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email: is@aber.ac.uk

The Hominin Sites and Paleolakes Drilling Project: High-Resolution Paleoclimate Records from the East African Rift System and Their Implications for Understanding the Environmental Context of Hominin Evolution

CHRISTOPHER J. CAMPISANO

Institute of Human Origins, School of Human Evolution and Social Change, Arizona State University, Tempe, AZ 85287, USA; campisano@asu.edu

ANDREW S. COHEN

Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA; cohen@email.arizona.edu

J. RAMON ARROWSMITH

School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA; ramon.arrowsmith@asu.edu

ASFAWOSSEN ASRAT

School of Earth Sciences, Addis Ababa University, Addis Ababa 1176, ETHIOPIA; asfawossen.asrat@aau.edu.et

ANNA K. BEHRENSMEYER

Department of Paleobiology, National Museum of Natural History, Washington, D.C. 20013, USA; behrensa@si.edu

ERIK T. BROWN

Large Lakes Observatory, University of Minnesota-Duluth, Duluth, MN 55812, USA; etbrown@d.umn.edu

ALAN L. DEINO

Berkeley Geochronology Center, Berkeley, CA 94709, USA; adeino@bgc.org

DANIEL M. DEOCAMPO

Department of Geosciences, Georgia State University, Atlanta, GA 30303, USA; deocampo@gsu.edu

CRAIG S. FEIBEL

Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08854, USA; feibel@eps.rutgers.edu

JOHN D. KINGSTON

Department of Anthropology, University of Michigan, Ann Arbor, MI 48109, USA; jkingst@umich.edu

HENRY F. LAMB

Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, UNITED KINGDOM; hfl@aber.ac.uk

TIM K. LOWENSTEIN

Department of Geological Sciences and Environmental Studies, Binghamton University, Binghamton, NY 13902, USA; lowenst@binghamton.edu

ANDERS NOREN

CSDCO and LacCore, University of Minnesota, Minneapolis, MN 55455, USA; noren021@umn.edu

DANIEL O. OLAGO

Department of Geology, University of Nairobi, Nairobi, KENYA; dolago@uonbi.ac.ke

R. BERNHART OWEN

Department of Geography, Hong Kong Baptist University, Kowloon Tong, Hong Kong; owen@hkbu.edu.hk

JON D. PELLETIER

Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA; jdpellet@email.arizona.edu

RICHARD POTTS

Human Origins Program, National Museum of Natural History, Washington, D.C. 20013, USA; and, Department of Earth Sciences, National Museums of Kenya, Nairobi, KENYA; pottsr@si.edu

KAYE E. REED

Institute of Human Origins, School of Human Evolution and Social Change, Arizona State University, Tempe, AZ 85287, USA; kaye.reed@asu.edu

ROBIN W. RENAUT

Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK S7N 5E2, CANADA; robin.renaut@usask.ca

JAMES M. RUSSELL

Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI 02912, USA; james_russell@brown.edu

JOELLEN L. RUSSELL

Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA; jrussell@email.arizona.edu

FRANK SCHÄBITZ

Institute of Geography Education, University of Cologne, D-50931, Cologne, GERMANY; frank.schaebitz@uni-koeln.de

JEFFERY R. STONE

Department of Earth and Environmental Systems, Indiana State University, Terre Haute, IN 47809, USA; Jeffery.Stone@indstate.edu

MARTIN H. TRAUTH

Institute of Earth and Environmental Science, University of Potsdam, Potsdam 14476, GERMANY; Martin.Trauth@geo.uni-potsdam.de

JONATHAN G. WYNN

School of Geosciences, University of South Florida, Tampa, FL 33620, USA; jgwynn@gmail.com

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ABSTRACT

The possibility of a causal relationship between Earth history processes and hominin evolution in Africa has been the subject of intensive paleoanthropological research for the last 25 years. One fundamental question is: can any geohistorical processes, in particular, climatic ones, be characterized with sufficient precision to enable temporal correlation with events in hominin evolution and provide support for a possible causal mechanism for evolutionary changes? Previous attempts to link paleoclimate and hominin evolution have centered on evidence from the outcrops where the hominin fossils are found, as understanding whether and how hominin populations responded to habitat change must be examined at the local basinal scale. However, these outcrop records typically provide incomplete, low-resolution climate and environmental histories, and surface weathering often precludes the application of highly sensitive, state-of-the-art paleoenvironmental methods. Continuous and well-preserved deep-sea drill core records have provided an alternative approach to reconstructing the context of hominin evolution, but have been collected at great distances from hominin sites and typically integrate information over vast spatial scales. The goal of the Hominin Sites and Paleolakes Drilling Project (HSPDP) is to analyze climate and other Earth system dynamics using detailed paleoenvironmental data acquired through scientific drilling of lacustrine depocenters at or near six key paleoanthropological sites in Kenya and Ethiopia. This review provides an overview of a unique collaboration of paleoanthropologists and earth scientists who have joined together to explicitly explore key hypotheses linking environmental history and mammalian (including hominin) evolution and potentially develop new testable hypotheses. With a focus on continuous, high-resolution proxies at timescales relevant to both biological and cultural evolution, the HSPDP aims to dramatically expand our understanding of the environmental history of eastern Africa during a significant portion of the Late Neogene and Quaternary, and to generate useful models of long-term environmental dynamics in the region.

INTRODUCTION

Scientists have long speculated about how environmental conditions may have influenced hominin evolution. Research into this question is interdisciplinary, involving studies in anthropology, biology, and the earth sciences.

Most of the geologic research involves understanding the geochronological and paleoenvironmental context of hominin fossils. When and where did early hominins live? What climatic conditions did they experience? How did local and regional scale climatic processes combine with

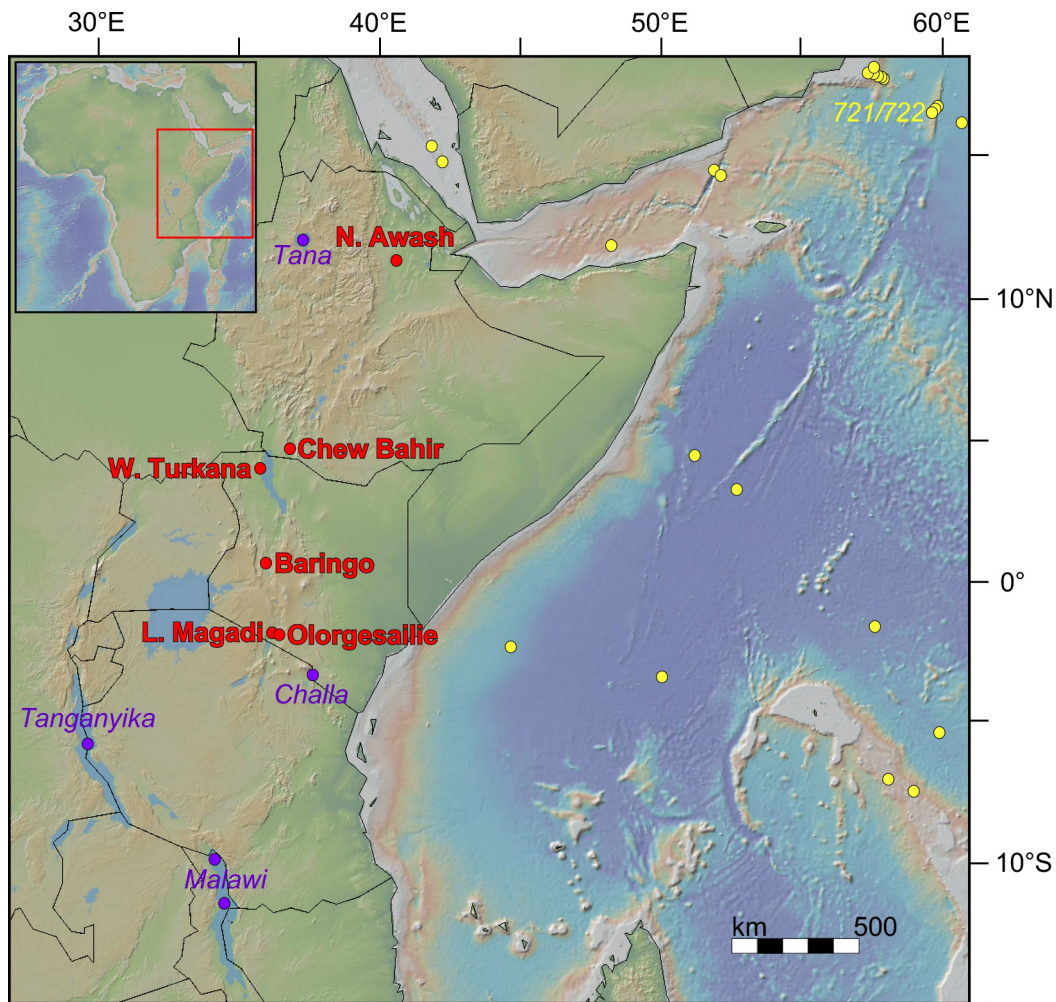


Figure 1. Map of eastern Africa showing the locations of the HSPDP drilling areas (red), modern lakes with long core records discussed in the text (purple), and ODP/DSDP drilling locations (yellow) with ODP Site 721/722 labeled (presented in Figures 4 and 9). The HSPDP sites span ~15 degrees of latitude and much of the last ~3.5 Ma. Base map generated from GeoMapApp.

tectonic processes to influence hominin food resources and demography? How and when did these conditions vary? Can the history of those conditions be related to evolutionary processes and events in the hominin lineage? Over the past two decades, scientists have made major advances in understanding East African paleoclimate (e.g., deMenocal 1995, 2004; Trauth et al. 2005), leading to more nuanced approaches that go beyond notions of a simplistic “savanna hypothesis” in which a unidirectional expansion of the savanna ecosystem drove most aspects of human evolution (e.g., Washburn 1960). With an increasing density and resolution of data, this simplistic view is now being replaced by more sophisticated models of climate as a forcing mechanism for the evolution of hominins and the ecosystems in which they lived (see reviews in Kingston 2007; Levin 2015; Maslin et al. 2015; Potts 1998a, 2013; Vrba 2007).

The Hominin Sites and Paleolakes Drilling Project (HSPDP) was developed to take the next step in addressing the relationship between environmental change and hominin evolution. The four primary goals of the HSPDP are to: 1) expand paleoenvironmental data collected at key paleo-

anthropological localities, upon which tests of hypotheses about environmental drivers of hominin evolution can be based; 2) enhance the resolution and quality of paleoenvironmental data available to address the role of Earth system dynamics in hominin evolutionary processes; 3) compare overlapping time segments to describe how global climate change is expressed at local levels, and thereby to build a high-resolution regional framework of climate and habitat change during hominin evolution in eastern Africa; and, 4) develop process models of environmental change and ecosystem responses during critical intervals of hominin evolution and evaluate these models against our high-resolution core paleorecords. To this end, the HSPDP scientific drilling campaigns from 2012–2014 collected approximately 2km of sediment drill cores from six different paleolake basins proximal to key paleoanthropological sites in Kenya and Ethiopia (Figures 1 and 2, Table 1). Details of the site selections, pre-drilling site surveys, drilling campaigns, and initial core descriptions are presented in Cohen et al. (2016). In this review, our goal is to introduce the HSPDP to the paleoanthropological community, summarize and

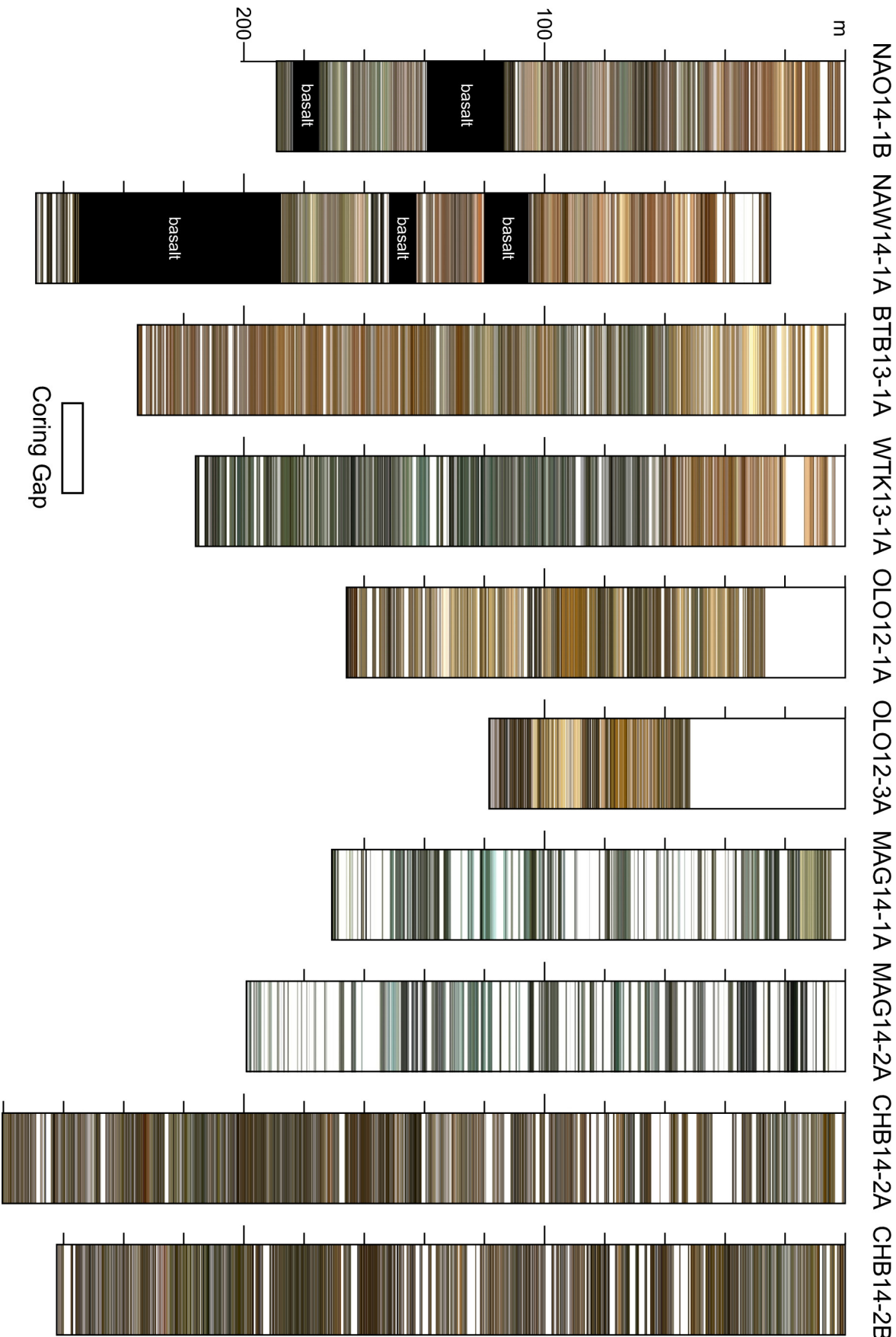


Figure 2. Composite color stratigraphy of the HSPDP drill cores generated from core images. Pure white intervals represent coring gaps (no material collected). Basalt intervals in NAO/NAW have been filled in and are not from color imagery. Coding represents repository prefix (location, year, site, borehole). NAO/NAW: Northern Atwas, BTB: Barrigo Tugen Hills, WTK: West Turkana, OLO: Olorgesatie/Koora Plain, MAG: Lake Magadi, CHB: Chero Bahir. Note: NAO14-1D, not shown, was drilled adjacent to -1B and fills in gaps in -1B. The surfaceltop of NAW is topographically lower than the top of NAO (~3km away) and position is based on tephrocorrelation at ~75m below surface in NAO. The upper portions of the OLO12 cores were auger drilled and sampled.

TABLE 1. HSPDP BOREHOLE SITE INFORMATION (modified from Cohen et al. 2016)
(CL=cored length, CR=core recovered. Does not include anchor, augered only, or short core boreholes where core recovery was less than 5 meters).

Drilling Area (Age)	Core ID	Lat.	Long.	CL (m)	CR (m)	CR (%) ¹
Northern Awash (Late Pliocene)	HSPDP-NAO14-1B	11.3152	40.7369	187.4	205.4	110
	HSPDP-NAO14-1D	11.3152	40.7370	166.7	181.9	109
	HSPDP-NAW14-1A	11.3254	40.7649	244.7	254.6	104
Baringo/Tugen Hills (Late Pliocene - Early Pleistocene)	HSPDP-BTB13-1A	0.5546	35.9375	222.6	210.0	94
West Turkana (Early Pleistocene)	HSPDP-WTK13-1A	4.1097	35.8718	215.2	202.6	94
Olorgesailie/Koora Basin (Middle - Late Pleistocene)	ODP-OLO12-1A	-1.7910	36.4011	139.1 ²	130.8	94
	ODP-OLO12-3A	-1.7887	36.4085	66.3 ³	66.7	101
Lake Magadi (Middle Pleistocene - Holocene)	HSPDP-MAG14-1A	-1.8805	36.2717	125.9	74.5	59
	HSPDP-MAG14-1C	-1.8806	36.2717	26.5	16.8	64
	HSPDP-MAG14-2A	-1.8516	36.2794	194.4	107.7	55
Chew Bahir (Middle Pleistocene - Holocene)	HSPDP-CHB14-1A	4.4225	36.5109	41.5	39.05	94
	HSPDP-CHB14-2A	4.7612	36.7668	283.5	245.4	87
	HSPDP-CHB14-2B	4.7613	36.7670	266.2	240.9	91

¹Core recovery may exceed 100% due to the expansion of sediment in core barrel once collected (particularly hydration of clays).

