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At the edge of the desert: The evolution of the Holocene environment in Lake Rkiz, Senegal River Valley

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Abstract

The analysis of faunal remains, pollen grains and other palynomorphs from a 4 m long core recovered at Lake Rkiz, Mauritania (16.911420 N, -15.172668 W, 0 m asl) documents the major phases of marine intrusion in the Senegal River system during the Holocene. Lake Rkiz was exposed to marine waters from 10 to 4 ka: a brackish lagoon developed at 10 ka, followed by a mangrove between 8.7 and 7 ka both in a calm environment. *Rhizophora* populations were never developed, however, either because they did not reach the core site at the northern extremity of the lake, or because they were restricted to the Senegal River bed. After 7 ka, the environment became increasingly unstable and the mangrove was replaced by a more clearly marine environment. During the last two millennia, a new, discrete phase of marine intrusion is recorded at Lake Rkiz. Contemporary to that already noted in the Ferlo River valley which feeds the Senegal River through Lake Guiers to the south, it also testifies to a positive oscillation of the sea level. The evolution of the regional vegetation of Lake Rkiz follows that of North tropical Africa with the expansion of a gallery forest of tropical humid affinity dominated by *Celtis* during the AHP. As elsewhere in the Sahara and Sahel, tropical plant types co-occurred with Saharan ones attesting to a mosaic-like landscape.

Keywords: Senegal River; Holocene mangrove; Marine intrusion upstream; Sea level; Pollen; Microfauna & mollusks

1. Introduction

The recent paleoenvironmental evolution of the Senegal River delta has been impacted by a combination of two distinct factors: The massive increase in humidity during the “African Humid Period” (AHP) that led to the wide dispersion of tropical plants across the Sahel and the Sahara (Watrín et al., 2009; Hély et al., 2014) and the post-glacial sea level rise from about -130 m during the Last Glacial Maximum (LGM) to the present level about 7000 years ago (Fleming et al., 1998) responsible for the penetration of the sea in low-lying coastal areas of western Africa (Faure et al., 1980). Tropical trees (e.g., *Alchornea*, *Macaranga*, *Elaeis guineensis*, *Tetracera*, *Celtis*, *Ficus*, *Syzygium*) formed dense gallery forests as soon as 10.7 ka in the interdunal fens of the Niayes area of Senegal located behind the Atlantic coastal strand between 15° and 16°N. Humid tropical trees were also present in the catchment area of Lake Guiers (Lézine, 1988) and in the Senegal River bed (Michel and Assémien, 1969; Médus, 1984). At the end of the AHP between 3000 and 2500 cal yr BP (labelled as 3 and 2.5 ka in the text), the degradation of environmental conditions has led to the destruction of these tropical gallery forests (Lézine, 2022). They still persist locally as relict vegetation formations

51 in the Niayes owing to the presence of a water table near the surface (Trochain, 1940), but
52 they disappeared from the banks of the Senegal River and its tributaries during the last few
53 centuries (Fofana et al., 2020; Lézine et al., 2023).

54 The increase in humidity during the AHP was also responsible for the massive development
55 of tropical humid *Rhizophora* mangroves on the West African coast during phases of
56 stabilization of the post-glacial sea level rise (Lézine, 1997). The morphology of the coastal
57 areas played a major role in the wide expansion of these mangroves, particularly in the
58 Senegal River area (Faure et al., 1980). In its lower valley, from the coast to approximately
59 225 km to the east, the bottom of the Senegal River bed is about 5 m below the present-day
60 sea level (Michel, 1973). This geomorphological feature facilitated the penetration of marine
61 waters eastward several hundred kilometers from the present coast and the development of
62 mangroves during periods of sea level rise in the Holocene (Trochain, 1940; Michel and
63 Assémien, 1969; Médus, 1975; Médus and Monteillet, 1981; Lézine et al., 1988). However,
64 our understanding of the Holocene evolution of the West African mangrove is severely
65 hampered by the lack of continuous records. Mangrove levels (most of the time in the form of
66 a peat layer a few centimeters thick) (*in* Lézine, 1997 and references therein) and shell
67 accumulations forming marine terraces in the interior were used to reconstruct the coastline
68 and its variations over the last millennia (e.g., Faure et al., 1980). The irregular and often
69 truncated nature of the sedimentary archives does not permit a continuous reconstruction of
70 the littoral evolution throughout the Holocene. Possible shore level tilt along the Senegal
71 River delta during the post glacial sea level rise may have introduced an additional difficulty
72 in our understanding of paleoenvironmental changes in this area (Faure et al., 1980).

73 In this paper we present a micro-faunal and palynological record from a continuous
74 sedimentary sequence from lake Rkiz (16.911420 N, -15.172668 W, 0 m asl) in order to
75 identify the timing and amplitude of the successive phases of marine intrusion upstream in the
76 Senegal River system from 10 ka to the present.

77

78 **2. Environmental setting**

79

80 Lake Rkiz occupies a large interdunal depression (Aftout ech Cherguil) north of the Senegal
81 River, about 110 km east of the present coastline (Fig. 1). The NE-SW orientation of the
82 depression is governed by that of the sand dune alignments established during the LGM over
83 much of southern Mauritania and northern Senegal (Michel, 1973).). Lake Rkiz is about 5 km
84 wide and 30 km long. It is a shallow lake (maximum depth 2.5 m), hydrologically connected
85 to the Senegal River through a network of multiple channels. The hydrological regime of the
86 lake reflects that of the river in its lower valley. During the rainy season (from June to
87 October) Lake Rkiz is supplied by the floodwaters of the Senegal River and its level can rise
88 by 3.5 m. During the dry season, when the inflow from the Senegal River ceases, the lake may
89 dry up completely.

