26	organic sediment	Poz-117159	3270 ± 30	3572-3409	3501 ± 40	352.8
Kur-07-US12-2459	Kurub-07	12	organic sediment	Poz-116197	3265 ± 30	3568-3407	3495 ± 41	352.8
Kur-07-K15-Spit8-663B*	Kurub-07	41	charcoal	Beta-4477956	3250 ± 30	3562-3400	3473 ± 45	352.8
Kur-07-L10-667	Kurub-07	10	charcoal	Beta-446444	3180 ± 30	3456-3356	3405 ± 30	352.8
Betba01log2A	Det Bahari-01	Palustrine layer	Shell	Beta 446440	9180 ± 30	10477 - 10245	10330 ± 55	372.5
Betba01log2B	Det Bahari-01	Palustrine layer	shell	Beta 446439	9000 ± 30	10236 - 9975	10199 ± 43	372.5
Stromatolis_US4	Stromatolis	4	terrestrial shell	Poz-116165	7730 ± 50	8593-8419	8506 ± 49	371.7
Kur-07-K15-US18-1488	Kurub-07	18	organic	Poz-107669	5990 ± 360	7587-6022	6853 ± 381	352.8

sediment

Table 2

Taxa	Kurub-07	Det Bahari-01	Lakora-03
Large mammals	28	4	67
Hippopotamus (*Hippopotamus amphibius)*		12	
Cattle *(Bos taurus)*	9		
Bovine (Bovini)	9		
Middle-sized bovid	165	8	
Sheep/goat (*Ovis aries/Capra hircus*)	16		
Gazella cf. dorcas	2		
Unidentified rodent	16		
Unidentified bovid	38		1
Nile crocodile *(Crocodylus niloticus)*		6	
Unidentified reptile	7		
Large cyprinid (Cyprinidae)			1
Clarias sp.			3
Clariidae			375
Siluriform	2	17	22
Tilapia (Haplotilapinii)	4	2	1
Unidentified fish	5	14	409
Total identified vertebrate	**301**	**63**	**879**
Ostrich eggshell	9		2
Melanoides tuberculata			3
Unidentified gastropod			3
Unidentified bivalve			1
Unidentified shell	6		3
Unidentified	*782*	*35*	1678
TOTAL	**1098**	**98**	**2569**

Table 3

Settlement period	**Aspects of subsistence**	**Aspects of Technology**	**Representative sites**	**Lake Abhe highstand (m a.s.l.)**
Early	Fishing, Hunting,	Blade oriented	Lakora-03	420 – 380

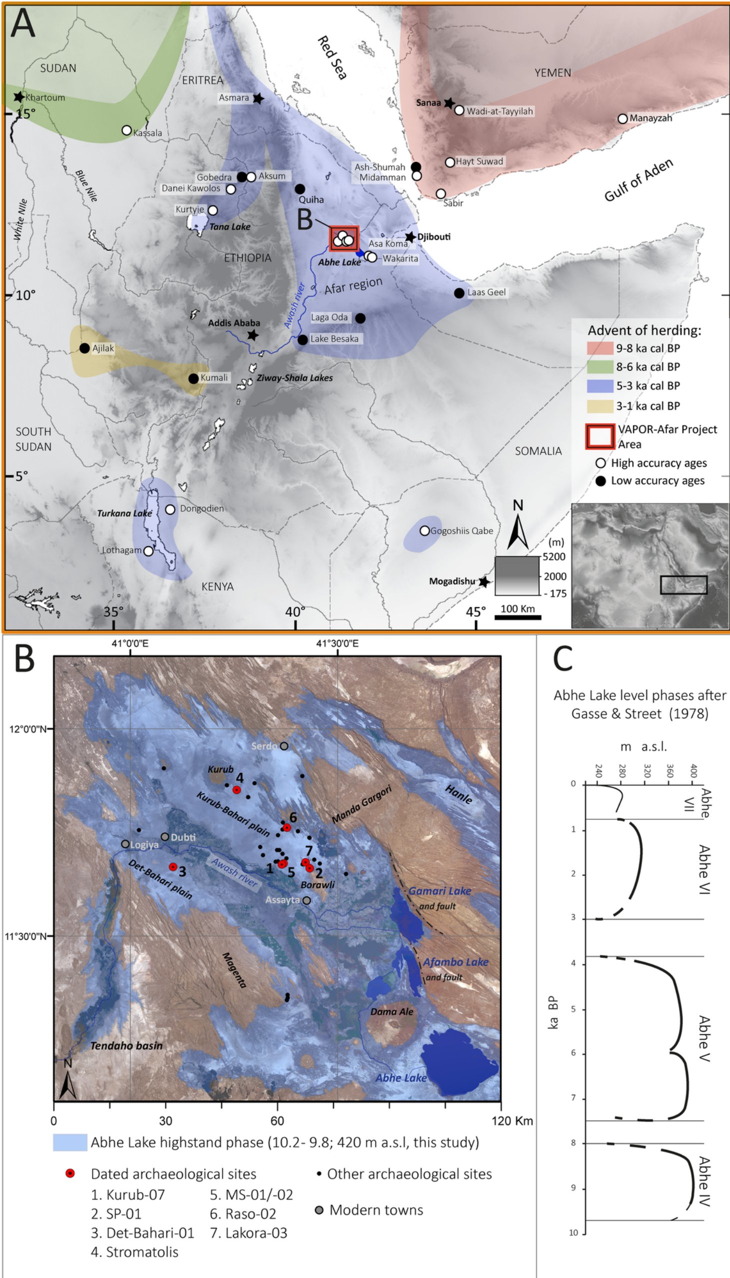
Holocene 11.7 – 8.2 ka	Gathering	debitage Personal adornment (ostrich eggshell beads) Bone tools?	Raso-02	
Middle Holocene 8.2 – 4.2 ka	Fishing, Hunting, Gathering	Ground stone Blade/bladelet oriented debitage/ curved backed pieces Simple circular structures	Stromatolis MS-01/02 SP-01 Det-Bahari-01	380
early Late Holocene 4.2 – 3 ka	Herding, Fishing, Hunting, Gathering Trade?	Ground stone Decorated pottery Flake oriented debitage/ curved backed pieces Personal adornment (diverse materials) Monumental funerary traditions Complex oven structures Long-distance interaction	Kurub-07	< 350

