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Ages of Quaternary pluvial episodes determined by uranium-series and radiocarbon dating of lacustrine deposits of Eastern Sahara

B.J. Szabo [a], C.V. Haynes Jr. [b], T.A. Maxwell [c]

[a] *U.S. Geological Survey, MS 974, Box 25046, Denver Federal Center, Denver, CO 80225, USA*
[b] *Departments of Anthropology and Geosciences, University of Arizona, Tucson, AZ 85721, USA*
[c] *Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, USA*

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Abstract

As documented by radiocarbon dating and geoarchaeological investigations, the now hyperarid northwestern Sudan and southwestern Egypt experienced a period of greater effective moisture during early and middle Holocene time, about 10–5 ka. We have used the uranium-series technique to date lacustrine carbonates from Bir Tarfawi, Bir Sahara East, Wadi Hussein, Oyo Depression, and the Great Selima Sand Sheet localities. Results indicate five paleolake-forming episodes occurred at about 320–250, 240–190, 155–120, 90–65 and 10–5 ka. Four of these five pluvial episodes may be correlated with major interglacial stages 9, 7, 5e, and 1; the 90–65 ka episode may be correlated with substage 5c or 5a. Our results support the contention that past pluvial episodes in North Africa corresponded to the interglacial periods farther north. Ages of lacustrine carbonates from existing oases and from the sand sheet fail to indicate pluvial conditions between about 60 and 30 ka. Age results and field relationships suggest that the oldest lake- and ground-water-deposited carbonates were much more extensive than those of the younger period, and that carbonate of the latest wet periods were geographically localized within depressions and buried channels.

1. Introduction

In northwestern Sudan and southwestern Egypt, today one of the driest parts of the Sahara (Kehl and Bornkamm, 1993), past periods of greater effective moisture are evident from archaeological sites associated with remnants of playa or lake deposits. An early Holocene pluvial cycle is well documented by geoarchaeological investigations at Neolithic playa sites in Egypt (Wendorf and Schild, 1980; Pachur and Braun, 1980; Kröpelin, 1987) and at sites of ancient lake beds in northern Sudan (Ritchie et al., 1985; Pachur and Röper, 1984; Gabriel and Kröpelin, 1989; Haynes et al., 1989; Pachur et al., 1990; Kröpelin, 1990). Late Pleistocene lake deposits with associated Early and Middle Paleolithic archaeological sites are best known from work in the Bir Tarfawi area of southwestern Egypt (Wendorf et al., 1987). Similar associations occur in northwestern Sudan but have not yet been studied in detail (Haynes, 1985; Haynes et al., 1989).

In 1981, side-looking radar carried aboard the space shuttle Columbia revealed ancient drainage systems hidden below the surface sands of the eastern Sahara (McCauley et al., 1982). Calcium carbonates associated with some of these buried river channels are believed to have precipitated in the upper portions of the zone of saturation during pluvial episodes, when water tables were higher. The only method available for determining the age of the deposits of the radar-revealed paleorivers,

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other than archaeological estimation, was uranium-series analyses applied to samples of groundwater-deposited carbonates. Szabo et al. (1989) did some analyses of this type and obtained results indicating four periods of widespread carbonate deposition occurred at >300, and at about 212, 141 and 45 ka. Carbonates formed at or within the uppermost part of a shallow water table or an emergent water table have been called phreatogenic, to distinguish them from pedogenic carbonates (Pachur et al., 1987). The extensive calcretes or kunkars in and around the Bir Tarfawi area most likely originated in this way and pre-date the deflation of the basins containing the lake beds and associated archaeological remains ranging from late Acheulian (⩾200 ka) to middle Paleolithic (160–70 ka) (Wendorf et al., 1989). The apparent success of the uranium-series technique in dating phreatogenic carbonates associated with the radar rivers led us to try the same technique on lacustrine carbonates and kunkars.

Previously, radiocarbon dating of late Pleistocene lacustrine carbonates and organic fractions from the eastern Sahara had suggested that pluvial conditions existed in some areas between about 50 and 25 ka. However, unlike in the western Sahara archaeological evidence has failed to support this contention; no sites of upper Paleolithic peoples have been found anywhere in the area (Wendorf and Schild, 1980). For our U-series dating, we selected some samples already dated by radiocarbon, some samples clearly connected with definable archaeological remains, and others that had no visible archaeological association but were of interest for dating what appear to be localized pond sediments in various places.

Here we describe dating results of Pleistocene and Holocene lacustrine carbonates and kunkars that represent past humid episodes in the eastern Sahara, and we compare some of the U-series ages to radiocarbon ages on lacustrine carbonates, organic fractions, and aquatic mollusk shells.

2. Study area

The Great Selima Sand Sheet, first recognized as a distinct geomorphic feature by Bagnold (1931) is a vast expanse of typically laminated medium and coarse sand centered on the border of Egypt and Sudan between the Nile Valley and the mountain of Uweinat at the western end of the border (Figs. 1 and 2a). The active surface is mostly flat but is undulatory in some areas, particularly in the southern portion, where crests separated by 0.5–1 km are as much as 10 m higher than depressions or troughs (Haynes, 1982). The recent deposits consist of a coarse sand to fine pebble lag of single-grain thickness overlying 1–5 mm of fine to medium sand that in turn may overlie a meter or more of similar alternating bimodal layers or may lie directly on the bedrock desert floor. However, the recent sand sheet in many areas overlies older sand sheet deposits and alluvium showing pedogenic alteration consisting of varying degrees of color intensification in red and yellow hues, turbation, crack formation, and induration (Haynes, 1985; Haynes et al., 1989).

