A humid corridor across the Sahara for the migration of early modern humans out of Africa 120,000 years ago

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Communicated by Wallace S. Broecker, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, May 8, 2008 (received for review February 25, 2008)

It is widely accepted that modern humans originated in sub-Saharan Africa ≈150–200 thousand years ago (ka), but their route of dispersal across the currently hyperarid Sahara remains controversial. Given that the first modern humans north of the Sahara are found in the Levant ≈120–90 ka, northward dispersal likely occurred during a humid episode in the Sahara within Marine Isotope Stage (MIS) 5e (130–117 ka). The obvious dispersal route, the Nile, may be ruled out by notable differences between archaeological finds in the Nile Valley and the Levant at the critical time. Further west, space-born radar images reveal networks of—now buried—fossil river channels that extend across the desert to the Mediterranean coast, which represent alternative dispersal corridors. These corridors would explain scattered findings at desert oases of Middle Stone Age Aterian lithic industries with bifacial and tanged points that can be linked with industries further to the east and as far north as the Mediterranean coast. Here we present geochemical data that demonstrate that water in these fossil systems derived from the south during wet episodes in general, and penetrated all of the way to the Mediterranean during MIS 5e in particular. This proves the existence of an uninterrupted freshwater corridor across a currently hyperarid region of the Sahara at a key time for early modern human migrations to the north and out of Africa.

Middle Stone Age | Eemian | neodymium | paleochannel | sapropel

The Saharan-Arabian desert is currently the largest hyperarid region on the planet, with annual precipitation as low as 1 mm. This region presented the most significant barrier to the migration of anatomically modern humans out of central sub-Saharan Africa during their dispersal into southwest Asia and Europe (1–4). So far, interest has focused on a northward dispersal route through the Sahara via the Nile at ≈130 thousand years ago (ka). However, new dates on fossils and archaeological sites have revealed a wide distribution of *Homo sapiens* all along the North African coast, north of the Sahara, during this period (5, 6). Moreover, there are considerable inconsistencies between archaeological finds in the Nile Valley and the Levant at the crucial time (4, 7), whereas it has been suggested that conditions in the Nile corridor were inhospitable during a similar Holocene Saharan wet phase (8).

We argue that the Nile should be seen as neither the only nor, perhaps, the most likely potential dispersal route. There is widespread evidence for episodes of significantly more humid conditions over much of the Sahara itself in the past (9–14), driven by orbital insolation-induced African monsoon maxima (15). The most recent of these so-called pluvials occurred during the early Holocene (≈10–5 ka), when decorated pottery and other archives attest to a flourishing Neolithic civilization in the heart of what is now desert (16). Our focus here is the even more intense wet phase that occurred during the last interglacial [Marine Isotope Stage (MIS) 5e], coincident with the migration of early modern humans out of Africa. We show that the radar-imaged fossil river channels (17) bore water during MIS 5e that is sourced in the internal Sahara and that penetrated all of the way to the Mediterranean. Our data represent an indication of an uninterrupted humid corridor stretching across the Sahara to the Mediterranean at a key time for the dispersal out of Africa of early modern humans.

Mediterranean Isotopic Anomalies at 124–119 ka and the Source of Freshwater Discharge to the Mediterranean

We use a combination of two data sets to investigate the existence of a humid corridor across the Libyan Sahara fueled by water that derived from the North African Watershed (≈21°N; Fig. 1) and that penetrated all of the way to the Mediterranean. Fig. 2 shows published $\delta^{18}O$ (18) and new neodymium (Nd) isotope data for surface-dwelling planktic foraminifera in the 135- to 110-ka interval of Ocean Drilling Program (ODP) Hole 971A (Fig. 1) from the western Ionian Sea. Previous work established that the pronounced $\delta^{18}O$ anomaly seen at ≈124–119 ka is difficult to explain in terms of any combination of temperature and/or ice-volume changes but, instead, reflects a dramatic change in the freshwater budget of this part of the Mediterranean (18, 19). The $\delta^{18}O$ anomaly, which is identifiable throughout the eastern Mediterranean, is related to significant surface-water freshening, a shutdown of eastern Mediterranean deep-water ventilation, and anoxia in the deep basin (18, 19). Moreover, the $\delta^{18}O$ anomaly is much stronger in the western Ionian Sea than elsewhere, which may suggest a freshwater source proximal to the Gulf of Sirte and the Libyan portion of the Sahara (18, 19).

