Oligocene climatic, tectonic and eustatic history off NW Africa (DSDP Leg 41, Site 369)

Atlantic
NW Africa
Oligocene
Clay
Climate
Eustacy
Tectonics
Atlantique
Afrique NW
Oligocène
Argile
Climat
Eustatisme
Tectonique

L. Diester-Haass[a], H. Chamley[b]
[a] Geologisches Institut der Universität, Pleicherwall 1, 87 Würzburg, Federal German Republic.
[b] Sédimentologie et Géochimie, ERA 764, CNRS, Université de Lille I, BP n° 36, 59650 Villeneuve-d'Ascq, France.

Received 25/5/79, in revised form 17/8/79, accepted 1/9/79.

ABSTRACT

Oligocene sediments of Hole 369 A (DSDP Leg 41) have been investigated by means of analyses of terrigenous matter in the clay (>2 µm) and coarse (< 40 µm) fraction and of shallow water particles. Four sedimentological zones are recognized, and are interpreted as follows :

Zone 1 (Core 31-6 to 26-5) appears to be influenced by an arid climate, corresponding to a period of high sea-level stand and tectonic stability. Three layers can be distinguished within zone I, pointing to a regression and thus to an increase in continental erosion and in shallow water material supply.

Zone II (Core 26-4 to 23-4) corresponds to a period of tectonic stability and high sea-level stand. Climate is rather humid, fluviatile terrigenous supply replacing the eolian input of zone I.

Zone III (Core 23-3 to 17) reveals numerous changes between transgressions and regressions. The climate appears to be similar to that of zone II in the beginning, and shows an increasing aridity in the upper part.

Zone IV (Core 16 to 14) is characterized by strong erosion on the continent with probable relief rejuvenation and high supply of shallow water material to the slope. These observations are interpreted by means of strong tectonic movements in the near-shore area.

Oceanol. Acta, 1980, **3**, 1, 115-126.

RÉSUMÉ

Évolution climatique, tectonique et eustatique durant l'Oligocène au large de l'Afrique nord-occidentale (LEG 41 DSDP, Site 369).

Les sédiments hémi-pélagiques déposés durant l'Oligocène au Site 369 (forage 369 A) sont étudiés du point de vue de la minéralogie des argiles et de l'abondance des particules grossières issues du continent et des zones océaniques peu profondes. Les résultats conduisent à proposer une interprétation relative aux variations du climat, de l'activité tectonique et du niveau de la mer, sur la marge nord-ouest de l'Afrique. Quatre zones sédimentologiques sont identifiées durant l'Oligocène, et expliquées de la manière suivante, dans l'ordre chronologique :

La zone I (carottes 31-6 à 26-5) paraît sous la dépendance d'un climat chaud et assez aride, marquant une période de haut niveau marin et de stabilité tectonique. Trois sous-zones apparaissent, indicatrices probables de régressions favorisant l'érosion continentale et les apports depuis les petits fonds.

La zone II (carottes 26-4 à 23-4) correspond à une période de stabilité tectonique et de haut niveau marin. Le climat continental semble assez humide, les apports terrigènes fluviatiles prenant le pas sur les apports éoliens caractéristiques de la zone I.

La zone III (carottes 23-4 à 17) suggère l'existence de nombreuses pulsations transgressives et régressives. Le climat, d'abord voisin de celui qui marque la zone II, semble ensuite devenir plus aride.

La zone IV (carottes 16 à 14) témoigne d'une forte érosion continentale probablement déterminée par un rajeunissement des reliefs, et accompagnée par d'abondants apports sédimentaires d'eau peu profonde vers la base de la marge africaine. La cause en est sans doute une phase tectonique marquée dans les zones côtières adjacentes.

Oceanol. Acta, 1980, **3**, 1, 115-126.

INTRODUCTION

The coring and drilling in the oceans in near continental areas provides a new tool for climatic studies diminishing the numerous problems encountered on land, especially the two problems of dating and discontinuous record. The terrigenous particles transported by wind or rivers to the sea can contain indicators of climatic changes.

It was the aim of our investigation to study the Oligocene climatic evolution of the northwestern Sahara in Site 369, Hole 369 A, of DSDP Leg 41 (26°35.55'N, 14°59.96'W; 1 752 m water depth), after the Quaternary and Neogene climate of the area has been described (Diester-Haass, 1976 *a*; Chamley *et al.*, 1977; Sarnthein and Diester-Haass, 1977; Diester-Haass, 1978; Diester-Haass, Chamley, 1978; Diester-Haass, 1979; Chamley, 1979; Chamley, Diester-Haass, 1979; Chamley, Giroud d'Argoud, 1979). It turned out that the climatic information is often hidden by other phenomena, linked to sea-level changes and tectonic activity.

MATERIAL AND METHODS

Smear slides from the Oligocene sediments (Cores 14 to 31) of Hole 369 A (Lancelot, Seibold *et al.*, 1978) indicate nannomarls and nannodiatom clays and marls, and diatom bearing nannomarls. One sequence (Core 27, 1-6, 35 cm) is a slump and consists of a radiolarian bearing diatom nanno ooze. Core 14 might be a slump, and in core 29-5 a small slump has been observed (*op. cit.*). A rather continuous sedimentation, except for the slumps, can be assumed at this site during the Oligocene, because all foraminiferal zones have been found (Krasheninnikov, Pflaumann, 1978).

Table 1

List of investigated samples, Oligocene Site 369 A, DSDP Leg 41.

Core	Sect.	Interva (cm)	Core	Sect.	Interval (cm)	Core	Sect.	Interval (cm)
14	1	118-120	20	4	40- 42	26	1	25- 27
	2	40- 42		5	40- 42		2	40- 42
	3	40- 42		6	40- 42		3	40- 42
	4	40- 42	21	1	130-132		4	40- 42
	5	40- 42		2	40- 42		5	40- 42
	6	40- 42		3	40- 42	27	1	110-112
15	1	40- 42		4	40- 42		2	117-119
	2	40- 42		5	40- 42		3	58- 60
	3	40- 42		6	40- 42		4	88- 90
	4	40- 42	22	1	80- 82		5	52- 54
	5	40- 42		2	48- 50		6	112-114
	6	40- 42		3	40- 42	28	1	133-135
16	1	78- 80		4	60- 62		2	68- 70
17	1	40- 42		5	40- 42		3	51- 53
	2	40- 42		6	38- 40		4	71- 73
	3	40- 42	23	1	40- 42		5	56- 58
	4	40- 42		2	40- 42	29	1	79- 81
	5	40- 42		3	40- 42		2	82- 84
	6	40- 42		4	40- 42		3	47- 49
18	1	80- 82		5	40- 42		5	69- 71
	2	40- 42		6	40- 42		6	47- 49
	3	40- 42	24	1	117-119	30	1	68- 70
	4	40- 42		2	41- 43		2	35- 37
	5	40- 42		3	40- 42		3	92- 94
	6	40- 42		4	36- 38		4	68- 70
19	1	115-117		5	40- 42		5	58- 60
	2	40- 42		6	40- 42	31	1	134-136
	3	40- 42	25	1	136-138		2	54- 56
	4	40- 42		2	40- 42		3	51- 53
	5	40- 42		3	40- 42		4	48- 50
	6	40- 42		4	40- 42		5	80- 82
20	1	115-117		5	40- 42		6	68- 70
	2	40- 42		6	40- 42			
	3	40- 42						

One sample per section (= 150 cm) has been investigated in the 175 m thick Oligocene sequence (Table 1) by means of a coarse fraction and clay mineral analysis.

For the mineralogical study of the clay fraction (< 2 µm) all samples were submitted to X-ray diffraction analysis. Successive treatments consisted of decarbonatation (N/5 HCl), centrifugations, microhomogeneization and deflocculation, decantation, sedimentation of oriented aggregates on calibrated glass slides. The X-ray investigation (CGR θ 60, Cu anticathode, quartz monochromator, scintillation counter) includes four passages between 1 and 16° θ: natural conditions, ethylenic glycol saturation, heating at 490°C during 2 hours, hydrazine hydrate saturation. Semiquantitative evaluations are based on major peak height and areas (Chamley, 1971). Heights of 001 illite and chlorite peaks (glycolated samples) are taken as references: smectite, attapulgite, sepiolite and irregular mixed-layers are corrected in addition of peak height, whereas well crystallized kaolinite is corrected in diminution. Final data are given in percentages, the relative error being of about $\pm 5\%$. In order to precise the quantitative evaluations, peak height ratios have been measured on diagrams of glycolated samples, in the following way:

— kaolinite/smectite: 7.1/18.0 Å;
— illite/smectite: 10.0/18.0 Å;
— kaolinite/illite: 7.1/10.0 Å.