Scattered limestone kunkar deposits surround Bir Tarfawi (Fig. 2b) and are widely dispersed in other locations on the sand sheet. Some of these carbonates are eroded, sandblasted remnants of dense, hard but sandy limestones, which, are now less than 1 m thick but cover areas from 10 to 1000 m^2. Basal portions of these lenticular masses in some areas are porous with amoebic or vermicular shaped rounded pores about 5 cm or less in diameter and as long as 20 cm. These carbonate lenses commonly rest on exhumed sand sheets showing phreatogenic calcification in some places and strong pedogenic alteration in others. A few lenses rest directly on bedrock sandstone or quartzite. They appear to be the result of local ponding within ancient sand sheets. From archaeological evidence all these deposits are beyond the age range of radiocarbon dating, because they contain Early Paleolithic Acheulian hand axes which, throughout Africa and Europe, are >300 ka. We collected samples for uranium-series dating from the carbonate lenses at various localities (Fig. 1, loc. *4*, *5*, *6*, *8*, *9*, and *10*).

At the margin of the sand sheet, the small basins of Bir Tarfawi and Bir Sahara East (Figs. 1 and 2a, loc. *1*, *2*, and *3*) in southern Egypt, and Selima (Fig. 1, loc. *10*) in northern Sudan contain remnants of lacustrine deposits. The small depressions

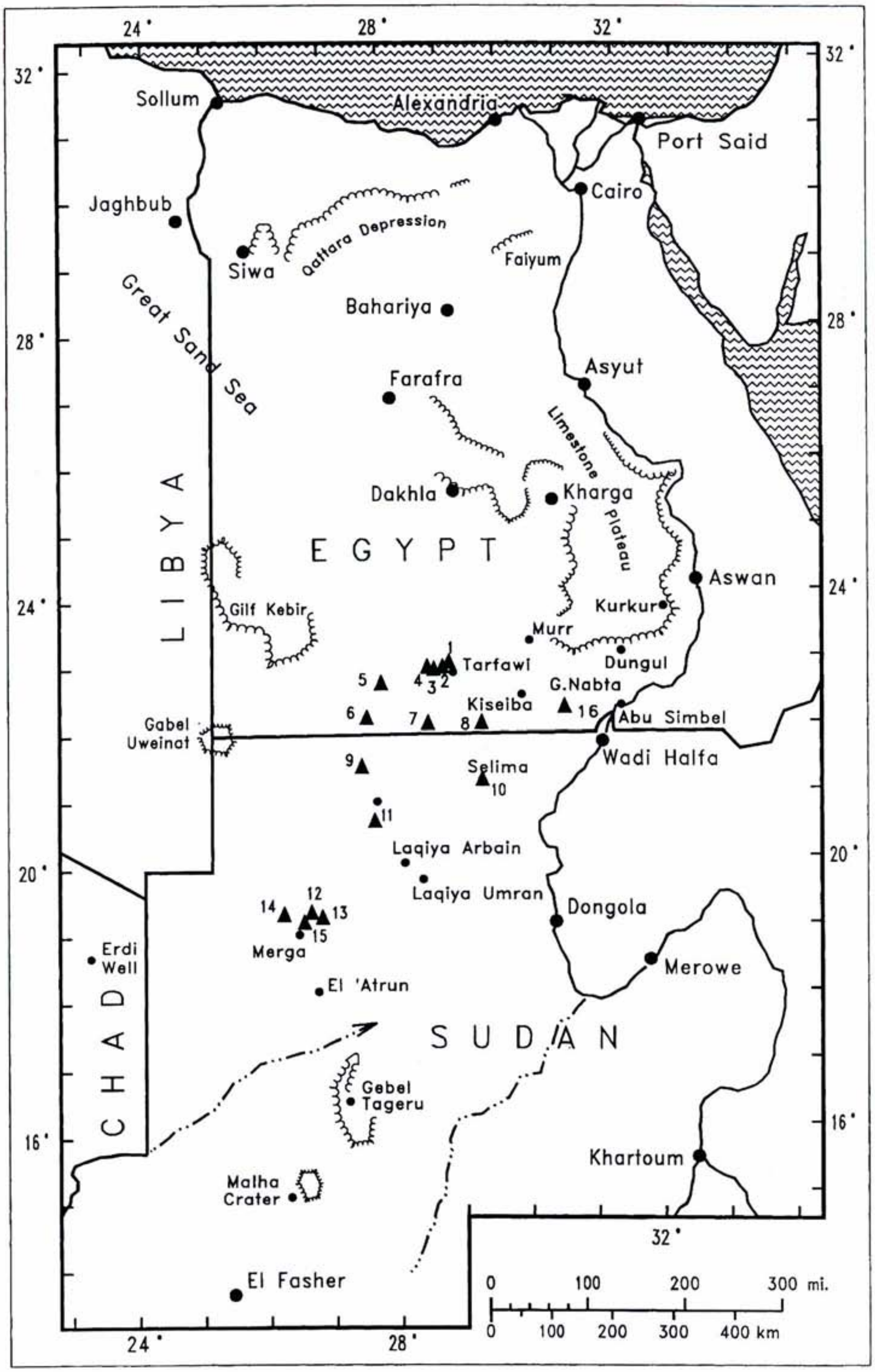

Fig. 1. Map of the eastern Sahara, Sudan and Egypt, showing carbonate sampling localities listed in Tables 1 and 2. Locality *7* is in the buried channel, Wadi Arid, revealed in 1981 by side-looking radar (SIR-A) of the space shuttle Columbia. It extends ENE to another buried valley, Wadi Safsaf, north of locality *8*, which may be an extension of Wadi Arid.


