Chapter 2
A Northeast Saharan Perspective on Environmental Variability in North Africa and its Implications for Modern Human Origins

J. C. Larrasoaña

Abstract In this chapter, we recall a record of Saharan dust supply into the eastern Mediterranean Sea (ODP Site 967) to document Middle-Late Pleistocene environmental variations in the Northeast Sahara (NES). Distinctive dust flux minima ca. 330, 285, 240, 215, 195, 170, 125, 100, and 80 ka attest to the expansion of subtropical savannah landscapes throughout the NES during boreal summer insolation maxima, which drove penetration of the West African summer monsoon front up to 25–27°N. Such "green Sahara" periods broadly correlate with U-series ages of lacustrine and spring carbonates scattered throughout the NES, which are often associated with Acheulean and Mousterian archaeological sites that attest to widespread occupation of the area during pluvial episodes. In contrast, Aterian sites are linked to spring deposits and mountain areas during a prolonged period of hyperarid climate, which suggests adaptation to desert conditions. The Site 967 dust record has important implications for understanding the evolution and population dynamics of modern humans in Africa. Thus, the monsoon-driven alternation of "green Sahara" and hyperarid desert conditions throughout North Africa, combined with similarly paced environmental variations within tropical Africa, provides a favorable scenario for the speciation of *H. sapiens*, for a gradual accumulation of African modern behaviors as a whole, and for frequent out of Africa dispersals of modern human populations.

Keywords Dust record • Eastern Mediterranean • Environmental magnetism • Green Sahara • Modern human dispersals • North Africa • Ocean Drilling Program • Pleistocene

Introduction

The origin of modern humans has led to one of the major debates in paleoanthropology over the last two decades (see Lahr and Foley 1998; McBrearty and Brooks 2000; Hovers and Kuhn 2006). At present, most genetic, paleoanthropological, and archaeological evidence point to a single origin of *Homo sapiens* in Africa (Stringer 2002; Mellars 2006), although the specific location and mechanism that gave birth to our species are the subject of a contested debate that is often taken beyond normal scientific inquiry into the realm of paradigmatic discussion (Lahr and Foley 1998; McBrearty and Brooks 2000).

One of the elements that is always considered to be a major factor conditioning human evolution is climatic variability, through its effect on landscape composition (Lahr and Foley 1998). Although temperate-cold climates have long been recognized as influencing recent human evolution in western Asia and Europe, it is still unclear what drove the evolution of modern humans in Africa (see Stringer 2002). Yet, and perhaps from a Eurocentric perspective, it is often assumed that evolution and behavioral development of modern humans in Africa was influenced by glacial-interglacial changes driven by climate variability at the high-latitudes (e.g., Lahr and Foley 1998; Mithen and Reed 2002; Stringer 2002; Mellars 2006). Thus, glacial periods would have conditioned the expansion of the Sahara at the expense of subtropical savannahs and equatorial rainforest. This situation would have been reversed during interglacial epochs in such a way that the Sahara might have nearly disappeared due to the expansion of subtropical savannahs (e.g., Lahr and Foley 1998). Although these dramatic expansions and contractions of tropical African landscapes are evidenced by paleoclimatic (Szabo et al. 1995; Jolly et al. 1998; Gasse 2000; Hooghiemstra et al. 2006; Weldeab et al. 2007; Tjallingii et al. 2008) and climate modeling data (Brovkin et al. 1998; Gasse 2000), a growing body of evidence accumulated over the last decade indicates that such contractions and expansions were driven primarily by internal dynamics of the monsoon system

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J. C. Larrasoaña (✉)
Instituto Geológico y Minero de España,
Unidad de Zaragoza, C/Manuel Lasala 44 9B,
50006 Zaragoza, Spain
e-mail: jc.larra@igme.es

J.-J. Hublin and S. P. McPherron (eds.), *Modern Origins: A North African Perspective*,
Vertebrate Paleobiology and Paleoanthropology, DOI: 10.1007/978-94-007-2929-2_2,

(Brovkin et al. 1998; Jolly et al. 1998; Gasse 2000), which is driven by incoming solar radiation in the low latitudes, rather than by high-latitude climate variability.

The debate on the African origin of modern humans has been further influenced by the fact that most researchers have focused their investigations on East and South Africa, but have largely ignored North Africa. This is surprising, especially in the case of Northeast Africa, because ample evidence attests to past Middle-Late Pleistocene pluvial episodes that fostered the recurrent occupation of what is a key location, now characterized by a hyperarid climate, in the gateway to Eurasia (Wendorf et al. 1993; Szabo et al. 1995; Smith et al. 2004, 2007; Kleindienst et al. 2008). Unfortunately, due to the intensive aeolian deflation in the Sahara Desert, continental records of North African climate variability are scarce, short, discontinuous, irregularly distributed, difficult to date, and provide only a fragmentary view of North African climate. Marine records of Saharan dust deposition into neighboring ocean basins (Tiedemann et al. 1994; de Menocal 1995, 2004; Matthewson et al. 1995; Moreno et al. 2001, 2002; Bozzano et al. 2002; Dinarès-Turell et al. 2003; Hamann et al. 2008; Itambi et al. 2009) might partly overcome these problems, but they are difficult to link with environmental variations at specific portions of the vast Saharo-Arabian Desert (Goudie and Middleton 2001; Prospero et al. 2002). As a result of these shortcomings, the paleoenvironmental and paleoclimatic scenario that framed the origin of modern humans in North Africa remains largely ignored.

In this chapter, we recall a record of Saharan dust deposition in the eastern Mediterranean Sea produced from Ocean Drilling Program (ODP) Site 967 (Larrasoaña et al. 2003). This record has been claimed to provide a proxy for the astronomically-controlled penetration of the West African monsoon into the northeastern Sahara (NES), which, in turn, conditioned variations in dust production in response to the expansion and retraction of savannah landscapes throughout the NES. We use the Site 967 record because, contrary to other marine dust records of North African climate variability from the Mediterranean Sea (Calvert and Fontugne 2001; Moreno et al. 2002; Dinarès-Turell et al. 2003; Hamann et al. 2008), the Atlantic Ocean (Tiedemann et al. 1994; de Menocal 1995, 2004; Matthewson et al. 1995; Moreno et al. 2001; Bozzano et al. 2002; Itambi et al. 2009) and the Arabian Sea (de Menocal 1995, 2004), it relates variations in dust production to environmental changes in a specific region within the Saharo-Arabian Desert belt, taking into account its complex physiography and interactions with climatic processes. The aim of this study is to use the Middle-Late Pleistocene (350–20 ka) record of Site 967 to: (1) develop a robust paleoclimatic and paleoenvironmental framework for human occupation of the NES; and (2) examine its implications in the origin of modern humans.

The ODP Site 967 Dust Record

ODP Site 967 was recovered at a water depth of 2,553 m on the northern slope of the Eratosthenes Seamount (34°04′N, 32°43′E) (Fig. 2.1). The studied sedimentary sequence of Site 967 consists of 90 m of Pliocene-Holocene hemipelagic bioturbated nannofossil oozes and nannofossil clays, and includes 79 visible sapropels (Kroon et al. 1998; Emeis et al. 2000). Sapropels are dark-colored layers that usually vary from 1 to 60 cm in thickness and contain up to 25% organic carbon (by weight) (Hilgen 1991; Lourens et al. 1996; Emeis et al. 2000). Sapropels are important because they mark the pace of an orbitally-driven climatic system that was exceptionally amplified due to the semi-enclosed nature of the Mediterranean basin. Formation of sapropels was controlled by ca. 21 kyr periodic changes in the amount of solar energy received in the northern low- and mid-latitudes during boreal summer insolation maxima (Hilgen 1991; Lourens et al. 1996; Emeis et al. 2000). At these times, intensification and enhanced northward penetration of the West African monsoon led to an increase in the freshwater discharge into the eastern Mediterranean (Rossignol-Strick 1983; Lourens et al. 2001; Rohling et al. 2002; Larrasoaña et al. 2003).