For the coarse fraction analysis the samples have been dried, weighed, wet sieved through a 40 and a 63 µm sieve. The residue has been dried, weighed and its percentage of the total sediment has been calculated. The > 63 µm fraction has been dry sieved into the following subfractions: 63-125, 125-250, 250-500, 500-1 000, $> 1\,000$ µm and the percentage of each fraction of the total sand fraction has been calculated. A component analysis has been performed (Sarnthein, 1971; Diester-Haass, 1978). In each fraction about 800 grains (if present) have been identified with distinction of various biogenous, terrigenous and authigenous components (Diester-Haass, 1980 *a*). For the grain size distribution of sand sized terrigenous matter the 63-125 µm fraction (where all or nearly all terrigenous matter occurs) has been sieved into the subfractions 63-80, 80-100, 100-125 µm. The amount of terrigenous matter in each fraction has been counted and the grain size distribution calculated.

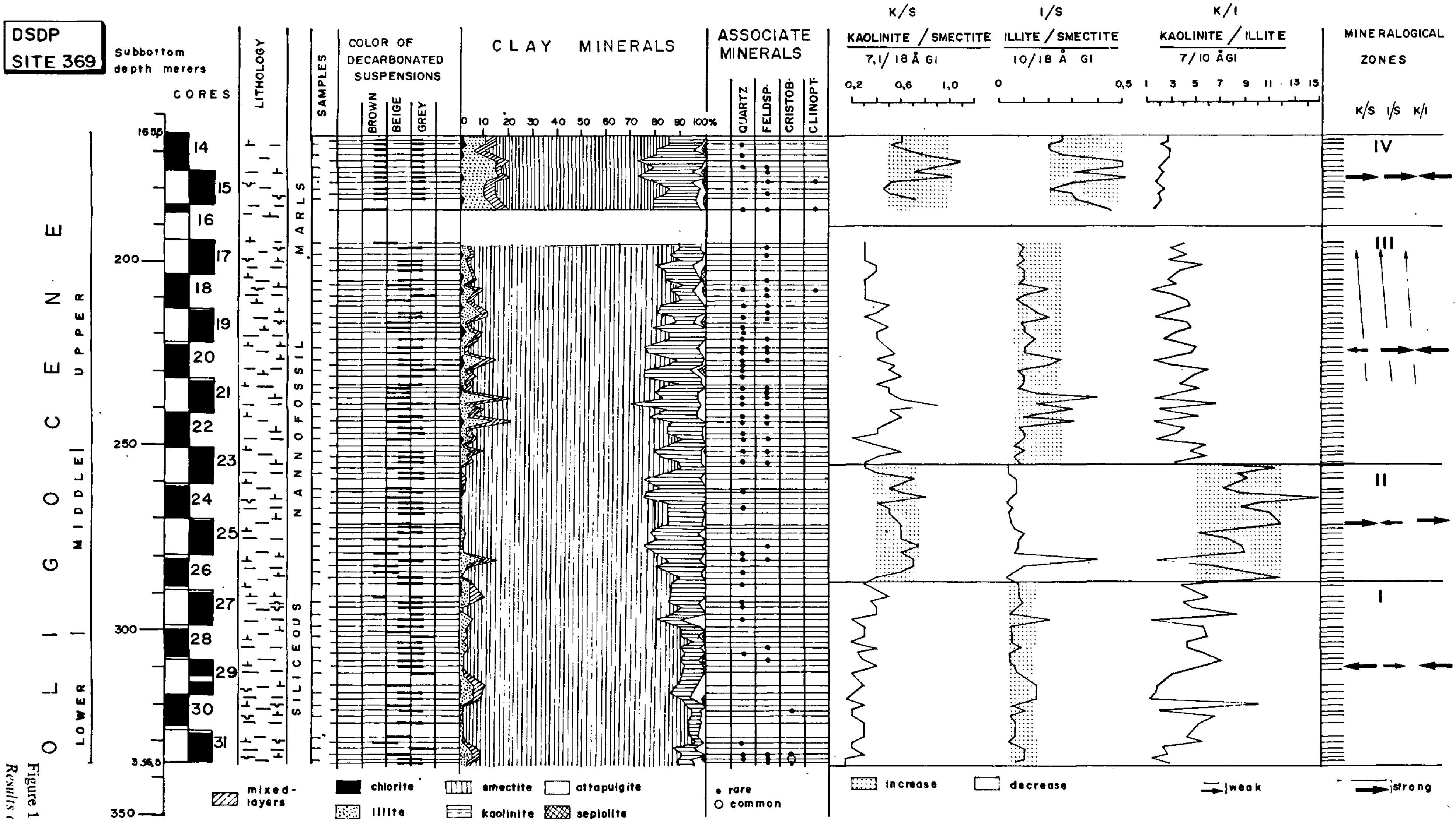
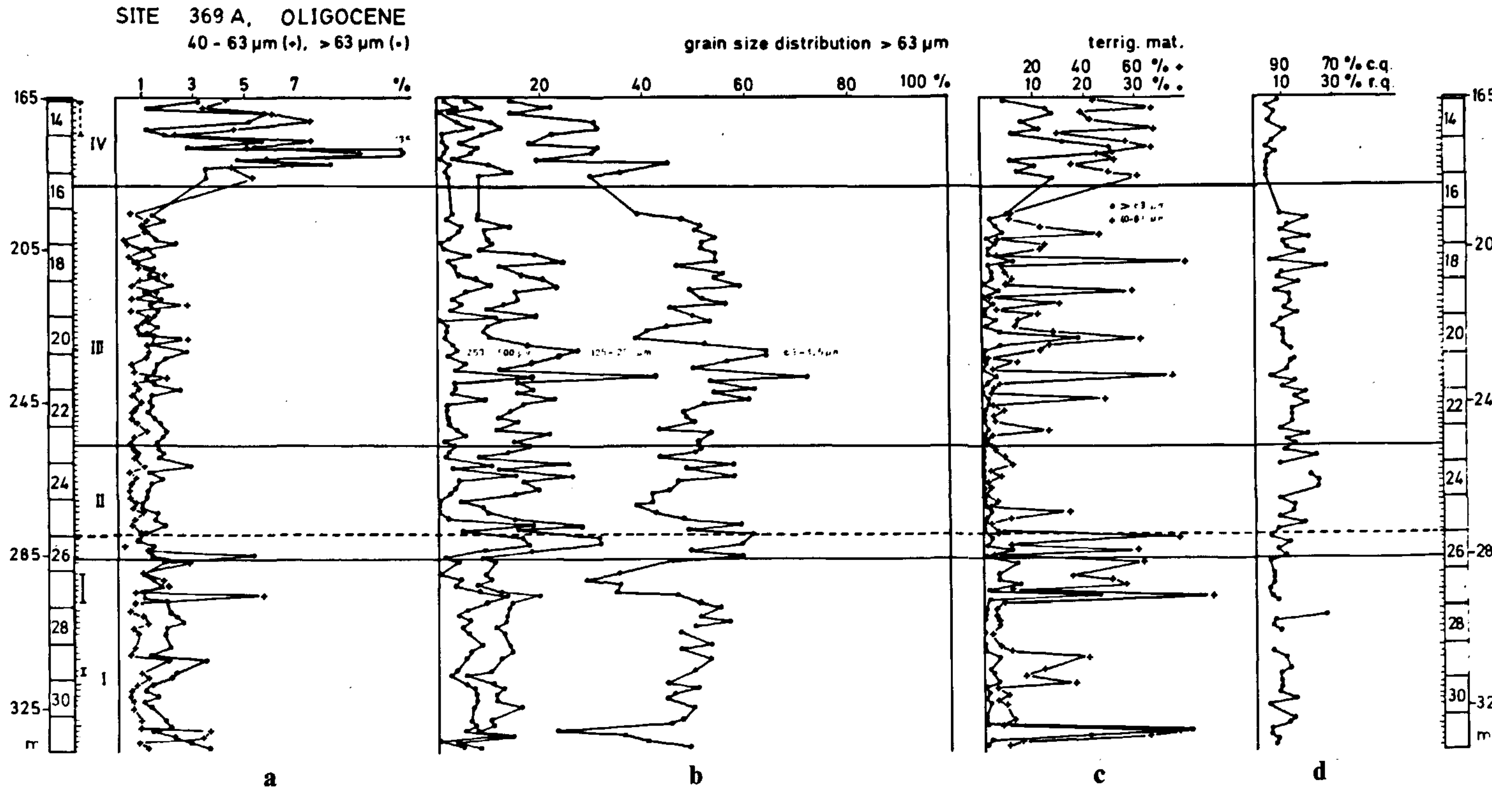


Figure 1
Results of clay mineral analysis.



