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Cover Page Footnote
I would like to gratefully recognize the contributions and assistance from Gary Stinchcomb, Marie White, the Afar People, Steven Driese, Steve Dworkin, Naomi Levin, Jay Quade, Nels Iverson, William McIntosh, Nelia Dunbar, Lee Arnold, Mathieu Duval, Margaret Peck, Rogers, Sileshi Semaw, Travis Rohr, Javus Yandal, Ben Ferguson, Lance Stewart, Bart Yates, The National Museum of Ethiopia, and the Authority for Research and Conservation of Cultural Heritage. The financial contributions of the National Geographic Society (Grant EC-52923R-18), the Watershed Studies Institute, the Leakey Foundation, and the Office of Research and Creative Activities, the Jones College of Science Engineering and Technology, and the Department of Earth and Environmental Sciences at Murray State University are deeply appreciated.
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Abstract

Environmental change is thought to have driven dispersals of Anatomically Modern Humans (AMH) out of Africa, yet the precise landscape context of these migrations remains unclear. Furthermore, river-based archives of paleoenvironment during periods of dispersal are scarce. Gona, an area in northeastern Ethiopia with one of the most continuous records of East African Paleolithic and Neolithic archaeology, contains abundant Middle to Late Pleistocene river deposits interbedded with volcanic ash. This study examines the physical and chemical changes of 11 fossilized soils (paleosols) extracted from Gona’s paleoanthropological sites that range in age from the Middle to the Late Pleistocene (~380-11 ka). The paleosols from Gona yield insight into the landscapes with which our earliest direct ancestors interacted, as they are a dynamic biogeochemical archive of weathering, related to the surrounding environment at the time of formation. We focus on paleo-Vertisols or paleosols with vertic features that formed in distal floodplain settings to provide a control on landscape position. The paleosols at Gona record evidence of wetter paleoclimates during periods of AMH migration and suggest that this terrestrial record is a unique source for paleoenvironmental data. This localized dataset complements additional regional-scale paleoenvironmental records when interpreting the forcing and responses of Out-of-Africa migrations.

Gary Stinchcomb is an Assistant Professor in the Watershed Studies Institute and Department of Geosciences at Murray State University. He holds a BA from Penn State (2001), MS from Temple University (2006), and a Ph.D. from Baylor University (2012). He served as a postdoctoral fellow at Penn State, focusing on soil geochemistry. His research interests include studying soil geomorphic response to environmental change. He currently studies soils in Ethiopia, Kenya, and the USA. Some of his current work focuses on buried soils and paleoflood deposits along the Middle Tennessee and Delaware Rivers with the aim of reconstructing relative flood magnitudes and frequencies during the Holocene. He’s also interested in the processes involved in the burial and storage of carbon along river valleys.
Introduction

Our understanding of the origins and subsequent dispersals of Anatomically Modern Humans (AMH) is incomplete – only a handful of AMH fossil sites are documented, and for those that do exist, the routes of migration to or from those sites are ambiguous. Thus, geologists and paleoanthropologists continue to debate the onset, development, and rate of change of AMH dispersal events throughout the East African Rift System (Quintana-Murci et al., 1999; McDougall et al., 2005; Aubert et al., 2012; Brown et al., 2012; Groucutt et al., 2015; Tierney et al., 2017; Lamb et al., 2018; Hershkovitz et al., 2018). Variations in climate and other environmental variables are often inferred to be the catalysts of these dispersals, yet the precise context, including climate effects on local flora and fauna, remains unclear (Tierney et al., 2017).

At this time, the earliest onset of a significant Out-Of-Africa dispersal event by AMH is hypothesized to have occurred in northern Ethiopia around 200 ka, supported by a combination of fossil discoveries in Israel and Greece, the Omo Kibish remains, and a genetic study that recorded the oldest known *Homo sapiens* mitochondrial DNA (Aubert et al., 2012; Posth et al., 2017; Hershkovitz et al., 2018; Harvati et al., 2019). This period coincides with a transition from a colder to a warmer climate, ranging around the boundary of Marine Isotope Stage (MIS) 7 and 6 (Figure 1) (Tierney et al., 2017).

