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General Palaeontology (Palaeoecology)

Middle Eocene radiolarian and diatom accumulation in the equatorial Atlantic (Demerara Rise, ODP Leg 207) Possible links with climatic and palaeoceanographic changes

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Abstract

Middle Eocene siliceous bioaccumulation on Demerara Rise is explored using taphonomic and palaeoecological studies of radiolaria and diatoms, respectively. Enrichment and improved preservation of silica began just above the Lower to Middle Eocene transition (ca. 49 Ma) and was mainly due to radiolarian productivity. It reflects a profound change in the zooplankton communities of the western Equatorial Atlantic, dominated previously by planktic foraminifera. Diatoms are a minor siliceous component of the Middle Eocene chalk. This microflora is dominated by robust planktic species, typical of neritic environments, and includes some upwelling indicators. Benthic species are absent. No continental taxa were recorded. Onset of biogenic silica accumulation was probably due to the establishment of a vigorous bottom current circulation and higher levels of productivity. It coincides with a major palaeoceanographic shift from a Lower Eocene stagnant to a more vigorous Middle Eocene ocean, following some as yet poorly understood global climatic change. ***To cite this article: T. Danelian et al., C. R. Palevol 6 (2007).***

Résumé

Bioaccumulation des radiolaires et des diatomées à l'Eocène moyen en Atlantique équatorial (Plateau de Demerara, Leg ODP 207). Possibles relations avec des changements climatiques et paléocéanographiques. L'enrichissement en silice est dû au pullulement des radiolaires et débute juste au-dessus du passage Éocène inférieur–moyen (environ 49 Ma). Il reflète une modification majeure du zooplancton de l'Atlantique équatorial, dominé jusque là par des foraminifères planctoniques. Les diatomées, qui constituent une composante mineure de la silice biogène, sont essentiellement représentées par des espèces planctoniques robustes, typiques des environnements néritiques. Des espèces indicatrices d'*upwelling* sont présentes. L'absence d'influence continentale est à noter. Le début d'accumulation de la silice biogène est probablement dû à la mise en place d'une intense circulation de courants profonds et à une plus forte productivité. Il coïncide avec un changement majeur d'un océan Éocène inférieur stagnant à un autre plus

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dynamique à l'Éocène moyen, à la suite d'un changement climatique global encore mal compris. ***Pour citer cet article : T. Danelian et al., C. R. Palevol 6 (2007).***

Keywords: Radiolarians; Diatoms; Demerara Rise; Eocene; Atlantic

Mots clés : Radiolaires ; Diatomées ; Plateau de Demerara ; Éocène ; Atlantique

Version française abrégée

Introduction

La bioaccumulation de microfossiles siliceux dans les océans modernes implique des processus océanographiques favorables à la productivité du plancton, mais également des processus assez complexes de préservation dans la colonne d'eau et les sédiments de surface. L'Éocène s'est avéré être une époque riche en sédiments siliceux [16,23], tout particulièrement dans l'océan Atlantique où des niveaux de cherts et de porcelanites d'âge Éocène moyen sont présents et ont longtemps empêché une bonne récupération des séries paléogènes. La situation s'est beaucoup améliorée avec les progrès techniques relatifs aux opérations de forage et à des campagnes récentes, conçues spécifiquement pour des études paléocéanographiques. Le plateau de Demerara contient une série dilatée et peu enfouie de sédiments pélagiques éocènes, qui offre ainsi la possibilité d'étudier, dès le début, l'événement siliceux de l'Éocène moyen. Nous explorons ici des aspects taphonomiques et paléoécologiques des radiolaires et des diatomées, respectivement, afin de comprendre les processus à l'origine de l'accumulation des microfossiles siliceux sur cette marge sud-américaine.

Cadre géologique et stratigraphique

Le Leg ODP 207 a foré la partie distale du plateau de Demerara (Fig. 1) et a récupéré des sédiments éocènes déposés dans un contexte typiquement équatorial (1°S [24]). Le site 1259, foré à 2354 m de profondeur, contient l'enregistrement siliceux éocène le plus complet parmi les sites forés (Fig. 2). Des analyses micropaléontologiques ont été effectuées sur les sédiments Éocène moyen, ainsi que des observations au MEB (nannofaciès) et des analyses aux rayons X dans la zone de transition afin de mieux la caractériser (Fig. 3).

Taphonomie des radiolaires

Les radiolaires sont rares et dissous dans la partie sommitale de la craie Éocène inférieur (Fig. 4a), laquelle est riche en foraminifères planctoniques et en zéolithes (Fig. 5a). Les analyses aux rayons X confirment l'abondance des zéolithes (entre 5 et 8% ; Fig. 3). La base de la carotte 30R enregistre un net enrichissement en silice, avec un niveau très riche en opale-CT (environ 40% ; Fig. 3). Des sphérules d'opale-CT sont particulièrement bien formées dans ce niveau et, en s'agglomérant, remplissent des vides entre les tests de foraminifères planctoniques. Ce niveau riche en opale-CT délimite un intervalle inférieur, encore riche en foraminifères planctoniques (Fig. 5b), d'un intervalle supérieur, riche en radiolaires (Fig. 5e), préservés en silice amorphe (Fig. 5f). La partie interne des tests des radiolaires est parfaitement bien préservée (Fig. 6c–f), alors que leur surface externe présente des signes de « corrosion », dus vraisemblablement à la formation de petites sphérules d'opale-CT (Fig. 6f), de traces de fracturation et d'étapes très précoces de recristallisation.

Paléoécologie des diatomées

Les diatomées sont rares ou absentes dans la partie inférieure de l'intervalle siliceux de la craie éocène. Elles sont plus diversifiées dans les parties moyenne et supérieure, où dominent des espèces planctoniques robustes, typiques des environnements néritiques (Fig. 7). L'abondance relative de *Paralia sulcata* (10%) pourrait suggérer le développement d'un *upwelling* le long du plateau profond de Demerara (au moins dans la partie supérieure du Lutétien). Il est intéressant de noter l'absence de diatomées continentales.

