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Cooling and drying in northeast Africa across the Pliocene

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A B S T R A C T

Terrestrial records suggest that Northeast Africa experienced drying during the Pliocene; however, these records are often incomplete in time and space, and questions about this shift in climate remain. Here, we use marine sediments from Deep Sea Drilling Project (DSDP) Site 231 in the Gulf of Aden to generate a multi-proxy organic geochemical record of northeast African climate spanning 5.3–2 Ma. This new record provides a regional perspective on climate and serves as context for the fossil record of early hominin evolution. We measured leaf wax carbon ($\delta^{13}C_{wax}$) and hydrogen (δD_{wax}) isotopic composition and TEX_{86} (tetraether index of 86 carbons) to investigate past changes in vegetation, aridity, and ocean temperature, respectively. In the earliest Pliocene, we infer warm subsurface ocean temperatures from TEX_{86}, semi-arid conditions on land and extensive C_4 grasslands based on δD_{wax}, $\delta^{13}C_{wax}$ and previously published pollen. After 5 Ma, ocean temperatures gradually cooled, and at 4.3 Ma there was a transition to arid conditions on land based on δD_{wax} and pollen. Grasslands yielded to a mid Pliocene landscape of dry shrublands. This drying appears to be an atmospheric response to cooling ocean temperatures, which may reflect changes in tropical ocean circulation, the intensification of Indian Monsoon winds or perhaps other changes associated with Pliocene cooling.

1. Introduction

The late Pliocene witnessed cooling of global climate after the warm climates that characterized the early to mid Pliocene. Climatically relevant geological changes that ensued across the Pliocene are thought to have included changes in ocean circulation (e.g., Cane and Molnar, 2001; Haug and Tiedemann, 1998), declining atmospheric carbon dioxide levels (e.g., Bartoli et al., 2011), and the initiation of high latitude glacial cycles. It has been proposed that changes in subsurface ocean temperatures (Cane and Molnar, 2001), surface temperature gradients (Brierley and Fedorov, 2010) as well as the onset of Northern Hemisphere Glaciation (deMenocal, 1995) may have led to a drying of east African climate. Here we focus on northeast African terrestrial environments during the Pliocene. We do so from the perspective of marine sediment downwind of northeast Africa, offering a regional sampling of terrestrial vegetation cover and climatic conditions, while also reconstructing ocean temperatures. Ocean conditions, rainfall changes, and the resulting vegetation responses, may have dramatically altered the terrestrial landscapes that were home to early human ancestors.

While most continents were in roughly present-day locations by 5 Ma, ongoing plate motions transformed tropical ocean gateways and uplifted new landmasses. The Central American Seaway closure was previously a candidate for climate change during the Pliocene (Haug and Tiedemann, 1998), but a more recent study has suggested completion in the mid Miocene (Montes et al., 2015). The shifting channels connecting the Pacific and Indian Oceans remain a viable mechanism for Pliocene climate change. Northward motion of the Indo-Australian plate (Daly et al., 1991) constricted and shifted circulation, and was hypothesized to alter the Indonesian Throughflow leading to Indian Ocean subsurface cooling (Cane and Molnar, 2001; and see Molnar and Cronin, 2015 for a recent review of the literature on bathymetric changes and dates). This hypothesis posits that as the seaway became more restricted, cooler water from the North Pacific would feed into intermediate depths in the Indian Ocean, leading to cooler upwelled water in the Arabian Sea (Cane and Molnar, 2001). This would be expected to cause regionally drier conditions, as cooler sea surface temperatures in the western Indian are generally associated with reduced rainfall in East Africa (Tierney et al., 2013). Exposure of more land on the emergent Maritime Continent (i.e., the Indonesian archipelago and nearby shallow seas) associated with tectonic motion of the Indo-Australian plate may have climatic implications, including a strengthening of the Walker Circulation (Molnar and Cronin, 2015), with consequences for African climate. In ad-

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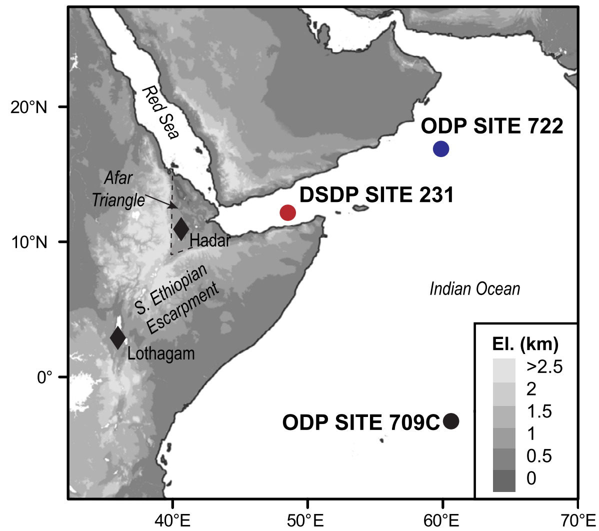

Fig. 1. Map of DSDP Site 231 in the Gulf of Aden (11.89°N, 48.25°E, 2152 m water depth) and locations of SST records and terrestrial sites discussed in the text.

dition, the uplift of fresh basaltic crust and exposure to chemical weathering in tropical latitudes has been proposed as a possible mechanism for pCO_2 drawdown and global cooling trends across the last 5 Myr (Molnar and Cronin, 2015).

