Late Paleocene event chronology : unconformities, not diachrony

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Key words. - Biostratigraphy, Diachrony, Isotope stratigraphy, Unconformities.

Abstract. – The chronology of the events associated with the late Paleocene thermal maximum (LPTM, Chron C24r) has been established through the construction of a composite reference section that involved chemomagnetobiostratigraphic correlations and assumed minimum diachrony of biostratigraphic events. On this basis, discrepancies between correlations in different sections were explained by inferred unconformities. However, diachrony between distant sections cannot be ruled out. We report here on two geographically close sections drilled onshore New Jersey that yield different records of chemomagnetobiostratigraphic correlations in the interval representing Chron C24r. Because of their proximity (~ 40 km apart), diachrony of biostratigraphic events between the two sections can be ruled out. In contrast, the marked lithologic disconformities in the sections explain well the different records of events. We thus conclude that the current relative chronology for Chron C24r is firmly based and that the upper Paleocene-lower Eocene stratigraphic record yields multiple unconformities, with Subzone NP9b rarely sampled. We examine the implications that undeciphered unconformities may have on the identification of proxies for paleoceanographic reconstruction, in particular with regard to the identification of the carbon isotope excursion (CIE) that reflects a dramatic latest Paleocene disturbance of the carbon cycle. We propose biostratigraphic means (short-lived calcareous nannoplankton and planktonic foraminifera taxa) that permit the unequivocal identification of the CIE not only in the oceanic realm but also in neritic settings.

Chronologie des événements de la fin du Paléocène : discordances *versus* diachronie

Mots clés. – Biostratigraphie, Diachronie, Stratigraphie isotopique, Discordances.

Résumé. – La chronologie des événements qui se sont produits durant le Chron C24r a été établie à partir de la construction d'une coupe composite fictive, établie sur la base de corrélations entre chimio-, magnéto- et biostratigraphie dans diverses coupes, et en supposant une diachronie minimale des événements biostratigraphiques. Deux coupes carottées dans le New Jersey, USA, nous permettent de démontrer le rôle des discordances sur les corrélations entre coupes, et d'établir la validité de la chronologie actuellement utilisée pour le Chron C24r.

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La chronologie des événements associés avec le réchauffement maximum de la fin du Paléocène (Late Paleocene Thermal Maximum ; Chron C24r) a été établie à partir d'une coupe composite fictive construite sur la base de relations entre stratigraphie isotopique, magnétostratigraphie et biostratigraphie, en supposant une diachronie minimale des événements biostratigraphiques. Dans cette perspective, les différences de corrélations entre différentes coupes stratigraphiques sont expliquées par la présence implicite de discordances. Toutefois, il est nécessaire de reconnaître qu'une diachronie pourrait exister entre coupes distantes. Nous analysons ici deux coupes géographiquement très proches carottées dans le New Jersey, qui ont la particularité de présenter des corrélations différentes entre magnétostratigraphie, biostratigraphie et stratigraphie isotopique dans l'intervalle correspondant au Chron magnétique C24r. En raison de leur proximité géographique (~ 40 km), il est possible d'exclure tout phénomène de diachronie. Par contre les disconformités lithologiques, bien visibles dans les coupes, expliquent clairement les différences de relations entre événements dans les deux coupes. Nous concluons par conséquent que la chronologie relative utilisée pour le Chron C24r a été fermement établie, et que l'enregistrement sédimentaire correspondant au Chron C24r est fortement discontinu, la Sous-zone NP9b étant rarement représentée. Nous analysons les conséquences qui résultent de discordances ignorées sur l'identification d'indicateurs paléocéanographiques, en particulier par rapport à l'identification de l'excursion isotopique du carbone (CIE), excursion qui reflète une perturbation dramatique du cycle du carbone à la fin du Paléocène. Nous proposons des éléments biostratigraphiques (espèces du nannoplancton calcaire et foraminifères planctoniques à durée de vie très courte) pour permettre d'identifier la CIE non seulement en domaine océanique, mais également en milieu néritique.

INTRODUCTION

The latest Paleocene (~ 55.5-54.5 Ma) has been identified as one the most critical times in Cenozoic history. The rapid global deep sea benthic foraminifera extinction [BFE ; Thomas, 1992], and simultaneous turnover among mid-bathyal ostracodes [Steineck and Thomas, 1996], the sharp turnover among calcareous nannoplankton [Aubry, 1998a] and rapid diversification in the planktonic foraminifera [Kelly *et al.*,

1996] are the recently discovered marine biotic events equivalent in amplitude and significance to the critical turnover that affected land mammals and has been known for over a century [see Hooker, 1998]. Correlative with these biotic events, a characteristic 3 to 4 ‰ carbon isotope excursion (CIE) occurs in the carbon isotopic composition of marine carbonates [e.g., Kennett and Stott, 1991 ; Bralower *et al.*, 1995 ; Pak and Miller, 1992], in soil nodules and the tooth enamel of terrestrial mammals [Koch *et al.*, 1992] and in

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terrestrial organic matter [Stott *et al.*, 1996; Sinha *et al.*, 1996]. These events occurred in connection with a sudden short-term warming event dubbed the Latest Paleocene Thermal Maximum (LPTM), during which sea surface and deep-water temperatures warmed by 5-6 °C and 4 °C, respectively [Zachos *et al.*, 1993].

The marine biotic, isotopic and sedimentologic changes that occurred during Chron C24r have been documented mainly through the study of numerous DSDP/ODP holes and outcrop sections deposited at bathyal depths, with the notable exceptions of two Tethyan neritic sections in Egypt [Charisi and Schmitz, 1995; Speijer *et al.*, 1996], and in New Jersey [Thomas *et al.*, 1997; Cramer *et al.*, 1999]. Whereas these changes are now well described qualitatively, they are difficult to describe quantitatively because there is as yet no firm numerical chronology established for Chron C24r [Berggren and Aubry, 1998]. In fact, the relative chronology of events in the chron remains controversial, and the amplitude of events as critical as the carbon isotope excursion varies by a factor of three between localities. Aubry *et al.* [1996] and Aubry [1998b] have proposed that inconsistent chemomagnetobiostratigraphic correlations between sections are best explained by the presence of multiple unconformities in different sections. Accordingly, establishment of the chronology of events during Chron C24r [Berggren and Aubry, 1996, 1998] has relied on the construction of a composite reference section using two disjunct stratigraphic records, one from the Southern Ocean (ODP Hole 690), the other from the North Atlantic Ocean (DSDP Hole 550). However, because these two records are geographically so distant, there was no definitive evidence that diachrony was not responsible, at least in part, for the inconsistent chemomagnetobiostratigraphic correlations between sections.

We discuss here two adjacent stratigraphic records of Chron C24r drilled on the New Jersey margin as part of the New Jersey Coastal Plain Drilling Project (Legs 150X, 174AX). Both records yield excellent biostratigraphy, a good magnetostratigraphy and a sharp carbon isotope excursion, and are thus readily correlated with deep sea sections. In addition, they are amenable to sequence stratigraphic analysis, and a number of erosional contacts (sequence boundaries) occur. Because of geographic proximity (the distance between the two sections is 40 km), diachrony of biostratigraphic events between the two records can be ruled out. Yet, the chemomagnetobiostratigraphic correlations between them differ considerably and the difference is clearly related to the erosional contacts. We demonstrate below that together, the two sections constitute an almost complete record of Chron C24r, and bring definitive evidence that the composite reference section of Aubry *et al.* [1996] – and thus the relative chronology of events in the chron [Berggren and Aubry, 1996; Aubry *et al.*, 1996] – are firmly based and reliable. We then explain that an apparent carbon isotopic "excursion" does not necessarily represent a true geochemical event and offer means of identifying the CIE with confidence. We conclude in arguing for the urgent need to recognize unconformities as an integral component of the stratigraphic record in order to read correctly the historical message embedded in it.

