Journal of Coastal Research	4	3	369–379	Charlottesville, Virginia	Summer 1988

Genesis of a Holocene Phosphate Placer Deposit on the Continental Shelf of Congo

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ABSTRACT

BARUSSEAU, J.P.; GIRESSE, P., AND MANONGO, L., 1988. Genesis of a Holocene phosphate placer deposit on the continental shelf of Congo. *Journal of Coastal Research*, 4(3), 369–379. Charlottesville (Virginia), ISSN 0749-0208.

Phosphatogenetic events occurred at several times between Maastrichtian stage and Miocene period in the Congo-Cabinda sedimentary basin. The structural evolution and eustatic movements locally controlled the subsequent formation of a Miocene phosphatic "preconcentrated" beach-rock. One of them, forming a shoal, outcrops off Djeno (Congo). During Quaternary sea-level variations the sediments were reworked; in consequence the modern form of the most accessible phosphatic sediments is the result of the last phase of the postglacial transgression, during which a stabilized level of the sea eroded the shoal.

A textural study was conducted on the Holocene sediments sampled by gravity cores and vibracores. A sorting pattern of the modal phosphatic populations of grain-size assemblages is presented, which points out the role of the wave refraction in the genesis of the transport and the deposition of particles. This conclusion does not support the idea of onshore transport. In spite of a lack of a good understanding of the hydrodynamic behaviour of phosphatic particles, the directions of possible concentration are assumed on the basis of drastic changes in modal values, reconstruction of longshore currents and evidence of convergent transport directions. Consequently, the mechanical reworking, which is not a genetic process of phosphates, played a major role to concentrate the deposit whose economical potential may be significant in a regional context.

ADDITIONAL INDEX WORDS: *Mechanical sorting, wave regime, phosphate placer, Holocene, Atlantic Ocean, Congo.*

INTRODUCTION

The offshore Congo phosphate deposits were first observed during dredging and coring operations, along the continental shelf of Gabon and Congo, between 1971 and 1979. The most important accumulations are located about 10 km from the coast, south of Pointe Noire harbour, off Djeno, at a 35-50 m depth, but other deposits may be observed scattered across the outer Gabonese shelf (GIRESSE and CORNEN, 1976; MALOUNGUILA-NGANGA, 1987). This paper describes phosphatic limestones from the Eocene, phosphatic conglomerates from the Miocene and the intertonguing coprolitic phosphate gravel encountered in the Congo offshore deposits. In a previous paper, GIRESSE *et al.* (1984) described the unconsolidated phosphate concentrate and its economic potential due to the relative ease with which it could be mined and processed. Two preliminary feasibility surveys were carried out during 1982 and 1983 on behalf of the United Nations Revolving Fund for Natural Resource Explorations (WOOLSEY *et al.*, 1984).

87025 received 28 June 1987; accepted in revision 3 December 1987.

In this paper, the main objective is to characterize the marine depositional environments in the Cenozoic and Quaternary assemblages of phosphatic sediments. Phosphatic layers were also recovered in Holocene sediments with textural variations and distributions of phosphatic clasts which demonstrate that an onshoreward movement during the transgression was not the dominant component of the particle transport. Hence, particular attention will be paid to ascertain the nature of the Holocene hydrodynamic regime of the area.

STUDY AREA AND GEOLOGICAL SETTING

The study area is located on the African shelf in the Atlantic equatorial zone. It lies within the Bas Congo-Cabinda sedimentary basin, one of the equatorial marginal basins that form a nearly continuous strip of Mesozoic to recent deposits along the west central coast of Africa (Figure 1).

The formation of this basin is related to the tectonics of the South Atlantic Ocean opening, beginning during the late Jurassic: (1) a lower continental fluvio-lacustrine sequence is attributed to the first phases of the rifting, (2) a mid-

