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Paleoenvironmental and paleogeographic characterization of the 12 frères borehole, fresco, southwestern Côte d'Ivoire: Palynological implication

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Abstract

Maastrichtian to Ypresian-dated sediments from the 12 Frères borehole. (Fresco, southwestern Côte d'Ivoire), are here investigated for paleoenvironmental and paleogeographic significance. For this study, the preparation of palynological slides in the laboratory is done in three steps.: (1) sampling and physical treatment, (2) chemical attacks (HCl 10%, HF 40%) to dissolve the mineral matter and preserve the organic matter contained in the sediments, (3) mounting the collected organic matter between slide and coverslip for microscopic study. Quantitative analyses of dinoflagellate cysts and other palynomorphs have allowed reconstructions of paleoenvironments. Thus, from bottom to top, nine (9) depositional environments ranging from outer neritic to inner neritic via a lagoon or estuarine environment were determined. Following Lentin and Williams (1980), the deposits in the 12 Frères section are attributed to a tropical to subtropical province paleogeography.

Keywords: Paleoenvironment; Paleogeography; Dinoflagellate cysts; Fresco; Côte d'Ivoire

1. Introduction

Côte d'Ivoire is a West African country that for oil interests has focused its biostratigraphic studies on the Cretaceous and neglected the Paleogene which is also very poorly known. In spite of some palynological studies on the basin in the framework of thesis of Diploma of Advanced Studies [3-5], Doctorate [6-7] and rare publications [1,8-14], this basin remains still badly known from the palynological point of view.

The present study, which is a continuation of the one already published on the biostratigraphy of the "12 Frères borehole" [1], deals with the paleoenvironment and paleogeography that prevailed during the emplacement of its sediments.

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2. Material and methods

2.1. Materials

23 samples from the 12 Frères borehole were studied. The 12 Frères borehole is located in the southwest of Côte d'Ivoire (Figure 1). Its geographical coordinates are 05°37'01.0" W (longitude) and 05°04'26.8" N (latitude). According to previous studies [6], its lithology consists of alternating red to light grey sandy levels with low clay content and red sandstone levels in the interval from 106 m to 51 m depth. The upper part of the hole (from 51 to 20.5 m) is characterized by alternating levels of black sandy clays, grey to red clayey sands and greenish glauconitic clays [6].

2.2. Methods

The preparation of palynological slides in the laboratory is done in three steps as described by [1-2]: (1) sampling and physical treatment, (2) chemical attacks (HCl 10%, HF 40%) to dissolve the mineral matter and preserve the organic matter contained in the sediments, (3) mounting of the collected organic matter between slide and coverslip for microscopic study.

