Reports

Geoidal Change and Shore-Level Tilt Along Holocene Estuaries: Sénégal River Area, West Africa

Abstract. *An expedition under "Projet Rhéomarge" traced marine deposits along the Sénégal estuary. Leveled and dated samples have made it possible to reconstruct portions of paleogeoids of 6500, 5500, and 1800 years before present. The surfaces of these geoids show that the tilt across continental margins predicted by mathematical models is less than 1 meter from the coast to 120 kilometers inland.*

Sea-level variations during the last 10^4 years (Holocene) have been related not only to the mass transfer of water and ice but also to gravitational changes arising from the earth's rheological properties (*1*). If the sea surface approximates the equipotential or geoid surface, measurements of shore-level displacement can reflect gravitational changes. Numerical models have been used to calculate possible global changes in relative sea level during postglacial time (*2*). The oceans have been divided into six zones, each of which has a characteristic curve of relative sea-level change (*3*). This study focuses on zone VI, which includes most continental margins and is a tilted transition zone between an ocean floor that is depressed by meltwater accession and a continental block that is raised by subcrustal mass transfer from under the oceans. Along a transect perpendicular to such a continental margin, the amount of emergence should therefore differ from the mouth of a long estuary to a point farther inland at its head (*3*).

The aim of "Projet Rhéomarge" (*4*) is to measure the elevation and age of former geoidal surfaces as represented by fossil water planes along well-chosen transects perpendicular to a continental margin, in order to test geophysical models and to improve our understanding of the earth's rheological properties. This report summarizes results obtained by Rhéomarge workers in the first test area, the Holocene estuary of the Sénégal River, including the Lake Rkiz and Ferlo Valley areas. Models (*2, 3*) predict in this region an emergence of about 4 m since 5000 years before present (B.P.) in a "continental" location and a submergence of 1.5 m in an "oceanic" location, 25 km beyond the continental margin.

The Sénégal River (Fig. 1) provides a favorable opportunity to investigate the transgression of Holocene sea-level rise in a lengthy estuary. At the mouth of the river, the tidal range is moderate and varies from 1.15 m at spring tides to 0.55 m at neap tides. During the low water stage (winter and spring), the river slope is less than 0.001 percent from the mouth to Podor (270 km inland) and the elevation of the bed remains below mean sea level as far as Bogué (380 km inland). As a consequence, the tidal oscillation penetrates far inland and the brackish-water interface is often found more than 200 km upriver. Even a very slight rise of sea level during a low water stage would cause marked ecological changes in the river. During flood discharge (usually from July to November, with the peak in September to October) the river slope increases to 0.002 to 0.003 percent and fresh water floods the shallow Rkiz and Guier basins. Extreme floods penetrated the Ferlo Valley before a dam was constructed in 1958 (*5*).

Deeply incised paleovalleys, now filled with Quaternary sediments (*5*), allowed the sea during Pleistocene time to penetrate several times very deeply into the African continent. The Holocene transgressions are the best known, owing to many radiocarbon-dated coastal deposits (*6*). In Holocene time, the Sénégal River area underwent large changes. Between 8870 and 8450 years B.P., the coastline was 10 km seaward on the continental shelf and along the lower part of the estuary as evidenced by fresh- and brackish-water peat found 23 m below sea level (*7*). After 7000 years B.P., the sea advanced far up the Sénégal estuary and penetrated between Pleistocene sand dunes, forming extensive shallow bays and lagoons. This transgression left fossil marine shell beds as far as Lake Rkiz, more than 120 km from the present coast. Between 4000 and 1800 years B.P., the shoreline prograded westward as longshore drift built a thick sandbar at the present coast that isolated former bays and lagoons from the sea and forced the river mouth southward (*5*). At about 2000 years B.P., a final marine transgression reentered the Sénégal River, leaving evidence of brackish environment far up the Ferlo Valley.

