14.8 Marine Sediment Records of African Climate Change: Progress and Puzzles

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14.8.1 Introduction

The ocean basins are the ultimate repositories of the world's sediments. Accumulating slowly and continuously, they offer a rich and detailed archive of Earth's climatic history. Scientific ocean drilling and sediment coring operations have collected cores from nearly all corners of the world's oceans, and these sediments inform much of our knowledge of the magnitudes and rates of past ocean circulation and global climate changes, as well as regionally specific paleoclimatic histories of adjacent continental land areas.

The African continent has witnessed some of the most sweeping changes in terrestrial climate and vegetation during the Cenozoic (**Chapter 14.9**). The hyperarid expanses of the Namib, Kalahari, and Sahara deserts that frame this continent today are geologically recent features. Terrestrial geologic and paleoecological evidence indicates that the African continent was warm, wet, and well vegetated during much of the early Cenozoic and that large deserts first appeared in the Kalahari and Namib region of SW Africa in the middle Miocene (after 17–18 Ma), followed by the development and expansion of the North African Saharan desert and East African grasslands after the latest Miocene (after 7 Ma; Cerling, 1992; Schuster, 2006; Senut et al., 2009; Swezey, 2009) related to high-latitude cooling events at these times (Zachos et al., 2001). It would be premature to conclude that a complete understanding of African paleoclimatic history is at hand, but these baseline paleoecological shifts illustrate to the scope of long-term secular and orbital-scale cyclical environmental changes on this continent.

Marine sediments accumulating along the margins of the African continent provide unique archives of Africa's paleoclimate history. Whereas terrestrial sequences are often incomplete due to faulting, erosion, and nondeposition, marine sediments accumulating in offshore basins and marginal environments off the African continent offer complete and well-dated archives spanning most of the Cenozoic. The spatial coverage of available deep-sea sediment cores and drill sites is quite high on some regions off West Africa and notably poor off Northeast Africa (**Figure 1**). Terrestrial sequences provide critical 'ground truth' information documenting conditions in specific regions of Africa. Marine sediment paleoclimate records are derived from changes in sedimentary flux, texture, composition, and organic biomolecular signatures delivered by wind transport and river drainage systems to the ocean basins. These proxies are used to infer past changes in regional surface climate, winds, and hydrology and typically represent a larger spatial-scale integration than the more site-specific focus provided by terrestrial archives, such as paleolakes, soils, and sedimentary sequences.

This chapter provides an overview of the range of applications and potential of marine sediments as archives of past changes in African climate. The last decade has seen major advances in both the quality and diversity of African paleoclimate records from marine sediments, building upon a nearly 40 years history of research that began with the pioneering marine sedimentation work off NW Africa in the early 1970s documenting Pleistocene changes in mineral dust supply from the Sahara (Folger, 1970; Hays and Perruzza, 1972; Parkin and Shacklet, 1973; Sarnthein, 1978). Rea (1994) provides an excellent but somewhat dated review of the deep-sea sedimentary record of eolian deposition (Rea, 1994).

Ongoing research on eolian sediment fluxes, composition, grain size, and organic biomolecular vegetation proxies preserved in deep-sea sediments has greatly clarified to our current understanding of how and why African climate has changed from historical to orbital and to geological timescales. These records comprise a robust complement to geological evidence from the continent itself. New questions have arisen as more data have become available, so this chapter concludes with some discussion of important unresolved 'puzzles' concerning the fidelity of paleoclimate proxies, reconciling terrestrial and marine evidence, and understanding the longer-term history of African paleoclimatic change.

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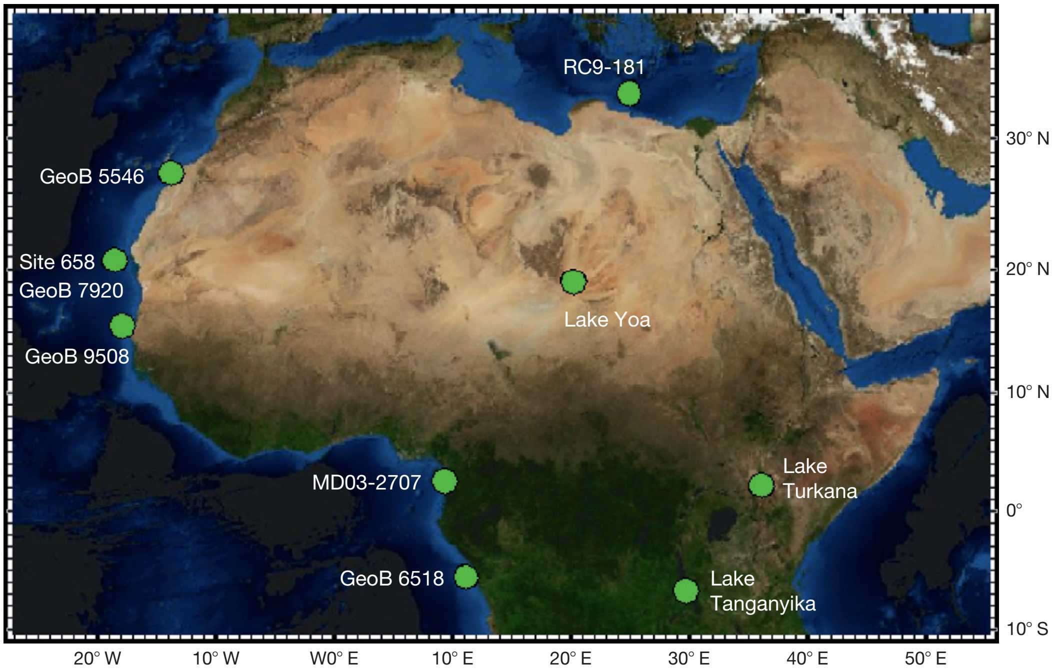

Figure 1 NASA visible earth image of North Africa (January) with selected marine and terrestrial paleoclimate records of past African climate change. Only core sites discussed in this chapter are shown here – many more published marine and terrestrial records of African climate, vegetation, and paleohydrologic change have been published.