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Sometime between MIS 5e and 5c, another dispersal event is hypothesized to have occurred (Grün et al., 2005a; Asrat et al., 2018). This interval includes climate fluctuations from an exceptionally wet period (MIS 5e), to an increasingly arid climate (MIS 5d), back to a relatively humid period (MIS 5c) (Tierney et al., 2017; Asrat et al., 2018; Lamb et al., 2018).

The next potential major episode of dispersals transpired amid the boundary of MIS 4 and MIS 3 (50-75 ka), and marine records from the Gulf of Aden show that this migration event occurred during sustained dry conditions in northeast Africa (Nielsen et al., 2017, Tierney et al., 2017). Conversely, a multi-proxy study of a lacustrine core from northern Ethiopia exhibits complex climatic variability during this period, with evidence of semi-arid conditions that punctuate an otherwise arid environment (Lamb et al., 2018).

It should be noted that fossils recently discovered in Jebel Irhoud, Morocco dating back to ~ 315 ka, have been deemed as sapiens, challenging the “Ethiopian Origin” interpretation (Hublin et al., 2017). At the time of writing, this claim is controversial, as the braincase of the Irhoud specimens displays characteristics that are akin to archaic human morphologies. Nonetheless, given the abundance of established fossil evidence, it is prudent to assume that Ethiopia was a departure point for Out-of-Africa migrations through the Levant (Grün et al., 2005; Hershkovitz et al., 2018).

Those paleoclimate studies mentioned above suggest that various climate states, e.g., warm-wet vs. cool-dry, could serve as significant catalysts for Out-of-Africa dispersals. However, the inconsistency of inferred climates that drive hominin dispersals suggests that other environmental factors may play a significant role. Numerous studies have focused on the paleoclimatic context of early human dispersal events out of Africa, yet early human behaviors, technology, and land use can be associated with the Critical Zone (CZ) (Blome et al., 2012,
Nordt and Driese, 2013). The CZ, or paleo-CZ when referring to evidence of buried or relict CZs, encompasses the full spectrum of environmental variability, from the top of the canopy to the groundwater table (Beverly et al., 2018; Stinchcomb and Beverly, 2019). This includes the atmosphere, hydrosphere, lithosphere, biosphere, pedosphere, and anthrosphere, changes within which would have affected our earliest direct ancestors (Stinchcomb and Beverly, 2019).

Studies that focus on localized shifts in the East African paleo-CZ during the Cenozoic are scarce, the majority of which focus on the early Neogene (Ashley et al., 2014; Driese et al., 2016; Lukens et al., 2017; Liutkus-Pierce et al., 2019). Additionally, terrestrial-based archives of the paleo-CZ, which provide temporally discontinuous and often localized records of environmental change, lack fluvial-based records. Due to these reasons, there is an absence of comprehensive terrestrial East African records of paleo-CZ during the Quaternary Period, particularly in sites with AMH activity (Figure 2) (Blome et al., 2012).

**Figure 2.** Map of Africa showing locations of climate records and fossil sites. A) Regional distribution of continental and marine climate sites. B) Regional distribution of paleoanthropological sites. Climate and fossil site data after Blome et al. (2012). Base layers from ESRI, Garmin, GEBCO, and NOAA/NGOC.

What types of local environments did our early ancestors interact with as they evolved and dispersed over the Middle-to-Late Pleistocene? Can we observe rapid, localized changes in
the paleo-CZ that are not necessarily seen in the large-scale MIS record? Were small-scale environmental shifts a potentially critical factor in driving hominin dispersals?