The Site 967 dust record is based on the high-resolution (1 cm) measurement of a laboratory-induced magnetization that was later demagnetized with an alternating magnetic field. The intensity of this so-called IRM@AF parameter is proportional to the content of hematite, which constitutes about a 6.5% (in weight) of the Saharan dust transported into the eastern Mediterranean (Tomadini et al. 1984). The correspondence between hematite contents and Saharan dust supply is evident in a Pliocene interval of the Site 967 record, which provides an exceptional view of African paleoclimate variability (Fig. 2.2) (Lourens et al. 2001). A distinctive cyclic pattern is evident in the Ti/Al ratio, with minimum values in the sapropels and highest values in the intercalated marls. Ti is linked to aeolian transport of heavy minerals in the distal marine sediments of Site 967 (Lourens et al. 2001), whereas Al is related to both aeolian (e.g., kaolinite; Foucault and Mélières 2000) and fluvial (e.g., smectite; Lourens et al. 2001) sources. Variations in Ti/Al can therefore be interpreted in terms of the relative contributions of aeolian (Saharan dust) and fluvial (Nile) sources. The Ti/Al curve strikingly parallels boreal summer insolation, which attests to a link between supply of Saharan dust and paleoclimate variability via the influence of solar radiation on monsoon dynamics in tropical Africa (Lourens et al. 2001). The amount of hematite, which is a mineral typically found in Saharan dust

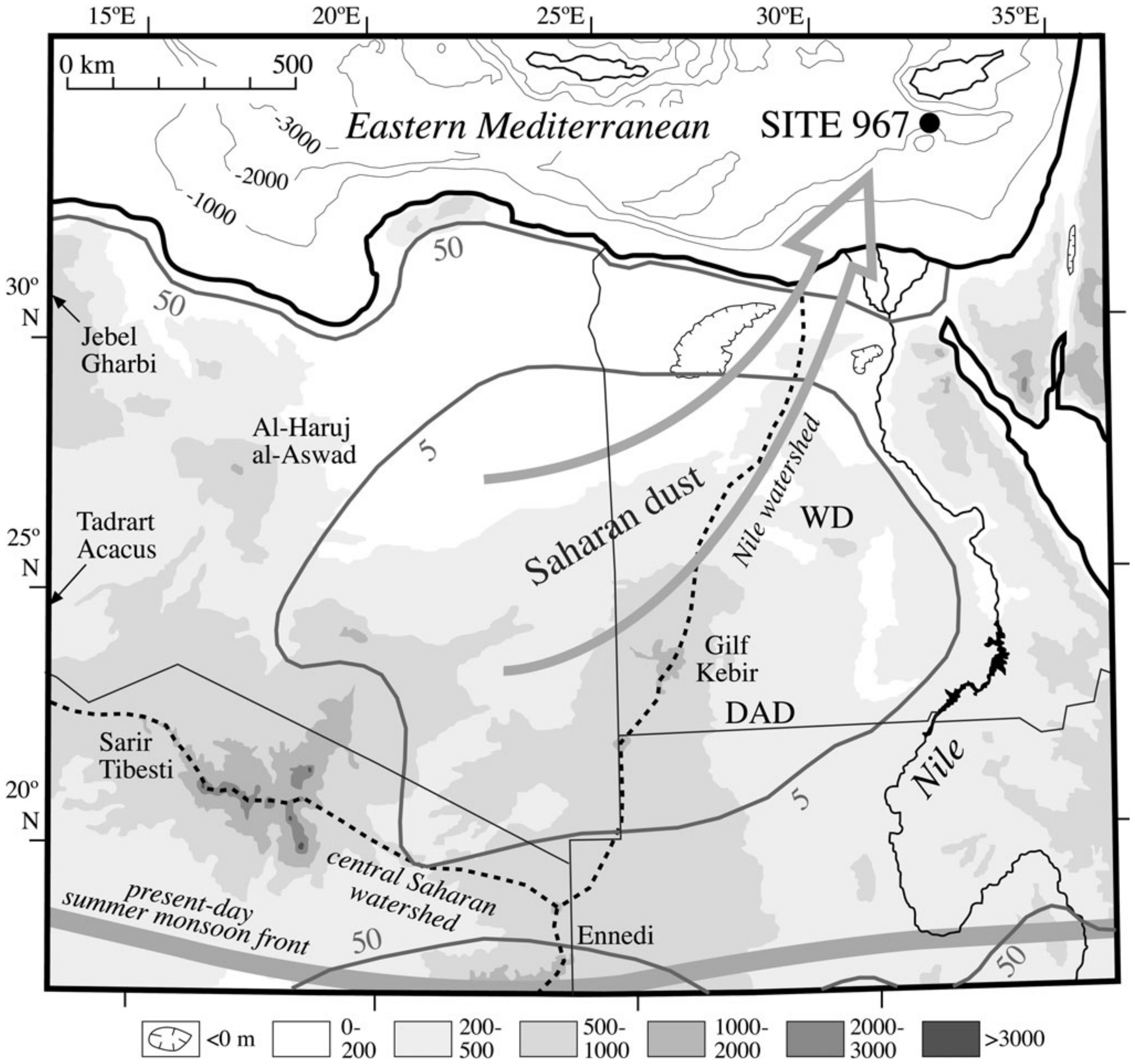


Fig. 2.1 Present-day physiography of the northeastern Sahara and the eastern Mediterranean Sea, with location of ODP Site 967 and the main trajectory of northeastern Sahara dust transport (Dayan et al. 1991; Goudie and Middleton 2001). Thin *gray lines* indicate mean annual isohyets in mm per year (after Petit-Maire 2002). *WD* Western Desert, *DAD* Darb el Arba'in Desert

(e.g., Goudie and Middleton 2001; Prospero et al. 2002), closely mimics the Ti/Al curve. This demonstrates that the IRM@AF parameter can be used as a proxy for Saharan dust supply into the eastern Mediterranean.

The Middle-Late Pleistocene Record

The interval of Site 967 between 2 and 16 revised meter composite depth (rmcd) includes sapropels S3 to S10 (Fig. 2.3). The age model for this interval is based on the characteristic sapropel pattern, which can be tuned to a summer insolation target curve by correlating sapropels to their corresponding insolation maxima (Hilgen 1991; Lourens et al. 1996; Emeis et al. 2000). IRM@AF values are larger than 0.2 A/m throughout the Middle-Late Pleistocene except within and around sapropels, where the IRM@AF parameter shows marked drops well below 0.1 A/m. This indicates that deposition of sapropels coincided with relatively short periods of decreased dust supply. As boreal summer insolation is driven by changes in the Earth's orbital precession (ca. 21 kyr cycles), and this, in turn, is modulated by the Earth's eccentricity (ca. 100 and

