Origin of surface textures on quartz grains in sediments of the upper Cayar deep-sea fan (Senegal-Gambia abyssal plain)

Surface textures Deposition processes Upper Quaternary African margin Atlantic Ocean

Exoscopie Modalités de dépôt Quaternaire supérieur Marge africaine Océan Atlantique

Jean-Paul BARUSSEAU, Guy L. KOUNKOU Laboratoire de Recherches de Sédimentologie Marine, Université de Perpignan, 66025 Perpignan Cedex, France.

Received 4/1/88, in revised form 14/9/88, accepted 20/9/88.

ABSTRACT

SEM examination of quartz grains provided by the turbiditic layers of a core of the Cayar deep-sea fan confirms the lack of specific mechanical features resulting from the gravity-flow regime of emplacement. The main signatures were acquired in the shallow marine (shelf), coastal (littoral, estuaries, deltas and lagoons) and continental (deserts) environments. Four kinds of sedimentary circuits were characterized in relation to the prevalence of either a mark of the final agent of transport and deposition (prior to the ultimate turbiditic reworking): littoral drift, sand-whirls and shelf-wandering, or a clear evidence of a long-lasting stagnation of the grain in a coastal environment. The typical grain found in a turbiditic layer would be a quartz grain deposited in a coastal environment during a regression phase, removed and transported in the source-area of the final turbidity current by aeolian actions or direct shifting off the shelf edge. The duration of the whole circuit explains that there was a time-lag between the first appearance of the grain in the marine environment and the final deposition in the deep-sea fan mainly during the warm-humid phases. The grains provided by the hemipelagic layers display the same pattern of surface features. However the absence of any turbidity current for the last migration bespeaks the prominent influence of aeolian processes during the deposition of the terrigenous component of the hemipelagic sediments.

Oceanologica Acta, 1989, 12, 2, 117-129.

RÉSUMÉ

Origine des caractères exoscopiques des quartz de la partie supérieure de l'éventail détritique profond de Cayar (plaine abyssale de Sénégambie)

L'analyse exoscopique des grains de quartz contenus dans les niveaux d'origine turbiditique de la partie supérieure du cône sous-marin de Cayar conduit à souligner l'absence de signature liée à ce type d'agent de transport. Par contre, les grains conservent la trace de leur passage dans des milieux peu profonds (littoral et plateforme), margino-littoraux ou continentaux (en particulier désertiques). Les circuits empruntés par ces grains indiquent l'existence de quatre scénarios principaux qualifiés soit en fonction de l'agent final du dépôt (avant l'ultime reprise turbiditique) : dérive littorale, tourbillons éoliens, dérive transépicontinentale, soit en fonction de l'empreinte majeure du milieu côtier (littoral et margino-littoral). La démonstration d'un court trajet entre l'avant-dernier milieu traversé et le lieu de la reprise turbiditique ultime ressort de l'examen des modifications subies par les traces dominantes et impose l'idée que le matériel a dû être mis en place près du rebord, en période de régression, avant son exportation. Cependant les périodes qui font suite aux bas niveaux marins apparaissent plus favorables aux transferts vers le bas de marge. Ainsi, les grains portent le plus souvent des empreintes acquises en périodes froides-arides même quand ils sont déposés dans le deep-sea fan en périodes chaudes-humides. Il existe un décalage dans le temps d'un épisode isotopique entre l'arrivée en domaine marin du matériel caractérisant les périodes de bas niveau marin et sa mise en place finale.

Les grains récoltés dans les niveaux hémipélagiques montrent des faciès identiques à ceux des niveaux turbiditiques. Des trois modalités susceptibles d'expliquer leur dépôt en zone profonde : reprise par des courants de contour, cascading grain par grain et

Contribution CNRS-INSU-DBT n° 45.

transferts lithométéoriques, les deux premiers apparaissent comme improbable (courants de contour) ou mineur (cascading). Le rôle de l'activité éolienne dans la formation des dépôts profonds de tout type est ainsi encore souligné.

Oceanologica Acta, 1989, 12, 2, 117-129.

INTRODUCTION

As far as we know, few studies have been realized on the surface characteristics of the quartz grains of deepsea sediments (Krinsley and McCoy, 1977 a; b). Indeed, the siliciclastic fraction is often formed by particules whose surface displays little or no evidence of the deepsea environments, notably because of their weak size and the correlative weak momentum.

More particularly, the hypothesis of marking or breakage during the grain transport by turbidity currents has probably not to be considered because the materials are transported in a reduced gravity-field. Consequently, Krinsley and McCoy (ibid.) consider that the overprint of a deep-water residence, even though displacement by a turbidity current occurs, is not visible. The grains they have studied in the south-western Atlantic (leg 39) show that neither solubilization nor diagenetic processes resulted in surface features, even over long intervals of time (up to the Cretaceous).

Accordingly, the quartz grains of deep-sea sediments furnish informations about transport mechanisms pertaining to sedimentary environments whose major factors differ greatly from deep-sea mechanical and chemical factors.

In the same study, Krinsley and McCoy show that the fine quartz fragments of the siliciclastic fraction really belong to grains whose original surface has a greater interest from an environmental point of view than the broken surfaces which have truncated it. Consequently, we have chosen to work on grains of a size greater than 150 µm (up to 540 µm), in order to avoid meeting too many broken grains where an important part of the information would have disappeared.

The purpose of this study was to recognize the features recorded on the grain surfaces during their passage through different environments and to discuss palaeogeographical and palaeo-climatical implications of these circuits.



Figure 1

Stratigraphic relation between hemipelagic layers of the normal hemipelagic record and turbiditic layers. H.L.: hemipelagic layers, T.L.: turbiditic layers.