MAGNETOCHEMOBIOSTRATIGRAPHIC FRAMEWORK AND CORRELATIONS

Stratigraphic framework

A high biostratigraphic resolution is available for the interval that represents Chron C24r and which essentially corresponds to calcareous nannofossil Zones NP9 and NP10 and planktonic foraminifera Zone P5 to Subzone P6b [see Berggren *et al.*, 1995]. Zone NP10 may be subdivided into 4 subzones (NP10a-d) based on the *Tribrachiatus* lineage, in particular the total range of *T. digitalis* and *T. contortus* [Aubry, 1996]. Developed in North Atlantic Deep Sea Drilling Project (DSDP) Hole 550, this subzonal scheme has now been successfully applied to deep water sections from the Pacific [Aubry, 1998b] and neritic sections from the Tethys [Schmitz *et al.*, 1996; Faris and Strougo, 1998] and the U. S. Coastal Plain [Miller *et al.*, 1994; Bybell and Self-Trail, 1997]. Zone NP9 has also been subdivided into two subzones [Bukry, 1973], but one of the two criteria used to delineate an NP9a/b subzonal boundary is unreliable [Bralower and Mutterlose, 1995; Aubry, 1999]. Although this will require refinement when suitable sections permit it, delineation of the NP9a/b subzonal boundary herein is based on the simultaneous lowest occurrences of several taxa, *i.e.*, *Rhomboaster calcitrapa*, *R. spineus*, *Discoaster araneus* and *D. anartios*. A thin stratigraphic interval characterized by the common occurrence of these taxa has been identified in several neritic and deep sections; its base is correlative with the LO of *Acarinina africana*, *A. sibaiyaensis* and *M. allisonensis* [see Cramer *et al.*, 1999] in Zone P5. Zone P5 has been recently subdivided into 2 or 3 subzones by different authors, but because planktonic foraminifera do not provide a means as powerful as calcareous nannofossils for the stratigraphy of neritic deposits, these subdivisions will not be considered here. The interested reader may refer to Berggren *et al.* [2000] for discussion. As defined, the NP9a/b subzonal boundary is also correlative with the base of the LPTM [see Cramer *et al.*, 1999]. The prominent CIE constitutes a powerful means for correlation within magnetozone C24r, synchronous with the HO of the *Stensioina beccariiformis* assemblage in deep sea settings.

It is important to recognize that the NP9a/b subzonal boundary as defined above is equivalent to the NP9/NP10 zonal boundary of Bybell and Self-Trail [1995, 1997] and Angori and Monechi [1996]. Different concepts of the species *Tribrachiatus bramlettei*, the marker of the base of Zone NP10 [Martini, 1971] is at the origin of the differences in the stratigraphic delineation of the NP9/NP10 zonal boundary [Aubry, 1996; Aubry *et al.*, 2000]. This has no consequence in this study because the calcareous nannofossil data used in this demonstration were generated by the same author (MPA), but should be taken into account if the correlations presented here are to be compared with published material in which a different taxonomic concept of *T. bramlettei* is used. The unfortunate consequence of this taxonomic disagreement is that depending on whose taxonomic framework is followed, the CIE lies at the NP9/NP10 zonal boundary, or at the NP9a/b subzonal boundary [compare Schmitz *et al.*, 1996 with Schmitz *et al.*, 1997]. An important point is that, as characterized herein, the NP9/NP10 zonal boundary can be reliability approximated based on the HO of *Fasciculithus tympaniformis*, which is essentially contiguous with the LO of *T. bramlettei* [e.g., Aubry *et al.*, 1996; Faris and Strougo, 1998]. Thus, independently of their nomenclatural assignments, the interval from the CIE to the LO of *T. digitalis* can be subdivided into two intervals : from the CIE to the HO of *F. tympaniformis* (= LO of *T. bramlettei*, i.e., nannoliths with an hexaradiate symmetry) and from this latter to the LO of *T. digitalis*.

Correlations

Whereas the relationships between the LO of *Discoaster multiradiatus* and HO of *Globanomalina pseudomenardii*
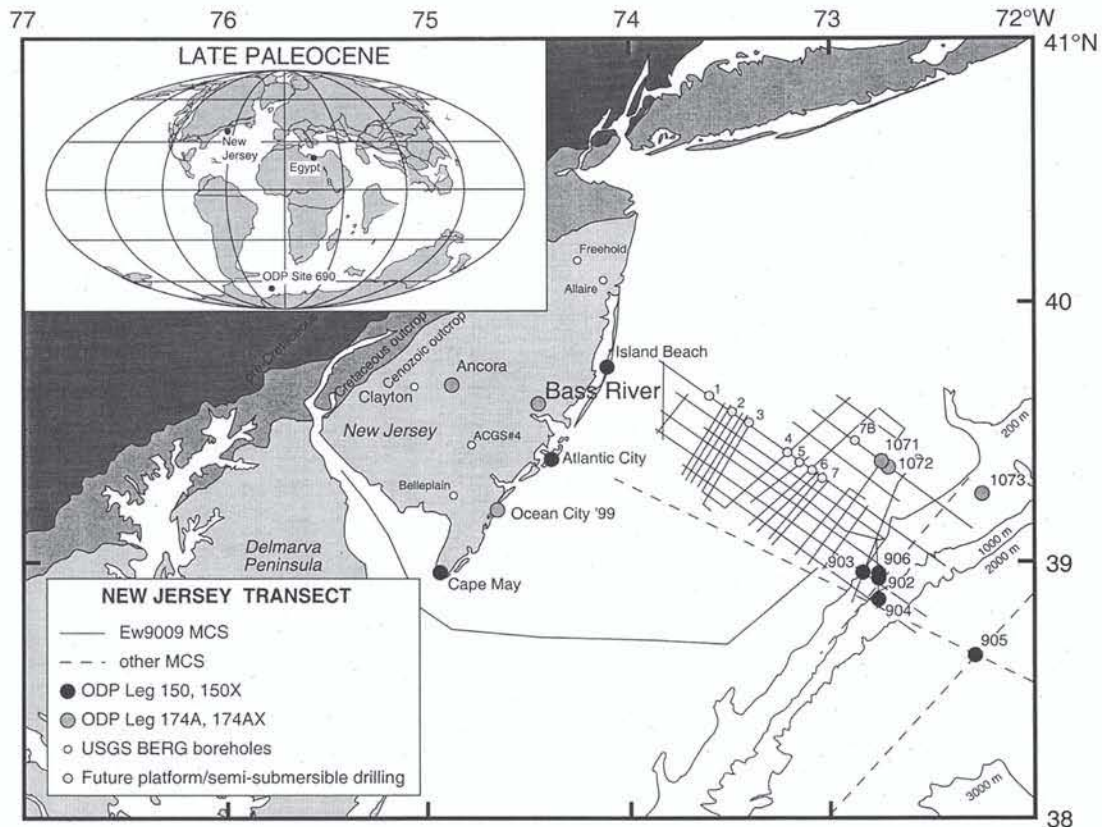
FIG. 1. – Location map.
FIG. 1. – *Cadre géographique.*

and the Chron C25n/C24r reversal boundary are well established, strongly inconsistent chemomagnetobiostratigraphic correlations occur between sections representing Chron C24r. For instance, among sections with a good magnetostratigraphic record, the CIE (and the BFE) occurs at the level of the NP9/NP10 zonal boundary in DSDP Holes 550 and 577, but it is separated from the zonal boundary by less than a meter in ODP Holes 865B, 2.6 m in DSDP Hole 549 and ~ 12 m in ODP Hole 690B. In addition, the CIE may occur as low as 23.5 % of the way up in Magnetozone C24r or as high as 41.3 % (ODP Hole 690B), whereas the NP9/NP10 zonal boundary may occur as low as 23.5 % (DSDP Hole 549) or as high as 76 % (ODP Hole 690B). In ODP Hole 865, which yields no polarity record, the thickness of Magnetozone C24r can be approximated (~ 24.60 m) based on biostratigraphic datums. In this hole, the NP9/NP10 zonal boundary is 64 cm above the CIE and located ~ 55 % of the way up in the interval seen to represent Chron C24r.