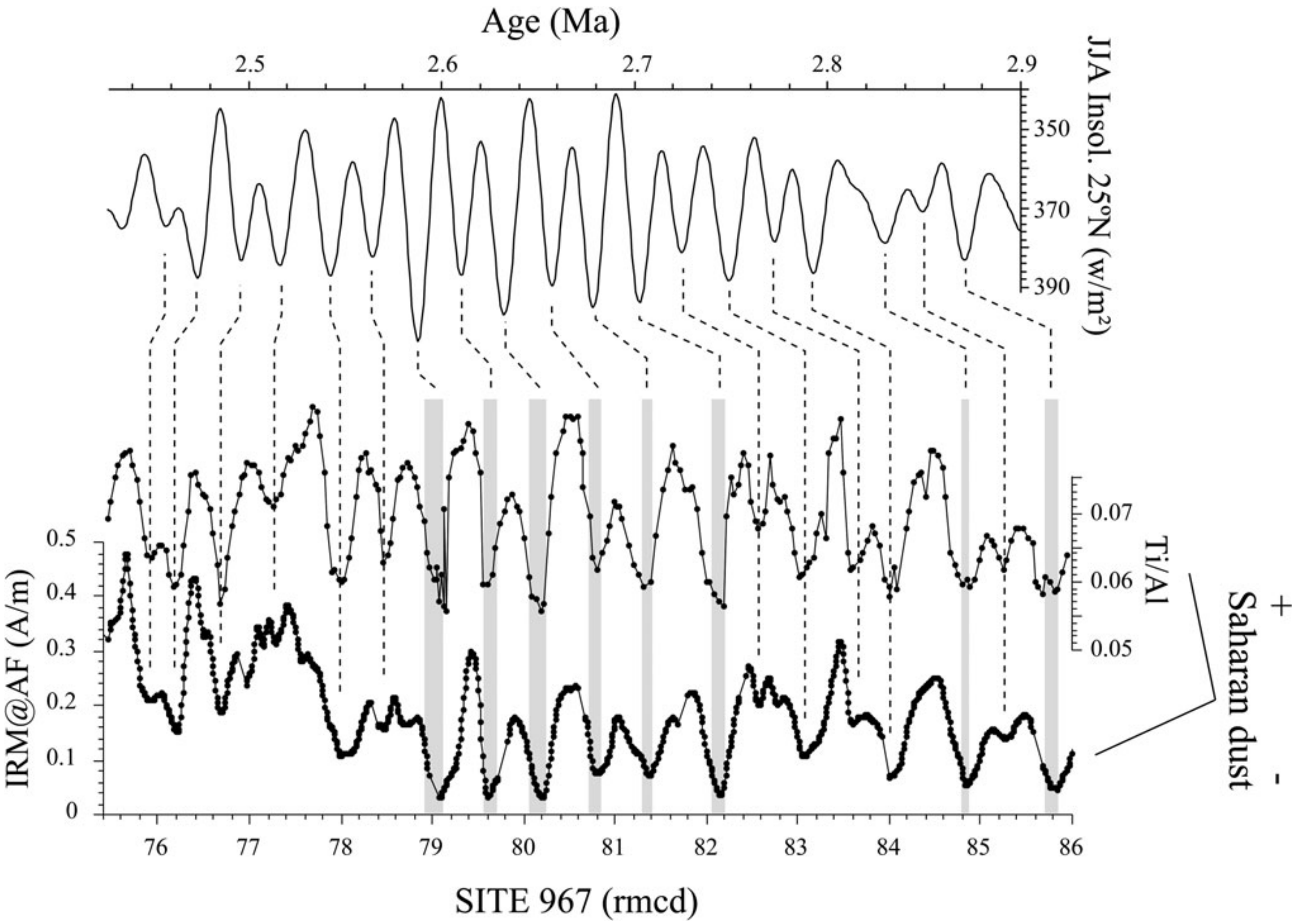


Fig. 2.2 Geochemical (Lourens et al. 2001) and magnetic (Larrasoaña et al. 2003) data from ODP Site 967 between 75 and 86 rmcd (2.4–2.9 Ma), plotted against boreal summer insolation at 25°N calculated after the astronomical solution of Laskar et al. (2004). *Gray shaded bars* indicate the positions of sapropels. The age model is after Lourens et al. (2001)

400 kyr cycles), boreal summer insolation maxima for the last 350 kyr, and hence sapropels with dust minima, cluster near 100 ka eccentricity maxima (Fig. 2.3b). In contrast to sapropels, high IRM@AF values of intercalated sediments indicate that the supply of Saharan dust was significantly higher during their deposition. This is especially clear for the latest Pleistocene interval between 75 and 20 ka, where IRM@AF shows the highest values of up to 1 A/m. The δ^{18}O record of the studied interval is characterized by oscillations (>4‰) that are mostly marked by distinctive negative isotopic excursions within sapropels (Kroon et al. 1998). These excursions are larger than simultaneous glacial-interglacial variations (<1.2‰) in the Atlantic Ocean, and have been classically explained by massive drainage of isotopically-light monsoon rainfall via the Nile River into the eastern Mediterranean (Rossignol-Strick 1983). Despite these isotopic excursions, the characteristic glacial-interglacial pattern of the Middle-Late Pleistocene interval between marine isotopic stages 10 to 2 (350 to 20 ka) is clearly recognizable in the δ^{18}O record (Fig. 2.3), which validates the age model based on the tuning of the sapropel pattern to the summer insolation target curve. It is worth noting that sapropels formed during interglacial stages (e.g., S3–S5 with stages 5a to 5e, S7 to S9 with stages 7 to 7e, and S10 to stage 9), but also during glacial stages such as S6 (stage 6). In addition, glacial stage 8 includes an interval characterized by a negative isotopic excursion and distinctively low IRM@AF values, typical for sapropels, and can therefore be interpreted as a sapropel (indicated by an arrow in Fig. 2.3) that has been erased by postdepositional oxidation (Larrasoaña et al. 2003, 2006).

In order to unravel the paleoclimatic and paleoenvironmental significance of the Site 967 dust record in the role of modern humans origins, we need to: (1) understand the climatic processes that control production and transport of Saharan dust into the eastern Mediterranean, and (2) integrate this knowledge with the paleoclimatic and archaeological evidence that portrays the response of landscape evolution and human adaptation to climate variability in the NES during the Middle-Late Pleistocene.

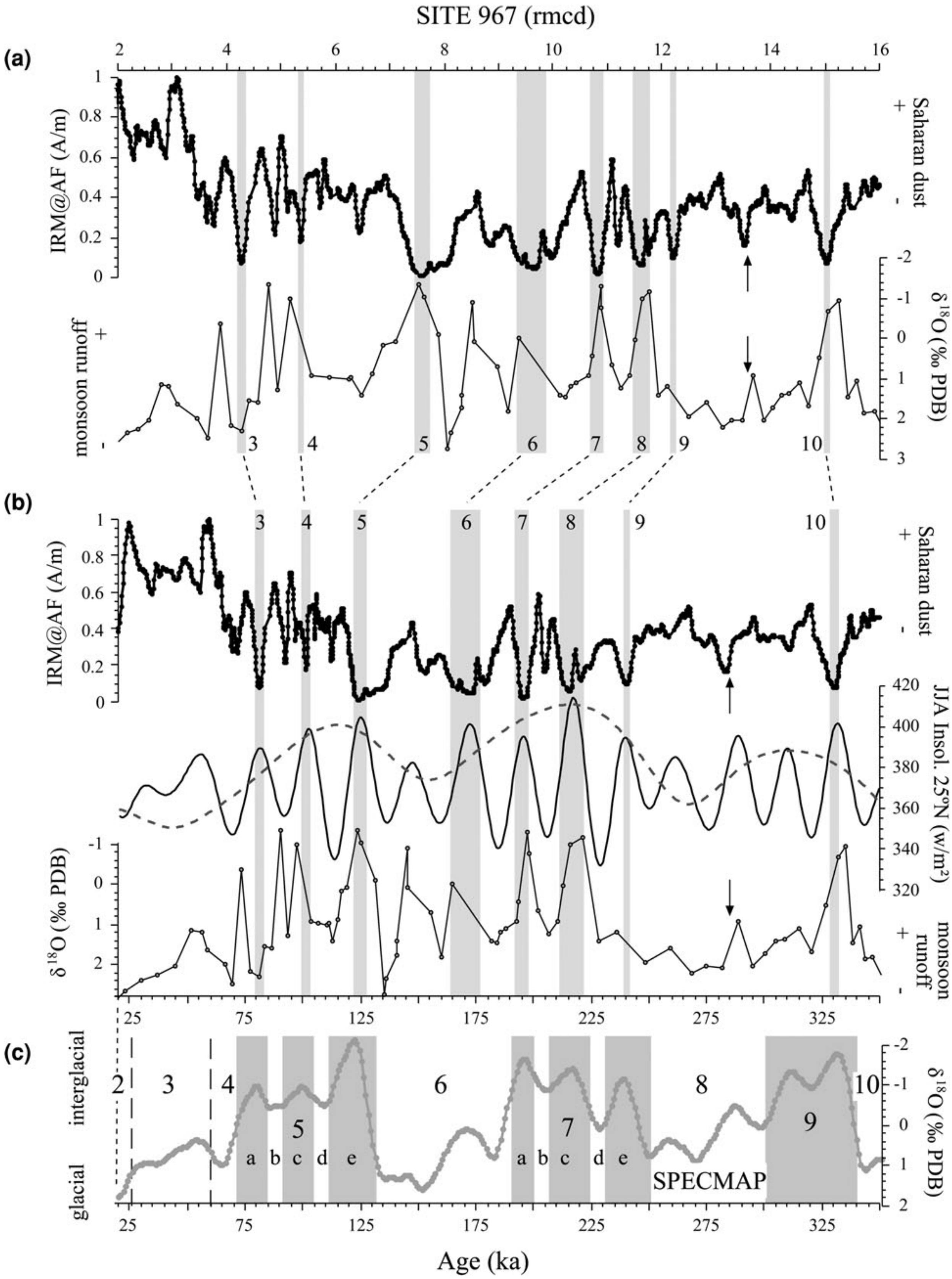


Fig. 2.3 **a** IRM@AF (Larrasoaña et al. 2003), oxygen isotopes (Kroon et al. 1998) and sapropels (*light gray shaded bars* 3–10) from ODP Site 967 between 2 and 16 rmcd. **b** IRM@AF and oxygen isotope data from the same interval plotted, together with sapropels and the boreal summer insolation curve (at 25°N) calculated after the astronomical solution of Laskar et al. (2004), against age. The *dashed lines* plotted with the insolation curve is the Earth's eccentricity parameter calculated after Laskar et al. (2004). The arrows indicate the position of an oxidized sapropel. **c** Oxygen isotope record of the SPECMAP (Imbrie et al. 1984). *White* and *gray bars* indicate glacial and interglacial periods, respectively

Satellite TOMS analyses (Prospero et al. 2002), geochemical data (Krom et al. 1999; Foucault and Mélières 2000; Weldeab et al. 2002), and back-trajectories of dust outbreaks (Dayan et al. 1991) indicate that the present-day dust source areas for dust transported into the eastern Mediterranean are the lowlands of eastern Libya, western Egypt, northeastern Chad and northwestern Sudan located between the Al-Haruj al-Aswad hill range, the Sarir Tibesti and Ennedi massifs, and the Nile River (Fig. 2.1). These areas broadly correspond to the driest part of the NES, which currently receives less than 5 mm of precipitation per year (Petit-Maire 2002). The hyperarid core of the NES contains fossil lacustrine and fluvial deposits and bedforms (Szabo et al. 1995; Pachur and Hoelzmann 2000; Rohling et al. 2002), and hosts a system of wadis that transport sediments from surrounding mountain areas into terminal alluvial fans, playas, and saline lakes (Pachur and Hoelzmann 2000). The easily weathered and deflated silt-rich sediments accumulated in these areas fuel the bulk of modern dust production (Goudie and Middleton 2001; Prospero et al. 2002).