An ideal locality to explore these questions is Gona, Ethiopia (11°04’N, 40°25’E), a significant paleoanthropological project area that contains an abundance of Early and Middle-to-Late Pleistocene archaeological and hominin fossil sites, fluvial sediments and soils, and a well-constrained chronostratigraphic record (Figure 3) (Roman et al., 2008; Quade et al., 2008; Stinchcomb et al., in prep.).

![Figure 3](image_url)  
**Figure 3.** A) Outline of Ethiopia, with the Afar Region highlighted in red. B) The Telalak District of the Afar region, highlighted in red. C) General location of Gona within the Telalak District. D) Gona, Ethiopia, with locations of paleosol excavations in yellow.

Paleosols are common at Gona and provide an ideal archive for reconstructing the localized changes in paleoenvironment associated with archaeological and hominin fossil sites. Soils and their buried or relict counterparts – paleosols – are an archive of biogeochemical dynamics related to the surrounding environment (Nordt and Driese, 2013). Soils cycle chemical elements in an open-system exchange with the surrounding Critical Zone and form from five

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primary environmental factors: climate, organisms, relief, parent material, and time (Equation 1) (Jenny, 1941).

**Equation 1** \( \text{soil} = f(c, o, r, p, t) \)

This study will focus on paleosols with expandable clays and shrink-swell features, otherwise known as paleo-Vertisols, as they reflect deposition and soil formation in a floodplain or fluvial terrace setting (Figure 4) (Quade et al., 2004).

![Figure 4. Fining-upward sequence and summary of the position of Gona paleosols with respect to the local floodplain topography and ecosystems of modern-day Gona.](image)

By constraining the paleosol selection to paleo-Vertisols, the study will focus on more well-developed soils in equilibrium with local climate and vegetation conditions (Quade et al., 2004). Conducting a study on a particular soil order that occurs in a relatively constant environment at Gona provides control on two of the five soil-forming factors, i.e., relief (a distal floodplain) and parent material (mixed volcaniclastic alluvium). Selecting paleosols with estimated relative ages will allow us to compare the paleoenvironment with documented pre- to post- AMH dispersal events.
Middle-to-Late Pleistocene Vertic paleosols between dated tuffs are prioritized and preferentially co-located with archaeological sites that have a known or estimated age (Figure 3D) (Quade et al., 2008; Stinchcomb et al., in prep.).

This study will use paleosols from AMH fossil and artifact sites from Gona to quantify the physical, chemical, and ecological conditions of soil formation throughout the Middle-to-Late Pleistocene to examine how localized changes in environmental factors at Gona may have influenced dispersal events over time. Rather than focusing on the shifts of one or two environmental variables of a vast region like many paleoenvironmental studies within the East African Rift System, the time-series generated from this study will provide a detailed record of the localized change in hydrosphere, atmosphere, lithosphere, biosphere, and pedosphere during crucial periods of AMH development, in an area known as the Cradle of Humankind.

Methods

Physical Characterization

Field Methods: Vertic paleosols were identified in the field based on changes in color, texture, and the presence of paleo-weathering features (root traces, peds, and slickensides). Multiple step-trenches were dug to expose unweathered paleosols for measurement and sampling, and paleosol horizons were described using the USDA National Resources Conservation Service’s descriptive techniques (Schoeneberger et al., 2012). Samples were then collected from each described horizon for laboratory analyses.

Particle Size Analysis: Soil texture, the proportion of sand, silt, and clay, influences significant soil properties such as water holding capacity, cation exchange capacity, pH buffering capacity, aeration, and drainage, which in turn will reveal environmental conditions at the time of soil formation (Dexter, 2004). Soil texture was measured for each sample using a laser analyzer to quantify sand, silt, and clay ratios (Arriaga et al., 2006).
**Soil micromorphology:** Petrographic thin sections of oriented soil clods were produced to observe structural, skeletal, and mineralogical changes in soil horizons through time. Calcite fabrics were examined to potentially determine the rate of diagenesis, and micromorphological characteristics relating to soil formation were noted, such as the translocation of clay. As subsoil horizons are correlated with high amounts of clay translocation, observations in thin sections were then compared to field observations to determine the accuracy of horizon designations (Stoops, 2003).