14.8.2 Marine Sediments as Recorders of Terrestrial Climate Change

14.8.2.1 Eolian Dust Supply, Composition, and Grain Size

The earliest investigations of marine sediments as proxies for past changes in North African climate noted that the deep-sea sediments accumulating off the margins of NW Africa were distinctive brick red in color, reflecting the abundant supply of wind-borne mineral dust transported from dust source areas in the Sahara and Sahel source regions principally from the Bodélé depression in Chad and sources in Mauritania and eastern Mali (Folger, 1970; Hays and Perruzza, 1972; Prospero et al., 2002; Sarnthein, 1978). Indeed, North Africa is one of the most prolific sources of eolian dust to the marine boundary layer, with the easterly Saharan air layer summer dust plume alone supplying over 250 Tg (Tg $=10^{12}$ g) of mineral dust annually to the subtropical Atlantic (Goudie and Middleton, 2001).

Hays and Perruzza (1972) observed that long sediment cores taken off the Senegalese coast contained alternating layers of red-brown, silty sediment interbedded with white, calcareous foram–nannofossil ooze and surmised, correctly, that the reddish layers most likely reflected past increases in the export of mineral dust from North Africa. This work was among the first to propose that the observed color variations in these deep-sea sediments were the result of changes in the supply of wind-borne mineral silt and clay that diluted a relatively constant background supply of biogenic carbonate tests from surface ocean productivity.

The most recent African humid period (AHP) between 15 and 5 ka BP represents one of the most spatially extensive and dramatic changes in continental climate of the late Pleistocene. During this interval, African monsoonal circulation and rainfall was enhanced due to increased boreal summer insolation resulting from periodic changes in orbital precession (**Figure 2(a)**; Kutzbach, 1981). With the invigorated African monsoonal circulation, the vast barren expanses of the modern Saharan desert were replaced during the early Holocene with widespread savanna and subtropical tree vegetation, with large and small lakes and abundant fauna, including hippos, crocodile, elephant, and abundant and diverse bovid populations (COHMAP Members, 1988; Hoelzmann et al., 1998; Jolly et al., 1998; Kroepelin et al., 2008; Street-Perrott et al., 1989). Evidence for hunter-gatherer and subsequent pastoralist human communities is borne by archeological and rock art evidence throughout the modern Saharan desert (Hoelzmann et al., 1998).

A continent-wide compilation of past lake-level reconstructions (the Oxford Lake Level Database, OLLD) (COHMAP Members, 1988; Street-Perrott et al., 1989) updated with lake-level reconstructions published in the last 20 years (Tierney et al., 2011) chronicles the changes in lake levels that occurred across North Africa during the AHP (**Figure 2(b)**). This database classifies lakes as 'low' (lake is within 0–15% of its potential volume or dry), 'intermediate' (lake is within 15–70% of its potential volume), or 'high' (lake is within 70–100% of its potential volume or overflowing) every 1000 (calendar) years during the late-glacial period and the Holocene. The difference in lake levels at 9000 years – the height of the AHP – relative to the conditions today shows that the extent of the AHP across the continent was vast, extending from the far northern Sahara to as far south as 10° S in East Africa (**Figure 3**). This African lake-level database documents maximum lake levels during the early Holocene, between 12 and 5 ka BP. The end of the AHP near