²The upper ~27m of the borehole was auger drilled with sediment collected in 1m intervals. Total borehole depth ~166m.

³The upper ~50m of the borehole was auger drilled with sediment collected in 1m intervals. Total borehole depth ~116m.

contextualize the debates and hypotheses that the HSPDP intends to address, the advances (and limitations) that scientific drilling can offer over previous strategies, and the “analytical toolkit” employed to reconstruct paleoenvironments and climate variability over space and through time. This introduction to the project provides the foundation and framework for forthcoming data-driven publications generated by the dozens of international scholars currently analyzing and synthesizing the tens of thousands of samples collected by the HSPDP.

PALEOCLIMATE AND HOMININ EVOLUTION

Vrba (1985, 1988) hypothesized that Plio-Pleistocene mammalian evolution and extinction occurred in coordinated *turnover pulses* (Figure 3), driven by directional environmental changes, such as the strengthening of Northern Hemisphere glaciation (NHG) and African aridification, with various lineages responding synchronously to environmental perturbations (Vrba 1995, 2005). However, East African mammalian fossil records now indicate that the

impact of these global mechanisms was mediated at local and regional levels and suggest multiple episodes of Plio-Pleistocene faunal turnover, including ~100 kyr periodicities in faunal changes, some of which correspond to speciation events in hominins (Alemseged 2003; Behrensmeyer et al. 1997; Bobe and Behrensmeyer 2004; Bobe et al. 2007; Reed 2008). In contrast to Vrba, Potts (1996, 1998b) proposed that adaptive evolutionary change might have been concentrated during periods of increased environmental variability (*variability selection*), such as during episodes of maximum insolation amplitude in Milankovitch cycles (Figure 4). Other researchers have explored the potential of strongly periodic climate variability to drive hominin evolution (deMenocal 2004), highlighted the role of short periods of extreme climate variability, such as in the *pulsed climate variability hypothesis* (Maslin and Trauth 2009; Trauth et al. 2005, 2007), and modeled the effects of climatic instability on plasticity and dispersal, such as the *accumulated plasticity hypothesis* (Grove 2014, 2015). Early research concluded that global-scale climatic forcing could

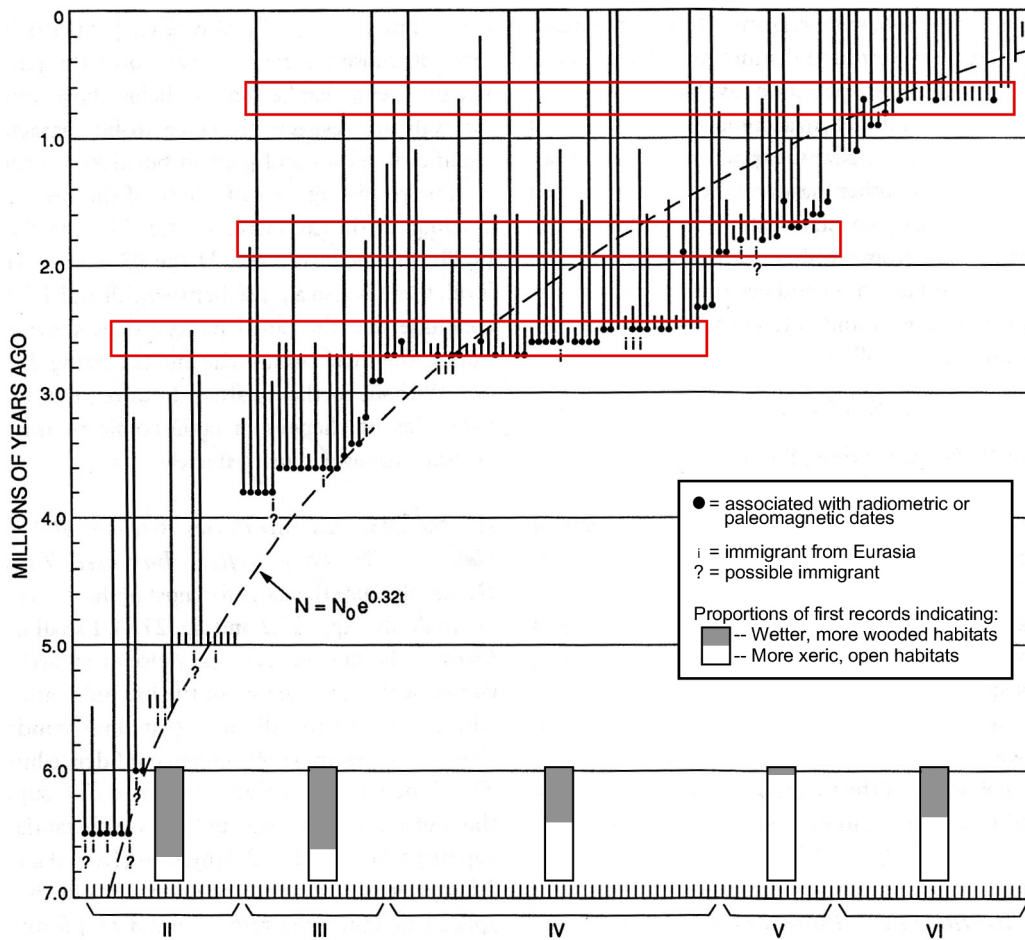


Figure 3. Range chart of first and last appearance datums (FADs/LADs) of African fossil bovids spanning the last 7 Myr as presented by Vrba (1995). The dashed line represents a theoretical “null hypothesis” assuming a uniform rate of faunal turnover set at 32% per million years with $N = N_0 e^{-0.32t}$. X-axis represents individual bovid species with groups (II-VI) based on FAD intervals. Notable faunal “turnover pulses”, clusters of originations, and extinction events are highlighted at ~2.7–2.5 Ma (highly significant), ~1.9–1.7 Ma (significant) and 0.8–0.6 Ma (highly significant). Changes in the proportion of arid-adapted fauna for each FAD interval are also noted. Modified from Vrba (1995).

only be linked to levels of diversity and extinction patterns of hominins (Foley 1994). With the addition of new hominin fossils and refined dating, more recent studies demonstrate that climatic forcing and periods of high climate variability may instead correlate to first and last appearances of hominin taxa and technological/dispersal events (Grove 2012, 2015a; Potts and Faith 2015). Extreme environmental perturbations, such as major volcanic eruptions (Ambrose 1998) or megadroughts (Cohen et al. 2007), have also been implicated as potential drivers of early modern human population fragmentation, genetic differentiation, range expansion events, and occupation of new habitats (Marean 2010; Mellars 2006).

Climate variability, evident from outcrop and core records, has spurred the development of dynamic paleoclimate theories to explain the large changes in precipitation observed in eastern Africa that are potentially relevant to hominin evolution (e.g., deMenocal 1995; Trauth et al. 2005, 2007). Debate has focused on the relative importance of oceanic heat transport versus continental/atmospheric interac-

tions for East African climate. At the longest timescale, Sepulchre et al. (2006) proposed that East African aridity was driven by Late Neogene uplift in eastern Africa, blocking zonal moisture delivery east of the rift margin highlands. Cane and Molnar (2001; Molnar and Cane 2007) attributed the aridification of eastern Africa over the last ~4 Myr to the end of persistent El Niño-like conditions and falling Indian Ocean sea-surface temperatures forced by closure of the Indonesian Seaway between 4 and 3 Ma. On intermediate timescales, there is controversy regarding the relative importance of high-latitude glacial cycles, Walker circulation intensification, and ENSO (El Niño-Southern Oscillation)/IOD (Indian Ocean Dipole) variability for regional aridity, lake expansions and seasonality in tropical Africa, all of which could have influenced the course of hominin evolution. For example, deMenocal (2004) suggested that abrupt increases in aridity and climate variability occurred at ~2.8, 1.7 and 1.0 Ma when high-latitude glacial cycles intensified, noting the temporal relationship of these changes with African mammalian fossil transitions (Figure 5). In

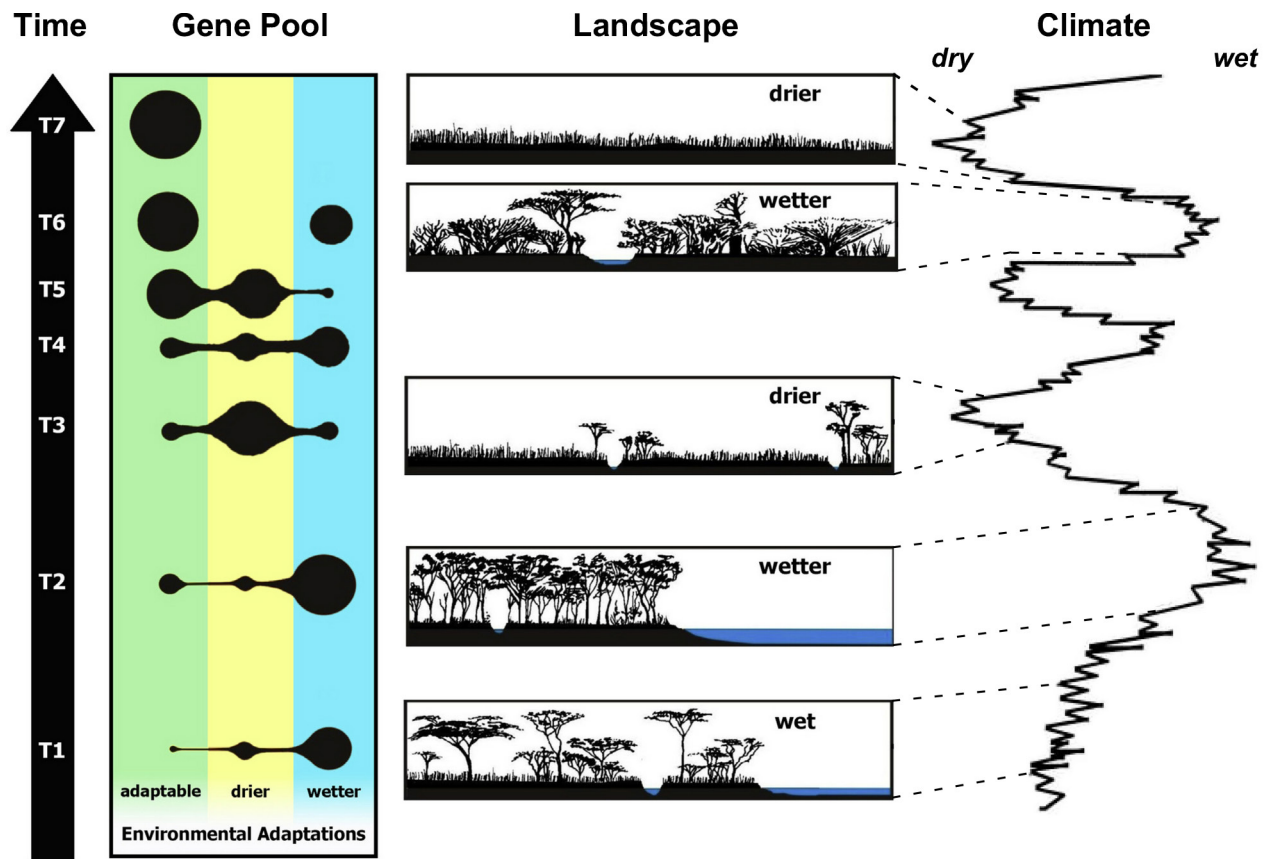


Figure 4. Conceptual model of variability selection based on Potts (1996, 1998). The size of the shapes in each gene pool (left) depicts relative fitness in each interval of time during an interval of high climate variability (right). Changes in a gene pool are hypothesized to result from selective advantages in specific habitats (e.g., adaptations favored in either wet or dry environments) versus the relative advantage of adaptable phenotypes (e.g., adaptations enabling the ability to buffer and adjust to change). Modified from Potts (1988) and Potts and Faith (2015).

contrast, Trauth and colleagues (2005, 2007, 2009) argued that insolation-forced lake expansions and wetter climates with enhanced seasonality occurred during these same intervals, which could have led to vicariance in hominin lineages (Figure 6).

On Milankovitch (~ 100, 40, and 20 kyr) timescales, there is debate about the role of orbital forcing, air-mass boundary positions, and high-latitude millennial-scale events in driving wet-dry cycles that exerted environmental pressures on African ecosystems (e.g., Armitage et al. 2011; Blome et al. 2012; Campisano and Feibel 2007; Kingston et al. 2007; Scholz et al. 2007; Tierney et al. 2011; Trauth et al. 2009), and how these might have influenced ecological parameters affecting hominins, such as the spatial-temporal distribution of resources (Reed and Rector 2007). Studies of Mediterranean sapropels (Kroon et al. 1998; Rossignol-Strick 1985) and terrigenous dust flux records from the Gulf of Aden (deMenocal, 1995) originally showed strong cyclicality in monsoonal precipitation and aridity in phase with both insolation and global ice-volume variations. Many records now show much stronger precessional cyclicality in the expansion and contraction of Plio-Pleistocene East African lakes and precipitation with eccentricity probably modu-

lating these cycles (e.g., Kingston et al. 2007; Joordens et al. 2011; Magill et al. 2012; Scholz et al. 2007). The consequences of eccentricity modulated precession seem to be variable, perhaps because of threshold insolation values required for precipitation changes (deMenocal et al. 2000; Ivory et al. 2016; Trauth et al. 2007). These contrasts between marine and terrestrial records, together with the spatial scale of response to insolation forcing, suggests that continental-scale records such as dust in marine cores may not capture the environmental variability experienced by hominins at the local or regional level (Trauth et al. 2009). This is crucial because many important events in hominin evolution are proposed to have occurred around 2.6, 1.8 and 1.0 Ma, during 400 kyr eccentricity maxima (Trauth et al. 2007). Critically, the implications of millennial-scale or even shorter events for early hominin evolution have scarcely been explored, despite the fact that such events are clearly linked to major demographic and population-level changes in the better known Holocene record of Africa (e.g., Foerster et al. 2015; Kröpelin et al. 2008). Similarly, seasonality has been implicated as a primary determinant of ecology, reproduction, sociality, and life history of tropical primates (Brockman and van Schaik 2005) and documenting the nature and

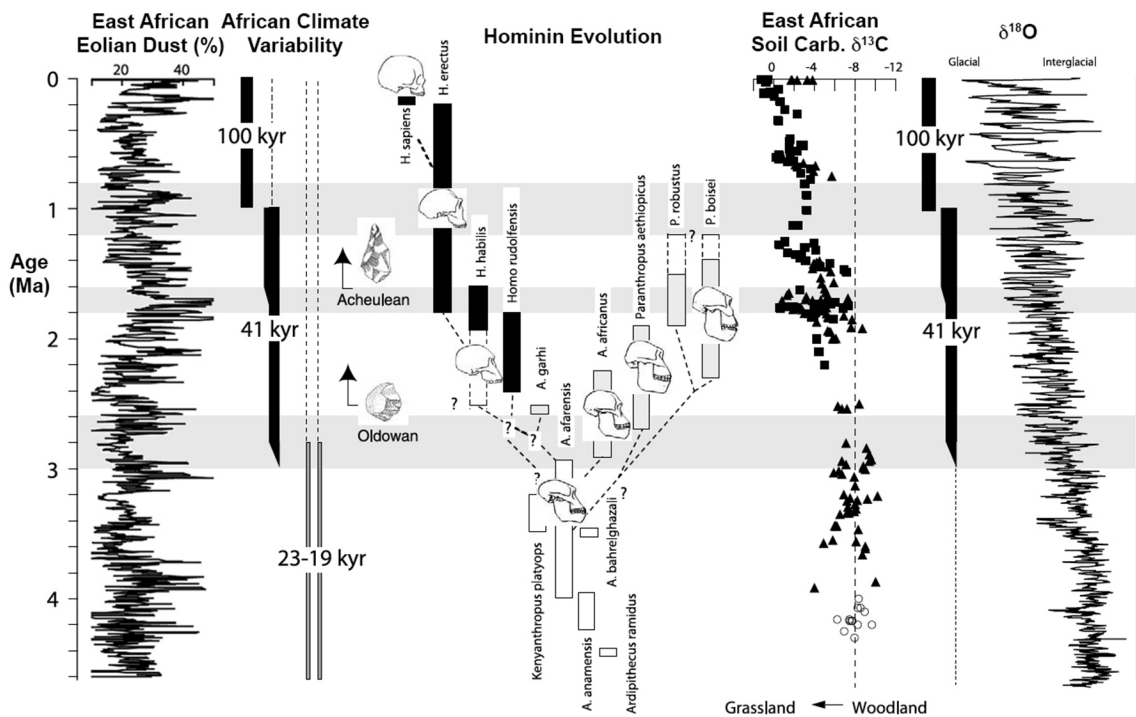


Figure 5. Summary diagram of important paleoclimatic and hominin evolution events during the Plio-Pleistocene as presented by deMenocal (2004). Gray bands indicate periods when African climate (as inferred from offshore dust records) became progressively more arid after step-like shifts near ~2.8 Ma and subsequently after ~1.7 Ma and 1.0 Ma coincident with the onset and intensification of high-latitude glacial cycles. From left to right: Percent of terrigenous dust in ODP site 721/722 with corresponding shifts in the dominant periodicity of the dust flux. Approximate first and last appearance datums and possible relationships among hominin taxa. Soil carbonate carbon isotopic data from East African hominin localities documenting a progressive shift from woodland to grassland vegetation. Composite benthic foraminifer oxygen isotope record illustrating the evolution of high-latitude glacial cycles and dominant periodicity of glacial variability. Modified from deMenocal (2004).

shifts of seasonality in the past has major implications for reconstructing early hominin strategies and selective forces.