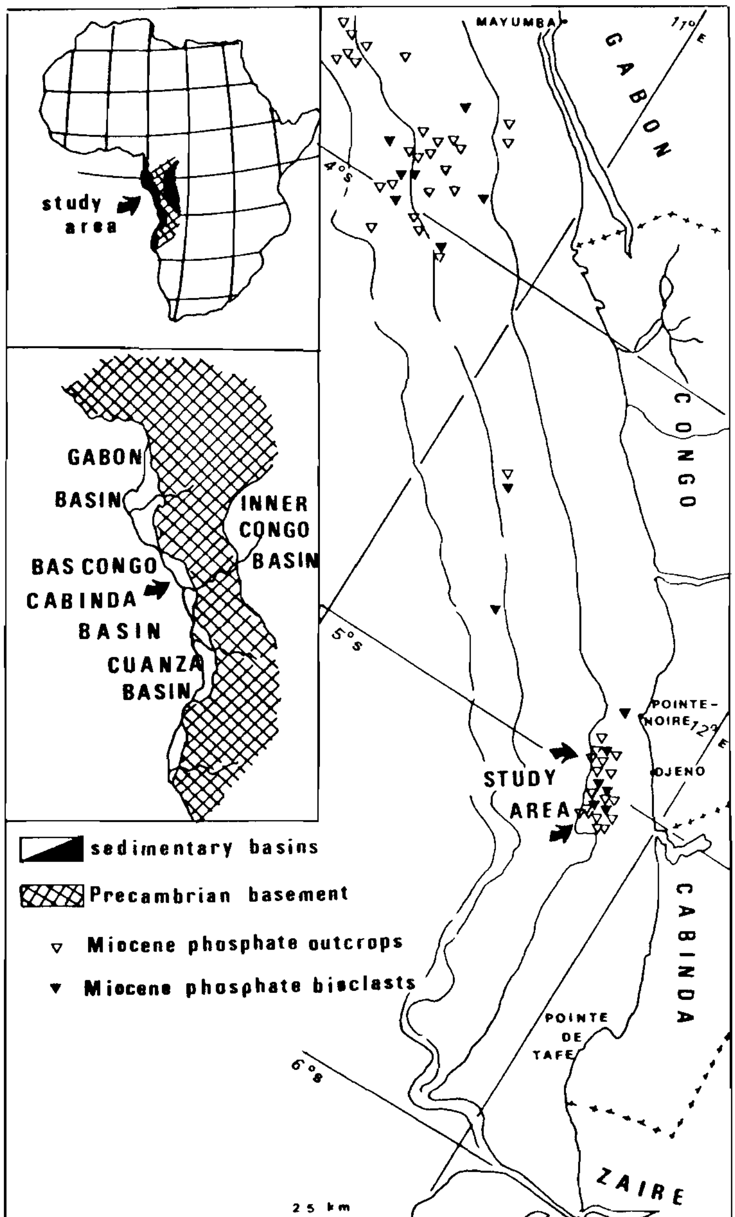

Figure 1. Location of the study area.

dle evaporitic sequence represents an earlier Aptian stage when the basin was subject to a restricted oceanic circulation, and (3) an upper marine sequence, commencing in the late Aptian stage, was deposited in a subsiding basin and thickens substantially seaward. With the exception of the detrital Cenomanian deposits, the marine littoral sediments are predominantly transgressive. The phosphate deposits of Congo are restricted to this upper marine sequence.

The earliest phosphatic sequence reported for this basin is the Holle Series of Maastrichtian age which occurs onshore, towards the eastern margin, near the Mayombe Precambrian massif. The beds are predominantly a coarse basal conglomerate with an extensively leached and weathered upper part. In Cabinda, at Landana, Paleocene beds consist of alternating thin layers of calcareous sandstones and thick layers of sandy clays containing phosphatic debris as coproliths. The Eocene deposits of the basin occur in isolated outcrops onshore and rest unconformably on Paleocene strata.

On continental shelf, the Paleocene and Eocene beds are folded along 110-120° trend, which is at a 20° angle to the coastline. A long period of emergence occurred from late Eocene through Oligocene, and a Miocene transgression deposited material on an irregular erosion surface. The Miocene deposits of the continental shelf occur as isolated patches scattered over Eocene strata, and one of these forms the shoals observed off Djeno.

The area of this study covers approximately 180 square kilometers including a steep shoreface (gradient about 0.012 between 0 and 14 m), decreasing progressively (0.0055 between 14 m and 28 m; 0.0023 between 28 m and 50 m). However, it is a rather regular slope in plan, with isobaths roughly parallel to the coast (Figure 2).

METHODS OF INVESTIGATION AND SAMPLE ANALYSIS

A geophysical survey using a mini-sparker type sub-bottom profiler, a dual side-scan sonar and a precision depth recorder was conducted. Data relating to the general bathymetry, the extent of bedrock outcrops and the topography of the bedrock on which sediments were deposited, were collected and used for the selection of sample sites. Vibracore samples (n = 142), with a maximum length of 3 meters, were taken on or near the outcrop; in addition 8 gravity cores and 14 bucket dredges were performed. Mineralogical, petrographical and geochemical examinations of the phosphates were realized using optical microscopy, scanning microscopy and X-ray diffraction. The thin sections used for optical examination were also analysed with a microprobe (CAMEBAX). To determine the mechanical method of the phosphate particle concentration and the actual extent of the outcrop, a granulometric study was undertaken and correlated to the swell action and to sea-level variations. Modal formulas and mode statistics were used to determine sedimentary types and to characterize the net transport due to the swell action.

STRATIGRAPHICAL, PETROLOGICAL AND MINERALOGICAL ANALYSES

Stratigraphical Position and Geological Setting of the Phosphate Deposits

The differential erosion during the regressive phases determined the relief of the most resistant layers (mainly carbonate and phosphates) and formed a shoal in the study area (GIRESSE and CORNEN, 1976). Paleocene strata consist of thin white beds of limestones, fine clays, phosphatic sandstones and foraminiferal sands. Microfauna and microflora indicate a Paleocene age for the limestones and the foraminiferal sand and a Early to Middle Eocene age for phosphatic sandstones or limestones. In these last strata, we observed chalky, phosphatic and elongate pellets with a size ranging from about 10 to 17 mm.

A long period of emergence occurred from Late Eocene through the Oligocene during which the Paleocene beds were partially reworked. In particular, the pellets were freed, oxidised and subsequently cemented by calcite into the shoreline lithofacies of the Miocene transgression. This beach-rock is the most frequent facies, but lateral variations are observed: calcareous sandstone or clay, as well as a phosphatised variety. Palynological analyses indicate a Neogene age for the sandstone and the cement of the beach rock, and a Paleocene age for the coproliths.