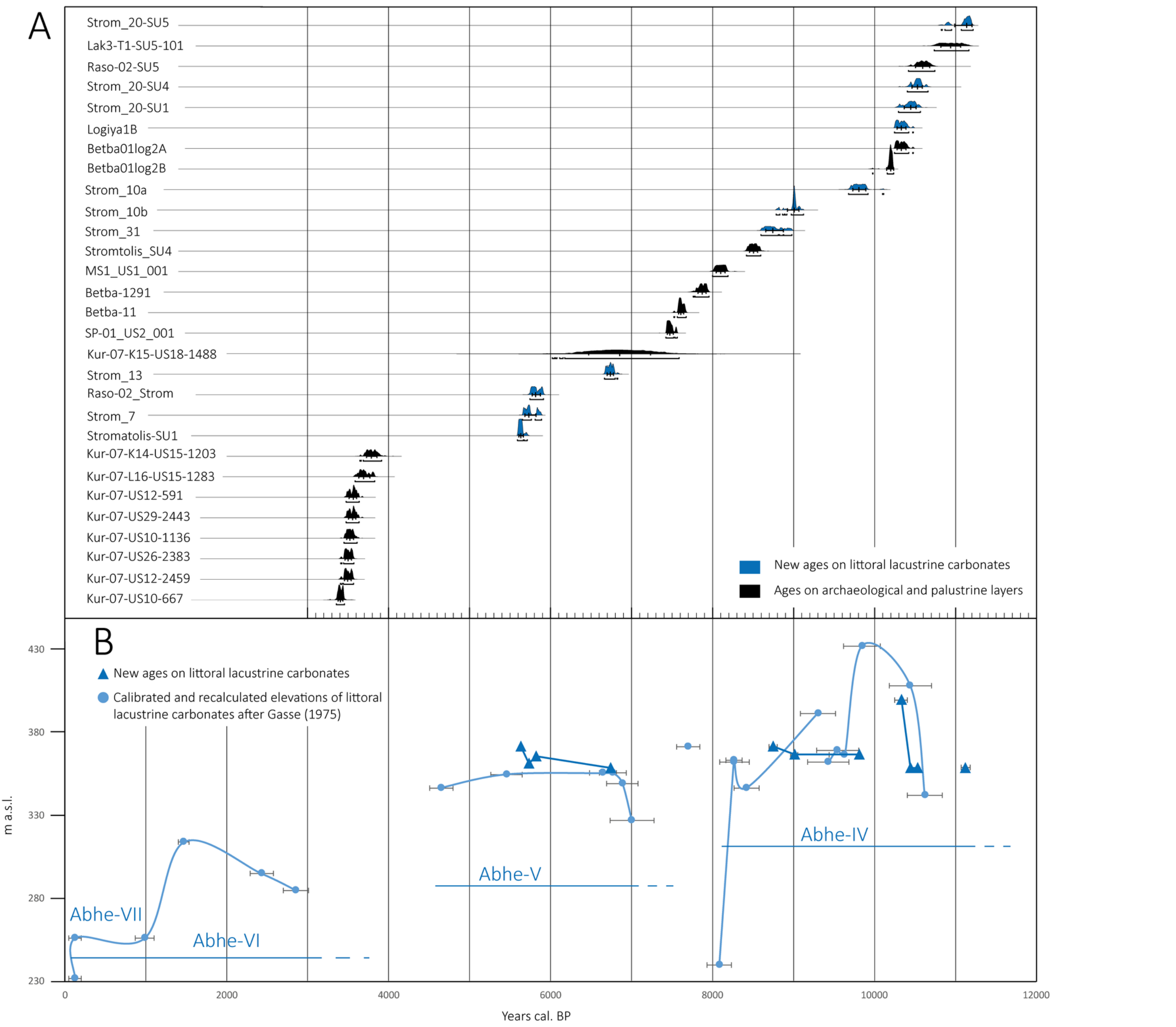
Table 4

N° (Gasse 1975)	Sample name (Gasse 1975)	Conventional age yr BP	Longitude	Latitude	Selection and rejection criteria	Calibrated ages yr BP (range 95.4 %)	Calibrated ages yr BP (median)	Recalculated elevations (DEM ± 12 m)
Gasse_1	B88	98.8 ± 1.2	41°48'	11°59'		255 – 31	121 ± 78	240
Gasse_2		100.6 ± 0.9	41°52'	11°09'		255 – 31	122 ± 78	231.7
Gasse_6	M 245	110 ± 50	41°50'	11°15'		276 – 9	124 ± 81	256.4
Gasse_7	M 108	1030 ± 100	41°41'	11°29'		1178 – 738	984 ± 115	256.4