Discussion

Trois points sont importants à souligner :

–(1) l'absence de diatomées continentales souligne le caractère pélagique biogène de la craie éocène. Néanmoins, l'abondance de diatomées néritiques suggère un environnement océanique agité par des courants, en surface [13] ou en profondeur [3]. En outre, la présence fréquente de *Paralia sulcata* suggère des niveaux de productivité relativement élevés, dus éventuellement au fonctionnement d'un *upwelling* [1,2,22] ;

–(2) la craie Éocène inférieur, située sous le niveau riche en opale-CT, contient d'abondants foraminifères planctoniques (Fig. 5b), alors que les radiolaires dominent dans la craie sus-jacente (Fig. 5e). L'enrichissement en silice (dû essentiellement aux radiolaires) ne peut être attribué à une dissolution des carbonates, puisque la quantité de ces derniers est globalement constante à travers la série éocène, voire même légèrement plus élevée à l'Éocène moyen (Fig. 2). Un changement profond de la structure communautaire du zooplancton vivant dans les eaux de Demerara a vraisemblablement eu lieu durant le passage Éocène inférieur à moyen, il y a environ 49 Ma. Le début d'enrichissement en silice dans les sédiments de Demerara se corrèle avec le réflecteur acoustique A^c, lequel est répandu en Atlantique septentrional et souligne une discordance généralisée et la présence de cherts et de porcelanites [17]. Le démarrage d'une circulation profonde vigoureuse, liée à une phase précoce de glaciation antarctique, est considéré comme à l'origine du réflecteur A^c [17]. L'abondance soudaine des radiolaires dans la série éocène de Demerara coïncide aussi avec des changements paléocéanographiques profonds, marqués notamment par d'importantes différences entre les bassins au niveau du cycle du carbone [20] ;

–(3) nos résultats établissent que la plus forte productivité siliceuse à l'Éocène moyen a amélioré le potentiel de préservation de la silice amorphe, confirmant ainsi des modèles diagénétiques proposés antérieurement [19].

Conclusions

Le site 1259 nous a permis d'analyser l'accumulation de silice biogène sur la marge distale de Demerara à l'Éocène moyen. La productivité siliceuse de l'Atlantique équatorial au large du Surinam s'est accrue à la base du Lutétien (à environ 49 Ma), essentiellement en raison de la plus grande importance des radiolaires par rapport aux foraminifères planctoniques dans le zooplancton de l'Atlantique équatorial. Les diatomées prennent de l'importance plus haut, dans la série de l'Éocène moyen. Cet événement siliceux se corrèle avec des hiatus et des niveaux de jaspe présents principalement dans l'Atlantique septentrional (réflecteur acoustique A^c). Il pourrait être dû à la mise en place d'un *upwelling* au large de la marge sud-américaine de Demerara et coïnciderait avec des changements paléocéanographiques importants qui auraient transformé un océan stagnant (Éocène inférieur) en un océan plus dynamique à l'Éocène moyen, à la suite de changements climatiques encore mal compris.

1. Introduction

Bioaccumulation of siliceous microfossils in modern oceans involves specific oceanographic processes favourable to plankton productivity, but also fairly complex processes of preservation in the water column and surface sediments. As oceans are undersaturated with respect to amorphous silica, siliceous microfossils are subject to dissolution. But in high-productivity areas (i.e. upwelling zones), where extensive export of biogenic silica to the sea floor occurs, pelagic sediments are rich in well-preserved siliceous microfossils (essentially radiolaria and diatoms) [4,14]. Preservation of the latter is favoured by a higher rate of biogenic silica production and burial. However, extrapolation of an actualistic model of biogenic silica accumulation is not always straightforward [18], especially in pre-Cenozoic times, during which diatoms were still uncommon or absent [12], and levels of dissolved silica in the ocean would have been much higher than today [10].

The Eocene is well known for its richness in siliceous sediments [16,23]. This is especially true for the North Atlantic Ocean, where widespread Middle Eocene chert layers or porcellanites occur and underline the acoustic reflector A^c [25]. The presence of chert in Eocene oceanic sequences provided many challenges to deep-sea drilling and recovery of continuous sedimentary sequences for palaeoceanographic studies. However, major progress has been achieved in the last ten years in better sampling of Eocene deep-sea sediments. Indeed, technical breakthroughs in piston coring and specifically designed ODP Legs enabled the recovery of expanded and shallowly buried Palaeogene sediments, which are little affected by diagenetic transformations due to burial. Recent Legs met very little or no chert in drilled sites and the recovered sequences offer a more suitable material for detailed studies in a more precise stratigraphic framework.

Demerara Rise, revisited recently during ODP Leg 207, preserves an expanded Lower to Middle Eocene pelagic biogenic sequence and offers the opportunity to study the onset and expression of the Eocene siliceous event in the equatorial Atlantic. We explore here some palaeoecological and taphonomic aspects of the Middle Eocene siliceous microflora and microfauna, to better understand the processes affecting their accumulation

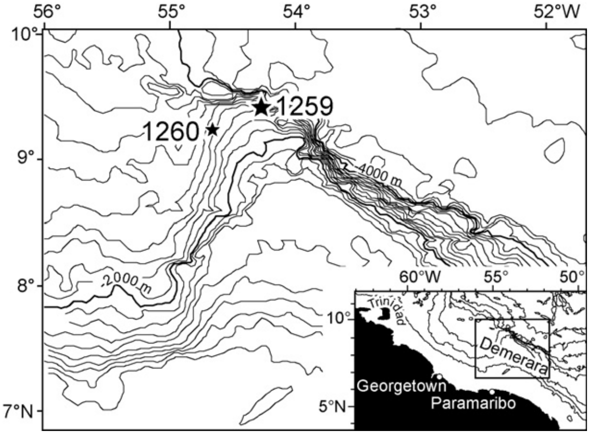

Fig. 1. Geographic location of Demerara Rise and two of the sites drilled during ODP Leg 207.

Fig. 1. Localisation géographique du plateau de Demerara et de deux des sites forés durant le Leg ODP 207.

on the Demerara South-American margin and to discuss also their possible palaeoclimatic and palaeoceanographic significance.

2. Geological and stratigraphic framework

ODP Leg 207 drilled the distal part of Demerara Rise (offshore Surinam; Fig. 1) in order to recover expanded, but shallowly buried sediments of Late Cretaceous to Palaeogene age [5]. Since the Eocene sediments of Demerara Rise accumulated at 1°S of palaeolatitude [25], the studied sequences represent biogenic sediment accumulation in a typical equatorial setting.