Further uplift occurred during the Pliocene.

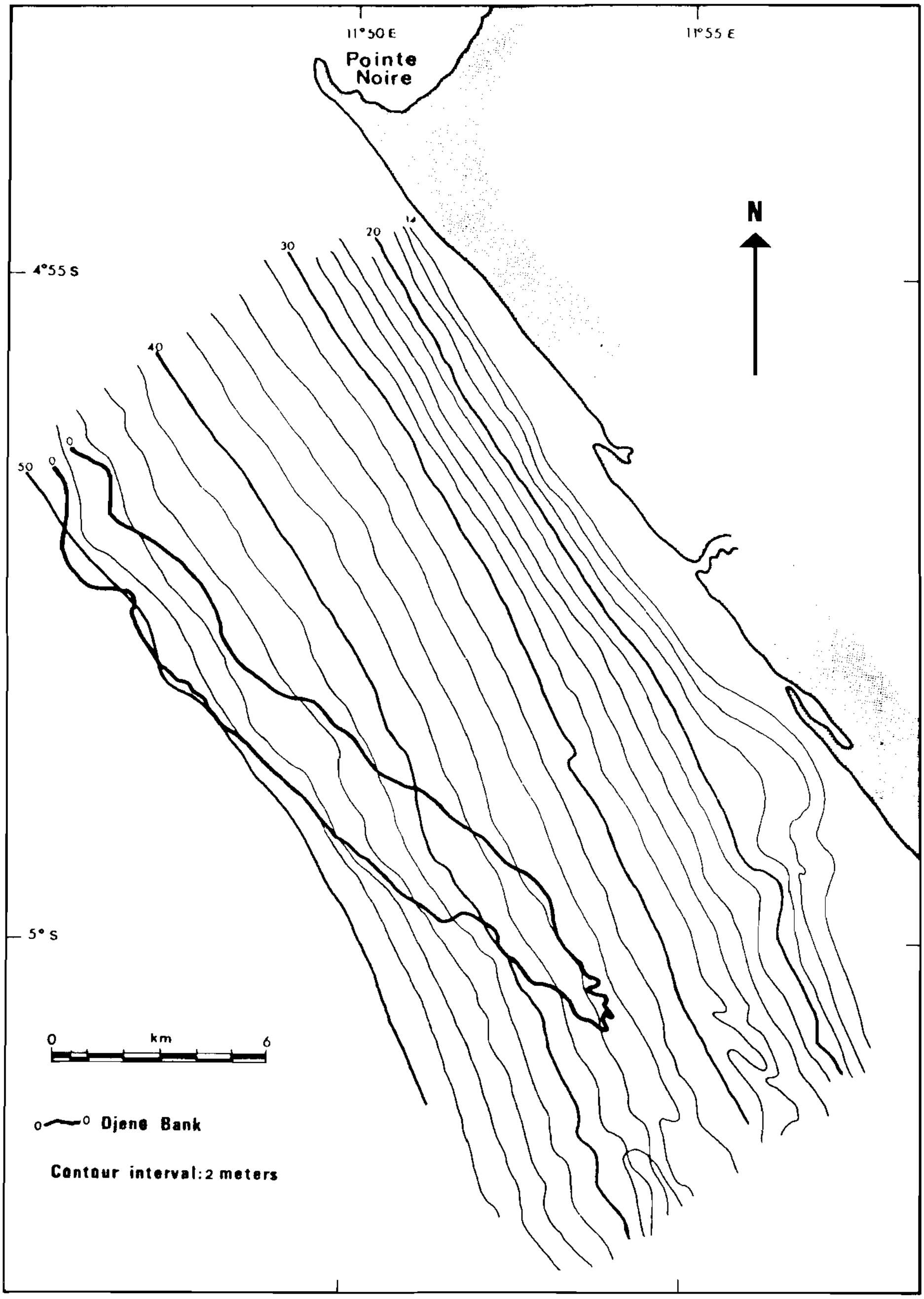

Figure 2. Bathymetric chart of the study area (from BARGERON, 1984). The O-contour is the limit of the phosphatic bank.

Then quartz sands and gravels including laterite clasts were deposited in the depressions of the bedrock forming the "Série des Cirques" which is an equivalent to the "Continental terminal" of the Congo. During the late eustatic rises and falls of the sea-level, leaching, alteration and reworking occurred to produce the final Holocene deposit.

Petrological Observation

Small fragments of Miocene conglomerate with a calcitic cement, or phosphatic sandstones were sometimes recovered, but generally the phosphorites are elongate and cylindrical Selacian fecal pellets associated with broken shells of the epifauna, and various amounts of mud and glauconite. The size of the coproliths ranges from about 3 to 20 mm, averaging about 7 mm, occasionally with marks related to the anal spiral valvula. The deposits are not barren of fossils, as proposed by BARGERON, Selacian or Skate palatine teeth are quite common. The brown shiny coproliths form approximately 95% of the dredge samples, instead in the vibracore samples, the coproliths are mixed with white and light-colored pellets. The white pellets are less indurated than the dark pellets; so, the specific gravity is lower than in apatite constituents, due to the porosity; the average gravity is 2.65, but it seems that the white pellets have an even lower specific gravity (as low as 2.22).