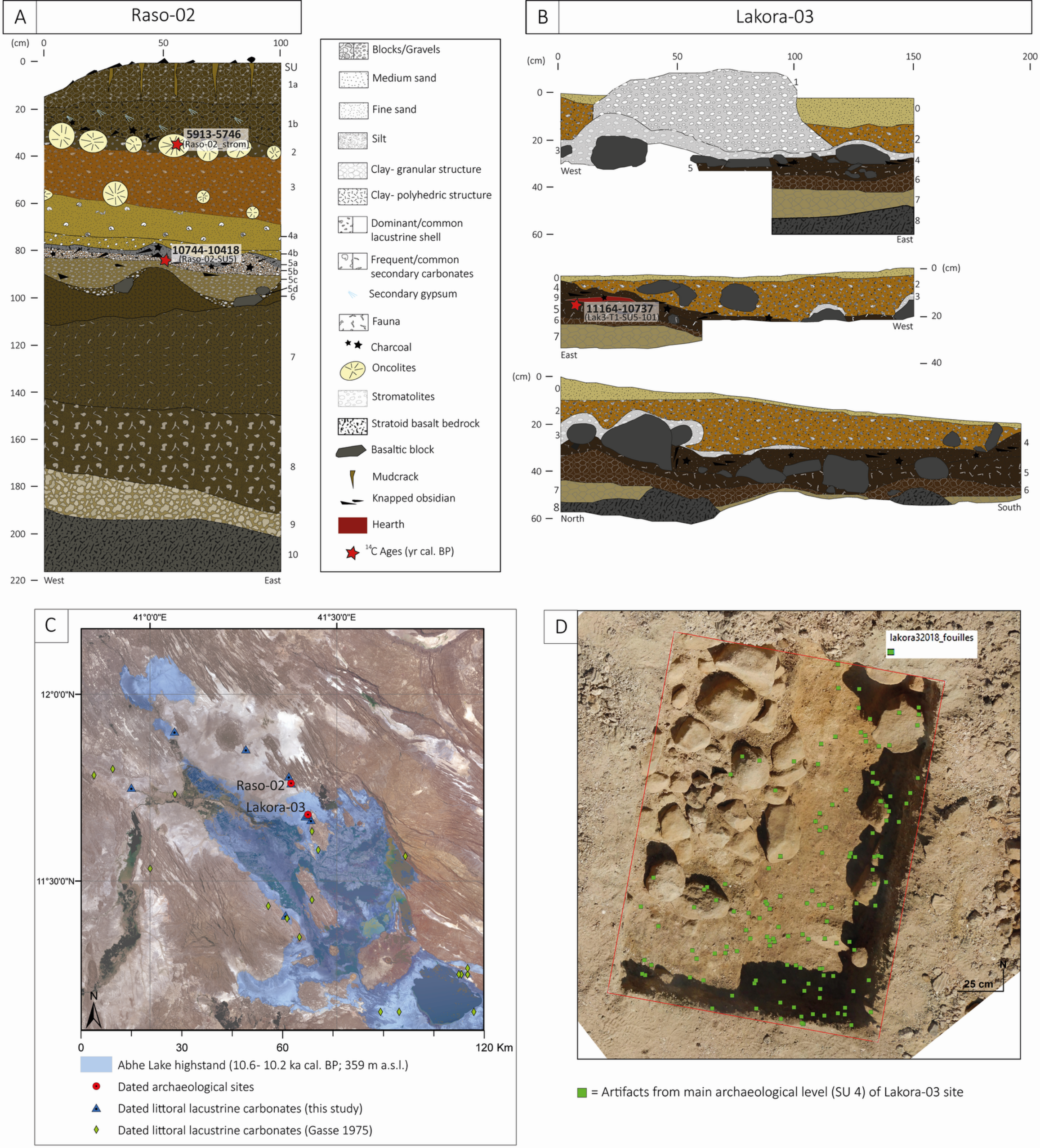
Gasse_8	M 104	1300 ± 100	11°37'	11°09'	Gamari residual lake	\	\	\
Gasse_9		**1570 ± 60**	**41°52'**	**11°09'**		**1597 – 1337**	**1464 ± 63**	**314**
Gasse_11		**2360 ± 80**	**41°52'**	**11°09'**		**2715 – 2160**	**2429 ± 140**	**295**
Gasse_13		**2720 ± 120**	**41°52'**	**11°09'**		**3172 – 2490**	**2850 ± 55**	**285**
Gasse_14	M 284	3290 ± 160	41°26'	11°39'	Residual lake	\	\	\
Gasse_16	**A 646**	**4120 ± 110**	**42°08'27**	**11°00'34''**		**4874 – 4297**	**4643 ± 144**	**346.8**
Gasse_18		**4740 ± 150**	**42°08'27**	**11°00'34''**		**5881 – 4983**	**5455 ± 93**	**354.9**
Gasse_19		4750 ± 230	42°08'	11°05'	Pedological deposit (Fontes et al. 1973)	\	\	\
Gasse_22	M 277	5080 ± 480			Incomplete coordinates	\	\	\
Gasse_29		5775 ± 115			Incomplete coordinates of pedological deposit (Semmel 1971)	\	\	\
Gasse_30	**B 38**	**5830 ± 140**	**42°09'**	**11°00'**		**6972 – 6316**	**6647 ± 167**	**355.6**
Gasse_33	**A 648**	**5930 ± 130**	**42°09'**	**11°00'**		**7156 – 6468**	**6769 ± 167**	**355.6**
Gasse_34	**A 32**	**6020 ± 160**	**41°24'**	**11°21'**		**7256 – 6501**	**6884 ± 196**	**349.6**
Gasse_35		**6130 ± 250**	**41°51'**	**11°15'**		**7498 – 6448**	**7002 ± 271**	**327**
Gasse_38		6290 ± 100	41°52'	11°09'	Lack of interpretation of formation processes (Fontes & Pouchan 1975)	\	\	\
Gasse_39		6335 ± 110			Incomplete coordinates of pedological deposit (Semmel 1971)	\	\	\
Gasse_40		6350 ± 105			Incomplete coordinates of pedological deposit (Semmel 1971)	\	\	\
Gasse_41	M 109	6360 ± 260	41°40'	11°36'	Gamari residual lake	\	\	\
Gasse_43		6610 ± 100			Incomplete coordinates of pedological deposit (Semmel 1971)	\	\	\
Gasse_44	M 105	6630 ± 220	41°41'	11°34'	Gamari residual lake	\	\	\
Gasse_47	M 105	6690 ± 160	41°41'	11°34'	Gamari residual lake	\	\	\
Gasse_49	**B 459**	**6835 ± 160**	**42°08'**	**11°05'**		**7965 – 7432**	**7697 ± 142**	**371.3**
Gasse_50	S 94	6910 ± 180	40°51'	11°47'	Incoherent age	\	\	\