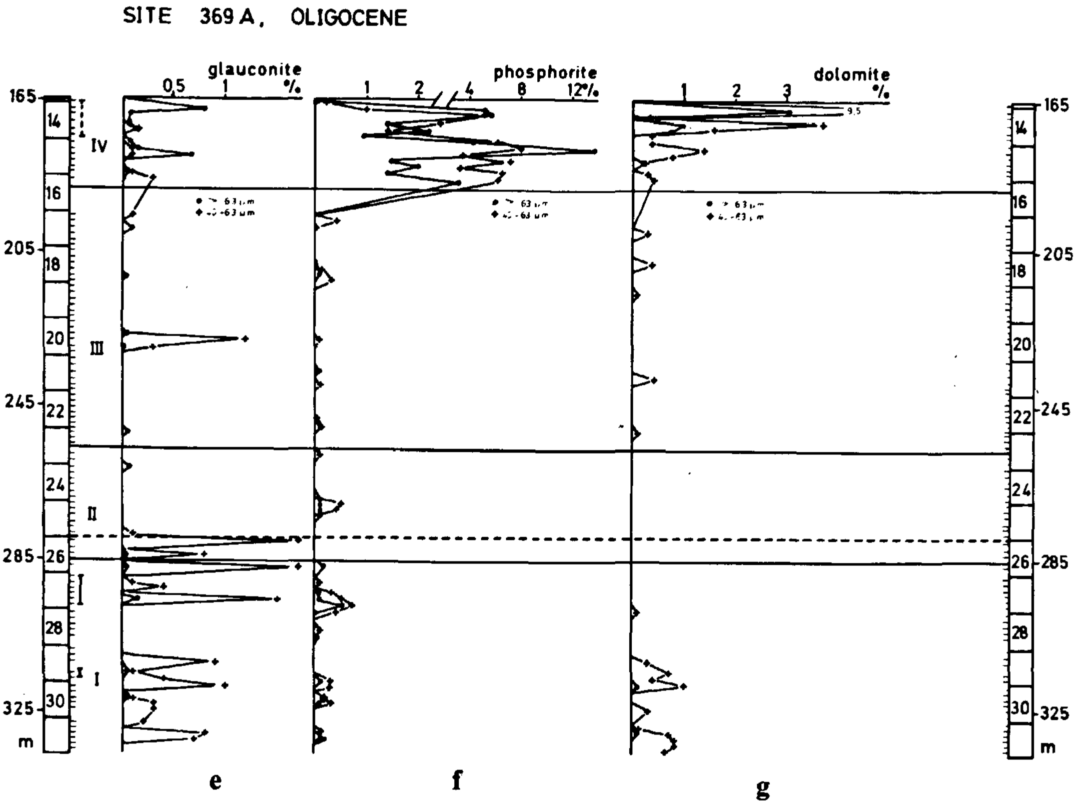


Figure 2

Results of coarse fraction analysis.
Numbers on right and left side: depth below sea-floor in meters.
Core numbers; thin horizontal lines indicate investigated samples.
Roman numbers: our zones I-IV, determined from sedimentological parameters.
a) Amount of 40-63 and > 63 µm fraction of total sediment.
b) Grain size distribution within the sand fraction.
c) Percentage of terrigenous matter in the 40-63 and > 63 µm fraction.
d) Ratio of red stained versus colorless quartz, calculated as (r. st. q./c. q. + st. q.) × 100.
e) Percentage of glauconite in 40-63 and > 63 µm fraction.
f) Percentage of phosphorite in 40-63 and > 63 µm fraction.
g) Percentage of dolomite in 40-63 and > 63 µm fraction.

RESULTS

Clay fraction (Fig. 1)

Ubiquitous minerals consist of well crystallized smectite (more than 50% of clay minerals), illite and kaolinite. Irregular mixed-layers (illite-smectite, illite-vermiculite, chlorite-smectite), attapulgite (palygorskite), quartz and feldspars occur frequently; chlorite, sepiolite, opal-CT and clinoptilolite occur rarely. Clay minerals show no sign of any diagenetic influence with the depth of burial. All minerals of the clay fraction are considered as inherited from the adjacent African continent (see Mélières, 1978; Timofeev *et al.*, 1978; Chamley *et al.*, 1979), except for zeolites and cristobalite which result from an early diagenesis of biogenic silica in a marine environment (Riech, von Rad, in press).

Four mineralogical zones appear in the Oligocene clay stratigraphy of Site 369, from oldest hemipelagic sediments upwards:

• Zone I, Cores 31-6 to 26-5. Smectite is very abundant (85% of clay fraction), associated with 5 to 10% of attapulgite and sometimes traces of sepiolite. Other noticeable minerals consist of low amounts of illite (traces to 5%) and kaolinite (5 to 10%). The average color of non calcareous fine particles is gray to beige. Zone I locally shows short increases in illite and kaolinite amounts, often associated with occurrences of irregular mixed-layers.

• Zone II, Cores 26-4 to 23-4. Smectite is still very abundant (80 to 85 of clay fraction), but it is accompanied by 15 to 20% of kaolinite. On the other hand, illite shows its lowest abundance, as do quartz and feldspars (traces or none). Chlorite and mixed-layers are generally missing as in zone I. Fibrous clays are very rare. The increase of kaolinite corresponds to more yellowish and brownish colors of the clayey suspensions, pointing to the detrital supply of subamorphous iron oxides.

• Zone III, Cores 23-3 to 17. Smectite content decreases (70-80% of the clay fraction), while illite content increases (up to 10%). Illite is accompagnied by irregular mixed-layers, frequent chlorite, quartz, feldspars and fibrous clays. Kaolinite amounts and average clay color show similar characteristics as in zone II. From core 20 upwards a progressive but slight decrease of kaolinite, illite, chlorite, quartz and feldspar amounts is observed.

• Zone IV, Cores 16 to 14. The uppermost Oligocene sediments strongly differ from the underlying series, from a mineralogical point of view. Smectite abundance is comparatively low (50 to 70%); illite shows its highest content (15%) and is constantly associated with chlorite and mixed-layers, frequently with attapulgite, sepiolite, quartz and feldspars. Here for the first time kaolinite and illite, both rather abundant, vary in a parallel way, whereas smectite varies in an opposite way. The color of the decarbonated fine sediment is grayish-brown.

Grain size distribution of total sediment

The sand (> 63 µm) and 40-63 µm fractions form only small percentages of the total sediment (Fig. 2*a*): the sand fraction is in general 0,5-2%. Only some samples and cores 14-16, which are rich in quartz and shallow water particles, have higher sand percentages.

The grain size distribution within the sand fraction (Fig. 2*b*) shows that the 63-125 µm fraction forms in general about 40-50% of the total sand fraction. Only in the quartz rich samples percentages increase up to 85%. The peaks in coarse (> 500, 250-500 µm) sand fractions are produced by pyrite and gypsum.

Composition of the sand fraction

The main constituents of the sand fraction are biogenous particles which are studied by Diester-Haass (1980 *a*). Amounts of terrigenous components show strong variations and are < 1 up to 25% of the sand fraction (Fig. 2*c*). In the coarse silt fraction the terrigenous material varies between less than 10 up to 90%, variations being parallel to those in the sand fraction.