**Chemical Characterization**

**Bulk Geochemistry:** The elemental concentration of soils can be used to infer both physical and chemical properties of paleosols, including climatic conditions, taxonomic classifications, fertility levels, and pedogenic pathways (Nordt and Driese, 2010).

In Vertic soils, the CALMAG index principally tracks the flux of Ca and Mg sourced from calcium carbonate, detrital clay, and exchangeable Ca\(^{2+}\) and Mg\(^{2+}\) (Equation 2) (Nordt and Driese, 2010):

\[
\text{CALMAG} = \frac{\text{Al}_2\text{O}_3}{(\text{Al}_2\text{O}_3 + \text{CaO} + \text{MgO})} \cdot 100
\]

The bulk elemental concentration of the Gona soils was analyzed, quantified, and then input into various pedotransfer functions and climofunctions to estimate the mean annual precipitation, mean annual temperature, salinity, hydrolysis, and concentration of CaCO\(_3\). It should be noted that when applied to paleosols, climofunctions do not take uniformity of parent material into account, and diagenetic processes can significantly affect results.

**pH/EC:** The pH and electrical conductivity (EC) have a significant influence on soil properties, which is reflected in the soil sample’s various ion concentrations. The pH, which determines the extent of acidity and alkalinity within a soil, is the concentration of H\(^{+}\) ions within a soil solution. The EC, a measure of the ability of a soil solution to conduct an electrical current, is primarily determined by the concentration of the Na\(^{+}\), K\(^{+}\), Mg\(^{2+}\), and Ca\(^{2+}\) ions.

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The concentration of these cations within the soil is determined by environmental factors, such as rainfall, degree of weathering, climate, and decomposition of organic matter. Shifts in physical and chemical soil properties were examined by analyzing the change in pH and EC over time. This provides crucial information regarding Gona’s paleoenvironment, such as localized shifts in water availability and degree of sodicity/salinity. The pH and EC were measured by using a pH electrode and an electrical conductivity probe on 1:1 soil/water extract (Schoeneberger et al., 2012).

Biological Characterization

Total Organic Carbon: The amount of total organic C (TOC) stored within soil organic matter (SOM) enters the soil through decomposition of soil biota, root exudates, microorganisms, and residues from flora and fauna. The introduction of organic carbon into the soil is crucial to the development of an ecosystem as it is one of the primary sources of energy for plant life and triggers nutrient availability. Additionally, carbon provides much of the cation exchange capacity and water-holding capacities of surface soils. Thus, the amount of TOC within soils can be interpreted as an indicator of soil quality, which in turn can signal ecosystem health (Buol, 1989). TOC and total carbon (TC) were measured by dry combustion using an elemental analyzer (Soil Survey Staff, 2017). TOC samples were pre-treated in 10% HCl to remove all traces of inorganic carbon. The TOC was then subtracted from the TC to find the total inorganic carbon.

Results and Discussion

Paleoenvironmental Synthesis: Paleosols become notably darker at MIS 5a and then again around MIS 1 (Figure 5A). Organic carbon (OC) content also increases in the darker paleosols with notable peaks at MIS 5a, early MIS 3, and MIS 1 (Figure 5B). CALMAG-based estimates of mean annual precipitation (MAP) range from 405 to 527 mm/yr (+/- 108), with the exception of notable increases at MIS 5a (688 mm/yr) and MIS 1 (656 mm/yr) (Figure 5C). These
increases in OC and MAP coincide with previously documented episodes of wetter climates, MIS-5a, and the African Humid Period. These correlations suggest that increased water availability may have promoted the development of a riparian grassland-type environment at Gona, as these environments are known to store OC due to aggregate soil and an extensive root network (Blazejewski et al., 2005). This increases the introduction of organic matter into the soil, which in turn imparts a darker color.