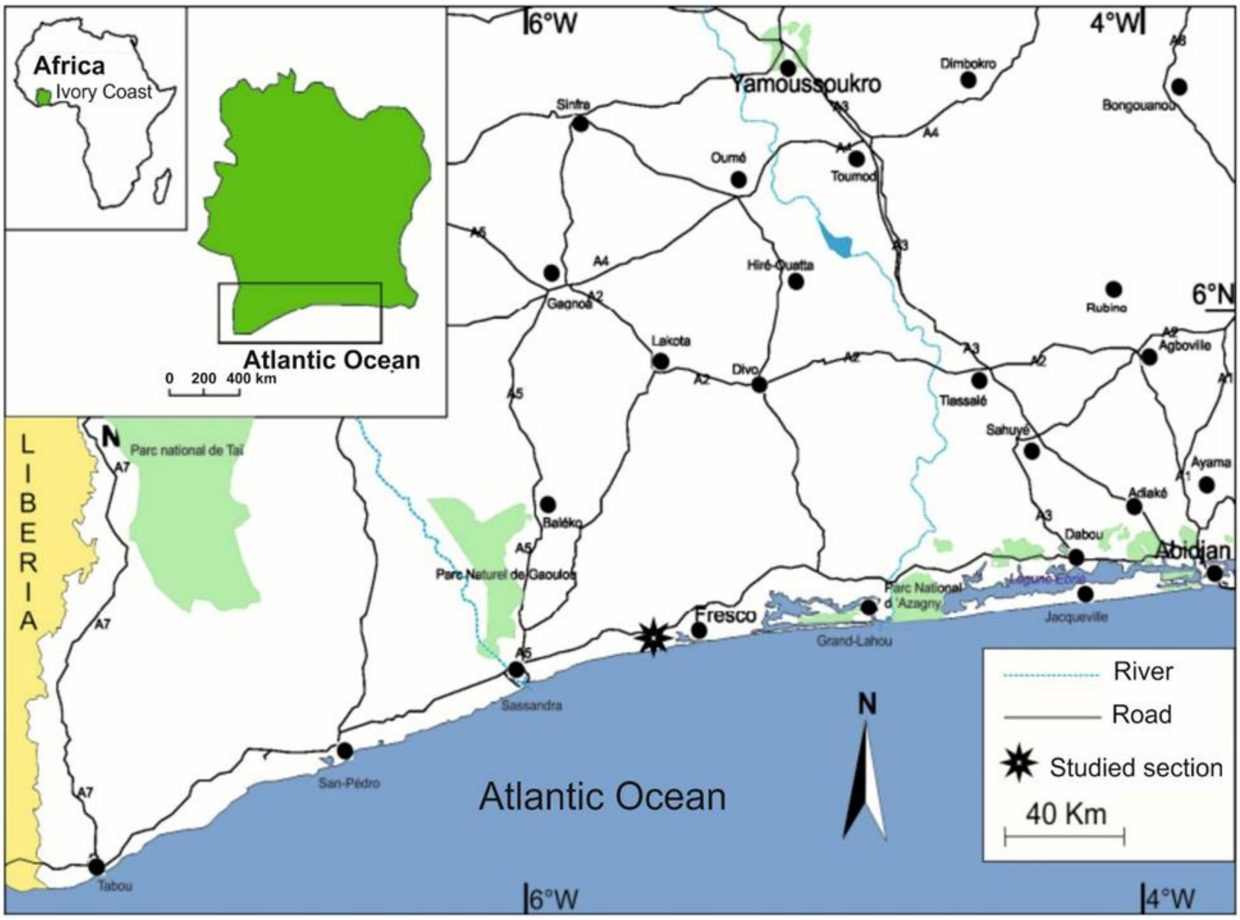

Figure 1 Geographic location maps of the "12 Frères" survey (Fresco, southwestern Côte d'Ivoire)

The determination of the paleoenvironment is based on the relative proportions of dinocysts (marine organisms) to spores and pollen grains (continental organisms) in the palynological assemblage [15]. Thus, the S/D ratio indicates the continental influence on the depositional environment. It is also calculated with the formula of [16]: ratio sporomorphs (spores and pollens)/dinocysts (dinocysts and acritarchs) (S/D),

$$(S/D = nS/(nD + nS) \text{ with } n = \text{number}.$$

Thus, we will qualify as continental paleoenvironment, any environment whose sedimentary deposit contains a palynological assemblage consisting only of spores, pollen grains and organic matter (wood debris).

On the other hand, if the palynological assemblage contains dinocysts and chitinous internal tests of microforaminifera in much higher proportions than the spores and pollen grains, with the presence of amorphous organic matter, we will say that this Paleoenvironment is marine.

When the proportions of dinocysts (marine organisms), spores and pollen grains (continental organisms) are more or less equal, we speak of deposition in a lacustrine or estuarine environment. However, the slight dominance of one species in proportion shows a continental or marine influence.

The depositional environment can also be determined based on the relative proportions of certain intraspecific groups of dinocysts that have a distribution preference along a neritic to oceanic transect.

The ratio of autotrophic to heterotrophic dinocysts or peridinioides/gonyaulacoides (P/G) ratio (P/G = nP/(nP + nG) sensu [16] provides information on the productivity of the sea surface.

The ratio between the number of dinocysts characterizing the inner neritic environments (IN) and that of dinocysts characterizing the external neritic environments (ON) or IN/ON ratio is calculated according to the formula: IN/ON = nIN/(nIN + nON) (cf. [16-17]). It provides information on the paleo-depth.