There are essentially two ways of explaining these discrepancies [Aubry, 1995, 1998b]. One is through the (overstated) diachrony of biostratigraphic events. The other is through the incompleteness of stratigraphic sections. The blurring effect that unconformities have on stratigraphic correlations has been demonstrated for at least some DSDP/ODP sections [Aubry *et al.*, 1996 ; Aubry, 1998b]. However, some authors have argued for a combined effect of the two mechanisms [e. g., Flynn and Tauxe, 1998], and diachrony between high and low latitude stratigraphies cannot be ruled out *a priori*. The only means to eliminate the role of diachrony would thus be the recovery of sections from similar latitudinal and water depth settings yielding

contrasted magnetochemobiostratigraphic correlations. Such sections were recently recovered as part of the New Jersey Coastal Plain Drilling Project, and provide the opportunity to test the reliability of the chronology of events in Chron C24r.

MAGNETOBIOSTRATIGRAPHIC CORRELATIONS BETWEEN THE TWO SECTIONS

The Bass River and Island Beach Boreholes drilled on the New Jersey margin less than 60 km apart have yielded two shallow water (neritic) upper Paleocene and lower Eocene sections with exceptional records of Chron C24r (fig. 1). These are easily correlated on the basis of lithostratigraphy, and both yield a clear unconformity at the lithologic contact between the Vincentown and Manasquan Formations. In addition, both yield a carbon isotope excursion and the calcareous nannofossil preservation and diversity are remarkable, permitting firm chemobiostratigraphic correlations between the two sections and with deep sea sections. We first correlate the two sections on the basis of litho-, magneto- and biostratigraphy. We then use this framework to compare the isotopic stratigraphies of the two sections.

Bass River borehole

In the Bass River Borehole (BRB ; 39° 36' 42" N, 74° 26' 12" W ; elevation of 8.53 m ; Miller *et al.* [1998], Magnetozone C24r, precisely delineated between the magnetic reversals at ~ 1192' (363.40 m) and ~ 1136' (346.25 m) [Cramer *et al.*, 1999] is 56' (27 m) thick (fig. 2). It spans
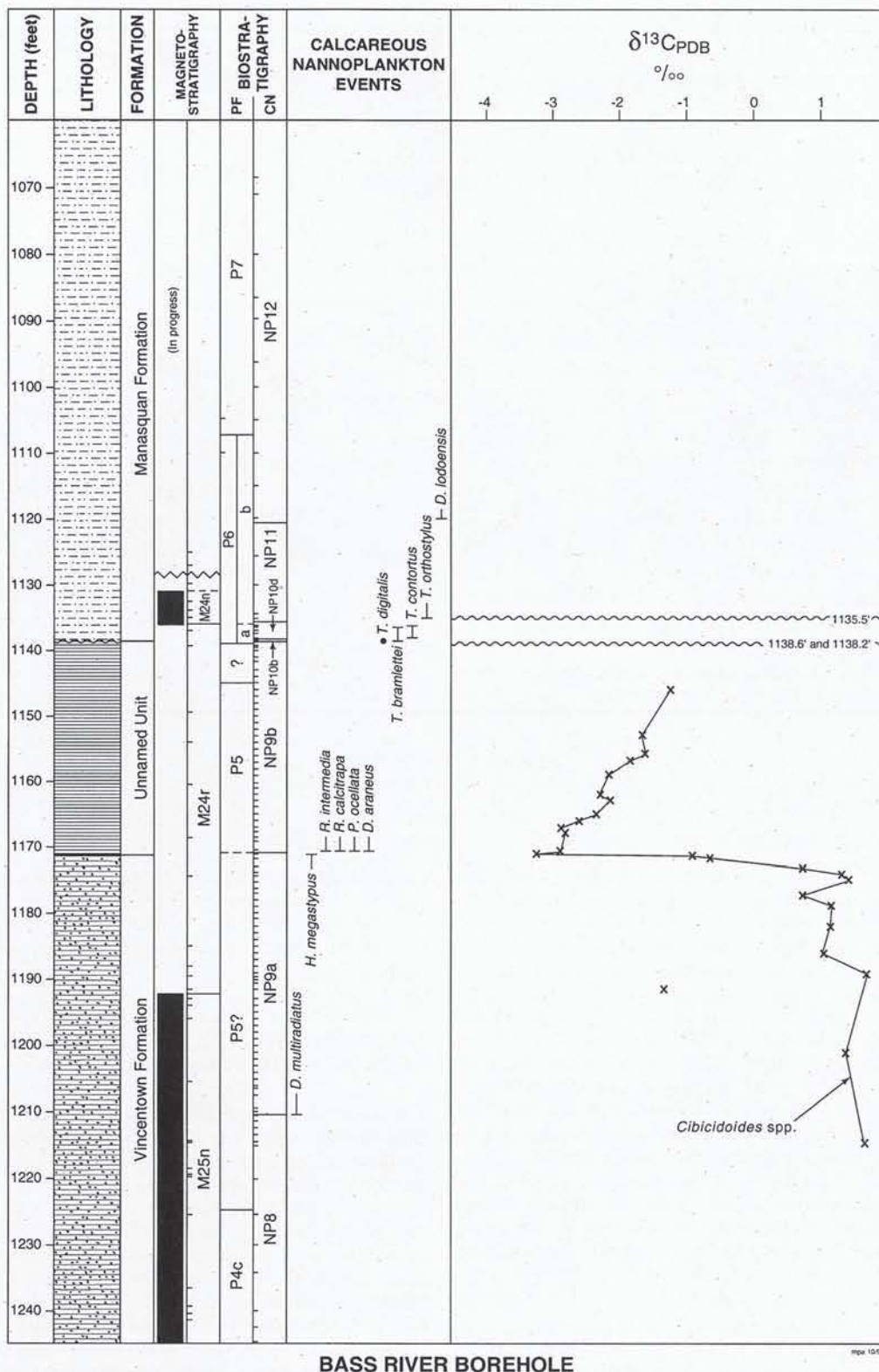
BASS RIVER BOREHOLE

Fig. 2. – The stratigraphic interval representing Chron C24r in the Bass River section : lithology, magnetostratigraphy, biostratigraphy (PF = planktonic foraminifera ; CN = calcareous nannoplankton) and isotope stratigraphy. Low isotopic resolution in the interval between 1080' and 1110' reflects the scarcity of benthic foraminifera.
Magnetostratigraphy and isotope stratigraphy : Cramer et al., [1999]; lithostratigraphy, biostratigraphy : Miller et al., [1998 and herein].
Tic marks indicate locations of samples in the cores. + indicates reworking; --- indicates irrregular occurrences.
Magnetostratigraphy : Black : normal polarity ; white : reversed polarity ; vertical lines : uninterpretable signal.
Note that unconformities associated with substantial hiatuses (> 0.6 m.y. and > 0.2 m.y., respectively) occur at 1138.6' and 1138.2'. For figure clarity they are represented as a single feature.