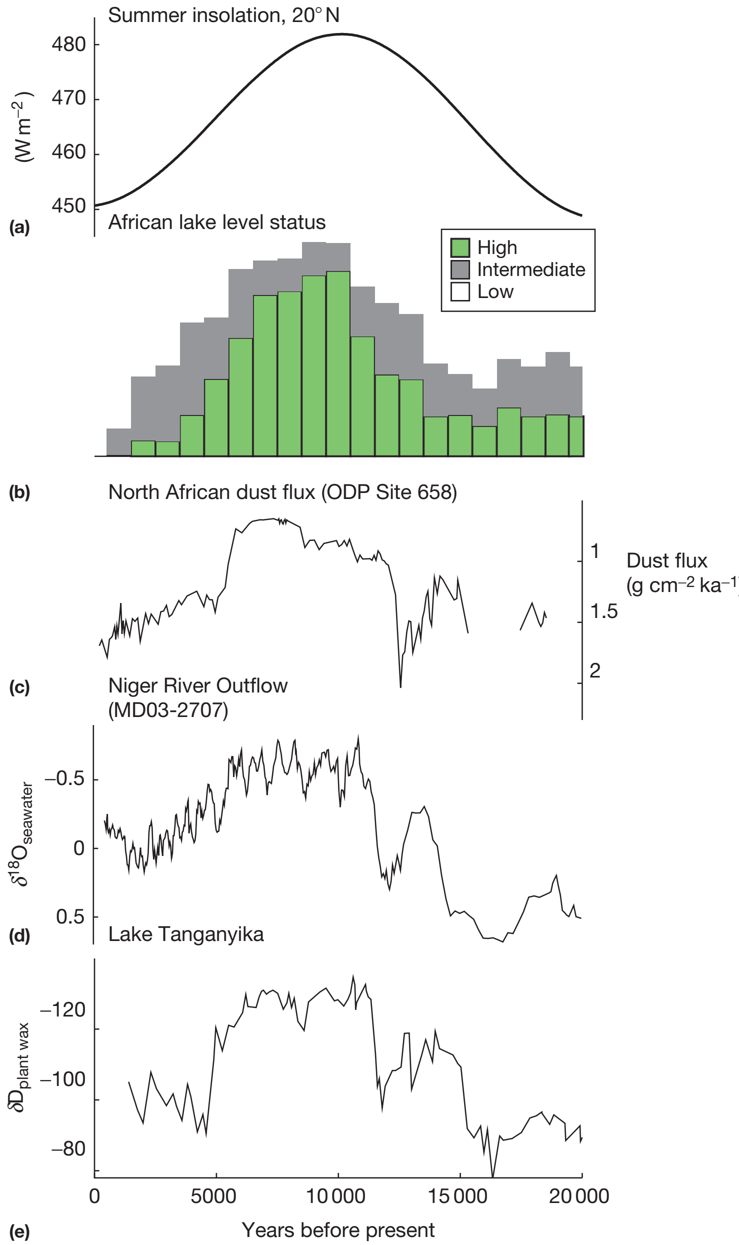

Figure 2 Selected terrestrial and marine records of North and equatorial African climate change between 0 and 20 ka BP (figure adapted from deMenocal PB and Tierney JE (2012) African Humid Periods paced by Earth's orbital changes. *Nature Education* 3: 12). (a) Boreal summer insolation at 20° N; (b) histogram of African lake-level status based on the OLLD (COHMAP Members, 1988; Street-Perrott et al., 1989) updated with lake-level reconstructions published in the last 20 years (deMenocal and Tierney, 2012; Tierney et al., 2011); (c) Th-normalized terrigenous dust fluxes at ODP Site 658 off Mauritania (deMenocal et al., 2000b); (d) a sediment core record from the Gulf of Guinea of $\delta^{18}O_{seawater}$, a proxy for local salinity and Niger River runoff based on foraminifer $\delta^{18}O$ and Mg/Ca geochemistry; (e) recorded Lake Tanganyika paleohydrology based on the hydrogen isotopic composition of plan leaf wax compounds preserved in lake sediments (Tierney et al., 2010).

5 ka BP occurs gradually over several millennia in this compilation, consistent with pollen evidence from Lake Yoa in NE Chad (Kroepelin et al., 2008) and Nile River runoff evidence from the eastern Mediterranean (Hamann et al., 2008).

The marine sedimentary record of North African dust export presents a good example of the value and utility of deep-sea sediments in complementing these terrestrial records. Marine sediments accumulating in the Atlantic Ocean and Mediterranean and Red Seas offer the dual advantages of relatively constant and continuous sedimentation rates (commonly between 5 and 50 cm ka^{-1}) and abundant microfossil shells that permit solid radiocarbon dating. The principal disadvantage of marine sediment eolian dust records is that the dust sources can derive from a broad geographic region that

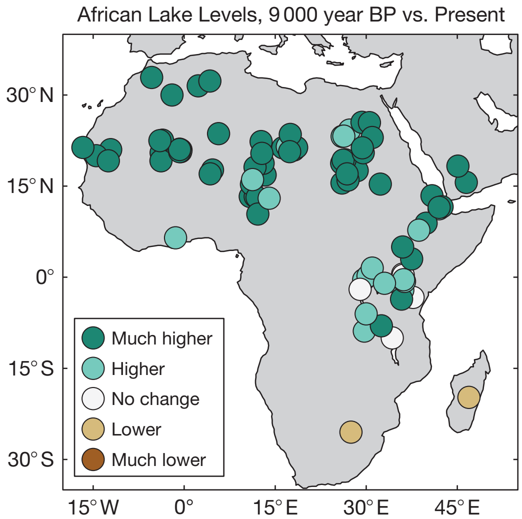

Figure 3 Map of reconstructed lake levels across Africa 9000 years ago relative to today. Data are from the OLLD (COHMAP Members, 1988; Street-Perrott et al., 1989) updated with lake-level reconstructions generated in the last 20 years (Tierney et al., 2011). Note the widespread existence of large and small lake bodies across North and East Africa.

can be difficult to constrain, so they are less spatially indicative than lake-level data, for example.

Interpretations of past variations in dust concentration in a deep-sea core have commonly conflated the separate influences of aridity (dust availability) and wind speed (entrainment and transportation) on dust delivery (Pye, 1987; Rea, 1994). Distinguishing between these processes sedimentologically is not trivial (Skonieczny et al., 2011; Stuut et al., 2002; Tjallingii et al., 2008). The dramatic post-1970s increase in dust flux recorded at an aerosol sampling station in Barbados is accurately in a high-sedimentation rate core off Senegal (GeoB9501) (Mulitza et al., 2010; Prospero and Lamb, 2003). Such studies, coupled with ocean sediment trap records (Fischer et al., 1996; Ratmeyer et al., 1999), provide broad support for deep-sea sediments as reliable records of North African climate change.

Many studies have used sediment cores from the NW African margin (**Figure 1**) to investigate the timing and causes of past changes in African climate. Ocean Drilling Program (ODP) Site 658 off Cap Blanc, Mauritania, and subsequent cores obtained from this location have been used to monitor past changes in North African aridity based on measurements of eolian dust concentration and burial flux (Adkins et al., 2006; deMenocal et al., 2000a; Mulitza et al., 2008), and a high-resolution dust concentration record developed at this site documented the AHP as a stratigraphic interval of markedly lower dust concentrations between about 15 and 5 ka BP, with a brief millennial-scale return to drier conditions during the Younger Dryas cold event between 13 and 12 ka BP (deMenocal et al., 2000a).

A valid critique of such studies had been that changes in dust concentration can arise from real changes in the supply of mineral dust or apparent changes due to dilutional biogenic carbonate sedimentation. To address this, Adkins et al. (2006) used Th-normalization as a means to develop quantitative particle fluxes at this site as a way to quantify the actual burial fluxes of eolian and biogenic sediments over the last 20 ka BP (in g $cm^2 ka^{-1}$ units). The Th-normalized eolian fluxes at Site 658 closely match the dust concentration data, documenting that the eolian time series here is indeed a record of past variations in eolian supply (**Figure 2(c)**).