In the Oligocene four zones can be distinguished from the amounts of terrigenous material (Fig. 2*c*), which correlate to those established by clay mineralogy. In the lower zone I terrigenous particle amounts are low, interrupted by three maxima. In zone II values are very low. In zone III several strong variations between maxima and minima occur and finally in zone IV values are generally high.

The terrigenous particles consist mainly of quartz, minor constituents are feldspars, white bluish-greenish rounded grains consisting of calcareous matter and clay minerals (von Rad and Riech, pers. comm.), mica and very few dark minerals. Within the quartz grains colourless quartz and red iron stained quartz were distinguished and plotted as a ratio (red stained quartz/colourless plus red stained quartz) × 100 (Fig. 2 *d*). The ratios show in general small values, with the following variations: in zone I values are very low, increase in zone II, are intermediate in zone III and low in zone IV.

Minor constituents of the sand fraction are glauconite, phosphorite and dolomite (Fig. 2 *e, f, g*). They occur in minor amounts, smaller than 2% of the 63-125 and 40-63 µm fractions. Only in cores 14 and 15 phosphorite and dolomite form about 10% of the coarse silt fraction in some samples. The presence of these particles as well as that of benthonic molluscs and serpulides is always linked to maxima in terrigenous material. Samples with small terrigenous input do not contain glauconite, phosphorite or dolomite. Pieces of quartz-siltstone and ooids are found in cores 14 and 15.

Pyrite is considered to be an authigenous formation. In general it occurs as a microcrystalline burrow filling, larger crystals being rare. The coarse fractions (> 250 µm) contain most of the pyrite. Its percentages vary strongly between about 2 and 35% of the sand fraction with some peaks of up to 50%. In the 40-63 µm fraction pyrite percentages rarely exceed 10%.

Gypsum occurs in nearly all samples in the > 250 µm fractions in a few pieces. There are coccolithes and some opal skeletons included in the crystals (von Rad Riech, pers. comm.). It is not clear, whether they have been formed during or after sedimentation, or during storage by oxidation of pyrite. The latter way of formation has been assumed for sediment cores from the Persian Gulf (Diester, 1972).

Grain size distribution of sand sized terrigenous matter

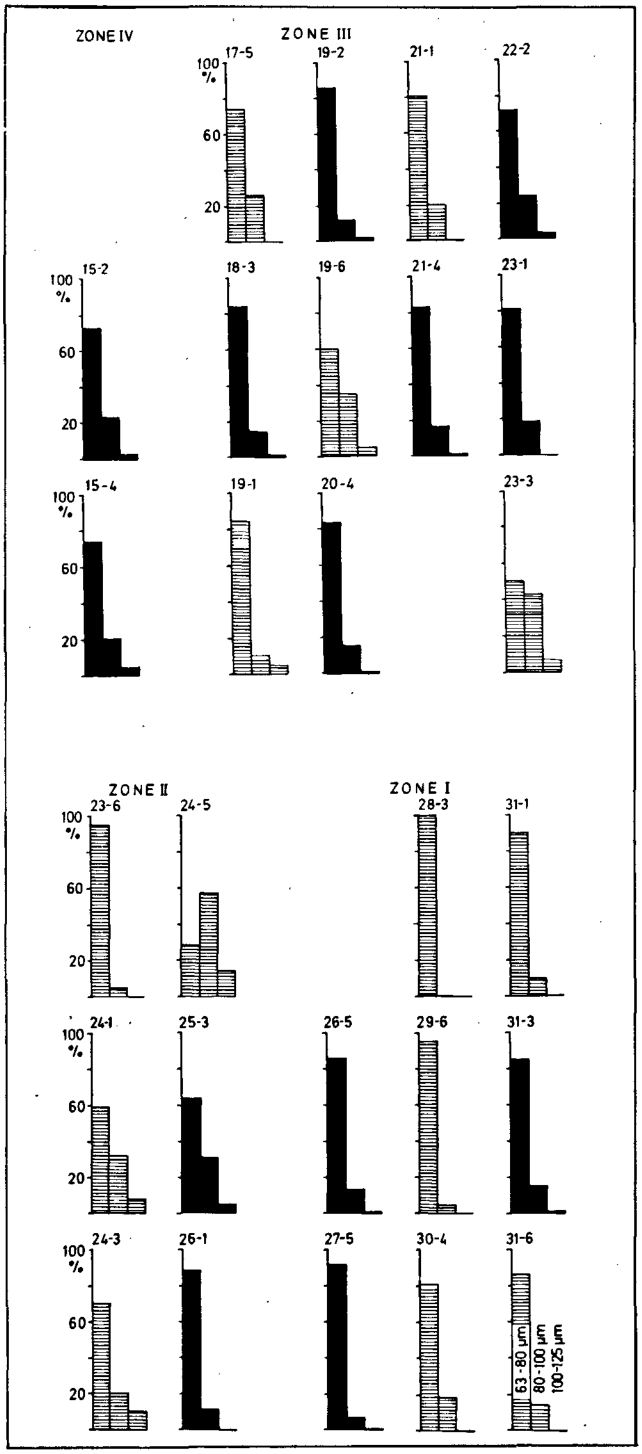
Sand sized terrigenous material (63-125 µm) is the coarsest fraction supplied from the continent to the ocean. We believe that the changes in grain size distribution of this coarsest material are a rather sensitive reaction on changes in transport mechanism or energy. In order to check this hypothesis, we studied the amount of 63-80, 80-100 and 100-125 µm sized terrigenous matter (= quartz, feldspars, other minerals, no mica) in 28 samples (Fig. 3).

In zone I we find a maximum of the 63-80 µm sized terrigenous material, the 100-125 µm fraction being absent except for the layers with high terrigenous input and shallow water material, which show minor amounts of 100-125 µm fraction. This can be attributed to bottom transport from shallow water.

In zone II grain size distribution of terrigenous matter is quite different (except for the upper and lower sample): the coarser fractions increase distinctly compared to zone I.

Figure 3

Grain size distribution of sand-sized terrigenous material in zone I to IV. In the grain size diagrams the left column shows the percentage of the 63-80 µm sized terrigenous fraction, the middle column that of 80-100 µm sized terrigenous material and the right column that of the 100-125 µm sized terrigenous material.
Hatched: samples with no shallow water material (=high sea-level).
Black: samples with shallow water material (=regressions).
Numbers above the columns: core and section number of investigated sample.



In zone III we find both types of grain size distribution, those of zone I and II or a mixture of both.

In zone IV the two examples of grain size distribution show rather high abundances of >80 µm fractions. Shallow water supply by bottom transport is strong and the grain size data of terrigenous material are obviously influenced by this transport mechanism.