(a)
1
4
3
2
Wadi Arid
7
6
9
Wadi Muktafi
25 km

Fig. 2a. Landsat mosaic of the northern part of the Selima Sand Sheet in southern Egypt and northern Sudan (Fig. 1). Two Multispectral Scanner scenes were used for this image; the northern half was taken 1/4/86, and the southern half was taken 2/4/85. Numbers are locations of samples used for radiocarbon and U-series dating (Fig. 1), and Wadis Arid and Muktafi are buried channels detected by Shuttle Imaging Radar. b. Enlargement of part of Fig. 2a showing area of limestone kunkar surrounding Bir Tarfawi and Bir Sahara East. Spectral contrast between the limestone and quartz lag deposits distinguishes these deposits in this area.

at the Merga area, Wadi Hussein (Fig. 1, loc. *12* and *15*), Oyo (Fig. 1, loc. *14*), and Wadi Hidwa (Fig. 1, loc. *13*) also contain lake beds. We sampled these lacustrine carbonates and organic materials for U-series and/or radiocarbon dating. We also collected samples for dating from the central portion of the buried channel determined by the shuttle imaging experiment (Fig. 1, loc. *7* and *11*), and from the alluvial fan deposit at Gebel Nabta (Fig. 1, loc. *16*).

3. Methods and results

The ^{14}C activities were measured following conventional techniques and the radiocarbon dates of the various materials are presented in Table 1. For the purpose of comparison of ^{14}C and uranium-series techniques, the U-series age results (discussed below) are also listed in the table. The carbonate samples for U-series dating were fragmented and the selected denser pieces were ground to a fine powder. Some of the sandy limestone samples were cleaned by sieving, and fractions that passed through a 0.05 mm sieve were ground further. All samples were then heated for about 6 hours at 900°C to convert $CaCO_3$ to CaO. Carbonate samples with less than about 6% acid-insoluble residue fractions were dissolved using a solution of about $6N$ hydrochloric acid, and the acid-insoluble residues were separated with a centrifuge. Samples with more than about 6% acid-insoluble fractions were dissolved using a solution of about $0.1N$ nitric acid, and the acid-insoluble fractions were again separated by centrifugation. The insoluble residues were then leached with a hot solution of about $0.5N$ HCl, and the leachates were added to their respective soluble fractions.

Uranium concentrations, and uranium and thorium isotopic activity ratios were determined by isotope-dilution alpha spectrometry using a combined ^{236}U–^{229}Th spike as a yield tracer. Results of the analyses and calculated ages are shown in Table 2. All uncertainties represent one standard deviation of propagated errors. Of the 19 samples analyzed, 8 contain a negligible amount of ^{232}Th relative to ^{230}Th, therefore yielding ^{230}Th/^{232}Th activity ratios larger than about 20. The other samples (and sample 17) are corrected for extraneous ^{230}Th contents, due to acid leaching of detrital materials, using plots of isotope ratios (Szabo et al., 1989) of samples assumed to be coeval such as those presented in Fig. 3. Samples corrected by the isochron plots scatter over a large area but they are plotted together because the entire study region constitutes a similar geomorphologic and hydrogeologic regime (Heinl and Thorweihe, 1993).

Originally we used only dilute HNO_3 to dissolve the lacustrine carbonates, but we discovered that, unless we dissolved the iron-manganese oxy-hydroxide component of the acid-insoluble fractions, some of the older-generation samples (such as, 13, 24, 10, and 25) yielded inconsistent apparent uranium-series dates that are too young when compared to archaeological estimates. The younger-generation samples (1, 2, 3 and 4) were unaffected by the choice of acid for sample dissolution. Further analyses revealed that the HNO_3-insoluble components ($<3\%$ by weight) of the older samples contain up to 90% of the in situ produced ^{230}Th from its ^{234}U parent nuclide, thus causing the apparent U-series ages of the dilute HNO_3-dissolved lacustrine carbonates to be too young.

4. Radiocarbon dating

Bir Sahara East (Tarfawi West of Haynes, 1985) on the northwestern edge of the Selima Sand Sheet (Fig. 1, loc. *3*) contains a sequence of lake deposits with associated middle Paleolithic archaeological remains (Wendorf and Schild, 1980). A white marl in the lower part of the section is underlain by a black, organic, manganiferous sand which contains middle Paleolithic Mousterian artifacts. This sand appears to be an eolian deposit on the basin floor that became saturated by a rising water table. As the lake expanded the people apparently moved their camps farther upslope. Eventually calcium carbonate was precipitated in a fairly deep lake ($\geqslant 2$ m) that supported a molluscan fauna.

After desiccation of the lake and a period of eolian activity, another lake phase began. It is represented in the strata by mollusk-bearing lacus-

Table 1
Comparison of uranium-series and radiocarbon dates on carbonate samples from the eastern Sahara (all dates in yr B.P.)