Relations stratigraphiques entre les niveaux hémipélagiques du log réduit et les niveaux turbiditiques. HL : niveaux hémipélagiques; TL : niveaux turbiditiques.

MATERIAL AND METHODS

The surface textures of the quartz-grains were examined with a Hitachi S520 scanning electron microscope.

The selected grains belong to previously determined depositional processes (turbiditic or hemipelagic) and to defined chronostratigraphic periods (Kounkou and Barusseau, 1988). This study of the M16401-4 core (Fig. 1) was made in order to distinguish the "normal hemipelagic record" (NHR) in which sedimentological, micropaleontological and isotope analysis has led to a time-frame which spans from isotopic stage E5 to the Present and the interbedded turbiditic layers.

The small number of analysed grains was prescribed by the duration of SEM observations. Several authors have pointed out the adequacy of a very small set of quartz grains to depict surface textures (Krinsley and McCoy, 1977 b; Manickam and Barbaroux, 1987). in the Cayar submarine valley or on the rise, both called here "source-area" because the triggering of the ultimate turbidity current took place within them.

Several theoretical scenarios (Fig. 2) can be considered for this evolution, taking into account the final agent of transport and deposition and/or the duration of the grain stagnation in a coastal environment prior to the ultimate turbidity current.

a) The grain may have undergone the effects of transport in the littoral drift. It may be assumed that this process resulted in an emplacement in the canyon. This transport in a high-energy environment has erased all the earlier marks except some deep aeolian ones (scenario 1).

b) The grain may have been deposited in a coastal environment before the reworking. Then neogenetic features of the deltaic environments, diatoms of the intertidal zone, were the main marks of this situation

Figure 2

Schematic diagram of transportation processes of quartz grains to locations (continental rise or canyon) where reworking by turbidity current may occur. Various trajectories of quartz grains: 1) littoral drift towards the canyon; 2) coastal environment (perhaps during a regressive phase) prior to an aeolian transport; 3) direct aeolian transport; 4) shelfwandering.

Schéma des processus de transport des grains de quartz jusqu'aux sites de départ des courants de turbidité sur le talus ou dans les canyons. 1) couplage dérive littorale+canyon; 2) cursus en domaine côtier pendant une phase régressive avant remaniement éolien; 3) transport éolien direct; 4) dérive transépicontinentale.

RESULTS AND DISCUSSION

Owing to a greater abundance of documents relative to the turbiditic layers, the results concerning these levels will be presented at the outset.

Sedimentary circuits of the siliciclastic grains of the turbiditic levels

SEM analysis of the quartz grains of the turbiditic levels confirms the absence of specific mechanical features due to the turbidity currents. Grains exhibit various patterns, but no common marks disclosing a special response of their surfaces to the characteristic mechanics of the turbidity currents.

On the other hand, the following signatures were met: opale coatings, neogenetic and growth features, diatom cementation, solution and mechanical features. All are already known as indicators of shallow marine environments (shelf and littoral), other coastal environments (estuaries, deltas, lagoons) and continental environments (especially deserts). Some of those environments were traversed by the grains prior to their deposition



(scenario 2). In some cases, it was possible to show that the coastal relay took place on the shelf, during a regressive period.

c) The passage of the grains down to a source-area, where the reworking by turbidity currents became possible, may have been the result of an aeolian transport, so rapid that even the brittle features where preserved. Such brittle features were inherited from either coastal (see above) or desert environments (amorphous coatings combined or not with mechanical aeolian features), without any other features from any aqueous environments (scenario 3).

d) The grain could have been subjected to a slow wandering on the continental shelf, under onshoreoffshore movements on the shoreface and resuspensions by storm(s) on the middle and outer shelves (scenario 4).

In the case of scenario 3, lithometeorical transport of reworked grains is needed. This process is not questionable when the particles are in coastal environments, especially when the shelf break is close to the beach and coastal dune system during regression phases. Then, sand-size grains may be displaced by the thermal eddies taking place above the bare surfaces of the continental shelf. Their high upward and rotational velocity accounts for the lifting and displacing of the particles up to heights of several tens or hundreds of metres (Courel, 1984) or more (Diaz et al., 1976). Following the hypothesis of Sarnthein et al. (1982) concerning a reinforcement of the atmospheric circulation during cold phases, it may be surmised that the strengthening of the easterly mid-tropospheric jet stream or of components of the tropical east jet (Walker, 1972; Lambergeon et al., 1981) is a consequence of such a climatic pattern. Accordingly, it can be assumed that the material moved westward since branches of these air layers were located at low altitudes (800 mb; about 2000 m).

Nevertheless, particles with a size range such as that found in some turbiditic levels $(300-400 \ \mu m)$ are

unlikely to have been transported over distances like those which separate the regions of Saharan dust production (namely to the west of the Ahaggar; Kalu, 1977) from the West African continental slope (1000-3000 km). So, for the coarsest gains, this process will be efficient only from coastal regions. However, small size fragments resulting from breakage processes and constituting the prominent part of the silt component of sediment (Krinsley and McCoy, 1977 *a* and *b*; Kounkou and Barusseau, 1988) could be more sensitive to these transfers (Tsoar and Pye, 1987).

Surface signatures of the different environments crossed by the grains and the main intervening processes

Grains conveyed by the littoral drift

In the course of littoral drift, grains are continuously subjected to an intense to-and-fro movement. This



Plate 1

Quartz grains from turbiditic layers. A & B (KMS 62; 595-596 cm; transition E3-E4).

This grain with blunt edges has recorded a severe attrition. Truncation of aeolian features (IB) has reduced them to "nail marks", except a few recognizable cups. Some solution features are exhibited on the right face of the grain.

C (KMS 24; 235-236 cm; transition E1-E2).