90 The regional climate is characterized by ca. 185 mm annual rainfall during the rainy season
91 from June to October (maximum 79 mm in August) and maximum temperatures between 33
92 and 40°C. As a consequence, the vegetation is of Sahelo-Saharan steppic type with a
93 discontinuous herbaceous cover mainly composed of *Cenchrus biflorus*. Trees (*Acacia*
94 *raddiana*, *A. scorpioides*, *Salvadora persica*, *Balanites aegyptiaca*...) are scarce (Adam,
95 1960; 1965).

96

97 **3. Material and Methods**

98

99 Core Rkiz-1 was collected in 1985 at the mouth of Wadi Mrea at the NE end of the lake
100 (16.911420 N, -15.172668 W, 0 m asl) using a Russian manual corer (Fig. 1). The

101 sedimentary sequence is 4m long (Fig. 2). Three main units can be distinguished: from the
102 base to 349 cm (Unit I), the sediment consists of a homogeneous light-yellow sand likely
103 derived from the dune sands deposited during the LGM. It is overlaid by a greenish clay
104 layer containing abundant malacological, crustacean and fish bones fragments, witnesses to
105 the Holocene marine transgression (Unit II: 349-190 cm). The upper unit (Unit III: 190-0 cm)
106 is composed of sandy clay with fine sand and gravel intercalations. This testifies for a less
107 homogeneous environment with runoff deposits from the lake edges (such as the ferruginous
108 gravels, Michel, 1973), lake and mangrove organic material and eolian sands. Thirty-six
109 samples were taken at 10 cm intervals for faunal and vegetation analysis.

110

111 **3.1 Dating control**

112

113 The core chronology was constructed using ^{14}C accelerator mass spectrometry (AMS) dates
114 on seven samples of marine shells (*Pachymelania fusca*) and bulk sediment (Fig. 2).
115 Radiocarbon dates on shells and shell fragments were calibrated using the Marine 20
116 calibration curve (Heaton et al., 2000) from Calib 8.2 software (Stuiver and Reimer, 1993)
117 taking into consideration the reservoir-age of 511 ± 176 years, calculated for the sector of the
118 West African coast closest to the site, facing the Senegal River delta (Ndeye, 2008). The bulk
119 organic sample at 95 cm was calibrated using the IntCal 20 calibration curve (Reimer et al.,
120 2020). Dates are given in calibrated 1000 years (ka) BP. The age-depth model was then
121 derived from a linear interpolation between two calibrated ^{14}C ages using CLAM (Blaauw,
122 2010). We assume a constant reservoir-age throughout the Holocene time.

123

124 **3.2 Faunal remains**

125

126 The faunal samples were sieved under water on a 0.5 mm mesh and then sorted under a
127 binocular microscope. Only 18 samples between 370 and 190 cm depth yielded identifiable
128 remains and the uppermost samples were found to be sterile (Fig. 3).

129 Anatomical and taxonomic identifications were conducted using a comparative reference
130 collection from AASPE (library of skeletons and tests), literature (Dautzenberg 1910, 1912,
131 Gregory 1933, Bouchet 1977, Pointier & Lamy 1998, Humann & DeLoach 1993, Grouard
132 2001, Serrand 2002, Ardovini & Cossignani 2004, Ahmedou Salem et al. 2014, Carpenter &
133 De Angelis 2016, Diedhiou et al. 2018, von Cosel & Gofas 2019, Taylor & Glover 2021), and
134 internet resources (MolluscaBase 2022, World Register of Marine Species 2022). The
135 nomenclature was updated from the WoRMS site.

136 Quantification of faunal remains used multiple measures often used in zooarchaeological
137 analyses (NRd: Number of Determined Remains and MNI: Minimal Number of Individuals).
138 Bivalves were classified into three groups (intact valve, broken valve but with umbo, and
139 fragments (Claassen, 1998; Giovas, 2009; Manca, 2017)). The Bivalve MNI was estimated
140 from the lateralized complete valves, lateralized hinges and hooks, edge and complementary
141 non-repetitive elements which allow, according to the cases, the maximum estimate. The
142 Gastropod fragmentation degrees were classified in several groups (complete, sub-complete,
143 complete without apex, complete without opening, margin and lip, lip, apex, apex and spire,
144 first spire, fragment of spire, parietal margin, spine, fragment of columella, fragment of
145 opening or base, umbilicus, fragment of base with umbilicus, columella and opening,
146 operculum. The Gastropod MNI was calculated based on complete shells, number of apexes
147 and complementary non-repetitive elements which allows, on a case-by-case basis, the
148 maximum estimate of complete labials (Serrand, 2002; Giovas et al., 2013; Tomadini, 2018).

149 In total twenty-eight taxa of Bivalvia, Gastropoda, Cnidaria, Crustacea and Teleostei were
150 identified out of 2610 remains. They were grouped according to their ecological affinity in 4

151 groups (marine, estuarine, mangrove, freshwater) according to World Register of Marine
152 Species 2022 (S-table 1; S-fig. 1).

153

154 **3.3 Pollen and NPP**

155

156 Pollen samples were processed using the standard HF method described by Faegri and Iversen
157 (1977). After sieving in a 5 µm mesh, the residue was stained with safranin and mounted in
158 glycerine. Pollen identification was based on the reference slide and photo collections of the
159 African Pollen Database (APD) (<https://africanpollendatabase.ipsl.fr>). Pollen nomenclature,
160 which follows the standards defined by the APD (Vincens et al., 2007), was based on Lebrun
161 and Stork (1991-2015). The pollen microflora was composed of 136 taxa (S-table 2). Pollen
162 taxa were grouped according to the phytogeographical and ecological affinity of the parent
163 species according to Trochain (1940) and Lebrun (1973), among others, with distinction of
164 Saharan, Sahelian, Sudanian and Guineo-Congolian pollen types, mangrove, wet indicators
165 and undifferentiated or common to all the phytogeographical entities mentioned above
166 (including Poaceae). Pollen percentages were calculated against a sum excluding mangrove
167 pollen types, wet pollen types (including Cyperaceae) and ferns, the percentages of which
168 were calculated separately against a sum including all the pollen grains and fern spores
169 counted. Non-Pollen Palynomorphs (NPP) include algae (mainly *Pediastrum* and
170 *Botryococcus*), undifferentiated Foraminifera, Dinocysts and Fungi. Their percentages were
171 calculated against the total NPP.

