Holocene pollen spectra from Oyo, northwestern Sudan: problems of interpretation in a hyperarid environment

J.C. Ritchie

(Scarborough College, University of Toronto, Scarborough, Ontario, Canada M1C 1A4)

Manuscript received 8 April 1993; revised manuscript accepted 1 July 1993

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PAPER

Abstract: The Oyo site is in the hyperarid core of the eastern Sahara. A 3.4 m core of lake sediment yielded a continuous pollen record for the period 9 to 4.5 ka BP. The lower, regularly-laminated carbonate sediments (9–6 ka) show a pollen assemblage with the tropical taxa dominated by plants of Sudanian and Sahelian affinity, and the local taxa dominated by grass and *Typha*. The upper sediments (6–4.5 ka), grading from laminated carbonates to coarsely bedded and massive layers with aeolian sands, have reduced frequencies of Sudanian pollen taxa, and increases in Saharan types and sedge-dominated local pollen spectra. A possible vegetational reconstruction is a mosaic of savanna woodlands associated with groundwater-supported lakes and marshes between 9 and 6 ka BP, and sparser cover of steppe and semidesert communities between 6 and 4.5 ka BP as water tables dropped and hyperarid conditions were restored.

Key words: pollen analysis, lake core, desert, savanna, palaeoclimate, groundwater, Sahara, Holocene.

Introduction

Hyperarid regions pose particular problems in attempts to reconstruct Holocene vegetation and associated environments from fossiliferous sediments. The primary limitations are: a paucity of sites due to removal by deflation; the desiccation of lacustrine and alluvial deposits with the resultant poor preservation of biological remains; and the relative impotence of pollen analysis applied to hyperarid regions (elaborated below). The eastern Sahara is such an area, having a mean annual precipitation of <5 mm (Leroux, 1983) and a predominantly-deflationary landscape.

None the less, some progress has been made in recent decades, as suitable sites have been found throughout the Saharan region, and particularly in the eastern sector (Haynes, Mehringer and Zaghloul, 1979; Haynes, 1987; Pachur and Hoelzmann, 1991; and others referred to later in the Discussion). One particularly productive site is Oyo in northwestern Sudan (Figure 1). A note was published on our preliminary findings from Oyo (Ritchie, Eyles and Haynes, 1985), and Haynes (1987) provides an account of the radiocarbon chronology and hydrological characteristics of the site; the present paper reports on a subsequent detailed analysis of the Holocene pollen record from the site.

The following description of the Oyo site is based largely on field observations, and on the report by Haynes (1989), in which the interested reader can find an account of the history of discovery of this 'Lost' oasis. Oyo is a deflationary depression, roughly triangular in form, with sides of 15 km length, located at 19° 17.7′N, 26° 27.6′E (based on Magnavox MX 6102 satellite navigation equipment). Two evaporite basins occur within the floor of the basin, one of which contains the laminated lacustrine sediments that provided the material for the present analysis. The lacustrine sedimentary units straddle the modern groundwater table, and are overlain by aeolian sand with surface accumulations of trona – a crystalline evaporite of hydrated sodium carbonate. Fragmentary capping Pleistocene limestones occur as mesas in the basins, 40–60 m above the floor, and the area is underlain by Cretaceous sandstone.

Oyo lies at the southern fringe of the eastern hyperarid core of the Sahara (Leroux, 1983), an essentially rainless region extending from latitude 20° in Sudan to 28° in Egypt (Figure 1). Rainfall increases southwards over a distance of 900 km, from <5 mm at the southern boundary of Egypt to almost 300 mm yr^{-1} at El Fasher, according to the map of isohyets (Leroux, 1983). It should be noted that interannual variability of >100 km in the position of the southern boundary of the Sahara has been reported, based on interpretation of satellite imagery for the period 1980–90 (Tucker *et al.*, 1991). The measured changes in the Sahara–Sahel ecotone for the decade correlate positively with changes in precipitation,