Fig. 2. – L'intervalle stratigraphique représentant le Chron C24r dans la coupe de Bass River. Lithologie, magnétostratigraphie, biostratigraphie (PF : foraminifères planctoniques ; CN : nannoplancton calcaire) et stratigraphie isotopique. La faible densité de mesures isotopiques dans l'intervalle entre 1080' et 1110' résulte de la rareté des foraminifères benthiques.
Magnétostratigraphie et stratigraphie isotopique : Cramer et al. [1999]; lithostratigraphie, biostratigraphie : Miller et al. [1998 et ce papier].
Les tirets (colonnes 5 à 7 à partir de la gauche) notent la position des échantillons ; + note remaniement ; --- note présence discontinue.
Magnétostratigraphie : noir : polarité normale ; blanc : polarité inverse ; lignes verticales : signal non interprétable.
Notez que les discordances associées à d'importants hiatus (> 0,6 Ma et > 0,2 Ma, respectivement) sont présentes à 1138,6' et 1138,2'. Par souci de clarté, elles sont confondues sur la figure.

the upper part of the Vincentown Formation (up to 1171' [356.92 m]; silty clay), a lithologic unit consisting of gray clay, also known from other subsurface cores, unnamed [e.g., Cramer et al., 1999] or assigned alternatively to the Vincentown [e.g., Owens et al., 1997] or the Manasquan [e.g., Gibson et al., 1993] Formation, and the lowermost part (glauconitic clays) of the Manasquan Formation. Whereas the contact between the typical Vincentown silty clays and the overlying gray clays is apparently conformable, the prominent contact between the gray clay and the Manasquan Formation, at 1138.6' (347.05 m), is erosional, and located at ~ 96 % up in the reversal.

Biozonal subdivision of Magnetozone C24r on the basis of planktonic foraminifera is tentative [Miller et al., 1998] but calcareous nannofossils afford an excellent biostratigraphic control. The deposits between 1210' (368.80 m) and the erosional contact at 1138.6' (347.04 m) belong to Zone NP9. There is a large contrast between the composition of the assemblages at 1171.1' (356.95 m) and at 1170.9' (356.89 m) where the simultaneous LOs of *Rhomboaster calcitrapa*, *Discoaster araneus*, and *D. anartios*, among others, are recorded. The NP9a/b subzonal boundary is thus drawn between these two levels. No nannolith assignable to the genus *Tribrachiatus*, which would indicate Zone NP10, was recorded below the unconformity at 1138.6' (347.04 m).

The silty clays between 1138.6' (347.04') and ~ 1135.5' (346.10 m) belong to Zone NP10. Subzone NP10b is well characterized at level 1138.4' (346.98 m) immediately above the unconformity. Subzone NP10d extends between 1138.1' (346.89 m) and 1136.2' (346.31 m). This implies a stratigraphic gap at about 1138.2' (346.92 m), with Subzone NP10c missing. The juxtaposition of the magnetic reversal at 1136' (346.25 m) and the NP10/NP11 (and possibly the P6a/P6b) zonal boundary, is indicative of an unconformity at ~ 1135.5' (346.10 m).

Island Beach borehole

In the Island Beach Borehole (IBB, 39° 48'N, 74° 05' W; elevation of 3.7 m; Miller et al. [1994]) Magnetozone C24r is not precisely delineated, but it is at least 30 m thick. This is based on the identification of the Chron C24n.3n/C24r magnetic reversal boundary at ~ 1018'8 (310.53 m) and the LO of *Discoaster multiradiatus* (correlative with mid Chron C25n; Berggren et al. [1995]) at ~ 1112' (~ 338.93 m; Miller et al. [1994]; Van Fossein [1997]) (fig. 3). The magnetozone spans the upper part of the Vincentown (outer-middle neritic clays) and lower part of the Manasquan (outer neritic silty clays) Formations separated by a distinct erosional contact at 1075'5 (327.81 m) [Miller et al., 1994; Browning et al., 1997; Liu et al., 1997a], thus approximately located at mid-point within the reversal. The gray clays intercalated between the typical Vincentown and Manasquan Formations in the BRB do not occur in the IBB.

Whereas the delineation of the planktonic foraminifera zonal/subzonal boundaries is uncertain [Liu et al., 1997b], the calcareous nannofossils provide an excellent stratigraphic control. The upper part of the Vincentown Formation (between 1220' [371.85 m] up to 1075.5' [327.81 m]) belongs to Zone NP9. Calcareous nannofossil assemblages are monotonous between 1112' (338.93 m) and 1077' (328.26 m), but a change occurs between 1077' and 1076' (327.96 m), with in particular the HO of *Discoaster megastypus* at 1077' and the LOs of *D. araneus*, *D. anartios* and *Rhomboaster calcitrapa* at 1076'. On this basis, an extremely thin sliver of sediments, delineated between

Datums	Age of events (Ma)	Bass River borehole	Island Beach borehole
Chron C24n/C24r	53.347	1135' — 1137'	1017.60' — 1020.40'
HO *T. contortus*	53.61	1136.2' — 1135.1'	1022' — 1020"
LO *T. orthostylus*	53.64	1136.2' — 1135.1'	1020' —1019'
HO *T. bramlettei*	53.89	1136.5' — 1136.2'	1020' — 1019'
LO *T. contortus*	53.93	1138.4' — 1138.1'	1022' — 1020"
HO *T. digitalis*	54.17	1138.4' — 1138.1'	1065' — 1062'
LO *T. digitalis*	54.37	1138.7' — 1138.4'	1076' — 1075'
LO *T. bramlettei*	55.00	1138.7' — 1138.4'	1076' — 1075'
LO *R. calcitrapa*	55.50	1171.1' — 1170.9'	1077' — 1076'
LO *D. araneus*	55.50	1171.1' — 1170.9'	1077' — 1076'
δ13C excursion	55.52	1173' to 1171.1'	begins at 1077'
Chron C25n	55.904	1191.6' — 1193'	not delineated
LO *D. muliradiarus*	56.	1210.6' — 1211.4'	1138' — 1112'

~ 1076.5' (328.11 m) and the unconformity at 1075.5' (327.81 m) is assigned to Subzone NP9b.

Zone NP10 is well characterized above the unconformity and up to 1020' (310.89 m). Subzones NP10b to NP10d are clearly delineated between 1075' and 1065' (327.66 and 324.61 m) and between ~ 1021' and 1020' (311.20 and 310.89 m), respectively. *Tribrachiatus digitalis* is common in all samples between 1075' (327.66 m) and 1065' (324.61 m), absent at level 1060' (323.08 m) and scarce between 1062' (323.69 m) and 1048' (319.43 m). We believe that it is reworked above 1065' (324.61 m) as a result of the erosion (during Subchron NP10c) of sediments that were deposited updip of this location. This is well supported by the high sedimentation rates (44' for 0.2 m.y.; see table I) for the NP10c subzonal interval in the IBB. Reworking of older sediments is indicated by the occurrences of upper Paleocene taxa (*Discoaster araneus*, *Fasciculithus schaubi*, *F. tympaniformis* and *Rhomboaster calcitrapa*) throughout the NP10c zonal interval. We thus believe that the sporadic occurrences of *Stensioina beccariformis* between 1073.8' (327.29 m) and 1055' (321.56 m) reported by Pak et al. [1997] and Browning et al. [1997] simply reflect the reworking of Paleocene sediments from even further updip. In this context, we point out that in the Clayton Borehole, situated much further updip than the BRB and IBB, middle Eocene deposits rest unconformably on uppermost Paleocene clays (Subzone NP9b, MPA, unpublished, contra Bybell and Self-Trail [1995] (see above)) which exhibit a good record of the LPTM, with calcareous nannofossil assemblages characteristic of Subzone NP9b (with *D. araneus* and *R. calcitrapa* in particular) and the CIE [Thomas et al., 1997].