Silica (radiolarian and diatom)-rich sediments were recovered from the Middle Eocene segment of the sequence, which is expanded at the two intermediate sites (1259 and 1260, Fig. 1). More particularly, Site 1259, at 2354 metres of depth, contains the most complete and expanded Middle Eocene siliceous record among the sites drilled (Unit IIB, Fig. 2). Micropalaeontological and nannofacies observations focused mainly on the interval that records the Lower to Middle Eocene transition, which is also underlined by a change in the colour of sediments (Fig. 3), the Lower Eocene (Unit IIC) chalk being darker due to the relative abundance in clays (and relative paucity in carbonate content), as compared with the Middle Eocene siliceous chalk (Unit IIB). Although core recovery was not complete throughout this transitional zone, the sedimentary sequence is devoid of any biostratigraphically detectable hiatus at this level [5,24]. A limited number of samples were also studied by XRD, in order to better characterise the Lower to Middle Eocene transitional zone.

3. Radiolarian taphonomy

We based our assessment of biogenic silica preservation mainly on radiolarian skeletons. Five samples were selected as representative of the various nannofacies found along an approximately 20-m-thick interval stretching along the silica-poor to silica-rich transition. Scanning Electron Microscope (SEM) observations of the texture and nannofacies were made on small fragments of chalk and complemented by optical observations of carbonate-free residues (Figs. 4–6).

The Lower Eocene chalk contains in general very few incomplete fragments of radiolarian tests that are poorly preserved and partly dissolved (i.e. sample 1259A-32R-1, 55–57 cm; Fig. 4a). Towards the top of the silica-poor sequence, rare relatively well-preserved radiolarian specimens might be observed in the carbonate-free residue (sample 1259A-31R-CC, 15–19 cm; Fig. 4b). However, radiolaria remain rare and none was seen during nannofacies observations with the SEM. These levels are still dominated by the presence of planktic foraminifera, as well as abundant zeolites spread within the sediment and within the foraminiferal chambers (Fig. 5a). The presence of abundant zeolites (ca. 5–8%) in the Lower Eocene chalk is also confirmed by XRD studies (Fig. 3).

The base of core 1259A-30R records a clear increase in radiolarian abundance (i.e. sample 1259A-30R-4, 55–57 cm). These are poorly or moderately well preserved (Fig. 4c), mainly in opal-CT (Fig. 6a and b). However, some may still be preserved in amorphous silica. Nannofacies observations reveal the presence of abundant planktic foraminifera and well-formed zeolites. Numerous, small opal-CT microspherules were observed for the first time.

Planktic foraminifera remain an abundant biogenic component up to sample 1259A-30R-3, 55–57 cm, which represents a critical level unusually rich in opal-CT (up to 40%; Fig. 3). Opal-CT lepispheres, with the typical blade-like structure, are particularly well-formed and abundant. They are grouped together in large agglomerates, especially in cavities formed between and within foraminiferal shells (Fig. 5c and d).

Radiolarian abundance becomes high towards the top of core 1259A-30R (Fig. 5e) and remains high for the rest of the Middle Eocene (Fig. 2). Radiolaria are preserved in amorphous silica (Fig. 5f). Detailed observations at high magnification reveal an excellent state of preservation, especially for the internal parts of skeletons, whereas its external surface is slightly ‘corroded’ (Figs. 6c–f). Quite a few opal-CT spherules and rare zeolites also occur. It is likely that the corroded surface of radiolarian tests

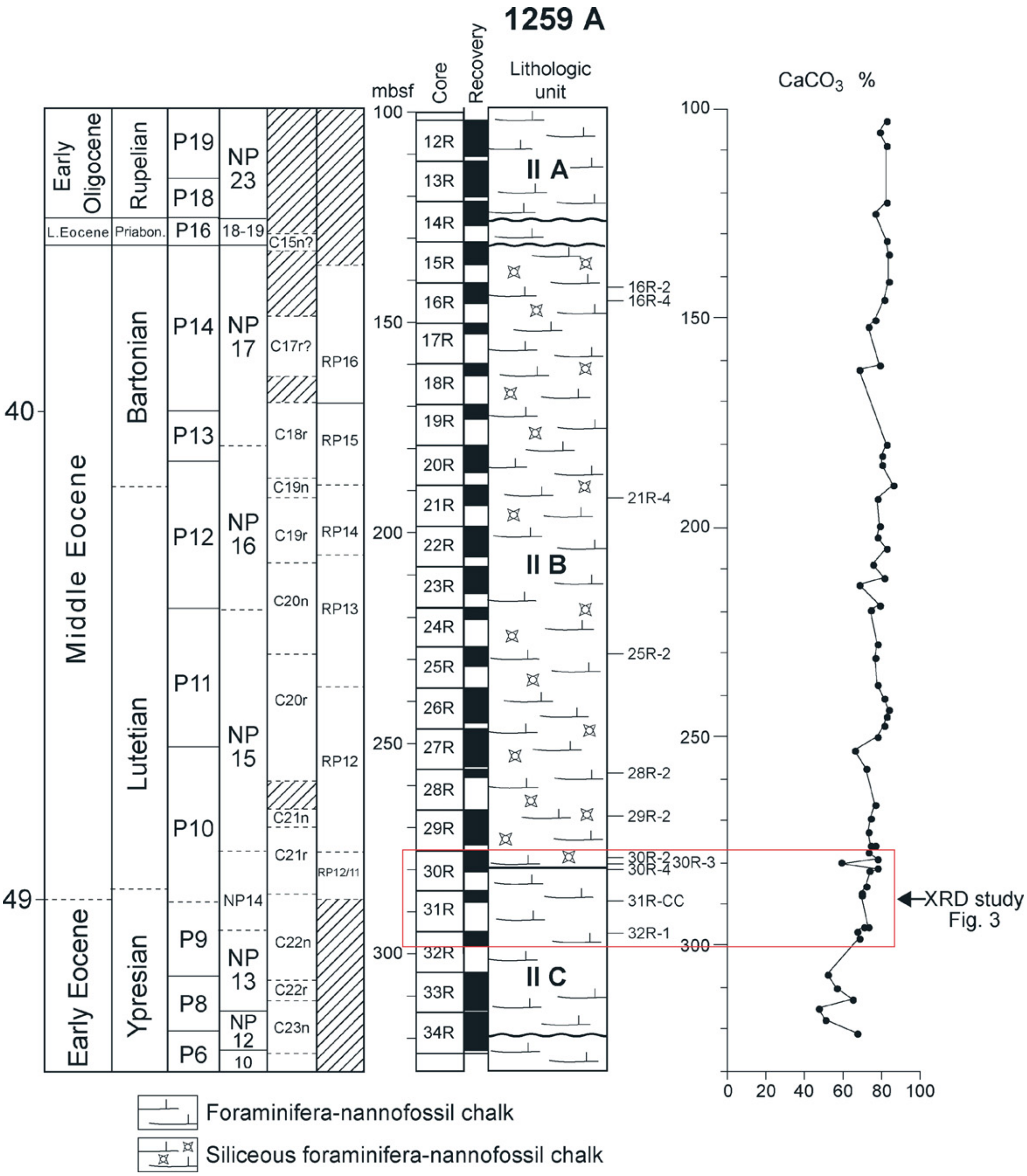

Fig. 2. Lithology and core recovery of Eocene sediments drilled at Hole 1259A. Intervals in black represent the thickness of recovered sediments in each core. Biostratigraphy according to [5]. Magnetostratigraphy according to [25]. $CaCO_3$ measurements according to [5] and this study.
Fig. 2. Lithologie et taux de récupération des sédiments éocènes forés au niveau du forage ODP 1259A. Les intervalles en noir représentent l'épaisseur de sédiments récupérés dans chaque carotte. Biostratigraphie d'après [5]. Magnétostratigraphie d'après [25]. Mesures de $CaCO_3$ d'après [5] et cette étude.