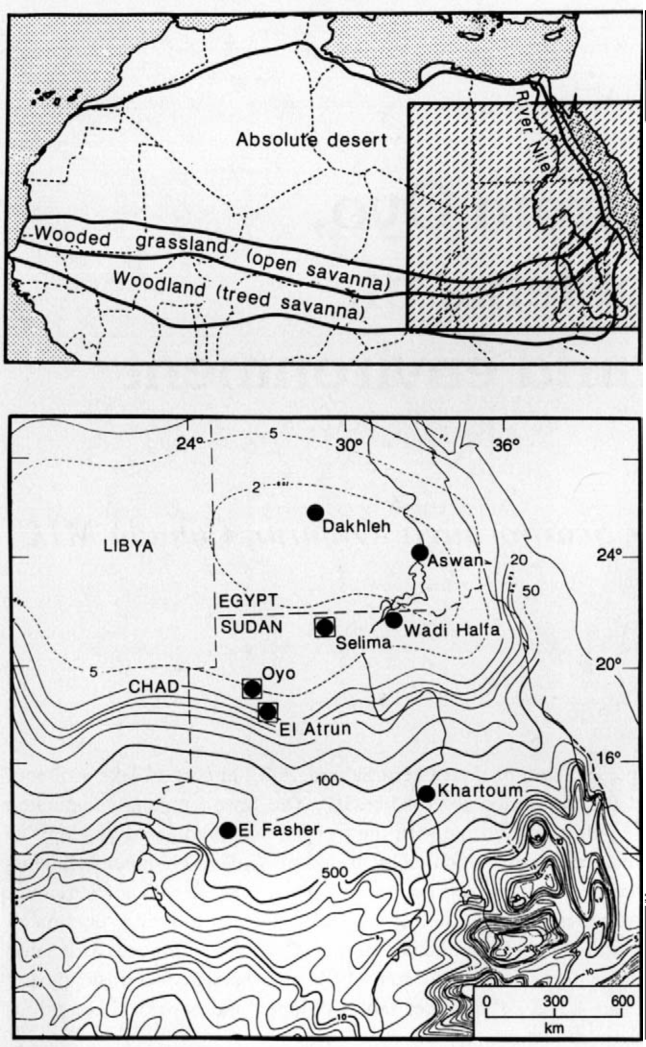

Figure 1 An outline map of north Africa showing the location of the study area (hatched) and the approximate limits of vegetational regions (above), and, (below) the location of study sites (enclosed dots), familiar geographical locations, and isohyets in mm (after Leroux, 1983).

Table 1 Radiocarbon age measurements, Oyo

Depth (cm)	^{14}C age	Lab. No.
170–180	4590 ± 140	A-2820
	4920 ± 200	SMU-1232
270–280	5880 ± 80	SMU-1223
310–320	6100 ± 80	SMU-1231
330–340	6700 ± 130	AA-1020
345–355	6490 ± 220	AA-1018
	6770 ± 130	AA-1019
365–375	6180 ± 110	AA-1017
	6220 ± 150	AA-1016
410–420	7450 ± 90	AA-1015
455–465	7790 ± 280	SMU-1230
	8490 ± 170	AA-253
485–495	8720 ± 170	A-2951
	8900 ± 120	A-2826

Notes: AA – Arizona National Science Foundation Regional Facility for Accelerator Mass Spectrometry.
A – University of Arizona Radiocarbon Dating Laboratory.
SMU – Southern Methodist University, Texas.

implying that maps of climatic and vegetational boundaries for the Sahara–Sahel transition should be viewed as broad generalizations.

When members of our project visited Oyo, between 1980 and 1986, living vegetation was absent, but moribund rhizomes and shoots of *Desmostachya bipinnata* and buried plants of date palm (*Phoenix dactylifera*) were noted in the dunes adjacent to the well site.

Material and methods

The primary set of samples was recovered in 1983 by excavating a pit to expose over 4 m of sediment, consisting of loose sand with trona, the sand becoming coarsely laminated at depth, overlying 2.8 m of carbonate limnic sediments. The limnic muds were sampled in overlapping, 1 m long, 5 × 5 cm trays, providing undisturbed, continuous samples of the deposit. Sampling by this method was impossible below 4.3 m because of the groundwater table. The lower unsampled unit of the deposit, to a depth from the surface of 5.32 m, was recovered during our 1986 expedition using a modified Livingstone stationary piston sampler.