The occurrence of lacustrine, palustrine, fluvial, and spring-related (tufa) deposits scattered throughout the NES attests to previous pluvial episodes during the Middle-Late Pleistocene (Szabo et al. 1995; Crombie et al. 1997; Sultan et al. 1997; Smith et al. 2004, 2007; Kieniewicz and Smith 2007; Kleindienst et al. 2008). Development of lake and fluvial systems and activation of springs has been linked to a poleward expansion of the tropical rainfall belt during periods of increased boreal summer insolation (Brovkin et al. 1998; Jolly et al. 1998; Gasse 2000). At those times, increased sensible heating over North Africa led to an intensification of the West African monsoon, which resulted in a northward shift of its summer front. Positive vegetation-albedo feedbacks pushed the summer monsoon front as far north as ~25° (Brovkin et al. 1998; Gasse 2000), and conditioned the expansion of savannah landscapes throughout the whole Sahara Desert as far north and east as the NES (e.g., the “green Sahara” state of the climate modeling community; Brovkin et al. 1998; Gasse 2000).

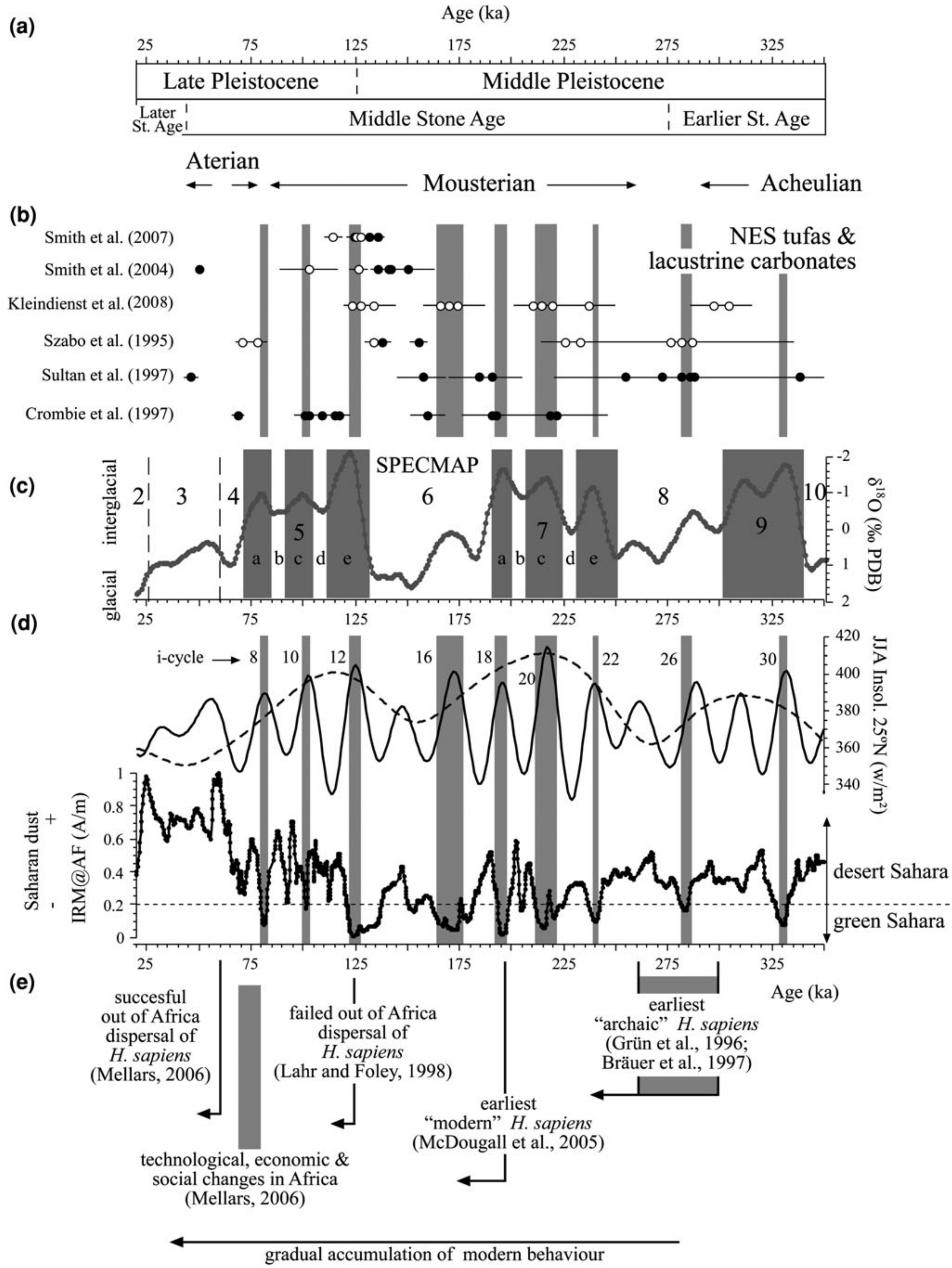
This “greening of the Sahara” constitutes a key concept for unraveling the paleoclimatic and paleoenvironmental significance of the Site 967 record because it explains the formation of lake and river systems in the NES and the simultaneous low dust contents and sharp negative isotopic excursion associated with sapropels. On the one hand, the enhanced penetration of the summer monsoon front up to ~25°N, well beyond the central Saharan watershed, accounts for the massive drainage of isotopically-light monsoon rainfall not only via the Nile, but along the whole North African margin, into the eastern Mediterranean. This explains why the lightest δ^{18}O values associated with sapropels are typically found between Libya and southwest Crete (Fontugne et al. 1994; Emeis et al. 2003) rather than off the Nile River, which, with its huge catchment, including both northern and southern hemisphere regions, drains monsoon rainfall with a relatively smaller range of isotopical variability throughout the year (Rohling et al. 2002). On the other hand, an increase in precipitation and vegetation cover would account for the stabilization of surface sediments in such a way that the production of dust would be severely dampened (Goudie and Middleton 2001; Prospero et al. 2002). The genetic link between “green Sahara” periods, sapropel formation, and insolation maxima is evidenced by the correspondence of lowest dust contents in sapropels with distinctive (>390 W/m^2) peaks in boreal summer insolation (Fig. 2.3). During periods of boreal summer insolation minima, which cluster at around 100 ka eccentricity minima, the weakened summer monsoon front would have remained south of the central Saharan watershed, which would have converted the NES into the barren hyperarid dust factory that it is today (e.g., the “desert Sahara” state of the climate modeling community, Brovkin et al. 1998). The dramatic hydrological changes in the NES, reported here on the basis of the Site 967 dust record, are consistent with in-phase changes in the Sahel (Tjallingii et al. 2008) and around the Gulf of Guinea (Weldeab et al. 2007). This points to a simultaneous response of the North African hydrological cycle to monsoon dynamics. In this regard, it is worth noting the key location of the NES in the farthest possible position away from the equatorial Atlantic Ocean, which is the source of moisture for the West African monsoon both along N–S and W–E transects. Identification of “green Sahara” periods in the NES therefore gives information on the occurrence of dramatic landscape variations that affected North Africa as a whole.