Because of complex controls on foraminiferal $\delta^{18}O$, such data alone cannot conclusively identify the origin of the anomalous freshwater influx. On the basis of a single proxy (oxygen isotopes), and lacking a transect of cores into the Gulf of Sirte to "trace" the inlet, the Rohling *et al.* (18) data set is very suggestive, but other processes involving isotope fractionation or regional oceanographic reorganization cannot be fully excluded. Our Nd isotope analyses of planktic foraminifera from 971A add a key constraint (Fig. 2; see also *Materials and Methods*). The Nd isotopic composition of the oceans is controlled by inputs from the continental crust (see ref. 20 for a review). Old continental crust, with a long history of low Sm/Nd ratios, has a lower $^{143}Nd/^{144}Nd$ ratio than material newly extracted from the mantle. $^{143}Nd/^{144}Nd$ ratios are expressed in terms of ε_{Nd}, or parts per

Author Contributions: D.V. and E.J.R. designed research; A.H.O. performed research; A.H.O., D.V., M.R. and N.F. contributed to fieldwork; A.H.O., D.V., E.J.R., N.B., and M.R. analyzed data; and A.H.O. and D.V. wrote the paper.

The authors declare no conflict of interest.

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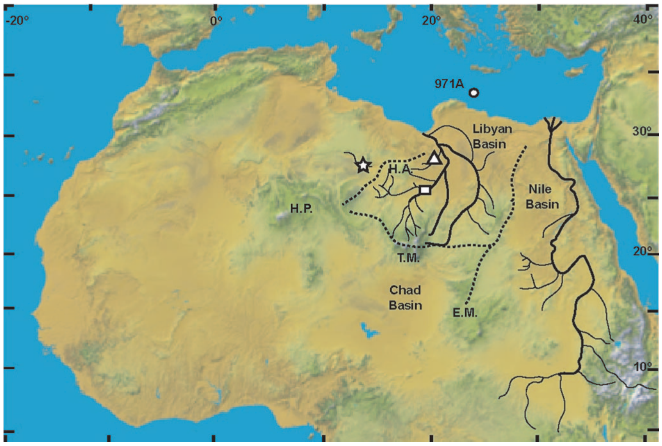

Fig. 1. Map of North Africa showing location of sampling sites for Nd isotopes in the Libyan Sahara (triangle, Wadi Behar Belama; rectangle, Wadi Quoquin; star, Wadi ash Shati), that of ODP Hole 971A in the western Ionian Sea (circle), a reconstruction of the fossil river channel network in the central eastern Sahara [Rohling *et al.* (18) adapted from Pachur and Altmann (25)] draining the volcanic Tibesti Mountains (T.M.), and Haruj Al Aswad (H.A.). The Tibesti Mountains are part of a watershed stretching across a significant portion of North Africa at ≈20–23°N and which also includes the Hoggar Plateau (H.P.) and the Ennedi Mountains (E.M.).

10,000 deviation of the measured $^{143}Nd/^{144}Nd$ from the bulk Earth value. Modern water flowing into the eastern Mediterranean through the Strait of Sicily has a low ε_{Nd}, ultimately derived from the relatively old continental crust surrounding the North Atlantic (21).

Planktonic foraminiferal shells record the Nd isotopic composition of contemporary surface seawater, and this signature is preserved after fossilization (22). Postmortem acquisition of radiogenic Nd by the foraminifera in deep water can be ruled out, because deep water in the Ionian Sea has an ε_{Nd} of -7 to -6 (23). The Nd isotopic composition of planktic foraminifera before the oxygen isotope anomaly in 971A is similar to the value