Other curves have been developed based on certain dinocyst groups that characterize a particular depositional environment, including:

- The *Areoligera* Group: It includes dorsoventrally compressed gonyaulacoides skolochorates taxa, such as *Areoligera* spp. and *Glaphyrocysta* spp. It characterizes inland and coastal neritic depositional environments [10,11,17-22].
- The *Spiniferites* Group consists of proximochorate and cosmopolitan gonyaulacoid cysts including *Spiniferites* spp. and *Achomosphaera* spp. It characterizes an outer neritic environment [10,11, 17-31].
- The *Senegalinium* Group includes cornucavate peridinioid cysts, such as *Cerodinium* spp, *Palaeocystodinium* spp, *Spinidinium* spp, *Senegalinium* spp, *Isabelidinium* spp, and *Deflandrea* spp, which are heterotrophic cysts marking a neritic to oceanic depositional environment. This group is associated with nutrients and high productivity levels [10,11,17-19,22,32,33].
- The *Fibrocysta* Group is composed of fibrous, proximate, chorate gonyaulacoid cysts such as *Fibrocysta* spp, *Kenleyia* spp, *Cordosphaeridium* spp, *Operculodinium* spp, *Carpatella* spp, *Damassadinium californicum*, and *Cribroperidinium* spp. This group generally characterizes an inner neritic depositional environment [10,11,17,20, 22, 26,34-36];
- The *Lejeunecysta* Group is composed of cornucavate proto-peridinoid cysts with proximate acavate and characterizes areas of high productivity [10,11,17, 22, 25, 26,34-39]
- *Impagidinium* spp. is rather composed of proximochorate gonyaulacoid cysts which are typical of oceanic marine environments [10,11,17, 18, 22,30,31,35,40-43]
- *Palaeohystrichophora* spp. consists of the peridinian cysts *Palaeohystrichophora infusorioides* and *Palaeohystrichophora palaeoinfusa*. It characterizes an outer neritic environment [10,11,22,44]
- *Odontochitina* spp. consists of the group of *Odontochitina costata, Odontochitina operculata, Odontochitina porifera* and *Odontochitina tabulata* cysts. It characterizes an outer neritic environment [10,11,22,43-44]
- *Odontochitina* spp. consists of the group of *Odontochitina costata, Odontochitina operculata, Odontochitina porifera* and *Odontochitina tabulata* cysts. It characterizes an outer neritic environment [10,11,22,44].

3. Results and discussion

3.1. Paleoenvironment of the 12 Frères borehole

Quantitative palynological analysis of the 12 Frères borehole sediments also revealed significant changes in the relative abundance of dinoflagellate cyst groups, sporomorphs, and IN/ON, P/G, and S/D ratios (Figure 2). These changes, which likely reflect changes in the paleoenvironment, revealed nine intervals from A to I that run from the bottom to the top of the borehole:

3.1.1. Interval A (106-99.5 m)

This interval contains the Lower Maastrichtian sediments (106-99.5 m). The palynological material is abundant, diversified and dominated by species of the *Senegalinium* group (*Senegalinium bicavatum, Palaeocystodinium golzowense*, etc.) with a relative frequency of 45%. The *Spiniferites* and *Fibrocysta* groups are represented with low frequencies of about 13% and 4% respectively. The abundance of the *Senegalinium* group (heterotrophic peridinoids) results in a high P/G ratio (0.6) indicating a high paleo-productivity environment that could be related to increased nutrient inputs.

The preponderance of the *Spiniferites* group (13%) which characterizes an outer neritic environment [10, 11, 16, 44] over the *Fibrocysta* group (4%), as well as the significant P/G ratio (0.6), suggest an outer neritic marine environment with high productivity for this interval.

The scarcity of sporomorphs (up to 4%), resulting in a low S/D ratio (0.03%), indicates a weak continental influence, thus a sedimentation far from the shore.