The younger part of Chron C24r is not represented in the IBB due to an unconformity at 1019' (310.59 m), well marked by the juxtaposition of the NP10d/NP11, (approximate) P6a/P6b subzonal boundaries and the magnetic reversal boundary.

Stratigraphic correlations

The magnetobiostratigraphic interpretations described above reveal that each section offers a partial representation of Chron C24r (fig. 4). The main unconformity at 1138.6' (347.04 m) in the BRB corresponds to a stratigraphic gap
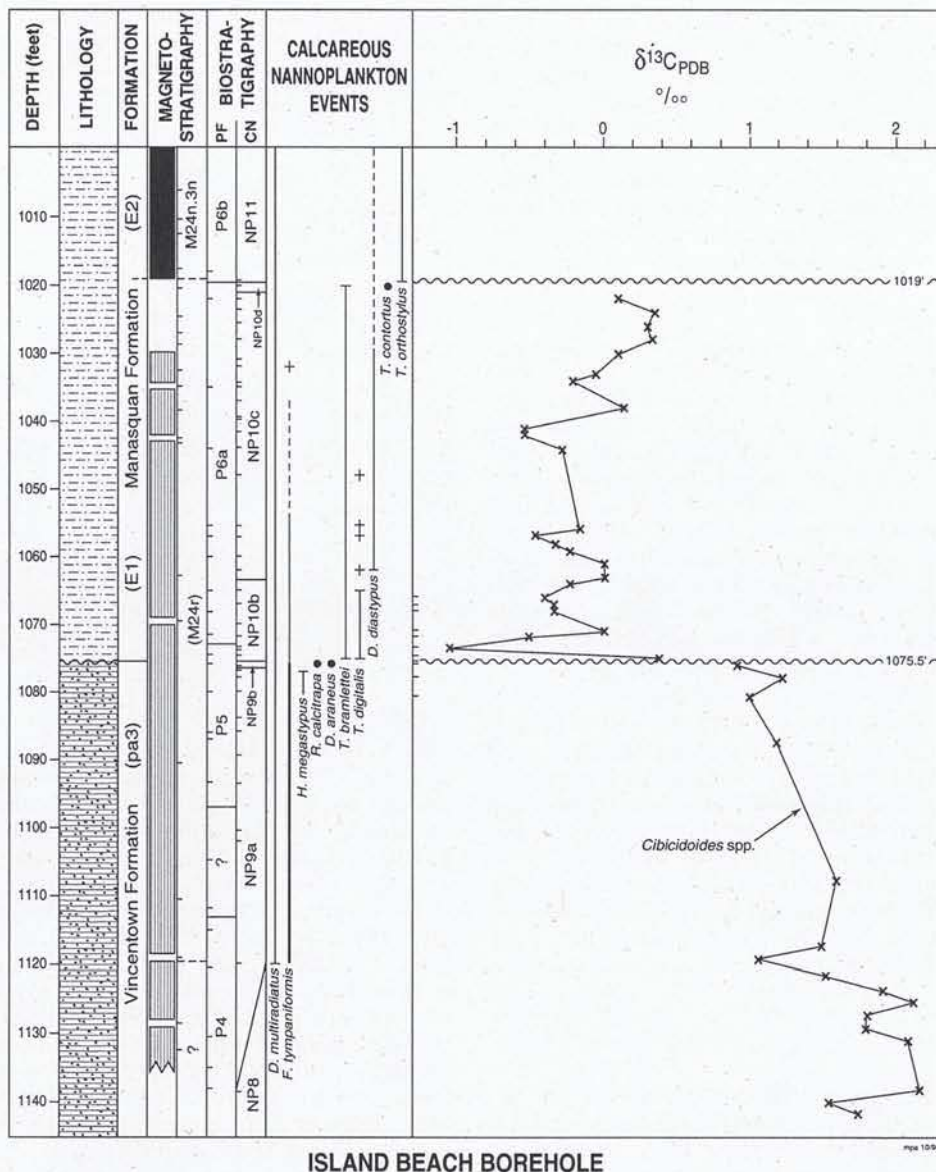
ISLAND BEACH BOREHOLE

Fɪɢ. 3. – The stratigraphic interval representing Chron C24r in the Island Beach section : lithology, magnetostratigraphy, biostratigraphy (PF = planktonic foraminifera ; CN = calcareous nannoplankton) and isotope stratigraphy.
Magnetostratigraphy [Von Fossein, 1997] ; litho- and sequence stratigraphy [Miller *et al.*, 1994 ; Browing *et al.*, 1997 ; Liu *et al.*, 1997a] ; Biostratigraphy [Liu *et al.*, 1997b and herein] ; isotope stratigraphy [Pak *et al.*, 1997].
Symbols as in figure 2.

Fɪɢ. 3. – *L'intervalle stratigraphique représentant le Chron C24r dans la coupe d'Island Beach : Lithologie, magnétostratigraphie, biostratigraphie (PF : foraminifères planctoniques ; CN : nannoplancton calcaire) et stratigraphie isotopique.*
Magnétostratigraphie [Von Fossein, 1997] ; lithostratigraphie et stratigraphie séquentielle [Miller et al.*, 1994 ; Browing* et al.*, 1997 ; Liu* et al., 1997a] ; Biostratigraphie [Liu* et al., 1997b et ce papier] ; stratigraphie isotopique [Pak* et al., 1997].*
Symboles comme pour la figure 2.

that encompasses Subzone NP10a and the upper and lower part of, respectively, Subzones NP9b and NP10b (since Subzone NP10a was not recovered). Based on the estimated ages of calcareous nannofossil FADs and LADs [Berggren *et al.*, 1995] the hiatus is at least 0.65 m.y.-long.

The stratigraphic gap at 1075.5' (327.81 m) in the IBB encompasses most of Subzone NP9b, Subzone NP10a and part of Subzone NP10b. The hiatus is at least 1.13 m.y.-long. The 1076' (327.96 m) level in the IBB correlates with the 1170.9' (356.89 m) level in the BRB (= NP9a/b zonal boundary, both with an age of ~ 55.52 Ma), based on the simultaneous LOs and HOs of several nannofossil species, but it is clear that the unnamed lithologic unit in the BRB

is missing in the IBB, except for a few centimeters of section below the unconformity at 1075.50' (327.81 m). In contrast, most of the interval that constitutes the lower part of the Manasquan Formation in the IBB is missing in the BRB. The lower surface of the sequence boundary at 1075.5' in the IBB is at least 1 m.y. older than that at 1138.6' in the BRB section, based on the chronology of Berggren *et al.* [1995]. In contrast, the upper surfaces of the sequence boundary in the two holes have approximately the same age (within Biozone NP10b, that has an estimated duration of 0.2 m.y.).