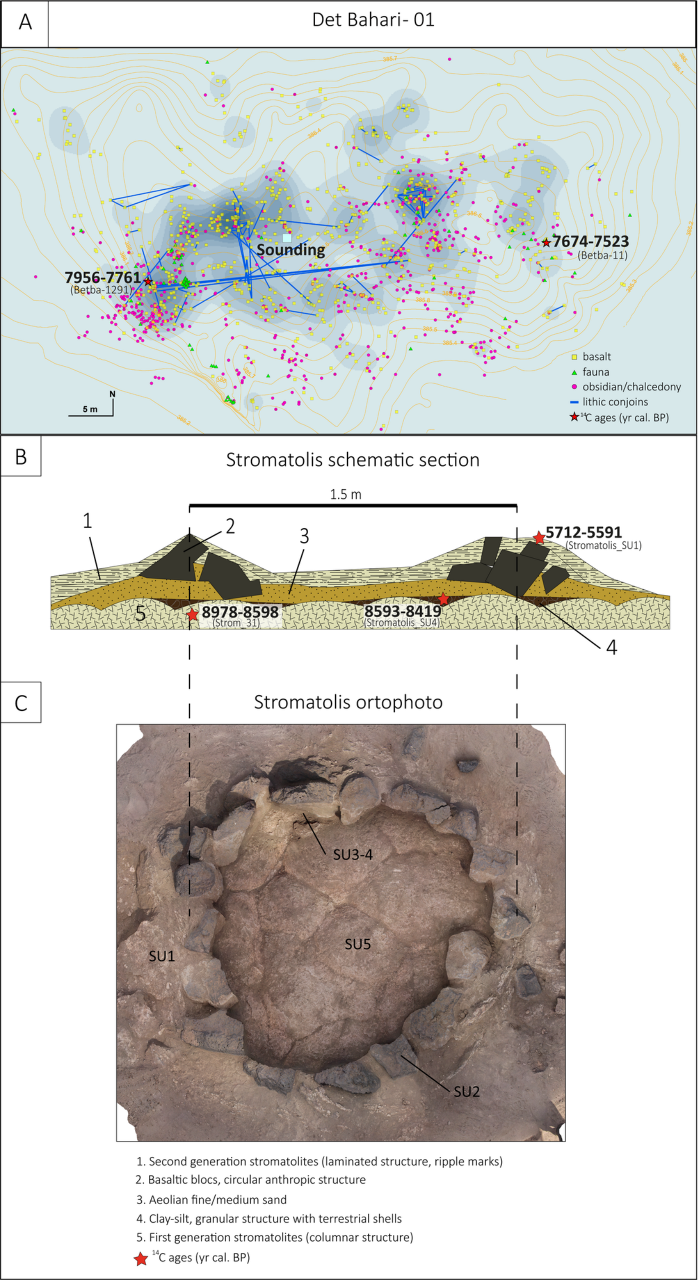
Gasse_53	C7	7000 ± 140	41°53'	11°08'	Deepwater lacustrine deposit	\	\	\
Gasse_54	B 87	7150 ± 320	41°49'	10°59'	Reworked sediment	\	\	\
Gasse_56	B 126	7190 ± 220	41°42	11°29'	Gamari residual lake	\	\	\
Gasse_57	**M 238**	**7250 ± 150**	**41°49'35**	**11°15'02**		**8375 – 7795**	**8082 ± 148**	**239.7**
Gasse_58		7265 ± 60	42°08'	11°15'	Inverted age with M 238	\	\	\
Gasse_62	**B 428**	**7450 ± 100**	**42°04'**	**11°06'**		**8416 – 8037**	**8263 ± 99**	**363.7**
Gasse_63	**A 30**	**7460 ± 180**	**41°22'**	**11°24'**		**8630 – 7934**	**8268 ± 181**	**362.2**
Gasse_64	**A 645**	**7610 ± 140**	**42°08'27**	**11°00'34''**		**8770 – 8054**	**8420 ± 158**	**346.8**
Gasse_74	A 100	8000 ± 170	41°29'	11°39'	Residual lake	\	\	\
Gasse_76	**M 185**	**8340 ± 180**	**41°26'**	**11°27'**		**9704 – 8770**	**9302 ± 219**	**391.8**
Gasse_77		8380 ± 100			Incomplete coordinates	\	\	\
Gasse_79	A11	8450 ± 190	41°?	11°32'	Incomplete coordinates	\	\	\
Gasse_80	**A 26**	**8450 ± 190**	**41°22'**	**11°24'**		**10129 – 8996**	**9434 ± 255**	**362.2**
Gasse_82	**A 6**	**8530 ± 190**	**41°04'**	**11°44'**		**10154 – 9090**	**9545 ± 263**	**369.6**
Gasse_84	M 282	8580 ± 160	41°26'	11°34'	Deepwater lacustrine deposit	\	\	\
Gasse_85	**M79**	**8600 ± 140**	**41°26'**	**11°38'**		**10151 – 9305**	**9633 ± 194**	**366.5**
Gasse_86	M2 246	8620 ± 75	41°45'	11°18'	Deepwater lacustrine deposit	\	\	\
Gasse_87	A 25	8650 ± 160			Incomplete coordinates	\	\	\
Gasse_88		8715 ± 120	41°20'	11°40°	Lack of interpretation and contextualizatio n of formation processes interpretation and contextualisatio n (Taieb 1971)	\	\	\
Gasse_90	**A 22**	**8770 ± 190**	**41°19'**	**11°26'**		**10273 – 9436**	**9848 ± 230**	**432.4**
Gasse_93		9180 ± 220	41°51'	11°?	Incomplete coordinates	\	\	\
Gasse_94	**S 119**	**9230 ± 180**	**40°54'**	**11°48'**		**11084 – 9917**	**10444 ± 260**	**408.2**
Gasse_96	**M 135**	**9380 ± 130**	**41°27'**	**11°35'**		**11086 – 10253**	**10623 ± 216**	**342.1**
Gasse_100	M 101	10760 ± 220	41°42'	11°28'	Gamari residual lake	\	\	\
Gasse_103	M 161	13170 ± 170	41°53'	11°08'	Residual groundwater carbonates	\	\	\