Accurate data on former sea levels require precise altimetric control on reliably dated samples that have been re-

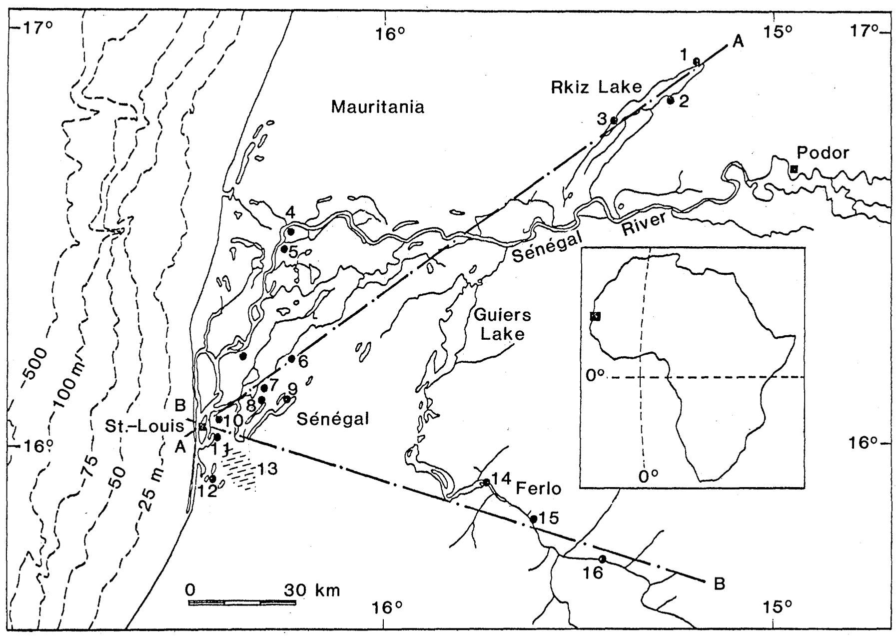

Fig. 1. Location map of the investigated area.

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lated to former water planes by clearly established ecological associations.

Elevation. The IGN (Institut Géographique National) first-order leveling, together with several levelings performed by other institutions, provides a dense network of benchmarks to which field data may be related. All levelings are relative to the IGN datum, that is, the 1942 to 1945 mean tide level in Dakar. At St. Louis near the mouth of the Sénégal River, the average tide level is about 0.05 m above the IGN value. Because of its uniform gentle slope, river level affords a datum to which to refer the elevation of nearby localities, especially if benchmarks allow control of water level and slope. Thus, in most cases, the elevation of Holocene marine deposits can be determined to within ± 0.3 m.

Carbon-14 age determinations. About 30 carefully collected samples at precisely leveled localities were used to construct time-distance-elevation diagrams. New measurements were repeated on samples collected from inland localities.

Holocene sea-level estimation. The vertical relationship of dated samples to sea level is usually difficult to establish accurately. The most realistic approach consists of referring fossil assemblages to comparable modern ecological associations (*8*). *Arca senilis* lives in shallow lagoons and estuaries at depths of 0.5 to 1.0 m. *Tympanotonus fuscatus* lives in the intertidal zone. Peat, especially of mangrove swamps, is also found near the intertidal zone. Thus, it is usually possible to estimate the former mean sea level with an accuracy of better than ± 0.5 m.

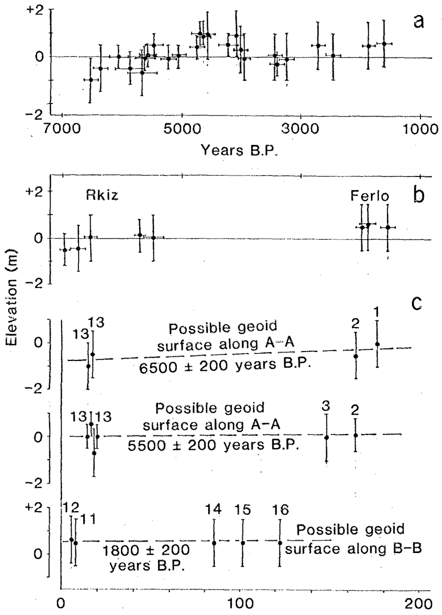

Fig. 2. Time-depth (a and b) and time-distance (c) diagrams of the investigated sea-level data. Samples collected near the present shoreline are plotted in (a), samples collected more inland in (b). For locations, see Fig. 1 and Table 1. The hypothetical geoidal surfaces (c) are almost parallel during the last 6500 years.