is due to the formation of pits within which opal-CT spherules formed (Fig. 6f). Parts of the external surface of the observed radiolarian skeletons display signs of ageing, with traces of fractures and very early stages of recrystallisation.

4. Diatom palaeoecology and preservation

Samples from the Middle Eocene chalk (including the ones studied for radiolarian preservation, Fig. 2) were studied for diatoms. These are very rare around the

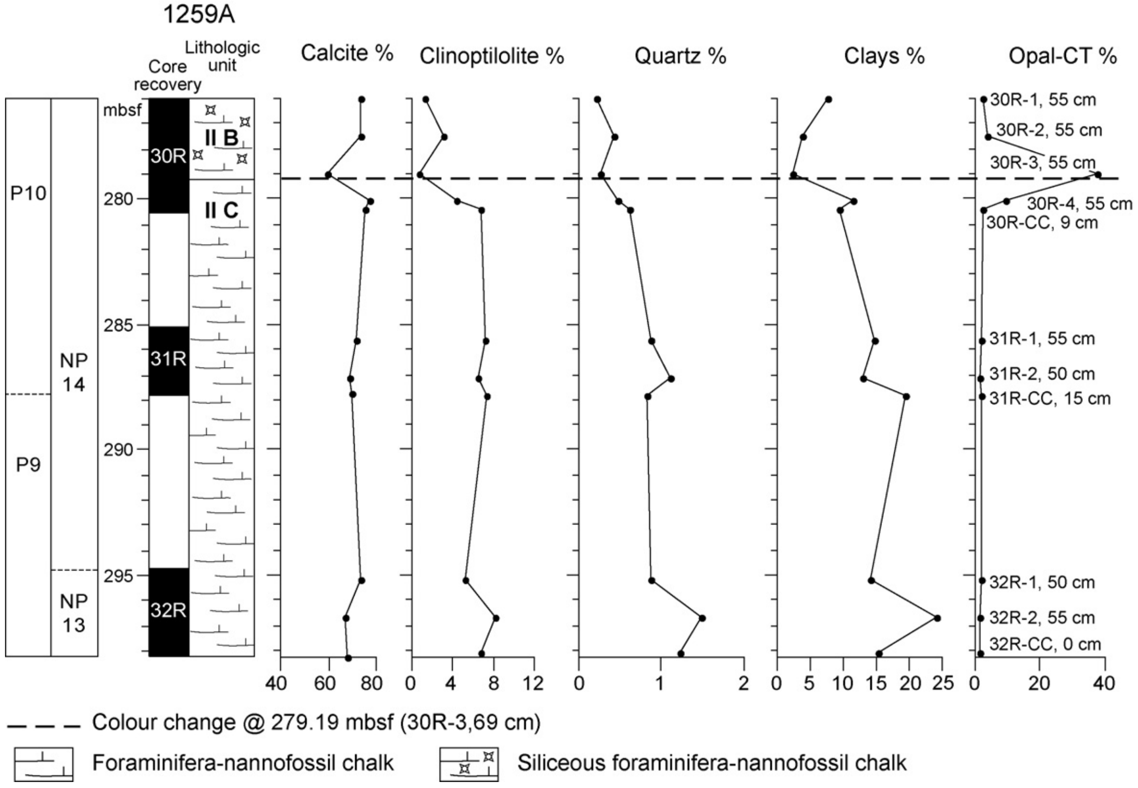

Fig. 3. Abundance changes of the main mineralogical components throughout the Lower to Middle Eocene transitional zone: calcite % based on carbonatometry; semi-quantitative evaluations for other minerals based on X-Ray diffraction results.

Fig. 3. Variations minéralogiques à la transition Éocène inférieur–Éocène moyen : pourcentage de calcite (calcimétrie) et estimation semi-quantitative des autres minéraux par diffraction des rayons X.

base of the silica-rich interval (a few fragmented diatoms were observed in samples 1259A-30R-2, 55–57 cm and 1259A-30R-4, 55–57 cm), but diversify rapidly further up the sequence (core 1259A-29R upwards).

Diatom assemblages preserved in the lower part of the silica-rich chalk (samples 1259A-29R-2, 55–57 cm and 28R-2, 54–56 cm) are dominated by typical Eocene species belonging to genera *Triceratium,*

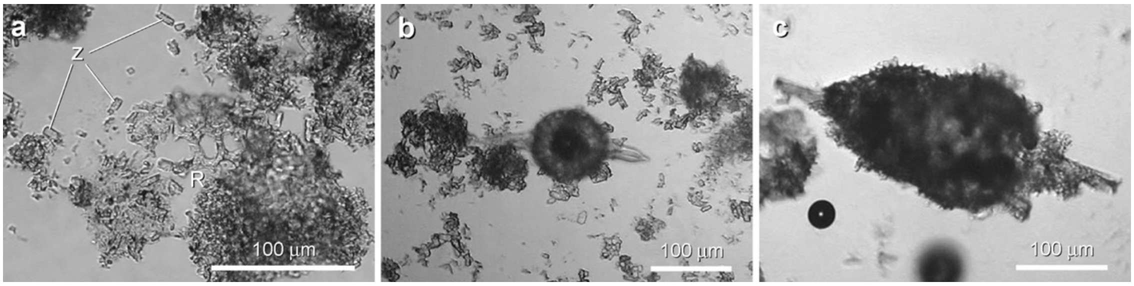

Fig. 4. Slide views illustrating radiolarian preservation and abundance of zeolites in decalcified residues. (a) Sample 1259A-32R-1, 50–52 cm: few poorly preserved and partly dissolved fragments of radiolaria (R) surrounded by abundant zeolites (z). (b) Sample 1259A-31R-CC, 15–19 cm; an entire and quite well-preserved radiolarian specimen surrounded by abundant zeolites. Many partially dissolved specimens also occur in this sample. (c) Sample 1259-30R-4, 55–57 cm: a complete, but a rather poorly preserved radiolarian specimen.