Figure 2.4 shows a comparison of the Site 967 dust record with the SPECMAP curve (Imbrie et al. 1984) and with uranium-series ages of lacustrine carbonates (Szabo et al. 1995) and tufas (Crombie et al. 1997; Sultan et al. 1997; Smith et al. 2004, 2007; Kleindienst et al. 2008) accumulated at different parts of the NES during past Middle-Late Pleistocene pluvial periods. The broad distribution of dates for the carbonates might result from the often large (>10 kyr) errors associated with most published uranium-series ages from lacustrine carbonates, but also from prolonged spring activity related to groundwater discharge (Smith et al. 2007). Despite the broad distribution of ages, statistical analyses based on probability density functions have demonstrated the clustering of carbonate deposition not only during most interglacial periods (e.g., during stages 5a, 5c, 5e, 7a, 7c, 7e), but also during glacial stages 6 and 8 (Fig. 2.4) (Smith 2012). Similar to what happens with sapropels, these data demonstrate that deposition of carbonates occurred more frequently than the 100 kyr glacial-interglacial cycles (Smith et al. 2007;

Smith 2012). We propose that such frequency corresponds with the ca. 21 kyr insolation cycles that are responsible for recurrent "green Sahara" periods. This interpretation, which might eventually be confirmed by improved uranium-series ages of NES carbonates, is further supported by the similar ca. 21 kyr pacing of increased groundwater movement in the NES, which is also driven by monsoon-fed aquifer recharge (Osmond and Dabous, 2004). These observations confirm previous claims suggesting that climate and landscape variability over North Africa are mainly driven by changes in incoming solar radiation via its influence on monsoon dynamics (Trauth et al. 2009), rather than by glacial-interglacial cycles linked to climatic variability at high latitudes, as has often been assumed (e.g., Lahr and Foley 1998; Mithen and Reed 2002; Mellars 2006). This does not imply that glacial-interglacial cycles do not have an effect on North African climate; this, in fact, has been demonstrated from several marine dust records in which glacial-interglacial oscillations are mainly reflected by changes in wind intensity and/or atmospheric circulation patterns (Matthewson et al. 1995; Moreno et al. 2001, 2002; Hamann et al. 2008; Itambi et al. 2009). It merely suggests that glacial-interglacial cycles exert a secondary imprint on a primary low-latitude climate mechanism in such a way that the influence of high-latitude climate variability becomes important at periods of lowest boreal summer insolation, when the monsoon system is severely weakened (Weldeab et al. 2007). Based on these results, and as has been proposed for sapropels (Lourens et al. 1996), we recommend that the "green Sahara" periods be named with the number of their correlative insolation peak (Fig. 2.4).

Developing a Paleoclimatic and Paleoenvironmental Framework for Human Occupation of the NES

The Site 967 dust record sheds new light on the paleoclimatic and paleoenvironmental context that framed human occupation in the NES during the Middle-Late Pleistocene. Many of the lacustrine, fluvial, and tufa deposits scattered throughout the NES are associated with archaeological remains attributed to the Acheulean culture of the Early Stone Age (ESA) and to the Mousterian culture of the Middle Stone Age (MSA) (McHugh et al. 1988; Wendorf et al. 1993; Szabo et al. 1995; Haynes et al. 1997; Hill 2001; Mandel and Simmons 2001; Smith et al. 2004, 2007; Kleindienst et al. 2008) (Fig. 2.4). Such archaeological remains are typically found within silts that directly overlay and/or underlay lacustrine, fluvial, and tufa deposits. Acheulean sites are associated with spring deposits from the oasis depressions of the Western Desert of Egypt at 24°–28°N (Smith et al. 2004), and with fluvial, lacustrine, and spring deposits from the Darb al-Arba′in Desert between Egypt and Sudan at 21–23°N (McHugh et al. 1988; Szabo et al. 1995; Haynes et al. 1997; Hill 2001; Mandel and Simmons 2001). Mousterian sites are mainly found in association with spring deposits from the Western Desert (Smith et al. 2004, 2007; Kleindienst et al. 2008), and with lacustrine carbonates from the Darb al-Arba′in Desert (Wendorf et al. 1993; Szabo et al. 1995). Previous studies have demonstrated that Acheulean and Mousterian sites attest to the recurrent human reoccupation of the NES during Middle-Late Pleistocene pluvial episodes. However, the precise timing and duration of these occupation events remains elusive, due to the discontinuity of the archaeological record and the often large errors associated with uranium-series dating of spring and lacustrine carbonates (Smith et al. 2007). The Site 967 dust record sheds light on these questions because it shows that conditions suitable for Acheulean and Mousterian occupation of the NES occurred during "green Sahara" periods ca. 330, 285, 240, 215, 195, 170, 125, 100, and 80 ka. "Green Sahara" periods paced by boreal summer insolation maxima also occurred before 350 ka (Larrasoaña et al. 2003), so they account for the occurrence of lacustrine and spring carbonates, often associated with Acheulean remains, whose ages are beyond the range of U-series dating (i.e., >350 ka) (Szabo et al. 1995; Crombie et al. 1997; Sultan et al. 1997; Hill 2001; Smith et al. 2004). Sedimentological, geochemical, and faunal evidence from lacustrine sediments of the Darb al-Arba′in Desert demonstrates that this area of the NES received at least 500 mm of annual rainfall during the "green Sahara" period ca. 125 ka, which enabled the widespread occurrence of wooded savannah landscapes inhabited by subtropical faunas (Kowalski et al. 1989; Wendorf et al. 1993). This 125 ka "green Sahara" period is associated with one of the highest boreal summer insolation maxima of the last 350 kyr, so it is likely that other "green Sahara" periods might have been characterized by relatively drier climates. In any case, paleoclimate evidence demonstrates that Middle-Late Pleistocene pluvial episodes were wetter than the Early-Middle Holocene "green Sahara" period between 6 and 10 ka (Szabo et al. 1995; Hoelzmann et al. 2000; Geyh and Thiedig 2008). At that time, rainfall in the Darb al-Arba′in Desert was <300 mm/year and oscillated between 50 and 150 mm/year in the Western Desert (Küper and Kröpelin 2006), so the whole NES then was covered by sparsely wooded grasslands and was inhabited by savannah to semi-desert dwellers (Nicoll 2004; Küper and Kröpelin 2006). Moreover, lacustrine deposits attest to the widespread occurrence of wetland area as far north as 26° (Szabo et al. 1995; Hoelzmann et al. 2000; Pachur and Hoelzmann 2000;


(a)
Age (ka)
25
75
125
175
225
275
325
Late Pleistocene
Middle Pleistocene
Later St. Age
Middle Stone Age
Earlier St. Age
Aterian
Mousterian
Acheulian
(b)
Smith et al. (2007)
Smith et al. (2004)
Kleindienst et al. (2008)
Szabo et al. (1995)
Sultan et al. (1997)
Crombie et al. (1997)
NES tufas & lacustrine carbonates
(c)
SPECMAP
interglacial
glacial
2
3
4
5
6
7
8
9
10
a
b
c
d
e
a
b
c
d
e
-2
-1
0
1
2
δ¹⁸O (‰ PDB)
(d)
i-cycle
8
10
12
16
18
20
22
26
30
420
400
380
360
340
JJA Insol. 25°N (w/m²)
Saharan dust
+
-
IRM@AF (A/m)
1
0.8
0.6
0.4
0.2
0
desert Sahara
green Sahara
Age (ka)
(e)
succesful out of Africa dispersal of H. sapiens (Mellars, 2006)
failed out of Africa dispersal of H. sapiens (Lahr and Foley, 1998)
earliest "archaic" H. sapiens (Grün et al., 1996; Bräuer et al., 1997)
earliest "modern" H. sapiens (McDougall et al., 2005)
technological, economic & social changes in Africa (Mellars, 2006)
gradual accumulation of modern behaviour

◀ **Fig. 2.4** Comparison of: **a** Age range of archaeological industries found in the northeastern Sahara (see text); **b** Uranium-series ages of lacustrine and spring carbonates from the northeastern Sahara (after Smith et al. 2007). *White* (*black*) symbols indicate carbonates with (without) associated archaeological remains; **c** SPECMAP curve (Imbrie et al. 1984); **d** Boreal summer insolation curve (at 25°N) calculated after the astronomical solution of Laskar et al. (2004) (*dashed line* is the Earth's eccentricity parameter), plotted along with the IRM@AF record of ODP Site 967 (Larrasoaña et al. 2003); **e** Significant events in the evolution of *H. sapiens* (after Grün et al. 1996; Bräuer et al. 1997; Lahr and Foley 1998; McBrearty and Brooks 2000; McDougall et al. 2005; Mellars 2006). *Gray bars* indicate the positions of "green Sahara" periods as identified from lowest (<0.2 A/m) IRM@AF values. Numbers denote correlative insolation cycles (Lourens et al. 1996)

Leblanc et al. 2006). These data strongly suggest that during Middle-Late Pleistocene wetter "green Sahara" periods, a subtropical climate with a N–S gradient in increased humidity enabled expansion of wetland-spotted savannah landscapes throughout the NES and even farther north, as demonstrated by the occurrence of freshwater lakes up to 28°N (Wendorf et al. 1993; Szabo et al. 1995; Kieniewicz and Smith 2007; Geyh and Thiedig 2008). It is important to note that, according to the Site 967 dust record, these savannah landscapes prevailed in the NES for less than 5–10 kyr, which is the time span within each insolation cycle where the summer monsoon front penetrated well beyond the central Saharan watershed. This suggests that Acheulean and Mousterian reoccupation of the NES during Middle-Late Pleistocene "green Sahara" periods was restricted to short (<5–10 kyr) intervals separated by intervening hyperarid periods devoid of human occupation.