In this section, all fecal pellets consist almost entirely of an isotropic cryptocrystalline apatite phase with minor inclusions of calcite and quartz. The texture is heterogeneous, with convolutions underlined by small organic inclusions, or by the extinction of bands of crystalline apatite. The greatest heterogeneity occurs in the pellet margins where we observe calcite grains attached along the edges of pockets of cryptocrystalline apatite. Frequently iron staining occurs on the margin of debris due to the alteration. Often the staining exists throughout the pellet or penetrates from the margins along a small fracture; rarely is the inner part dark and the margin light colored. White coproliths seem to be characterized by a higher content of amorphous apatite.

Mineralogical and Geochemical Descriptions

All samples exhibited similar or very similar X-ray diffractograms of carbonate-fluorapatite species known as francolite, regardless of their color, texture, size or sample location. Goethite was identified in several samples which were particularly iron-stained. Minor amounts of quartz and calcite were also noted. Unit cell parameters of the hexagonal-lattice francolite mineral were measured, where changes in the parameter are inversely proportional to the amount of substitution, particularly of PO_4 by CO_3 (McLELLAN and LEHR, 1969). The range of α-values has been calculated to be 9.155 to 9.347 Å (9.320 to 9.327 Å in BARGERON), indicative of a highly substituted francolite. Carbonate values calculated by Gulbransen's method, which measures only lattice CO_3, range from 4.2 to 6.63% indicating a moderate amount of weathering far less severe than the onshore Maastrichtian deposits (GIRESSE, 1980). Microprobe analysis shows small quantities of superficial aluminium, but X-ray diffraction did not identify the crandallite.

The Djeno coproliths are characterized by a relatively small variation in the percentage composition of nearly all the major constituents (P_2O_5, CaO, CO_3, Na_2O, F, Mg). The most important variation is attributable to iron, which shows frequent enrichment in the crown of the pellet (2 to 4%, one sample in excess of 10%). The effects of the removal of Na_2O, Sr, SO_4 and CO_3 by weathering is moderate (BARGERON, 1984), and comparable to that of the Moroccan shelf phosphorites (McARTHUR, 1978). Typically phosphorite coproliths exhibit a P_2O_5 content of about 26-32%, average F/P_2O_5 ratios of 0.125 and average CaO/P_2O_5 ratios of 1.65.

The uranium content is between 20 and 150 ppm which is a consistent value with that of marine phosphorites (ALTSCHULER *et al.*, 1958). However, microprobe analyses in the inner part and in the crown of coproliths show a significant concentration (x4) in uranium relatively to iron enrichment. Uranium, for the most part fixed and tetravalent, is mobilized after the deposition and shows radial changes in concentration which appear related to the organic matter distribution. Off Djéno the distribution of these Holocene phosphate deposits was obtained by the α-radioactivity field.

In summary the relatively moderate degree of weathering suggests only limited periods of subaerial exposure. The phosphatogenetic Miocene sea allowed a rapid reworking, before carbonate or apatitic cementation. Neither an extreme nor a prolonged weathering sequence is suggested by our data. It is difficult to draw definite conclusions about the age of the suc-