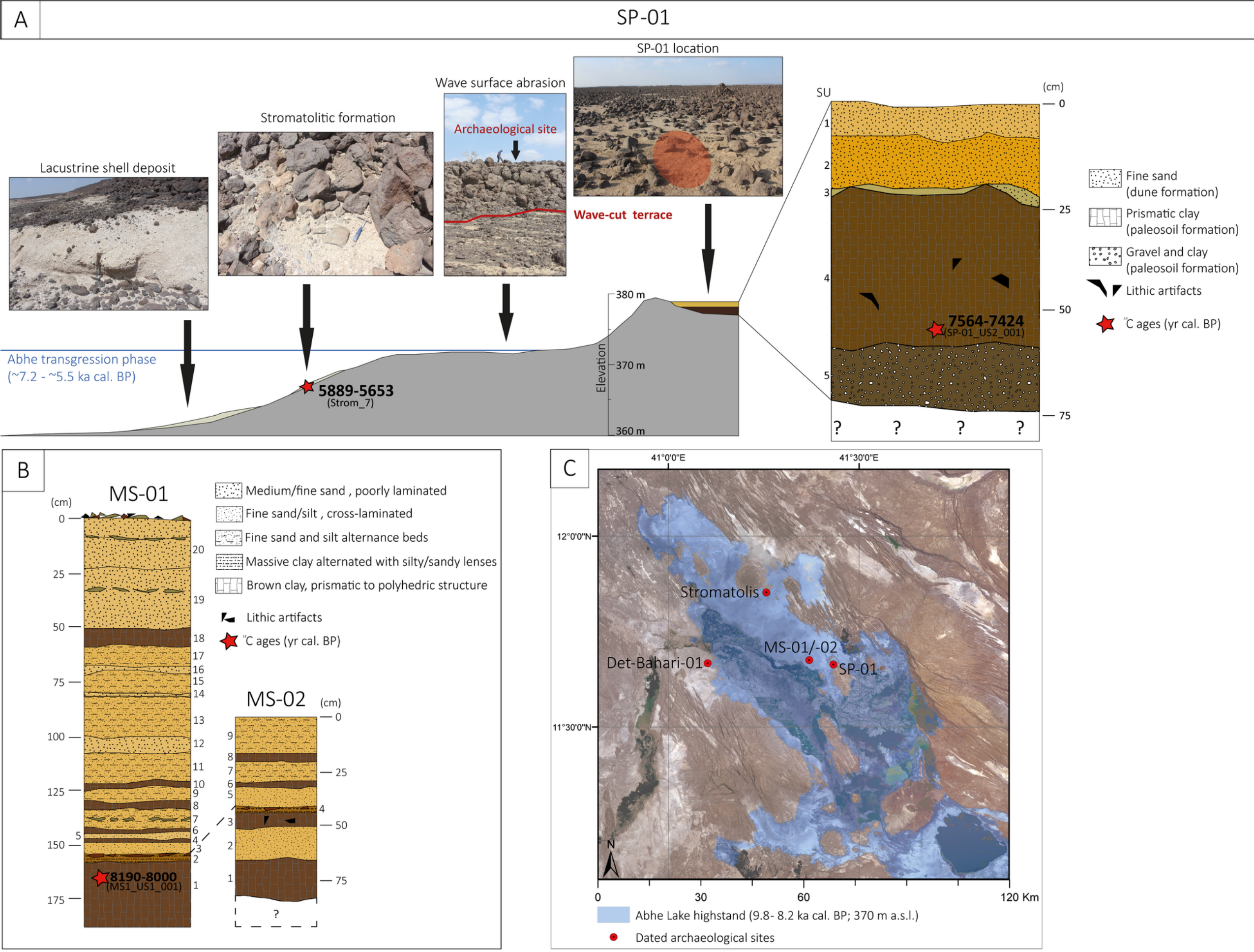

A
SUDAN
ERITREA
Red Sea
YEMEN
Khartoum
15°
Kassala
Asmara
Sanaa
Wadi-at-Tayyilah
Manayzah
Blue Nile
White Nile
Gobedra
Aksum
Danei Kawolos
Quiha
Ash-Shumah
Midamman
Hayt Suwad
Sabir
Gulf of Aden
Kurtyje
Tana Lake
B
Djibouti
Asa Koma
Wakarita
Abhe Lake
ETHIOPIA
Afar region
Awash river
10°
Laas Geel
Laga Oda
Addis Ababa
Lake Besaka
Ajilak
Kumali
Ziway-Shala Lakes
Advent of herding:
9-8 ka cal BP
8-6 ka cal BP
5-3 ka cal BP
3-1 ka cal BP
VAPOR-Afar Project Area
High accuracy ages
Low accuracy ages
SOUTH SUDAN
SOMALIA
5°
Turkana Lake
Dongodien
Lothagam
Gogoshiis Qabe
KENYA
Mogadishu
N
(m)
5200
2000
- 175
100 Km
35°
40°
45°
B
41°0'0"E
41°30'0"E
12°0'0"N
11°30'0"N
Serdo
Kurub
4
Kurub-Bahari plain
Manda Gargori
Hanle
6
Dubti
Logiya
7
3
1
5
2
Awash river
Det-Bahari plain
Borawli
Assayta
Gamari Lake and fault
Afambo Lake and fault
Magenta
Dama Ale
Tendaho basin
Abhe Lake
N
0
30
60
120 Km
Abhe Lake highstand phase (10.2- 9.8; 420 m a.s.l, this study)
Dated archaeological sites
1. Kurub-07
2. SP-01
3. Det-Bahari-01
4. Stromatolis
5. MS-01/-02
6. Raso-02
7. Lakora-03
Other archaeological sites
Modern towns
C
Abhe Lake level phases after Gasse & Street (1978)
m a.s.l.
240
280
320
360
400
0
1
2
3
4
5
6
7
8
9
10
ka BP
Abhe VII
Abhe VI
Abhe V
Abhe IV



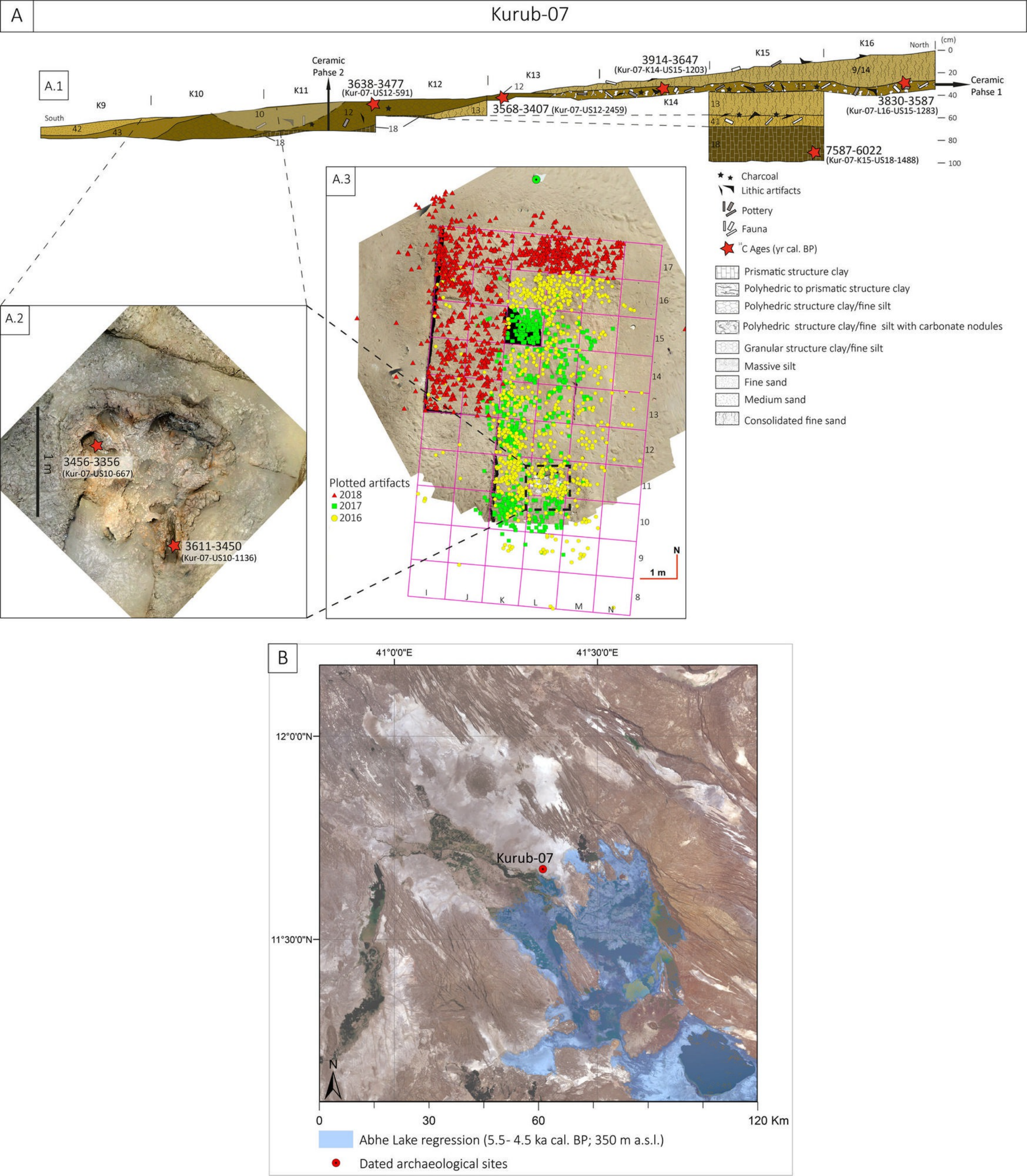
A
Strom_20-SU5
Lak3-T1-SU5-101
Raso-02-SU5
Strom_20-SU4
Strom_20-SU1
Logiya1B
Betba01log2A
Betba01log2B
Strom_10a
Strom_10b
Strom_31
Stromtolis_SU4
MS1_US1_001
Betba-1291
Betba-11
SP-01_US2_001
Kur-07-K15-US18-1488
Strom_13
Raso-02_Strom
Strom_7
Stromatolis-SU1
Kur-07-K14-US15-1203
Kur-07-L16-US15-1283
Kur-07-US12-591
Kur-07-US29-2443
Kur-07-US10-1136
Kur-07-US26-2383
Kur-07-US12-2459
Kur-07-US10-667
New ages on littoral lacustrine carbonates
Ages on archaeological and palustrine layers
B
New ages on littoral lacustrine carbonates
Calibrated and recalculated elevations of littoral lacustrine carbonates after Gasse (1975)
430
380
330
280
230
m a.s.l.
Abhe-VII
Abhe-VI
Abhe-V
Abhe-IV
0
2000
4000
6000
8000
10000
12000
Years cal. BP