Three sedimentary units have been distinguished as follows: Zone I from 5.32 to 3.30 m depth, consisting of annually laminated carbonate sediments, deposited in a relatively deep, chemically stratified, meromictic lake, with distinct dark brown bands of algal sapropel and a basal layer of compressed charcoal; Zone II from 3.30 to 2.90 m depth, a transitional unit with deformed structures in calcite carbonates; and Zone III, above 2.90 m depth, consisting of increasingly-deformed carbonate muds becoming coarser upwards into crudely-bedded aeolian sands, interpretable as a response to dropping water levels culminating in the extinction of palaeolake Oyo. Further descriptions of the sediments can be found in our earlier report (Ritchie *et al.*, 1985), and detailed later analysis of physical characteristics will be the subject of a future paper.

Eleven samples of organic sediment from different levels in the sediments were analysed for radiocarbon dating; the results have already been reported and discussed by Haynes (1987), but they are included here in tabular form for reference (Table 1). Fresh samples of 1 or 2 ml were taken at 5 to 8 cm intervals along the cores and processed for pollen analysis by standard methods described in our reports on other sites from the Sahara (Ritchie, 1987; Haynes *et al.*, 1989). Pollen sums ranged from 245 to 4678, for 53 levels, yielding 57 identifiable taxa; pollen preservation was excellent, with <1% unidentifiable taxa due to degraded grains, and <0.1% unassigned to a taxonomic category. The unusually high degree of preservation of pollen from these sediments, and those from El Atrun (Ritchie, 1987) and Selima (Haynes *et al.*, 1989), is probably the result of the original depositional environment of a meromictic lake with primarily autochthonous sediment; these lacustrine sediments probably remained continuously moist, within or close to the groundwater table, throughout the Holocene.

The pollen record

The pollen record is presented as a percentage diagram (Figure 2) showing the 19 taxa with continuous, or almost continuous occurrences, the percentages of the three general phytogeographical groups, and a tabular summary (Table 2) of the other 40 taxa that were recorded infrequently, in some cases only once. I have followed the authorities Gillet (1968), Lebrun (1976, 1977, 1979), Quézel (1969), Sahni (1968), White (1983) and Wickens (1976) in assigning taxa to the phytogeographical groups, as follows: Saharo-Mediterranean – *Artemisia*, *Ephedra*, *Erica arborea*; *Aerva*, *Commicarpus*,