A large breakage surface with aeolian cupules cutting a strictly continental grain. Absence of reworking marks on the breakage surface implies rapid transportation.

D (KMS 6; 75-76 cm; episode 1).

More than grain IC, the shape of this grain is determined by strong impacts which broke the initial grain whose surfaces have disappeared.

Grains de quartz provenant de niveaux turbiditiques.

A et B (KMS 62; 595-596 cm; transition E3-E4). Sur ce grain aux arêtes émoussées s'observe une profonde usure. Le rabotage des marques éoliennes les réduit à des « coups d'ongle », à l'exception de quelques rares cupules. Noter des traces de dissolution à droite. C (KMS 24; 235-236 cm; transition E1-E2). Grandes cassures à cupules éoliennes, fracturant un grain strictement continental. L'absence de retouche de la face de fracture implique un transport rapide.

D (KMS 6; 75-76 cm; épisode 1). Plus que dans le grain précédent, la forme est ici due à des fractures de collision ayant éliminé toute surface naturelle du grain.



Plate 2

Quartz grains from turbiditic layers. A & B (KMS 13; 145-146 cm; transition E1-E2).

This grain is characterized by an important coating of amorphous silica. Prior aeolian impact features are visible (IIB, left part) with an incomplete infilling. Under the coating, the general shape of the grain resulted from prior processes, including impact breakages (left).

C (KMS 73; 705-706 cm; episode 4). The coating is visible in different parts of the grain (i. e. upper part). Truncation was caused by large breakage surfaces.

D (KMS 46; 435-436 cm; episode 2). In contrast with grain IIC, breakage surfaces have been concealed by siliceous deposits. These crystalline growings sometimes appear as flat contact figures. The shape prior to coating is still clearly visible.



Grains de quartz provenant de niveaux turbiditiques.

A et B (KMS 13; 145-146 cm; transition E1-E2). Une épaisse pellicule de silice amorphe caractérise ce grain. Une marque éolienne antérieure est incomplètement recouverte. Sous la pellicule, la forme générale est façonnée par les fractures de collision (à gauche).

C (KMS 73; 705-706 cm; épisode 4). Une pellicule apparaît en différents points du grain (partie supérieure par exemple); elle est recoupée par de grandes surfaces de fracture.

D (KMS 46; 435-436 cm; épisode 2). Dépôts siliceux postérieurs à une surface de cassure. La croissance cristalline peut être stoppée au contact d'un autre grain donnant une surface aplatie. La morphologie anté-pellicule est visible.

transport over long distances determines a well-developed shaping of the grains with blunt edges and often a well-rounded shape; previous features are practically erased, except the aeolian "nail marks" whose deepest parts are only preserved (PII A-B). The grain is naturally very clean, free of any deposit (neogenetic crystallizations, coatings, diatoms), which could have originated at the time of the grain passage in the coastal domain (channels, sheltered zones of banks, mouths and lagoons, intertidal zones). At the end of its course, such a grain is funnelled into the Cayar submarine valley.

As stated above, ultimate displacement, perhaps in several stages, towards the deep-sea fan and during one or several phases of gravity flow, sliding or turbiditic current, fails to determine new features on the surface.

Strictly continental grains

Some of the grains show a complete lack of aquatic (fluvial as well as marine) marks. They appear under three forms. Some of them are broken, the fractures having the same linear sizes as the grain without any further erosion (Pl. IC-D). Some are very rough (Pl. ID), but have undergone earlier transport stages before, as is evidenced by the roundness of edges. Indeed, Mazzullo *et al.* (1986) showed the rapid effectiveness of aeolian transport on the shape of quartz grains and the increase of roundness even during short transport phases. A third kind of grains is covered by a complete coating without any further alteration (Pl. II A-B) or broken by an impact during an aeolian transportation phase (Pl. II C). Finally, these grains display a sequence of phases of breakage and deposi-



tion of opale coatings which mould the irregular broken surfaces (Pl. II B-D). This set of characters typifies a desert evolution implying frequent and rough aeolian reworking, but also some immobilization phases that permit the coating formation with, sometimes, growth aspects (Pl. II D) or flowing casts (Pl. III A). This last case shows that oversaturation inside droplets submitted to gravity must be taken into account and cannot occur in environments where the interstitial water is under hydrostatic pressure (phreatic environments, continental or marine). In vadose environments, as well as in the desert domains, dew produces such amorphous silica. It is therefore important to consider the undercoating morphology which indicates the possible occurrence of prior stages of aqueous transportation. An irregular underlying shape (Pl. II C-D) and the presence of aeolian pitholes smoothed by the thin amorphous layer (Pl. IIB) is thus generally necessary to identify a desert grain. Cases where the coating morphology does not indicate a gravity influence (no flowing casts) must be attributed to an intertidal supersatu-

Plate 3

Quartz grains from turbiditic layers. A (KMS 30; 295-296 cm; transition E1-E2).

A coating with flowing casts implies a crystallisation phase within a vadose environment where gravity forces are liable to exert their action.

B (KMS 73; 705-706 cm; episode 4).

Presence of marine diatoms agglutinated on the surface of an intertidal quartz (littoral environment; determination: F. Gasse).

C (KMS 15; 165-166 cm; transition E1-E2).

On this view of the grain, characteristic dissolution features are displayed on an intertidal grain with silica growth features fully developed (contact surfaces), silica globules and diatoms.

D (KMS 70; 675-676 cm; episode 4).

This grain exhibits various siliceous deposits forming coatings, growing figures, contact figures (upper part, on the left of the summit) and prismatic neogenetic marks (arrow). Such neogenetic marks are generally considered (Le Ribault, 1975) as deltaic features. Grains de quartz provenant de niveaux turbiditiques.

A (KMS 30; 295-296 cm; transition E1-E2). Pellicule en coulée montrant une phase de cristallisation géopète en milieu vadose.