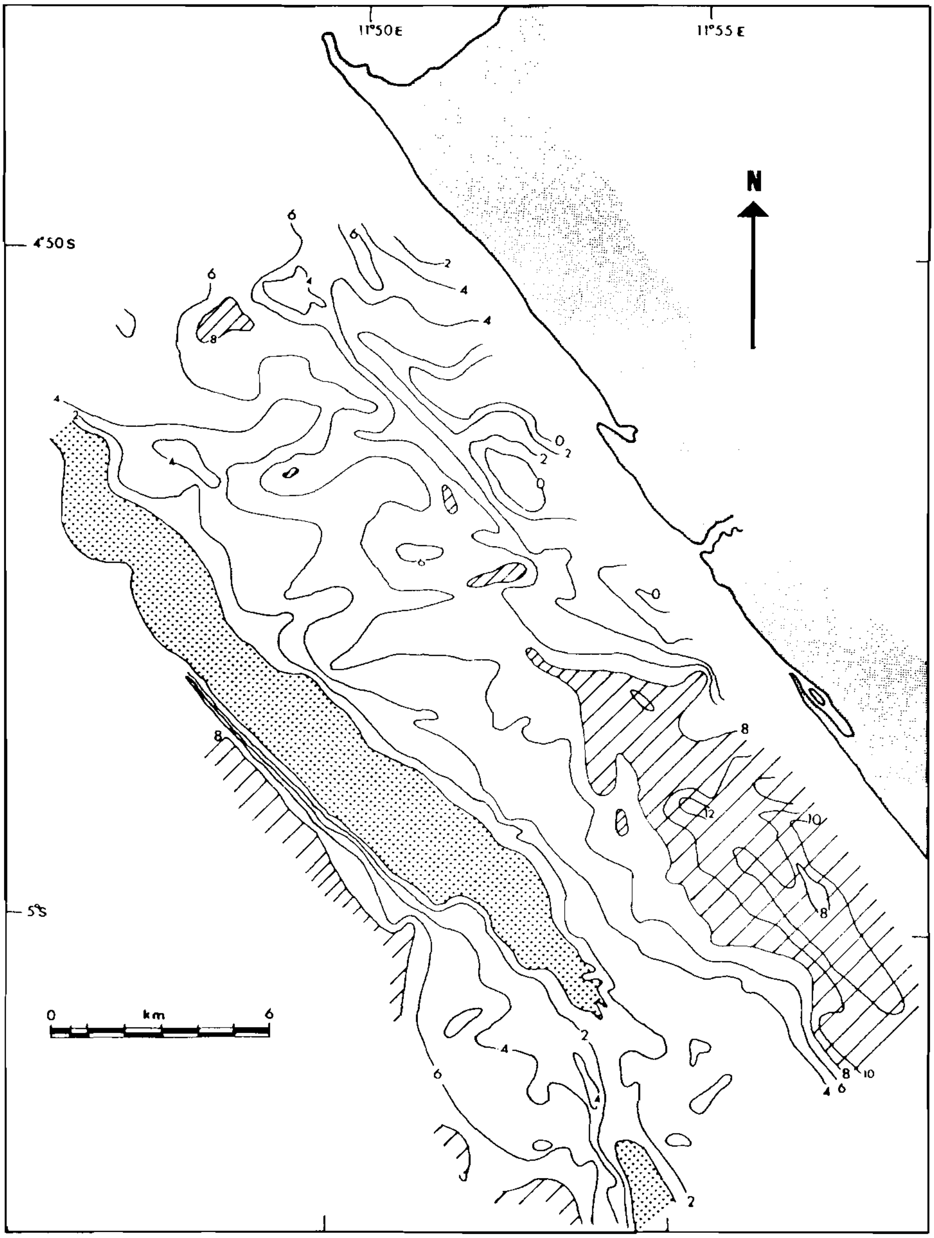

Figure 3. Relative Holocene bathymetric map of the study area (modified from BARGERON, 1984). The paleobathymetry is derived directly from the isopach map. Reference surface is the present slope of the shelf. Hatched zones are deeper than −8 m below the present sea floor. Dotted zones correspond to unchanged morphology.

cessive reworkings, but it seems that the last periods of emergence and transgression were particularly efficient with respect to this accumulation, and we will now consider the Holocene depositional process.

FORMATION OF THE HOLOCENE PHOSPHATIC PLACER

Despite the regular pattern of modern isobaths, the paleobathymetry (Figure 3) was not even. The Miocene shoal is flat and falls sharply on both sides (up to 8 m on the southwestern slope and from 3 to 4 m on the northeastern one). Between the bank and the present coast, an irregular trough (lying 10 to 20 m below the bank crest) deepens to the SE. The whole feature is buried under unconsolidated Holocene sediments composed mainly of muds from the Congo River and deposited within a clockwise gyre as a part of the Congo plume. In the littoral zone sands are prominent. This Holocene sedimentary sequence is very thin or absent on the bank itself, whose upper part outcrops. Due to its oblique position, the bank is shallower at its southeastern end, while the NW end lies between 47 and 50 m (Figure 2). The pre-Holocene bathymetry can be divided into three regions: (1) the tabular surface of the bank, 2 to 3 km wide, whose top was karstified with irregular pockets and pits about 1 m deep; (2) the bank slopes, steep on the open sea, but gentler and lower on the trough side; (3) the trough.

The last post-glacial rise of sea-level intersected abruptly with the pre-Holocene morphology. The area was covered between 9 to 7000 years BP after a rapid rise of sea level from the previous stand. It is important to consider the effects of this transgressive deceleration or stopping for one or two thousand years, a sufficiently prolonged period to produce extensive sedimentary units in a littoral and shoreface environment. It was a unique period for Holocene littoral placer formation and deposition of reworked material from both the Miocene conglomerate and, at a lesser extent, from the Paleocene phosphatic limestone. In fact, between the stillstands, the high rate of transgression prevented any deposition. Unfortunately, during exploration of the deposit, the survey and the sampling pattern were based on the assumption that the fast transgressive Holocene sea, after sweeping the bank, deposited detrital particles in the trough, especially on its south part (the NE slope of the bank). Therefore, 60% of the 150 cores were taken in this flank region and in the trough.

Sedimentary Types of the Phosphatic Holocene Sediments

Grain-size analyses were performed at 30 cm intervals on a selected number of vibracores and gravity cores (27). Each polymodal curve was considered as a mixture of unimodal sedimentary components, whose characteristics were graphically extracted by using an analysis method described in a previous work (BARUSSEAU, 1973) and by writing a modal formula which involves the different basic grain-size values (= mode), and the corresponding percentages directly estimated from the cumulative curve. Modal values cluster also into a limited number of populations. These populations may be extracted from the cumulative frequency curve of all the modal values given by the different modal formulas depicting the different grain-size curves. Each mode population is considered as a sedimentary type which is assumed to be a sedimentological entity having its own origin and geological history or to represent different responses to a given hydrodynamic regime because of various shapes of particles.