**Figure 5 (left).** Modeled soil profiles (A), organic carbon (B), and mean annual precipitation (C) paleosol data from eleven sites within Gona, Ethiopia. Refer to Figure 1 to correlate each site with an approximate age date, and Figure 3D to correlate each profile with its modern-day landscape position.

Pedotransfer function results alongside pH and EC measurements reveal that Gona paleosols are almost consistently alkaline (pH > 7.3), sodic (exchangeable sodium percentage > 15%), and saline (EC > 4 mS/cm for sites older than late MIS 3), suggesting that salt-affected soil development was common at Gona between MIS 11-1 (Figures 6A, 6B, 6C). As such, Gona is likely to have hosted a series of halophytes, which are prevalent in modern-day tributary and trunk-channel floodplains. While Gona remains sodic, sites < late MIS 3 become significantly less alkaline and saline, which could have the capacity to host a broader range of flora and fauna.

**Figure 6 (left).** Modeled pH (A), exchangeable sodium percentage (B), and electrical conductivity (C) paleosol data from eleven sites within Gona,
Ethiopia. Refer to Figure 1 to correlate each site with an approximate age date, and Figure 3D to correlate each profile with its modern-day landscape position.

Soils from sites associated with a near-margin and/or near-tributary landscape position (namely, Ma’our and Yaalu Tributary) have lower fine clay values than their counterparts (Figure 7). Additionally, profiles from the same age with variable landscape positions show notable variations in fine clay percentage. This can be associated with proximity to river channels and helps suggest the variability in landscape positions over a localized area.

Petrographic analyses show that peds from sites < MIS 5a have a much more granular, darker microstructure, alongside impregnated iron and manganese stains on carbonates (Figure 8A). This dark microstructure is attributed to an increased rate of shrinking and swelling clays, with the impregnated carbonates indicating an abundance of water in the system.

In sites predating MIS 5a, subangular blocky structures are prevalent, an indicator of shrink/swell, but not as frequent as a granular structure (Figure 8B). Impregnation of carbonates is not observed as well, which could suggest a possible pedofacies shift. The ability of a soil to shrink or swell, otherwise known as coefficient of linear extensibility (COLE), derived from pedotransfer functions show this as well, with a significantly higher COLE values post MIS 5a. These observations suggest a shift in landscape position, as the main channel of the Awash River avulsed to its current position (Figure 9).

**Figure 7 (right).** Fine clay data from eleven sites within Gona, Ethiopia. Refer to Figure 1 to correlate each site with an approximate age date, and Figure 3D to correlate each profile with its modern-day landscape position.
**Figure 8 (left).** Thin sections of Gona, Ethiopia, in plane polarized light. A) The granular microstructure of Kilaitoli (MIS 1). B) The subangular microstructure of Yaalu Tributary (MIS 5a).

**Figure 9 (below).** Coefficient of linear extensibility data from eleven sites within Gona, Ethiopia. Refer to Figure 1 to correlate each site with an approximate age date, and Figure 3D to correlate each profile with its modern-day landscape position.

**Conclusions**

Data extracted from paleosols at Gona, Ethiopia suggest that the soil-forming environment has changed from the Middle Pleistocene to Early Holocene and appears to track the Marine Isotope Stage record while providing evidence of minor, localized shifts in environment.

Overall, during the Middle-to-Late Pleistocene, the Gona environmental record, derived from paleosols mirrors marine-based climatic records, but also provide windows into the landscapes of the past. During humid periods associated with AMH migration, the local
environment at Gona was likely to host a broader range of halophytes and fauna. A shift in landscape position within the fluvial environment at Gona is apparent at MIS 5a, and as we approach the cusp of the Holocene, the overall soil environment becomes less salt affected, with a more neutral pH. Therefore, during more humid periods, Gona could have provided a conducive environment for early AMH as they migrated out of Africa, but as the climate becomes increasingly arid, floral and faunal resources become scarce, making such journeys less feasible.

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Referenced Materials


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