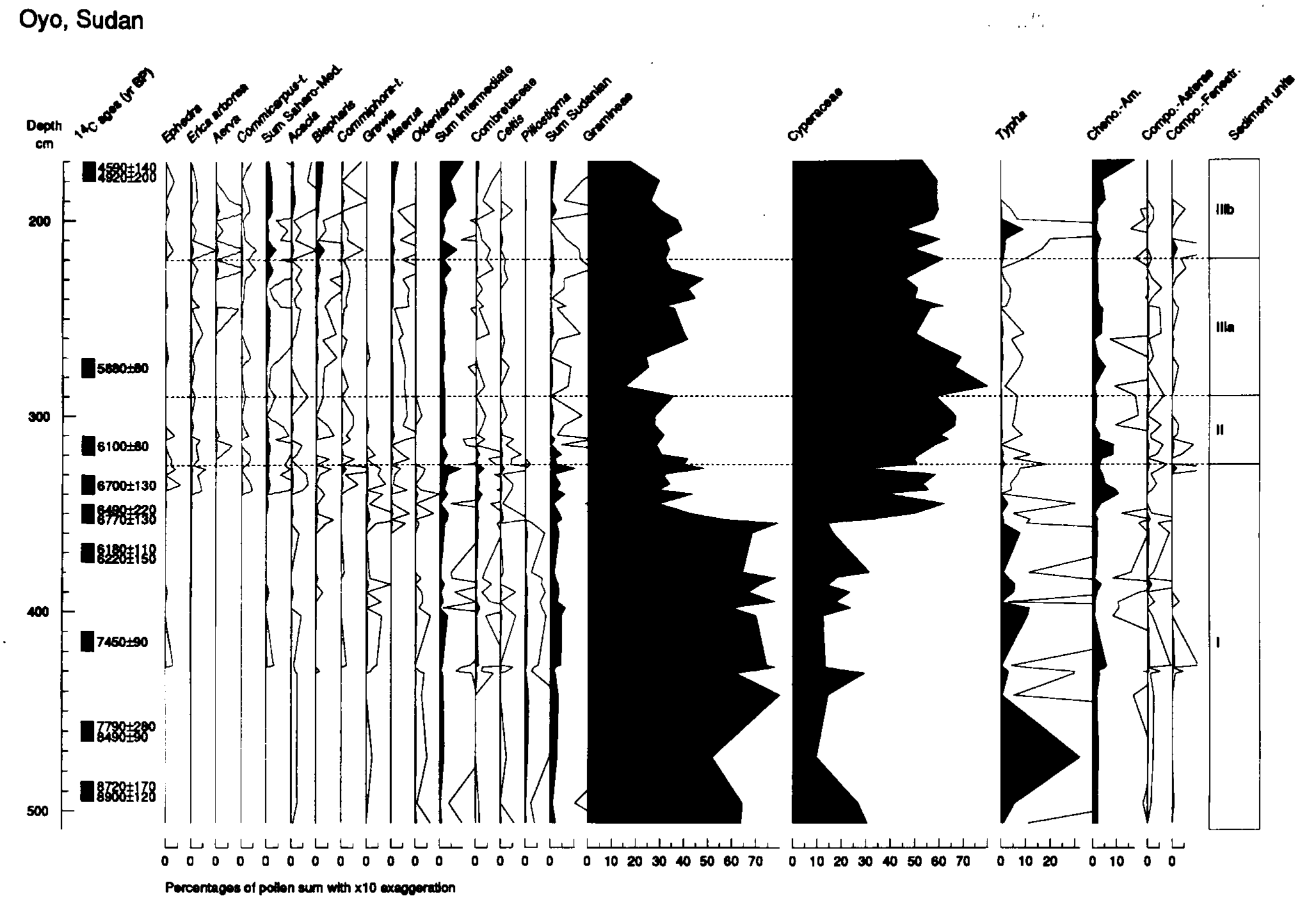

Figure 2 Pollen percentages of the main taxa plotted against depth from the surface. Percentage totals of the three phytogeographical groupings are shown, with the main taxa in each case shown to the left of the heading. The sediment units are described in the text, and the particulars of the radiocarbon determinations are listed in Table 1. Pollen taxa not included here are listed in Table 2.

Cornulaca, Cruciferae, *Salvadora*, *Tamarix*, *Tribulus*, and *Ziziphus*; Sudanian – *Burkea*, Combretaceae, *Celtis*, *Delonix*, *Hyphaene*, *Jatrophe/Croton*, *Justicia*, *Lannea*, *Mitragyna*, *Piliostigma*, *Ruellia* and *Vernonia*. The others are grouped under 'Intermediate' because they include taxa whose modern ranges span the entire Saharo–Sahelian region.

The general features of the pollen record are obvious – the spectra fall into two stratigraphically-distinct assemblages, correlating reasonably closely with the sediment stratigraphy, except that the Zone I–II sediment boundary occurs roughly 25 cm higher in the section than the major shift in pollen spectra. The lower sediments (Zone I) are characterized by high frequencies of grass pollen, high but irregular *Typha* peaks, and a preponderance among the tropical taxa of Sudanian types, albeit in very low frequencies. The upper sedimentary units, from 350 cm depth, yielded pollen spectra showing an almost exact inversion of the ratio of grass and sedge frequencies, and the occurrence of taxa in the Saharo–Mediterranean group and a decrease, both qualitative and quantitative, of the Sudanian element.

Discussion

What can be inferred from the Oyo pollen record? Three levels of inference can be suggested – phytogeographical, vegetational, and palaeoclimatic, in descending order of reliability.