The dust flux time series bears a close resemblance to the OLLD (COHMAP Members, 1988; Street-Perrott et al., 1989) (updated with lake-level reconstructions published in the last 20 years; Tierney et al., 2011) that chronicles Holocene changes in lake-level basins across Africa (**Figure 2(b)**). This database classifies lakes as 'low' (lake is within 0–15% of its potential volume or dry), 'intermediate' (lake is within 15–70% of its potential volume), or 'high' (lake is within 70–100% of its potential volume or overflowing) every 1000 (calendar) years during the Holocene. The difference in lake levels at 9000 years – the height of the AHP humidity – relative to the conditions today shows that the extent of the AHP across the continent was vast, extending from the far northern Sahara to as far south as 10° S in East Africa (**Figure 3**). Recent studies of cores taken elsewhere along the NW African margin have shown that dust concentrations were reduced during the AHP at many sites, from Senegal (15° N) to Morocco (27° N; GeoB 5546), illustrating that humid conditions prevailed over much of NW Africa during this period (Henderiks et al., 2002; Kuhlmann et al., 2004; Matthewson et al., 1995; Mulitza et al., 2008).

The mineralogy and chemical composition of deep-sea sediments have been used to constrain the provenance of eolian sediments and signatures of chemical weathering linked to climate. These data compliment eolian flux measurements by informing whether the observed variability reflects changes in the sediment supply from the same or a different terrain. Radiogenic isotope ($^{87/86}$Sr and εNd) analyses of detrital sediments are remarkably powerful provenance indicators, especially when coupled with major, minor, and trace element geochemical assays. Radiogenic Sr and Nd isotopic variations and detrital major, minor, and trace geochemistry can be used to define geologic terrains and dust source areas (Goldstein and O'Nions, 1981; Grousset and Biscaye, 2005; Grousset et al., 1988). This approach has been exploited by many studies because the geochemical signatures of African dust and potential source areas are very distinctive relative to mean marine sediment compositions (Caquineau et al., 2002; Cole et al., 2009; Jung et al., 2004; Matthewson et al., 1995; Mulitza et al., 2008; Sirocko et al., 2000; Skonieczny et al., 2011; Zabel et al., 2003).

One example of this approach that follows on the eolian sediment flux patterns described in the previous text is an analysis of the radiogenic and elemental geochemistry signatures of the AHP. In an effort to define whether dust source areas changed in association with this large climate excursion, Cole et al. (2009) analyzed the $^{87/86}$Sr and εNd compositions and detrital elemental geochemistry of Site 658 sediments off Mauritania. Their εNd was constant with values near −15, showing that the parent rock composition of the eolian dust did not change over the last 20 ka (**Figure 4**). However, the Sr isotopic data revealed the surprising result that the AHP eolian sediments showed strong evidence of weathering and leaching prior entrainment and transport, perhaps consistent with the more humid conditions at the time. Typical late Holocene or last Glacial sediments have the Sr isotopic ratios near 0.723,