Sample no.	Field no.	Locality* (no. on Fig. 1)	Material	U-series age (yr)	^{14}C age (yr)	
					(organic C)	(carbonate C)
Holocene						
1	198 Eg 86	Selima Oasis (10)	tufa (aragonite)	9000 ± 1000		
2	196 Eg 82	Selima Oasis	tufa (calcite)	5000 ± 1000	8650 ± 340 (AA-109)	6840 ± 120 (av. of 3-A-2856, 2858, and 2859)
3	199 Eg 82	Selima Oasis	tufa (aragonite)	7000 ± 1000		
4	21 Eg 82§	Wadi Hidwa (13)	marl (aragonite)	18,000 ± 5000	7220 ± 190 (A-3243)	
Pleistocene						
5	52 Eg 79B	Selima Oasis (10)	limestone		21,770 ± 1460 (AA-101)	27,010 ± 1400 (A-2100)
6	50 Eg 80	Selima Oasis	limestone	155,000 ± 4000		
7	42 Eg 79	Selima Oasis	limestone		25,310 ± 950 (A-2098)	
8	56 Eg 79	Selima Oasis	limestone			21,580 ± 2060 (A-2106)
9	144B Eg 85†	Wadi Arid (7)	limestone	78,000 ± 4,000		40,100 ± 2200 (AA-1045)
10	115 Eg 80	Wadi Hussein (15) (west)	limestone	226,000 ± 11,000		
11	12a Eg 82	Wadi Hussein (12) (east), Bakia Playa	mudstone		21,600 ± 600 (A-3256)	
12	14 Eg 82‡	Wadi Hussein	calcite concretions	71,000 ± 4000		
13	126 Eg 82	Oyo depression (14)	dolomite	287,000 ± 40,000		
14	29 Eg 74	Bir Tarfawi (north) (1)	organic silt		21,950 ± 490 (SMU-214)	
15	32 Eg 74	Bir Tarfawi	organic silt			26,530 ± 470 (SMU-205)
16	? VH 73	Bir Tarfawi	snail shell			44,190 ± 1380 (SMU-177)
17	172 Eg 79a	Bir Sahara East (3)	marl (calcite)	155,000 ± 4000	> 25,000	(A-2190)
18	29 VH 73	Bir Sahara East	marl (calcite)			34,600 ± 970 (SMU-215)
19	172 Eg 79	Bir Sahara East	snail shell			> 40,000 (A-2157)
20	11 VH 73	Bir Sahara East	snail shell			> 44,000 (SMU-79)
21	27 VH 73#	Bir Sahara East	organic sand		37,740 ± 1980 (SMU-95) 28,000 ± 1250 (SMU-108)	
22	30 Eg 74	Bir Sahara East	organic sand		33,080 ± 1120 (SMU-218)	
23	234 Eg 84	Debis West (8)	limestone	138,000 ± 4000		
24	183 Eg 79	Bir Tarfawi South (2)	limestone	> 350,000		36,200 ± 4600 (A-2156)
25	73 Eg 86	Bir Tarfawi N. (1)	limestone	$233{,}000 \pm ^{17000}_{14000}$		
26	11 Eg 88	Selima Sandsheet (6)	limestone	134,000 ± 4000		

Table 1 (*continued*)

Sample no.	Field no.	Locality* (no. on Fig. 1)	Material	U-series age (yr)	^{14}C age (yr)	
					(organic C)	(carbonate C)
27	9 Eg 88	Selima Sandsheet (4)	limestone	>350,000		
28	14 Eg 88	Selima Sandsheet (9)	sandy limestone	155,000 ± 4000		
29	203 Eg 83	Selima Sandsheet (11)	sandy limestone	78,000 ± 4000		
30	56 Eg 89	W. of Bir Sahara (5)	sandy limestone	277,000 ± 22,000		
31	GN Eg 77	Gebel Nabta (16)	limestone	$281{,}000\pm^{28\,000}_{22\,000}$		

*Coordinates of localities shown on Fig. 1: (1) 22°59°.1′N; 28°53.2′E, (2) 22°54.7′N; 28°51′E, (3) 22°55′N; 28°46′E, (4) 22°57.2′N; 28°31.1′E, (5) 22°45.9N; 27°44′E, (6) 22°14.5′N; 27°31.4′E, (7) 22°11′N; 28°35′E, (8) 22°09′N; 29°27′E, (9) 21°35.8′N; 27°27.7′E, (10) 21°22.2′N; 29°18.5′E, (11) 20°42′N; 27°36′E, (12) 19°25′N; 26°30′E, (13) 19°19′N; 26°40′E, (14) 19°16′N; 26°10′E, (15) 19°16′N; 26°22′E, (16) 22°32.6′N; 30°38.4′E.

[§] Marl overlies black sand with charcoal dated 7220 ± 190 a (A-3243).

[†] Racemization age estimate is >100 ka (G.H. Miller, pers. comm.). This and ^{14}C age are on *Corbicula* shells correlated with this limestone and middle Paleolithic artifacts.

[‡] Carbonate probably exchanged with Holocene lake that inundated the Pleistocene lake beds between 10,000 and 6000 a.

[#] Humate fraction dated 37,740 ± 1980 a (SMU-95). Both 27 VH 73 (sample 21) and 30 Eg 74 (sample 22) underlie the marl.

trine silts suggesting change from initial deep water ($\geqslant 2$ m) to shallow (<1 m) conditions and eventual desiccation (Gautier, 1980). Radiocarbon dating of the black sand underlying the white marl produced ages of 33,080 ± 1120 a (Table 1, sample 22) on bulk residue and 37,740 ± 1980 a and 28,000 ± 1250 a (Table 1, sample 21) on humate extracts. The overlying marl produced a bulk carbonate age of 34,600 ± 970 a (Table 1, sample 18), and brackish-water tolerant snail shells (*Melanoides tuberculata*) from the uppermost lake bed produced carbonate ages of >40,000 a (Table 1, sample 19) and >44,000 a (Table 1, sample 20).

The differences in ages between the black layer and the carbonates were interpreted as being due to two counter acting processes. The "hard-water effect" where the H_2CO_3 is deficient in ^{14}C relative to atmospheric CO_2 (Deevey et al., 1954) makes the apparent radiocarbon age of the precipitated carbonate (marl or chalk) too old. On the other hand, chemical exchange between atmospheric CO_2 and CO_3^{2-} in the very porous chalk can make the apparent radiocarbon age too young (Rubin et al., 1963), possibly enough to more than compensate for the hard-water effect. The shell carbonate, not being so porous and not recrystallized, is less subject to atmospheric exchange than the marl, but could be depleted in ^{14}C due to HCO_3^- in the lake water coming from dissolved limestone or ancient soil gas CO_2 in vadose water. This interpretation was supported by testing shells of the same species known to be of Graeco-Roman age and finding apparent ages of 18,500 ± 170 a (SMU-383; Haas and Haynes, 1980) due to the uptake of ancient carbonates in artesian ground water.

Similar results were obtained at Bir Tarfawi, a much larger basin 11 km to the east (Fig. 1, loc. *1* and *2*), where the organic fraction of a calcareous, organic, lacustrine silt gave an age of 21,950 ± 490 a (Table 1, sample 14) compared to a carbonate age of 26,530 ± 470 a (Table 1, sample 15) and a snail shell (*M. tuberculata*) carbonate age of 44,190 ± 1380 a (Table 1, sample 16).