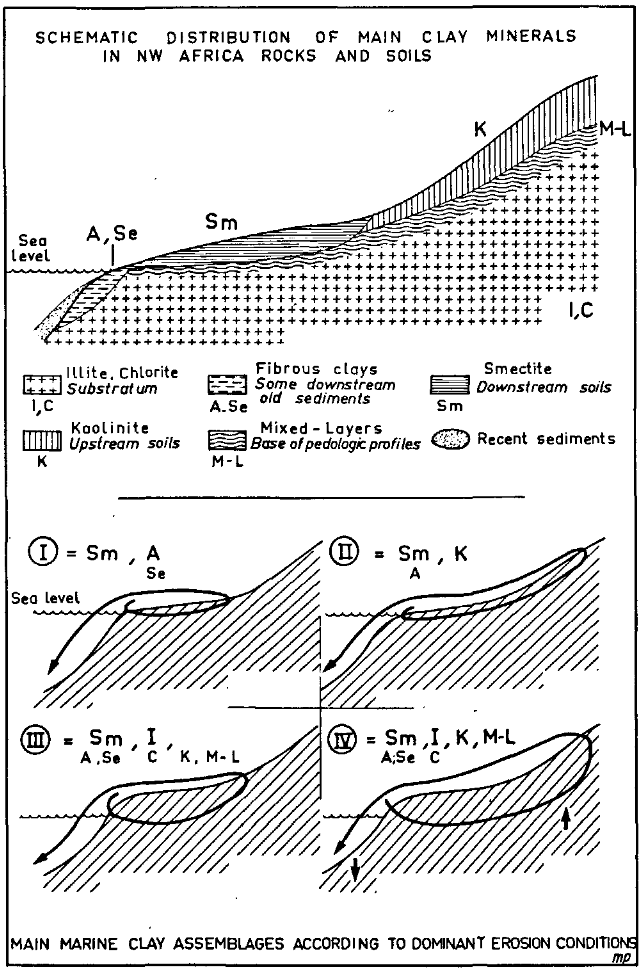
DISCUSSION

General significance of sedimentary clay associations

The main occurences of phyllites in the North-West African continent as well as in other crystalline or old sedimentary terrestrial zones submitted to warm climates (see in Millot, 1964; Pédro, 1968; Paquet, 1970; Chamley, 1979), statistically show a schematic distribution as follows (Fig. 4): 1) Illite and chlorite abundantly and widely exist in old rocky substrates, together with quartz and feldspars. 2) Fibrous clays (attapulgite, sepiolite) and sometimes smectite are developped in calcareous and marly rocks formed in marginal confined areas under arid conditions and during distinct geological stages (i.e. Early Eocene); their present outcrops chiefly lie in coastal continental areas. 3) Most of the smectite is formed in gray soils of badly drained terrestrial areas submitted to warm temperatures and alternating short wet and long dry

Figure 4

Significance of clay mineral data (schematic graph).



seasons. The preferential location of such formations, probably extending very largely in Paleogene times, occurs in downstream surficial soils. 4) Kaolinite is a typical pedogenic clay mineral formed in well-drained areas under hot and humid conditions; its main outcrops lie in upstream and sloping surficial areas. 5) Irregular mixed-layers represent moderate and incomplete degradations of common clay minerals such as illite, chlorite or smectite; in North-West Africa they chiefly develop at the base of pedological profiles where weathering starts off.

With such a schematic continental distribution of clays in mind, the marine clay assemblages, which are essentially terrigenous and supplied from North-West Africa into the Eastern Atlantic basin (see for instance Chamley *et al.*, 1977; Diester-Haass, Chamley, 1978; Chamley, Giroud d'Argoud, 1979), may be tentatively interpreted as markers of the source areas and conditions of erosion. Four main outlines may be envisaged:

I. Very large abundance of smectite, associated with variable amounts of fibrous clays: erosion mainly of surficial downstream soils and rocks.

II. Association of abundant smectite and noticeable amounts of kaolinite: erosion of surficial downstream and upstream pedogenic formations.

III. Association of abundant smectite and noticeable amounts of illite, with presence of chlorite, mixed-layers, quartz and feldspars: erosion of both surficial soils and deeper rocks occurring in downstream areas. The presence of kaolinite, whose abundance does not covariate with that of illite, suggests a minor and secondary contribution from slope zones.

IV. Mixtures of smectite, of illite and kaolinite varying together, of irregular mixed-layers, and of various other minerals: erosion of both surficial and deep formations existing in both downstream and upstream continental zones.

These four possible relations between sedimentary clay facies and continental erosion patterns are sketched on Figure 4. We will further try to interpret them in terms of climatic, eustatic and tectonic conditions on the nearby African land-masses during the Oligocene.

General significance of coarse terrigenous material

The coarse fraction investigated here forms only a small percentage (in general less than 3%) of the total sediment, and it seems questionable to base conclusions on these quantitatively unimportant constitutents. But one has to bear in mind that the coarse silt and sand sized terrigenous particles are only the coarsest tail of terrigenous input, which clearly reflects changes in terrigenous supply, since changes are most obvious in "boundary conditions" (Diester-Haass, 1976*a*). Accumulation rate changes of sand sized terrigenous material are generally parallel to those of total terrigenous material (Diester-Haass, 1976*b*). Glauconite, phosphorite and dolomite are minor constituents, but their presence can be a valuable indicator of shallow water transport. Even a few debris of these grains indicate that transport had occurred. What kind of deductions can be made from coarse silt and-sand-sized terrigenous material? Since no mineralogical investigations have been done in these fractions, only quantitative variations and grain size data can be judged.

In Quaternary and Neogene sediments off the Sahara and in the same site (369/369 A) some observations have been made (Diester-Haass, 1976 *a*; Chamley *et al.*, 1977; Diester-Haass, 1978, 1979 *a*). They are summarized here and compared with results from the Oligocene sediments (Fig. 5).

During arid climatic phases and high sea-level:

— total terrigenous input is low;

— input of sand-sized terrigenous material is very low;

— the stained quartz amounts are high (ratio of red stained/colourless quartz up to 100-200). These high values indicate either a red staining during these arid intervals or a preservation of red staining from older periods;

— the grain size distribution of terrigenous material in the 63-125 µm fraction shows that the 63-80 µm fraction is most important and that the 100-125 µm fraction is absent (Fig. 5 and Fig. 6 B, oxygen stages 1 and 5);

— shallow water material such as corroded shells, glauconite, phosphorite is absent in water depth below about 1 000-2 000 m.

During more humid climatic periods, correlated to lowered sea-level, the parameters show the opposite trend:

— terrigenous input is high;

— sand sized terrigenous material is abundant;

— the stained/colourless quartz ratios are very low, pointing to non-formation or destruction of red iron staining;

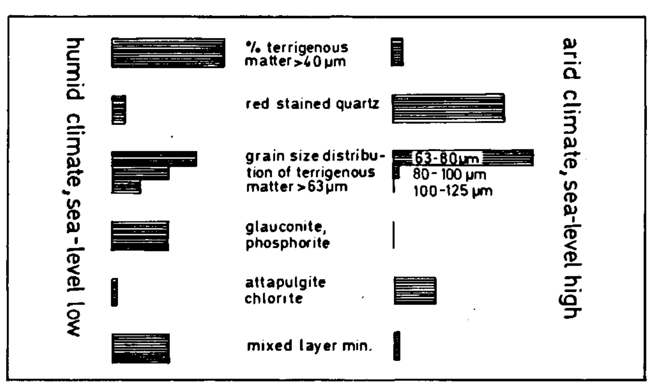
— the grain-size distribution of sand-sized terrigenous material in oxygen stages 2, 3 and 4 (Fig. 6 B) shows a considerable increase in the 80-100 µm fraction compared to the arid stages and the presence of 100-125 µm sized terrigenous material;

— shallow water particles are present.

Clay mineral data (Chamley et al., *1977) agree with these results (Fig. 5): sediments from arid periods contain attapulgite and chlorite, which indicate scarceness of chemical weathering and thus very little rainfall. Humid periods, however, are characterized by an increase in mixed-layer minerals, which allow the conclusion that higher rainfall led to hydrolysis.*

Figure 5

Schematic graph showing the response of some coarse and clay fraction results to Late Quaternary climatic and sea-level changes off the northern Sahara (20-27°N).



An opposite climatic interpretation, presented by Sarnthein (1978 *a*), Lutze *et al.* (1979) and Sarnthein and Koopmann (1979), is based on the investigation of terrestrial and marine sediments from the 18 000 and 6 000 years BP level. For details in differences of interpretation see discussion of Sarnthein (1980) and Diester-Haass (1980 *b*).

The grain size distribution of the coarsest terrigenous material seems to us to be a rather important parameter for the distinction of climatic changes. After Bagnold (1954) no quartz > 80 μm can be transported by wind in suspension. Furthermore, dusts collected over the Atlantic did not contain as big particles (Chester, Johnson, 1971 *a* and *b*; Chester *et al.*, 1971, 1972). Dust samples described by Jaenicke *et al.* (1971) also did not contain particles > 80 μm. When as big grain sizes were present, they were aggregates. We believe that the presence of 100-125 μm sized quartz in cores off North-West Africa might be in favour of another than eolian supply i.e. either by bottom transport from shelf-upper slope areas or by rivers.