The hypotheses linking environmental change and hominin evolution proposed over the past several decades are still debated amongst paleoanthropologists and geologists. Many could be tested with adequately resolved fossil and paleoenvironmental records. Past attempts to test these ideas have foundered on a fundamental mismatch of spatial and temporal data scales, casting globally or continentally-averaged records of climate change against essentially basin-scale records of faunal change, or the evolution of individual hominin species. This approach uses broad strokes to paint the picture linking environmental change and biotic evolution and largely ignores basin-scale environmental dynamics relating to changes in regional climate, local tectonics, and geomorphology, which are also key drivers of mammalian population dynamics. Additionally, current interpretations of East African Rift Valley environmental history use terms such as alternating 'wet' and 'dry' intervals. It is essential to move beyond gross characterization by quantifying paleo-precipitation, water balance (i.e., precipitation-evaporation), and paleotemperature changes, including seasonality, and by articulating the

controls on past environmental changes. Principal controls on the distribution of vegetation and, by extension, dietary resources and community ecology of animal consumers in tropical and subtropical Africa, are total annual rainfall, temperature, and the timing, duration, and intensity of the dry season(s) (e.g., Goheen et al. 2013; Hempson et al. 2015; Ivory et al. 2013; Kartzinel et al. 2015). Furthermore, climate changes are interactive: wet/dry seasons associated with elevated/reduced temperatures would affect the biota in very different ways than when associated with reduced/elevated temperatures.

The objective of the HSPDP is to move beyond these problems and transform this debate, providing an opportunity to test the existing hypotheses and predictions relating global climate change to hominin evolution, as well as more specific hypotheses relevant to each of our study areas. Rather than assume a linkage between environmental history and evolution, we designed this study as a series of data collection and modeling exercises to explicitly test these and other hypotheses discussed below. Such tests need replicability through a series of well constrained "historical experiments" in which congruence and possible cause-effect relationships of environmental and biotic change can be evaluated.

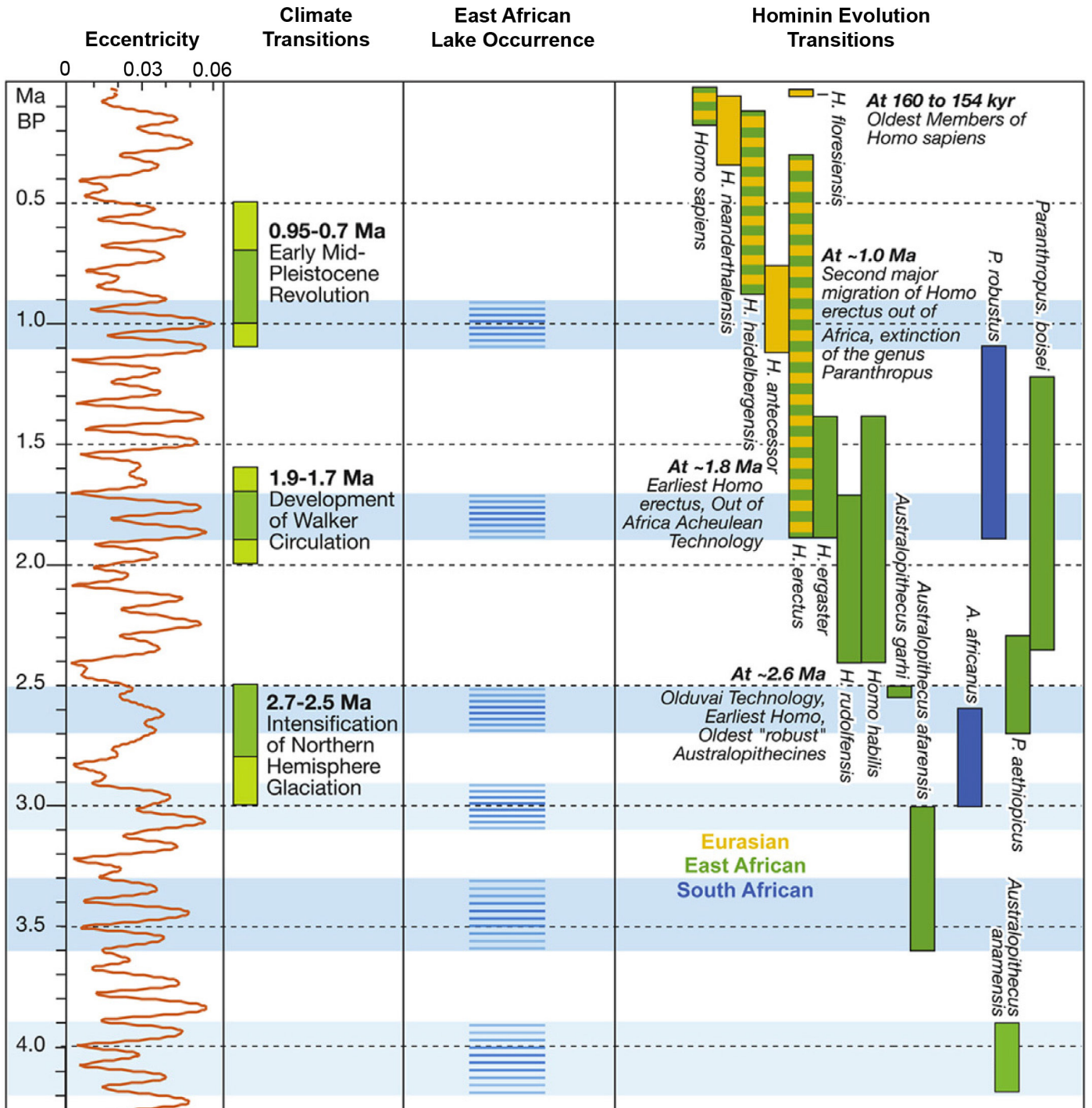


Figure 6. Summary diagram of global climate transitions, East African lake occurrences and hominin evolution as presented by Trauth et al. (2007). Lake occurrences are suggested to cluster during eccentricity maxima prior to 2.7 Ma, then during periods of global climate transitions associated with eccentricity maxima after 2.7 Ma. Modified from Maslin et al. (2014).

ISSUES OF SCALE

Records of extreme climate variability at many timescales are evident in tropical African lake core records (Brown et al. 2007; Tierney et al. 2008). Data (Grove et al. 2015; Kröpelin et al. 2008) and model simulations (Carto et al. 2009; Cowling et al. 2008) for the late Pleistocene suggest these types of events may have been pivotal in influencing diversification and range expansions/contractions of hominins, yet the importance of similar events in deep time for earlier hominin evolution has scarcely been explored. To a large extent, this is because highly-resolved continental climate records prior to the Pleistocene are still rare in Africa. For the Pliocene and early Pleistocene, studies that focus on the long-term environmental trends and hominin evolution have typically been couched in precessional timescales or longer (e.g., Potts and Faith 2015; Trauth et al. 2005, 2007). Largely, this legacy stems from deMenocal's seminal publication and its iconic figure (e.g., Figure 5) of hominin evolution set against the background of orbital-driven increases in aridity and shifts in variability (deMenocal 1995). For the past two decades, orbital precession has provided a convenient and environmentally relevant conceptual framework for hominin evolution, particularly as the temporal resolution and precision of the terrestrial environmental records from hominin localities has only rarely exceeded this resolution. Similarly, alternating "packets" of high and low variability driven by eccentricity modulated precession have provided yet another, larger-scale framework for testing adaptive hypotheses (deMenocal 2004; Potts and Faith 2015).

A major question, of course, is what are the appropriate timescales for studying morphological and behavioral evolution in the hominin record? Clearly, the answer depends on the specific question one is asking, as different timescales are appropriate for different questions. For some aspects of biological evolution, precessional timescales are likely suitable, especially for complex evolutionary transitions involving multiple characters. However, although the rates of mammalian evolution based on fossil lineages typically suggest that evolution is very slow, Gingerich and others have shown that rates of phenotypic change can be very rapid, occurring at generation scale in the face of strong selection pressures, and that results on longer timescales are cumulative, reflecting evolutionary history (Gingerich 1993, 2001, 2009; Grove 2014; Hendry and Kinnison 1999; Kinnison and Hendry 2001). Cultural adaptation and evolution, on the other hand, consistently operate on much faster timescales and are likely more important when considering the more recent Pleistocene and Holocene intervals of hominin evolution (Perreault, 2012; Richerson and Boy, 2005). During the Holocene, adaptive changes in modern human populations have occurred on generational to millennial timescales (e.g., Lorenzo et al. 2014; Perreault 2012; Tishkoff et al. 2007), and comparable evolution in Middle/Late Pleistocene hominin populations may have occurred equally rapidly. To examine the possibility of climatic influences on evolution at such timescales, we need paleoenvironmental records that can reveal decadal (i.e., genera-

tional) to millennial-scale patterns, as we shift our focus to sub-precessional climate dynamics and their potential impact on the East African landscape.

Half (~11 kyr) and quarter (~5.5 kyr) precession-related insolation cycles have been predicted at the equator and in intertropical regions and are evident in vegetation models for African monsoon regions (Ashkenzy and Gildor 2008; Berger et al. 2006; Tuenter et al. 2007). This is supported by empirical data from low-latitude marine sites that imply suborbital climate variability recorded in ocean cores, particularly half-precession cycles, can be attributed to a non-linear response to precession (e.g., Billups and Scheinwald 2014; Hagelberg et al. 1994; Niemitz and Billups 2005; Oppo et al. 2003). Similarly, lacustrine outcrop records from Lake Naivasha and core records from Lake Challa (equatorial Kenya) and Lake Malawi have demonstrated variation in monsoon rainfall at half-precessional cycles in phase with orbitally-controlled insolation forcing (Ivory et al. 2016; Trauth et al. 2003; Verschuren et al. 2009).

Millennial-scale climate variability during the last glacial period has been well documented, particularly Dansgaard-Oeschger (D-O) events that are characterized by a rapid warming from a cold stadial to a warm interstadial phase followed by a gradual cooling back to stadial conditions, possibly driven by changes in convective thermohaline ocean circulation (e.g., Dokken et al. 2013; Rahmstorf 2002 and references therein). D-O events have a quasi-periodicity of ~1,470 years (Bond et al. 1997; Rahmstorf 2003) and the transition periods from cold to warm (decade or less) and, possibly, from warm to cold (~50–200 years), would have been experienced on human generational timescales. D-O event teleconnections have been recognized beyond the North Atlantic and into the tropics (e.g., Brown et al. 2007; Burns et al. 2003; Hendy and Kennett 2000; Wang et al. 2001) including data from the HSPDP site of Chew Bahir, Ethiopia, which records millennial-scale climate variability (wet-dry phases) resembling D-O cycles over the past 46,000 years (Foerster et al. 2012, 2014). The cooling related to D-O and, in particular, Heinrich events in northern latitudes have been suggested to lead to increased aridity and a southward shift in the ITCZ migration to lower latitudes (Brown et al. 2007; Carto et al. 2009; Schneider et al. 2014; Tierney et al. 2008). Climate model simulations by Carto et al. (2009) centered on Heinrich Event 9 (~105 ka) have been used to propose that large parts of North, East and West Africa would have been unsuitable for hominin populations and led to the dispersal of early *Homo sapiens* out of Africa at this time. However, a more recent model integrating climate and dispersal by Timmerman and Friedrich (2016) indicates that although D-O variability impacted the habitability and population density in the Levant and North Africa, the overall effect on human dispersal times (such as during MIS 5) may be negligible. Evidence suggests that millennial-scale D-O-like climate variability was not restricted to just the last glaciation, but may have been a pervasive component of all glaciations for the last million years (Hernandez-Almeida et al. 2015; Raymo et al. 1998) and possibly since the onset of Northern Hemi-

sphere glaciation ~2.75 Ma (Bartoli et al, 2006; Hayashi et al. 2010). If so, then such millennial-scale variability would have characterized the environmental context of our genus *Homo*, perhaps since its origin. The broad latitudinal and temporal range of the HSPDP sites can also be integrated with datasets from other scientific drilling projects to provide insights into the abruptness, amplitude, and duration of potential D-O and D-O-like events and impacts on hominin landscapes.

The HSPDP endeavors to generate environmental records on a variety of timescales to understand the frequency, rates, magnitude, and directionality of environmental change. All of these variables affect the availability, distribution, and seasonality of resources (e.g., vegetation cover, food resources, water quality) upon which hominins might have depended and thus are crucial for understanding how environmental change may have influenced hominin evolution and technological innovation. As noted by Foerster et al. (2015), we also need to examine adaptation as a matter of timescale and determine whether short-term events, long-term gradual transitions, or both (possibly reinforcing or amplifying each other) were the relevant drivers. If we assume that the modulation between “wet-dry” cycles in African climate had important implications for hominin evolution, then investigating the characteristics of transitions between these two states becomes paramount. Abrupt changes to unfavorable habitats may have triggered local extinctions, dispersal, or behavioral changes such as alternative subsistence strategies that could have allowed a population to persist in the same location. Alternatively, assuming a critical threshold is not crossed, gradual transitions would allow a longer period for populations to adapt morphologically and/or behaviorally to changing environments.

In order to evaluate the congruence of environmental change and hominin/large mammal evolution in eastern Africa, two requirements must be met: 1) a highly resolved paleoenvironmental record to examine environmental change at any temporal scale that could realistically serve as an evolutionary trigger or alter the parameters of natural selection on individuals and populations. This record would span the range from sub-annual records preserved in archives such as seasonal lake deposits, pollen records of seasonally-sensitive plants, lipid markers of temperature, etc., to geochemical or sedimentological records of phenomena such as major tectonic uplift or paleoceanographic events, which might operate over $>10^6$ years; and, 2) a record of faunal change dynamics from the same region that is sufficiently detailed to study responses to environmental change within particular clades, ecological guilds, or mammal communities. HSPDP is designed to improve understanding of the implications of ecosystem change for hominins in two ways: 1) to provide orbital- to sub-millennial-scale environmental data at key time periods that correspond to morphological and/or behavioral transitions or other perceptible evolutionary change in hominin and other mammalian lineages; and, 2) to compare these data in six different basins located in a broadly similar geological

setting. Integrating records of environmental change from cores with the record of environmental, faunal, and cultural change from outcrops affords us the opportunity to test hypotheses of Earth system drivers of evolution at different temporal and spatial scales. Such responses might play out on numerous scales, and with potentially variable time-lags, which is precisely why it is essential for our experimental design to have several areas from which to obtain highly-resolved environmental records and compare them.

WHY DRILL?

Scientific drilling at or near lacustrine depocenters can offer three key advantages over traditional outcrop-based studies of paleoenvironmental records: greater continuity, higher temporal resolution, and greater potential for unweathered and unaltered material. Valuable records have been assembled from outcrops (e.g., paleosols and ecologically-sensitive fossil remains) associated with paleoanthropological localities (e.g., Cerling et al. 2011; Kingston and Harrison 2007; Levin et al. 2011; Reed 2008). These records are critical for documenting environmental conditions at hominin fossil sites, especially in terms of revealing spatial variation and trends in paleoenvironments, and will ultimately be integrated with the drilling datasets. However, most of these existing records are discontinuous, time-averaged, and/or of relatively low temporal resolution. Obtaining the high-resolution, high-sensitivity records needed to address the questions raised here typically requires the continuity, completeness, and precision that can only be supplied by marine and lacustrine drill cores. Deep-sea paleoclimate records obtained from drilling have been useful in framing hominin evolution - paleoclimate debates (e.g., Feakins et al. 2005; deMenocal 1995, 2004), as have deep lake drill cores from southeastern Africa (e.g., Cohen et al. 2007; Lyons et al. 2015). However, these records have their own limitations, notably their great distance from the outcrop belts where the vast majority of hominin fossils have been found. Also, most East African lake cores collected to date cover only the Late Pleistocene and Holocene. Lake deposits archive many paleoenvironmental variables, with a combination of long duration high-resolution and spatial information that is unmatched. Recent drill-core studies by some members of the HSPDP science team have demonstrated the ability of these types of records to provide high-resolution records ($\sim 10^1$ yr) of climate, landscape, and vegetation change (Brown et al. 2007; Ivory et al. 2012; 2016; Jackson et al. 2015).