The salient features of the dated material that could be closely related to sea level are summarized in Table 1. The data are plotted in Fig. 2 to reveal local sea-level variations as a function of time, both for points near the present coast (Fig. 2a) and farther inland (Fig. 2b). The general trends found in earlier investigations (*6*) are confirmed. Sea level has been within 1 or 2 m of its present position since 6000 years B.P. However, there are some geographical anomalies. Coastal data from the St. Louis area range widely in age from 6500 years B.P. to recent time. Inland data are more localized in space and in time. The oldest dates are concentrated in the north

Table 1. Location and elevation of dated sea-level indicators in the Sénégal River area.

Locality				Elevation (m, IGN)					
Label (Fig. 1)	Name	Latitude (N)	Longitude (W)	Sample	Paleo sea level	Material	Age (years B.P.)	Laboratory No. (sample No.)	Source
5	Eudoxie borehole	16°30′	16°17′	−23.0 ± 1.0	−22.0 ± 2.0	Peat	8870 ± 240	Ly-1269	(*7*)
4	Lea borehole	16°30′	16°17′	−23.5 ± 1.0	−22.5 ± 2.0	Peat	8450 ± 220	Ly-1270	(*7*)
2	Rkiz	16°51′	15°16′	−1.0 ± 0.5	−0.5 ± 0.7	Shells	6970 ± 90	(Rk 3D)	This study
2	Rkiz	16°51′	15°17′	−1.0 ± 0.5	−0.5 ± 1.0	*A. senilis*	6740 ± 130	I-2928	(*6*)
13	Rao-Gandon area	15°57′	16°26′	−2.1 ± 0.1	−1.0 ± 1.0	*A. senilis*	6540 ± 130	Gif-4260	(*9*)
1	Rkiz	16°55′	15°11′	−0.2 ± 1.0	0.0 ± 1.0	*A. senilis*	6520 ± 100	(Rk 5)	This study
13	Rao-Gandon area	15°57′	16°26′	−1.4 ± 0.1	−0.5 ± 1.0	*A. senilis*	6360 ± 130	Gif-4261	(*9*)
7	Ndielem	16°08′	16°20′	−0.1 ± 0.2	0.0 ± 0.5	Peat	6060 ± 150	Ly-1930	(*10*)
6	Mbodiène	16°12′	16°16′	−0.5 ± 0.5	−0.5 ± 0.7	Peat	5895 ± 250	(R 3)	This study
2	Rkiz	16°51′	15°16′	−0.4 ± 0.5	+0.1 ± 0.7	*A. senilis*	5700 ± 90	(Rk 3B)	This study
13	Rao-Gandon area	15°56′	16°26′	−1.3 ± 0.1	−0.7 ± 1.0	*A. senilis*	5670 ± 240	Ly-1345	(*10*)
13	Rao-Gandon area	15°57′	16°26′	−0.9 ± 0.1	0.0 ± 0.5	*A. senilis*	5650 ± 150	Ly-985	(*11*)
13	Rao-Gandon area	15°56′	16°25′	−0.5 ± 0.1	0.0 ± 0.5	*A. senilis*	5590 ± 140	Ly-987	(*11*)
13	Rao-Gandon area	15°56′	16°26′	+0.4 ± 0.1	+0.5 ± 0.5	*A. senilis*	5470 ± 110	T-463	(*6*)
3	Rkiz	16°47′	15°25′	−0.5 ± 0.5	0.0 ± 1.0	*A. senilis*	5465 ± 120	(Rk 6)	This study
13	Rao-Gandon area	15°54′	16°26′	−0.5 ± 0.1	0.0 ± 0.5	*A. senilis*	5250 ± 120	Ly-983	(*11*)
13	Rao-Gandon area	15°55′	16°25′	−0.5 ± 0.1	0.0 ± 0.5	*A. senilis*	5070 ± 120	MC-1562	(*9*)
9	Ndiasseou	16°05′	16°17′	+0.4 ± 0.2	+0.4 ± 0.5	Peat	4750 ± 130	Gif-1450	(*5*)
13	Rao-Gandon area	15°56′	16°25′	+0.8 ± 0.1	+1.0 ± 0.5	*A. senilis*	4720 ± 140	Ly-986	(*11*)
13	Rao-Gandon area	15°54′	16°26′	+1.1 ± 0.1	+1.0 ± 0.5	*A. senilis*	4670 ± 120	Ly-982	(*11*)
13	Rao-Gandon area	15°55′	16°26′	−0.1 ± 0.1	+0.5 ± 0.5	*A. senilis*	4220 ± 160	Ly-1344	(*10*)
8	Khant	16°03′	16°21′	+0.8 ± 1.0	+1.0 ± 1.0	*A. senilis*	4080 ± 120	I-2774	(*6*)
13	Rao-Gandon area	15°57′	16°26′	−0.7 ± 0.1	+0.3 ± 1.0	Shells	4010 ± 110	MC-1563	(*9*)
13	Rao-Gandon area	15°58′	16°26′	−0.8 ± 1.0	0.0 ± 1.0	*A. senilis*	3970 ± 105	I-2294	(*6*)
13	Rao-Gandon area	15°57′	16°26′	−0.5 ± 0.1	0.0 ± 1.0	*A. senilis*	3430 ± 100	Gif-4259	(*9*)
13	Rao-Gandon area	15°57′	16°26′	−0.3 ± 0.1	−0.3 ± 0.5	*T. fuscatus*	3410 ± 130	Ly-984	(*10*)
13	Rao-Gandon area	15°55′	16°27′	−1.0 ± 0.5	0.0 ± 1.0	*A. senilis*	3250 ± 110	I-2298	(*6*)
10	Aviation St.-Louis	16°03′	16°27′	+0.7 ± 0.1	+0.5 ± 1.0	Shells	2710 ± 100	I-2297	(*6*)
13	Rao-Gandon area	15°58′	16°27′	0.0 ± 0.5	0.0 ± 1.0	*A. senilis*	2470 ± 110	I-2295	(*6*)
14	Diellel	15°53′	15°46′	+0.5 ± 0.5	+0.5 ± 1.0	*T. fuscatus*	1980 ± 100	(F 3)	This study
11	Sor	16°00′	16°29′	+0.8 ± 0.1	+0.5 ± 1.0	Shells	1880 ± 100	I-2296	(*6*)
16	East of Mbeyene	15°40′	15°30′	+0.5 ± 1.0	+0.5 ± 1.0	*T. fuscatus*	1860 ± 120	(F 9A)	This study
12	Ndel-Gandiol	15°54′	16°29′	+0.6 ± 0.1	+0.6 ± 1.0	*A. senilis*	1620 ± 120	Gif-363	(*6*)
15	Naudi	15°48′	15°39′	+0.5 ± 1.0	+0.5 ± 1.0	*T. fuscatus*	1545 ± 120	(F 8)	This study