172

173 The Shannon Diversity index (Pielou, 1966) which accounts for both abundance and evenness
174 of the taxa present was used to evaluate the diversity of pollen and faunal remains using Past
175 4.03 software (<https://www.nhm.uio.no>). Both pollen and faunal data are presented under the
176 form of percentage diagrams using Tilia software (Grimm, 1991).

177

178 **4. Results**

179

180 **4.1 Faunal remains**

181

182 **4.1.1 Diversity**

183 The MNI calculated is 1312. Gastropoda largely dominates this collection with an MNI of
184 684 calculated from 886 identified remains (NRd), immediately followed by Crustacea
185 (MNI= 426; NRd=848), and Bivalvia (MNI=185, NRd762). Cnidaria and Teleostei are poorly
186 represented with MNI= 13 (NRd=122) and MNI=4 (NRd=4), respectively (Fig. 3).

187

188 Maximum of Gastropoda and Crustacea is present at the 8 ka level. These two groups are then
189 replaced by Bivalvia which reach peaks at two distinct levels respectively dated at 7.3 then
190 6.3 ka. Bivalvia are the most diverse with 12 species and 9 families present, largely
191 accounting for the maximum Shannon diversity index reached at 7 ka. They are followed by
192 Gastropoda with 7 species and 7 families present. On the contrary, only one species of
193 Teleostei, 1 Cnidaria undiff., and 2 Crustacea (Cirripedia and Ostracoda) were present.

194

195 **4.1.2 The mollusk assemblages**

196

197 Figure 4 shows the diversity and MNI of the main mollusk taxa, the preservation of which
198 allows distinguishing two main zones. From 10 to 7 ka (zone 1), the preservation rate is high
199 (mean=76%), though fluctuating from 100% to 32%. It abruptly falls to values as low as 3%
200 in the overlying zone 2 (mean=13%).

201
202 Three sub-zones can be distinguished within zone 1:
203 - Zone 1a: From 10 to 8.7 ka, the presence of *Peringia ulvae* and the highest values of
204 the preservation rate indicate a sheltered lagoon, out of the direct influence of
205 waves;
206 - Zone 1b: From 8.7 to 7.5 ka: *Peringia ulvae* was associated with *Pachymelania fusca*,
207 both largely dominating the mollusk assemblages, suggesting the progressive
208 development of a mangrove at the coring site. Freshwater inputs are indicated by the
209 presence of Ampullariidae (*Lanistes ovum*). The lower values of the preservation rate
210 compared to zone 1a (75-50% versus 100%) suggest more dynamic environment;
211 - Zone 1c: From 7.5 to 7 ka: *Peringia ulvae* and *Pachymelania fusca* strongly decreased
212 and the mollusk assemblage greatly diversified with the appearance of marine and
213 estuarine species such as various Veneridae and *Ungulina rubra*. The high amplitude
214 of the variations in the preservation rate suggests the alternation of phases of calm seas
215 and strong swells.
216 Zone 2, from 7 to 5.6 ka, is characterized by the disappearance of the mangrove species and
217 their replacement by marine ones, as shown by the high MNI of Veneridae and Lucinidae
218 species. The lowest values of the preservation rate for this zone indicate significant tidal and
219 backwash movements.

220 221 **4.2 Pollen and NPP**

222
223 The pollen diagram (Fig. 5) is characterized by the dominance of the herbaceous taxa Poaceae
224 undiff. and various types of Amaranthaceae whose cumulative percentages reach up to 90%
225 of the pollen sum, indicating the presence of an open environment throughout the Holocene.
226 As usual in tropical Africa, the pollen percentages of trees are rarely higher than 1% with the
227 exception of Combretaceae, *Celtis* and *Rhizophora* which reach up to 9%, 23% and 7%
228 respectively.

229
230 Three main zones can be distinguished from the pollen grain, spores and NPP diagram:

231
232 Zone 1 (10-8.7 ka) is typified by exceptionally high percentages of *Celtis* (maximum: 23%).
233 Among the herbaceous plants, taxa from the lake margin such as *Typha* and Cyperaceae, are
234 present. *Botryococcus* dominates the NPPs suggesting shallow and nutrient poor fresh to
235 brackish water. The presence of *Ephedra* pollen grains, even in percentages lower than 1%
236 suggest a Saharan (desert) influence. (This pollen zone corresponds to Zone 1a of the mollusk
237 assemblages).

238
239 Zone 2 (8.7-4.5 ka) records the decline of *Celtis*. The other tropical tree taxa, notably
240 *Alchornea* and various types of Combretaceae remain present though in small percentages.
241 Among the herbaceous plants, the abundance of Amaranthaceae and in particular
242 *Amaranthus/Chenopodium*-type and *Suaeda* allows identification of sub-zone 2a (8.7-7.1 ka)
243 (= Zones 1b and 1c of the Mollusk assemblages). The presence of *Suaeda* suggests saline
244 conditions while the presence of Fungi confirms the, partial or seasonal, desiccation of Lake
245 Rkiz at the core site. The replacement of *Botryococcus* by dinoflagellates within the NPP
246 indicates that a marine influence was present, which is confirmed by the occurrence of
247 *Rhizophora* mangrove pollen grains. Pollen types present in subzone 2a continue into the
248 overlying subzone 2b (7.1-4.5 ka) (= Zone 2 of the Mollusk assemblages) though in smaller
249 percentages, suggesting drier conditions. The NPPs suggest an unstable environment with

250 alternating saline (Dinoflagellate cysts in particular at 6.2 ka) and freshwater to brackish
251 (*Botryococcus*) conditions.