Even well-exposed outcrop records have discontinuities at all scales imposed by outcrop belt exposure, as well as hiatuses represented by paleosols and erosional surfaces. Drilling adjacent sediments in lacustrine depocenters avoids or minimizes many of these gaps, and allows for high-resolution records to be collected over the same intervals when the hominin fossils accumulated nearby in more fragmentary stratigraphic contexts. Although hiatuses do occur in lacustrine basin depocenters, including in many of the HSPDP cores, their frequency is typically much lower than in the terrestrial deposystems where hominin fossils

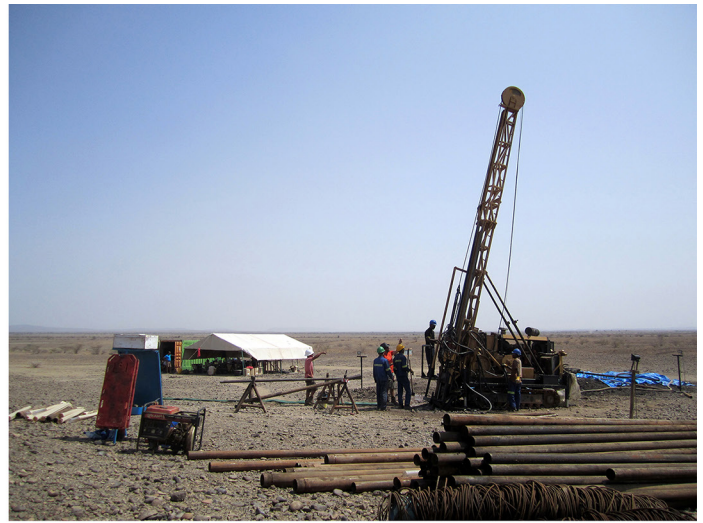


Figure 7. Photos of the HSPDP drilling operations. Left: West Turkana (WTK) site using a truck-mounted PRD Multistar drilling rig operated by Drilling and Prospecting International (DPI) used for all Kenyan drilling campaigns (photo credit: Craig Feibel). Right: Northern Awash (NAO) site using a track mounted Christensen CS14 drilling rig operated by Geosearch (now Orezone Drilling) used for Ethiopian campaigns (photo credit: Beau Marshall).

are typically found. Their presence can be identified sedimentologically and reasonably estimated using age modeling and the numerous geochronological techniques at our disposal (e.g., Deino et al. 2016; Scholz et al. 2007). Additionally, compared to discrete outcrop sampling, drilling allows for the continuous measurement of key variables and the methods for high-resolution analysis of long stratigraphic intervals are well developed for drill cores (e.g., Brown et al. 2007). The potential of continuous, automated scanning techniques on cores (e.g., multisensor core-logging or scanning XRF) and high-resolution color imaging to provide annual-decadal scale data is lost when using discrete samples.

In many cases, surficial weathering of outcrops can destroy key paleoclimate indicators such as organic compounds and alter sediment chemistry. Weathering studies of outcropping lake beds in arid climates show significant and unpredictable loss of organic matter down to at least 4m below the surface (Petsch et al. 2000), and weathering features can even extend tens of meters below the surface in drill cores (Clyde et al. 2013, 2016). Coring is the only way to avoid this problem given that organic geochemical proxies (“biomarkers”) play a crucial role in our quantitative paleoclimate reconstructions of temperature, precipitation, and vegetation type (e.g., Castañeda and Schouten 2011; Clyde et al. 2013). Diagenetic or pedogenic alteration can also change primary lacustrine geochemical and mineralogical signatures in carbonate, silicate, and sulfide/sulfate systems (Deocampo 2010, 2015; Fike et al. 2015). The preservation of microfossil environmental indicators also is highly susceptible to surface alteration or dissolution (e.g., Campbell and Campbell 1994; Deocampo and Ashley 1999), as is the preservation of fine sedimentary structures such as laminations and redox sensitive sediment chemistry (e.g., Jaffe et al. 2002; Petsch et al. 2003) analyzed by

scanning X-ray fluorescence (XRF) that are critical to unraveling changes in seasonality.

THE HSPDP SITES

The HSPDP drilling locations (see Figure 1, see Table 1) were selected following a series of international workshops and extensive consultation with the broader paleoanthropological and earth science communities to identify sequences that would yield high-resolution paleoclimate records associated with hominin fossil and/or artifact sites spanning critical intervals of hominin evolution (Cohen and Umer 2009; Cohen et al. 2006, 2009). Our primary criteria for selecting sites were: 1) high stratigraphic continuity and resolution through the time interval of interest so that high-quality and representative paleoclimate records could be assembled; 2) lake deposits at or near important fossil/artifact sites, such that high-quality paleoenvironmental records could be directly linked to paleontological and archaeological assemblages at the watershed scale; and, 3) accessible at reasonable cost by a truck-mounted drill rig (Figure 7). Additionally, the selected sites were evaluated based upon outcrop and subsurface geophysical data to identify the exact drilling location within each basin (Cohen et al. 2016).

THE NORTHERN AWASH, ETHIOPIA

The Northern Awash region of Ethiopia has yielded one of the densest accumulations of Pliocene fossil hominins including ~90% of the species *Australopithecus afarensis* (Alemseged et al. 2006; Kimbel et al. 2004; Johanson et al. 1982). The region also preserves a rich and highly-resolved record (<10⁵ yr) of late Pliocene mammalian fauna and flora (Bonnefille et al. 2004; Geraads et al. 2012; Reed 2008). The drilling target for this site was the lacustrine depocenter of the Hadar Formation ~3.6–2.9 Ma, which is located in the

Ledi-Geraru area, ~30km northeast of the *Australopithecus afarensis* bearing exposures of Hadar and Dikika (Campisano and Feibel 2008; DiMaggio et al. 2008; Dupont-Nivet et al. 2008; Quade et al. 2008; Wynn et al. 2008). Two sites were drilled (~3km apart) for a composite stratigraphic interval of approximately 270m. The top of the core captured the top of the Hadar Formation (e.g., above Gulfaytu Tuff D, <2.93 Ma, DiMaggio et al. 2015), whereas the age of the base of the core is still to be determined, but is well below a tephra dated to 3.22 Ma (Garello et al. 2015a). The lithology of the core is dominated by fine-grained sediments, principally lacustrine deposits, some with evidence of periodic subaerial exposure and pedogenesis in the upper half, as well as three basalt sequences (Figure 8A–C) (Campisano et al. 2014; Garello et al. 2015a). Diatom assemblages indicate that the lake was episodically deep and well-mixed (Mohan et al. 2016; Stone et al. 2016).

Utilizing a variety of geochronological tie points ($^{40}\text{Ar}/^{39}\text{Ar}$ dating, tephrostratigraphy, and the Kaena and Mammoth paleomagnetic subchrons), this site will provide the environmental backdrop against which >500 kyr of the evolutionary history of *A. afarensis* and associated fauna can be interpreted from multiple adjacent paleoanthropological project areas including Hadar, Dikika, Gona, Ledi-Geraru, and Woranso-Mille. This history includes a distinct faunal turnover at ~3.1 Ma indicating a significant ecological change with an increase in, and influx of, more arid-adapted mammalian taxa (Reed 2008). This turnover coincides with the onset of high-amplitude climate oscillations and increased aridity in eastern Africa between 3.15 and 2.95 Ma as noted in marine core isotope and dust records (Campisano and Feibel 2007; Trauth et al. 2009). Additionally, this high-resolution lacustrine depocenter has the potential to record the local environmental response to Milankovitch cycles prior to the onset of Northern Hemisphere glaciation and high-latitude glacial cycles (Campisano and Feibel 2007). The change in the robustness of *A. afarensis* mandibles after 3.1 Ma (Lockwood et al. 2000) may be linked to the taxon becoming more resource-stressed in response to glacial cooling after 3.2 Ma as a result of reduced mean annual rainfall (MAR) and/or extended dry seasons. Reed and Rector (2007) hypothesized that a decrease in MAR and terrestrial temperatures, with corresponding seasonal and vegetation fluctuations, may have resulted in dietary changes in fallback foods for *A. afarensis*.

THE TUGEN HILLS/BARINGO BASIN, KENYA

The Tugen Hills of the central Kenyan Rift Valley comprises the most complete late Neogene section known from the East African rift, with sedimentary strata spanning the last 16 Myr (Behrensmeyer et al. 2002a; Chapman and Brook 1978; Hill 2002). Within this sequence, the drilling target was a Pliocene portion of the Chemeron Formation (~5.3–1.6 Ma, Deino and Hill 2002; Deino et al. 2002), which contains ~100 fossil vertebrate localities, including three hominin sites, within 3km of the drill site that can be directly linked to the core. Elsewhere in eastern Africa at this time period we also observe the diversification of *Paranthropus*

and *Homo*, the earliest evidence of lithic technology, and the earliest evidence for Oldowan stone toolmaking (Harmand et al. 2015; Semaw et al. 1997; Villmoare et al. 2015; Walker et al. 1986). The ~228m borehole from the Tugen Hills, positioned ~20m from cliff exposures of Chemeron sediments, spans approximately 3.4–2.6 Ma and records fluviolacustrine deposits and floodplain paleosols dominating the lower half of the core, with cyclic deep-lake diatomites and subaerially deposited sediments in the upper half (Figure 8D–E) (Garello et al. 2015b; Kingston et al. 2015). A high-resolution chronostratigraphic framework for the sequence based on $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of multiple tephras from local stratigraphic sections (Deino and Hill 2002; Deino et al. 2002, 2006; Kingston et al. 2007) will provide additional age-control and correlations to the core (Garello et al. 2016).

The upper portion of the core can be directly correlated to the outcrop sequence between 2.69 and 2.58 Ma, consisting of a distinctive series of lacustrine/diatomite units documenting abrupt and repeated cycles of major freshwater lake-systems alternating with terrigenous sediments. The lacustrine phases have been linked directly to insolation forcing by precession at 23 kyr pacing, at the maximum of an eccentricity cycle (Deino et al. 2006; Kingston et al. 2007). The specific link between the timing of the five paleolakes and insolation maximum for the June/July 30°N insolation curve, indicates that precipitation patterns in the region were controlled by the orbital forcing of the African summer monsoon and that climatic processes outweighed tectonic influences on hydrologic patterns at 10^5 yr timescales during the early Pleistocene in the Baringo Basin. Critically, this sequence provides the first high resolution record on the African continent to span the period from prior to Northern Hemisphere glaciation, through the onset of glaciation, and continuing into the period of intensification of glaciation. This provides us with a unique opportunity to explore not only how tropical terrestrial communities responded across a major global climate transition, but also how shifting insolation patterns and/or glacial cycles influenced environmental changes in the Rift Valley via pervasive, short-term climatic fluctuations.

WEST TURKANA, KENYA

The Turkana Basin of northern Kenya and southern Ethiopia contains one of the richest long-term records of Plio-Pleistocene faunal evolution (Bobe 2011). The cored interval targeted the early Pleistocene lacustrine strata of the Kaitio and Natoo Members of the Nachukui Formation. The core spans ~1.9–1.4 Ma (Feibel et al. 2015) and documents a well-known lacustrine interval in the basin (the Lorenyang Lake) that existed during a phase of overall increasing African continental aridity punctuated by major lake-level fluctuations, which appear to reflect insolation-forced climate cycles (Joordens et al. 2011; Lepre et al. 2007). The ~216m borehole from the Kaitio locality was positioned adjacent to exposed outcrops of equivalent age, which are the subject of a parallel study. The lower three-quarters consist of massive to laminated lacustrine clays with intervals of episodic exposure and pedogenesis, whereas the upper quarter of

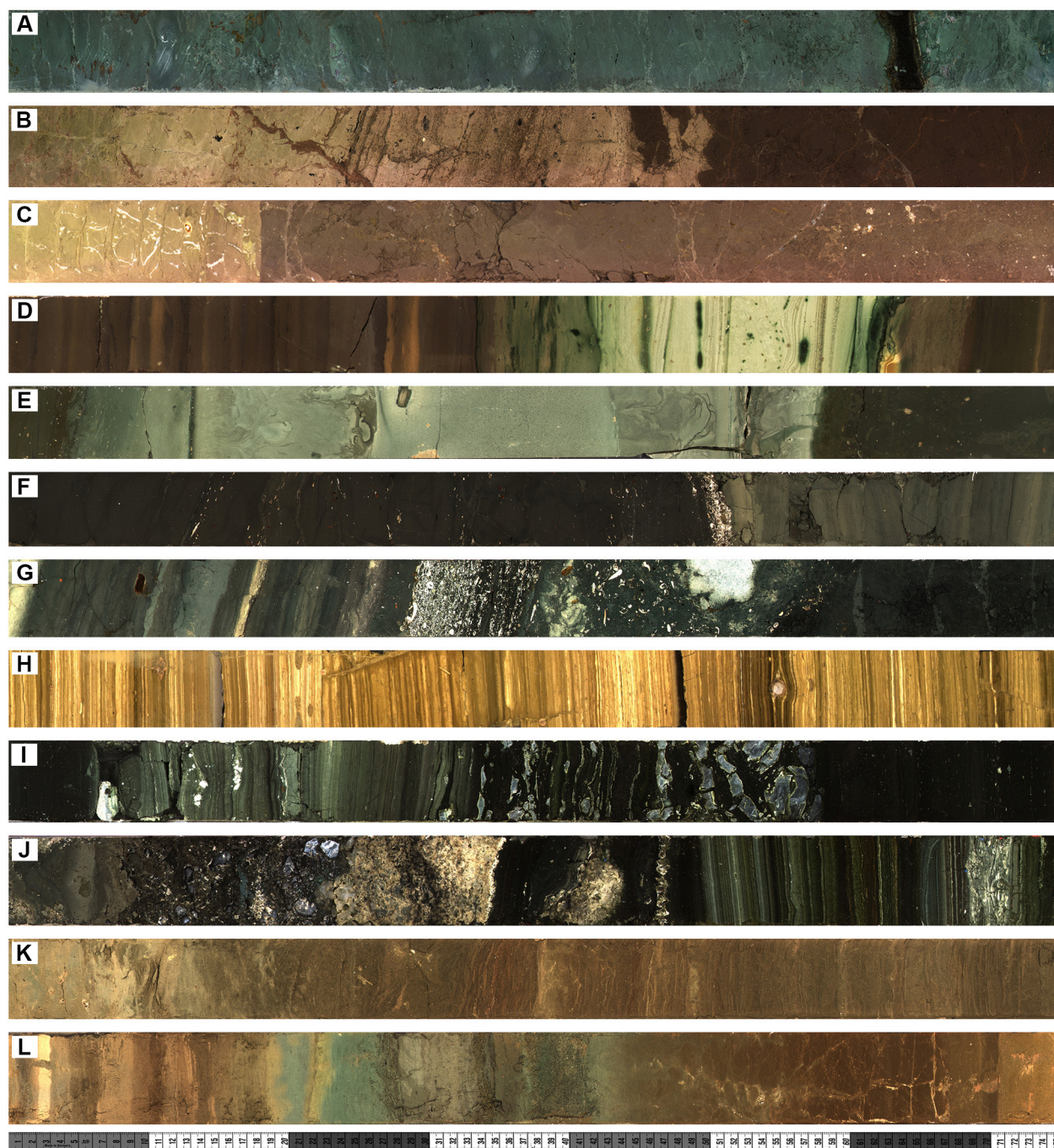


Figure 8. Examples of lithologies from the HSPDP drill cores. Core segments labeled as in Table 1 and Figure 2 with approximate meters below surface (mbs) noted. All core segments have been cropped to 75cm long sections with depth increasing to the right. A) NAO14-1B (~72mbs), massive and laminated green clays with basaltic vitric tephra. B) NAW14-1A (~31mbs), laminated diatomaceous clay overlying massive brown silty clay. C) NAW14-1A (~50mbs), laminated light green clay overlying massive brown silty clay overlying brown silty clay paleosol. D) BTB13-1A (~111mbs), greenish white tuffaceous silt (altered) between dark brown laminated and bedded silts. E) BTB13-1A (~65mbs), greenish grey silts with soft sediment deformation overlying dark massive silts. F) WTK13-1A (~89mbs), dark greenish grey clay with shell fragments and coquina bed at base overlying bedded greenish grey clay. G) WTK13-1A (~150mbs), laminated and bedded green silty clays overlying coquina and massive sandy clay overlying massive dark green clay. H) OLO12-1A (~108mbs), finely laminated diatomite and diatomaceous clay with two tephra (gray and black units). I) MAG14-1A (~77mbs), finely laminated green silty clay overlying black silty clay with interbedded chert overlying laminated black clayey silt. J) MAG14-2A (~66mbs), (upper ~20cm is drilling breccia) trona overlying black clay with trona and chert overlying finely laminated green and black clay. K) CHB14-2A (~217mbs), light brown shelly silt overlying finely laminated brown sand. L) CHB14-2B (~75mbs), laminated brown and green silty sand overlying massive brown clay and clayey silt.

the core reflects more terrestrial deposition (Figure 8F–G). Overall the succession represents a regressive lacustrine sequence from deep lake, to fluctuating lake margin, to delta plain (Feibel et al. 2015).