The significance of the grain size data for the distinction between fluviatile and eolian input can be shown by a comparison between grain size data off the northern Sahara and off Senegal in the late Quaternary (Fig. 6 A and B). Off Senegal the opposite climatic evolution as off the northern Sahara is unanimously accepted by all students of the area (see in Diester-Haass, 1975, 1976 *a*; Michel, 1973; Sarnthein, 1978 *a*; Rossignol-Strick, in press). Here a humid Holocene (oxygen stage 1) is preceded by a very arid oxygen stage 2. Grain size data reveal the presence of 80-100 and 100-125 μm sized quartz in the Holocene where the Senegal river supplies material, and the absence of 100-125 μm sized quartz in the oxygen stage 2. There sea-level was lowered, thus the distance of the site of deposition from the continent reduced, and wind strength was increased (Sarnthein, Walger, 1974). These facts are probably responsible for the presence of some 80-100 μm sized quartzes. The arid Holocene off the northern Sahara has no quartz > 80 μm (Fig. 6 B), except for one sample taken 3 cm above the coarser late Glacial sediments and which is probably influenced by bioturbation supply of coarser material.

The late Glacial stages 2, 3 and 4 off the northern Sahara show a similar or even coarser grain size distribution as the humid Senegal—influenced Holocene off Senegal—. The comparison of stage 2 grain sizes off the Sahara (Fig. 6 B) and off Senegal (Fig. 6 A) shows that during the period of lowered sea-level very different grain size distributions occur in both areas, suggesting a different climate. If wind could supply quartz > 100 μm, we do not see why it is not found off Senegal. So we suggest that the high amounts of 80-100 and 100-125 μm sized terrigenous matter are at least partly supplied by rivers off the northern Sahara, an interpretation which is enhanced by the clay mineralogy data and the data on red stained quartz.

In the following discussion we will try to interpret the Oligocene sediments under the aspect of the results obtained from Quaternary and Neogene sediments (although unsolved paleoenvironmental questions remain, especially as to morphology and marine currents). The water depth of the site can be assumed to have been similar to the present one or slightly shallower due to subsidence and lowered sea-level (Lancelot, Seibold *et al.*, 1978; Diester-Haass, 1978), suggesting that the distance from the coast also remained constant. A major difference between Quaternary/Neogene and Oligocene sediments is that the red stained/colourless quartz ratios: 1) are much smaller (< 25 %) in the Oligocene, and 2) do not show a correlation with amounts of terrigenous material. In the Neogene and Quaternary, maxima in terrigenous input are correlated to minima in red stained quartz amounts. Here in the Oligocene, variations of red stained quartz are of minor importance and in general independant of quartz amounts.

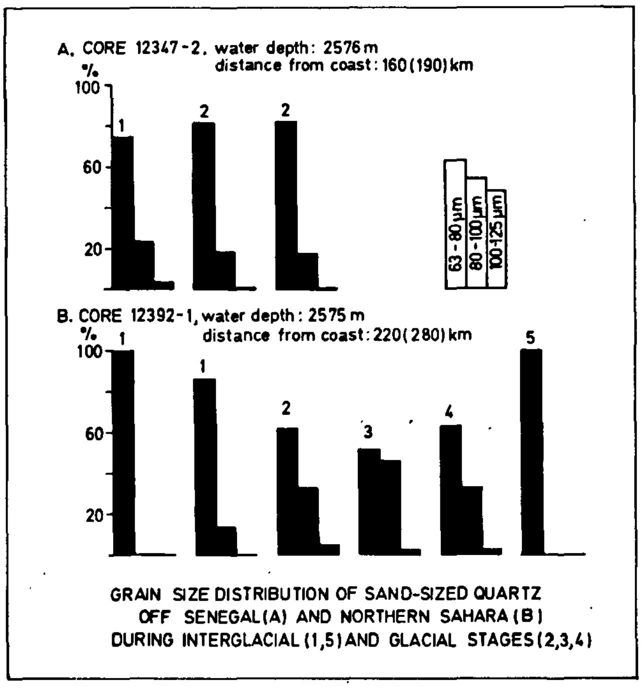
Red stained quartz ratios, however, correlate with pyrite contents. Smallest pyrite amounts of about 2-5% in core 23 to 25, for instance, correlate with highest red stained quartz ratios, whereas the lowest values in zone III e.g., correlate to peaks in pyrite content (peaks up to 30-50% pyrite in the sand fraction). These observations indicate that red staining might have been destroyed by reduction in Oligocene sediments as it is the case in a late Glacial core where the same correlation between increasing pyrite content and decreasing red staining has been made (cp. Diester-Haass, 1975). Thus in the Oligocene sediments no inferences can be made from the red stained quartz percentages.

Interpretation of the Oligocene results

On the background of the described clay mineral distribution in nearby continental areas and of the knowledge of Neogene and Quaternary eustatic and

Figure 6

Comparison of the grain size distribution of sand-sized terrigenous material (> 63 μm) off Senegal (A) and off the northern Sahara (B) in Late Quaternary interglacial (oxygen stages 1 and 5) and glacial periods (oxygen stages 2, 3 and 4).



climatic changes and their effect on terrigenous coarse and clay fractions, we will try to discuss the possible sedimentation processes during the Oligocene, especially the influence of tectonics, sea-level changes and climate.

Zone I (*core* 31-6 *to* 26-5).

Two types of sediment occur during this period. Type 1 is characterized by a very high smectite content and rather abundant attapulgite. These minerals suggest a weak erosion on the continent, which takes place only in the near coastal basins, where they are formed in poorly drained areas. The small kaolinite content (smallest percentages in all the Oligocene) suggests that the erosion products of upstream areas did not reach the ocean in the Site 369 area. Coarse terrigenous particles are rare and shallow water material is absent or rare. All these facts point to a weak erosion, due either to a high sea-level stand and no tectonic movement, or to a rather arid climate with only a short humid season, or to both of these causes. The absence of shallow water material points to a high sea-level stand. If climate has been rather humid, kaolinite should be more abundant. Furthermore, grain size data of sand-sized terrigenous material (Fig. 3) are very similar or equal to those from arid late Quaternary periods (Fig. 6 A, oxygen stage 2; 6 B, stages 2, 3 and 4), suggesting perhaps a mainly eolian input. *So we conclude that both factors,—high sea-level/no tectonic movements and rather arid climate with mainly eolian input and only a short rainy season,—influenced sedimentation processes during the part of period I characterized by the first type of sediments.*

A second type of sediments is found in three levels within zone I: here high sand-sized and coarse silt input, shallow water particles and an increase in illite and mixed-layers occur. These data point to an intensification of erosion, attaining the deeper layers in near coastal areas and also the upstream kaolinite area. The shallow water particles, including serpulides, which do not live deeper than about 200 m (van der Spoel, Amsterdam, pers. comm.) indicate that the shore-line probably moved seawards, reducing the transport path of shallow water material to the slope. Grain size distributions of sand sized terrigenous material reveal a slight increase in coarse fractions (Fig. 3), probably due to bottom transport of terrigenous material, but the influence of eolian input appears to remain dominant. *Probably the type* 2 *sediments within zone I were deposited during a lowered sea-level, leading to increased erosion on the continent and to shallow-water material supply on the slope. Climate probably has not changed compared to the periods of type* 1 *sediment deposition.* Note that core 27, containing "type 2" sediments, is a slump after shipboard descriptions (Lancelot, Seibold *et al.*, 1978). Its composition, however, is not different from the rest of the "peaks" within our zone I. So we adopt the same interpretation for all "peaks".

Zone II (*core* 26-4 *to* 23-4) is characterized by abundant smectite and rather high kaolinite amounts, whereas illite is nearly absent. Sand-sized terrigenous input is extremely small, shallow-water particles are more or less absent. The clay mineral observations indicate a rather important continental erosion, which attacked the more distant well-drained slope areas with the kaolinite. The absence of shallow water particles is in favour of a high sea-level. So the increased erosion cannot be explained by deepening of the erosion basis, and we conclude that increased erosion occurred as a consequence of an increase in rainfall, which led to river erosion. This interpretation of fluviatile supply is supported by the grain size data of sand-sized terrigenous material, which in zone II show highly increased 80-100 and 100-125 µm fractions compared to zone I (see discussion above). The grain size diagrams strongly resemble those of the humid oxygen stages (late Quaternary) 2, 3, 4, off the northern Sahara and the humid Holocene off Senegal (Fig. 6 A and B). Only the samples close to the boundary of zone II (24-1 and 26-1) show a distribution which resembles eolian supply.