Phytogeography

Phytogeographical inferences have proved to be useful in attempts to establish past atmospheric circulation patterns from the pollen record of offshore marine sediments (e.g., Hooghiemstra, 1988; Lézine, 1991). Hooghiemstra *et al.* (1992) have extended this approach by grouping the pollen taxa recorded in four Atlantic offshore cores into phytogeographical categories, then, stepwise, inferring the vegetation zonation of the adjacent mainland through time, and then reconstructing past climate. The validity of these large-scale reconstructions rests on the results of an investigation of modern spectra in offshore sediments by Hooghiemstra, Agwu, and Beug (1986), and on a comparison of modern pollen spectra from Atlantic and terrestrial sites between 13° and 21°N by Lézine and Hooghiemstra (1990). The interpretive step from recognizing phytogeographical patterns in past marine-core spectra to reconstructing vegetation zones on the adjacent mainland is more speculative, in the absence of secure corroborative data from terrestrial sites.

The Oyo record can be interpreted with some confidence in these broad, phytogeographical terms (Figure 2; Table 2). The Zone I sediments yield spectra dominated, in the tropical elements, by Sudanian taxa (12, comprising 25% of the tropical taxa recognized in the Oyo palynoflora), associated with 28 taxa of broader modern geographical range, loosely referred to as Saharo–Sudanian (58% of the tropical taxa), and eight primarily Saharan taxa (17% of the tropical taxa), grouped together here with the three primarily Mediterranean elements, *Artemisia*, *Ephedra*, and *Erica arborea*. The radiocarbon chronology can be assessed from Figure 2 and Table 1. The dates provide reasonable upper and lower age limits to the deposit, and the internal inconsistencies are probably due to the differences in sample material, as discussed by Haynes (1987).

The nearest discrete geographical region that is floristically

Table 2 Percentages of minor taxa

	Depth (cm)																										
Taxa	170	180	190	195	200	205	210	215	220	225	230	235	240	244	245	258	261	270	275	285	290	300	305	310	312	315	320
Saharo-Mediterranean species																											
Artemisia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.66	0
Cornulaca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.62	0.43	0	0	0	0	0	0	0	0	0	0
Cruciferae	0	0	0	0	0.32	0	0	0	0	0	0.32	0	0	0.17	0	0.25	0.38	0	0	0	0	0	0.28	0	0	0	0
Salvadora	0	0	0.56	0.14	0	0	0	0.3	0.27	0.43	0	0	0	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0
Tamarix	0	0.55	0	0.41	0	0.06	0	0.6	0	0.43	0	0	0	0	0.06	0	0	0	0	0	0	0	0	0.14	0	0	0
Tribulus	0.4	0.22	0	0	0	0.06	0.08	0	0	0	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ziziphus	0	0.88	0.56	0	0	0.12	0.17	0	0	0	0	0	0.1	0	0	0	0	0.06	0	0	0	0	0.19	0	0	0	0
Intermediate species																											
Abutilon	0	0	0.69	0.27	0	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0	0	0	0	0	0	0
Ambrosia	0	0	0	0.21	0.1	0	0	0	0.18	0	0	0	0.1	0.09	0	0.13	0.05	0	0	0.09	0.29	0	0	0	0	0.22	0.07
Balanites	1.22	0	0.56	0	0	0	0	0.16	0	0	0	0.35	0.13	0	0.11	0.25	0.05	0.45	0.26	0	0	0.25	0.28	0	0	0	0
Borreria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.19	0	0	0	0	0.19	0	0	0	0	0	0.21
cf. Boscia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.18	0	0	0	0	0	0	0
cf. Cadaba	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0
cf. Capparis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.32	0	0	0	0	0	0	0	0	0	1.34
Cassia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chrozophora	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cleome	0	0	0	0.2	0	0	0	0	0	0.57	0	0	0.06	0	0	0	0.22	0.06	0	0	0	0	0	0.07	0	0	0
Corchorus	0	0	0	0	0.03	0	0	0	0	0	0	0	0.03	0	0	0	0	0.19	0	0	0	0	0	0	0	0	0
Cucumis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0.07
Dalechampia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Indigofera	1.22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.18	0	0	0.09	0	0	0	0
Laurembergia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22	0
Merremia	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mitracarpus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22	0
Pavonia	0	0	0	0	0	0	0	0	0	0	0	0	0.06	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0
Peristrophe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phyllanthus	0	0	0	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0	0	0.16	0.09	0	0	0	0.28
Polygala	0	0.11	0.14	0	0.03	0	0	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07
Tephrosia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sudanian species																											
Burkea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Delonix	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
Hyphaene-t.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jatrophe/Croton	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Justicia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lannea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mitragyna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ruellia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vernonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	244	904	721	1461	3067	1768	2396	670	1123	696	2502	2537	3031	2295	4678	1602	1855	1555	1170	1089	1004	1205	1036	1374	2082	456	1410