A
Raso-02
(cm)
SU
1a
1b
2
3
4a
4b
5a
5b
5c
5d
6
7
8
9
10
5913-5746
(Raso-02_strom)
10744-10418
(Raso-02-SU5)
West
East
Blocks/Gravels
Medium sand
Fine sand
Silt
Clay- granular structure
Clay- polyhedric structure
Dominant/common lacustrine shell
Frequent/common secondary carbonates
Secondary gypsum
Fauna
Charcoal
Oncolites
Stromatolites
Stratoid basalt bedrock
Basaltic block
Mudcrack
Knapped obsidian
Hearth
^{14}C Ages (yr cal. BP)
B
Lakora-03
(cm)
West
East
11164-10737
(Lak3-T1-SU5-101)
North
South
C
41°0'0"E
41°30'0"E
12°0'0"N
11°30'0"N
Raso-02
Lakora-03
N
0
30
60
120 Km
Abhe Lake highstand (10.6- 10.2 ka cal. BP; 359 m a.s.l.)
Dated archaeological sites
Dated littoral lacustrine carbonates (this study)
Dated littoral lacustrine carbonates (Gasse 1975)
D
lakora32018_fouilles
25 cm
N
= Artifacts from main archaeological level (SU 4) of Lakora-03 site

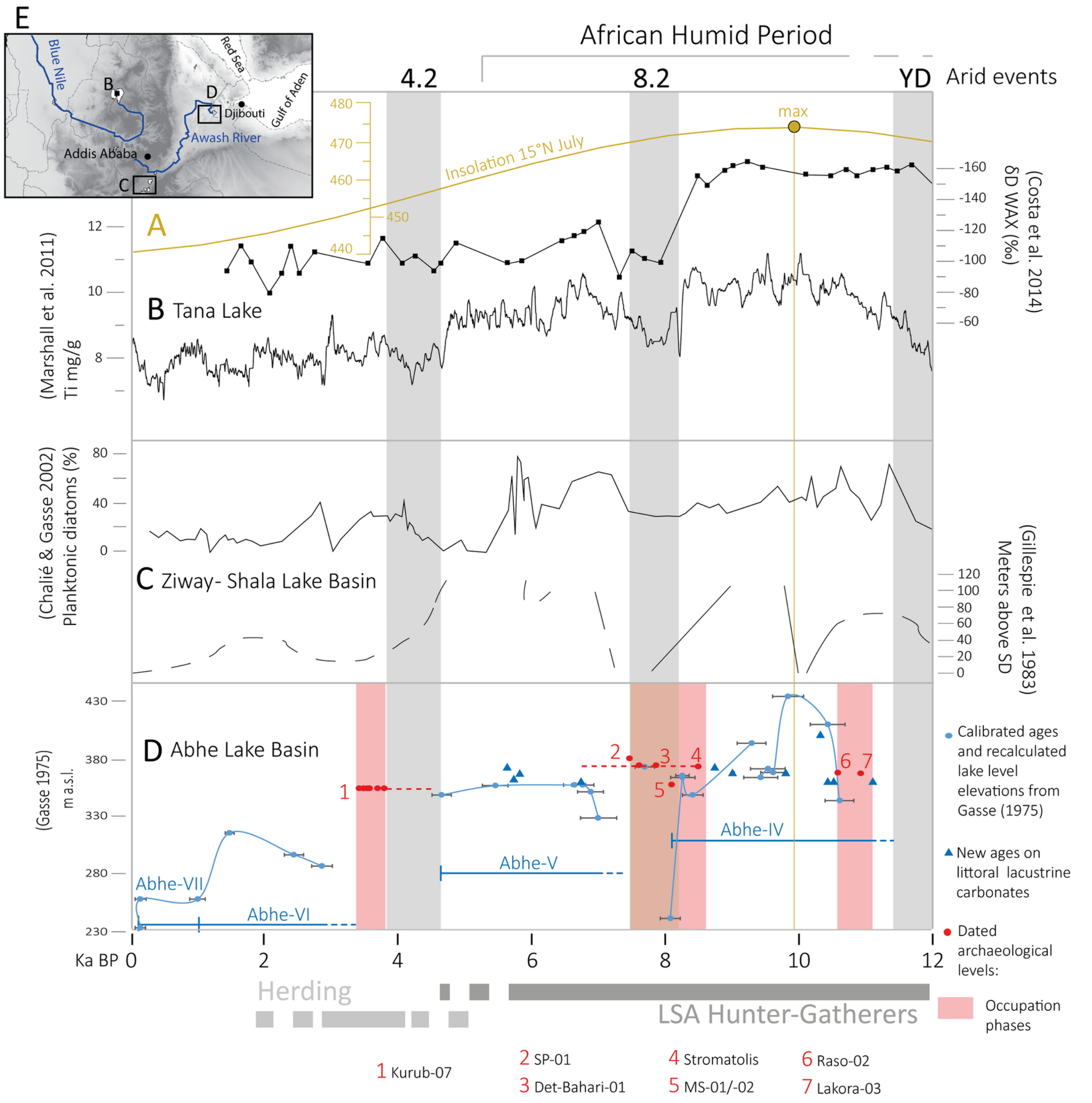

A
Det Bahari- 01
Sounding
7956-7761
(Betba-1291)
7674-7523
(Betba-11)
N
5 m
basalt
fauna
obsidian/chalcedony
lithic conjoins
14C ages (yr cal. BP)
B
Stromatolis schematic section
1.5 m
1
2
3
4
5
5712-5591
(Stromatolis_SU1)
8978-8598
(Strom_31)
8593-8419
(Stromatolis_SU4)
C
Stromatolis ortophoto