Using the top of the Olduvai paleomagnetic subchron and several tephrostratigraphic tie points, the Kaitio core can be directly associated with the rich Pleistocene paleontological and archaeological record of the Turkana Basin (Feibel et al. 2016). The hominins in this time frame include important specimens, including some of the earliest and most complete fossils of early *Homo* (*H. habilis/rudolfensis*) and *H. ergaster*, and the archaeological inventory includes both Oldowan as well as the earliest known Acheulean material (Lepre et al. 2011; Roche et al. 2003). The critical interval covered by the Kaitio core also includes the period when hominins first displayed fully terrestrial adaptations similar to modern humans as well as when they expanded their range outside of Africa, an expansion of East African grassland habitats, and an episode of major faunal turnover in the region (Antón 2003; Bobe and Behrensmeyer 2004; Bobe and Leakey 2009; Levin et al. 2011; Rose 1984). The West Turkana datasets will allow us to test several key hypotheses relating major events in hominin and other faunal evolution shortly after 2 Ma to environmental change. In particular, we can explore if and how Turkana Basin environments, especially the Lorenyang Lake, responded to a peak in high-latitude climate sensitivity (Ravelo et al. 2004), increased precessional forcing and African humid phases (Trauth et al. 2007), and/or an intensification in the development of Walker circulation in the Pacific Ocean (Ravelo 2006; Ravelo et al. 2004) starting around 1.8 Ma. Additionally, we can test whether potentially non-climatic forcings, such as volcano-tectonic events, may have led to hydrologic or topographic changes in the basin that altered basal habitats (e.g., Lepre 2014).

THE KOORA BASIN AND LAKE MAGADI, KENYA

The HSPDP and its sister project, the Olorgesailie Drilling Project, targeted two adjacent Pleistocene-modern depocenters in the southern Kenya rift to provide regional equatorial paleoclimate records over the past ~1 Myr, encompassing the history of the major Middle-Late Pleistocene climate transitions. Extensive outcrops of the Olorgesailie Formation (0.5–1.2 Ma) and post-Olorgesailie Formation sediments (~5–310 ka) in the southern Kenya Rift provide a rich and well-calibrated record of archaeological sites, faunas, and changing paleoenvironments (e.g., Behrensmeyer et al. 2002b; Owen et al. 2008; Potts et al. 1999; Sikes et al. 1999). This includes a record of the major transition from the persistent Acheulean technology, which is characterized by large cutting tools from nearby rock sources, to a novel system of behavior, the early Middle Stone Age (MSA), characterized by diverse tool kits and greater dependence on distant rock sources for stone tools. Prior research on the Olorgesailie outcrops has already fueled hypotheses and debates about climate-evolution relationships (e.g., Owen et al. 2008, 2009a, b; Trauth and Maslin 2009), which will be

tested with our new cores.

The Koora Basin site is located ~25km south of the Olorgesailie outcrops. Three locations were cored or auger-drilled with a maximum depth of ~162m before reaching the trachyte bedrock. The cores consist of massive and laminated mudstones and diatomites, fine to coarse sands, and numerous pumice-rich gravel and conglomerate units (Figure 8H) (Cohen et al. 2016; Potts et al. 2014). Preliminary age ranges of the core extend from the ~1.1 Ma trachyte to ~90 ka near the top (Deino et al. 2016). The outcrop and core records can be correlated via $^{40}\text{Ar}/^{39}\text{Ar}$ dating and tephrostratigraphy using the numerous volcanoclastic ashes and pumice-rich units preserved in the core as well as the Brunhes/Matuyama paleomagnetic boundary (Deino et al. 2016). This enables direct temporal links between Olorgesailie archeological sites documenting the Acheulean-MSA transition and the paleoenvironmental evidence from the core.

Less than 20km from the Koora Graben site, the HSPDP also targeted Lake Magadi, a regional sump for water and sediments in the axis of the southern Kenya Rift. Modern Lake Magadi is a saline pan, a successor to a series of paleolakes that have likely occupied the basin for about one million years. Earlier drill-cores (Surdam and Eugster 1976), none of which survive, and geophysical evidence (Prodehl et al. 1997; Simiyu and Keller 2001) confirmed prior to HSPDP that a thick sequence of lacustrine sediments underlies Lake Magadi. The oldest sediments previously drilled, the Oloronga Beds (~0.8–0.3 Ma or later), are tuffs, fossiliferous limestones, diatomaceous siltstones, and cherts that were deposited in a large lake (Baker 1958, 1963; Behr 2002). These are overlain by the Green Beds (98–40 ka in outcrop though full age range is unknown), lacustrine silts and zeolitic tuffs that were deposited in an alkaline lake (Behr, 2002; Goetz and Hillaire-Marcel 1992). The succeeding High Magadi Beds are silts, zeolitic tuffs, rhythmic laminites, and evaporites that formed in a larger alkaline to fresh water paleolake during the late Pleistocene and early Holocene (~23–10 ka) (Butzer et al. 1972; Damnati and Taieb 1995; Taieb et al. 1991). Earlier coring had shown that as much as 40m of bedded trona (the Evaporate Series of Baker [1958]) was deposited upon the older sediments since the early to mid-Holocene.

Two different sites were cored by the HSPDP at Lake Magadi, ~3km apart. Similar to the Koora Basin site, cores reached the bedrock trachyte at a maximum depth of ~194m. The age-models for these cores, to be constructed via radiocarbon, Uranium-series (of cherts), $^{40}\text{Ar}/^{39}\text{Ar}$, and paleomagnetic dating techniques, are in progress. Most of the cores are composed of laminated or massive lacustrine muds interbedded with varying proportions of chert (Figure 8I–J). These abrupt contrasts in lithology complicated coring efforts and resulted in core recovery of only ~60% (see Table 1, see Figure 2). The upper 30–40m of the cores are trona and trona-bearing mud (Cohen et al. 2016). In sharp contrast to modern conditions, diatom, fossil, and mineral assemblages indicate freshwater phases early in the history of Lake Magadi (McNulty et al. 2016; Rabide-

aux et al. 2015).

Despite their proximity, the Koora and Magadi basins have been hydrologically separated for most of their history, but have experienced nearly identical regional climatic conditions. As such, their parallel records can be used to address local and regional responses to larger-scale climate change, including, for example, differentiating climatically controlled environmental changes from tectonic- or groundwater-controlled changes. The southern Kenya Rift cores will provide a record of local paleoclimatic conditions and water availability during an important turnover in the large mammal fauna ~600–362 ka, documented at nearby Lainyamok (~15km from the Magadi drill site), when the dominant mid-Pleistocene, large-bodied grazers of the Kenya Rift became extinct and were replaced by a faunal community largely composed of mammals typical of the modern East African ecosystem (Faith et al. 2012; Potts and Deino 1995). These cores will also fill the gap between Ologesailie Formation and post-Ologesailie Formation outcrops and provide a record of climate dynamics coincident with the local disappearance of Acheulean technology. These records also span the critical transition in middle Pleistocene hominin adaptation into the Middle Stone Age (Brooks et al. 2007), the latter of which has a first appearance prior to ~280 ka in other parts of the rift valley (Deino and McBrearty 2002; Morgan and Renne 2008).

CHEW BAHIR, ETHIOPIA

The modern surface of the Chew Bahir basin in southern Ethiopia is a playa/saline mudflat. Seismic surveys of the basin for petroleum exploration by Tullow Oil Company confirmed the presence of more than 3km of underlying sediment fill. Chew Bahir lies at the transition between the Main Ethiopian and Kenyan Rifts, and between the distinct Ethiopian and Kenyan highlands. The basin also lies in the transition between tropical equatorial and summer monsoonal climates, and between Atlantic and Indian monsoon systems. Short cores up to ~20m deep from Chew Bahir, collected during a pilot study, have already been analyzed and provide a record back to ~60 ka (Foerster et al. 2012, 2015). Results indicate fluctuations in moisture availability on decadal to centennial and millennial timescales, as well as the precessional timescale. In close cooperation with European-based scientific projects, a 40m core was collected in March 2014 from the central part of the Chew Bahir basin, while two parallel cores with a maximum depth of ~280m were drilled closer to its southwestern border in November 2014. Sediments from these long cores consist predominantly of silty and sandy clays, with occasional coarser silt and sand beds, particularly in the upper 100m. Shell-rich horizons also occur throughout the core (Cohen et al. 2016) (Figure 8K–L). Based on initial results, the longer cores are estimated to extend back to about 550 ka (Foerster et al. 2017).

Chew Bahir is located ~100km east of the earliest documented *Homo sapiens* fossils (Omo I and II) in the adjacent Lower Omo Valley that date to ~195 ka (Brown et al. 2012;

Fleagle et al. 2008; Leakey 1969; McDougall et al. 2005, 2008). Additionally, the southwest Ethiopian Highlands are hypothesized to have been a refugium during hyper-arid intervals of the Late Pleistocene, where a bottleneck population of anatomically modern hunter-gatherers could have developed the social, technological, and linguistic skills necessary to survive and eventually spread across Africa and onward to Asia, Australia, and Europe (Brandt et al. 2012; Carto et al. 2009). Subsequent economic innovations, technology transfer, and subsistence intensification in the SW Ethiopian highlands and Turkana basin led to the emergence of distinct food production systems in the Horn (intensive highland agriculture) and eastern Africa (pastoralism) (Brandt 1984; Marshall and Hildebrand 2002). The Chew Bahir cores are not from the same sedimentary basin as the Omo I and II fossils, so attempts to link the chronology of the two sequences via geochronology and tephrostratigraphy are underway. Nonetheless, the Chew Bahir cores will still provide a regional-scale environmental context for the first appearance and subsequent evolution of *H. sapiens* in the adjacent lower Omo valley and SW Ethiopian Highlands over the last 200,000 years.

CRITICAL INTERVALS IN HOMININ EVOLUTION

The combined temporal extent of the HSPDP cores, ~3.4 Ma to the present, provides us with the opportunity to test most climate-based hypotheses for events in hominin evolution with our high-resolution paleorecords (Table 2), and compare the regional East African paleoclimate and paleoenvironmental records with other records of Plio-Pleistocene global climate change (Figure 9). Furthermore, temporal overlap between several of the HSPDP cores will also allow us to test for regional responses to larger-scale climate dynamics and evaluate how global climate forcing mechanisms were experienced locally within key hominin locales. For example, most of the time interval covered by the Northern Awash core is also covered by the Tugen Hills core, ~1,300km away. Preliminary results indicate that there is at least 300,000 years of overlap between the two sites during the late Pliocene (~3.25–2.95 Ma) where records can be interrogated to determine which environmental changes recorded in the cores may be the result of local or regional drivers (non-synchronous changes) and which that may be linked to larger-scale global drivers (similar synchronous changes). Similar comparisons can also be made over the last half-million years from temporally overlapping records from the Magadi, Ologesailie, and Chew Bahir cores, and over even longer intervals when combined with existing paleolimnological and paleoceanographic records elsewhere in and around Africa (see below), to identify and differentiate responses to environmental change at different spatial scales. As noted earlier, each drilling site has specific, locally-relevant hypotheses to test with these new paleolake records, many of which relate to large-scale global climate transitions at critical intervals of hominin evolution.

TABLE 2. FIRST AND LAST APPEARANCE DATUMS¹ (FADs/LADs) OF HOMININ TAXA, AND TIMING OF KEY BEHAVIORAL AND BIOGEOGRAPHIC EVENTS IN EASTERN AFRICA OVER THE LAST ~3.5 MILLION YEARS (MA) (modified after Potts and Faith [2015], see references therein unless otherwise noted) (HSPDP cores that temporally overlap with events are noted, bold indicates at/near locality of event).

Paleoanthropological Event	MA	HSPDP Site Coverage
Late Stone Age technology FAD	0.0617–0.0521	MA , CB
<i>Homo sapiens</i> dispersal out of Africa	0.08–0.05 ²	OL , MA , CB
<i>H. sapiens</i> FAD	0.198–0.194	OL , MA , CB
Middle Stone Age technology FAD	0.280–0.272	OL , MA , CB
Bodo cranium ³	0.60	OL , MA? , CB?
African <i>H. erectus/ergaster</i> LAD	0.97–0.90	OL
<i>Paranthropus boisei</i> LAD	1.34–1.19	WT?
<i>H. habilis</i> LAD	1.65–1.47	WT
Acheulean technology FAD	1.78–1.75	WT
<i>H. erectus</i> dispersal out of Africa	1.85–1.78	WT
<i>H. rudolfensis</i> LAD	1.87–1.78	WT
African <i>H. erectus/ergaster</i> FAD	1.90–1.88	WT
<i>H. habilis</i> FAD	2.09–1.98	-
<i>H. rudolfensis</i> FAD	2.09–2.03	-
<i>P. boisei</i> FAD	2.33–2.27	-
<i>P. aethiopicus</i> LAD	2.36–2.33	-
<i>Australopithecus garhi</i> ⁴	2.5–2.45	-
Oldowan technology FAD	2.58–2.53	BT?
<i>P. aethiopicus</i> FAD	2.75–2.58	BT
<i>Homo</i> sp. FAD	2.80–2.75	BT
<i>A. afarensis</i> LAD	3.03–2.97	BT , NA
Lomekwian technology FAD	3.31–3.21	BT , NA
Dikika cut-marked bones	3.42–3.39	BT? , NA?
<i>A. deyiremeda</i> ⁵	3.5–3.3	⁷ BT , NA ⁵
<i>Kenyanthropus platyops</i> ⁶	3.6–3.25	⁷ BT , NA
<i>A. afarensis</i> FAD	3.85–3.79	-

¹It is unlikely that empirical FADs/LADs represent the actual age of the event due to insufficient sampling or gaps in the geological record (e.g., Bobe and Leakey 2009); they represent the minimum age of appearance or the maximum age of disappearance, and the uncertainties on these ages depend primarily on the quality of the fossil record below or above the recorded datums, respectively.

²Range determined from estimates in Behar (2008), Soares et al. (2012), and Henn et al. (2012).

³The taxonomic status of the Bodo cranium is debated, but often classified under *H. heidelbergensis*. Age estimate for the specimen from Clark et al. (1994) and cannot be used as a reliable FAD or LAD for the population.

⁴*A. garhi* (Asfaw et al. 1999) is known primarily from a single partial cranium. Although the age is well constrained, the single occurrence cannot be used as a reliable FAD or LAD for the taxon.

⁵*A. deyiremeda* (Haile-Selassie et al. 2015) is not well represented in the fossil record and has a poorly constrained temporal range that unlikely represents its true FAD or LAD. The taxon is reported from the Woranso-Mille project area, ~25km NW of the Northern Awash drill site.

⁶*Kenyanthropus platyops* (Leakey et al. 2001) is known primarily from a single partial cranium and isolated dentition from a restricted spatial area. The specimens are unlikely to represent a reliable FAD for the taxon and additional specimens attributed to the taxon that represent the current LAD are poorly constrained (Brown et al. 2013).

⁷The oldest portions of the Baringo (BT) and Northern Awash (NA) cores should overlap with the youngest portion of the range indicated.