B (KMS 73; 705-706 cm; épisode 4). Diatomées marines cimentées à la surface d'un grain intertidal (milieu littoral; détermination : F. Gasse).

C (KMS 15; 165-166 cm; transition E1-E2). Figures de dissolution, globules et cristallisations de silice avec surfaces de contact et diatomées caractéristiques d'un grain intertidal. D (KMS 70; 675-676 cm; épisode 4). Pellicules, figures de croissance, surface de contact (partie haute, à gauche du sommet) et marques prismatiques de néogenèse: ces productions de silice néogénétique sont considérées par Le Ribault (1975) comme des indicateurs d'environnement deltaïque.

rated environment, a situation which cannot be encountered in the shoreface but which may occur in other coastal domains (lagoonal, intertidal or deltaic environments). Ferrallitic soil formation is also a favourable factor. The distinction between both occurrences will depend on the presence of the supplementary features. Consequently, continental grains will be characterized by the aeolian underlying morphology as in the previous case, but also by the lack of mechanical aquatic features, of deltaic neogenetic deposits and of marine diatom aggregation.

Thus characterized, continental grains are sometimes sizeable (up to 400 μ m) and the prior discussion about the ability of the aeolian fluxes to carry such particles must be therefore taken into account. Two conclusions may be emphasized: 1) a problable low-range transportation during present-like conditions; 2) during cold stages, the strenghtening and lowering of the zonal jet streams constituting a useful source of displacement of particles uplifted by dust and sand whirls (about 1000-1500 m).

Grains submitted to a coastal evolution prior to a direct transfer towards the source area, during a regressive phase

The passage of grains in the coastal zone is clearly exemplified in the samples of turbiditic layers in the M16401-4 core. Characteristic features are: presence of marine diatoms (Pl. III B); existence of dissolution marks (Pl. III C); occurrence of neogenetic deposits with a prismatic facies in deltaic originated grains (Pl. III D); or a sparsed globular facies restricted to depressions of the surface on the intertidal grains.

Frequently, various mechanical features betray the fact that, these grains have circulated in channels of the tidal zone or undergone several exchanges between the beach and the dune.

Most of the time, the preservation of these features, particularly the brittle ones (neogenetic deposits, diatoms), supports the further occurrence of rapid transport toward the source-area, a condition which was all the more evident as the shoreline was located near the shelf edge. During the regression phases, such types of transfer ought to be more frequent with two main modes: meteoric exportation and wandering on the shelf.

In the first case, a rapid transfer is denoted by diatom preservation (Pl. IV B), and the action of the transport agent is shown by rare aeolian collision marks with sharp edges. In the second case, the delicate features of the coastal zone are preserved (diatoms, globules in Pl. IV C-D) and there are no hints of high to moderate energy transport. Between the passage in the coastal zone and the grain deposition in the source-area, transport was rapid, in a reduced-gravity medium, which excludes any lengthy excursion across the shelf. A regression index is thus recorded.

Grains resulting from an oscillating transport across the shelf

As in the previous case, features of a coastal or a continental evolution are registered, but these marks show an obvious abrasion which often prevents the preservation of any brittle marks. Such an erosion state may be related to low energy environments (some

Plate 4

Quartz grains from turbiditic layers. A & B (KMS 13; 145-146 cm; transition E1-E2).

Abundant indications of a coastal marine environment (diatoms, shock marks, v's, polishing). In addition, cups with sharp edges (IV B, upper part) record the action of an aeolian transportation since these marks are not reworked by an aquatic evolution. C & D (KMS 73; 705-706 cm; episode 4).

Passage in a coastal environment is indicated by diatom occurrence and solution marks. Slight alteration on the edges shows that the transport took place in an aqueous environment, with the removal of almost all the brittle features. However, this process did not succeed in imparting a significant roundness. Of interest here is an indication of transport after the coastal evolution by the so-called "shelf wandering".

Grains de quartz provenant de niveaux turbiditiques.

A et B (KMS 13; 145-146 cm; transition E1-E2). Nombreuses marques de milieu littoral (diatomées, marques de chocs, « V », polissage). En outre, des cupules à bord net, non retouchées par une reprise aquatique ultérieure (4 B, partie supérieure) signalent une phase éolienne.

C et D (KMS 73; 705-706 cm; épisode 4). Les diatomées et les marques de dissolution indiquent un passage dans un milieu littoral. Un léger émoussé des arêtes traduit une aquatisation malgré tout ménagée, qui supprime les traces les plus fragiles mais n'entraîne pas un arrondi important. Cette opposition caractérise selon nous le processus de dérive transépicontinentale.





B X2.50K 12.0um



x600 50um

128um

X250



(250 120um C

Plate 5

Ouartz grains from turbiditic layers. A & B (KMS 20; 195-196 cm; transition E1-E2).

Grain showing a marine evolution denoted by a great cleanness of faces and blunt edges. The large cup under the summit is at an early stage of alteration. However, the shape remains irregular; deposits concealing ancient friction marks are preserved. this set of characteristics is regarded as a result of a final transport by oscillating movements on the shelf ("shelf wandering") before deposition in the source-areas.

C & D (KMS 62; 595-596 cm; transition E3-E4).

This grain exhibits an advanced solution of siliceous material which is typical of a soil formation evolution. Subsequently, edges were altered by a moderate aqueous activity. Its great cleanness betraying a marine influence, this grain, after entering the coastal zone without any prolonged residence, was displaced across the shelf.

Grains de quartz provenant de niveaux turbiditiques.