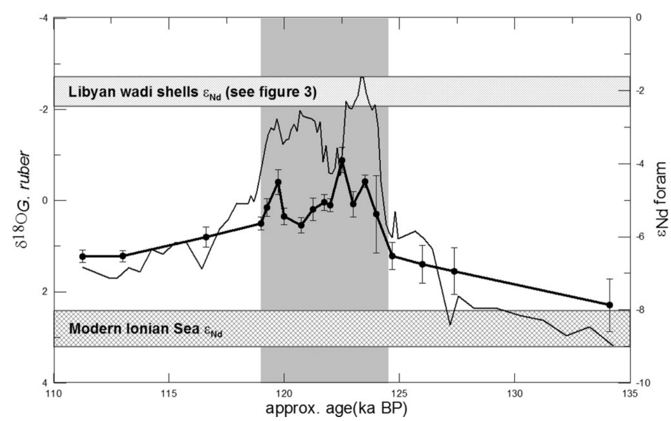

Fig. 2. Oxygen [thin line (18)] and Nd isotopes (bold line and points with uncertainties; see *Materials and Methods* for details of analyses) in planktic foraminifera from a portion of ODP Hole 971A [see Fig. 1 for location; age model from Rohling *et al.* (18)], spanning MIS 5e (130–117 ka) and adjacent times. The dark-gray vertical band marks the visible extent of organic-rich deep-sea sediment deposited during sapropel event S5 and caused by deep anoxia related to convective stabilization of the water column after anomalous freshwater addition to the surface eastern Mediterranean (18). The lower horizontal shaded bar gives the ε_{Nd} value of modern Ionian Sea surface waters (21), and the upper bar denotes the ε_{Nd} value of freshwater gastropods in lake sediments recovered from beneath the modern Saharan sands in central eastern Libyan wadis that drain the Tibesti Mountains (data shown in Fig. 3).

for modern surface water (21), and after the oxygen isotope anomaly the ε_{Nd} tails back toward such a value (Fig. 2). However, the oxygen isotope anomaly itself is accompanied by significantly more radiogenic Nd, with an ε_{Nd} as high as -4, indicating a transient source of radiogenic Nd at this time that must be local to the eastern Mediterranean. The observed ε_{Nd} excursion must reflect changes in surface-water properties and, thus, an increase in the flux of terrestrial radiogenic Nd to the Ionian Sea. Saharan dust is too unradiogenic, with an ε_{Nd} of -13 (24), to account for this, and all of the rivers that drain into the Mediterranean except the Nile (23) also have ε_{Nd} values that are too negative (i.e., unradiogenic).

Rohling *et al.* (18) use the remarkable geographic gradient in the oxygen isotope anomaly to suggest that the extra freshwater was delivered into the Gulf of Sirte via fossil river channels through the Sahara. These—now buried—channels (Fig. 1) are visible with space-borne radar (17) and form part of a >800-km-long system of channels that are, in places, more than 5 km wide (17, 25). The system extends from the North African watershed, locally defined by the Tibesti mountains at 21°N, all of the way to the Gulf of Sirte in Libya. The Tibesti mountains, at 21°N, and the Haruj-Al-Aswad, further north at 27°N (Fig. 1), predominantly comprise young, recently mantle-derived basalts with ε_{Nd} values at 5 to 7 and $^{87}Sr/^{86}Sr$ ratios of 0.7032:0.7035 (26). Thus, the excursion toward radiogenic Nd recorded by planktic foraminifera in the 119- to 124-ka interval of ODP Hole 971A would be consistent with drainage of freshwater from as far south as the Tibesti Mountains northward to the Mediterranean.