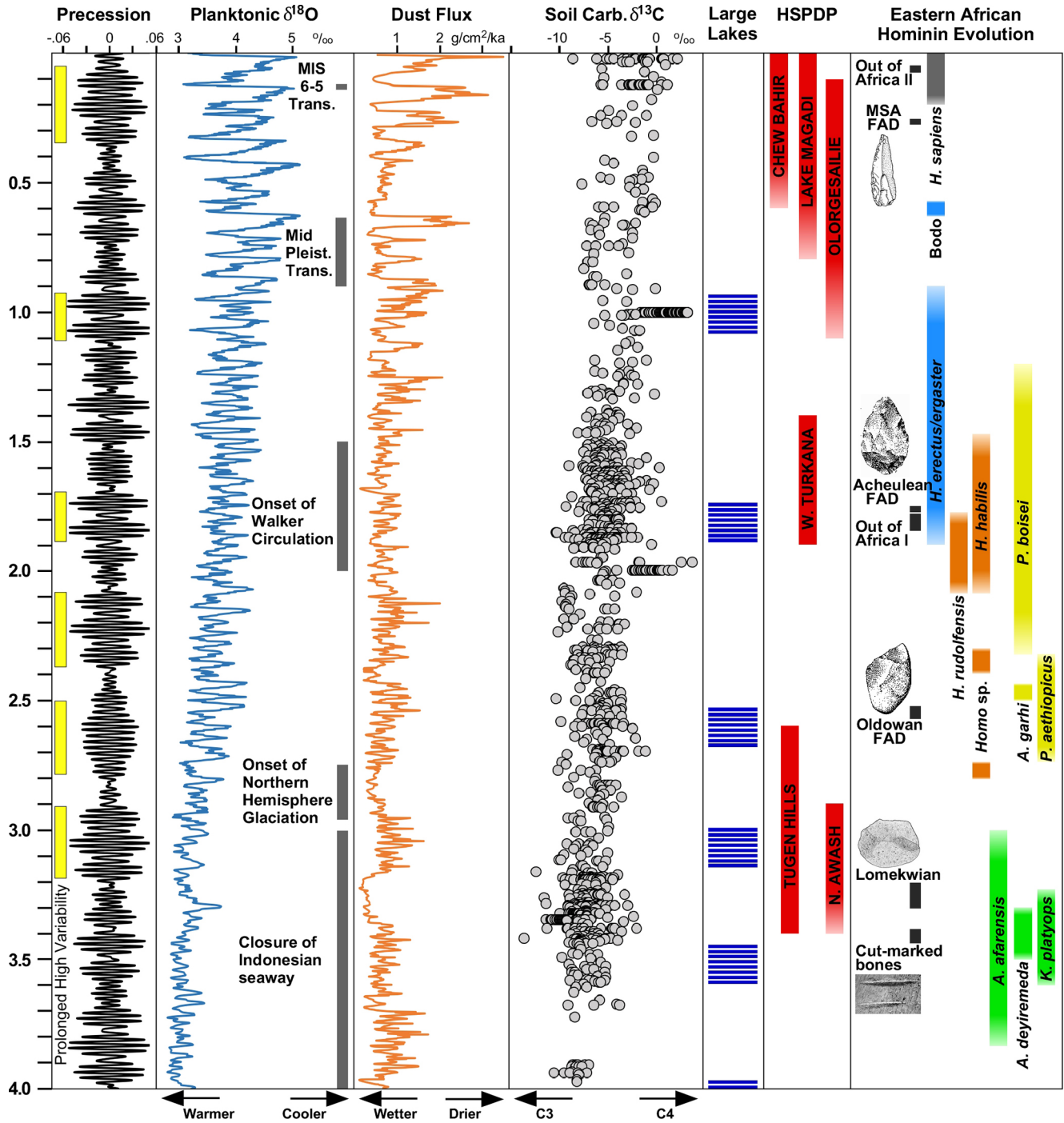


Figure 9. Compilation of major events, trends, and variation in global paleoclimate and eastern African paleoenvironments and hominin evolution, and the temporal coverage of the HSPDP core records. From left to right. Precessional index ($\epsilon \sin \omega$) generated from the La04 solution of Laskar et al. (2004). Intervals of prolonged high climate variability (yellow boxes) as defined by Potts and Faith (2015). Composite record of benthic foraminifera $\delta^{18}\text{O}$ values from the LR04 stack of Lisiecki and Raymo (2005) with the timing of major global climate transitions discussed in the text. Terrigenous dust record from the Arabian Sea (ODP Sites 721/722) from deMenocal (1995). Composite record of soil carbonate $\delta^{13}\text{C}$ values from eastern Africa (Tanzania, Kenya, Ethiopia) compiled by Levin (2015). Timing of fluctuating major lake phases in eastern Africa as proposed by Trauth et al. (2007). Currently estimated temporal coverage of the HSPDP drill cores. First and last appearances (FAD/LAD) of eastern African hominin taxa and the timing of behavioral innovations and demographic transitions compiled predominantly from Potts and Faith (2015) and references therein. FADs and LADs in figure represent earliest date of FAD range and latest date of LAD range as reported in Table 2. Colors represent groups of hominin taxa following Wood and Boyle (2016); green=archaic hominins, yellow=megadont archaic hominins, orange=transitional hominins, blue=pre-modern Homo.

HOMININ EVOLUTION IN A PRE-NHG WORLD

The narrative of paleoclimate and hominin evolution often begins with the onset of Northern Hemisphere glaciation (NHG) ~2.75 Ma (Kleiven et al. 2002). However, characterizing mid-late Pliocene hominin environments and their change provides a baseline for evaluating the climate-evolution relationship in the pre-NHG world, a time when the accumulating fossil record provides evidence of a much richer diversity of hominin species than was appreciated even 20 years ago (Haile-Selassie et al. 2016). Both the Northern Awash and Tugen Hills core records allow us to document not only the climatic conditions and variability at two different locations in eastern Africa prior to the onset of NHG, but more importantly, the impacts associated with the lead-up to the growth of major Northern Hemisphere ice sheets. Trauth et al. (2007) have identified the interval between ~3.15 and 2.95 Ma as a period of eccentricity maxima associated with lake phases in eastern Africa, as well as the three most significant changes in marine core records of terrigenous dust flux (central tendency) over the last 5 Ma occurring at 3.35 Ma (decrease), 3.15 (increase), and 2.95 Ma (decrease) (Trauth et al. 2009). Potts and Faith (2015) have also identified this interval as one of the longest periods of high climate variability. The Afar and Baringo records will allow us to obtain the first continuous, high-resolution Afrotropical climate records across this interval and test for any regional terrestrial response to these dramatic changes and the possibility that they correlate to the Hadar faunal turnover at ~3.1 Ma (Reed 2008). We can also test the hypothesis that changes in the Hadar vegetation record are responding to Antarctic glacial cycles (e.g., MIS M2 and MG2) as proposed by Bonnefille et al. (2004).

INTO THE ICE AGE

All of the major climate-driven hypotheses of hominin evolution have linked the onset of NHG to major changes in East African climate dynamics and landscapes. This includes a change from 21 kyr (precession) to 41 kyr (obliquity) dominated climate cycles (superimposed on precession cycles) and an increase in African aridity (deMenocal 1995, 2004), extreme wet/dry climate variability (Trauth et al. 2007), a prolonged interval of high climate variability (Potts and Faith 2015), and a pan-African faunal turnover (Vrba 1988, 1995). This global climate change has been argued to have been the fundamental driver behind the origins of two hominin genera (*Homo* and *Paranthropus*) and Oldowan technology (e.g., Vrba 1988; Stanley 1992). Outcrop studies from the Tugen Hills have already demonstrated that equatorial Africa responds to insolation forcing by precession at 23 kyr pacing (Deino et al. 2006; Kingston et al. 2007). However, there is still an ongoing discussion regarding the tempo of terrestrial environmental response to climatic forcing, particularly the extent to which there are lags, threshold effects, and/or buffering (Maslin and Trauth 2009; Trauth et al. 2015). Data from the Tugen Hills core are crucial for developing models of environmental and biotic responses across this critical interval. They will

also allow us to further explore the timing and nature of annual precipitation/evaporation regimes during this transition as well as millennial-scale climate variability such as that recorded in the diatom record (Wilson et al. 2014).

DRYING OUT (AND SPREADING OUT)

Similar to the onset of NHG, the interval between ~1.9 and 1.6 Ma has been identified as another phase of climate transitions that possibly altered East African landscapes and the course of hominin evolution. This includes a second shift in African aridity (deMenocal 1995, 2004) coincident with a prolonged interval of high climate variability (Potts and Faith 2015) and a peak in high-latitude climate sensitivity (Ravelo et al. 2004), and another, smaller, turnover pulse in the African bovid record (Vrba 1988, 1995). This time period also corresponds to another proposed phase of wet/dry climate variability linked to eccentricity maximum (Trauth et al. 2005, 2007) possibly tethered to a significant intensification and shift in Walker Circulation (Ravelo et al. 2004) that Trauth et al. (2009) argue resulted in a more dramatic increase in East African aridity and climate variability than the intensification of NHG. As noted earlier, the rich paleontological and archaeological record of the Turkana Basin, combined with existing outcrop geological studies, preserves direct evidence of the ~1.9–1.6 Ma interval and documents key transitions in hominin anatomy, behavior, biogeography, and taxonomic diversity combined with a shift towards grassland environments. In fact, many of the Turkana records have been used to develop and support the existing, dominant theories on paleoclimate and hominin evolution that principally revolve around water-limited environmental conditions (e.g., Bobe and Behrensmeyer 2004; Levin et al. 2011). The highly-resolved West Turkana core-based environmental records will more accurately resolve the nature of paleoclimatic states, permit additional evaluation of the existing hypotheses, and allow us to examine the role of shorter duration climate events in remolding ecosystems. For example, with regards to faunal turnover, core records will allow direct comparison of the overall pattern of community response to environmental signals through this temporal window. A close correspondence of the tempo and mode of these records will support the implication of specific environmental drivers in lineage and community evolution, whereas a lack of correspondence would falsify this commonly invoked linkage. Similarly, in regards to the hominin record, the verification of potential environmental triggers leading evolutionary and biogeographic developments would provide supportive evidence, whereas a lag in this relationship would falsify the hypothesis.

BECOMING HUMAN

Vrba (1988, 1995), deMenocal (1995, 2004) and Trauth et al. (2005, 2007) also highlighted the ~1.0–0.7 Ma interval as a period of significant global climate change with implications for hominin evolution. The Koora-Olorgesailie cores span this interval, allowing tests of hypotheses associated with the Mid Pleistocene Transition (MPT, ~900–650 ka)

when high-latitude glacial cycles shifted from 41 kyr to 100 kyr periodicity (e.g., deMenocal 1995; Elderfield et al. 2012; Trauth et al. 2005). The HSPDP cores from Olorgesailie, Magadi, and Chew Bahir are relevant for the last ~0.5 Myr of hominin evolution, which includes one of the longest phases of high climate variability (~358–50 ka) during the last 5 Ma (Potts and Faith 2015). The HSPDP data sets are essential for testing the predictions of Potts' (1996, 1998b) variability selection hypothesis and of Grove's (2015a) accumulated plasticity hypothesis in relation to the first appearance of *Homo sapiens* and their dispersal out of Africa, as well as the transition from the Acheulean technology to the Middle Stone Age, then the Later Stone Age (Potts and Faith 2015). Our paleolimnological records can also be used to provide an environmental context for genetic studies reconstructing the demography and geography of early human populations in Africa over the last 200,000 years (e.g., Henn et al. 2012; Karmin et al. 2015; Lippold et al. 2014; Mallick et al. 2016; Nielsen et al. 2017; Pagani et al. 2016; Rieax et al. 2014).

Although it has been demonstrated that low-latitude insolation forcing has had a pronounced effect on paleoclimate variability in equatorial regions of Africa, questions remain regarding how far north and south of the equator precessional influences extended versus high latitude (100 kyr) forcing and their relative importance, particularly in transitional zones. The Middle and Late Pleistocene paleorecords from HSPDP, combined with a large latitudinal transect of existing paleolimnological records, can elucidate the response of regional hydrology to high- versus low-latitude insolation forcing, and also the role of Indian and Atlantic Ocean sea-surface temperature variations. The new core records can also reveal the regional expression of global climate events such as the Middle to Late Pleistocene transition ~145–125 ka (OIS 6–5) (Scholz et al. 2007; Trauth et al. 2003), Heinrich and Dansgaard-Oeschger events during OIS 4–3 (Brown and Gasse 2003), the Last Glacial Maximum (OIS 2) (Barker and Gasse 2003), and the Pleistocene-Holocene transition (Gasse 2000; Gasse et al. 2008). On a continental-scale, these cores will provide new records on the spatial extent and impacts of events such as megadroughts recorded in the southern Afrotropics during the early Late Pleistocene (Ivory et al. 2016; Scholz et al. 2007) and intensification of the African monsoon during the African Humid Period (~15–5 ka, deMenocal et al. 2000). They can also be used to test recent hypotheses about long term climate transitions in eastern Africa, such as the proposed increase in precipitation through the Middle-Late Pleistocene (Johnson et al. 2016). The short cores from Chew Bahir have already begun to address some of these climate events for the latest Pleistocene and Holocene (Foerster et al. 2012, 2014, 2015), and can be integrated with other existing short cores from the rift valley lakes, such as Lake Albert (Beuning et al. 1997), Lake Victoria (Johnson et al. 1996), and Lake Kivu (Haberyan and Hecky 1987), as well as those that extend further back in time (see Discussion section below). When compared to the archaeological and fossil record (e.g., Blome et al. 2012), these combined records will pro-

vide additional evidence that can be examined for potential impacts of these climate shifts on modern human biology, behavior, and demography.

ANALYTICAL ARSENAL

From its inception, the HSPDP has operated under the principle that fundamental advances in our knowledge of the environmental context of hominin evolution will require the application of highly sensitive, state-of-the-art paleoenvironmental methods to local sedimentary basins that resolve environmental change at the temporal and spatial scales of human generations living within patchy African landscapes. Testing hypotheses concerning hominin or other biotic responses to environmental change requires collection of paleoenvironmental archives that quantitatively record paleotemperature, paleoprecipitation, vegetation type, climate seasonality and watershed hydrology. Reconstructing landscape elements that hominins encountered and relied on (directly or indirectly), such as soils, vegetative cover, potential food resources, water quality, lake levels, and fire history are also crucial. Because not all analytical techniques are appropriate for all types of sediments encountered, and because uncertainties can arise from using single types of records to establish paleotemperature, paleoprecipitation and other paleoenvironmental inferences, our strategy employs a multi-proxy/indicator approach, since each technique may be recording different aspects of the environment. These records include both traditional, well-understood techniques as well as more recent, cutting-edge approaches (Table 3). As noted previously, the quality of many geochemical and paleoecological records is compromised in weathered outcrop samples. For all techniques employed, our goal is to achieve the high temporal sampling resolution required to address the hypothesized evolutionary drivers discussed above, while also providing multiple paleoenvironmental records that can be compared to ensure robust interpretations. Using conservative estimates of core sedimentation rates, the initial sampling resolution of ~32cm used for most analyses already represents sub-millennial scale sampling, with significantly higher-resolution sampling underway for intervals of interest and importance.

Quantitative paleotemperature estimates are being reconstructed using organic and inorganic geochemical methods. The TEX₈₆ paleothermometer, which is based on membrane lipids of Thaumarchaeota (Schouten et al. 2002, 2013), has been widely applied to East African lakes (e.g., Berke et al. 2012a, b; Powers et al. 2005, 2009; Tierney et al. 2008, 2010;) and is applicable to many of Africa's largest lakes. A related technique, the MBT/CBT paleothermometer (Weijers et al. 2007) is based on membrane lipids of bacteria (e.g., Sinninghe Damsté et al. 2011). Recent work has generated a new high-precision temperature calibration for these compounds using 111 East African lake sediment samples, and has applied that calibration to generate credible temperature records from smaller East African lakes (Loomis et al. 2012, 2014, 2017). The compounds used for these two paleothermometers are ubiquitous in East African lake sed-

TABLE 3. ANALYTICAL DATA TYPE AND TYPICAL INITIAL SAMPLING FREQUENCY USED TO DETERMINE VARIOUS ASPECTS OF CORE HISTORY (see text for additional examples and references).

Data Type	Typical Sampling Frequency	Depositional/Environmental or Other Information
<i>Physical Property Records</i>		
Gamma Density	0.5cm	Generalized depositional setting (lake vs terrestrial); stratigraphic correlation
Magnetic Susceptibility	0.5cm	Generalized depositional and climate setting (lake vs terrestrial, wet vs. dry) and provenance; stratigraphic correlation
Natural Gamma Radiation	2cm	Sediment provenance, stratigraphic correlation
Non-contact electrical resistivity	0.5cm	Generalized depositional setting (lake vs terrestrial)/lithology; stratigraphic correlation
pWave velocity	0.5cm	Generalized depositional setting/lithology
Color reflectance	0.5cm	Generalized depositional setting (lake vs terrestrial); redox conditions
<i>Sedimentological Records</i>		
Facies analysis	Opportunistic but descriptions on cm scale	Generalized depositional environment, subaerial exposure
Paleosol Structure	Opportunistic but descriptions on cm scale	Soil/climate humidity, duration of subaerial exposure and soil development, vegetation cover
<i>Geochemical/Mineralogical Records</i>		
Scanning XRF	1cm (0.2mm for special studies)	Provenance, watershed weathering intensity, diatom productivity, CaCO ₃ saturation; redox; pedogenic alteration and diagenesis;
Sedimentary Petrography (Smear Slides)	Opportunistic but generally 50–100cm	Generalized depositional environment, first pass characterization of fossil and mineral content
XRD-Bulk	16cm	Brine evolution, lake salinity/alkalinity/pH/redox conditions; provenance, chemical alteration index/aridity; diagenetic alteration

TABLE 3. ANALYTICAL DATA TYPE AND TYPICAL INITIAL SAMPLING FREQUENCY USED TO DETERMINE VARIOUS ASPECTS OF CORE HISTORY (see text for additional examples and references) (CONTINUED).

Data Type	Typical Sampling Frequency	Depositional/Environmental or Other Information
<i>Geochemical/Mineralogical Records</i>		
XRD-Ultrafine clays	Opportunistic	Brine chemistry
Igneous petrology and microprobe analysis of basalts (NA area)	Opportunistic	Subaerial/subaqueous exposure during eruptions, correlation, source of eruption and landscape evolution
TOC/TIC (LOI and Coulometry)	32cm	Generalized depositional environment, redox and pH conditions
Tephrostratigraphy	Opportunistic	Correlation
Stable Isotopes ($\delta^{18}\text{O}$ / $\delta^{13}\text{C}$) on carbonates	Opportunistic based on appropriate CaCO_3 sample availability	Precipitation-Evaporation; Open vs. closed lake conditions; C_3 vs. C_4 vegetation (for paleosol carbonates). Hydrologic seasonality through sclerochronologic analysis of growth bands
Sr isotopes on fish bones	Opportunistic	Provenance
Evaporite Fluid Inclusions	Opportunistic based on appropriate evaporite sample availability	Paleotemperature of crystallization in brine
Clumped Isotopes (C,O)	Opportunistic based on appropriate CaCO_3 sample availability	Paleotemperature of lake (mollusk/ostracode shell) or shallow soil subsurface (paleosol)
GDGTs (TEX ₈₆)	1m or as warranted by organic matter content	Paleotemperature (soil or lake metalimnion)
δD of Leaf Wax	1m or as warranted by organic matter content	Rainfall/hydrology

TABLE 3. ANALYTICAL DATA TYPE AND TYPICAL INITIAL SAMPLING FREQUENCY USED TO DETERMINE VARIOUS ASPECTS OF CORE HISTORY (see text for additional examples and references) (CONTINUED).