Fig. 4. Prises de vue sur frottis de la préservation des radiolaires et de l'abondance des zéolithes dans des résidus décalcifiés. (a) Échantillon 1259A-32R-1, 50–52 cm : quelques fragments de radiolaires (R) d'une mauvaise préservation entourés par d'abondants cristaux de zéolithes (z) ; (b) échantillon 1259A-31R-CC, 15–19 cm : un spécimen de radiolaire entier et assez bien préservé, entouré par d'abondants zéolithes. De nombreux fragments de radiolaires partiellement dissous sont également présents dans cet échantillon ; (c) échantillon 1259-30R-4, 55–57 cm: un radiolaire entier, mais mal préservé.

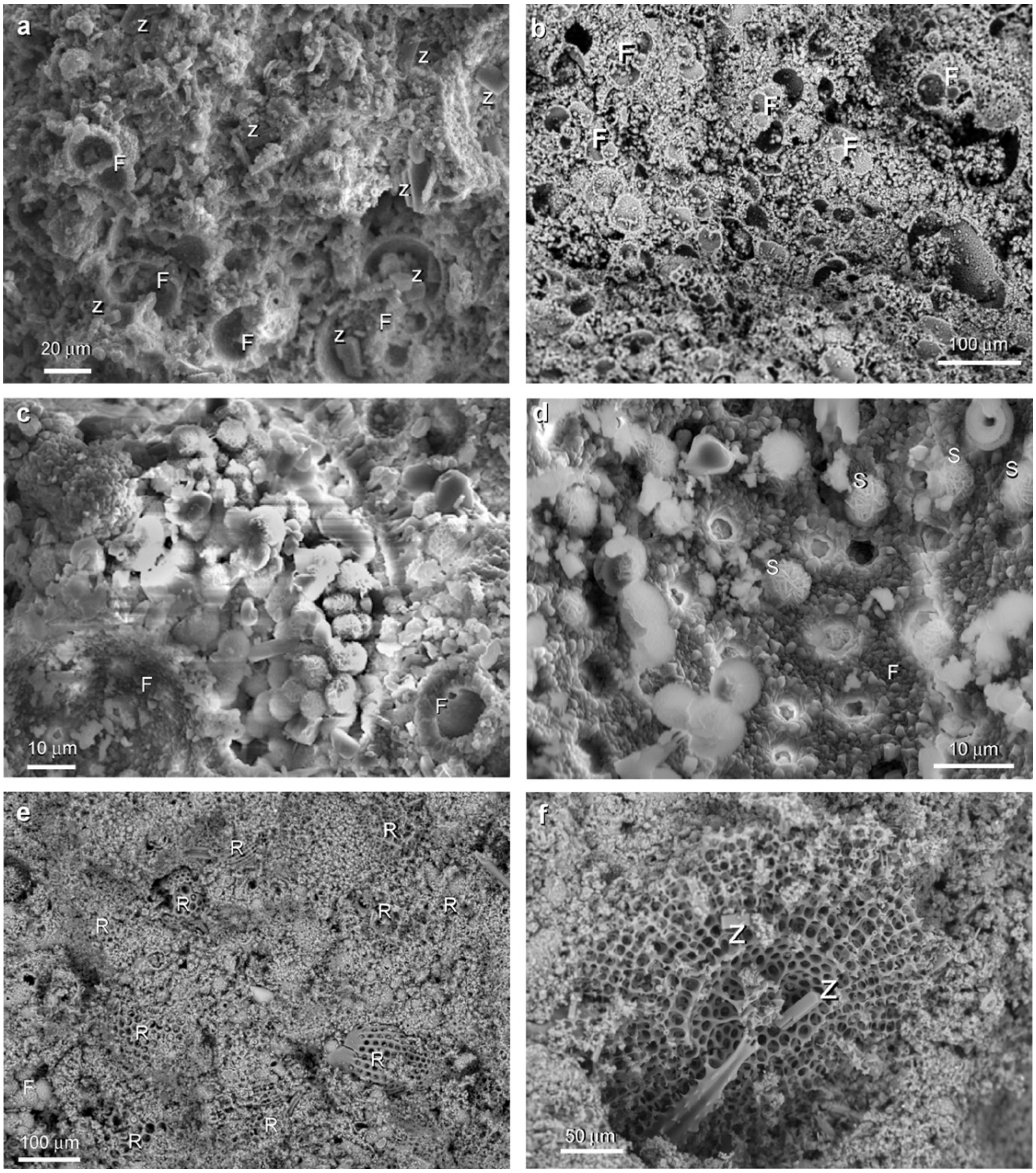

Fig. 5. Scanning electron micrographs. (a) Sample 1259A-31R-CC, 15–19 cm: abundant planktic foraminifera (F) and well-formed crystals of zeolites (z) can be observed all around the sediment. (b–d) Sample 1259A-30R-3, 55–57 cm: (b) general view of the sample surface reveals the abundance of planktic foraminifera (F)– no radiolaria were observed on the explored piece of sample –; (c) close-up of numerous clustered well-developed opal-CT spherules (s) fill the space left between planktic foraminifera (F); (d) close-up of the internal part of a planktic foraminiferal chamber, with few opal-CT lepispheres (s). (e–f) Sample 1259A-30R-2, 55–57 cm: (e) general view of the sample surface displaying numerous radiolarian tests (R) as compared to Foraminifera (F); (f) view of the inner part of a broken spumellarian radiolarian test. Note the very good preservation of the inner visible parts and the presence of few, well-developed zeolite crystals (z).

Fig. 5. Photographies au microscope électronique à balayage. (a) Échantillon 1259A-31R-CC, 15–19 cm : d'abondants foraminifères planctoniques (F) et des cristaux de zéolithes bien formés (z) peuvent être observés sur toute la surface du sédiment. (b–d) Échantillon 1259A-30R-3, 55–57 cm: (b) vue générale de la surface de l'échantillon étudié illustrant l'abondance des foraminifères planctoniques (F) et l'absence de radiolaires de la surface examinée ; (c) détail illustrant de nombreuses sphérules (s) d'opale-CT dans les vides entre les tests de foraminifères planctoniques ; (d) détail de paroi interne de la loge d'un foraminifère planctonique, avec quelques sphérules d'opale-CT. (e–f) Échantillon 1259A-30R-2, 55–57 cm : (e) vue générale de la surface de l'échantillon étudié illustrant l'abondance des tests de radiolaires (R) par rapport aux foraminifères (F). (f) Vue de la partie interne d'un test cassé de radiolaire spumellaire ; noter la très bonne préservation des parties internes visibles et la présence de quelques cristaux de zéolithes (z) bien formés.