Selima, an uninhabited oasis in northern Sudan 200 km southeast of Bir Tarfawi (Fig. 1, loc. *10*), contains limestone-capped erosional remnants of late Pleistocene lacustrine beds against which lie Holocene lake beds and shoreline tufas (Haynes et al., 1989). The Pleistocene limestones provided organic residue ages of 25,310 ± 950 a (Table 1, sample 7) and 21,770 ± 1460 a (Table 1, sample 5), and a carbonate age on the latter of 27,010 ± 1400 a (Table 1, sample 5). A sample of the tufa gave Holocene radiocarbon dates of 8650 ± 340 a on organic residue and 6840 ± 120 a on carbonate (Table 1, sample 1).

Table 2
Analytical data and calculated uranium-series ages of carbonates from eastern Sahara

Sample no.	Field no.	Loc. no.	Locality	Residue (%)	Uranium (ppm)	Activity ratios			Calculated	Corrected
						$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	age[1] (ka)	age[2] (ka)
25	73Eg86	1	Bir Tarfawi N.	<0.1	15.3±0.2	0.771±0.007	191±25	0.814±0.012	233^{+17}_{-14}	n.a.
24	183Eg79	2	Bir Tarfawi S.	<0.1	12.7±0.2	0.926±0.008	154±14	0.945±0.014	>350	n.a.
17	172Eg79a	3	Bir Sahara E.	3.1	12.5±0.2	0.780±0.007	23±1	0.728±0.013	160±7	155±4
27	9Eg88	4	Sel. Sand Sheet	6.4	6.14±0.06	0.941±0.005	28±1	0.992±0.011	>350	n.a.
30	56Eg89	5	W. Bir Sahara	34	2.95±0.04	0.988±0.010	15±1	0.932±0.014	297^{+28}_{-22}	277±22
26	11Eg88	6	Sel. Sand Sheet	0.9	2.21±0.03	0.871±0.007	35±2	0.691±0.009	134±4	n.a.
9	144BEg85	7	Wadi Arid	29	0.980±0.012	1.066±0.010	1.98±0.04	0.658±0.012	115±4	78±4
23	234Eg84	8	Debis West	0.3	6.62±0.07	0.777±0.006	87±4	0.683±0.008	138±4	n.a.
28	14Eg88	9	Sel. Sand Sheet	13	1.34±0.03	1.075±0.021	3.87±0.10	0.804±0.018	171±10	155±4
1	198Eg86	10	Selima Oasis	0.1	4.15±0.04	0.688±0.004	18±2	0.084±0.003	9.5±0.2	9±1
3	199Eg82	10	Selima Oasis	<0.1	4.03±0.05	0.702±0.007	14±1	0.065±0.002	7.4±0.2	7±1
2	196Eg82	10	Selima Oasis	1.4	5.57±0.06	0.695±0.005	4.6±0.2	0.051±0.001	5.7±0.2	5±1
6	50Eg80	10	Selima Oasis	4.2	0.89±0.01	0.861±0.005	12±1	0.750±0.009	162±5	155±4
31	GNEg77	16	Gebel Nabta	<0.1	0.932±0.015	0.943±0.016	112±16	0.908±0.016	281^{+28}_{-22}	n.a.
29	203Eg83	11	Sel. Sand Sheet	31	1.755±0.011	1.060±0.015	2.71±0.06	0.604±0.011	99±3	78±4
12	14Eg82	12	Wadi Hussein	0.4	1.10±0.01	1.398±0.012	7.31±0.19	0.525±0.007	77±2	71±4
4	21Eg82	13	Wadi Hidwa	3.5	4.39±0.05	1.133±0.008	2.47±0.03	0.201±0.003	24±1	18±5
13	126Eg82	14	Oyo Depression	<0.1	2.37±0.03	1.120±0.011	7.26±0.13	0.989±0.015	337^{+36}_{-27}	287±40
10	115Eg80	15	Wadi Hussein	1.0	6.89±0.09	1.152±0.009	40±2	0.905±0.013	226±11	n.a.

Errors of activity ratios and U-concentrations from α-spectrometry represent 1 standard deviation of propagated error. Ground water collected from well GPC79-P1, near Bir Tarfawi, at 11.6 m has an U-concentration of 44 ppb and $^{234}U/^{238}U$ activity ratio of 0.75±0.06; ground water collected from GPC Selima West well, about 100 km west of Selima, at ~250 m has U concentration of 0.24 ppb and $^{234}U/^{238}U$ activity ratio of 1.20±0.15.

[1] ^{230}Th age, calculated using half-lifes of ^{230}Th and ^{234}U of 75,200 and 244,000 yr, respectively.

[2] Calculated age is corrected using plots of activity ratios. See example shown in Fig. 3.

n.a. = not applicable.