Data Type	Typical Sampling Frequency	Geochemical/Mineralogical Records	Depositional/Environmental or Other Information
$\delta^{13}\text{C}$ of Leaf Wax	1m or as warranted by organic matter content		Index of relative abundance of C_3/C_4 vegetation and water stress
n-alkanes	1m or as warranted by organic matter content		Aquatic vs. Terrestrial organic matter sources
Cosmogenic Radionuclides (^{10}Be , ^{26}Al)	Opportunistic		Paleoerosion rates and watershed provenance
Detrital Apatite/Zircon Thermochronology	Opportunistic		Paleoerosion rates and watershed provenance
<i>Paleoecological Records</i>			
Diatoms	32cm		Lake ecology, salinity/alkalinity, lake productivity, hydrodynamics, water depth
Other Siliceous Algae	32cm		Lake ecology, salinity/alkalinity, lake productivity, hydrodynamics, water depth
Ostracodes (Faunal Assemblage and Taphonomy)	32cm		Lake ecology, salinity/alkalinity, hydrodynamics, water depth
Molluscs	32cm		Lake and fluvial ecology, water depth
Fish	32cm		Lake and fluvial ecology
Pollen	1m		Generalized depositional environment; Local/regional vegetation, hominin resources, rainfall seasonality
Phytoliths	1m		Generalized depositional environment; Local/regional vegetation, hominin resources, C_3 vs. C_4 vegetation discrimination
Charred Particles	32cm		Watershed vs. Regional fire history
Trace Fossils	Opportunistic		Generalized depositional environment (lake vs. terrestrial), community structure

iments, and we have begun the application of these two paleothermometers, where appropriate (e.g., Castañeda and Schouten 2011). Carbonate ‘clumped isotope’ thermometry (Eiler 2007; Ghosh et al. 2006; Tripathi et al. 2010) examines the proportion of ^{13}C and ^{18}O bound to each other within the carbonate mineral lattice (measured $^{13}\text{C}^{18}\text{O}^{16}\text{O}$ in CO_2 produced by acid digestion of CaCO_3 ; Ghosh et al. 2006), with disorder increasing as temperature increases (Schauble et al. 2006). This approach has proven useful for African temperature reconstruction in both paleosols (Passey et al. 2010) and lake deposits (Tripathi 2015), and is currently being applied to carbonate-bearing core intervals. Although the HSPDP cores are unlikely to have continuous carbonate deposition throughout the drilled intervals, clumped isotopes will provide valuable alternative perspectives on paleotemperatures from the organic geochemical-based inferences, since they record conditions in differing micro-environments and over different temporal intervals. Fluid inclusion paleotemperature analysis, which uses known homogenization temperatures for fluids trapped in salts, will also be useful for the Lake Magadi core record (e.g., Lowenstein et al. 1999). This comparative, multi-proxy approach for reconstructing temperature is essential as each paleorecord is likely recording different microenvironmental phenomena. For example, the TEX_{86} results may correspond to temperature at the oxicleine rather than surface water temperature (Kraemer et al. 2015), whereas clumped isotopes on mollusks and ostracods likely reflect growth temperatures in the littoral zone, and subsurface soil temperatures for paleosol carbonates.

Precipitation variability will be examined from plant leaf wax δD (e.g., Berke et al. 2012b; Konecky et al. 2011; Tierney et al. 2008). Leaf wax δD provides information on past precipitation amount and the atmospheric circulation processes that regulate rainfall (e.g., Konecky et al. 2011; Tierney et al. 2008). It thus provides relatively direct information into atmospheric processes, unlike many lake-based indicators that are strongly sensitive to surface evaporation. Precipitation/evaporation ratios can also be quantitatively assessed from studies of paleolake levels and paleohydrology derived from a variety of paleoecological, sedimentological and geochemical data. Studies of diatom, ostracode, fish, and mollusc paleoecological data, and $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of carbonate minerals and fossils to reconstruct lake levels and hydroclimate (e.g., Cohen et al. 2007; Owen et al. 2008; Reinthal et al. 2011; Stone et al. 2011) are currently underway. This paired approach may allow us to distinguish changes in regional precipitation from basin-scale hydrologic reorganizations driven, for instance, by rift tectonics.

Watershed paleoecological responses to climate variability are being assessed using studies of pollen and phytolith samples (e.g., Ivory et al. 2012; Yost et al. 2015), by analysis of both macro- and micro-charcoal concentrations (e.g., Cohen et al. 2007), which record fire activity at the watershed- and airshed-scale, respectively, and through carbon isotopic analyses ($\delta^{13}\text{C}$) of terrestrial leaf waxes and paleosol carbonates (e.g., Castañeda et al. 2007; Cerling et

al. 2011). These are powerful, complementary approaches to vegetation reconstruction. The $\delta^{13}\text{C}$ of plant leaf waxes mainly distinguishes the relative abundances of C_3 plants (e.g., trees) and C_4 grasses. Phytolith analyses can further distinguish major clades within climatically sensitive C_4 grasses, whereas pollen will resolve major groups of C_3 plants (i.e., tree taxa). Mineralogical/XRD studies (Rabideaux et al. 2015) are being directed at reconstructing the paleohydrology of basins, including lake water paleosalinity and hydrochemistry (e.g., Deocampo 2015; Deocampo et al. 2010). Scanning XRF elemental data from cores (including trace-element variability) has proven extremely useful in African lake deposits for obtaining highly resolved records of climate change (including cyclic environmental variability at varying scales), sediment provenance, and weathering (Brown et al. 2007). Similarly, strontium isotopic records ($^{87}\text{Sr}/^{86}\text{Sr}$) of fish fossils provide a useful record of temperature-independent lake chemistry changes that have been used to resolve changes in water provenance and monsoon-driven rainfall cyclicity (e.g., Joordens et al. 2011).

Many of the paleoenvironmental records listed above are well suited for producing high-resolution reconstructions. For example, the vegetation response in tropical Africa has been particularly sensitive to changes in precipitation and rainfall seasonality, particularly the interaction between the ITCZ and the Congo Air Boundary (Hély et al. 2006; Ivory et al. 2013; Schefuß et al. 2003). Changes in the regional vegetation, as recorded in high-resolution pollen and phytolith records from African lake cores, can serve as a useful tool for deciphering both long-term and abrupt seasonal changes in these circulation patterns (e.g., Ivory et al. 2012). Total annual rainfall and, more importantly, its distribution over the year (e.g., dry season length) are important for the regional distribution of woody vegetation and pollen data can provide insights into decreased rainfall seasonality and dry season severity (Bonnefille 2010; Ivory et al. 2012, 2013). Similarly, the $\delta^{13}\text{C}$ of plant leaf waxes responds strongly to drought stress, due to trade-offs between plant carbon and water use efficiency, providing a way to examine dry season stress within C_3 ecosystems (Diefendorf et al. 2010). Phytoliths are extremely abundant in some intervals of the cores (Yost et al. 2015) and can more readily resolve C_3 vs. C_4 grasses compared to pollen, and can be used to identify C_4 grass subfamilies that have different temperature and precipitation requirements. For example, the abundance of the mesophytic Panicoideae has a positive relationship with precipitation, whereas the xerophytic Chloridoideae have an inverse relationship with precipitation (Cabido et al. 2008; Taub 2000), yet both would yield similar isotopic ratio signals if that method alone was being used to analyze the organic matter derived from these grasses. The numbers of wet- and dry-season months, which influence plant productivity, has been identified as an important component in reconstructing hominin habitats and diets, particularly in regards to “fallback foods” in the dry season when preferred or primary food resources may be unavailable (Lambert 2007; Reed and

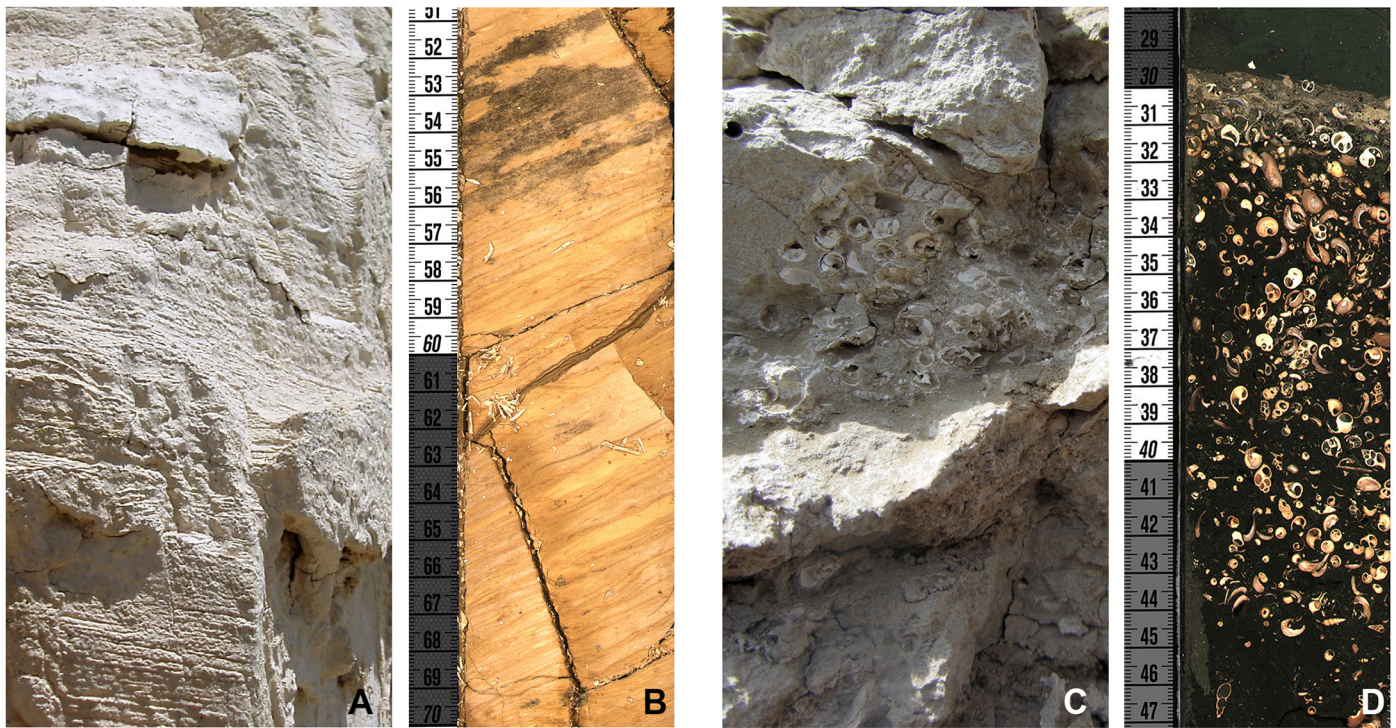


Figure 10. Comparison of outcrop versus drill core preservation. Close-up of diatomite outcrop adjacent to drilled Tugen Hills sequence (A) and laminated diatomite from BTB13-1A (B). Close-up of coquina adjacent to drilled West Turkana sequence (C) and coquina from WTK13-1A (D). Note that outcrop examples may not reflect exact correlates of drill core examples.

Rector 2007). Although precipitation and its seasonal distribution is a more important control on vegetation than temperature, temperature (the objective of several HSPDP investigations) is still an essential component. For example, temperature controls evaporation rates and may have influenced the timing and duration of growing seasons for particular resources on which hominins were dependent. At Hadar, during the time interval covered by the Northern Awash core, pollen assemblages have already been used to establish seasonal contrasts using differences in the reconstructed mean annual temperature and the mean temperature of the coldest month (Bonnefille et al. 2004).

Outcrop samples from one of the diatomite sequences from Baringo have been analyzed via paired oxygen isotope and XRF measurements of biogenic silica, combined with taxonomic changes in diatom assemblages (Wilson et al. 2014). Results indicate a rapid onset and gradual decline of deepwater conditions with a cyclicity of ~1400–1700 years, similar to Dansgaard-Oeschger events, potentially reflecting fluctuations in the relative balance between input/precipitation and output/evaporation in the lake system, specifically, enhanced precipitation coincident with increased monsoonal strength. This diatomite sequence (sampled at ~10cm resolution) was exposed and preserved well enough for these analyses and will provide useful outcrop-to-core linkages. However, not all diatomite sequences in the HSPDP cores have well-preserved outcrop correlates. Additionally, diatomite/diatom-rich sequences in the HSPDP cores have been sampled at continuous 2cm intervals for diatoms

and have been XRF scanned at 1cm resolution (with up to 0.2mm (~annual/seasonal) resolution possible for intervals of interest), significantly increasing our temporal resolution and ability to observe sub-millennial climate variability. High-resolution analyses are not restricted to diatomites, but can be applied to any laminated or varved intervals. For example, preliminary microfacies and high-resolution (~1mm) XRF analysis of portions of the Olorgesailie cores (see Figure 8H) have already demonstrated fluctuations in diatom productivity and autochthonous carbonate precipitation in the paleolake at orbital, millennial, and sub-millennial scales (Cappio et al. 2015; Stockhecke et al. 2015). The laminated mudstones and rhythmicity of the evaporite deposits of the Lake Magadi core are also ideally suited for this sort of high-resolution scanning (see Figure 8I-J).

Paired outcrop-core studies have already demonstrated the exceptional preservation of fine-scale features and facies transitions in the cores compared that are not visibly identified in outcrops due to weathering and oxidization (Figure 10). For example, an outcrop study underway at Turkana that is adjacent to the coring site preserves ~33 lacustrine flooding surfaces, whereas the core record over the same interval preserves almost three times as many, which has been interpreted to reflect sub-Milankovitch frequency (Beck et al. 2014, 2016; Feibel et al. 2015, 2016). As with the Baringo diatomite sequence, if the Turkana data are congruent with sub-Milankovitch cycles driving ITCZ rainfall patterns, then this has important implications for the timescales of environmental change and variability operating on

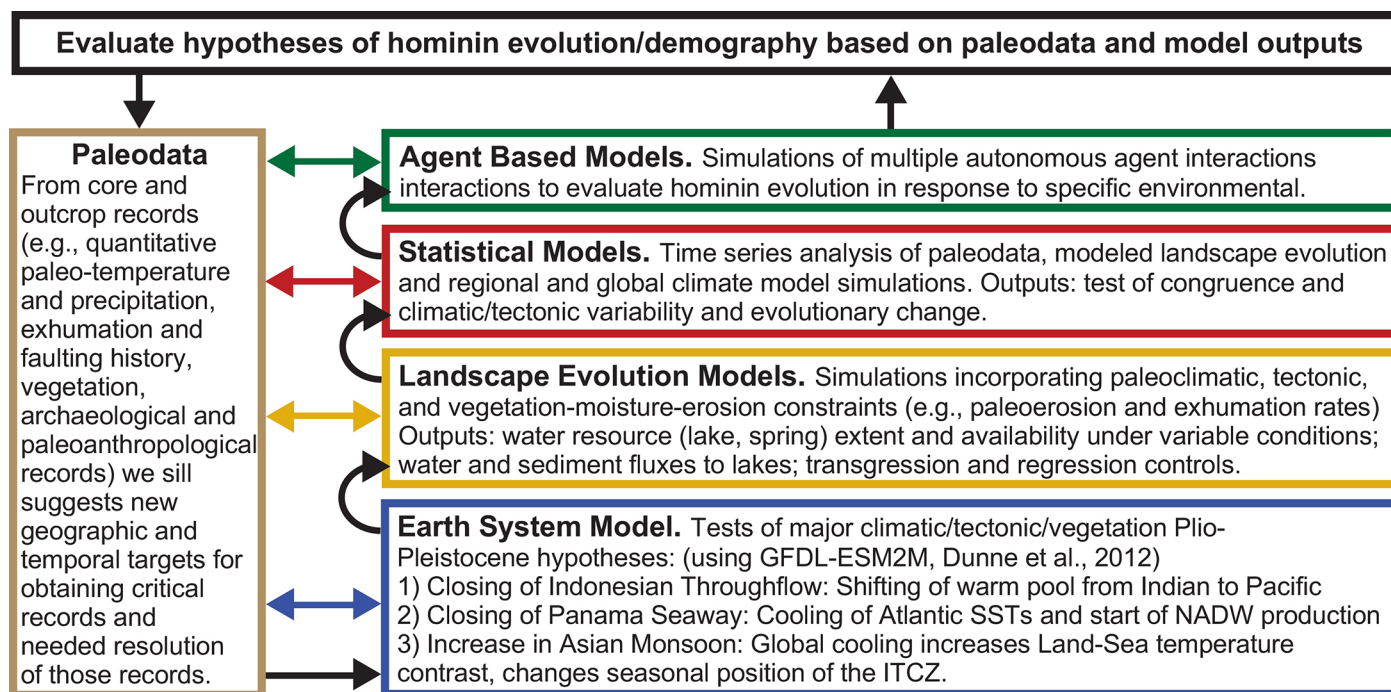


Figure 11. Ongoing and planned modeling experiments to explore environmental dynamic controls on hominin distribution and feedbacks between scales and between models and paleodata.

hominin habitats. Although the Turkana data may inform us of the frequency of this change, it must be combined with other paleorecords (e.g., pollen, phytoliths, charcoal) to get a better sense of the vegetational responses and magnitude of these changes. Additionally, the details preserved and visible in the core have also been used as a basis to reinvestigate outcrops more precisely to identify subtle details preserved over a greater spatial scale than what the cores alone allow (Feibel et al. 2016).