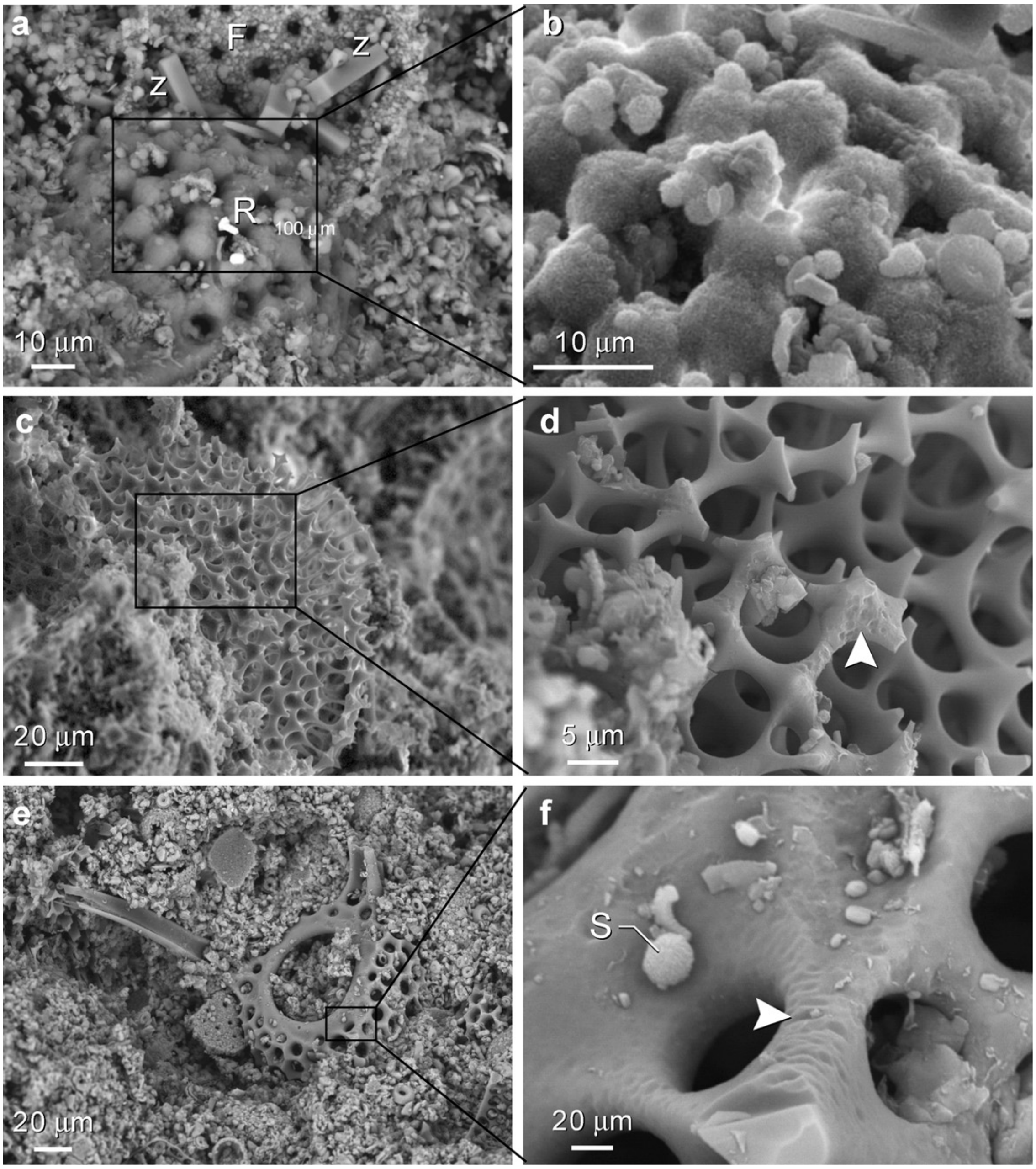

Fig. 6. Scanning electron micrographs. (a–b) Sample 1259A-30R-4, 55–57 cm: (a) rare radiolaria (R), preserved in opal-CT (close-up in (b) displays a rough and knobbly outer surface), surrounded by well-developed zeolites (z), calcareous nannofossils and planktic foraminifera (F). (c–f) Sample 1259A-30R-2, 55–57 cm: (c) view of a broken multi-shelled spumellarian radiolarian test; close-up (d) of the outer shell displays a pitted ('corroded') surface, in contrast to the perfectly well-preserved inner parts of the test; (e) general view of a nassellarian radiolarian test surrounded by a calcareous nannofossil ooze; close-up of the peristome (f) reveals a pitted surface and the presence of small spherules (opal-CT?) placed in the pits.

Fig. 6. Photographies au microscope électronique à balayage. (a–b) Échantillon 1259A-30R-4, 55–57 cm : (a) rares radiolaires (R), préservés en opale-CT (le détail en (b) montre une surface externe rugueuse et nodulaire) et entourés par des cristaux bien formés de zéolithes (z), nannofossiles calcaires et foraminifères planctoniques (F). (c–f) Échantillon 1259A-30R-2, 55–57 cm : (c) test d'un radiolaire à plusieurs coques et détail de la coque externe (d) montrant une surface « corrodée », en contraste avec la surface parfaitement bien préservée des parties internes du test ; (e) vue générale du test d'un radiolaire nassellaire au sein d'une boue à nannofossiles calcaires ; (f) détail du péristome montrant une surface rugueuse (flèche) légèrement « corrodée » et la présence de petites sphérules (s : opale-CT ?).