SU3-4
SU5
SU1
SU2
1. Second generation stromatolites (laminated structure, ripple marks)
2. Basaltic blocs, circular anthropic structure
3. Aeolian fine/medium sand
4. Clay-silt, granular structure with terrestrial shells
5. First generation stromatolites (columnar structure)
14C ages (yr cal. BP)

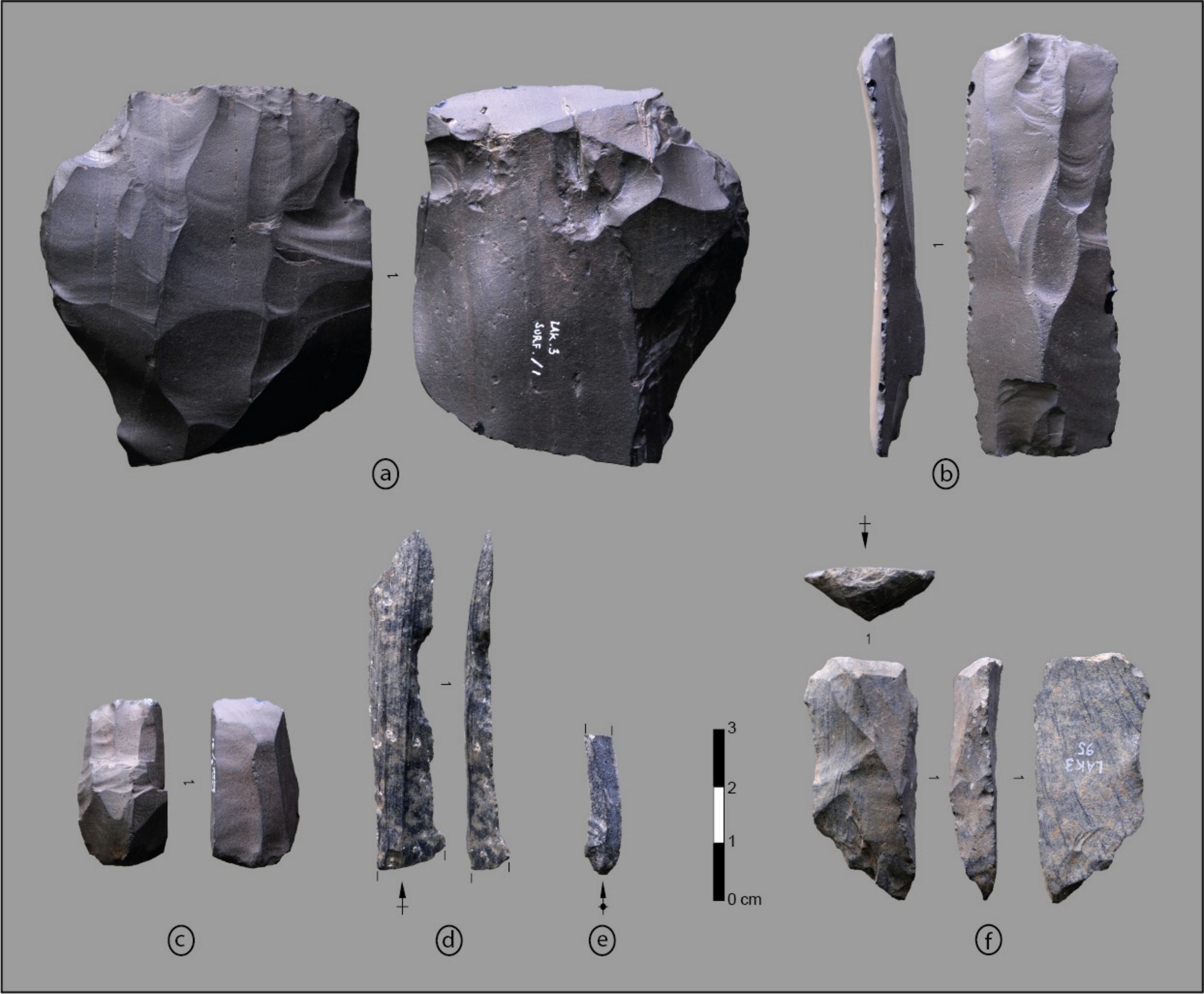


A
SP-01
SP-01 location
Wave surface abrasion
Stromatolitic formation
Lacustrine shell deposit
Archaeological site
Wave-cut terrace
SU
(cm)
Fine sand
(dune formation)
Prismatic clay
(paleosoil formation)
Gravel and clay
(paleosoil formation)
Lithic artifacts
14C ages (yr cal. BP)
7564-7424
(SP-01_US2_001)
380 m
370 m
360 m
Elevation
Abhe transgression phase
(~7.2 - ~5.5 ka cal. BP)
5889-5653
(Strom_7)
B
MS-01
MS-02
Medium/fine sand , poorly laminated
Fine sand/silt , cross-laminated
Fine sand and silt alternance beds
Massive clay alternated with silty/sandy lenses
Brown clay, prismatic to polyhedric structure
Lithic artifacts
14C ages (yr cal. BP)
8190-8000
(MS1_US1_001)
C
41°0'0"E
41°30'0"E
12°0'0"N
11°30'0"N
Stromatolis
MS-01/-02
Det-Bahari-01
SP-01
0
30
60
120 Km
Abhe Lake highstand (9.8- 8.2 ka cal. BP; 370 m a.s.l.)
Dated archaeological sites