It might be argued that the proposed link between "green Sahara" periods and human reoccupation of the NES is too speculative, considering the errors associated with the uranium-series ages of lacustrine carbonates and tufas and the fact that not all lacustrine carbonates and tufas are associated with archaeological remains. New archaeological and geological surveys are clearly necessary to improve our knowledge on the link between human populations and climate variability in the NES. In the meantime, we can gain some insights on this topic by examining the latest Pleistocene-Holocene record in the NES. This period is characterized by a single "greening-yellowing of the Sahara" cycle, which has conditioned the preservation of a significant number of archaeological sites (nearly 300) for which accurate radiocarbon-based ages and environmental constraints are available (Nicoll 2004; Küper and Kröpelin 2006).

Geological and paleoclimatic data provide evidence for extensive eolian deflation under a hyperarid climate when the NES was devoid of human occupation between 20 and 10 ^{14}C ka (Stokes et al. 1998; Maxwell and Haynes 2001; Swezey 2001), as demonstrated by the pervasive lack of Late Paleolithic archaeological remains (Szabo et al. 1995; Nicoll 2004; Küper and Kröpelin 2006) (Fig. 2.5). Between 9.8 and 9.5 ^{14}C ka, the NES rapidly shifted toward a semi-arid subtropical climate that was driven by the intensification and ~800 km northward shift of the West African summer monsoon front in response to a maxima in boreal summer insolation (Brovkin et al. 1998; Jolly et al. 1998; Gasse 2000). Geological, paleontological, and archaeological data indicate that the NES then hosted widespread wetland areas, was covered by sparsely wooded grasslands, and was inhabited by savannah to semi-desert dwellers that included hunter-gatherers (Nicoll 2004; Küper and Kröpelin 2006). The stabilization of this semi-arid climate by 8–7 ^{14}C ka led to the development and widespread practice of sedentarism, pottery production, and domestic livestock keeping (Nicoll 2004; Küper and Kröpelin 2006). At ~6.3 ^{14}C ka, a decrease in boreal summer insolation led to the rapid southward retreat of the West African summer monsoon front (Brovkin et al. 1998; Jolly et al. 1998; Gasse 2000) and conditioned the rapid return of hyperarid desert conditions to the NES (Stokes et al. 1998; Maxwell and Haynes 2001; Swezey 2001; Nicoll 2004; Küper and Kröpelin 2006) (Fig. 2.2d). This led to the exodus of human populations into neighboring, previously inhabited areas located to the south and east. Humans migrated to either the Sudanese plains, following the retreating summer monsoon rains, or to the Nile Valley, where they found stable refugium along the vegetated banks of the Nile. These migrations caused dramatic changes in population density and associated social structures, and ultimately led to the spread of pastoralism into tropical Africa and the emergence of the pharaonic civilization, respectively (Fig. 2.5) (Nicoll 2004; Küper and Kröpelin 2006). Human occupation of the NES after ~6.3 ^{14}C ka became restricted to ecological refugia such as the Gilf Kebir plateau. By ~4.7 ^{14}C ka, permanent settlements had disappeared, with the exception of the groundwater-fed oasis of the Western Desert of Egypt (Nicoll 2004; Küper and Kröpelin 2006).

The ODP Site 967 dust record captures the response of NES landscapes and human populations to climate variations strikingly well (Fig. 2.5a). On the one hand, the high dust contents characterizing the hyperarid latest Pleistocene display a sharp decrease that coincides with the initial spread of wetland spotted grasslands and the onset of human occupation at 9.8–9.5 ^{14}C ka. On the other hand, low dust content throughout most of the Early-Middle Holocene, which coincided with the deposition of sapropel S1 in the eastern Mediterranean (Mercone et al. 2001), underwent a sharp increase at around 6 ^{14}C ka that marks the return of hyperarid desert conditions and the beginning of the exodus from the desert.

We are aware that the archaeological record is still too scarce and its chronology too coarse to demonstrate a