252
253 Zone 3 (4.5 ka-modern) records a change in the environment with the disappearance of
254 mangrove taxa. In sub-zone 3a (4.5-2.4 ka) *Celtis* and *Alchornea* disappear but the presence
255 of e.g., *Lannea* suggests that the tropical influence was still present, although significantly
256 reduced. After 2.4 ka (sub-zone 3b (2.4-1.6ka)) the Sahelian taxa *Acacia* and *Commiphora*
257 which are associated with the Fabaceae family increase, indicating the transition to the
258 modern environment. Rare tropical plants of Sudanian or more humid types (e.g., *Lannea*,
259 *Macaranga*, *Bridelia*...) are occasionally present but in percentages lower than 1%, and the
260 reappearance of the Saharan taxa (*Ephedra*) indicates the return to dry conditions. The
261 lacustrine environment is dominated by *Botryococcus*. The populations of the lake edge
262 develop progressively with *Typha* in sub-area 3b then Cyperaceae in sub-zone 3c. The
263 predominance of fresh-water during sub-zone 3c (1.6-0.83 ka) and 3d (0.83-modern)
264 indicated by the dominance of *Pediatrum* in the NPP assemblages is interrupted around 1.3 ka
265 by the discrete reappearance of mangrove taxa and dinoflagellates, testifying for the brief
266 return of marine influence.

267 268 **5. Discussion**

269 270 **5.1 The Holocene sea level variations and their impacts in the Lake Rkiz area**

271 272 **5.1.1 The *Rhizophora* mangrove**

273
274 The Senegal River delta is the northernmost limit of the major West African mangrove
275 species, *Rhizophora racemosa* (Trochain, 1940; Adam, 1965; Spalding et al., 1997). Today
276 this tropical humid species is present only as small populations or isolated individuals along
277 the creeks closest to the coast in the Senegal River delta near Saint Louis (Senegal) or on the
278 Thiong island (Mauritania) at roughly 16°N. As the sea level rose after the LGM, and thanks
279 to the intensification of the monsoon rains, it spread widely along the West African coasts
280 during the AHP (Lézine, 1997) as far north as 21.25°N (core GIK16017-2, Hooghiemstra
281 1988). In the Senegal River area, *Rhizophora* was present on the continental shelf opposite the
282 present-day delta at 13.8 ka (core Rosilda N 110-Z ; Lézine, 1987). It penetrated eastward in
283 the rear delta after 11.4 ka (Médus and Monteillet, 1981) and in the Potou interdunal
284 depression at the southern limit of the delta (Lézine, 1987). In this context, and given the
285 topography of the Senegal River bed, the intrusion of the coastal and marine influence up to
286 Lake Rkiz from 10 to 4.7 ka is not unlikely. Between 10 and 8.7 ka, the low faunal diversity,
287 the only occasional presence of dinoflagellates and the very low percentages of *Rhizophora*
288 pollen, show that the mangrove was only slightly developed and that *Rhizophora* populations
289 did not reach the core site, i.e., the most distant sector from the channels connecting Lake
290 Rkiz to the Senegal River. Excellent faunal preservation eliminates the potential long-distance
291 transport and suggests the presence of a lagoon protected from the direct influence of swells
292 and strong water currents. The time interval between 8.7 and 4.7 ka during which the
293 mangrove developed at Rkiz encompasses the transgressive episode of the "Nouakchottien"
294 (Elouard, 1968). During this episode centered around 6-5 ka, the sea level was higher by 1 to
295 2 m compared to its current position (Faure et al., 1980). Sea water intrusion inland, in the
296 rear delta, and along the Senegal River and its tributaries, is attested by numerous
297 accumulations of marine shells forming terraces (e.g., Faure et al., 1980 and references
298 therein) (Fig. 6 and 7A; S-table 3), palaeobotanical (*Rhizophora* pneumatophores) and
299 botanical (relict species of mangrove forests) observations (Trochain, 1940), and pollen

300 analyses (Médus, 1975; Médus and Monteillet, 1981; Lézine, 1988). According to Michel and
301 Assémien (1969), *Rhizophora* populations could have spread up to Bogué, 250 km east of the
302 present coast in the bed of the Senegal River during this episode (Fig. 6). At Rkiz, the
303 mangrove was progressively exposed to increased marine influence after 7 ka and a more
304 dynamic environment subject to waves, marine and freshwater inputs was established as
305 shown by the important presence of Bivalvia, Veneridae (notably *Pelecycora isocardia*) and
306 Lucinidae in the fauna, the strong fragmentation of faunal remains and the alternation of
307 dinoflagellates and freshwater algae within the NPP assemblage. Increased currents and wave
308 turbulence led to the complete destruction of the faunal remains from the sediment at 5.6 ka.
309 However, *Rhizophora* pollen grains show that the mangrove influence persisted up to 4.2 ka.
310 These results agree with previous studies showing that the decline of *Rhizophora* mangroves
311 along the northern coast of Senegal occurred, according to the sites, between 5.6 ka at 14.9°N
312 (Thiaye, Lézine et al., 1985) and 3.6 ka off the Senegal River delta at 16.0°N (Core GeoB
313 9503-5, Bouhimetarhan et al., 2009). Evidence of marine influence disappeared from the
314 pollen and NPP assemblages between 4.2 and 2.1 ka that closely corresponds to the
315 “Tafolian” sea level regression (Hébrard, 1972). Then, the renewed presence of a few
316 *Rhizophora* pollen grains between 2.1 and 0.6 ka shows that the last, discrete episode of saline
317 intrusion into the Senegal and Ferlo Rivers during the last millennium (Faure et al., 1980;
318 Monteillet et al., 1981; Fofana et al., 2020) also reached Lake Rkiz. The absence of faunal
319 remains in the sediment and the very low *Rhizophora* pollen percentages confirm that this
320 event was minor.