3.1.2. Interval B (97.5-77 m)

Interval B starts with samples 97.5 m to 77 m of Upper Maastrichtian to Danian age. It is characterized by the abundance of the *Spiniferites* group, which reaches 38.5% at 85 m, followed by a low proportion of the *Fibrocysta* group (5% at 97.5 m and 82 m), resulting in a low IN/ON ratio (0.09) at 85 m. The *Spiniferites* group that dominates this interval characterizes an outer neritic environment [10, 11, 16, 44], whereas the *Fibrocysta* group present in low proportion generally characterizes inner neritic depositional environments [17, 35, 36]. The scarcity of peridinoid dinoflagellates and sporomorphs in the B interval lead to low P/G (0.05) at 82m and S/D (0.03) ratios at 82m. In contrast, there is an increase in CaCO3 from 3% to 28% from 97.5m to 8 2m respectively. The dominance of the *Spiniferites* group over the *Fibrocysta* group, coupled with the low IN/ON, P/G and S/D ratios, suggests an outer neritic depositional environment with very low productivity in the B interval (97.5-77 m). This slight change may be reflected in a higher sea level rise than in the previous interval.

3.1.3. Interval C (75 m)

This interval frames sample 75 m, of Danian age. Deposits in this interval show a decrease from 38% (at 85 m) to 6% (at 75 m) of the *Spiniferites* group that characterizes outer neritic environments in favor of an increase in the proportions of the *Fibrocysta* group (indicative of inner neritic environments) from 4% (at 85 m) to 13% (at 75 m), resulting in a high IN/ON ratio (0.6). In the C interval, the rarity of peridinoid dinoflagellates and sporomorphs favors low P/G (0.06) and S/D (0.08) ratios [10, 11].

The preponderance of the *Fibrocysta* group over the *Spiniferites* group, as well as the low P/G and S/D ratios indicate an inner neritic depositional environment without productivity in the C interval (75 m), thus a regression.

3.1.4. Interval D (69.5 m)

This interval frames the 69.5 m Danian sample. It is dominated by the *Spiniferites* group (26%), indicative of an outer neritic marine environment, followed by the *Fibrocysta* group (5%). This implies a low IN/ON ratio (0.16). The slight increase in sporomorphs leads to a slight increase in the S/D ratio (0.33) which still remains low. It is also observed that in this interval the P/G ratio remains low as in the previous interval.

The preponderance of the *Spiniferites* group over the *Fibrocysta* group, coupled with low IN/ON (0.16), P/G (0.04), and S/D (0.33) ratios, indicates an outer neritic depositional environment in the D interval (69.5 m), thus a return to a high marine level, as observed in the B interval [10, 11].

3.1.5. Interval E (63.5-51 m)

This interval from sample 63.5 m to 51 m is of Danian age. It is characterized by the scarcity of dinocyst groups observed in the preceding intervals (A-D) from the Lower Maastrichtian to the Lower Danian. The *Fibrocysta* group is the only group that persists with an acceptable relative frequency of 8% in the 51 m sample. On the other hand, there is an exceptional richness of continental sporomorphs (acme of *Longapertites marginatus* at 63.5 m) and consequently a significant increase in the S/D ratio that reaches its maximum value (0.94) in the 63.5 m sample, suggesting a decrease in depth and an approach to the shore. The P/G ratio remains zero in the E interval.

This important change in the percentage of sporomorphs and dinoflagellates can be explained by a strong regression with a considerable continental input, thus a lagoon or estuarine environment [10, 11, 22].

3.1.6. Interval F (48 m)

This interval frames the 48 m Danian age sample. Deposits in this interval are dominated by the *Senegalinium* group (50%), indicative of a neritic to oceanic depositional environment, associated with the relative abundance of the *Spiniferites* group (11%) that characterizes outer neritic environments, at the expense of the *Fibrocysta* group (1%), indicative of inner neritic environments. In the F interval, there is an increase in the P/G ratio (0.56), a decrease in the IN/ON (0.15) and S/D (0.01) ratios, and an increase in the CaCO3 content (16%), reflecting a distance from the shoreline, and thus a marine transgression.

The preponderance of the *Spiniferites* group over the *Fibrocysta* group, as well as the increase in the P/G ratio and the drop in the IN/ON and S/D ratios indicate an outer neritic depositional environment with high productivity, thus a rise in sea level [10,11,22].