We recently published a similar Nd isotope record from ODP site 967C in the eastern Levantine Sea (23), which showed qualitatively similar anomalies to those for site 971A shown in Fig. 2 and which we attributed to increased Nile outflow during MIS 5e. Thus, a key alternative hypothesis that could explain the new Nd isotopic data from site 971A is that enhanced Nile outflow causes the signals seen at both sites, with the signal at site 971A simply representing a distal version of that at site 967C. However, a detailed consideration of the relative sizes of the anomalies at the two sites rules this out. The least negative ε_{Nd} datum found here (-3.90 ± 0.35) is slightly less radiogenic, although actually indistinguishable at the extremes of analytical uncertainty, than the least negative datum at site 967C (-3.26 ± 0.31). The ε_{Nd} of modern Levantine Sea water is approximately -5 (21, 22). This signal is also recorded in forams from outside sapropel horizons at site 967C (23) and is clearly a long-term feature of the "ambient" Levantine Sea. The ε_{Nd} of modern Ionian Sea water is approximately -8 to -9 (Fig. 2) (23). Again, this is the same as pre-MIS 5e forams from site 971A and is a long-term feature of the recent "ambient" Ionian Sea. The important consequence of all this is that the maximum ε_{Nd} shift seen at 971A during MIS 5e is 4–5 ε units. The maximum shift seen at site 967C is 1.7 ε units. In other words, the absolute magnitude of the shift away from the background values is two to three times greater at site 971A than at 967C, which argues strongly in favor of a proximal source for the 971A signal rather than a residual distal signal from Nile outflow. Similarly, the size of the Nd isotope anomaly at 971A, as a proportion of the total possible signal [4 or 5 ε units of the possible 6 or 7 between the background and the freshwater source of -2 (see next section)] is greater at ≈70% than that recorded at site 967C (1.7 ε units of a possible 3) at 55%.

Intriguingly, the above-mentioned comparison of 971A with 967C shows that, although it is probable that MIS 5e saw increased runoff through both the Nile corridor and the Libyan wadis, the Nd isotopic data from the two sites would be best explained in terms of runoff proximal to 971, with the 967 signal being distal to it. This suggestion would agree with the nature of the surface ocean circulation in the Mediterranean. The Mediterranean's general cyclonic circulation is determined by the large-scale atmospheric circulation, and the basin has not moved from its current position between the temperate westerlies in the North and the subtropical/trades to the South. Hence, the overall vorticity input into the basin remains cyclonic, with a general eastward surface flow in a slightly south-of-central position in the basin known as the Mid-Mediterranean Jet (MMJ) (27). This MMJ flows virtually over the top of ODP site 971A. Westward "return" flow occurs along the northern margins of the Mediterranean. The overall cyclonic nature of the circulation is enforced by significant net buoyancy loss in the easternmost Mediterranean with freshwater additions along the margins. The MMJ is a pervasive feature of the surface circulation that "protects" ODP site 971A from the chemical properties of the westward return flow (which may have been affected by Nile discharge). Hence, one would expect, from dynamical reasons alone, that site 971A is highly unlikely to show an undiluted Nile impact. Instead, one would expect ODP site 971A to show a strong dominance of Atlantic-derived properties, with modifications caused by any nearby (upstream or southwest of the site) discharges. The eastward surface flow over site 971A then puts 967C in a "downstream" position, where it would be likely to record a distal version of the signature seen in 971A.

Nd Isotopic Characterization of the Wet Corridor Through the Sahara

The inferred causal relationship between radiogenic Nd in the southern volcanic mountains and a shift to more radiogenic values in the eastern Mediterranean would require that the freshwater in the fossil river systems carried the radiogenic Nd signal toward the Mediterranean. We test this hypothesis by using the isotopic compositions of freshwater mollusks from assemblages that thrive in shallow lakes or slow-moving rivers (see *Materials and Methods*). These were recovered from Quaternary sediments beneath the modern Saharan sands in Libya, both within the major channels imaged from space, at Wadi Quoquin and Behar Belama, and outside them at Wadi ash Shati (Fig. 1). The data for Wadi Quoquin and Wadi Behar Belama indicate waters that carried unradiogenic Sr and—crucially—radiogenic Nd signatures, with ε_{Nd} values reaching as high as -2 (Fig. 3). As with the Mediterranean foraminiferal analyses, such a Nd signature cannot be derived from any proximal source and must, instead, come from the volcanic mountains to the south, in agreement with the layout of the channel network (25). These results contrast sharply with those for the mollusks from Wadi ash Shati, outside the main water courses, the Sr and Nd signatures of which do not require a basaltic source, with ε_{Nd} values as low as -12 (Fig. 3).