	Depth (cm)																										
Taxa	322	325	327	330	335	338	340	345	350	353	355	360	380	383	386	390	395	398	402	427	428	430	431	442	473	496	506
Saharo-Mediterranean species																											
Artemisia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cornulaca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cruciferae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Salvadora	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tamarix	0	0	0	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tribulus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ziziphus	0	0.21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intermediate species																											
Abutilon	0	0.59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ambrosia	0.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08
Balanites	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Borreria	0	0	0	0.15	0	0	0	0	0	0	0.39	0.78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cf. Boscia	0	0	1.99	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
cf. Cadaba	0	0.41	1.99	0.15	0	0	1.02	0.09	0.7	0.71	0.15	0.78	0	0.07	1.01	0	0	0	0.84	0	0.07	0	0	0.26	0.24	0	0
cf. Capparis	0	0	0	0	0.09	0.22	0.34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cassia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chrozophora	0	0	0	0.39	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26	0.24	0	0
Cleome	0	0	0	0.15	0	0	0	0.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Corchorus	0	0	0	0.15	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cucumis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dalechampia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Indigofera	0	0.21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.16
Laurembergia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21	0	0	0	0.37	0	0.37	0	0
Merremia	0.07	0	0	0	0	0	0	0	0	0	0	0	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mitracarpus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21	0	0	0	0.37	0	0	0	0
Pavonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Peristrophe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21	0	0	0	0	0	0	0	0
Phyllanthus	0	0	0	0.55	0	0	0	0	0	0.48	0	0	0	0	0	0	0	0	0.21	0.11	0	0	0	0	0	0	0
Polygala	0	0	0	0	0	0	0	0	0	0	0	0	0.12	0	0	0	0.61	0	0	0	0	0	0	0.26	0	0	0
Tephrosia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.43	0.43	0	0	0.26	0	0	0
Sudanian species																											
Burkea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0	0.18	0	0	0	0.11	0	0	0	0	0	0	0
Delonix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hyphaene-t.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jatrophe/Croton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0
Justicia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lannea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26	0.24	0	0.08
Mitragyna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.46	0.42	0	0	0	0	0	0	0.07	0
Ruellia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.34	0	0.3	0	0	0.22	0	0	0	0	0	0	0
Vernonia	0	0	0	0	0	0	0	0	0	0	0.15	0	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1339	967	501	1268	1004	446	294	3170	1555	419	672	644	807	1327	297	1118	658	732	478	933	1383	1138	812	773	812	1284	1268

similar to the Oyo assemblage is the Ennedi Massif (350 km west), described in detail by Gillet (1968). All taxa recorded at Oyo are found at Ennedi, except the three Mediterranean taxa mentioned above, all anemophilous taxa of sporadic occurrence in the sediments, indicating long-distance dispersal from uplands in the northern Sahara. It should be noted that these three are the only taxa in the record whose occurrence can best be explained by long-distance transport.