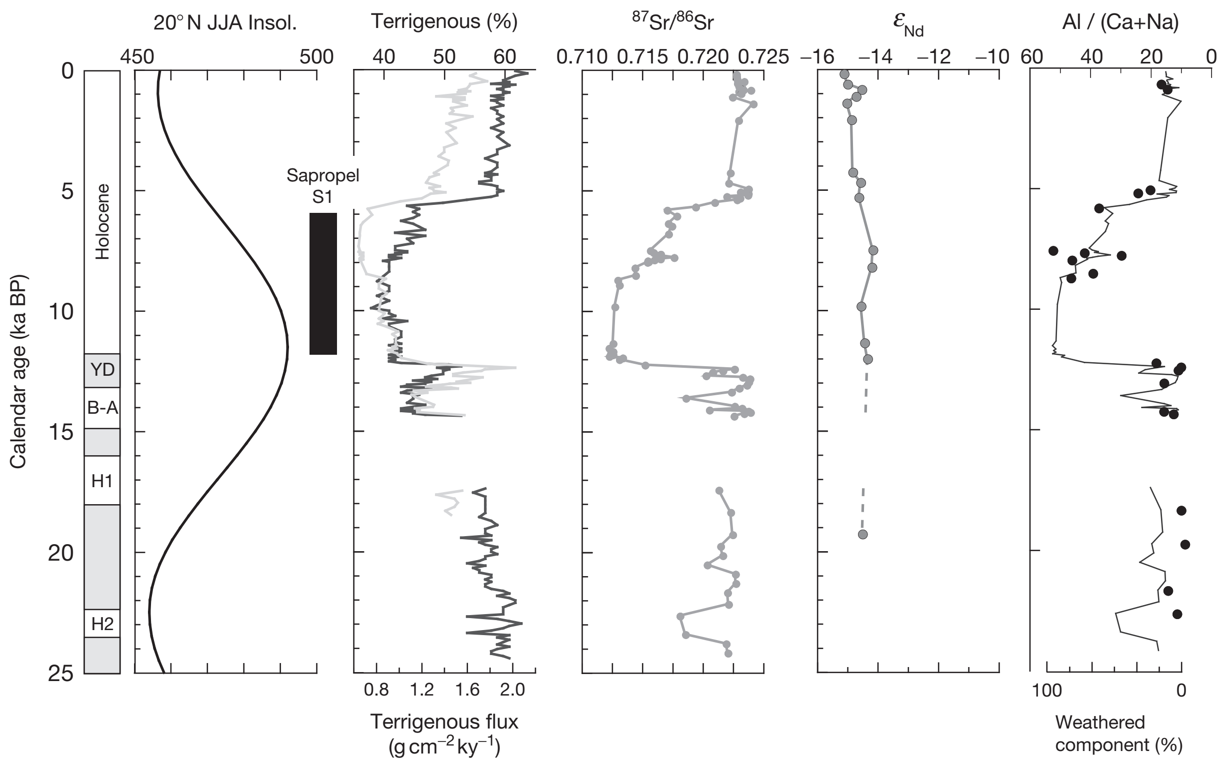

Figure 4 NW African eolian dust provenance at ODP Site 658 over the last 25 ka BP (adapted from Cole JM, Goldstein SL, deMenocal PB, Hemming SR, and Grousset FE (2009) Contrasting compositions of Saharan dust in the eastern Atlantic Ocean during the last deglaciation and African Humid Period. *Earth and Planetary Science Letters* 278: 257–266). Boreal summer insolation at 20° N and terrigenous dust percentages and Th-normalized fluxes from Site 658 (Adkins et al., 2006; deMenocal et al., 2000b). Coretop Sr and Nd isotopic values are consistent with eolian contributions from key likely source areas (Bodélé depression, Chad). The lack of variability in εNd downcore suggests the source rock material has not change over the last 25 ka BP, but the large $^{87/86}$Sr shift to less radiogenic values during the AHP indicates alteration of the sediment. Terrigenous major and minor element geochemistry (increased chemical index of alteration values, (Al/(Ca + Na)) suggests greater weathering and chemical leaching of terrigenous sediments during the AHP (Cole et al., 2009). Finer grain sizes during this interval suggest enhanced fluvial contributions (Tjallingii et al., 2008), although this interpretation is not fully compatible with the observed sediment geochemistry (Cole et al., 2009).

consistent with a nearly pure Saharan dust contribution, most likely originating in the Bodélé basin in Chad (Cole et al., 2009; Grousset and Biscaye, 2005). In contrast, the AHP had much lower $^{87/86}$Sr ratios near 0.715 and fivefold greater chemical indices of alteration (Al/(Ca + Na)), indicating significant leaching and weathering of the sediments prior to transport (**Figure 4**). Tjallingii et al. (2008) noted that the AHP grain-size distributions were markedly finer than late Holocene or Glacial sediments and proposed a fluvial origin for these sediments, whereas Cole et al. (2009) suggest that the geochemical composition is most consistent with eolian transport of an authigenic lake-margin origin for these fine-grained, highly leached sediments.

Sediment grain-size analysis has been shown to be useful for distinguishing detrital transport mechanisms for marine sediments off NW Africa. Wind-borne grains are commonly coarser (>50–100 μm diameter) and better sorted, and fluvially derived or hemipelagic sediments are often clay-rich (<5–10 μm; **Figure 5(a)**) and less well sorted (Parkin, 1974; Stuut et al., 2005). Tjallingii et al. (2008) presented one of the more elegant applications of this approach for core GeoB7920 off Mauritania (**Figures 1** and **5(b)**) near Site 658. Grain-size spectra were obtained for closely spaced samples using a laser particle sizer and these data were reduced statistically using an end-member modeling algorithm to determine the relative proportion of grains in each sample that derived from eolian or fluvial sources. The authors then developed a 'humidity index' as a simple ratio of fluvial to eolian grains and the downcore record is shown in **Figure 5(b)**.

The value of this approach is that it clearly isolates two separate climate forcing mechanisms influencing North African climate over the last 100 ka: prolonged wet (fine-grained) phases linked to precessional forcing of the African monsoon and shorter, millennial-scale windy, arid (coarse-grained) episodes that are in-phase with North Atlantic cool Heinrich and Dansgaard–Oeschger (D–O) cool events (Tjallingii et al., 2008; **Figure 5(b)**). This record is one of the clearer examples of remote high-latitude forcing of subtropical climate superimposed on regional orbital-scale wet–dry cycles paced by orbital precession.

14.8.2.2 River Runoff, Paleohydrology, and Vegetation Proxies

In addition to the detrital contributions to deep-sea sediments, biogenic phases, such as foraminiferal shells, organic matter, and biomolecular compounds, have also been shown to

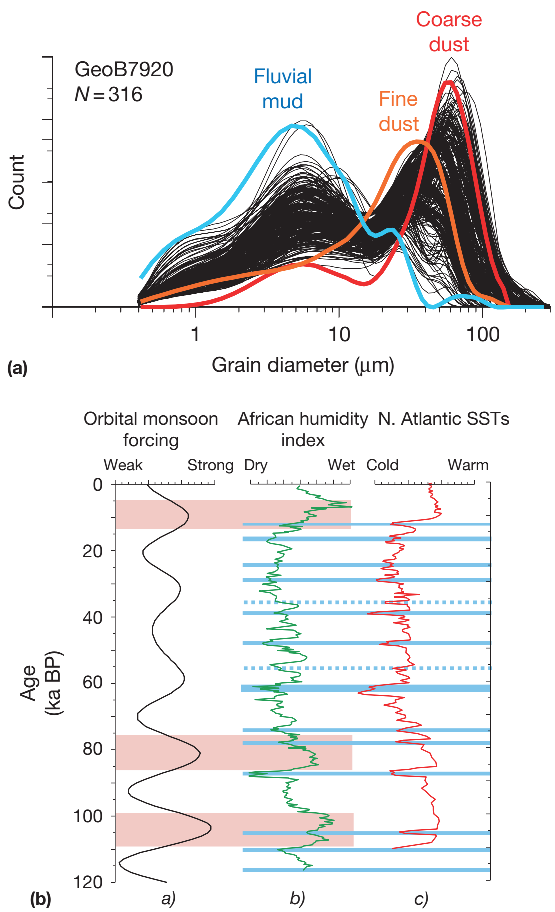

Figure 5 Deep-sea sediment records of the dual high-latitude and low-latitude influences on NW African climate during the late Pleistocene. Tjallingii et al. (2008) used sediment grain-size analyses on core GeoB 7920 off NW Africa to examine changes in sediment transport mechanisms over time. (a) Grain-size distributions in the core are comprised of two well-sorted, coarse grain modes (40–80 μm dia grains), which are interpreted to reflect wind-borne, eolian transport, and a single, fine-grained mode near 5 μm that is interpreted to reflect fluvial contributions (figure courtesy of Jan-Berend Stuut). (b) An 'African humidity index' was developed as a ratio of fine- to coarser grain modes, and the downcore record shows broad precessionally paced increases in the fine-grained component, consistent with increased fluvial runoff during these times. There are many short-lived (millennial-scale) increases in coarse-grained components that were interpreted to reflect increases in surface wind speeds and greater coarse-grained dust entrainment and transport (Tjallingii et al., 2008). These were found to be in-phase with known Heinrich and Dansgaard–Oeschger cooling events in the subpolar North Atlantic (Bond et al., 1993).

provide powerful and diagnostic proxies for past changes in North African river runoff, terrestrial vegetation, and paleohydrology. These data provide a separate but complimentary perspective of terrestrial climate change as preserved in the marine sedimentary record.