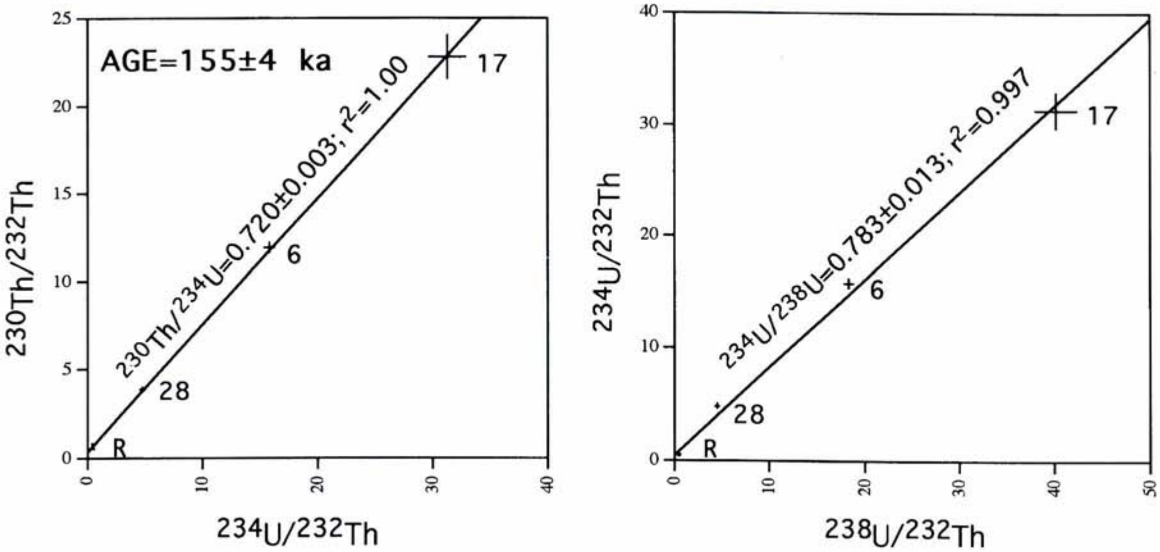

Fig. 3. Chronograph showing plots of activity ratios used to correct for acid-leaching effect of U-series dated authigenic carbonates. The example is a plot for samples 6, 17, and 28 (data from Table 1). Also plotted are the activity ratios of acid-insoluble residue (*R*) samples Sch-1R, -5R, -6R and -18R from Wadi Safsaf and Wadi Arid localities (analytical data from Table 1 of Szabo et al., 1989). Error bars indicate 1 standard deviation analytical uncertainties. Lines were obtained by least-squares fitting. The slopes of the lines are the detritus-corrected ^{230}Th/^{234}U (A) and ^{234}U/^{238}U (B) activity ratios. From these values, the average U-series group age of 155±4 ka is calculated using half-lives of ^{230}Th and ^{234}U of 75,200 and 244,000 yr, respectively.

Wadi Hussein (Fig. 1, loc. *12* and *15*), approximately 370 km southwest of Selima, is another depression containing Pleistocene and Holocene lake beds. Organic residue from a lacustrine mudstone provided an age of 21,600±600 a (Table 1, sample 11).

These 17 radiocarbon apparent ages (Table 1), some on organic fractions and others on carbonates, represent lacustrine deposits in four basins scattered across 500 km of the hyperarid core of the eastern Sahara. Although most of these are minimum ages, together, they provide evidence that pluvial conditions and/or high water tables existed at various times during the late Pleistocene and the early Holocene. These data are in agreement with the findings of other researchers based upon radiocarbon dating of lacustrine carbonates and ground water (Petit-Maire, 1986; Fontes et al., 1985; Pachur et al., 1987).

5. Uranium-series dating

We calculated individual U-series ages with the assumption that the samples were homogeneous, authigenic deposits, they incorporated uranium free of thorium at the time of formation, and they remained in a closed system with respect to uranium and ^{230}Th through time. The uranium concentrations vary between about 1 and 7 ppm except for samples 17, 24 and 25 which have U concentrations between about 12 and 15 ppm (Table 2). In the Holocene samples (1, 2, 3 and 4), the U concentrations vary between about 4 and 6 ppm. Fontes et al. (1992) reported that either gain or loss of U may occur in lacustrine samples due to changing redox conditions. Uranium gain causes the calculated U-series date to be younger and U loss causes the date to be older than the true age.

We have two pairs of detritus-free samples having similar U-series ages but factor of two different U concentrations which allow us to test the possibility of secondary U gain. The about 145 ka old samples 23 and 17 have U values of about 6.6 ppm (near Holocene value) and 12.5 ppm (twice Holocene value), respectively. The >350 ka old samples 27 and 24 have U values of about 6.1 ppm (near Holocene value) and 12.7 ppm (twice Holocene value), respectively. The average $^{234}U/^{238}U$ activity ratio of the Holocene samples at Selima is 0.70 ± 0.01 and the $^{234}U/^{238}U$ in modern ground water near Bir Tarfawi is 0.75 ± 0.06 (see note in Table 2). If samples 17 and 24 experienced recent U uptake, then their measured $^{234}U/^{238}U$ values should be significantly different. In fact, the $^{234}U/^{238}U$ activity ratios in the two pairs of samples discussed above are identical within limits of their experimental errors indicating that the process of U gain did not occur in spite of the large differences in U concentrations of these samples.

The possibility of U loss affecting the dated lacustrine samples is difficult to asses. If the concentration of 4–6 ppm is a reasonable estimate for the modern lacustrine samples at the study area, then samples 6, 9, 12, 13, 26, 28, 29, 30, and 31 having U concentrations between about 1 and 3 ppm may have experienced up to 80% recent loss of U. If such magnitude of recent U loss had occurred, then we would expect a random scattering of the apparent U-series ages from the younger to the older age range. On the contrary, we have groupings of ages averaging about 80, 134–155, and 280 ka suggesting that recent U loss may not be a significant process affecting the accuracy of the calculated ages. In addition, all of the older samples from localities of southern Egypt and northern Sudan have $^{234}U/^{238}U$ activity ratios greater than the about 0.70 value measured in the Holocene lacustrine samples at Selima (Table 2).

6. Discussion

The comparison of U-series ages with radiocarbon apparent dates in Table 1 shows approximate agreement between the two independent techniques only on Holocene tufas from Selima. The differences can be attributed to errors in the radiocarbon dates caused by the hard-water effect on the bicarbonate ion and on algal remains, which make up most of the organic fractions. The discrepancy between radiocarbon and U-series ages becomes much greater with the lacustrine carbonates (Table 1). The differences of an order or more of magnitude between the radiocarbon and U-series ages are most readily explained as the result of an early Holocene exchange of carbonate ions in the lake beds with younger carbonate ions from ground water and perhaps from soil CO_2 in vadose water (Rubin et al., 1963).