(Rkiz), and the youngest ones are in the south (Ferlo).

Sea-level data are also plotted in terms of distance from the present coast (Fig. 2c). This transect profiles the geoid at different times and shows little change in the parallelism of successive geoid surfaces. From 6500 years B.P. to the present, the tilting seems less than ± 1 m. No clear evidence of crustal tilting is observed for more recent geoids.

In conclusion, if the slight emergence simulated by models is in any way evident in this 120-km transect of West Africa, its seaward tilting is limited. This result seems to imply that the lithosphere is more rigid than has been assumed in models.

H. FAURE
Laboratoire de Géologie du Quaternaire, Centre National de la Recherche Scientifique, Case 907, Faculté des Sciences de Luminy, F-13288 Marseille Cédex 2, France
J. C. FONTES
Laboratoire d'Hydrologie et de Géochimie Isotopique, Bâtiment 504, Université Paris-Sud, F-91405 Orsay Cédex, France
L. HEBRARD
Laboratoire de Géologie du Quaternaire, Centre National de la Recherche Scientifique, Faculté des Sciences, Université de Dakar, Dakar-Fann, Sénégal
J. MONTEILLET
Laboratoire de Géologie, Institut Fondamental d'Afrique Noire, B.P. 206, Université de Dakar
P. A. PIRAZZOLI
Laboratoire de Géomorphologie, Ecole Pratique des Hautes Etudes, F-92120 Montrouge, France

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Upper Wisconsinan Till Recovered on the Continental Shelf Southeast of New England