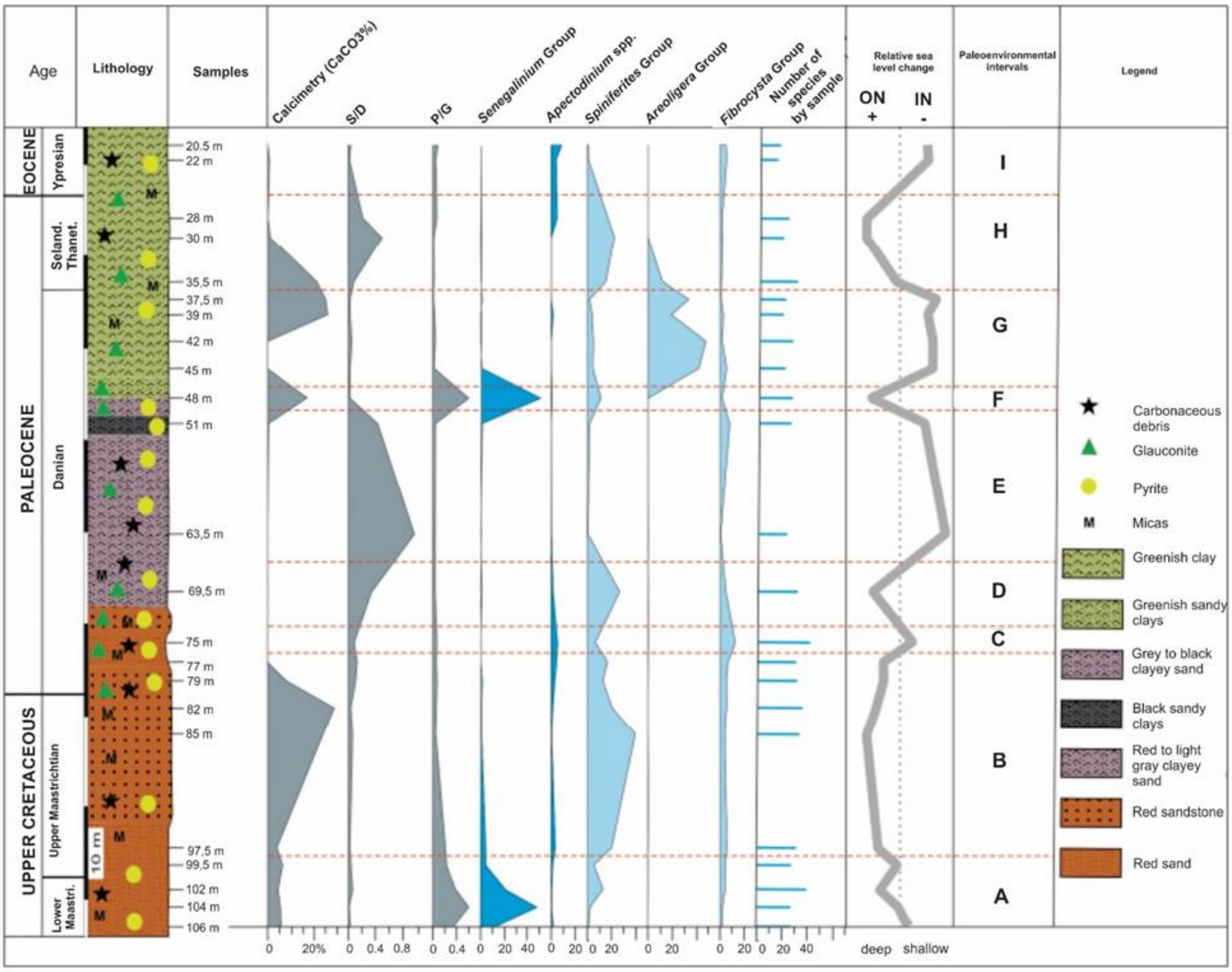

Figure 2 12 Frères survey: Calcimetry curve; Sporomorphs to Dinoflagellates ratio curve; Peridinoid to Gonyaulacoid ratio curve (productivity); relative abundances of morphologically and ecologically related dinoflagellate cysts; species diversity per sample; relative sea level change curve (IN/ON) and palynological intervals