The rainfall probably was not very intense and the erosion attacked only the surficial soils and not the unaltered deeper rocks because illite and other primary minerals (chlorite, quartz, feldspars) are very rare or absent. The small amounts of sand-sized terrigenous particles are in favour of a weak erosion. Tectonic activity can be excluded, because of only surficial erosion. Only two samples show a composition similar to that of "peaks" in zone I, suggesting a regression.

We conclude that during period II the marine sedimentation on the continental slope was probably influenced by a rather humid climate with fluviatile input, that sea-level was high and that no tectonic activity occurred.

Zone III (*core* 23-3 *to core* 17) shows numerous changes between two types of sediments. The first type is a sediment with rather important occurrences of illite and mixed-layers, and sometimes of chlorite, quartz and feldspars, correlated to a reduced kaolinite content. Smectite is abundant, but slightly reduced compared to zone II. In these sediments the coarse terrigenous material is abundant and shallow water material, including benthonic molluscs and serpulides, is present. The latter indicate a lowered sea-level, which also produces an intensification of continental erosion. The occurrence of primary minerals in the clay fraction agrees with this interpretation: the erosion mainly attacked deeper layers of the near-shore basins during these regressive periods.

The second type of sediments is alternating with these "regression sediments". They are characterized by the nearly absence of chlorite, the diminution of illite and sometimes mixed-layers, and by increased amounts of kaolinite and sometimes smectite. Coarse terrigenous input is low (but higher than in zone II) and no shallow water particles are found. Probably here the sea-level was high, restricting the erosional acticity to the more surficial soil layers and rocks.

Climatic deductions cannot be made from the "regression sediments", because the erosional influence hides the climatic information. The second type of sediments, deposited during transgressions, indicates a climate similar to that in zone II in the deeper part (cores 23-20) and an aridification in the upper part, revealed by decreased kaolinite and increased smectite contents.

Grain size data of sandy terrigenous matter resemble in general fluviatile material (cp. Fig. 3 and 6), with the presence of the 100-125 µm fraction. Some samples, however, are intermediate between typical eolian and typical fluviatile grain-size curves. A reason might be a climate with distinct arid and humid seasons, leading to both fluviatile and eolian input and thus to a long-range mixture of both types of grain-size curve types. The aridification in the upper part of zone II, as suggested by clay mineral results, is not reflected in grain-size data, what could be determined by differences in transport energy (Chamley, Diester-Haass, 1979).

As a conclusion, zone III appears to be marked by a succession of several transgressions and regressions, during a rather humid climate, showing however a tendency towards aridification in the upper part.

Zone IV (cores 14-16) contains highest illite and mixed-layers amounts, associated with chlorite. Smectite shows lowest values, kaolinite is rather important. The terrigenous input in the coarse fractions is highest and considerable amounts are found in the sand fraction. Shallow water material, including ooids, is abundant. These data suggest a regression and/or tectonic movements, affecting the coastal area as well as the upstream areas, because sub-marine near-shore particles such as ooids and dolomite are eroded as well as illite, chlorite and kaolinite (Fig. 4). The presence of quartz and feldspar in the clay fraction is also in favour of strong erosion. The fact that kaolinite and illite increase simultaneously is in favour of a rather important tectonic activity, leading to erosion in up-and downstream areas. The rather high amounts of kaolinite could hardly be supplied by fluviatile erosion alone, a rejuvenation of the relief seems necessary. A strong tectonic activity in the uppermost Oligocene/lowest Miocene has also been suggested by Dillon and Sougy (1974) and has been described for the early Miocene (Sarnthein, Diester-Haass, 1977; Diester-Haass, Chamley, 1978; Diester-Haass, 1978). Note that a climatic interpretation of the uppermost Oligocene cannot be given, because the strong tectonic influence hides other informations.

To conclude, the uppermost Oligocene is probably characterized by strong uplift movements leading to an intense erosion of both upstream and downstream soils and underlying rocks, and of marine shallow-water particles. In the marine realm the effect of tectonic near-shore movements and of an eventual regression cannot be separated.

Causes of sea-level changes

Our results suggest that Oligocene changes in shoreline position played an important role besides climatic changes. In general, there are three possible factors responsible for transgressions and regressions:

1) tectonic movements (uplift and/or subsidence);
2) changes in accumulation rates on the shelf;
3) sea-level changes.

1) Local tectonic movements in the coastal area can produce local trans- or regressions. As discussed above, this reason is probably responsible for the strong and deep erosion in up- and downstream continental and submarine near-shore areas during the uppermost Oligocene, which is a period of major folding in the Atlas area (Dillon, Sougy, 1974).

2) Variations in the accumulation rates on the shelf can lead to seaward or landward movement of the shoreline (Vail *et al.*, 1977 *a*). This is a regional effect and little evidence is available for the Oligocene off NW Africa (*op. cit.*).

3) Global sea-level changes are mainly due to geotectonic and glacial phenomena.

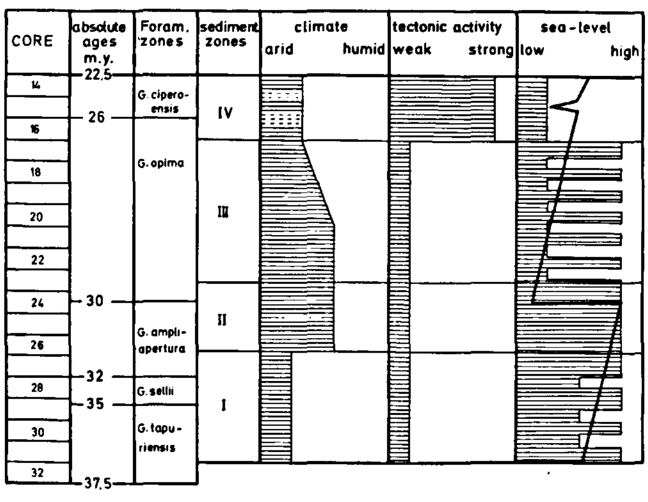
a) Volumetric changes in the mid-oceanic ridge systems are the fastest way to change sea-level, apart from eustatic changes (Rona, 1973; Pitman, 1978). Both authors found a major Oligocene regression, which has been dated by Vail *et al.* (1977 *b*) to be in the *Globorotalia opima opima* zone.

Our results show a rather good correlation to the mentionned investigations: the *opima* zone is in cores 24-16, our zone III is in cores 23-16, where we found major regressions alternating with short transgressions (Fig. 7). Note that prior to that major regression period our data suggest the presence of a period of high sea-level, which corresponds to the curve of Vail *et al.* (*op. cit.*). In the Early Oligocene (zone I) we found a high sea-level and three periods with smaller regressions: this might correlate with a lower sea-level in the beginning of the Oligocene compared to the 30 MY level (Vail *et al.*, *op. cit.*).

b) Glaciations of the Arctic occurred only since 3 MY (Berggren, 1972). In the Antarctic, however, glaciers descended to sea-level in the Oligocene. Although the size of these glaciers has only been a small fraction of the present one (Shackleton, Kennett, 1975), it seems probable that climatic variations led to extensions and diminutions in size of the glaciers, which might have produced small scale global changes in sea-level since the Oligocene.

Figure 7

Schematic graph showing stratigraphy and interpretation of course and clay fraction results from Oligocene sediments of hole 369 *A. The heavy line in the sea-level graph is the sea-level curve from Vail* et al. (1977 *b*). *Absolute ages from Berggren and van Couvering* (1974), *foraminiferal zones from Lancelot, Seibold* et al. (1978), *sedimentary zones after our results.*



c) To conclude, it appears that since the Oligocene both geotectonic and eustatic phenomena controlled the global sea-level, whereas prior to the Oligocene only the geotectonics played a role (Pitman, 1978). Arguments in this way are provided by models established by Pitman (1978). This author studied the importance of changes in the rates of sea-level rise or fall for transgressive or regressive events, and he combined the effect of sea-level changes (by geotectonic and eustatic phenomena) to that of rates of subsidence and sedimentation on continental margins. His results indicate a major regression in the Oligocene.