321

322 **5.1.2 Vertical movements in the Rkiz Lake area during the Holocene?**

323

324 The elevation of mangrove levels and shell accumulations have been used to reconstruct the
325 long-term evolution of sea level rise off Senegal: The peat layer in the Rosilda N 110 Z core
326 located at -60 m below sea level is dated 13.8 ka (Lézine, 1987). In the rear delta of the
327 Senegal River Médus and Monteillet (1981) identified a *Rhizophora* mangrove level at -33.6
328 m dated at 11.4 ka in line with the dating of the Eudoxie and Lea long cores by Faure et al.
329 (1980) (9.9 ka and 9.4 ka at -23 and -20.5 m, respectively). All these dates are consistent with
330 the general trend of the post-glacial sea level rise (Fleming et al., 1998). The most surprising
331 result of our study is the depth at which the early Holocene mangrove development has been
332 identified at Rkiz. There is a difference of about 20 m with the depth of the contemporary
333 levels identified in the rear delta of the Senegal River (Fig. 7B). Early Holocene vertical
334 movements are therefore suggested by our data in the sector of Lake Rkiz located in a region
335 known to have also been affected by significant deformations during the Quaternary, such as
336 the subsidence of the Senegal River delta, and the faulting of the “Dôme de Guiers” (Michel,
337 1973; Barusseau et al., 2009).

338

339 **5.2 The regional vegetation**

340

341 During the AHP, lakes and wetlands expanded in the present day Sahara and Sahel
342 (Lézine et al., 2011) while large paleodrainages were formed or re-activated (Drake et al.,
343 2011), in response to the increase in monsoon rainfall. As a result, tropical plants widely
344 spread into the Sahel and the Sahara (Watrin et al., 2009). Due to the scarcity of data in these
345 (semi-) arid environments where lacustrine archives are poorly preserved, the major difficulty
346 in understanding this profound environmental change was to identify how the tropical humid
347 plants could have migrated north and where they developed. Instead of a general displacement
348 of the vegetation zones towards the north and therefore the development of a more or less
349 wooded savannah in the Sahara and the Sahel (Hoelzmann et al., 1998), pollen data show the

350 presence of gallery forests of tropical humid type (Sudanian to Guineo-Congolian) in a drier
351 regional environment. It has been suggested that tropical plants have used the banks of the
352 rivers where they benefited from the moisture of the soil as migration routes to enter the Sahel
353 and Sahara (Watrín et al., 2009; Hély et al., 2014). At Rkiz the regional landscape has always
354 been extremely open as shown by the percentages of herbaceous taxa, which may be equal to
355 or higher than 90% in total. Tropical plants (Guinean-Congolian, Sudanian) have co-existed
356 with typically Sahelian species (e.g., *Acacia*, *Commiphora*) and even Saharan species
357 (*Ephedra*, *Artemisia*). This mixture of plants, which today can only be found in distinct
358 vegetation zones, explains the peak in diversity observed between 8.8 and 8.3 ka, which is
359 consistent with the Holocene forest optimum in tropical North Africa (Lézine, 1989) (Fig. 8).
360 Tropical influence at Lake Rkiz persisted until 2.4 ka which is consistent with what we know
361 from the end of the AHP in Western Africa (Lézine, 2021). In the nearby Niaye region along
362 the Atlantic coast between Dakar and St Louis for instance, the dense gallery forests, which
363 widely developed during the AHP dramatically collapsed around 2.5 ka. At Rkiz, the decrease
364 of tropical taxa was gradual and an arid phase emerged as early as 4 ka. The discrete
365 reappearance of tropical taxa after 2 ka suggests the forest galleries that extended along the
366 Senegal River during the Holocene had not completely disappeared over the last millennia.
367 They were still present in the Saint Louis area as late as 0.35 ka (Fofana et al., 2020).

368
369 Thirty-six pollen taxa of humid tropical type were found at Rkiz. This number is surprisingly
370 similar to that observed on the opposite bank of the Senegal River, about 95 km to the south at
371 Guiers 3 (16.28°N) (Lézine, 1988). However, the percentages calculated over the entire
372 period covered by the pollen series are on average two and a half times lower at Rkiz (6%)
373 than at Guiers (15.5%). Comparing all pollen sites in Senegal and Mauritania, humid tropical
374 taxa are 68 at Diogo (15.2°N) where they account for an average of 25% of the pollen sum.
375 These values drop to 37 taxa and 15.5% at Guiers 3, 36 taxa and 6% at Rkiz and finally 15
376 taxa and 1.5% at Chemchane (20.93°N). The contrast between the percentages of tropical taxa
377 between Guiers and Rkiz only less than a hundred kilometers apart suggests that the Senegal
378 River may have constituted a barrier to the northward migration of tropical plants during the
379 AHP in north west Africa. One exception is *Celtis*, which has reached exceptionally high
380 percentages at Rkiz (23%) and so far unreported in tropical North Africa during the Holocene.
381 The modern distribution of *Celtis toka* does not exceed 16°N (Fig. 9). During the Holocene, it
382 expanded widely into Mauritania (Monod, 1983) and more widely across the whole Sahara to
383 southern Libya at 24.8°N (Mercuri, 2008). However, *Celtis* percentages never exceeded 4% at
384 any of the Saharan and Sahelian pollen sites, suggesting that, with the exception of Rkiz, this
385 species never expanded much within the gallery forests.