A et B (KMS 20; 195-196 cm; transition E1-E2). La propreté des faces, l'usure des arêtes indiquent une évolution du grain en conditions marines. La grande cupule, sous le sommet, commence même à être retouchée. Le grain, cependant, demeure irrégulier, des dépôts cachetant d'anciennes marques de friction sont préservés. Là encore, le processus de dérive transépicontinentale pourrait être évoqué. C et D (KMS 62; 595-596 cm; transition E3-E4). Dissolution avancée des néogenèses pédogénétiques siliceuses. Une reprise aquatique ultérieure

a déterminé une usure modérée des arêtes. La propreté du grain marque une évolution en conditions marines. Le grain, après son passage en milieu littoral, a été transporté dans le profil, à travers la plateforme.

estuary or deltaic channels or lagoon). However, the further need to explain that the grains were in position to be reworked by a turbidity current poses the question of their displacement towards the so-called sourceareas. Sediment resuspension occurs frequently as a result of oscillatory currents due to surface gravity waves (Larsen et al., 1981; Jago and Barusseau, 1981; Vincent et al., 1981) coupled with various unidirectional current components (Flemming, 1981). Net water particle excursions, measured for instance on the Atlantic outer continental shelf of the United States during winter storms, were about 5-10 km across the shelf (Knebel, 1981). Consequently, the grains can slowly migrate towards the open sea across the shelf, a process called here "shelf-wandering". During this transport, the grain shape is slightly modified (Pl. V A-D), weak features are exceptionally preserved (Pl. VI A-C), coating undergoes a more or less intense erosion in relation to their position (Pl. VI D).

Distribution of the different types of quartz evolution found in the turbiditic levels

General results

SEM examination was carried out on 28 levels of the different turbidites distributed along the M. 16401-4 core; 55 grains were examined (Table 1). Several observations can be made:

1) The Cayar canyon functioned as a direct outlet of the sedimentary load carried by littoral drift only during the Inchirian sea level rise during which the sea level, lower than the Present one (Monteillet, 1986), intersected the submarine valley and also during the subsequent regression. The sedimentary contribution played by the canyon is therefore much less than has been formerly supposed (Ruffman et al., 1977; Barusseau, 1983). In spite of numerous unknown parameters, it is unlikely that the greatest part of the Quaternary



Plate 6

Quartz grains from turbiditic layers $A \notin B$ (KMS 22; 215-216 cm; transition E1-E2).

This grain is completely coated by agglutinated diatoms. Diatom tests exhibit a moderate polishing which resulted in truncation. Between the coastal environment where agglutination occurred and the source-areas, this attrition betrays a transport by oscillating movements across the shelf. C (KMS 91; 875-876 cm; episode 5).

The exceptional preservation of a "silica flower" in a depression of the surface (upper left) shows that transport towards the source-areas failed to erase such a brittle feature. The oriented marks are mechanical features previously recorded and emphasized by solution.

D (KMS 30; 295-296 cm; transition E1-E2).

The coating with flowing casts which is clearly visible in the lower left part of the grain disappeared in the vicinity of the edges as a result of slight erosion by the transportation agent acting between the coastal zone (coatings) and the source-areas.

Grains de quartz provenant de niveaux turbiditiques.

A et B (KMS 22; 215-216 cm; transition E1-E2). Grain entièrement revêtu de diatomées dont les frustules sont légèrement tronquées par un léger polissage. Là encore, une dérive à travers la plateforme serait la cause de la modération des retouches.

C (KMS 91; 875-876 cm; épisode 5). Préservation d'une fleur de silice, il est vrai protégée dans une dépression (en haut, à gauche). Le transport vers les grands fonds a ménagé de telles marques en dépit de leur fragilité. La netteté de marques mécaniques orientées est accusée par la dissolution.

D (KMS 30; 295-296 cm; transition E1-E2). Pellicule en coulée en bas à gauche ayant subi une érosion près des arêtes exposées.

Table 1

Different evolution processes of turbiditic quartz grains in relation to the depositional period. Différents types d'évolution des grains de quartz de turbidites en fonction de la période de dépôt.

	Number	Number	Various evolutions			
Isotopic stage	of studied layers	of examined grains	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	12	30	-	19	8	3
2	2	3	1	-	2	-
3	2	4	1	_	1	2
4	4	8	-	5	2	1
5 (part)	8	10	-	4	5	1
Total	28	55	2	28	18	7

Scenario 1: grains conveyed by the littoral drift and probably deposited through the Cayar canyon.

Scenario 2: grains showing a coastal relay.

Scenario 3: grains indicating a direct lithometeorical transfer from desert environments.

Scenario 4: grains deposited in source-area after a phase of shelf-wandering.



Figure 3

Theoretical cases of the sedimentary trajectories of quartz grains with a relay in the coastal environment. Number 2 refers to supply and accumulation within a coastal environment. A, B or C signify the location (respectively: coastal zone, continental shelf or shelf edge). The last figure -(1), (2) or (3) - characterizes the type of remobilization (respectively: by littoral drift, by dust - and sand - whirls or by the socalled "shelf-wandering" mechanism).

Trajectoires théoriques des grains de quartz subissant un épisode de façonnage en milieu côtier. L'indice 2 correspond à un apport sédimentaire en environnement côtier; A, B et C correspondent à la position de la zone de mise en place (respectivement : zone littorale, plateforme ou rebord). Le dernier chiffre-(1), (2) ou (3) – est relié au type de remaniement (respectivement : dérive littorale, reprise éolienne, dérive transépicontinentale).

material was trapped in the canyon (a triangular groove $370,000 \times 5,500 \times 250$ m in size), which should have been filled in barely 250-500 ky by a sedimentary littoral drift assessed at 0.5-1 million m³ × year⁻¹. The possibility of a change in the discharge rate of the littoral drift during the late Quaternary must be taken into account, as well as the well-documented tendency of main depocentres to be distributed in various positions in the deep-sea fan by diverting turbidity currents (Bowen *et al.*, 1984).