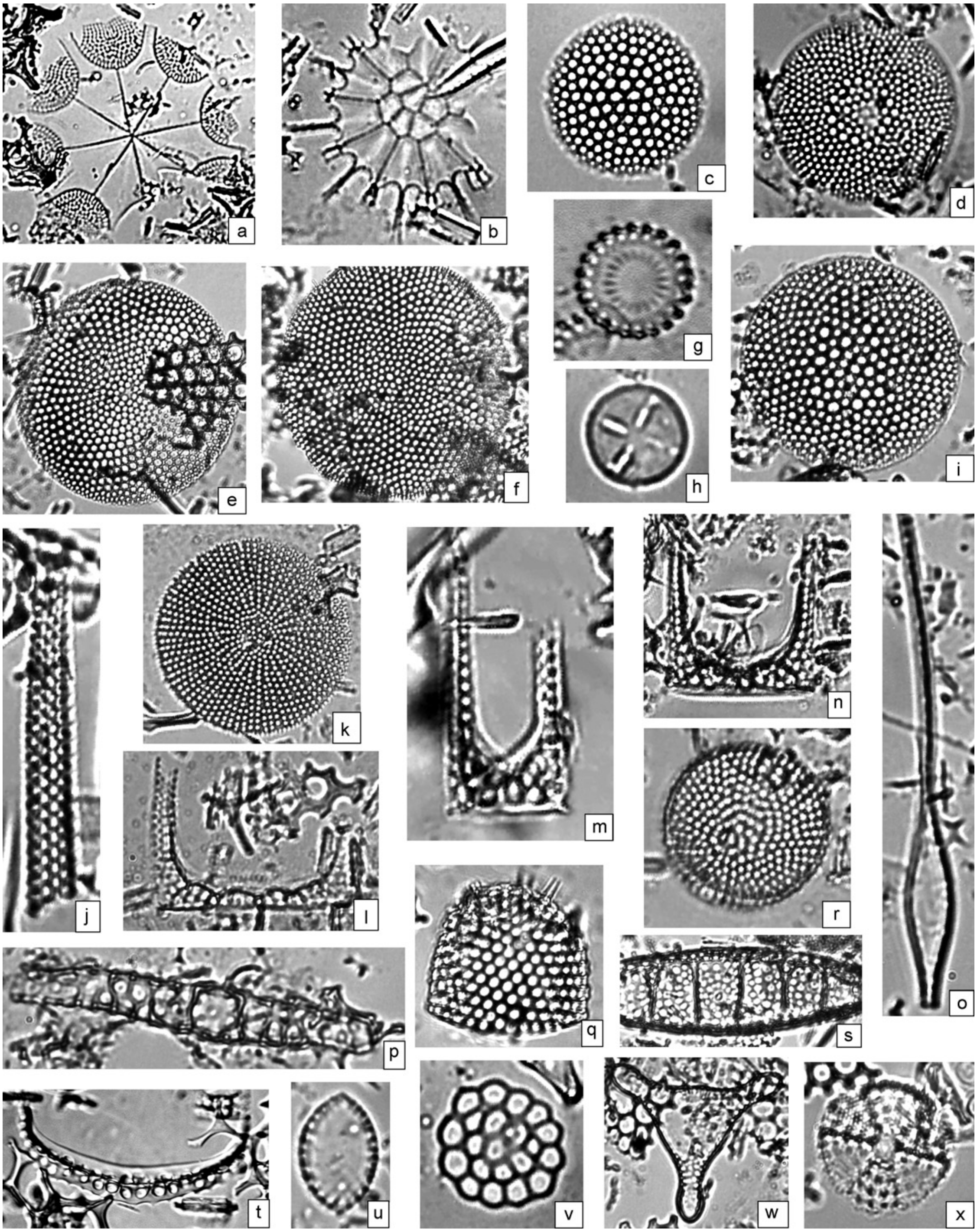

Fig. 7. Diverse diatom assemblage from sample 1259A-16R-2, 54–56 cm. (a) *Asterolampra marylandica*, × 300; (b) *Asterolampra insignis*, × 500; (c) *Coscinodiscus decrescens*, × 830; (d) *Brightwellia hyperborea*, × 700; (e) *Coscinodiscus obscurus*, × 400; (f) *Coscinodiscus oculus-iridis*, × 400; (g) *Paralia sulcata*, × 1300; (h) *Liostephania* sp., × 1300; (i) *Coscinodiscus bulliens*, × 1000; (j) *Pyxilla gracilis*, × 600; (k) *Coscinodiscus oligocenicus*, × 750; (l) *Hemiaulus inaquilaterus*, × 540; (m) *Hemiaulus subacutus* sensu Gombos (1976), × 840; (n) *Hemiaulus polycystinorum* var. *mesolepta*, × 500; (o) *Clavularia barbadensis*, × 1000; (p) *Hemiaulus gondolaformis*, × 500; (q) *Stepahopyxis turris*, × 1000; (r) *Stictodiscus kittonianus*, × 930; (s) *Hemiaulus polycystinorum*, × 1000; (t) *Hemiaulus gondolaformis*, × 570; (u) Spore, × 780; (v) *Pseudorocella barbadensis*, × 1300; (w) *Triceratium subcapitatum*, × 1800; (x) *Actinoptychus senarius*, × 900.

Fig. 7. Association diversifiée de diatomées, issue de l'échantillon 1259A-16R-2, 54–56 cm.

Hemiaulus and *Riedelia*. *Paralia sulcata* is also present. Curiously, those observed in the middle part of the Middle Eocene sequence are poorly preserved (samples 1259A-25R-W, 55–57 cm and 21R-4, 50–52 cm). Genus *Hemiaulus* is abundant and represented by many typical Eocene species. Other taxa include *Pyxilla*, *Riedelia*, *Triceratium*, *Paralia* and *Melosira*.

The richest diatom microflora was observed in the upper part of the sequence, in core 1259A-16R (Fig. 7). Most of the 44 identified species observed in the two studied samples are typical of the Eocene low-latitudinal realm [7]. Assemblages are dominated by various species of genus *Hemiaulus* (i.e. *H. gondolaformis*, *H. alatus*, *H. grassus*), which constitute ca. 50% of the preserved diatom microflora. Among the other taxa, *Paralia sulcata* (ca. 10%), *Coscinodiscus decrescens* and *Pseudorocella barbadensis* are also abundant. Many of the identified species are common with the Middle–Late Eocene diatom microflora described by [7] and [9] from the equatorial Atlantic.

Diatom assemblages observed in the studied samples are essentially composed of planktic chain-forming species of genera *Hemiaulus, Paralia* and *Stephanopyxis*. It is noteworthy that no continental or benthic forms were observed. Diatom resting spores, such as *Goniothecium, Pterotheca, Xanthiopyxis*, are also present and are indicative of accumulation on a shelf area. Some of the planktic taxa that can be considered as neritic (associated with shelf areas) are abundant (i.e. *Hemiaulus, Stephanopyxis, Actinoptychus*), while others regarded as exclusively oceanic (part of the open oceanic realm; i.e. species *Asterolampra, Cestodiscus, Pseudoreocella*, some species of *Coscinodiscus*) are subordinate.