Thus the BRB and IBB sections complement each other for a more complete representation of Chron C24r, although
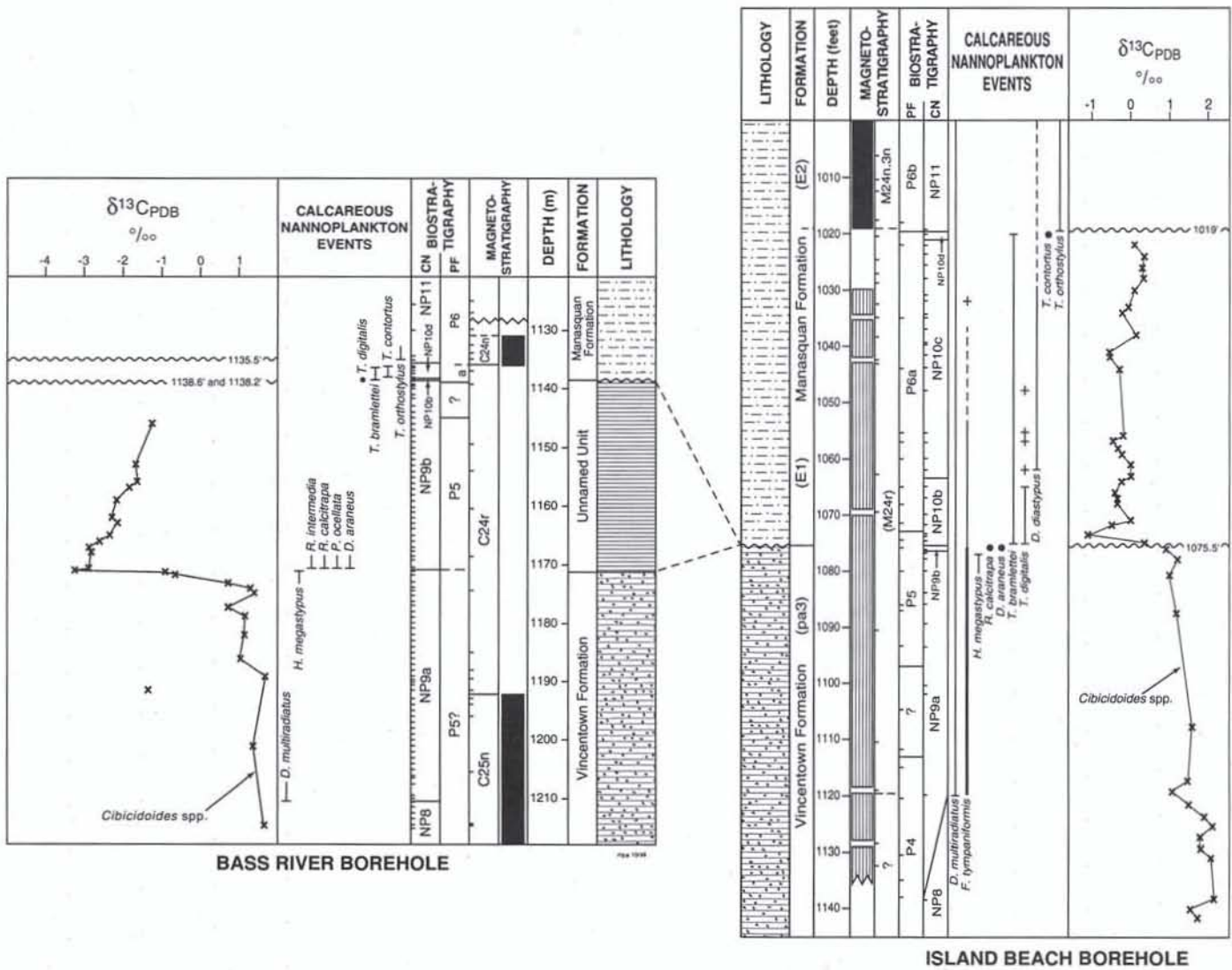
FIG. 4. – Correlation of the intervals representing Chron C24r in the BRB and IBB sections.
FIG. 4. – *Corrélation entre les intervalles représentant le chron magnétique C24r dans les coupes BRB et IBB.*

neither the younger part of Chron C24r (late Biochron NP10 to early Biochron NP11) nor the latest Biochron NP9 and earliest Biochron NP10 (Biochron NP10a) is represented in the composite record (fig. 5). As diachrony of calcareous nannofossil events between such nearby locations can be definitely excluded, we remark appropriately that the differences in biozonal representation between the two sections are solely explained by the occurrence of unconformities.

CARBON ISOTOPE STRATIGRAPHY OF THE SECTIONS

Carbon isotopic records, established from mixtures of *Cibicidoides/Cibicides* spp., have been established for both sections. They show similar trends in the BRB and IBB, and are generally comparable with upper Paleocene-lower Eocene deep-sea carbon isotopic records. Like their oceanic counterparts, the two neritic records register a negative isotope excursion but of different amplitudes. In the BRB, the

negative excursion is of 4 ‰ [Cramer et al., 1999] whereas in the IBB it is of 1.2 ‰ [Pak et al., 1997]. Equal maximum isotopic values are recorded just below the BRB and IBB excursions (1.20 ‰ at 1179' [359.35 m] in BRB; 1.22 ‰ at 1078' [328.57 m] in IBB) and the decrease in isotopic values occurs at the NP9a/b subzonal boundary in both sections. This supports our interpretation that both sections have registered the beginning of the CIE. However, only the BRB yields an essentially complete record of it, so that the amplitude of the isotopic decrease in the section is equivalent to that in Hole 690B [Kennett and Stott, 1991]. The IBB yields only the very beginning of the CIE, represented by the value of 0.91 ‰ at 1076' (327.96 m). Concatenation of two disjunct records below and above the unconformity at 1075.5' (327.81 m) has resulted in an isotopic excursion that was thought to correspond to the CIE [Pak et al., 1997] but which, in fact, is merely an insignificant pseudoevent, similar to that already identified in DSDP Hole 577 [Aubry, 1998b].

The critical element of our discussion is now to consider the chemomagnetobiostratigraphic correlations. Both the
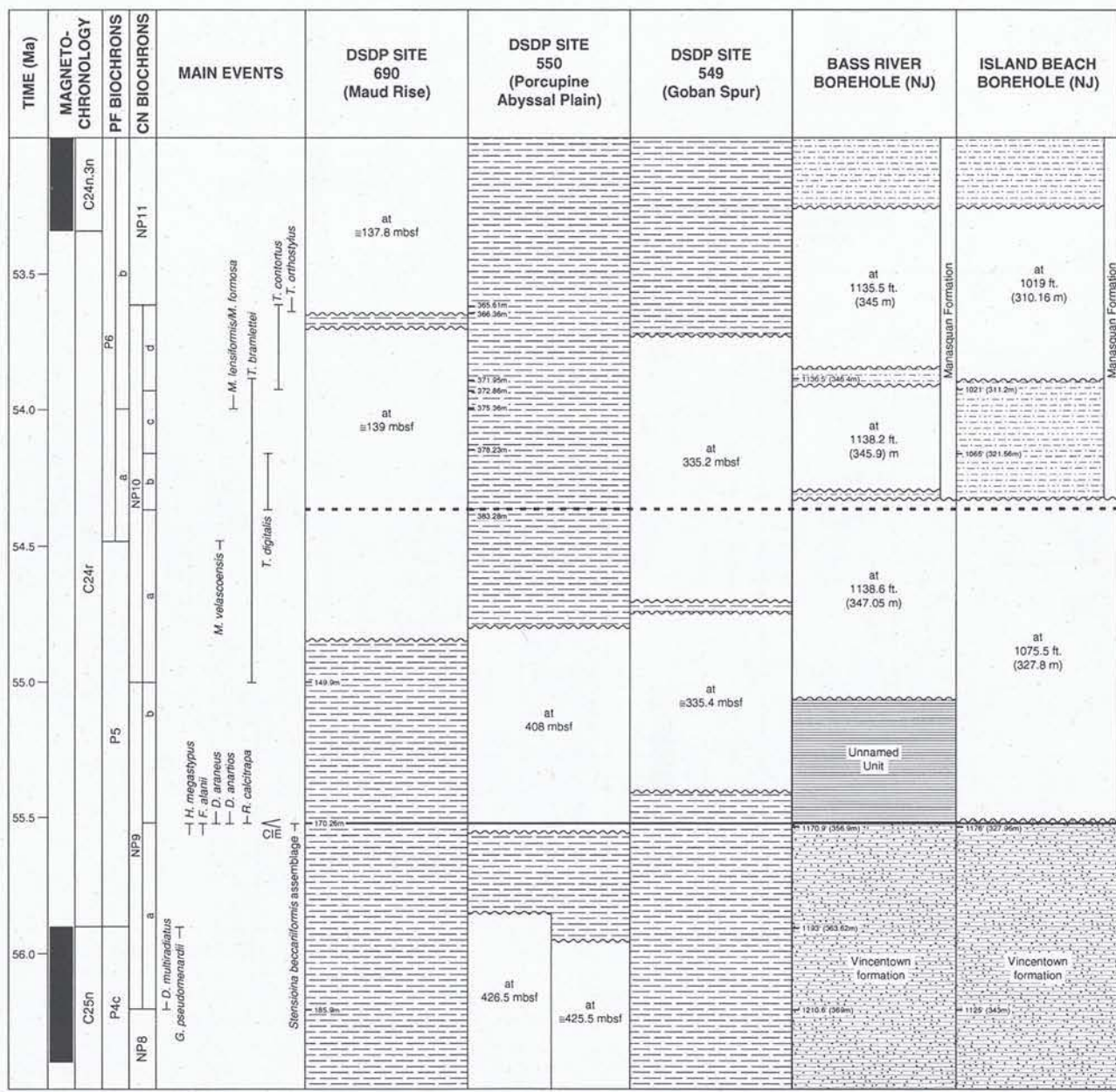
FIG. 5. – Temporal interpretation of the IBB and BRB and temporal correlation with DSDP Holes 550, 549 and ODP Hole 690B.
DSDP Hole 549 is included because its isotopic record below the unconformity at 335.4 mbsf was critical in correlating correctly the records in Holes 690B and 550. The ages of the surfaces and duration of the hiatuses for Holes 550, 549 and 690B were established in Aubry *et al.* [1996] and Aubry [1998b]. The datums used to establish the temporal interpretations of the New Jersey boreholes are given in table I.
Thick plain line = age of the CIE (and LPTM). Thick dash line = age of the Ypresian transgression as dated by base of the London Clay Formation [see Aubry, 1996]. Wavy lines = unconformities. Blank between wavy lines represent hiatuses.