Planktonic foraminifera are single-celled, free-floating protozoa that inhabit the upper, sunlit layers of the ocean. Over their short (several week) life spans, they build small (0.1–1 mm) calcitic chambered shells, or tests, the geochemistry of which can be used to infer many basic properties of the oceans they once lived in, such as temperature, salinity, nutrients, and pH.

One of the more promising developments in foraminiferal geochemistry to deduce has been to develop a proxy for ocean salinity to monitor past changes in African freshwater river runoff to the oceans. A widely used approach for estimating past changes in surface ocean salinity employs paired Mg/Ca ratio and $\delta^{18}O_{shell}$ analyses of surface-dwelling foraminifer shells to calculate surface ocean $\delta^{18}O_{seawater}$, a robust proxy for surface ocean salinity. The approach is elegantly simple: the $\delta^{18}O$ composition of planktonic foraminifera shells records both the local $\delta^{18}O_{seawater}$ and the calcification temperature (through the kinetic fractionation effect), whereas shell Mg/Ca ratios should mainly record the calcification temperature (Anand et al., 2003; Lea et al., 1999). Shell $\delta^{18}O$ values and Mg/Ca ratio calcification temperature values are substituted into the oxygen isotope paleotemperature equation (Bemis et al., 1998) to solve for $\delta^{18}O_{seawater}$, providing surface paleosalinity estimates for the distant past (Arbuszewski et al., 2010; Flower et al., 2004; Lund and Curry, 2006; Schmidt et al., 1999, 2004, 2006; Weldeab et al., 2005, 2007).

Weldeab et al. (2007) applied this approach to a sediment core from the Niger River delta and developed a detailed and long (160 ka) record of past variations in local $\delta^{18}O_{seawater}$ as a proxy for Niger River outflow. This record clearly shows the very strong precessional control of Niger River outflow through its capture and drainage of monsoonal rainfall within its large, north subtropical African catchment basin. Impressively, this oceanographic signature of past changes in African monsoonal rainfall and runoff closely tracks the dust flux records from Site 658 off Mauritania, suggesting that deep-sea sediments can reliably and independently monitor shifts in North African paleoclimate (**Figure 2(d)**). Like the dust records, this salinity proxy record similarly records dry, glacial, and stadial conditions as periods of elevated salinity, reflecting reduced Niger River outflow during.

One of the first applications of marine sediments to infer past changes in African climate was the discovery of Mediterranean sapropel sediment layers. Sapropels are dark and exceptionally organic-rich sediments typically deposited under highly anoxic conditions where deep water ventilation is absent. Sediment cores taken from the eastern Mediterranean were found to have regular, dark sapropel layers, each typically 10–30 cm in thickness and separated by light, high carbonate sediments typical of normal pelagic marine sedimentation. Dating of these sapropel layers revealed that they occur as regular, 20 ky cycles during times of peak (precessional) northern hemisphere summer insolation when the African monsoon was invigorated (Rohling, 1994; Rossignol-Strick, 1983, 1985). The sapropels formed due to bottom water stagnation resulting from the enhanced Nile River outflow and density stratification of surface waters, which prevented the bottom water formation and ventilation during humid phases (Sachs and Repeta, 1999). The detrital geochemistry of these sapropel sediments indicated greater contributions of Nile-derived sediment as well (Wehausen and Brumsack, 1999). The most recent sapropel layer, S_1, spans the peak of the most recent AHP between roughly 11.5 and 6 ka BP.

Deep-sea sediments are also rich archives of past changes in North African vegetation. Early studies used pollen preserved in marginal sediments to document the profound vegetation shifts associated with the AHP. Pollen preserved along the NW African margin is believed to have been transported principally by NE trade winds (Dupont, 1989). During the AHP, the currently barren or xeric (dry-adapted) vegetation of the western Sahara was replaced by northward migration of humid-adapted tropical trees, mangroves, shrubs, and grasses (dependent upon location) (Dupont, 1989; Hoogheimstra et al., 2006; Lezine, 1991). Available pollen evidence from terrestrial sites indicates that the Sahara was nearly completed vegetated (Jolly et al., 1998).

A promising development in understanding past changes in North African vegetation and surface hydrology has been the application of stable isotopic analyses of plant-derived biomolecular compounds preserved in ocean sediments (Sachse et al., 2012). Higher plants have epicuticular (leaf surface) waxy compounds that protect the leaf surface and limit water loss. These plant wax compounds commonly contain long-chain lipid molecules, such as *n*-alkanes, *n*-alcohols, and *n*-alkanoic acids, that are resistant to bacterial degradation and survive long-distance transport and sedimentary burial (Eglinton and Eglinton, 2008; Sachse et al., 2012). These plant wax biomolecular compounds are transported to ocean basins by winds along with eolian mineral dust, pollen, and other wind-borne constituents from dust source areas. Instrumentation and automation advances have enabled compound-specific hydrogen and carbon isotopic analyses to be conducted on trace quantities of these compounds (typically $\mathrm{ng\,g^{-1}}$ of dry sediment) once they are extracted from deep-sea sediments.