In the study area six sedimentary types have been distinguished: (1) a clay-silt assemblage and (2) a coarse-silt population, both originating from Congo estuary and deposited under low energy conditions in various environments (offshore, back-barrier or lagoonal), (3) a fine sand population, representing a littoral environment; (4) (5) and (6) three populations (medium sand, coarse sand and gravel) each with a phosphatic fraction. The usual presence of several sedimentary types to constitute the grain-size assemblage evinces the proximity of different sources but, generally, only 4 or 5 sedimentary types are represented in the sediments, because types (1) and (2) are mutually exclusive, and the coarsest types are sometimes absent.

RESULTS

The phosphatic fraction occurs in the three coarser sedimentary types, but is present throughout the size range of the populations only in the coarse-sand and gravel types. Consequently, we will pay particular attention to these components.

In the cores, the coarse phosphatic sedimentary types are irregularly distributed; the gravel type is less frequent than the coarse sands. However, there are differences between the topographic regions. On the southwestern slope, the gravel component varies but is always abundant in the bottom of the core. On the bank the occurrence of phosphatic sediments also varies with the irregularity of the sea floor morphology. The gravel content is always greater than that of the coarse sand with percentages up to 50% of the sediment. On the northeastern slope, gravels are important, while on the trough flank, gravels are rare, except in the southern part, near the bank slope where the phosphatic fraction is mainly composed of coarse sand, with moderate to low contents of gravels.

The regional distribution of modal values has been shown to be significant (LONG, 1975). Theoretically, isochron levels must be compared, but in order to define the bare outline of a hydrodynamic model we preferred to consider the whole values present in a core. Another reason is the smaller standard deviation between modal values of a specific population in a given core relative to the others.

On the southwestern slope, coarse sand type modal values regularly decrease from SE to NW (Figure 4). A decreasing value with two steps may be also observed for the characteristic value of the gravel (from 10 to 2 mm). In both cases, this trend indicates a sorting process, with transportation from the south to the north which suggests a longshore current on the seaward flank of the bank. It is noticeable that the extent of gravel transportation was not great and that we can recognize two preferentially eroded areas.

On the northeastern slope (Figure 5), similar sorting is apparent with a decreasing trend of gravel modal values from NW to SE. This direction of transport is also supported by the decreasing content of lateritic gravel from local outcrops of the "Série des Cirques". However a secondary sorting is displayed in an opposite direction from the southernmost end of the bank and only over a 3 km length.

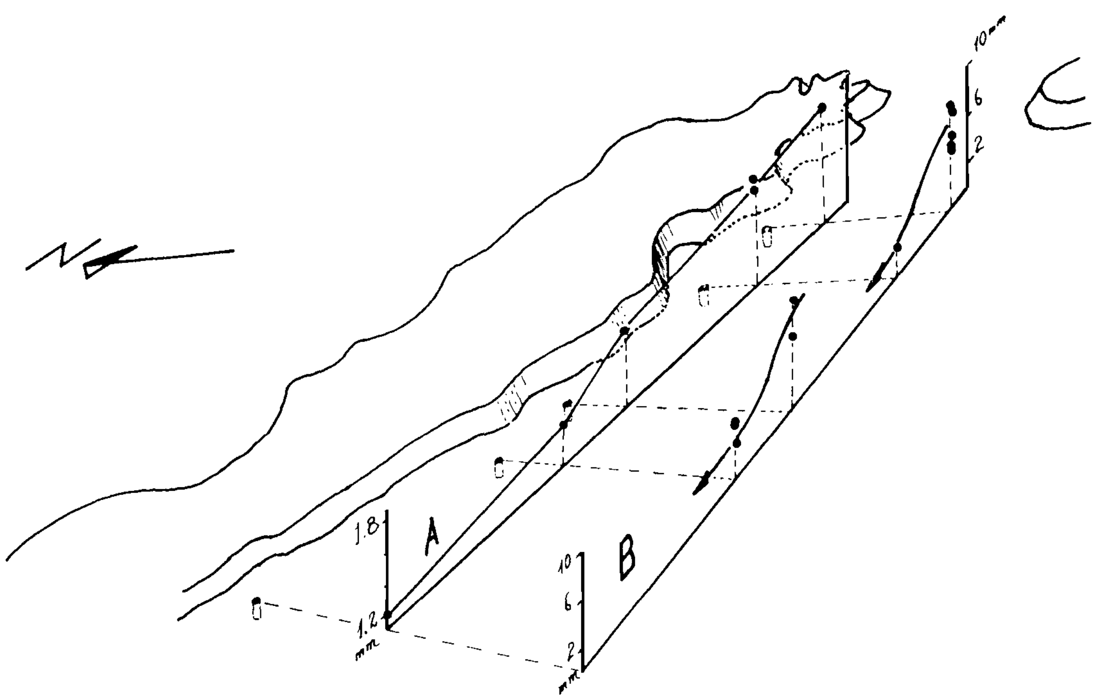

Figure 4. Schematic diagrams of decreasing trend of modal values for coarse sands (A) and gravel (B) on the seaward slope of the bank. Location of cores is indicated by a small cylinder at the base of the bank slope; viewed from the seaward side.