FIG. 5. – *Interprétation temporelle de IBB et BRB et corrélation temporelle avec les puits DSDP 550, 549 et ODP 690B.*
Le puits DSDP 549 est inclus parce que son enregistrement isotopique au-dessous de la discordance à 335,4 mbsf apporta un élément critique permettant d'étayer la corrélation entre les puits ODP 690B et DSDP 550. Les âges des surfaces et la durée des hiatus aux puits 550, 549 et 690B furent établis dans Aubry et al. *[1996] et Aubry [1998b]. Les datums utilisés pour établir l'interprétation temporelle des puits du New Jersey sont donnés dans le tableau I.*
Ligne continue épaisse : âge de la CIE (et du commencement du LPTM). Ligne discontinue épaisse : âge de la transgression yprésienne datée par la base de la formation du London Clay [voir Aubry, 1996]. Lignes ondulées : Discordances. Les blancs entre ces lignes représentent les hiatus.

BRB and IBB excursions are located essentially at midpoint in Magnetozone C24r, but the former is located in mid Zone NP9 whereas the latter is located across an NP9/NP10 (lowermost NP9b/NP10b) zonal contact. If the BRB and IBB sections were geographically far apart, the similar location of the BRB and IBB excursions with respect to the whole extent of Magnetozone C24r could easily be seen as a demonstration that the excursion constitutes a reliable correlation level in both sections, with the consequence that the biostratigraphic events would be seen diachronous. However, on the ground of three complementary pieces of evidence, this reasoning cannot apply to our case. The two first pieces of evidence, litho- and biostratigraphic, were discussed above. The third is brought by chemostra-

tigraphy itself. If both the BRB and IBB excursions represented the CIE, it would be difficult to explain the difference in amplitude of the BRB and IBB excursions (~ 4 ‰ and 1.2 ‰, respectively), particularly in view of the large excursion in the Clayton Corehole [Thomas *et al.*, 1997]. The difference in amplitude between the BRB and IBB excursions is easily explained if only the BRB excursion represents the CIE. The BRB and IBB sections thus provide a clear demonstration that unconformities can account for the reported discrepancies regarding the variable location of the $\delta^{13}C$ excursion with regard to the magnetobiostratigraphy in different sections. They also provide a sound justification for the differences in the amplitude measured for excursions in different sections.

We can safely and firmly conclude that differences in chemomagnetobiostratigraphic correlations between sections can result *solely* from truncations in the stratigraphic record. We can also add that (1) as the Chron C24r was one of the warmest interval of the Cenozoic, and (2) as a strong warming affected the high latitudes during the LPTM [Kennett and Stott, 1991; Zachos *et al.*, 1993], it is reasonable to assume minimum diachrony of biostratigraphic events during that chron.

DISCUSSION

Our demonstration that two nearby neritic sections through Chron C24r show (somewhat unexpectedly) substantially different magnetochemobiostratigraphic records have several fundamental implications for deep sea stratigraphy and the study of latest Paleocene-earliest Eocene history. These are examined in turn below.

The composite reference section and the relative chronology for Chron C24r

The first implication of our demonstration concerns the reliability of the composite reference section of Chron C24r that Aubry *et al.* [1996] and Berggren and Aubry [1996] constructed in order to derive a chronology for the chron. Using integrated magnetochemobiostratigraphy rather than relying on magnetochemostratigraphic correlations alone, these authors constructed a reference section using the early and late records of Chron C24r as preserved in ODP Hole 690 and DSDP Hole 550, respectively. In so doing, they assumed minimum diachrony of biostratigraphic events and explained the discrepancies between chemomagnetobiostratigraphic correlations in the deep sea sections by the occurrence of multiple unconformities [see Aubry, 1998b, c].

Our two neritic records are easily correlated with deep sea records through magneto-, chemo- and calcareous nannofossil stratigraphy. They correlate well with the records of Chron C24r in DSDP and ODP Holes 550 and 690B. The upper part of the Vincentown Formation between ~ 1210' (386.80 m) and 1171' (356.92 m) in the BRB is essentially equivalent with the interval between ~ 195.94 mbsf and 170.26 mbsf in Hole 690B, and the unnamed lithologic unit between 1171' (356.92 m) and 1138.6' (347.04 m) in the borehole equivalent with the 170.26 mbsf to ~ 150 mbsf interval in the ODP hole. In turn, the lower part of the Manasquan Formation in the IBB between 1075.5' (327.81 m) and 1019' (310.59 m) is essentially correlative with the interval between 383.28 mbsf and 372 mbsf in DSDP Hole 550 [Aubry *et al.*, 1996, Table 3]. This allows us to establish temporal correlations between the four sections (fig. 5), a key to sound geological reconstructions [Aubry, 1995].

Thus we believe that the composite reference section constructed from DSDP Site 550 and ODP Site 690 [Aubry *et al.*, 1996] is corroborated by the data presented above and that future correlations between upper Paleocene-lower Eocene sections can rely on the existing relative chronology for the Chron established by Aubry *et al.* [1996] and Berggren and Aubry [1996]. The BRB provides confirmation that the CIE occurs at about the mid-point in Zone NP9 [Aubry *et al.*, 1996; Schmitz *et al.*, 1996], even though the NP9/NP10 zonal boundary was not recovered in that section. Thus, although variations in sedimentation rates are difficult to estimate with the current numerical chronology available, records in which the excursion occurs close to the NP9/NP10 zonal boundary should be considered suspect.