This explanation will not work for the organic fractions, which we believe must have been contaminated by younger organic matter perhaps during the Holocene pluvial period. There is archaeological evidence that Bir Sahara East may have held salt marshes or sabkhas at this time. Several open-bottom ceramic pots having separate, perforated-disc bottoms found at Bir Sahara East (Wendorf and Schild, 1980) are probably salt molds. These artifacts imply that the area was a source of brine, which typically hosts algae and other organic matter. Upon decay to mobile humic and/or fulvic acids these could contaminate older organic sediments. It is more realistic to explain the discrepancies in this way than to surmise that the U-series ages are too old. The accuracy of the older U-series ages could be off by more than a standard deviation but hardly by an order of magnitude.

Szabo et al. (1989) reported a U-series age of 15 ± 2 ka on a rootcast in Bir Tarfawi, and we obtained a U-series age of 18 ± 5 ka on marl in Wadi Hidwa (Table 2, sample 4). The former U-series date is less likely to represent pluvial conditions than hyperarid condition in which deflation exposes the water table. This model of phreatogenic carbonate precipitation could also apply to earlier episodes of kunkar deposition, but the limestones, marls, and other lacustrine beds clearly reflect pluvial conditions. The Wadi Hidwa carbonate is lacustrine and can be correlated to Neolithic archaeology, so, in this case, the radiocarbon date (7220 ± 190 a, Table 1) is the more reliable.

In this study, three samples dated by radiocarbon as belonging to a moist period estimated at about 45 ka were analyzed using uranium-series. The new U-series results suggest significantly older ages for these samples, which are all from the northern part of the Selima Sand Sheet (Tables 1 and 2, samples 9, 17, and 24). Earlier archaeological research from Bir Sahara East and Bir Tarfawi did not preclude the about 45-ka interpretation, because artifacts attributed to the Aterian technocomplex associated with the upper lacustrine deposits in both basins had been dated elsewhere as of similar age (Close, 1980). However, Wendorf and Schild (1980) considered the Aterian at Bir Sahara East to be older than 44 ka, on the basis that the oldest snail shell date was a minimum value. They assumed that the radiocarbon content of the lake water hosting the *M. turberculata* was in equilibrium with atmospheric radiocarbon. However, Haas and Haynes (1980) offered an alternative interpretation that the snail carbonate dates could be too old by about 18,000 yr, because a significant hard-water effect in spring-fed lakes appears to be the rule rather than the exception. Our U-series ages support the interpretation of Wendorf and Schild (1980).

Uranium-series dating of the limestone lenses suggests a potential relationship with the now-buried channels detected by the Shuttle Imaging Radar A experiment. Two samples from the central portions of the buried channels have detritus-corrected age of about 78 ka (Table 2, samples 9 and 29), whereas samples from smaller limestone pans and from the extensive kunkar deposits surrounding Bir Tarfawi exhibit a wider range in ages. The highly eroded limestone fragments surrounding Bir Tarfawi and Bir Sahara East (Fig. 2b) are either >350 ka or within the oldest ^{230}Th-dated pluvial period (233 ka for Table 2, sample 25 of Bir Tarfawi North and 277 ka for Table 2, sample 30 west of Bir Sahara). Samples from interfluves and from other regions that lack channels show ages that belong to older moist periods. Although more dates are needed to confirm these relationships, these data suggest (1) that the oldest lake- and ground-water-deposited carbonates were much more extensive than those of the younger periods, and (2) that carbonates of the latest wet periods either were geographically localized within depressions or in shallow ground-water systems confined to the buried channels.

The prevailing hypothesis is that the pluvial episodes in arid North Africa correspond to the interglacial periods of high-latitude northern hemisphere areas, and the glacial conditions in those areas are contemporaneous with hyperarid condition in the Sahara. This view is supported by radiocarbon dates of various lake-related materials in North Africa (Fontes et al., 1985; Ritchie et al., 1985; Petit-Maire, 1986; Ritchie and Haynes, 1987; Brookes, 1989; Haynes et al., 1989; Gasse et al., 1990), evidence of wind-transported continental materials in eastern Atlantic sediments (Pokras and Mix, 1985), and consideration of oxygen isotopes in foraminifera from Red Sea and Gulf of Aden sediments (Deuser et al., 1976). By relating oxygen-isotope chronology to analyses of pollen and dinocysts in eastern Atlantic sediment, Lézine and Casanova (1991) reported on the timing of continental humid intervals. In North Africa, the major humid intervals occurred at 140–118 and 12–2 ka and they also found evidence for increased humidity at about 103, 80, and 47 ka. Uranium-series dating of shells from lacustrine deposits in northern Sahara indicates that one or probably two humid episodes occurred between about 150 and 75 ka (Gaven et al., 1981; Causse et al., 1988; Causse et al., 1989; Fontes and Gasse, 1991).

The U-series dating results (Table 1) are grouped by sampling regions in Fig. 4. Results from the Merga region, limestone pans, Selima, southern Egypt (loc. 5, 7, and 8), and Gebel Nabta (Fig. 4, columns *A–E*) indicate five episodes of paleolake formation during the last 350 kyr. The lacustrine sediments in Bir Tarfawi and Bir Sahara East have been studied in detail (Wendorf et al., 1989; Kowalski et al., 1989; Miller et al., 1991). The lacustrine episode correlated with oxygen isotope substage 5e is represented in Tarfawi basin by three separate lake episodes, grey lakes 1–3 (Wendorf et al., 1987). Published results pertaining to these basins, displayed in column F, include U-series and amino-acid dates (Szabo et al., 1989; Miller et al., 1991) and U-series ages from this study. Published U-series group ages of carbonates from Wadi Arid and Wadi Safsaf (Szabo et al., 1989) are presented in column G. Also shown in the same column is the range of radiocarbon ages (10–4 ka) on various Holocene lake-related materials (Ritchie et al., 1985; Ritchie and Haynes, 1987; Haynes et al., 1989; and this study).