387 6. Conclusion

388
389 Our study shows that, despite a substantial distance of more than 180 km from the mouth of
390 the Senegal River, Lake Rkiz was subject to marine water influx during two distinct episodes
391 of sea level rise. The first one, from 10 to 4.5 ka, is a long period during which the
392 environment of Lake Rkiz changed from a calm coastal environment evolving from a lagoon
393 to a mangrove to a more pronounced, unstable, marine environment. Two major features
394 emerge from our study: (1) the elevation of the marine influence reported in core Rkiz-1, is
395 significantly higher than what is known from the global sea level curve, which suggests
396 important vertical movements at Lake Rkiz (2) the “Nouakchottian” transgression, that led to
397 the development of mangroves in Lake Guiers and in the Senegal River bed up to Bogue
398 during the Middle Holocene, resulted in a highly variable environment at Rkiz as evidenced
399 by the increased fragmentation in the faunal remains. A second discrete phase of marine

400 intrusion is detected during the last 2 millennia, after the regressive phase of the “Tafolian”.
401 Regional vegetation at Rkiz was open, dominated by herbaceous plants throughout the
402 Holocene. Tropical trees however formed gallery forests along the river and lake beds. These
403 results are consistent with the general pattern observed in the landscape evolution of West
404 Africa during the Holocene.

405

406 **Author contributions**

407 AML and SG designed research; AML performed fieldwork; AML and SG performed
408 research: AML palynology and SG zooarchaeology; AML and SG analyzed data; AML and
409 SG wrote the paper with contributions from both authors.

410

411 **Data availability**

412 Pollen data are deposited in the African Pollen Database (APD)
413 (<https://africanpollendatabase.ipsl.fr>; DOI:<https://doi.org/10.14768/apd.0bba-rk05>). Data for
414 fossil *Celtis* distribution are from the APD (<https://africanpollendatabase.ipsl.fr>), and for the
415 modern one from GBIF (<https://www.gbif.org>) and MNHN (<https://www.mnhn.fr>) databases
416 and the literature. Microfauna data are presented in the Supplementary Material.

417

418 **Declaration of competing interest**

419 The authors declare that they have no known competing financial interests or personal
420 relationships that could have appeared to influence the work reported in this paper

421

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432

433

434 **References**

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627
628

629 List of Figures

630

631 Figure 1: Lake Rkiz. A: The general map is from en-us.topographic-map.com. The dashed
632 rectangle indicates the Lake Rkiz area detailed in Figure 1B. B: The detailed map of Lake
633 Rkiz is redrawn after Vache-Grandet (1959). The shaded area within the lake indicates the
634 area of the lowest level identified by the author in 1954. The Lake was entirely dry at the time
635 of coring. The star indicates the location of core Rkiz1 (this study).

636

637 Figure 2: Core Rkiz1: Lithostratigraphy and ¹⁴C ages.

638

639 Figure 3: Core Rkiz 1 Minimum Number of Individuals (MNI) *versus* age. From left to right,
640 this figure shows the MNI of all the faunal remains encountered. On the right, the
641 preservation index and the Shannon diversity index are shown.

642

643 Figure 4: Core Rkiz 1 synthetic diagram of MNI of the mollusk taxa *versus* age. On the right,
644 the preservation and diversity indexes are shown. Pollen zones are shown to the right of the
645 figure for easy comparison.

646

647 Figure 5: Core Rkiz 1 synthetic diagram showing, *versus* age from left to right, the main
648 pollen and NPP taxa. Percentages are shown in black, gray shading shows the same results,

649 multiplied by 10 for highlighting. Mollusk zones are shown to the right of the figure for easy
650 comparison.

651

652 Figure 6: Location map of sites attesting to the marine influence in the area of the Senegal
653 River and its delta during the Holocene. Black circles indicate pollen sites, gray circles
654 indicate marine shells, and white squares represent peat samples. At Lake Rkiz, the black
655 square show our coring site, while the diamonds indicate shell samples from Faure et
656 al.(1980). Satellite image from Google Earth.

657

658 Figure 7: Dated evidence of marine intrusion along the Senegal River and Lakes Guiers and
659 Rkiz (S-Table 3). The colored circles correspond to dates extracted from marine shells
660 collected in 3 major locations: from the West and East: the delta, Lake Guiers and the Ferlo
661 river, and Lake Rkiz. Red circles correspond to the dates of this study at Lake Rkiz, pink
662 circles to those of Faure et al. (1980). Squares correspond to the dates of the long cores from
663 the bed of the Senegal River (white squares are dates on bulk sediment (peat); blue squares
664 are dates from shells. A: the dates are presented as a function of time and longitude in order to
665 evaluate the distance of the marine intrusion from the coast, B: as a function of (non
666 corrected) altitude/depth when indicated by the authors. The dark gray arrows indicate the
667 average position of the two Holocene marine transgressions. The light gray double arrow
668 highlights the difference in depth between the sea level records in the Senegal River bed
669 (Eudoxie, Leo, Keur Marsal) and in Lake Rkiz.