3.1.7. G interval (45-37.5 m)

This interval extends from sample 45 m to 37.5 m and is dated to the Upper Danian. Deposits in this interval show a decrease in the relative frequency of the *Spiniferites* group around 4% in favor of the *Areoligera* group (47%) at sample 42 m, indicative of inner and coastal neritic environments [10,11,17,22], thus favoring a high IN/ON ratio (0.9). In the G interval, the P/G ratio still remains low (0.02) with a similarly low S/D ratio (0.02), but peaks in CaCO3 concentration of 25% and 24% are observed in samples 39 m and 37.5 m respectively. The preponderance of the *Areoligera* group over the *Spiniferites* group associated with the high IN/ON ratio followed by low P/G and S/D ratios indicates an unproductive inland and coastal neritic depositional environment in the G interval (45-37.5 m), which corresponds to a slight drop in sea level from the previous interval.

3.1.8. Interval H (35.5-28 m)

The H interval is between sample 35.5 m and sample 28 m, and is dated to the Sélandien-Thanétien. This interval is marked by an important proportion of the *Spiniferites* group (22%) and the S/D ratio (0.47) at the expense of the *Areoligera* (0%) and *Fibrocysta* (2%) groups, thus a low IN/ON ratio. The scarcity of peridinoid dinoflagellates in this interval results in a low P/G ratio (0.01) in the whole interval. There is also a drop in CaCO3 at 35.5 m (20%), then at 28 m (0%) and a relative decrease in palynomorph diversity (especially dinoflagellates), from 29 species in the 35.5 m sample to 18 species in the 30.5 m sample. The dominance of the *Spiniferites* group, which characterizes an outer neritic environment [10,11,16,17,22,29] over the *Areoligera* and *Fibrocysta* groups, as well as the low IN/ON and P/G ratios suggest an outer neritic depositional environment in the H interval (35.5-28m) implying at the same time a slight rise in sea level.

3.1.9. Interval I (22-20.5 m)

It runs from sample 22 m to sample 20.5 m and is dated Ypresian. Deposits in this interval show a drop in the relative frequency of the *Spiniferites* (1%) and *Areoligera* (0%) groups, while that of the *Fibrocysta* group, indicative of inner neritic environments, stagnates around 5%, resulting in a high IN/ON ratio (0.8). We note in this interval, a low proportion of peridinoid species *Apectodinium* spp. (8%), implying a still low P/G ratio (around 0.08); the scarcity of sporomorphs in this interval generates a low S/D ratio of about 0.03; the CaCO3 level is almost null. There is a drop in species diversity that could be explained by poor preservation conditions of the fossils.

The preponderance of the *Fibrocysta* group over the *Spiniferites* group, the high IN/ON ratio, and the low P/G and S/D ratios indicate an inner neritic depositional environment, reflecting a decrease in sea level [10,11,22].

3.2. Paleobiogeography

3.2.1. Paleoprovincialism

Following the paleoprovinces defined by [45], the different assemblages of dinoflagellate cyst species observed allowed us to highlight a paleo-provincialism in the 12 Frères borehole. Indeed, for [45] the latitudinal distribution of peridinioid dinoflagellate cysts in the Campanian allows to define three provinces:

- The tropical to subtropical or Tethyan province with the "Malloy suite" type association is characterized by the abundance of species of the genera *Andalusiella, Cerodinium, Lejeunecysta* and *Senegalinium*. Assemblages of this suite have been observed in Campanian to Danian deposits of the peri-Mediterranean basins [18,21,46-49], in Côte d'Ivoire [1,8,50-52], in Senegal [53], in equatorial zones [50,51,54,55], in the southeastern United States of America [32,56-58], in the Caribbean [59], and in Caribbean Mexico [60].
- The temperate province with the "Williams suite" type association is characterized by species of the genera *Alterbidinium, Chatangiella* (small forms), *Isabelidinium, Spinidinium* and *Trithyrodinium*.
  Assemblages of this suite have been recognized in northern Europe [61-67]. and in the northeastern United States of America [32,56,68].
- The boreal province with the McIntyre suite type association is composed of *Chatangiella* species (large forms) and *Laciniadinium*. Assemblages of the boreal province have been demonstrated in high latitude regions of Greenland [33,69], Arctic Canada [70], and Russia [71],