2) During all the post-Eemian times the direct transfers (scenario 3) are active. However, they are not notably more frequent during cold phases (late episode 5, episodes 4 and 2) than during the so-called "warm" episodes (E3 and E1). Everything points to a oneperiode delay between the deposition of grains in the source-areas and turbiditic transport towards the deepsea fan. The removal will continue throughout the entire subsequent period of high sea level. Thus, the surface marking and the final emplacement of the grains would be out-of-phase.

3) The importance of sedimentary patterns that cross and record the coastal zone must be cited, and the good and frequent preservation of coastal markings, notwithstanding the necessary transfer towards the source-area, is amazing. This kind of scenario is always well represented except during the Ogolian

Table 2

regression (E2) and during the prior high-sea-level time (E3) when the sea-shore was in a middle-shelf position. It is particularly abundant after the last episode of low sea level (19 cases after episode 2).

If we suppose that the supply in the source-areas is more abundant during the regressive phase, then the assumption of a one-episode delay for the passage of the grains to the deep-sea fan may be stated.

Circuits implying coastal immobilization

Due to the sea level rises and falls, the acquisition of a coastal patina may have took place at various positions of the shoreline on the shelf. Three cases are illustrated in Figure 3.

Some of these circuits are practically unprovable. For instance, those for which passage in the littoral drift followed the passage in a coastal environment have had their attendant markings erased. Fortunately, they are not very numerous (*see* Table 1). In some cases, a doubt subsists about the position of the shoreline on the shelf, where the coastal patina was gained (scenario 2X2). The most representative cases are discussed below. The general results are reported in Table 2 for the 28 cases where a passage in the coastal zone (excluding the littoral drift) has been established. If too rare kinds of evolution are excluded, only two main scenarios are more firmly supported:

- a scenario 2X2, with a transport phase by sand-whirls;

- a scenario 2C4, where the grain, after an evolution in a regressive coastal zone shifted in an outer position, slides beyond the shelf edge during onshore-offshore exchanges.

The first case seems to have occurred during episodes corresponding to the glacial-interglacial transitions. It is noticeable that it was not more frequent during the most arid episodes (cf. E4: 1 grain out of 5). In the majority of cases, an aeolian reworking is denoted, as stated above, by the preservation of the marks of a coastal environment (some of them delicate) and the presence of further sharp mechanical features. The drastic limitation to be considered in the use of the aeolian transfers of sand-size particles (Tsoar and Pye, 1987) is in favour of restricting this process to nearby regions. A similar conclusion is also the result of lithometeor analysis in Northern Nigeria (McTainsh, 1984). Both stated that the distance could not be greater than a few kilometres (e.g. Tsoar and Pye, 1987; fig. 3). Therefore X = B (middle platform) or X = C (outer platform or shelf edge) can be advanced. In these conditions, the lack of a noticeable record in the deep-sea

Time occurrences of the various evolution processes implying a passage across a coastal environment of the quartz grains.

Localisation dans le temps des différents scénarios de mise en place reconnus sur les grains de quartz ayant circulé dans les environnements côtiers.

Isotopic stage	2X2	2X4	2B4	2C4	
1	3	1		15	
2			not observed		
3			not observed		
4	1	-	1	3	
5 (part)	1	-	1	2	
Total	5	1	2	20	

Figure 4

Schematic diagram showing quartz grain reworking on the exondated continental shelf and transportation down to the continental rise base by outof-phase turbidity currents. (I): deposition on the slope during a cold phase, according to scenario 2X2. (II): reworking by turbidity currents triggered during a subsequent warm episode (perhaps during a transgression). TR: transgression. REGR: regression.

Schéma montrant les modalités de remobilisation des grains de quartz sur une plateforme exondée et leur transport vers le bas de marge par les courants de turbidité au cours d'une phase climato-custatique postérieure. (I) : dépôt sur la pente en phase froide (scénario 2X2); (II) : remaniement par courants de turbidité déclenché pendant un épisode de réchauffement et de transgression. TR : transgression. REGR : régression.

fan during the periods when the continental shelf were uncovered would indicate again that a time-lag could exist between the exportation of the grains out of the coastal zones and the terminal transport. The duration of this time-lag would correspond to the residence time in the source-area, which is quite unknown, but at least equal to one climatic alternation (Fig. 4).

The second case is more frequent and corresponds to grains in which coastal features are disturbed neither by aeolian sharp cupules nor by the moderate but extensive attribution of shelf-wandering. Consequently, the coastal marking must have been acquired in an outer position on the shelf in order to explain a short displacement towards the upper continental slope. The frequency of this process is particularly large during episode E1, after the large regression accompanying isotopic stage 2. This could be linked to the establishment of a thermal stratification with a thermocline impinging on the outer shelf. The material, deposited in outer regions of the shelf during low sea level stage, would be reworked after the stabilization of a permanent regime of benthic thermocline. Since the shelf edge is an intensely reworked zone, the time-lag is unlikely to last one episode.

In summary, whatever the manner of deposition in the source areas, whether by a lithometeoric transfer or by reworking under internal waves during a postglacial rise, this material corresponds to a coastal deposit on an exondated shelf.

Sedimentary circuits of the siliciclastic grains of the hemipelagic layers

Observations were made on the same size-class of quartz (modal values: $315-400 \mu m$), so that the cause-effect associations could be the same.

The analysed grains (19 grains provided by 11 layers) exhibit features quite equivalent to those described on the grains of the turbiditic layers: diatoms, high-energy mechanical features, dissolution marks and coatings (Pl. VII A, B, C). However, the frequence of the environmental signals seems quite different: rare diatoms and dissolution features and, conversely, a greater occurrence of large breakage surfaces and their attendant marks (conchoidal marks, aeolian cupules).