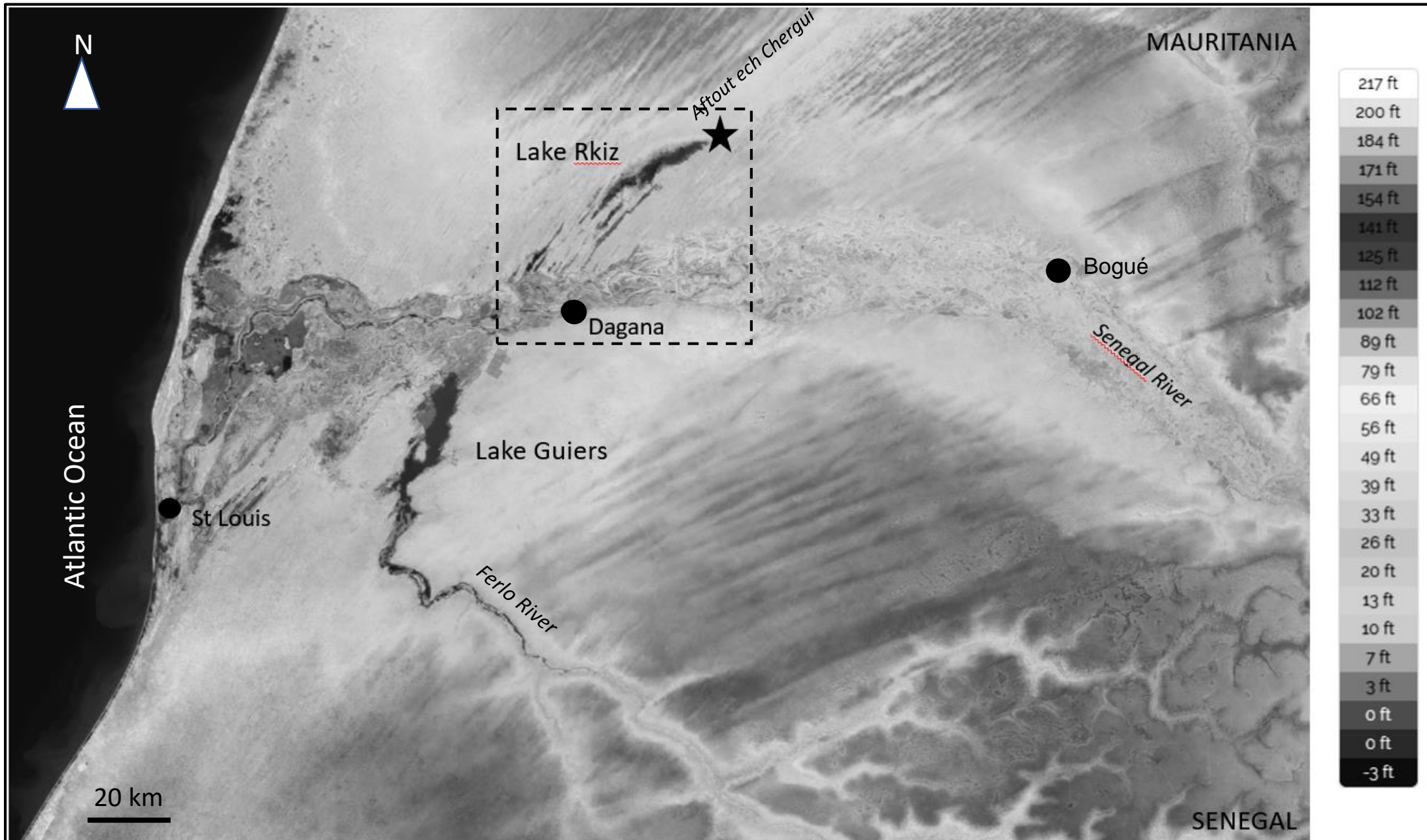
670

671 Figure 8: Synthetic diagrams showing the main features of the local (on the right) and
672 regional (on the left) environment of Lake Rkiz from 10 ka to the present. On the right,
673 mangrove pollen percentages (dark purple) are calculated against the sum of all pollen and
674 fern spores. Light shading shows the same results, multiplied by 10 for highlighting.
675 Percentages of mangrove (purple triangles) and marine (black dots) fauna are calculated
676 against the sum of all the determined mollusk shells (in black: power trend line). Only
677 samples with more than 20 determined remains are represented. On the left, pollen data are
678 presented under the form of phytogeographical group of plants from the most humid
679 (Guinean/Sudanian tropical taxa) to the most arid (Saharan desert) (aquatics and ferns
680 excluded from the pollen sum).

681

682 Figure 9: Modern (red dots) and Holocene (green dots) distribution of *Celtis toka* in tropical
683 West Africa. Pollen data are from the APD (<https://africanpollendatabase.ipsl.fr>), modern data
684 are from the GBIF (<https://www.gbif.org>) and MNHN (<https://www.mnhn.fr>) databases, and
685 the literature (Trochain, 1940; Hutchinson and Dalziel, 1954-1972). Simplified vegetation
686 map from White (1986).