Vegetation

The objective, semiquantitative translation of a pollen sequence into a reconstruction of vegetation requires comparable modern pollen spectra, from similar depositional environments (lacustrine in the present case), and from potential vegetational analogues. Potential analogues of the Oyo assemblages are probably desert, steppe, and wooded savanna communities. The few studies of modern pollen in the central and eastern Sahara are useful only at the qualitative, floristic level of interpretation, as they are based on flux-dust samples (Maley, 1977; Cour and Duzer, 1980; Schulz, 1984). On the other hand, Lézine (1987) has reported on modern pollen spectra from lacustrine sites in coastal Senegal that have enabled her to distinguish between various vegetational associations occupying interdunal depressions. Similar sites, obviously, are extremely rare in the eastern Sahara.

In the light of these uncertainties the following is offered as a parsimonious, speculative interpretation: the Zone I assemblage at Oyo reflects a region with a mosaic of deciduous savanna woodland and scrub vegetation, similar in composition, structure, and habitat preference to what is found today on the Ennedi Massif, the Darfur uplands (described in Quézel, 1969), and in the savanna woodland region between roughly 12°N and 15°N in present-day Kordofan province. A similar assemblage and conclusion was reported for a site at Bir Atrun, 125 km south–southeast of Oyo (Ritchie, 1987). The Oyo spectra in the upper sedimentary units (Zones II and III) might be interpreted as a decrease in the extent of wooded savannas and increases in semidesert scrub. However, it should be stressed, that, as Gillet (1968) describes so precisely for Ennedi, the occurrence and extent of particular plant communities is governed by topographic and edaphic patterns within the prevailing range of rainfall and hydrogeological conditions. Attempting more precise descriptions, far less mapping vegetation cover, in our present primitive state of knowledge, would be misleading. None the less, the indication from a comparison of the pollen records at Bir Atrun with that from Selima (Ritchie and Haynes, 1987), that a broad vegetational zonation prevailed during the Holocene, similar to the present day but displaced northward, is strengthened by the Oyo record.

Palaeoclimate

Attempts to estimate Holocene palaeoclimate in the Saharan region are even less precise, as the ongoing, rather circular argument between the 'minimalists' and the 'maximalists' (discussed in Muzzolini, 1987; Schulz, 1991; and elsewhere) illustrates. Pollen data will probably not be useful in resolving the question of the degree of increased precipitation, but the argument made by Muzzolini (1987: 164) that 'Recent studies have shown pollen contaminations to be very frequent in the arid zone; the previous lists of common plants have become unreliable, is spurious, at least with respect to the most recent investigations by Maley (1977), Lézine (1987), Schulz (1991) and all the sites reported so far from northwest Sudan and referred to in this paper. The suggestion that long-distance transport or contamination from older sediments have been important factors is untenable with respect to the Oyo material, with the possible exception of the three Mediterranean taxa referred to above. The limnological evidence at Selima, Bir Atrun and Oyo is explicable only in terms of the presence of deep, meromictic lakes depositing primary sediment, and almost entirely lacking in aeolian and other clastic sediments (Haynes, 1987). The occurrence of large, often thick-walled, beautifully preserved pollen of zoophilous and amphiphilous plants in these sediments points clearly to a proximate vegetation source, contemporaneous with the lacustrine sedimentation processes. The recently-reported investigation of radiocarbon-dated charcoal samples from the eastern Sahara provides compelling proof that many of the Sahelian and Sudanian woody taxa reported in Holocene pollen profiles from the same region were present locally (Neumann, 1989; 1991). The change in the Oyo record at approximately the Sediment Zone I–II boundary could be interpreted as a modification of an earlier predominantly monsoonal climatic regime by one with increasing interaction with northern, Atlantic/Mediterranean cyclonic systems.

Applications of pollen analysis in arid regions are difficult for the following reasons:

1) Most of the taxa (70% for this site) are under-represented in the sediments, being neither anemophilous nor copious pollen producers. In consequence, the required quantitative rigour of modern pollen analysis cannot be achieved, as is obvious from the pollen diagrams published so far from all parts of the Sahara.

2) Many vascular plants of desert environments persist during arid periods in various dormant states and have rapid response times, in both germination and growth processes, to intermittent rainfall. The familiar 'gizu' phenomenon (Wilson, 1978) illustrates this point, as well as records of germination responses to single events of seasonal rain (Haynes *et al.*, 1987).