The combined dating results presented in Fig. 4 indicate five paleolake episodes or increased-

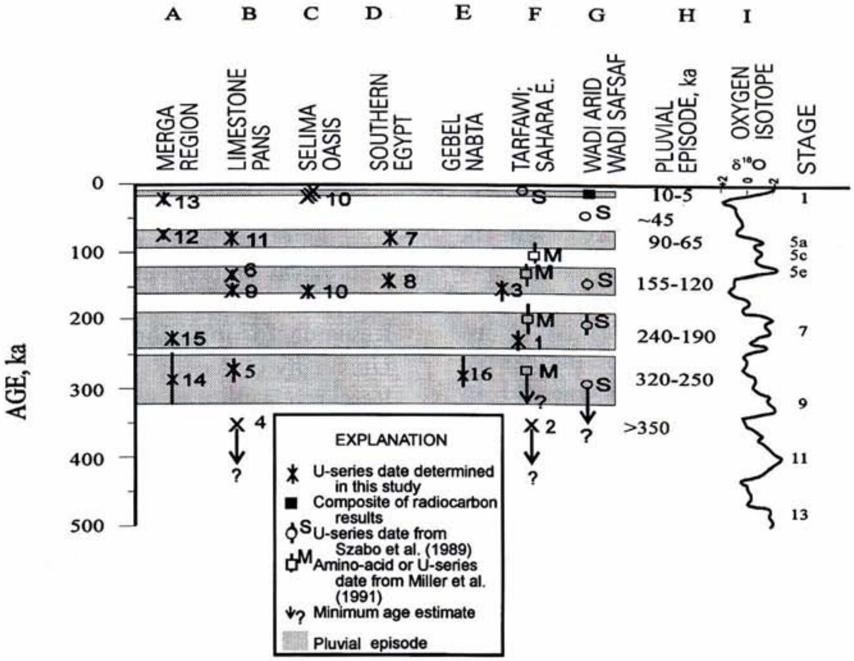

Fig. 4. Uranium-series ages grouped by sampling regions in columns A–G (Fig. 1 and Table 2). Errors shown (vertical bars) are propagated one standard deviation. The solid square in column G is a composite of radiocarbon results. Letter *S* next to sample symbol represents U-series ages from Szabo et al. (1989). Letter *M* next to sample symbol represents amino-acid and U-series dates after Miller et al. (1991). A line with a question mark indicates minimum age estimate. Age estimates for pluvial episodes are shown in column H and the stippled horizontal areas are graphical representation of their duration. The marine oxygen-isotope record shown in column I is from Imbrie et al. (1984). High sea levels and warm global temperatures are suggested by the negative excursions of $\delta^{18}O$, and low sea levels and cold temperatures are indicated by the positive $\delta^{18}O$ excursions. The interglacial stages are shown on the right side of the $\delta^{18}O$ curve.

humidity episodes occurred at about 320–250, 240–190, 155–120, 90–65, and 10–5 ka. Four of these episodes may be correlated with the major interglacial marine oxygen isotope stages 9, 7, 5e, and 1; the episode dated at 90–65 ka may be correlated with substage 5c or 5a (Fig. 4, column I). Two samples from Bir Tarfawi South and Selima Sand Sheet localities (samples 24 and 27, Table 2) yielded minimum age estimate of >350 ka. These samples may have been deposited during an early pluvial episode or during marine oxygen isotope stage ⩾11.

Pluvial lake sediments at Bir Tarfawi yielded faunal assemblages indicating much increased precipitation during the paleolake episodes, probably due to the northward displacement of the monsoon belt during interglacial times (Kowalski et al., 1989). Fluctuation of local precipitation may have been enhanced by the prevaling surface temperature, albedo, and soil moisture of the land (Gasse and Fontes, 1992). The early human occupations are also synchronous with the increase of wetness, the rise of the water table, and the formation of lakes. Archaeological evidence suggests three major prehistoric human occupations in the eastern Sahara. Acheulian people lived near lakes and springs during early pluvials that may be correlated with marine oxygen-isotope stages ⩾11 and 9. Mousterian–Aterian occupation was during the middle Paleolithic, correlating with marine oxygen isotope stages 7, 5e, and 5c or 5a.

The area was probably unoccupied by humans from about 65,000 years ago until the Holocene. The lack of archaeological artifacts indicates hyperarid conditions between the middle Paleolithic and Neolithic occupations of the eastern Sahara.

This interpretation is supported by the occurrences of dune sands instead of lacustrine sediments and phreatogenic carbonates, and raises doubts about the existence of paleolakes within the time span equivalent to marine isotope stage 3. Because the eastern Sahara is one of the driest part of the Sahara, probably the driest region on earth (Kehl and Bornkamm, 1993), it is possible that the reported evidences of more mesic conditions during this period elsewhere in North Africa, (e.g., Lake Chad and the western Sahara), are valid. Evidence of Neolithic occupation of the eastern Sahara about 10–5 ka is well documented by concentrations of Neolithic artifacts observed around lakes and springs and by numerous reliable radiocarbon dates on wood charcoal (Wendorf and Schild, 1980).

7. Conclusions

We consider the U-series ages of lacustrine carbonates to be reasonable estimates of the true ages. Some of our samples (Table 2, samples 4, 9, 6, 28, and 29) required age correction for detrital contamination but they appear to yield consistent results. Expect for the ~45 ka episode, our data are compatible with the uranium-series ages obtained previously for the radar-revealed paleoriver carbonate deposits (Szabo et al., 1989) and with the results of the Combined Prehistoric Expedition in 1985–1987 which dated the middle Paleolithic deposits at Bir Tarfawi and Bir Sahara East (Miller et al., 1991). The U-series results of samples previously dated as belonging to the ~45-ka pluvial period suggests that the apparent radiocarbon ages of these samples, some at the limit of the technique, were much too young. It appears that lacustrine carbonates older than Holocene may be contaminated; thus, samples with apparent radiocarbon ages older than about 15 ka should be tested by uranium-series or other relative dating methods.

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