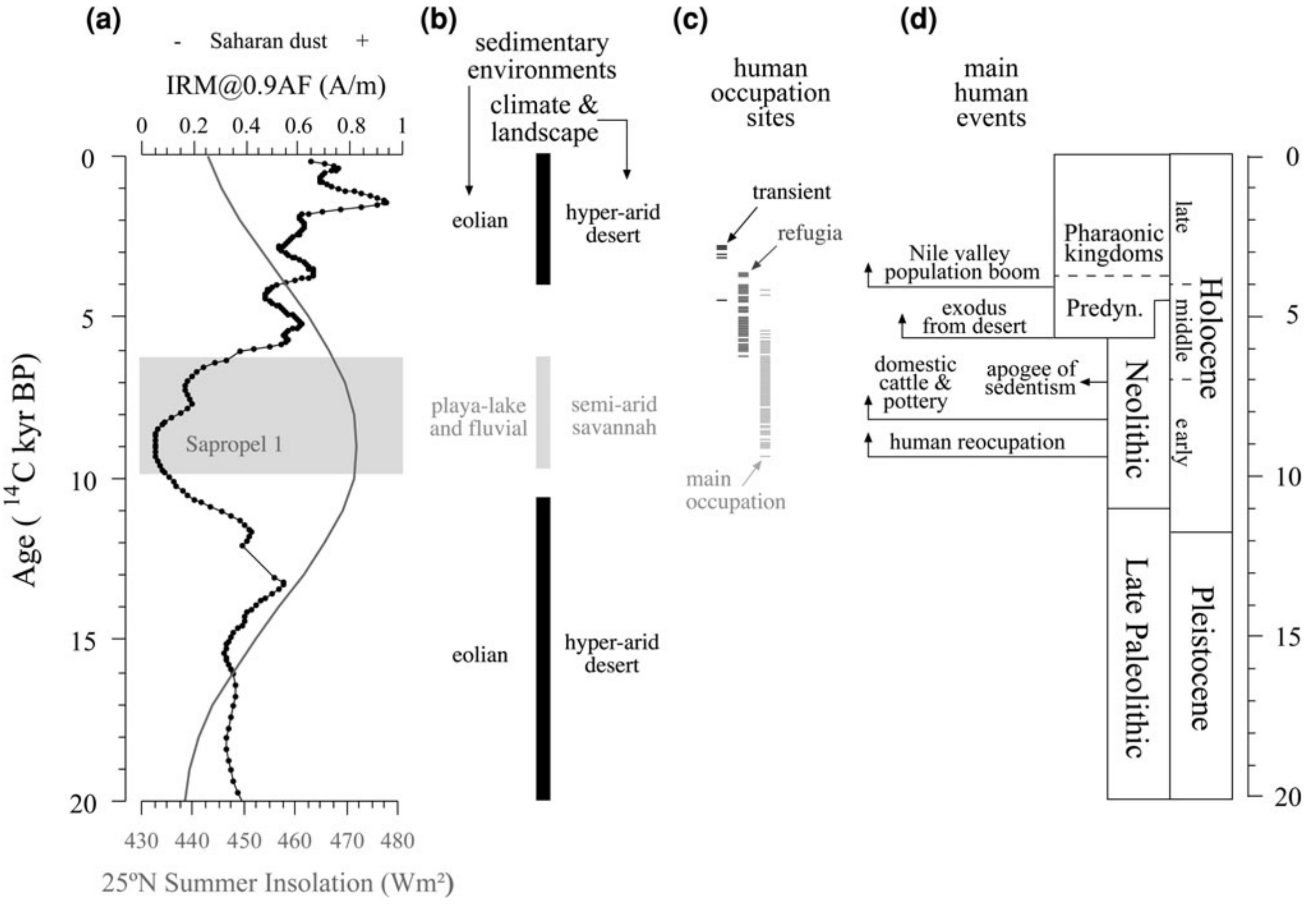


Fig. 2.5 **a** IRM@AF values (Larrasoaña et al. 2003) from the latest Pleistocene-Holocene record of ODP Site 967, plotted along with the summer insolation curve at 25°N calculated after the astronomical solution of Laskar et al. (2004). The chronology for the interval is based on linear interpolation of ages between the top of the core, ^{14}C ages of the top and bottom of sapropel 1 (*gray shaded bar*) (Mercone et al. 2001), and the age of the previous sapropel (Kroon et al. 1998). **b** Prevailing sedimentary environments, climatic conditions, and landscapes in the northeastern Sahara (after Stokes et al. 1998; Jolly et al. 1998; Gasse 2000; Maxwell and Haynes 2001; Swezey 2001; Nicoll 2004; Küper and Kröpelin 2006). **c** ^{14}C ages of archaeological remains in the northeastern Sahara (from Küper and Kröpelin 2006). **d** Chronology of main events in human history in the northeastern Sahara (after Nicoll 2004; Küper and Kröpelin 2006)

similar link between "green Sahara" periods and human reoccupation of the NES during the Middle-Late Pleistocene. However, we consider that the Holocene provides a valid "proof of concept" for relating human occupation and climate variability in the NES at previous times, especially when one considers that all Middle-Late Pleistocene "green Sahara" periods are linked to higher insolation peaks (and hence to more humid conditions) than those that prevailed during the Early-Middle Holocene.

Aterian sites in the NES, which range between 40 and 80 ka (Cremaschi et al. 1998; Smith et al. 2004; Barich et al. 2006; Garcea and Giraudi 2006), are associated with either tufa deposits from the Western Desert of Egypt and the Jebel Gharbi region of Northwest Libya (Smith et al. 2004; Barich et al. 2006; Garcea and Giraudi 2006) or with aeolian sands in the Tadrart Acacus range in Southwest Libya (Garcea 2004). The Site 967 dust record indicates that, between 75 and 20 ka, the NES was dominated by an especially severe hyperarid climate that was conditioned by a weakened monsoon circulation at the time of lowest boreal insolation maxima. The presence of Aterian remains only near tufa deposits and in mountain areas under a prevailing hyperarid climate supports the view that Aterian groups were especially well-adapted to desert landscapes (Garcea 2004), provided that water was available in isolated areas that functioned as ecological refugia.

Implications for the Origin and Population Dynamics of Modern Humans in North Africa

One of the key issues regarding the origin of modern humans is the evolution of *H. sapiens* as a distinctive species. Climate variability has been considered as one of the factors that might have influenced the speciation of

H. sapiens, but to date, no detailed causal paleoenvironmental scenario has been proposed. Here, we argue that environmental variability in the Sahara, and in the NES in particular, might have played a critical role in driving the speciation of *H. sapiens*, because it is the region that has witnessed the most dramatic environmental variations within tropical Africa.

H. sapiens is often divided into "modern *H. sapiens*" (also known as "recent *H. sapiens*" or "*H. sapiens sensu stricto*"), which includes all living *H. sapiens* and their closest past relatives, and "archaic *H. sapiens*," which includes members of the stem group that are more closely related to "recent *H. sapiens*" than to *H. heidelbergensis* (McBrearty and Brooks 2000; Stringer 2002). The earliest fossil remains of "modern *H. sapiens*" are those from the Kibish Formation in southern Ethiopia. They date back to ca. 195 ka, and are related to an insolation-driven wet period around Lake Turkana that has been tentatively correlated to sapropel 7 (McDougall et al. 2005). The earliest fossil remains of "archaic *H. sapiens*," formerly attributed to *H. helmei* (e.g., Lahr and Foley 1998), might date back to ca. 300 ka (Bräuer et al. 1997), with the earliest well-dated fossil being those of Florisbad (South Africa) ca. 260 ka (Grün et al. 1996). If, as suggested by Stringer (2002) on anatomical grounds, "archaic *H. sapiens*" is cladistically included within *H. sapiens*, the origin of our own species (*H. sapiens* hereafter) was around 260–300 ka, coinciding with the appearance of MSA technology (McBrearty and Brooks 2000; Stringer 2002).

According to the Site 967 dust record, "green Sahara" periods cluster at around 100 kyr eccentricity maxima centered at 315, 215, and 115 ka (Fig. 2.4). Within each of these clusters, short (<5–10 kyr) "green Sahara" periods in the NES were separated by relatively longer (10–15 kyr) hyperarid periods. On the contrary, during 100 kyr eccentricity minima at around 270, 150, and 45 ka, hyperarid desert conditions prevailed uninterrupted for longer time periods (>40 kyr). Especially significant is the fact that the time span between 260 and 300 ka, when *H. sapiens* most likely speciated, is centered around a long (ca. 90 kyr) period of hyperarid conditions in the NES that was only interrupted at ca. 285 ka by a brief "green Sahara" period that is related to the oxidized sapropel at 13.5 rmcd (Fig. 2.3). Prolonged hyperarid conditions in the NES in response to a long-term weakened monsoon, and simultaneous relatively drier conditions in sub-Saharan Africa (see McDougall et al. 2005; Basell 2008), might have driven the fragmentation of habitats suitable for human occupation throughout most of tropical Africa. Between 325 and 290 ka, and between 280 and 225 ka, the NES (and the whole Sahara Desert) was most likely inhospitable except near ecological refugia associated with aquifer-related spring activity, mountain areas, and permanent rivers such as the Nile. Any human population inhabiting the Sahara during the "green Sahara" episodes either ca. 330 or 285 ka might have been subsequently forced to migrate into these ecological refugia, to the Mediterranean or Red Sea coastal areas, or to the South, in search of more hospitable habitats (Fig. 2.6a). In sub-Saharan Africa, an insolation-driven change to relatively drier conditions (see McDougall et al. 2005) would have conditioned the contraction of autochtonous human populations around favorable habitats such as lake basin and mountain areas (Basell 2008), where they might have had to compete with immigrant populations. Prolonged habitat fragmentation, coupled with isolation in ecological refugia, adaptation to overall drier habitats, and competition between different human groups provide the optimum conditions for the accentuation of any genetic difference between separate groups, which might be pushed to the point of an effective reproductive isolation and thus lead to the emergence of *H. sapiens* as a distinct species. Since habitat fragmentation and isolation in ecological refugia was common throughout North and East Africa, it is difficult at present to make inferences on the specific region where the emergence of *H. sapiens* took place. Subsequent changes towards wetter conditions during the "green Sahara" episodes ca. 330 and 285 ka might account for an eventual rapid expansion of the most successful human species, *H. sapiens*, together with its technological innovation (e.g., MSA industries), through tropical Africa (Fig. 2.6b). Subsequent repeated expansions and contractions of landscapes suitable for human occupation, driven by monsoon dynamics, would have favored recurrent contact between different African human populations, which provides support for models of modern human origins that advocate for a coalescence of genetic attributes within Africa (see Stringer 2002).

In addition to its potential implications for the emergence of *H. sapiens*, climate variability might have also had an important impact on *H. sapiens* population dynamics. Previous studies have demonstrated that an initial dispersal of *H. sapiens* into Southwest Asia through the NES and the Levant occurred ca. 125 ka (Bar-Yosef 1998; Lahr and Foley 1998; Grün et al. 2005). The Site 967 dust record suggests that climatic conditions favorable for the expansion of *H. sapiens* throughout the NES occurred more frequently, e.g., during at least 8 "green Sahara" episodes after 300 ka (Fig. 2.4). At these times, the subtropical savannah was connected with the narrow band of mild climate around the Mediterranean coast by a fringe of semiarid climate in such a way that sub-Saharan human populations could reach the Mediterranean coast of North Africa not only by following the Nile River or the Red Sea coast, but also by crossing the Sahara. Although trans-Saharan crossing was possible throughout any location (Fig. 2.6b), preferential routes were the then-active rivers that drained the Tadrat

Acacus, Sarir Tibesti, Ennedi and Gilf Kebir massifs into the eastern Mediterranean (Fig. 2.1) (Drake et al. 2008; Osborne et al. 2008). The reason why only the "green Sahara" period around 125 ka witnessed a human expansion a step further across the Levant might lie in the fact that, only at that time, fully interglacial climate conditions operating in the Levant coincided with intensified monsoon conditions in tropical Africa in such a way that a "climatic window" was opened between Africa and Asia (Vaks et al. 2007). If so, similarly suitable conditions for previous "out of Africa" dispersals of humans also occurred at least at ca. 330 and 195 ka, coinciding with interglacial 9/green Sahara 30 and interglacial 7a-green Sahara 18, respectively (Fig. 2.4).