All these markings permit the supposition of the prevalence of desert and coastal influences as quoted by Krinsley and McCoy (1977 a; b) concerning the quartz grains of the south Western Atlantic. The frequence of high-energy mechanical aeolian marks is particularly high, suggesting a strong influence of the desert environment. A direct supply from the littoral zone is also demonstrated by the observations.

Deprived of the possibility of using the turbidity current as a master agent to convey sand-size grains in the deep-sea, three major processes may intervene: grain-by-grain downslope transport (Bein and Fütterer, 1977; Lutze, 1980); aeolian transfers; and the action of contour currents (Hollister, 1973). However, the latter may be discarded since their presence in this region is unlikely (Jacobi and Hayes, 1982).

Grain-by-grain transport is supported by numerous observations (Diester-Haass, 1975; Bein and Sass, 1978). Here, it can efficiently act during the low sea level episodes but it must be discarded as an agent conductive to long-range transport across the shelf. Furthermore, sharp impact marks cutting prior aquatic features (v's, coatings) show that a final overprint of aeolian transport (Pl. VII D) must be also taken into account. However, further observations must be carried out to confirm the processes and determine in what proportion they play a role.

CONCLUSION

The surface features of quartz grains representative of turbiditic and hemipelagic layers from the upper deepsea fan of Cayar are indicative of the main processes which determined the various stages during transportation. However, the small number of quartz grains examined prevents any quantitative analysis of the respective part of the various phenomena involved in the sedimentation. The different evolutions recognized have been inserted in a chronological frame based upon a prior work. Four main scenarios cover the major part of the information provided by SEM examination of grain surfaces. The particles encountered in the turbiditic layers followed: 1) the littoral drift-Cayar submarine valley circuit; 2) a displacement pattern



A X6.00K 5.0um



B <u>X250 120um</u>

Plate 7 Quartz grains from hemipelagic layers.

A (KMS 69; 665-666 cm; episode 4). Littoral diatoms (Navicula sp.; determination: F. Gasse).

B (KMS 69; 665-666 cm; episode 4).

This grain exhibits indices of an intense transport (aeolian crescentic marks, breakage surfaces) prior to the formation of a silica coating which invades the upper face of the grain. C (KMS 96: 925-926 cm; episode 5).

Solution marks are rather rare on hemipelagic grains and never as developed as the dissolution features recognized on turbiditic grains (see Plates 3 C and 5 C, D). On this close view of the surface, characteristic dissolution features are displayed on a rounded grain with vestigial coating (lower part), silica globules and tiny aquatic marks of an intertidal environment.

D (KMS 69; 665-666 cm; episode 4). On this grain, the most recent alterations are sharp aeolian marks which demonstrate that the ultimate course towards the source-areas was aerial.

c Xé đấK Š ĐậM



Grains de quartz provenant de niveaux hémipélagiques.

A (KMS 69; 665-666 cm; épisode 4). Diatomées littorales (Navicula sp.; détermination : F. Gasse).

B (KMS 69; 665-666 cm; épisode 4). Des marques éoliennes en croissant, des surfaces d'impact trahissent un transport éolien antérieur au développement d'une pellicule siliceuse qui tend à envahir le grain.

C (KMS 96; 925-926 cm; épisode 5). Plutôt rares sur les grains hémipélagiques, les marques de dissolution ne sont jamais aussi développées que sur les grains de niveaux turbiditiques (cf. planches 3 C et 5 C, D). A fort grossissement, ce grain arrondi montre des marques de dissolution caractéristiques et les indices (pellicule, globules siliceux, marques aquatiques) d'un milieu intertidal.

D (KMS 69; 665-666 cm; épisode 4). Sur ce grain, les dernières traces enregistrées sont de nettes marques éoliennes trahissant un dernier trajet éolien.

characterized by a strong coastal influence; 3) an aeolian transfer, directly from the desert sources or, more probably, after a reworking from a position not far from the shelf edge, during a regressive phase; or 4) a migration across the shelf or across a narrowed shelf during regression phases under the influence of hydrodynamic agents. On the other continental margins, especially mid-latitude shelves, fluvial input plays a prominent role (Prusak and Mazzullo, 1987); no observation on that subject has been recorded here. The first scenario was surprisingly found to be rare and limited to the period during which the sea level intersected the Cayar submarine valley (isotopic episode 3). The aeolian input is not characteristic solely of the arid phases, but is also largely recorded in the layers belonging to the warm-humid intervals. The reason is a time-lag between deposition in environments where the last marks were acquired and reworking by the turbidity current. A major part of the grains underwent a passage in a coastal environment. The frequency of such grains in layers became higher when the coastal zone was shifted towards the shelf edge, particularly during the last regression phase. A timelag is also clearly recorded between the moment of surface marking and the time of deposition in the deepsea fan, with an increasing of coastal grains in layers pertaining to the warm-humid stage. The quartz grains provided by the hemipelagic layers show similar surface aspects in relation to the turbiditic layers. Three agents are theoretically responsible for their deposition: reworking by contour-currents; grain-by-grain migration down to the fan along the continental rise; and direct lithometeorical transfers. Because of the unlikeliness of the first two, the role of aeolian transportation is again emphasized.

Acknowledgements

We are indebted to Michael Sarnthein for the opportunity of sampling the M16401-4 core (Meteor "Geotropex 83").

REFERENCES

Barusseau J.-P. (1983). Analyse sédimentologique des fonds marins de la « petite côte » (Sénégal). Une étude de l'environnement côtier au Sud du Cap-Vert. *Rapport provisoire du C.R.O.D.T.*, 65-83.