Abstract. *Basal till was identified in two sediment cores collected about 69 kilometers southeast of Nantucket Island on the east and west sides of Great South Channel. These are the first samples of till collected on the outer continental shelf off the northeastern United States. The carbon-14 age of the total organic carbon in the tills provides a "no older than" age of about 20,000 years before present and suggests that the tills were deposited during the late Wisconsinan glaciation. This conclusion is in support of the hypothesis of an extensive Laurentide ice sheet that extended to the northern side of Georges Bank.*

A number of features on the continental shelf off the northeastern United States have been cited as evidence for Pleistocene glacial ice in areas seaward of the present shoreline. The location of gravel in surface sediments has been used to estimate the southern limit of glacial ice on Nantucket Shoals and along the northern edge of Georges Bank (*1*). Moraine-like features have been observed in high-resolution, seismic-reflection profiles of the shelf south of Martha's Vineyard (*2*). Glacial ice in the Gulf of Maine has been inferred from the morphology of the deep closed basins in the central area of the gulf (*3*) and from the morphology of Northeast Channel, which resembles a glaciated valley (*4*).

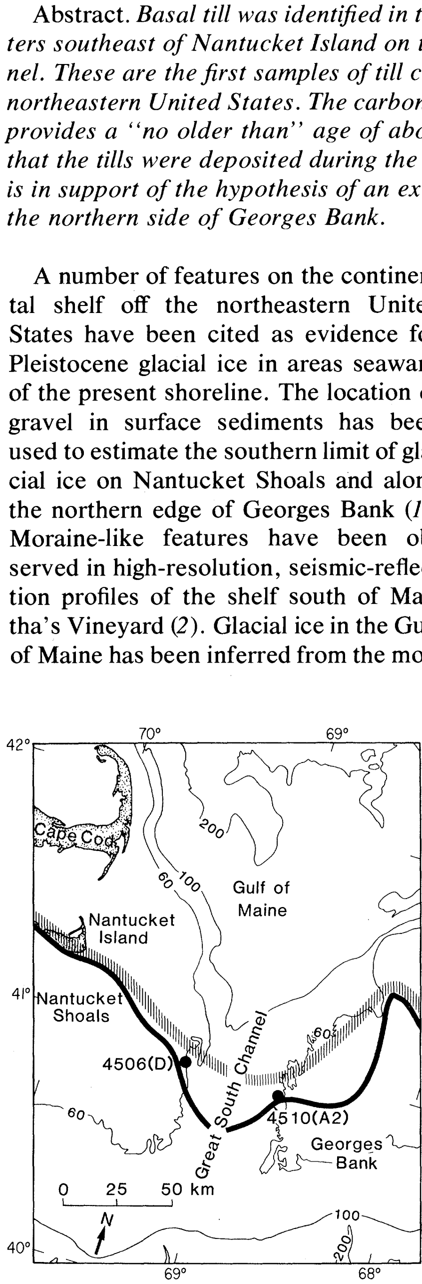

Fig. 1. The locations of vibrocores on the east and west sides of Great South Channel are indicated by the black circles. The heavy line designates the southern limit of abundant gravel, and the vertical series of short lines indicates the southern limit of probable late Wisconsinan ice advance (*1*). Bathymetric contours are in meters.

The glacial features presently recognizable on the continental shelf are generally assumed to be of late Wisconsinan age because multiple regressions and transgressions of sea level would have tended to obliterate evidence of earlier glaciations. Evidence confirming the existence of late Wisconsinan ice on the continental shelf off New England is lacking, however, because ice-contact sediments have not been recovered for dating.

The presence of late Wisconsinan ice seaward of Cape Cod is documented from reworked, carbonitized wood found in glacial outwash on the outer cape. The wood has a radiocarbon age of 26,000 ± 2,000 years before present (B.P.) (*5*) and gives a maximum age of the last advance of ice. On Martha's Vineyard, leaves in clay stratigraphically below till are dated at 15,300 ± 800 years B.P. (*6*).

We describe here till recovered in two sediment cores (*7*) from the continental shelf southeast of Nantucket Island at water depths of 49 and 60 m (Fig. 1). We discuss the interpretation of ^{14}C ages determined on the total organic carbon in these sediments.

The sediment texture throughout core 4506(D) is similar to that of till. Samples consist primarily of sand, but measurable quantities of gravel, silt, and clay are also present (*8*). Scattered subangular and subrounded cobbles, as much as 8 cm in diameter and having sharp irregular edges, were found in this

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