The mollusks preserved throughout the HSPDP cores from the West Turkana, Afar, and Chew Bahir sites are also suitable for high-resolution sclerochronological studies that take advantage of the periodicities in accretionary shell growth. Mollusks record environmental changes in their shells that are reflected by variation in their growth rates (incremental widths), microstructure and in their geochemical/isotopic composition. Of interest to this project is the ability for the shells to preserve a record of seasonal water temperature ranges and inter-annual variability, including seasonality. Additionally, data from multiple time intervals using the same taxon and from the same facies can establish meaningful trends in average temperature and seasonal range over time (Ivany 2012; Schöne and Surge 2012). The directionality of any trends, or abrupt changes in trends, could then be compared against other proxy records, both within and outside the cores, for possible environmental influences. Marine bivalves are typically the most common taxa used in sclerochronology, but freshwater bivalves and gastropods have also been successfully employed (e.g., Dettman et al. 2001; Leng et al. 1999). Incremental stable isotope records of bivalves shells from the east side of Lake Turkana, coeval with the West Turkana Lorenyang Lake

drill core, demonstrate the environmental control on isotopic values, but also highlight several caveats for paleoclimatological interpretations, such as sampling across different sedimentary facies (Vonhof et al. 2013).

HSPDP MODELING EXPERIMENTS

Physics-, chemistry-, and biology-based numerical models of environmental change and ecosystem responses are being developed for critical intervals of hominin evolution that can then be compared to and evaluated by the new, high-resolution paleorecords generated from our cores. These simulations are examining how climate change and landscape response (including hydrology, vegetation cover, and geomorphology) across a wide range of temporal and spatial scales impacts the durability and predictability of ecosystem resources for hominins. They will allow us to evaluate the importance of climatic thresholds and abrupt environmental changes, and to understand how Earth system dynamics that might have shaped human evolution. Our modeling is being conducted as a cascade of experiments at various scales: global and regional climate and vegetation simulations to identify primary forcing of precipitation and cover; sediment transport and landscape evolution to determine the relationships among climate forcing, soil development, and sediment routing to depozones; and agent-based models to generate and evaluate specific hypotheses about causal links between environmental change and biotic response (Figure 11). In addition to these process-based models, we are using statistical models to test the congruence of environmental and evolutionary changes. The model explorations include a range of levels of site specificity with some being as explicit as pos-

sible, given available data, and other emphasizing heuristic exploration of idealized parameters and relationships. In aggregate these explorations provide a theoretical, repeatable, and quantitative context for interactively querying our existing hominin fossil records and our new core-based paleoenvironmental records to generate new, testable hypotheses of hominin evolution and Earth system dynamics, and potentially transform the debate about whether and how hominin evolution in Africa has been impacted by environmental change.

EARTH SYSTEM AND COUPLED CLIMATE MODELING

Vegetation simulations using fully coupled GCMs have already proven useful for understanding Quaternary climate changes relevant to the evolution of *H. sapiens* (Cowling et al. 2008). We are investigating the climate dynamics that link climatic and evolutionary histories and can take this effort to the next level by providing the ground truth for quantitative climate histories on the African continent. We are assessing the effects on African climate due to orography, CO₂ forcing, ocean circulation, and ocean gateway changes that can be linked with existing marine and lacustrine drill core records. These experiments have been conducted in a pair of Earth System Models (ESM2M and ESM2G that differ only in their ocean components, Dunne et al. 2012), developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). The ESMs are being used to quantify the various effects of different, large-scale climatic forcings on annual and seasonal temperature, precipitation, and vegetation in eastern Africa.

The ESMs include a dynamic land/vegetation model (LM3V, Shevliakova et al. 2009) that simulates ecosystem dynamics and exchanges of water, energy, and CO₂ between land and atmosphere. The biogeography parameterization in LM3V uses the total biomass in combination with prevailing climatic conditions to determine the vegetation type, and was specifically designed to address the consequences of shifting climate and/or land use. LV3V tracks the dynamics of natural vegetation, cropland, pastures, and secondary vegetation, and simulates five vegetation types: C₃ and C₄ grasses, temperate deciduous, tropical, and cold evergreen trees. We continue to investigate the dynamics behind the differing regional responses in basin vegetation and hydrology. With new paleotemperature and paleoprecipitation records derived from the HSPDP studies in southern Kenya and Chew Bahir, combined with the existing terrestrial and marine records, we will be able to establish much more realistic boundary conditions for assessing the large-scale causes of climate variability in Africa over the last several million years.

HYDROLOGIC AND GEOMORPHIC MODELING

Quantitative modeling of Earth surface processes is being used to constrain the geomorphic and hydrologic development of the watersheds linked to the core sites using input data from paleoclimate modeling and paleoenvironmental

proxies derived from the sediment cores and additional data from the watersheds. Process-based models that link climate variation, vegetative cover, sediment production, sediment flux, and water resources enable exploration of sensitivity of the geomorphic system at varying levels of site specific realism. In addition, landscapes "filter" climate signals (e.g., Godard, et al. 2013). Thus, we can assess the response spectrum and quantify coherence between climate inputs and geomorphic inputs, adding process-based constraints to interpretation of the core records.

This work provides a key linkage between paleoclimate modeling and paleoenvironmental factors (e.g., water resources, vegetation, hillslope, channel, and lake forms) most relevant to hominin survival. Hydrologic models provide a quantitative linkage between paleoenvironmental conditions (mean annual and seasonality of temperatures and precipitation) and the spatial extents and volumes of paleolakes (e.g., Cross et al. 2001; Shanahan et al. 2007). Particularly important is the identification of threshold paleoclimatic conditions under which lakes and springs no longer contain water in any part of a basin, which could have severely limited the local survivability for hominins as well as the many other biota on which hominins would have depended. Notable moisture-vegetation-erosion linkages (Forester et al. 2012, Pelletier 2014; Torres-Acosta et al. 2015) are significant modulators of sediment flux over time; potentially influencing the lacustrine systems physically and geochemically. These numerical modeling approaches are allowing us investigate the apparently disparate hydrological responses of East African lake basins to insolation-driven precipitation changes (e.g., Campisano and Feibel 2007; Kingston et al. 2007; Scholz et al. 2007, Trauth et al. 2003), which have in turn been hypothesized as important drivers of local mammalian evolution and hominin demography (e.g., Trauth et al. 2010). Practically, the models may also help to address the critical role that rapid regression and transgression in the lacustrine systems has on soil development and ecosystem response.

Identifying important parameters, initial configurations, and rate constraints for the process models can be done by synthesizing available paleoclimatic and tectonic/exhumation constraints into a model for paleotopographic reconstruction. The landscape evolution models use the modern topography and available constraints on vegetation, paleoclimate, active faulting, exhumation rates (determined by low-temperature (U/Th)/He thermochronology sampling ~10³m and 10⁵⁻⁶ yrs; e.g., Hodges 2014), and erosion rates (determined from cosmogenic ¹⁰Be in detrital samples sampling ~10⁰⁻¹m and 10³⁻⁴ yrs; e.g., Balco and Rovey 2008; Granger 2014; von Blanckenburg and Willenbring 2014) as a starting point for reconstructing the paleotopography of each basin through time. Landscape evolution models calculate the erosion and deposition at each point on the landscape through time as a consequence of tectonic uplift, landcover variation, and geomorphic processes driven by relief production. The geomorphic model simulates the topographic development of the region from a range of hypothetical paleotopographic scenarios (e.g.,

Pelletier 2007, 2010; Pelletier et al. 2011).

AGENT-BASED MODELING OF HOMININ DEMOGRAPHY AND EVOLUTION

Questions involving how evolution actually occurs, how terrestrial communities respond to environmental change, and what were the critical environmental selective forces in hominin evolution are also amenable to modeling approaches through Agent-Based Modeling. This is a “bottom-up” approach to simulation modeling which has been used to explore how simple rules can shape emergent properties of complex systems in space and time (applications in anthropology and ecology: e.g., Barton et al. 2016; Beekman and Baden 2005; Dunbar 2002; Griffith et al. 2010; Grimm and Railsback 2005; Grove et al. 2014; Marean et al. 2015; Premo and Hublin 2009). Through simulations of multiple autonomous agents interacting dynamically with each other and their environment, these models can experimentally evaluate hypotheses about how early hominins evolved in response to changes in the magnitude and timing of specific environmental parameters. For example, preliminary models are exploring the relative success of hominin strategies to deal with persistent, oscillating environmental change by invoking developmental plasticity, micro- or macroevolution, behavioral flexibility, and/or habitat tracking (Kingston and Bathina 2015). These models suggest that subtle shifts in the temporal and spatial scale of environmental change, as well as the nature of the change, can have major influences on the response of biological systems. Based on these data, it is crucial to carefully characterize intervals of environmental change documented in the core and use these analyses to refine attempts to model potential evolutionary outcomes of the variable scales and types of environmental change.

DISCUSSION

The HSPDP is a massive undertaking, with several generations of results to be developed over the years to come. The project is composed of a multidisciplinary international team involving dozens of senior scientists and a comparable number of early career scientists spread across 10 countries. More than 30,000 discrete samples from the HSPDP cores are currently under analysis, and that represents only the initial, low-resolution round of sampling. With the initial core descriptions and sampling completed, preliminary results are now beginning to emerge, with more complete analytical results forthcoming as components of numerous Master’s theses and Ph.D. dissertations. Despite extensive planning and site surveys, the cores retrieved were full of unexpected surprises. For example, the presence of thick basalt sequences in the Northern Awash cores (Campisano et al. 2015), an early fresh water phase for Lake Magadi (Rabideaux et al. 2015), peak phytolith abundances correlated with insolation maxima in several of the cores (e.g., Yost et al. 2015), and the evidence of cyclicity in pedogenic overprinting of lacustrine deposits in virtually all of the cores that have proven helpful in documenting the dynamic fluctuations of the lakes (Beck et al. 2016; Beverly et

al. 2016). As noted in the cores from the Tugen Hills and West Turkana, there are numerous lithologic observations that are not observable or appreciated from outcrops, demonstrating the importance and power of the core preservation for understanding the higher-resolution environmental records.

The HSPDP cores do not exist in isolation, but can be integrated with existing (and planned) lake and paleolake cores from eastern Africa and the Middle East that have been drilled, sampled, and analyzed under similar protocols. This will allow for interregional comparisons across a significant latitudinal transect to document and investigate environmental heterogeneity during the Quaternary in general and the Middle and Late Pleistocene in particular, which is critical to our understanding of the environmental context of modern human origins. In addition to the HSPDP, these sites include Lake Van, Turkey (~600 ka, Litt and Anselmetti 2014), the Dead Sea, Israel (~240 ka, Neugebauer et al. 2014), Lake Tana, Ethiopia (~150 ka, Grove et al. 2015b), Lake Challa, Kenya (~25 ka, Verschuren et al. 2009), Olduvai Gorge, Tanzania (Plio-Pleistocene, McHenry et al. 2016; Njau et al. 2015), Lake Tanganyika (~100 ka, Burnett et al. 2011), Lake Malawi (~1.3 Ma, Lyons et al. 2015; Scholz et al. 2011), and Tswaing Crater, S. Africa (~200 ka, Partridge 1999). Additionally, a longer core (~250 ka target) from Lake Challa has recently been collected (Verschuren et al. 2013) and a deep-drilling project extending into the Miocene at Lake Tanganyika is in the early stages of planning (McGlue and Scholz, 2016; Russell et al. 2012). Records from this impressive collection of cores significantly contribute to the original objectives of the IGBP (International Geosphere-Biosphere Program) and PAGES (Past Global Changes) sponsored PEP III (pole-equator-pole transect through Europe and Africa) Stream 2 (last ~200 kyr) to understand how and why climate has varied along this transect in the past (Battarbee et al. 2004). Similarly, these records can be integrated with a major theme of the DFG (Deutsche Forschungsgemeinschaft) sponsored *Our Way to Europe* (CRC-806), a major sponsor of the Chew Bahir component of the HSPDP, that focuses on the environmental and cultural context of modern human origins and subsequent dispersal from Africa. The HSPDP has also served as a template and proof-of-concept for other paleoanthropological/paleontological localities. The drilling project at Olduvai followed rapidly on the heels of HSPDP and several other potential spin-off projects in eastern Africa have been proposed (Soreghan and Cohen 2013).

The results of the HSPDP studies also have implications for our understanding of modern climate change including the impact that Quaternary climate change has had on human populations and habitats as well as lessons on adaptability. Both the Northern Awash and Tugen Hills cores span the mid-Piacenzian Stage of the Pliocene (3.264–3.025 Ma) and both core data and HSPDP modeling efforts can contribute to the USGS-sponsored PlioMIP and PRISM initiatives (e.g., Dowsett et al. 2010; Haywood et al. 2013; Pound et al. 2014). PRISM seeks to understand the forcing mechanisms, impact, and feedbacks during the

mid-Pliocene as an analog to document and model Earth's response to the last time when temperatures and CO₂ concentrations were similar to those predicted for the 21st century (Dowsett et al. 2013; Haywood et al. 2011). The relevance of past climate change as recorded by East African drill core records for understanding climate change challenges to modern human society in the Anthropocene has been an important component of the HSPDP outreach with partner institutions and to local communities at the drill sites (Cohen et al. 2016), as well as the subject of a short 3-D film produced by Earth Images Foundation in conjunction with the HSPDP (2-D version available at <http://youtu.be/B1iU0fBTfUw>).

This project has high expectations to address long-standing issues of paleoclimate and hominin evolution. As the drill core data are analyzed and synthesized, we may find that the resulting high-resolution record of environmental change over time will still not establish causal linkages with the existing lower-resolution hominin fossil record from outcrops, or even with the better resolved evolutionary records of all large mammal taxa. Similarly, the degree to which we can establish isochronous tie-points between core and fossiliferous exposures varies not just between each site, but even within a single core. For example, while multiple tie-points exist where the fossiliferous outcrops themselves were drilled for some location (e.g., Baringo and West Turkana), other drilling locations are tens of kilometers away (e.g., Northern Afar and Chew Bahir) and may rely primarily on age models to establish more general correlations to fossiliferous outcrops. However, even where one-to-one correlations cannot be established between core and outcrop, the core paleorecords will allow us to document the various environmental parameters for the region where the fossil communities lived and, in particular, understand the frequency, rates, magnitude, and directionality of environmental change that they may have experienced. Results from the core may also promote an iterative process of returning to the field (or museum) to target specific temporal or stratigraphic intervals for additional scrutiny, such as has already been done at West Turkana (Beck et al. 2016).

Comparing patterns of environmental/evolutionary correlation between the six study areas will greatly increase our potential to test specific hypotheses, while simultaneously improving the chance of identifying repeated patterns of evolutionary change associated with environmental change that would support one hypothesis over another. The problem of comparing our high-resolution paleoenvironmental records with the lower-resolution vertebrate fossil record will continually be ameliorated with improved databases, additional dating, new fossil discoveries, and refined taxonomy. One of the most important contributions to understanding possible links between climate and hominin evolution is likely to come from understanding the "internal anatomy" of large-scale environmental trends and events through the high-resolution core records. Such understanding can then help to bridge the gap between local and short-term environmental processes

that would have driven natural selection and the larger-scale trends that are so apparent and intriguing in both the paleoclimate and faunal records.

We expect that the new data archives to be generated by this project will drive paleoanthropologists not only to question and test existing hypotheses of evolution-environment linkages, but even more importantly, engender new hypotheses that emphasize previously unexplored (i.e., shorter time and smaller spatial) scales of interaction between evolving hominin lineages, their use of resources, and their environment. The opportunity that this research creates—a huge expansion of our understanding of the environmental history of eastern Africa during much of the Late Neogene and Quaternary, and the opportunity to carefully model the dynamics behind this record—will be a major outcome of the project even if we cannot refute particular hypotheses of environmental-evolutionary linkages. We accept that simply demonstrating temporal correlation does not prove causation in evolutionary history, but we note that a lack of correlation in multiple, well-constrained records is *prima facie* evidence against any particular hypothesis. For example, consistently finding negative evidence for precessionally-driven wet/dry cycles at eccentricity maxima across our paleolake basins would strongly support the falsification of the pulsed climatic variability hypothesis. It is also possible that environmental changes documented in our core records cannot be linked with observed events in faunal evolution. Competing environmental hypotheses may all be falsified and/or non-ecological factors (e.g., sexual selection, competition) may have been paramount in hominin evolution. Such findings would be of tremendous interest, as they would force us to rethink the major driving mechanisms within the hominin lineages at the regional scale.

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