Through its impact on population dynamics, climate variability over the Sahara might also be behind the successful "out of Africa" migration of *H. sapiens* ca. 60 ka (Mellars 2006). Thus, massive depopulation of the Sahara following the end of the "green Sahara" period ca. 80 ka might have conditioned a rapid migration of Saharan populations into desert ecological refugia, coastal areas along the Mediterranean and the Red Seas, and sub-Saharan Africa. This, in turn, might have triggered the important technological, economic, and social changes observed in Africa between 80 and 70 ka (Mellars 2006) through fierce competition for the most favorable, yet far less abundant, habitats and resources. These changes ultimately made possible the successful colonization of Eurasia, which involved crossing the southern Red Sea through the Bab el-Mandeb Strait, seafaring along the Red Sea coast of the Sinai Peninsula, or a continental route through the Sahara and the Sinai Peninsula (see Derricourt 2005; Mellars 2006). Although speculative, this idea of a Saharan-forced "out of Africa" migration of *H. sapiens* should not be dismissed without a careful scrutiny of the paleoclimatic and archaeological Holocene record of the NES. Thus, during the Holocene, all the archaeological evidence demonstrates that a single "green Sahara" period, in which a rapid repopulation of the NES was followed by an "exodus from the desert," is primarily responsible for key events in human history, such as the emergence of the pharaonic civilization along the Nile River and the spread of pastoralism throughout tropical Africa (Fig. 2.5) (Nicoll 2004; Küper and Kröpelin 2006).

A last issue that might be also linked to climate variability through its impact on human population dynamics is that of modern human behavior. According to McBrearty and Brooks (2000), modern behavior resulted from a gradual accumulation of individual behavioral, economic, and technological innovations that are found scattered

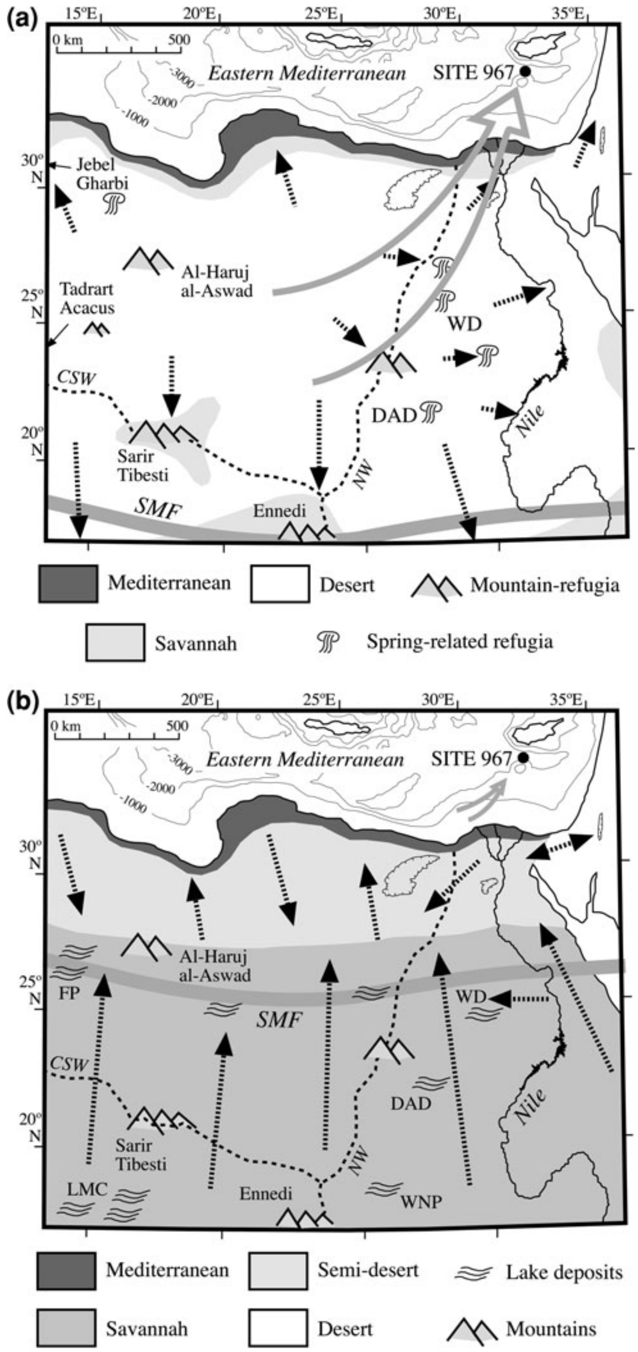


Fig. 2.6 Schematic reconstruction of environmental scenarios in the northeastern Sahara during: **a** "desert Sahara" state; **b** "green Sahara" state (e.g., 215, 195, 170, 125, 100, and 80 ka). SMF denotes the position of the boreal summer monsoon front (Gasse 2000). CSW and NW denote the central Saharan and Nile watersheds, respectively. The thickness of the *gray arrows* indicates the relative importance of dust supply into the eastern Mediterranean. *Dashed arrows* indicate potential dispersal routes for human populations. *WD* Western Desert, *DAD* Darb el Arba'in Desert, *WNP* West Nubian paleolake (Hoelzmann et al. 2000), *LMC* lake Mega Chad (Leblanc et al. 2006), *FP* Fezzan paleolake (Geyh and Thiedig 2008)

throughout most African regions, albeit sometimes at different times. Our results suggest that relatively fast (<20–40 kyr) expansions and contractions of human populations within tropical Africa in response to monsoon dynamics and the concomitant changes in landscape composition are a common element of the African Middle-Late Pleistocene. Such repeated expansions and contractions favored recurrent contact between different African populations, which is, in turn, necessary to explain the widespread occurrence of most behavioral, economic, and technological innovations throughout most African locations, from the Sahara to South Africa (McBrearty and Brooks 2000).

Conclusions

The Middle-Late Pleistocene dust record from Site 967 presented here documents distinctive dust flux minima at ca. 330, 285, 240, 215, 195, 170, 125, 100, and 80 ka. These dust minima are linked to the insolation-driven penetration of the West African summer monsoon front over the NES, which, in turn, resulted in the expansion of subtropical savannah landscapes and suppressed dust production. These so-called green Sahara periods broadly correlate with U-series ages of lacustrine and spring carbonates scattered throughout the NES, which are often associated with Acheulean and Mousterian archaeological sites that attest to widespread occupation of the area during pluvial episodes. In contrast, Aterian sites are linked to spring deposits and mountain areas during a prolonged period of hyperarid climate in the NES, which suggests adaptation to desert conditions. The Site 967 dust record has important implications for understanding the evolution and population dynamics of modern humans in Africa. Alternation of "green Sahara" periods with hyperarid desert conditions in North Africa, coupled with simultaneous climate variability in sub-Saharan Africa, provide a scenario of fragmented habitats, isolation in ecological refugia, and competition for resources that would have favored speciation of *H. sapiens* 260–300 ka. Subsequent repeated expansion and contraction of subtropical savannah landscapes within Africa would have favored the coalescence of genetic and behavioral attributes of different human populations, providing the context for a gradual accumulation of African modern behaviors as a whole. Moreover, the disappearance of the Sahara during "green Sahara" periods might have made possible frequent out of Africa dispersals of human populations, whose success might have been ultimately controlled by climate conditions in the Levant. Finally, a sudden expansion of the Sahara in the latest Pleistocene ca. 75 ka, and a concomitant "exodus from the desert," might have triggered the important technological, economic, and social changes that made the successful out of Africa dispersal of modern humans ca. 60 ka possible.

Acknowledgments I thank Jean-Jacques Hublin and Shannon McPherron, organizers of the meeting "Modern Origins: A North African Perspective" (Leipzig, August 2007) and editors of this volume, for making my attendance to the meeting and the publication of this contribution possible. I am also very grateful to Ana Moreno, who also facilitated my participation in the meeting, and to three anonymous reviewers, whose constructive comments and criticism greatly improved this manuscript. Samples were provided by the ODP, which is sponsored by the U.S. National Science Foundation and participating countries (including the U.K.) under management of Joint Oceanographic Institutions, Inc.

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