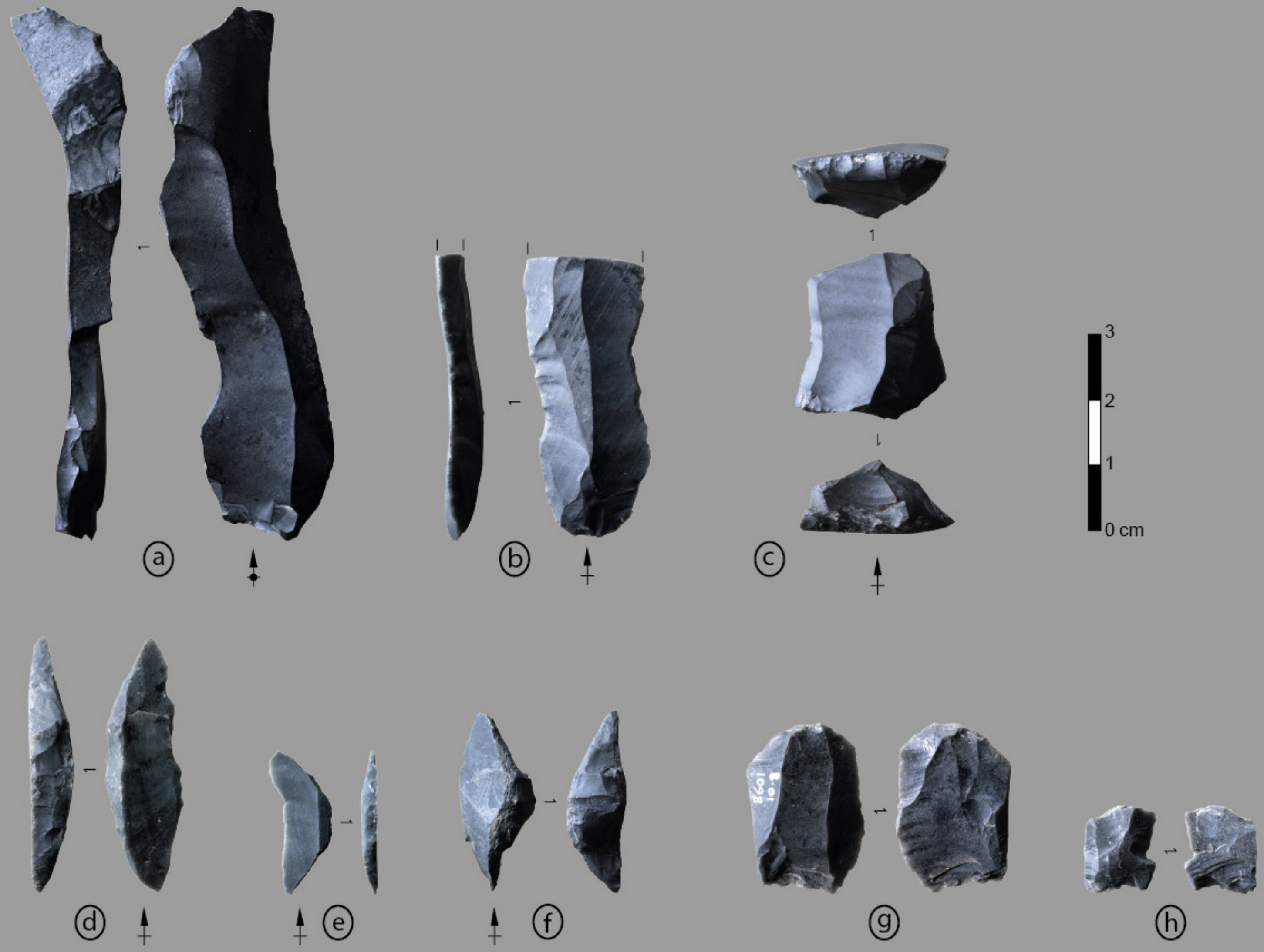


A
Kurub-07
A.1
South
North
K9
K10
K11
K12
K13
K14
K15
K16
Ceramic Pahse 2
Ceramic Pahse 1
3638-3477 (Kur-07-US12-591)
3568-3407 (Kur-07-US12-2459)
3914-3647 (Kur-07-K14-US15-1203)
3830-3587 (Kur-07-L16-US15-1283)
7587-6022 (Kur-07-K15-US18-1488)
(cm)
Charcoal
Lithic artifacts
Pottery
Fauna
14C Ages (yr cal. BP)
Prismatic structure clay
Polyhedric to prismatic structure clay
Polyhedric structure clay/fine silt
Polyhedric structure clay/fine silt with carbonate nodules
Granular structure clay/fine silt
Massive silt
Fine sand
Medium sand
Consolidated fine sand
A.2
1 m
3456-3356 (Kur-07-US10-667)
3611-3450 (Kur-07-US10-1136)
A.3
Plotted artifacts
2018
2017
2016
1 m
N
B
41°0'0"E
41°30'0"E
12°0'0"N
11°30'0"N
Kurub-07
0
30
60
120 Km
Abhe Lake regression (5.5- 4.5 ka cal. BP; 350 m a.s.l.)
Dated archaeological sites


E
Blue Nile
Red Sea
Gulf of Aden
B
D
Djibouti
Awash River
Addis Ababa
C
African Humid Period
4.2
8.2
YD
Arid events
max
Insolation 15°N July
A
B Tana Lake
(Marshall et al. 2011)
Ti mg/g
δD WAX (‰)
(Costa et al. 2014)
(Chalié & Gasse 2002)
Planktonic diatoms (%)
C Ziway- Shala Lake Basin
(Gillespie et al. 1983)
Meters above SD
D Abhe Lake Basin
(Gasse 1975)
m a.s.l.
Abhe-VII
Abhe-VI
Abhe-V
Abhe-IV
Ka BP
Calibrated ages and recalculated lake level elevations from Gasse (1975)
New ages on littoral lacustrine carbonates
Dated archaeological levels:
Occupation phases
Herding
LSA Hunter-Gatherers
1 Kurub-07
2 SP-01
3 Det-Bahari-01
4 Stromatolis
5 MS-01/-02
6 Raso-02
7 Lakora-03



a
b
c
d
e
f
LAK.3
SURF. /1
3
2
1
0 cm


a
b
c
d
e
f
g
h
3
2
1
0 cm
B.01.
1098


A
C
0
5 cm
B
Phase 1: SU 15, 16 and 17
D
Phase 2: SU 7-12
E
F
G
H
I
J
K