Our data represent direct evidence for an uninterrupted humid connection between the southern Sahara region and the Mediterranean at ≈120 ka. These data supplement previous suggestions that the latitudinal extent of the Sahara desert was much reduced during orbital insolation maxima, especially at 130–120 ka, caused by northward expansion of the African monsoon—the so-called greening of the Sahara. This greening is best documented for the most recent, ^{14}C-datable, Holocene pluvial (see ref. 25 for a review). Palynological studies as well as dated tufas and lacustrine sediments indicate an even more significant extension of wetter conditions during the pluvial of 130–120 ka (9–14). These inferences are consistent with the fact that the orbital insolation forcing of climate was more pronounced during MIS 5e than during the Holocene (15), and Global Climate Models confirm that the resultant northward displacement of the ITCZ (and associated "greening" of the Sahara) would have been more extreme during MIS 5e than during the Holocene (28).

Perhaps the two largest lakes in the Sahara during ancient wet phases were megalakes Chad and Fazzan (14, 29). In neither case has their been any previous suggestion that they drained to the

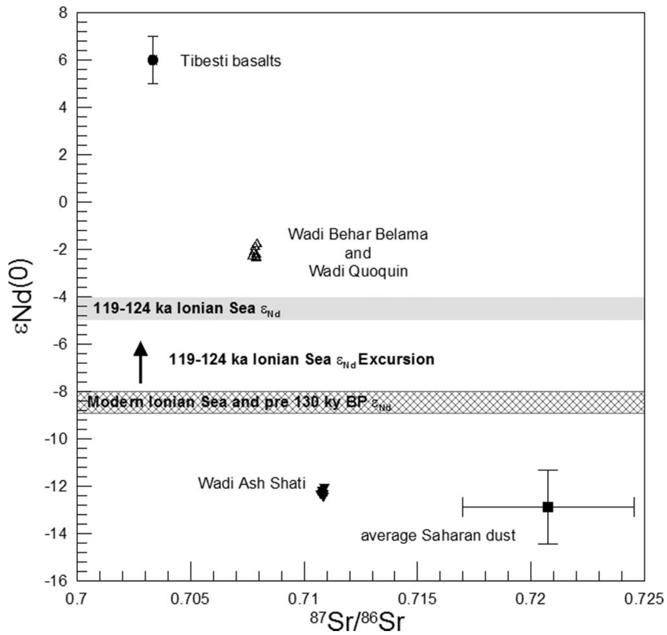

Fig. 3. Nd and Sr isotopic data for mollusks collected from lake sediments recovered from central and eastern Libyan wadis that drain the Tibesti Mountains and the Haruj-Al-Aswad (open triangles, Wadi Behar Belama and Wadi Quoquin) and for mollusks from gravels in a wadi further west (black triangles, Wadi ash Shati) that drains local Phanerozoic sediments and is not linked to the Tibesti Mountains. Uncertainties are about the same size as the symbols (see *Materials and Methods* for analytical details). Also shown is the isotopic composition of average Saharan dust (23) (black square with an error bar denotes 1 SD). The lower cross-hatched bar gives the Nd isotopic composition of both the modern surface Ionian Sea (21) as well as foraminifera from outside the 119- to 124-ka oxygen and Nd isotope excursion (see Fig. 2). The excursion to more radiogenic Nd (arrow and upper horizontal gray bar), accompanied by much lighter oxygen, is explicable in terms of only one local source. That source, and that of the Nd in the wadi mollusks, is the Tibesti Mountains (26) (circle with error bar).

Mediterranean Sea, with Lake Chad probably draining to the south (29) and Lake Fazzan in Libya almost certainly being an internal basin (14). Crucially, and in contrast to previous findings, our data link the Mediterranean and the internal Sahara with a humid corridor.

Conclusions and Outlook

The very widespread distribution of Middle Stone Age (MSA) Aterian assemblages across the Sahara (30) and their precocious appearance in North Africa at the end of MIS 5 or earlier (31) suggest a widespread dispersal of *H. sapiens* at this time. The absence of similar industries from the Nile Valley (32) implies the existence of separate migrations along routes across the Sahara as far north as the Mediterranean coast. The similarity of Aterian assemblages in the Western Desert of Egypt (33) and the Libyan Sahara, extending into coastal areas of Cyrenaica and Tunisia, implies a strong connection between the cultural traditions of these regions. Combining these observations with our evidence for continuous humid corridors through the central Sahara at the critical time, fed by strongly enhanced precipitation over the central Saharan watershed, we infer that northward dispersal from sub-Saharan Africa likely took place through regions that currently rank among the most arid on Earth.