Bein A. and D. Fütterer (1977). Texture and composition of continental shelf to rise sediments of the north-western coast of Africa. An indication for downslope transportation. *Meteor Forschergebn.* 27, 46-74.

Bein A. and E. Sass (1978). Analysis of log-probability plots of recent Atlantic sediments and its analog with simulate mixtures. *Sedimentology*, 24, 575-582.

Bowen A. J., W. R. Normark and D. J. W. Piper (1984). Modelling of turbidity currents on Navy submarine fan, California continental borderland. *Sedimentology*, 31, 169-186.

Courel M. F. (1984). Étude de l'évolution récente des milieux sahéliens à partir des mesures fournies par satellites. *Thèse Doctorat* d'État, Université Paris I, 407 pp.

Diaz H. F., T. N. Carlson and J. M. Prospero (1976). A study of the structure and dynamics of the Saharan air layer over the northern equatorial Atlantic during Bomex. NOAA Tech. Memorandum, ERL WMP, 32, 61 p.

Diester-Haass L. (1975). Sedimentation and climate in the Late Quaternary between Senegal and the Cape Verde Islands. *Meteor Forschergebn.*, 20, 1-32.

Flemming B. W. (1981). Factors controlling shelf sediment dispersal along the southeast African continental margin. *Mar. Geol.*, 42, 259-277.

Hollister C. D. (1973). Deep-ocean basin sedimentation, In: Soc. Econ. Paleont. Mineral., Pacific section, short course, Abeheim, G. V. Middleton and A. H. Bouma, editors, 79-118.

Jacobi D. R. and D. E. Hayes (1982). Bathymetry, microphysiography and reflectivity characteristics of the West African margin between Sierra Leone and Mauritania, In: Geology of the Northwest African Continental Margin, U. von Rad, K. Hinz, M. Sarnthein and E. Seibold, editors, 182-212.

Jago C. F. and J.-P. Barusseau (1981). Sediment entrainment on a wave-graded shelf, Roussillon, France, In: Sedimentary dynamics of continental shelves. C. A. Nittrouer, editor. Mar. Geol., 42, 279, 299.

Kalu A. E. (1977). The African dust plume: its characteristics and propagation across West Africa in winter. In: Saharan dust, John Wiley and sons, 14, 95-118.

Knebel H. J. (1981). Processes controlling the characteristics of the surficial sand sheet, U.S. Atlantic outer continental shelf. Mar. Geol., 42, 349-368.

Kounkou G. L. and J.-P. Barusseau (1988). Terrigenous sedimentation of the upper Quaternary in the Cayar deep-sea fan (Cabo-Verde abyssal plain; Atlantic Ocean). Oceanologica Acta, 11, 4, 359-368. Krinsley D. H. and F. W. MacCoy (1977 a). Surface features on quartz sand and silt grains: Leg39 D.S.D.P. In: Initials Repts Deep Sea Drilling Proj., 39, 445-452.

Krinsley D. H. and F. W. McCoy (1977 b). Significance and origin of surface textures on broken sand grains in deep-sea sediments. Sedimentology, 24, 857-862.

Lambergeon D., S. Dzietara and S. Janicot (1981). Comportement du champ de vent sur l'Afrique occidentale. La Météorologie, 25, 69-82.

Larsen L. H., R. W. W. Sternberg, N. C. Shi, M. A. H. Marsden and L. Thomas (1981). Field investigations of the threshold of grain motion by ocean waves and currents. *Mar. Geol.*, 42, 105-132.

Le Ribault L. (1975). L'exoscopie; méthode et applications. Notes Mém. Cie fr. Pétrol., 12, 231 p., 456 fig.

Lutze G. F. (1980). Depth distribution of benthic Foraminifera on the continental margin of northwest Africa. *Meteor Forschergebn.*, 32, 31-80.

Manickam S. and L. Barbaroux (1987). Variations in the surface texture of suspended quartz grains in the Loire River; an SEM study. Sedimentology, 34, 495-510.

Mazzullo J., D. Sims and D. Cunningham (1986). The effects of aeolian sorting and abrasion upon the shapes of fine quartz sand grains. J. sedim. Petrology., 56, 45-56.

McTainsh G. (1984). The nature and origin of the aeolian mantles of central northern Nigeria. Geoderma, 33, 13-37.

Monteillet J. (1986). Évolution quaternaire d'un écosystème fluviomarin tropical de marge passive : environnements sédimentaires et paléoécologie du delta et de la basse vallée du Sénégal depuis environ 100 000 ans. Thèse Doctorat d'État, Université Perpignan, 264 pp.

Prusak D. and J. Mazzulo (1987). Sources and provinces of Late Pleistocene and Holocene sand and silt on the Mid-Atlantic continental shelf. J. sedim. Petrology., 57, 278-287.

Ruffman A., L. J. Meagher and J. McG. Stewart (1977). Bathymétrie du talus et du plateau continental du Sénégal et de la Gambie, Afrique de l'Ouest. In: *Baffin-Levé au large du Sénégal et de la Gambie*. Publ. Ministère des Pêches et de l'Environnement, Ottawa, Canada, 1, 130 pp.

Sarnthein M., J. Erlenkeuser and R. Zahn (1982). Termination I: the response of continental climate in the subtropics as recorded in deepsea sediments. *Bull. Inst. Géol. Bassin Aquitaine*, 31, 393-407.

Tsoar H. and K. Pye (1987). Dust transport and the question of desert loess formation. Sedimentology, 34, 139-153.

Vincent C. E., D. J. P. Swift and B. Hillard (1981). Sediment transport in the New York Bight, North American Atlantic shelf. Mar. Geol., 42, 369-398.

Walker J. (1972). Monsoon and the global circulation. Met. Mag., Lond., 101, 1205, 349 pp.

130

.