Most of the diatoms identified in the studied samples possess robust frustules (*Hemiaulus, Stephanodiscus, Paralia, Pyxilla, Aulacodiscus*). Although it is well established that thick and heavily silicified frustules are a common attribute of Palaeogene diatoms (as opposed to the majority of Neogene ones), some specimens of fragile taxa (i.e. *Asterolampra* and *Clavicula*) were also observed in the Demerara material. It is worth noting that all *Asterolampra* specimens observed displayed broken frustules, which may be suggestive of partial dissolution. The latter may be also inferred by the rare occurrence of *Liostephania* specimens in the studied material. *Liostephania* is considered to be internal moulds of diatom valves (possibly belonging to genus *Asterolampra*), preserved in amorphous silica [11,21]. They are commonly found in Middle–Upper Eocene sediments and considered to be very resistant to dissolution [8]. According to Fenner [6], the occurrence of *Liostephania* indicates initial stages of diagenetic dissolution.

5. Discussion

There are clearly a number of interesting points that can be inferred based on the Middle Eocene siliceous plankton record of Demerara Rise:

- (1) the absence of continental diatoms highlights the exclusively pelagic, biogenic nature of the depositional setting, in which the silica-rich Middle Eocene chalk accumulated. However, the abundance of neritic diatom taxa (i.e. *Hemiaulus*) may be suggestive of a relatively agitated depositional environment, either due to bottom [3] or surface current activity [13]. Moreover, the common occurrence of *Paralia sulcata* (a species which still exists today, often found in temperate coastal waters) suggests elevated levels of productivity (at least during zone RP16, where this species is relatively abundant), due possibly to a regional coastal upwelling system along the Demerara subsided plateau [1,2,22];
- (2) enrichment of Eocene chalk in biogenic silica cannot be considered to be due to carbonate dissolution, since carbonate biogenic components (foraminifera, calcareous nannofossils) are abundant (carbonate content is elevated; ca. 60% on average; Figs. 2–3). Radiolarians are rare and dissolved in the uppermost part of the Lower Eocene chalk, which is rich in planktic foraminifera. The latter are also present in the Middle Eocene chalk, but SEM nannofacies observations establish clearly the dominance of radiolaria in this interval (Fig. 5e). Thus, the Lower to Middle Eocene transition reflects a profound change in the community structure of zooplankton that lived in the equatorial Atlantic, possibly due to the establishment at that time of moderately high levels of productivity. However, it is worth noting that the enrichment in biogenic silica is mainly due to radiolaria, since diatoms form only a small part of it. This is also the case in time-equivalent sediments of the equatorial Pacific, drilled recently during Leg 199 [15]. What kind of palaeoenvironmental changes could have been at the origin of the sudden burst in radiolarian productivity? The transitional zone between silica-poor and radiolarian-rich Eocene chalk is situated within core 1259A-30R (at approximately 49 Ma; base of the Middle Eocene). Thus, the onset of radiolarian productivity at Demerara correlates well with the age of the acoustic Reflector A^c, which is widespread in the North Atlantic and is due to the development of an unconformity

and presence of cherts and porcellanites. The age of the base of this siliceous level is fairly well constrained in the base of zone P10 of planktic foraminifera and the base of magnetozone C21r [16]. The abundance of silica in Middle Eocene oceans was interpreted initially as a consequence of extensive Early Eocene volcanism (and subsequent climate warming), which was followed by Middle Eocene cooling and oceanic upwelling [16]. Abrupt onset of vigorous deep-water circulation, possibly linked to an early phase of Antarctic glaciation, might be a suitable working hypothesis to explain the origin of Reflector A^c [17], although oxygen isotope curves available so far do not display any major cooling step at the Early–Middle Eocene transition [20,26]. However, the carbon isotope curve established recently by Sexton et al. [20] on monospecific benthic foraminifera from Demerara Rise argues for important intrabasinal changes in carbon cycling which took place during the same time as silica enrichment at Demerara, pointing to a more vigorous oceanic circulation during the Middle Eocene. Thus, silica enrichment at Demerara and coeval gaps and cherts in the North Atlantic coincide with profound changes in the palaeoceanography of the equatorial Atlantic, as compared with higher latitude sites;

- (3) radiolarian preservation appears to be positively related to the abundance of biogenic silica in the sediment. Our results from Demerara establish that high siliceous productivity, as well as the very high sedimentation rates recorded in the Middle Eocene [5] improved the preservation potential of biogenic silica. Our observations confirm the diagenetic model put forward by Riech and von Rad [19]. Zeolites are very abundant mainly in the radiolarian-poor Lower Eocene chalk. The depauperate and poorly preserved radiolarian fauna included in these sediments would have probably been their source of silica. Zeolites are still present in the radiolarian-rich Middle Eocene interval, mainly preserved in the internal parts of radiolarian skeletons. Increased abundance of siliceous microfossils which occurs at the Lower to Middle Eocene transitional zone appears to have favoured preferentially the formation of opal-CT as a product of biogenic (amorphous) silica dissolution. The peak of opal-CT measured and observed in sample 1259A-30R-3, 50–57 cm, underlines the stratigraphic level of silica enrichment in the Eocene sequence. Traces of an early phase of dissolution on radiolarian skeletons preserved in the Middle Eocene chalk indicate that the Middle Eocene radiolarians would have been preserved as opal-CT, if silica had not been abundant enough to sustain amorphous silica preservation in the radiolarian-rich interval.

6. Conclusions

Siliceous plankton productivity increased in the western equatorial Atlantic (offshore Surinam) during the Lower to Middle Eocene transition, at about 49 Ma and correlates temporally with the extensive development of unconformities and chert in the North Atlantic. Biogenic silica accumulation was mainly due to radiolarian productivity and constitutes a major shift in the structure of zooplankton communities of the equatorial Atlantic, dominated in the Lower Eocene by planktic foraminifera. Diatoms increase in significance further up the Middle Eocene chalk. Preservation of siliceous microfossils in the sediments improved greatly following increased biogenic silica accumulation rates on Demerara Rise, possibly due to the establishment of an upwelling along the distal margin and a more vigorous bottom current circulation. The onset of silica enrichment coincides with profound palaeoceanographic changes that transformed a stagnant Lower Eocene ocean into a more vigorous Middle Eocene one, perhaps following an as yet poorly defined global climatic change.

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