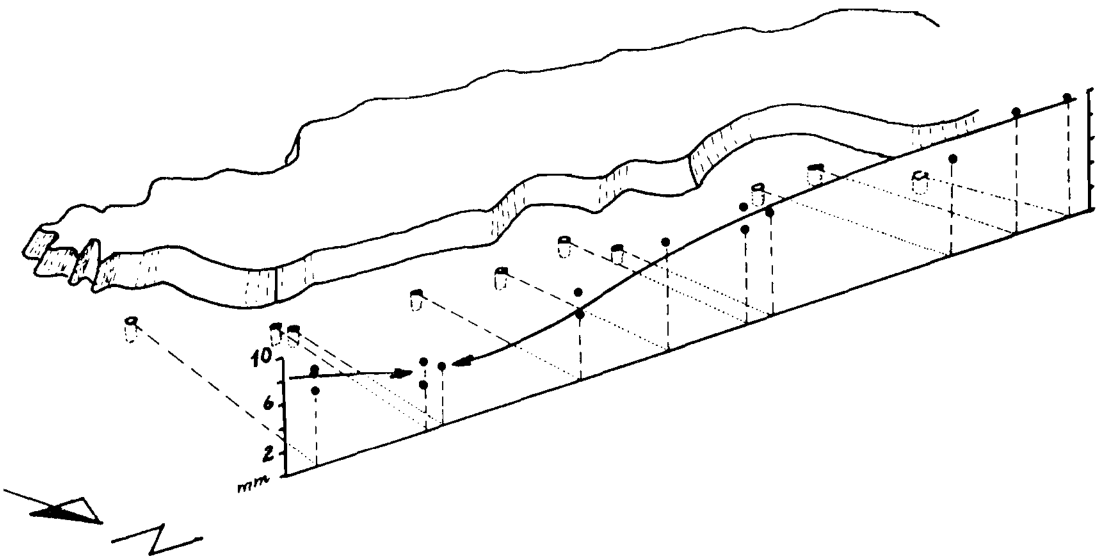

Figure 5. Schematic diagram of the double decreasing trend of modal values for gravel on the NE slope of the bank. Location of cores as in Figure 4; viewed from the landward side.

In the other areas of the bank, no clear pattern can be discerned because of rapid changes from level to level, and core to core, and to sparsity of information from the area of the trough.

DISCUSSION

The occurrence of a well-defined distribution pattern of the presently submerged sediments on both steep margins of the Holocene bank suggests swell action as the dominant process (Figure 6). If, during the Holocene sea level stand at 40 m, a similar swell pattern to that at present is assumed, then the orientation of the bank favoured sediment entrainment by littoral drift (swell direction between N 180° and N 225°).

This process had a marked effect on the sea-facing slope of the bank but, because of the wave refraction around the southern end, was also responsible for the transport routes that we observed in the southern part of the internal slope of the bank. In a similar fashion, wave refraction deflected the orthogonals across the northern submerged part of the bank, and caused a reverse sedimentary drift on the lee-side. Such strong curvature of the wave crests is not surprising in view of the sharp reduction of velocity along the Holocene northern shoreline (7 times between 1 and 5 m in relation to the Holocene MSL of this stage).

The material distributed by the different drift components was provided by the erosion of the bank with only small quantities carried onto the flank of the trough by gravity-driven processes rather than hydrodynamic processes (no onshore component may result from a wave refraction behind a barrier island).

The extent of sediment transport was probably limited. In spite of our poor knowledge of the hydraulic behaviour of particles (such as phosphatic grains and coproliths), some conjectures may be valid. For instance in the case of coarse sand, critical velocities computed by different methods (MANOHAR, 1955; RANCE and WARREN, 1968; KOMAR and MILLER, 1973; 1975a; 1975b) give similar values (40 $cm.s^{-1}$) for the initiation of particle movement. Corresponding waves about $H = 0.50$ m and $T = 5$ s at a 3 m depth, are quite realistic and consideration of the drag coefficient of such particles indicates a deposition threshold velocity of 38 $cm.s^{-1}$. Consequently, a very narrow velocity