Indian Ocean temperature reconstructions have found signs of the predicted cooling across the Pliocene. In particular, changes appear to have occurred in the subsurface, with a freshening at 4.3 Ma and cooling between 3.5 Ma and 3.0 Ma evident at DSDP Site 214 based on foraminifera *Globorotalia crassaformis* δ^{18}O and Mg/Ca (Karas et al., 2009). This shift in subsurface conditions in the eastern Indian Ocean occurs close to the timing of emergence of Timor (Nguyen et al., 2013). Cooling in the Leewin Current (Karas et al., 2011) and the Benguela Current (Marlow et al., 2000) have been linked to this transition, indicating the broad regional implications of Indonesian Throughflow changes. In the northwestern Indian Ocean, in the upwelling region of the Oman margin, Pliocene cooling has also been detected by alkenone reconstructions (Huang et al., 2007), but the cooling may be underestimated as the proxy is close to its upper limit of 28 °C in the early Pliocene. Additional information comes from alkenone and total organic carbon contents in the sediments (Huang et al., 2007) that both indicate increased productivity between 4 and 3 Ma, although *Globigerina bulloides*, often assumed to be an upwelling indicator (Gupta et al., 2015), decreases at the same time. The organic productivity rise may be consistent with intensification of monsoonal winds over the Arabian Sea enhancing upwelling. More puzzling is the foraminiferal Mg/Ca record from the central western Indian Ocean ODP Site 709 (Fig. 1) that shows sea surface temperatures (SST) warming out of the early Pliocene warm period (Karas et al., 2011), while global temperatures cooled. However, questions about Mg/Ca proxy fidelity associated with possible Mg/Ca seawater chemistry changes have elsewhere suggested upward revision of early Pliocene SST estimates (O'Brien et al., 2014). Delving further into Indian Ocean changes is of interest not only to resolve general questions of proxy fidelity (O'Brien et al., 2014), but also because those temperature patterns influence precipitation changes in East Africa (Tierney et al., 2013).

East African rainfall changes, and resulting vegetation responses, may have dramatically altered the terrestrial landscapes that were home to species of the hominin family tree, including *Ardipithecus ramidus* and *Australopithecus afarensis*. Those fossil specimens, as well as the wider record of hominin fossil fragments, dentition and most recently a surge of information on their dietary preferences (Cerling et al., 2013; Levin et al., 2015; Wynn et al., 2013) provide anthropological interest motivating climate and vegetation reconstructions. Existing marine and terrestrial records (see Levin, 2015 for a review) leave plenty of room to fill in additional details of northeast African environments during the Pliocene. However, the active tectonics in the East African Rift Valley graben includes complex changes in topography, hydrology and lake formation (Maslin et al., 2014), which may not be clearly linked to regional precipitation change.

Marine sediments of the Gulf of Aden provide a downwind repository of terrestrial proxies blown off northeast Africa, and have yielded valuable paleoclimate evidence from analyses of dust (deMenocal, 1995), pollen (Bonnefille, 2010), and plant leaf waxes (Feakins et al., 2013; Tierney and deMenocal, 2013) over various timescales from Miocene to recent. Here, we present a study of Pliocene climate based on organic geochemical analyses of sediment from DSDP Site 231. Using $\delta^{13}C_{wax}$ and δD_{wax} and previously published pollen data (Bonnefille, 2010), we assess how changes in northeast African hydrology influenced vegetation cover. To test the role of Indian Ocean temperatures on northeast African hydrology, we generated a TEX_{86} record from the Gulf of Aden. We evaluate changes in western Indian Ocean SSTs based on prior alkenone (Huang et al., 2007; Herbert et al., 2010) and Mg/Ca (Karas et al., 2011) reconstructions from the Arabian Sea and western Indian Ocean. We seek to connect oceanographic conditions and East African climate through an examination of ocean temperatures and regionally significant terrestrial environmental reconstructions in the same sediments. Specifically, we ask whether the ocean adjacent to Africa cooled during the Pliocene and whether there was, at the same time, a regional drying of terrestrial environments.

2. Regional climate

2.1. Precipitation amount and isotopic composition

The Horn of Africa today receives 100–200 mm yr^{-1} of precipitation (Nicholson, 2000). Rainfall occurs during the biannual passage of the ITCZ with long rains from March to May and short rains from October to November (Nicholson, 2000). Precipitation isotopes (stable oxygen and hydrogen isotopes; δ^{18}O and δD) act as tracers for moisture sources. Moisture derived from the Indian Ocean is generally more depleted in the heavier isotopes by Rayleigh distillation from prior rainout, while rare incursions of westerly moisture are isotopically enriched due to the recycling of moisture in west African rainforests (Levin et al., 2009). Isotope-enabled climate model simulations support the use of hydrogen isotopes as a hydroclimate indicator in the region (Tierney et al., 2011). Although there is a paucity of precipitation isotope collections in this region, theory and model simulations suggest that lower values of δD in precipitation indicate wetter conditions, i.e. more prior rainout from Indian Ocean sources. Conversely, higher values of δD occur as a result of less antecedent rainout and increased evaporative enrichment during raindrop descent in arid conditions, especially in the Afar Triangle.

2.2. Atmospheric circulation and transport of wind-blown proxies

Atmospheric circulation over northeast Africa is dominated by the seasonal reversal of monsoon winds. During the boreal winter, northwesterly wind speeds average 2–4 m s^{-1}, whereas from May to September southwesterly winds of the Somali Jet in the lower troposphere can reach wind speeds of 30 m s^{-1} (Ramage et al., 1972). The summer season is thus expected to dominate the year round wind-transport of terrigenous material to the Gulf of Aden. The Somali Jet is steered by the Ethiopian Highlands, and this circulation has likely been prevalent throughout the Pliocene as the surface uplift of the Highlands predates the Pliocene

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