In putting forward our hypothesis, we note that it is eminently testable. Although a significant amount of work has been done on the archaeology of the Mediterranean littoral itself, there is as yet very little evidence to link sites in these areas with finds of MSA material in the Sahara, most of which is undated, found in low concentration, and comes from surface scatters, often from ill-defined or disturbed contexts. Our hypothesis would suggest that a concerted effort along the edges of the drainage channels would prove fruitful and would yield higher density sites of comparable age to those on the coast.

Materials and Methods

Samples. For the foraminiferal Nd analyses, mixed samples of *Globigerinoides ruber* and *Orbulina universa* were picked from the 250- to 355-μm fraction of ODP Hole 971A (24°41′N, 33°43′E; water depth = 2,026 m) and cleaned by using methods described elsewhere (22). Mixed samples were used on the basis of previous work, which obtained identical results for each species (23). The freshwater mollusk samples from within the Libyan wadis were recovered from the top 1 m of limnic sediments, now buried beneath ≈0.5 m of desert sands, during fieldwork in December 2006. The Wadi Behar Belama (27°27.627′ N, 21°15.603′ E) and Wadi Quoquin, (25°44.888′ N, 19°09.863′ E) shells were all gastropods, and the species assemblage (*Biomphalaria pfeifferi*, *Bulinus truncatus*, *Gyraulus ?ehrenbergi*, and *Lymnaea peregra*) indicates that the areas were once shallow freshwater lakes or slow-moving rivers that may have become seasonally dry. Mollusk samples from outside the major channel network, from Wadi ash Shati (27°30.703′ N, 14°02.736′ E), were collected from coquina-type deposits in a 2.6-m-high outcrop, location XV discussed by Petit-Maire *et al*. (9) and the same location as samples FZ11 and FZ12 discussed by Armitage *et al*. (14). The assemblage (*Melanoides tuberculata* and *Cerastoderma ?glaucum*) and previous work (9) indicate that this is a ''beach-rock'' type of deposit from the shores of a brackish to saline lake. All mollusk samples were cleaned and analyzed by using the same methods as for the planktonic foraminifera with the exception of the reductive cleaning step, which was omitted.

Isotopic Analysis. Nd and Sr were separated from all carbonate samples by using chemical procedures described elsewhere [see Vance *et al*. (22) and references therein]. Nd isotopic analysis was performed on a Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) at the Bristol Isotope Group by using the procedure described in detail by Vance and Thirlwall (34). Between 7 and 9 La Jolla standards were analyzed per analytical session, and the measured $^{143}Nd/^{144}Nd$ varied from 0.511843 ± 0.000004 (2 SDs) to 0.511854 ± 0.000008 (2 SDs) for a single analytical session. All isotopic analyses were normalized to a La Jolla value of 0.511857. Sr isotopic analysis of the mollusk samples was also analyzed on the Bristol Neptune MC-ICPMS and normalized to an $^{86}Sr/^{88}Sr$ of 0.1194. Between 8 and 10 analyses of the National Institute of Standards and Technology Standard Reference Material 987 Sr standard were performed per session, and the measured $^{87}Sr/^{86}Sr$ varied from 0.710254 ± 0.000012 (2 SDs) to 0.710257 ± 0.000012 (2 SDs). For the mollusk analyses, individuals from each of the species collected were analyzed and, for samples from the same location, there were no significant differences in the measured isotopic compositions of Sr and Nd.

ACKNOWLEDGMENTS. We thank Salah Subhi of the British Council in Tripoli for help with the logistics of our fieldwork in Libya, J. Todd of the Natural History Museum, London, for help with identifying the Libyan mollusk samples, Peter deMenocal and Tom Johnson for reviewing our manuscript, and the Ocean Drilling Program for the provision of the 971A samples. This research was supported by a Natural Environment Research Council (United Kingdom) studentship (to A.H.O.). E.J.R. and N.B. acknowledge support from the Natural Environment Research Council-Response of Humans to Abrupt Environmental Transitions. M.R. recognizes the British Geomorphological Research Group and Hull Environment Research Institute for their fieldwork support.

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