Deuterium/hydrogen isotopic analyses of plant wax compounds (δD_{wax}) record, with an offset, the δD of precipitation that once nourished the plant community (Sachse et al., 2012; see also **Chapter 14.20**). In the tropics and subtropics, δD decreases with increasing precipitation due to the 'amount effect' (Dansgaard, 1964). In tropical regions where rainfall seasonality is high and temperature seasonality is low, the isotopic composition of precipitation is related to the amount of precipitation, with stronger depletion at higher precipitation rates.

A record of hydroclimate from Lake Tanganyika based on the δD_{wax} composition of fossil leaf waxes highlights the major features of the AHP in East Africa (Tierney et al., 2008; **Figure 2(e)**). In this inland lake setting, leaf waxes are ablated from vegetation surrounding the lake and transported by wind and water to the sediments. Like the marine sediment records of African dust flux and composition, Niger River outflow, and North African paleolake levels (**Figure 2(b)–2(e)**), the wetter conditions of the AHP are easily recognized in the δD_{wax} record from Lake Tanganyika. The very low δD_{wax} values that occur between 11 500 and 5000 years before present are interpreted to reflect enhanced Atlantic-sourced rainfall to this near-equatorial basin during this interval (Tierney et al., 2008). Like the dust flux record, the initiation and termination of the humid period at Lake Tanganyika is abrupt, occurring within a few centuries. At Lake Turkana in northern Kenya, the mid-Holocene drop in lake level at the end of the humid period is similarly abrupt (Garcin et al., 2012). Another δD_{wax} record has been developed for equatorial West Africa based on deep-sea sediment core GeoB 6518 off the Congo fan (Schefuß et al., 2005). This record shows a similar hydroclimate evolution, with wettest conditions between 11 and 6 ka BP, although the transitions are less abrupt.

14.8.3 Marine Sediment Records of African Paleoclimate: Progress and Puzzles

14.8.3.1 Summary of North African Climate Evolution Since the Last Glacial Maximum

North African climate change since the last glacial maximum is largely one of the cooler, drier, and gustier conditions associated with the remote effects of high-latitude ice sheets and millennial-scale cooling events during the last glaciation. Several climate modeling and African paleoclimate data compilation studies have documented the profound sensitivity of North African precipitation and trade wind speeds to subpolar North Atlantic sea-surface temperatures (deMenocal, 1995; deMenocal and Rind, 1993; Mulitza et al., 2008; Tjallingii et al., 2008). Establishment of cool North Atlantic SSTs during peak glacial stages or millennial-scale cooling events, such as Heinrich or D–O stadials, establishes strong high-pressure anomalies that enhance the meridional temperature gradient and thus increase trade wind circulation and also diminish the penetration and competence of the North African monsoonal rains.

As ice sheets receded after 14.5 ka BP, and especially after the end of the Younger Dryas near 12.5 ka BP, the rising influence of orbital precession on the African monsoon intensity abruptly brought wetter conditions, and the vast subtropical desert was replaced within centuries by a nearly fully vegetated landscape with large lakes, swollen rivers, and abundant fauna. This humid phase ended (abruptly or gradually or both) near 5 ka BP and the most recent incarnation of the Sahara desert was established. Most studies find this dry-to-wet climate transition to have been very abrupt, completed in less than a century or significantly less (Adkins et al., 2006; deMenocal et al., 2000b; Garcin et al., 2012; Tierney et al., 2008; Weldeab et al., 2007), as observed in high-latitude records (Alley et al., 1993; **Figure 2**). From dry Younger Dryas to wetter, earliest Holocene transitions time from the end of the drier conditions of the Younger Dryas to the onset

14.8.3.2 Fidelity of Aridity Proxies: Dustiness or Gustiness?

A curious feature of the Site 658 African dust flux record is that eolian sediment fluxes during the last glacial maximum near 20 ka BP were roughly the same as present values. This is curious because many other lines of evidence point to significantly more open and arid and windy conditions during the last glacial (COHMAP Members, 1988; Gasse, 1990, 2000; Mulitza et al., 2008; Ruddiman, 1997; Tjallingii et al., 2008; Weldeab et al., 2007; Zhao et al., 1995). Although this particular record is not continuous across this interval, other Th-normalized dust flux records along the NW African margin that do capture the complete 0–25 ka BP interval support this conclusion (McGee et al., submitted).

Several authors have commented on this puzzle – If Africa was so dry during the last glacial, then why weren't dust fluxes markedly greater? (Adkins et al., 2006; Cole et al., 2009). This has led to a discussion of the paleoclimatic interpretation of dust flux records and whether they reflect changes in continental aridity sensu stricto or whether they reflect enhanced dust transport by greater wind speeds, turbulence, and gustiness. Ruddiman (1997) noted that (conventionally measured) eolian dust fluxes were markedly greater during glacial stages for cores that were core sites that were significantly more distal from the continental margin and concluded that elevated wind speeds and greater gustiness but have contributed to the higher glacial dust supply. This view supported the markedly greater eolian grain sizes for glacial stages observed by Tjallingii et al. (2008), who reached a similar conclusion. Still, strong evidence for greater glacial aridity remains (COHMAP Members, 1988; Gasse, 2000; Sarnthein, 1978; Weldeab et al., 2007).

One potential area of reconciliation between the glacial aridity and gustiness hypotheses may be that greatly elevated dust fluxes are known for the Younger Dryas (Adkins et al., 2006) and Heinrich events (even though the glacial maximum values near 21 ka BP are not elevated), and these stadials are also known to have very coarse eolian grain sizes (Tjallingii et al., 2008), so low-resolution records may smooth this distinction and register the whole glacial stage (MIS 2) as a period of enhanced flux and coarse grains. In this case, dry and dusty conditions prevailed only during millennial-scale North Atlantic cooling events, as opposed to the entire glacial stage. A challenge to this is that glacial dust fluxes were also high during the early Pleistocene glacial periods (41 ky world; deMenocal and Bloemendal, 1995; Tiedemann et al., 1994), when Heinrich and D–O events were presumable absent (Hodell et al., 2008).