A



Atlantic Ocean

N

20 km

MAURITANIA

SENEGAL

Lake Rkiz

Aftout ech Chergui

Dagana

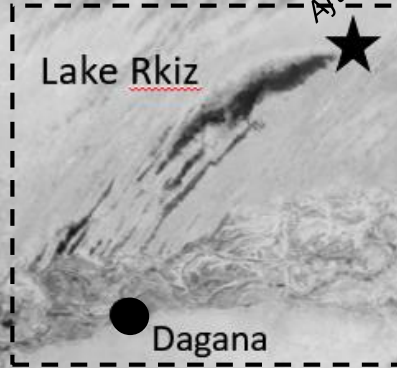
Lake Guiers

Ferlo River

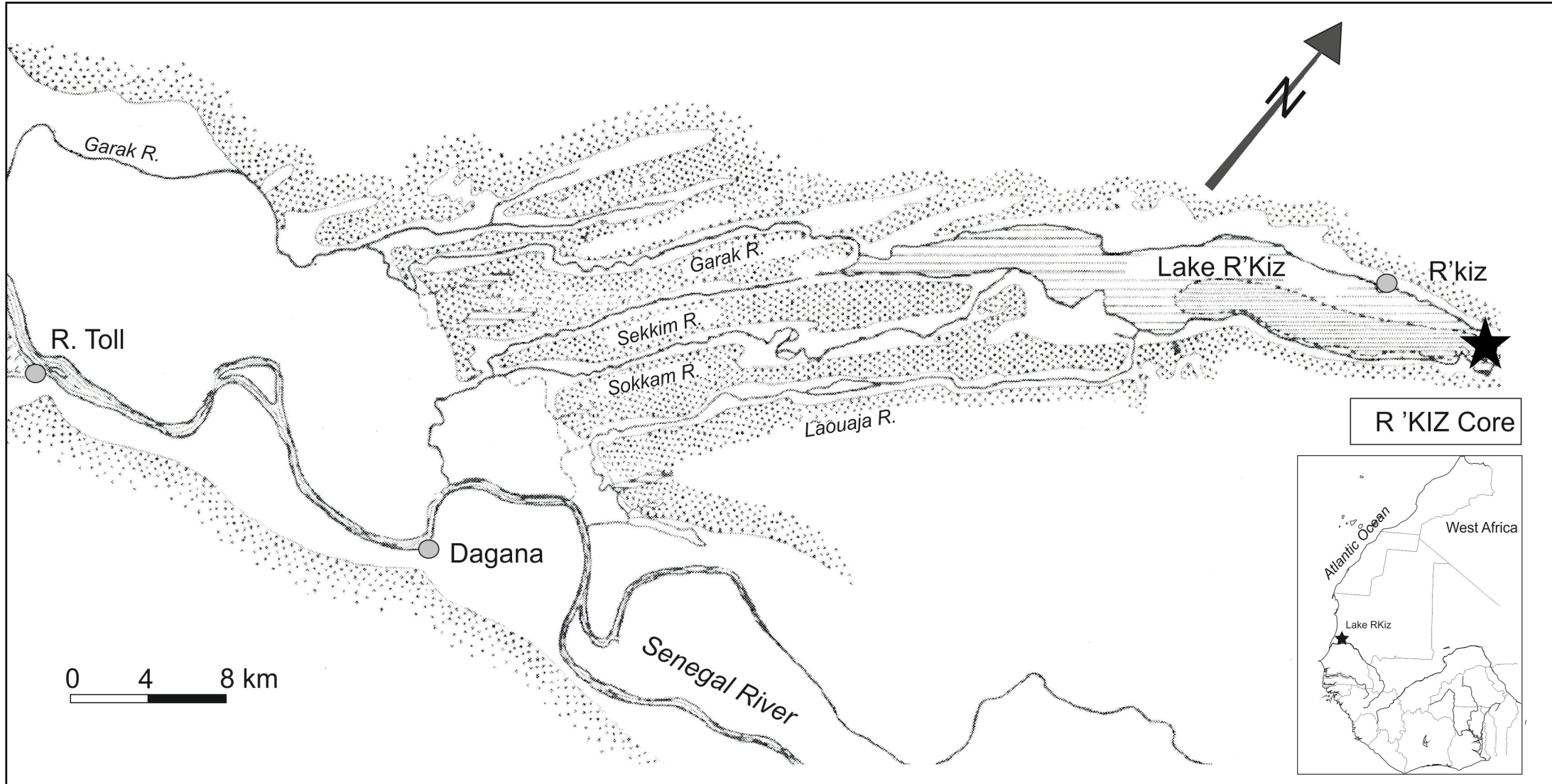
Bogue

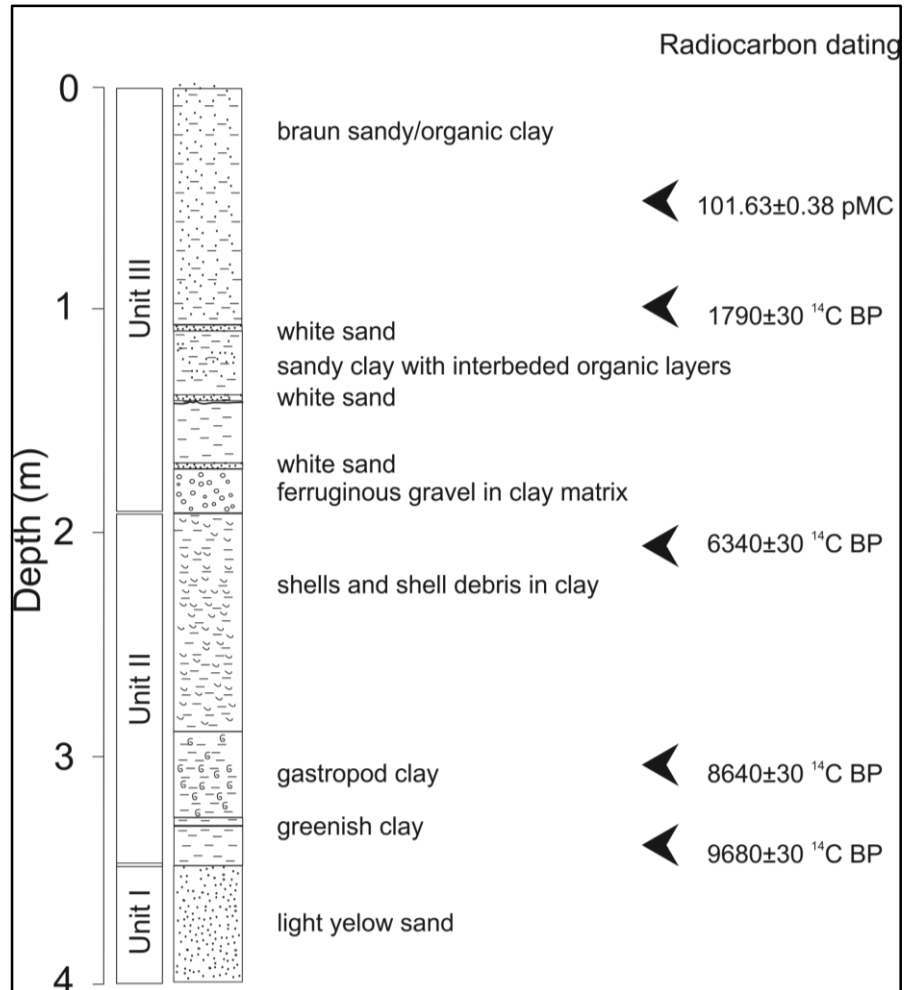
Senegal River

St Louis



B





Radiocarbon dating				
Mean depth (cm)	¹⁴ C age BP	error	Laboratory number	Material dated
5	101,63 +/-0,38		Beta-564997	Bulk organic
95	1790	30	Beta-564998	Bulk organic
205	6340	30	Beta-564999	Shells
245	6850	30	Beta-616716	Shells
285	7710	30	Beta-616717	Shells
305	8640	30	Beta-565000	Shells
325	9160	30	Beta-616718	Shells
345	9680	30	Beta-565001	Shells