We suggest that our sea-level curve deduced from the Oligocene of Site 369 *A might reflect both phenomena: the general trend which resembles the Vail* et al. (1977 *b*) *curve might essentially be influenced by geotectonics (first and second order cycles), whereas the small scale, rather rapid variations in sea-level might be essentially a mirror of Antarctic glaciations and deglaciations (third order cycles). This assertion has to be checked by means of oxygen isotope investigations.*

Accumulation rates

The average accumulation rate of Oligocene sediments in Site 369 is 11.3 mm/1 000 years and thus by a factor of about 100 lower than Quaternary ones in the same area and water depth (Diester-Haass, 1976 *b*). This difference is attributed to four factors: 1) Compaction. 2) Reduced accumulation rates of biogenous carbonate (Diester-Haass, 1980 *a*). 3) Reduced terrigenous input. Davies *et al.* (1977) also interpret their results of strongly reduced global Oligocene marine accumulation rates in terms of decreased terrigenous input. In the South Atlantic the same observation has been made (McCoy, Zimmermann, 1977, p. 1062). 4) Bypassing. When eustatic sea-level lowering has added to the rate of sea-level fall occurring due to ridge contraction, it might have been possible that the shore-line has migrated beyond the shelf. This would allow sediments to bypass the shelf-slope area, leading to strongly reduced accumulation rates in these areas (Pitman, 1978).

More detailed accumulation rates (Table 2) have been calculated for the five foraminiferal zones given by Lancelot, Seibold *et al.* (1978) (absolute ages from Berggren and van Couvering, 1974). It can be seen that in cores 28-32, where we suppose a more arid climate, accumulation rates are distinctly lower than in core 16-27, where we suggest a more humid climate.

Table 2

Accumulation rates of total sediment in five foraminiferal zones (boundaries taken from Lancelot, Seibold et al., 1978; *absolute ages taken from Berggren and van Couvering,* 1974).

Foraminiferal zone	Core	Age (MY)	Accumulation rate (mn/1 000)
G. ciperoensis	14/15	22.5/26	(5)
G. opima	16/24-3	26/30	20.2
G. ampliapertura	24-4/27CC	30/32	16.9
G. sellii	28/29-2	32/35	4.2
G. tapuriensis	29-3/32	35/37.5	9.9

Note that the accumulation rate calculated for our zone IV (cores 14-15) is probably not correct, because part of the sequence may be absent.

Climate and continental drift

Berger and von Rad (1972) made a reconstruction of the geography of the Atlantic Ocean in various geologic times. In the late Eocene Site 369 would have been in about 15°N, in the early Miocene in about 20°N (today in 26°35′N). That means that during the Oligocene the site would have "traversed" the subtropical semihumid region, if climatic zonality of the Tertiary can be compared to the present one. This is in agreement with our climatic deductions of a climate with rainfall and fluviatile input in most parts of the Oligocene. Our results correlate to those of the Namib desert in SW Africa, where Siesser (1978) found more humid conditions during all the Oligocene.

The data and interpretations presented here suggest that during the Oligocene the western Sahara has not yet existed as a desert. Strong desert conditions developed not before the early Miocene (Sarnthein, Diester-Haass, 1977; *Diester-Haass,* 1978; *Sarnthein,* 1978 *b; Diester-Haass, Chamley,* 1978).

CONCLUSIONS

The main interpretations of the investigations presented in this paper are summarized in a schematic graph (Fig. 7), showing foraminiferal and sedimentary zones, absolute ages, climatic changes, variations in tectonic activity and sea-level changes.

Acknowledgements

We thank the National Science Foundation of the United States for providing samples from DSDP material. Discussions with collegues from the Kiel Geological Institute, especially E. Seibold and U. Pflaumann and with W. H. Berger (La Jolla) and W. von Rad (Hannover) were most helpful. We thank M. Acquaviva and C. F. Froget (Marseille), F. Dujardin (Lille) and M. Draga (Würzburg) for technical assistance and H. Hagedorn and W. Schnitzer (Würzburg) for supporting this investigation. The financial support of the Centre National pour l'Exploitation des Océans and of Deutsche Forschungsgemeinschaft (L. D.-H.) is gratefully acknowledged.

REFERENCES

Bagnold R. A., 1954. *The physics of blown sand and desert dunes*, Methuen and Co, Ltd, 000 p.

Berger W. H., Rad U. von, 1972. Cretaceous and Cenozoic sediments from the Atlantic Ocean, in D. E. Hayes, H. C. Pimm *et al.*, *Initial Reports of the Deep Sea Drilling Project*, **14**, Washington (US Government Printing Office), 787-954.

Berggren W. A., 1972. Late Pliocene-Pleistocene glaciation, in A. S. Laughton, W. A. Berggren *et al.*, Initial Reports of the Deep Sea Drilling Project **12**, Washington (US Government Printing Office), 953-963.

Berggren W. A., Van Couvering J. A., 1974. The Late Neogene: biostratigraphy, geochronology and paleoclimatology of the last 15 MY in marine and continental sequences, *Paleogeogr., Paleoclimatol., Paleoecol.*, **16**, 1-216.

Chamley H., 1971. Recherches sur la sédimentation argileuse en Méditerranée, *Sci. géol.*, Strasbourg, mém. 35, 225 p.

Chamley H., 1979. North Atlantic clay sedimentation and paleoenvironment since the late Jurassic, in M. Ewing Series, edited by M. Talwani *et al.*, **3,** *Amer. Geophys. Union*, 341-361.

Chamley H., Debrabant P., Foulon J., Giroud d'Argoud G., Latouche C., Maillet N., Maillot H., Sommer F., 1979. Mineralogy and geochemistry of Cretaceous and Cenozoic Atlantic sediments off the Iberian peninsula (Site 398, Leg 47 B DSDP), in W. B. F. Ryan, J.-C. Sibuet *et al.*, *Initial Reports of the Deep Sea Drilling Project*, **47,** Washington (US Government Printing Office), in press.

Chamley H., Diester-Haass L., 1979. Upper Miocene to Pleistocene climates in North-West Africa deduced from terrigenous components of Site 397 sediments (Leg 47 A DSDP), in W. B. F. Ryan, U. von Rad *et al.*, *Initial Report of the Deep Sea Drilling Project*, **47,** Washington (US Government Printing Office). **1,** 641-646.

Chamley H., Diester-Haass L., Lange H., 1977. Terrigenous material in East Atlantic sediment cores as an indicator of NW African climates, "*Meteor*" *Forschungs. Ergebn. Reihe C*, **26,** 44-59.

Chamley H., Giroud d'Argoud G., 1979. Clay mineralogy of Site 397,

Lancelot Y., Seibold E. *et al.*, 1978. *Initial Reports of the Deep Sea Drilling Project.*, Washington, **41,** 1259 p.

Lutze G., Sarnthein M., Koopmann B., Pflaumann U., Erlenkeuser H., Thiede J., 1979. Meteor cores 12309: Late Pleistocene reference section for interpretation of the Neogene of Site 397, in W. B. F. Ryan, U. von Rad *et al.*, *Initial Report of the Deep Sea Drilling Project*, **47,** Washington (US Government Printing Office), in press.

McCoy F. W., Zimmermann H. B., 1977. A history of sediment lithofacies in the South Atlantic Ocean, in P. R. Supko, K. Perch-Nielsen *et al.*, *Initial Report of the Deep Sea Drilling Proejct*, **39,** Washington (US Government Printing Office), 1047-1079.

Melières F., 1978. X-Ray mineralogy studies, Leg 41, Deep-Sea Drilling Project, Eastern North Atlantic Ocean, in Y. Lancelot, E. Seibold *et al.*, *Initial Report of the Deep Sea Drilling Project*, **41,** Washington (US Government Printing Office), 1065-1086.

Michel P., 1973. Les bassins des fleuves Sénégal et Gambie. Étude géomorphologique, Mém. ORSTOM, Vol. 63, Paris.

Millot G., 1964. *Géologie des argiles*, Masson, Paris, 499 p.

Paquet H., 1970. Évolution géochimique des minéraux argileux dans les altérations et les sols des climats méditerranéens et tro-