Also the application of satellite data to document the shifts in the southern boundary of the Sahara between 1980 and 1990, by Tucker *et al.* (1991), provides compelling evidence of the rapid response of desert vegetation to changes in precipitation.

3) It has been demonstrated in the Negev Desert that the process of rainfall runoff, controlled by the intensity and duration of precipitation and by the physical properties of the ground surface, results in much greater spatial variability in the amount of soil water available to plants than in temperate regions. Accordingly, very slight increases in precipitation can be intensified in such runon habitats as wadis and depressions, but not retained in runoff habitats (reviewed in Schmida *et al.*, 1986). The interaction between precipitation and topographic pattern is further complicated by variability of rainfall type, discussed in general by Maley (1982), and illustrated in detail for the Ennedi Massif by Gillet (1968). The modern pattern at Ennedi, for example, shows two basic rainfall types – rainfall of large drop-size from intense storms of short duration, and continuous rainfall periods of low intensity, primarily monsoonal rains. Maley (1982) has distinguished between these rainfall types in the sediment stratigraphy of the Chad basin, showing a relationship between soil type, vegetation, and inferred rainfall pattern for mid-Holocene deposits.

Finally, as Haynes (1987) and Kropelin and Pachur (1991) have pointed out, our understanding of the Holocene climate of the eastern Sahara depends on a secure knowledge of the links between precipitation and groundwater recharge. Haynes (1987) has concluded that the sediment stratigraphy of the lacustrine basins found so far, including Oyo, suggests strongly that the lakes began in response to groundwater recharge in advance of direct precipitation. He offers a model that proposes a rise in the groundwater, both forming a lake in the particular basin, and promoting the establishment of a peripheral zone of vegetation dominated by reeds and acting as a sediment filter; subsequent arrival of the precipitation front was characterized by a monsoonal rainfall type that produced minimal runoff. The model assumes that groundwater recharge was predominantly local. Pachur and Hoelzmann (1991) have summarized the palaeolimnological and faunal evidence from a large area that includes Oyo but extends southwards to 16°N, and they conclude (p. 257) that 'between 9300 and about 4000 yr BP, there were widespread lake and swamp environments with freshwater molluscs, ostracods, and diatoms, and a species-rich savanna mammal fauna'. With respect to the Oyo pollen record such an environmental reconstruction is concordant with my suggestions above about the vegetation, but the question of past rainfall amounts remains open.

Conclusions

The Holocene pollen record at Oyo confirms and elaborates data from other sites in the region that indicate that many of the important taxa in modern Sudanian savanna landscapes were present in this area of the southeast Sahara during the period between 9k and 5k radiocarbon yr BP, but the low, often erratic pollen frequencies preclude secure reconstruction of the source vegetation. Palaeoenvironmental inferences from other proxies, particularly limnological, that several deep, chemically stratified, groundwater-supported lakes occurred in scattered localities, as well as faunal and archaeological evidence (e.g. Haynes and Mead, 1987; Kropelin and Soulie-Marsche, 1991; and Street-Perrott and Perrott, 1993), lend support to the proposition that a less arid climate prevailed. The broad agreement of these observations with the model simulations based on changes in solar radiation due to orbital variations (COHMAP, 1988) has been noted by several authors. In particular, the modelled simulations show, in response to the postulated increase in July insolation between 12 and 6 ka, an intensification of the African monsoon.

Acknowledgements

This work is part of a long-term project, directed by Professor C.V. Haynes Jr, supported by funds and material assistance from: The National Science Foundation; the National Geographic Society; the Smithsonian Institution; the Geological Survey of Egypt; and the Geological and Mineral Resources Department of Sudan. The author acknowledges the continuing support by the National Science and Engineering Research Council of Canada, the assistance of his colleagues at Laboratoire de Palynologie, CNRS, Montpellier, France (particularly Jean Maley and Danielle Duzer), and Dr Keith Bennett and K.A. Hadden for technical assistance. Comments on the manuscript by Drs H. Hooghiemstra and E. Schulz were very helpful.

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