3.2.2. Provincialism observed in the 12 Frères Borehole (Maastrichtian-Danian)

The dinoflagellate cyst assemblages observed in the Maastrichtian to Danian interval of the 12 Frères well show an abundance of species of certain groups characterizing the "Malloy suite" type association (Table 1) such as those of the genera *Andalusiella* (*A. dubia, A. gabonensis, A. ivoirensis, A. mauthei* subsp. *mauthei, A. mauthei* subsp. *punctata, A. polymorpha, A. rhomboides* and *A. spicata*), *Cerodinium* (*C. diebelii* and *C. granulostriatum*), *Lejeunecysta* (*L. hyalina, L. izerzenensis* and *L.* sp. cf. *globosa*) and *Senegalinium* (*S. bicavatum, S. laevigatum* and *S. microgranulatum*).

Species characterizing McIntyre suite and Williams suite associations were not observed in the 12 Frères deposits.

The abundance of species characteristic of the Malloy Suite type association at the expense of those characterizing the McIntyre Suite and Williams Suite type associations (absent) suggests a tropical to subtropical province for the 12 Frères survey.

Table 1 Assemblages of peridinioid dinoflagellate cysts observed in the Maastrichtian-Danian interval of the 12 Frères borehole according to the paleo-provinces associations defined by [45]

12 Freres borehole (Maastrichtian to Danian)					
Williams Suite	**Malloy Suite**				**Mcintyre Suite**
	Andalusiella (8 species)	***Cerodinium (2 species)***	***Lejeunecysta (3 species)***	***Senegalinium (3 species)***	
	Dubia, *A. gabonesis* *A. ivoirensis* *A. mauthei subsp. mauthei,* *A. mauthei subsp. punctata,* *A. polymorpha,* *A. rhomboids* *A. spicata*	*C. diebelii* *C. granulostriatum*	*L. hyalina* *L. izerzenensis* *L. sp. cf. globosa*	*S. bicavatum,* *S. laevigatum* *S. microgranulatum*	

The Malloy suite of Lentin and Williams [45], has been demonstrated in Campanian, Maastrichtian and Danian sediments of the Tethyan regions [18,21,46-48,72-74], in Ivory Coast [1,8,50-52], in Senegal [53], under the Equator [54,55,75], in the Southeastern United States of America [32,56-58], and in India [76].

4. Conclusion

Qualitative and quantitative analysis of the palynological content of the 12 Frèress borehole shows significant changes in the relative abundance of morphologically and ecologically related dinocyst groups, reflecting variations in the paleoenvironment. This analysis indicates that the Upper Cretaceous deposits of the 12 Frères Borehole in Côte d'Ivoire were deposited in an outer neritic marine environment under a transgressive regime. This interpretation is based on the preponderance of the *Spiniferites* group that characterizes an outer neritic environment over the *Fibrocysta* and *Areoligera* groups characterizing inner neritic environments, hence the high IN/ON ratios. The passage from the Maastrichtian to the Danian is marked by species that are markers of inner neritic environments with a drop in the IN/ON ratio leading to a marine regression. The Paleogene is marked by several episodes of transgression and regression.

The recognition of different species assemblages of peridinoid dinoflagellate cysts in this study allowed us to highlight paleo-provincialism in the 12 Frères borehole. Indeed, following the latitudinal distribution of peridinoid dinoflagellate cysts as defined by Lentin and Williams (1980), we note that the assemblages of peridinioid dinoflagellate cysts from the 12 Frères are marked by the abundance of species characteristic of the "Malloy suite" type association to the disadvantage of those characterizing the "McIntyre suite" and "Williams suite" type associations (absent), hence the attribution of its paleogeography to a tropical to subtropical province.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that there are no conflicts of interest.

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