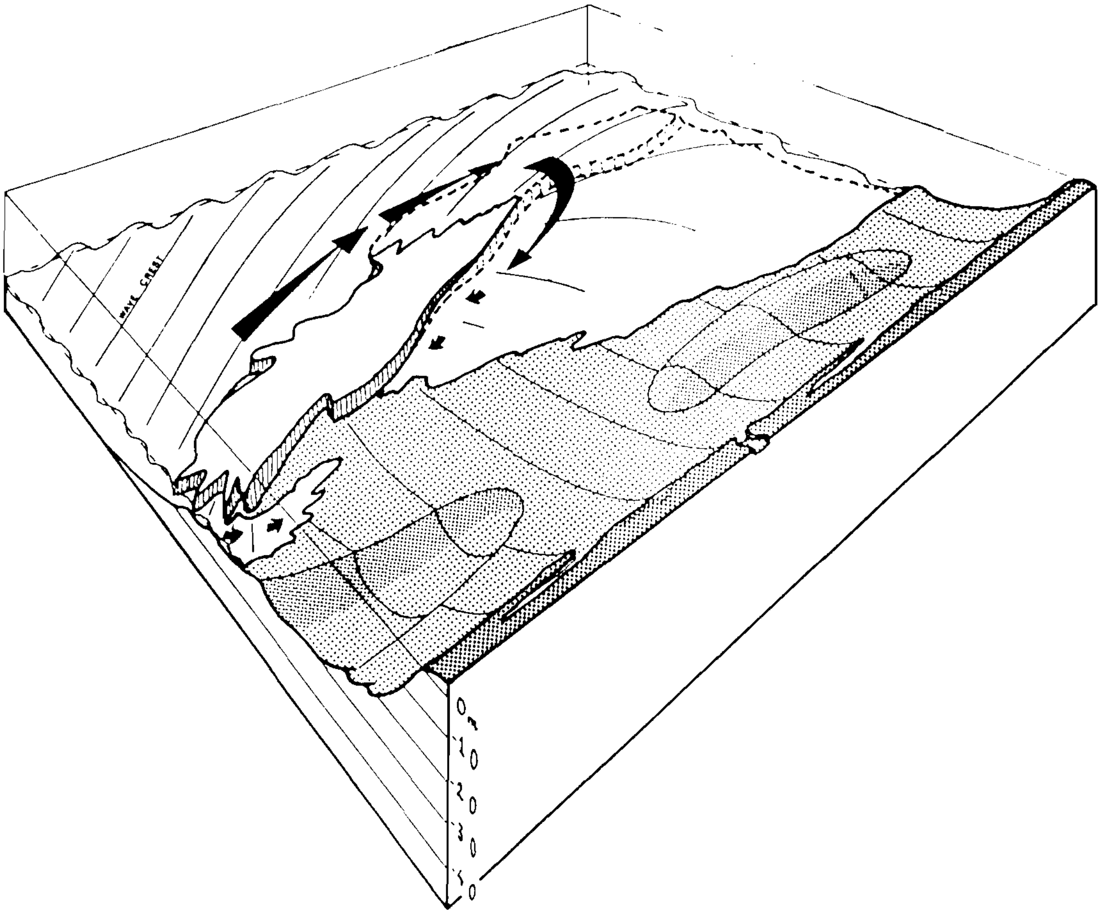

Figure 6. Interpretative diagram of refraction of waves around the Djéno Phosphatic Bank. Large arrows = littoral drift; dotted areas = emerged parts of the inner shelf and present land. The sketch represents the 6,500-8,500 years BP palaeogeography.

range separates the conditions of motion and deposition. The low probability of transportation explains the short duration of the sorting processes.

CONCLUSION

Five conclusions result from this study.

(1) The successive Miocene and Holocene placers are a good example of the frequent influence of mechanical reworking to produce economically viable deposits.

(2) The initial working hypothesis used for the survey and sampling was found not to be valid. Subsequently, a littoral drift model over a partially emerged bank acting as a barrier island was developed. Based on this, two targets can be identified: the southernmost part of the sea-facing slope of the bank (because it was under the direct influence of the waves) and the palaeo-downdrift ends of the bank (because of the transport of the material along the marginal slope northward on the exposed side, southward on the lee-side to a convergence point about 3 km from the southern end of the bank).

(3) There is a lack of knowledge on the hydrodynamic behaviour of phosphatic particles; we were reduced to speculation to formulate models. Even if the assumed specific gravity is coincidently close to the usual value used in the empiric model (derived from quartz grains), the

shape factor (drag coefficient) is probably very different and accurate data on the subject are needed.

(4) Contrary to the suggestions of WOOLSEY *et al.* (1984), phosphorite occurrences around the periphery of the outcrop are not scarce. On one hand, our work suggests a weak probability that phosphatic layers occur to the east of the bank because of the inefficiency of onshore components of wave motion during the subsequent transgressive phase; relatively to the strong transportation and depositional effects of alongshore components during the prior period of stand and progressive submergence of the bank. Consequently, slope zones display more favourable clues but the exploration phase is not yet complete in this area.

(5) The economical viability of such a placer is supported by several factors: shallow water depth; an unconsolidated texture and an easily disposable pelitic fraction; a suitable grain-size function of phosphatic particles; an association with carbonate shell debris; and, finally, the proximity of Pointe-Noire harbour. In the very acid podzolic or ferralitic soils of this inter-tropical area, the unprocessed product may be of direct interest for local or regional use. An agronomic pilot study is needed to evaluate this aspect.

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□ RÉSUMÉ □

La phosphatogenèse s'est produite à plusieurs reprises entre le Maestrichtien et le Miocène dans le bassin sédimentaire du Congo-Cabinda. La prèconcentration localisé du matériel, sous la forme d'un grès de plage miocène phosphaté, est imputable à l'évolution structurale et aux variations eustatiques. L'un d'eux, au large de Djéno, constitue un haut-fond subaffleurant. Au cours des mouvements eustatiques quaternaires, le remaniement du matériel a conduit à la distribution actuellement observable, déterminée surtout pour la dernière phase transgressive, au cours d'un épisode de stabilisation pendant lequel le haut-fond a été érodé.

Une étude texturale sur les sédiments holocènes aboutit à présenter les gradients de triage des populations granulomètriques phosphatées. Leur transport et leur dépôt est interprété en fonction de la réfraction des paléohoules. Cette conclusion contredit l'hypothèse d'une accumulation vers la côte.

En dépit d'une relative méconnaissance du comportement hydrosédimentaire des particules phosphatées, les changements rapides des valeurs de modes granulométriques permettent d'établir les directions principales de transport - sous la dépendance de la dérive littorale - et les zones de concentration. Le gisement est donc homologue d'un placer.