14.8.3.3 An Abrupt or Gradual End of the AHP near 5 ka BP

As summarized in **Figure 2**, there is abundant terrestrial and marine evidence that the transition out of the AHP and into the current arid climate occurred within a few centuries near 5 ka BP (Adkins et al., 2006; Cole et al., 2009; deMenocal et al., 2000b; Tierney et al., 2010; Weldeab et al., 2007). There also exist abundant, and equally valid, terrestrial and marine evidences that this important climatic transition was not this abrupt and took place over several thousands of years centered near 5 ka BP (COHMAP Members, 1988; Hoelzmann et al., 2004; Kroepelin et al., 2008; Schefuß et al., 2005; Street-Perrott et al., 1989). This event, whether it was gradual or abrupt, led to the collapse of the fertile-rich terrestrial ecosystem of the early Holocene that was replaced by a barren, hyperarid landscape that defines the Sahara desert today.

This puzzle is important because upon it hinges a critical question of whether North African climate responds linearly or nonlinearly to insolation (and other) forcing. A linear response is perhaps the most readily understood and there are many climate model simulations that have gradual, linear responses of the African monsoon intensity to precessional insolation forcing (Kutzbach and Liu, 1997; Renssen et al., 2006). However, climate models that include full ocean–atmosphere–vegetation feedbacks to insolation forcing have shown that North African climate and vegetation can respond very nonlinearly – abruptly – to insolation forcing (Claussen et al., 1999; Liu, 2006). In the Claussen et al. (1999) study, the nonlinearity arose from a (positive) feedback between diminishing rainfall and vanishing vegetation cover that increased regional albedo, weakened monsoonal circulation, and promoted further rainfall reductions. These feedbacks, evident only in simulations with active vegetation feedbacks, repeatedly produced the rapid transitions from 'green' to 'desert' North African climate solutions.

It is likely that the puzzle may be reconciled if we accept the validity of both sets of observations. The pollen record from Lake Yoa (northern Chad) demonstrates clearly that the vegetation shift there was indeed gradual, requiring thousands of years, whereas the AHP transitions at Site 658 and Lake Tanganyika are unequivocally abrupt, occurring within a few centuries. Neither dataset contradicts the other because there is no geographic location where both rapid and gradual responses have been observed. Advocates for each perspective are not demanding that their view applies uniformly across all of North Africa, and indeed, the answer may lie in a spatially heterogeneous response where some regions are indeed changing gradually and others abruptly. What is missing is a comprehensive sense of how these mid-Holocene changes from wetter to drier conditions played out spatially and temporally across North Africa.

14.8.4 Summary and Future Directions

One of the main conclusions that can be drawn from the wealth of African terrestrial and marine paleoclimate research is that this vast region has experienced massive and sweeping changes over the last 25 ka. North Africa is several times larger than the continental United States, and there is abundant evidence that nearly the entire region cycled from drier conditions during the glacial stages to wetter conditions during the early Holocene and back to drier conditions after the mid-Holocene. It would be folly to use any one record as a template for North African climate evolution, and it is clear that these paleohydrologic changes occurred at different times regionally, with varying amplitudes and abruptness. Still, the sheer size of the region and the general conformity of paleoclimate records are impressive.

Despite our general understanding of the narrative of North African climate change, there remain fundamental questions that cannot be addressed with the available data. Some of these have been discussed in the previous text and elsewhere, such as the duration of climate transitions and whether they were regionally synchronous or varied spatially in some coherent manner. A new question has emerged whether the massive networks of presently dry wadi channels that incise the continental margins to the sea were active as permanent water courses during the peak humid conditions of the early Holocene. Some evidence, largely incomplete, points to activation of ancient river networks along the now-arid West and North African coasts of Mauritania and Libya, respectively. The Cap Timiris Canyon off Mauritania cuts a sinuous submarine channel nearly 300 km long originating in a region that, today, has little to no measurable rainfall (Zuhlsdorff et al., 2007). The Kufra and Sirt basins in western Libya define a topographic corridor to the Mediterranean where synthetic aperture radar has identified networks of fossil river drainage beneath the desert sand veneer (Pailloux et al., 2009). It is known that this drainage system was active in feeding river runoff to the central Mediterranean at least as recently as the last interglacial period (MIS Stage 5e; Osborne et al., 2008). A better understanding of the number and density of these fossil river systems would add a novel dimension to understanding African paleoenvironments.

One of the most fascinating aspects of the AHP is its impact on North African human sustainability and cultural development (Hoelzmann et al., 2002; Kuper and Kröpelin, 2006). North Africa was nearly completely vegetated during the height of the AHP (Jolly et al., 1998) populated with nomadic hunter-gatherer communities that increasingly practiced pastoralism (husbandry of cattle, sheep, and goats). Rock art and gravure images are found throughout North Africa, which depict the physical environment and abundant wildlife at the time, as experienced by their early Holocene artists. These masterfully rendered images depict pastoral scenes with abundant elephants, giraffe, hippos, aurochs (a wild ancestor of domestic cattle), and antelope, occasionally being pursued by bands of hunters. The Sahara is very likely the world's largest art museum with hundreds of thousands of elaborate engravings and paintings adorning rocky caves and outcrops. The incongruence of these lively images in such lifeless settings intrigued Barth, who noted that the artwork "bears testimony to a state of life very different from that which we are accustomed to see now in these regions" (Barth, 1857).

Toward the end of the AHP between 7000 and 5000 years ago, the progressive desiccation of the region led to a widespread depopulation and abandonment of North African sites. These populations did not disappear; however, the large-scale exodus away from the increasingly arid interior was coincident with the rise of sedentary life and pharaonic culture along the Nile River (a perennial water source) and the spread of pastoralism throughout the continent (Kuper and Kröpelin, 2006). The abundance of North African paleoclimate and archeological data highlights the fundamental importance of water availability on sustainability and human populations and the central role of climate in shaping major events in cultural development leading to the rise of complex, urban cultures.

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