Isotopic excursions and the CIE

Carbon isotope stratigraphy is extensively used to correlate upper Paleocene-lower Eocene stratigraphic sections, and many a record of Chron C24r have been "tuned" using "the" carbon isotope excursion (assumed to represent the CIE) and magnetic reversals, and purposely avoiding biostratigraphic datums because of their assumed diachronous nature [e.g., Pak and Miller, 1992, Zachos *et al.*, 1993; Thomas and Shackleton, 1996; Pak *et al.*, 1997]. While it is tempting to do so, incorrect interpretation of isotopic features in sections results in the miscorrelation of stratigraphic records. $\delta^{13}C$ excursions that reflect a true disturbance of the carbon cycle are extremely powerful stratigraphic and temporal markers because of the short duration of the carbon cycling [6×10^3 yrs, Broecker, 1974], and such is the case for the CIE. However, interpreting an excursion as the CIE when in reality it constitutes a pseudoevent has several serious consequences. It results in incorrect stratigraphic and temporal resolution and correlations [see Aubry, 1998b, Fig. 3.3. and 3.4], and ultimately in incorrect paleoceanographic interpretations. For instance, interpretation of a $\delta^{13}C$ excursion in Hole 577 as corresponding to the CIE has resulted in the unwarranted comparison between high and low latitude isotopic records and unsubstantiated conclusions regarding late Paleocene-early Eocene deep sea circulation [Aubry, 1998b].

The interpretation of chemostratigraphic events and isotopic excursions in particular requires a careful evaluation of data in a manner similar to the identification of magnetozones. In other words, the identification of the CIE requires close scrutiny and support from biostratigraphic events. The frequent association of "the" $\delta^{13}C$ excursion with the HO of the *Stensioina beccariiformis* is often cited as supporting evidence that the excursion represents the CIE; yet, this is utterly insufficient because the upper range of a taxon or group of taxa can easily be truncated by unconformities. For instance the HO of the *S. beccariiformis* in DSDP Hole 577 does not correspond to the BFE [Aubry, 1998b]. Multiple criteria are necessary to firmly identify isotopic events. Specifically, to be unequivocally identified, an excursion must be bracketed by non iterative events and the amplitude of the excursion must probably not be significantly different at different locations.

We propose that identification of the CIE should rely on major evolutionary planktonic events. Kelly *et al.* [1996] have shown that the CIE is associated with a rapid diversification among planktonic foraminifera, in particular with the occurrence of *Acarinina africana*, *A. sibaiyaensis* and *Morozovella allisonensis*. This may serve to predict the location of the CIE in deep sea sections but also in neritic settings. The three taxa cited above occur in the BRB section [Miller *et al.*, 1998; Cramer *et al.*, 1999] two of them

extending up to the NP9/NP10 biozonal contact (they were not found in the IBB section, confirming, if necessary, the different stratigraphies in the two holes, and *contra* Pak *et al.* [1997]. More readily, the LO of some calcareous nannoplankton species, including *Discoaster araneus, D. anartios, Rhomboaster calcitrapa* and *R. spineus,* may be used to identify the CIE at least in neritic and some deep sea sections where these species appear suddenly at the level of the excursion and dominate the assemblages over a thin stratigraphic interval representing possibly a few (? 0.2 m.y.) hundred thousand years. This has been observed in the Atlantic (e.g., BRB), Indian (e.g., DSDP Site 213 ; MPA and D. Norris, unpublished data) and Tethyan (e.g., Alamedilla section ; Aubry *et al.,* submitted) oceans. We regard these taxa as the calcareous nannoplankton counterpart of the excursion planktonic foraminifera, that also evolved in response to the event reflected by the CIE. What differentiates them is their poor symmetry, which contrasts strongly with the symmetry that all other coccoliths/nannoliths exhibit. At no other time in the Cenozoic history of calcareous nannoplankton were poorly symmetrical coccoliths massively secreted.

Confirmation that the correlation established by Aubry *et al.* [1996] between the sections representing Chron C24r in Holes 550 and 690 are essentially correct revives the question regarding the occurrence of multiple $\delta^{13}C$ excursions or rapid shifts in lower Biozone NP10. Aubry *et al.* [1996] and Stott *et al.* [1996] suggested that at least one other $\delta^{13}C$ excursion may exist but this has not yet been proved. This situation may reflect the fact that the interval of interest has not been recovered from deep sea sections, and we agree with Thomas *et al.* [1999] that only integrated high resolution isotopic and biostratigraphic studies will help to determine whether the LPTM was unique or one of several short-term events.

Deep sea unconformities

Perhaps the most important implication of our demonstration on a general level is the fact that unconformities should be recognized as integral components of the stratigraphic record, and this is true for the deep sea basins as well as for the continental shelves [Aubry, 1986]. While the discontinuous nature of stratigraphic sections deposited on epicontinental margins is well recognized, the view that deep sea sections are continuous remains prevalent. This study supports the documentation that upper Paleocene-lower Eocene deep sea records are discontinuous at many locations [Aubry *et al.,* 1996, 1998b, c, and unpublished]. As Chron C24r was a time of global warmth, latitudinal diachrony must be minimal in the upper Paleocene and lower Eocene stratigraphic record, and we can be confident that most chemomagnetobiostratigraphic discrepancies between sections most likely reflect truncation by unconformities. We emphasize that the hiatuses that have been described in Chron C24r are not of negligable duration. Many are 1 m.y. long or longer. This duration is greater than the life span in Chron C24r of some of the marker species [e.g., *T. digitalis* : ~ 0.2 m.y. ; *T. contortus* : ~ 0.32 m.y., Berggren *et al.,* 1995]. There may be shorter hiatuses as well (< 50 × 10³ yrs), but the current means available to assess the completeness of stratigraphic sections do not permit their confident identification.

Considering our current understanding of the Earth System, it is difficult to conceive of the widespread occurrence of deep sea unconformities, but their progressive documentation is the first step towards resolving their enigmatic origin. Other widespread Paleogene deep sea unconformities have also been described, in particular around the lower/middle Eocene boundary. Recognizing the incompleteness of the deep sea record will have a double benefit, (1) to permit the correct temporal correlations between sections and thus the correct timing of the major events that have punctuated Earth history, and (2) to determine the architecture of the stratigraphic record in particular concerning the relationships between marginal and deep sea deposits, in order to identify the basic forcing mechanism(s) that shaped it.

The origin of the multiple upper Paleocene-lower Eocene unconformities that seem to occur both in deep sea and marginal settings remains unclear, and it would be premature to consider them related in any fashion to the LPTM, mainly because multiple unconformities occur at other times as well (e.g., around the lower/middle Eocene boundary). Nevertheless, it is clear that ignoring them can only blur the historical message embedded in the stratigraphic record and eventually delay a sound understanding of what really happened 55.5 to 54.5 million years ago.

CONCLUSIONS

This study of two neritic records of Chron C24r which offer an excellent magneto-, bio- and chemostratigraphic record has demonstrated that the current relative chronology of marine events in Chron C24r is sound, and that unconformities rather than diachrony is responsible for the inconsistent chemomagnetobiostratigraphic correlations that have been made between geographically distant sections. However, we caution that, for reasons that have been discussed elsewhere [Berggren and Aubry, 1998 ; Aubry, 1998b], the numerical chronology is as yet unverified, and is likely to be revised. The New Jersey sections do not shed new light on the location of the NP9/NP10 biochronal boundary in Chron C24r, a boundary that has been used as a tie-point in the calibration of the current GPTS [Cande and Kent, 1992, 1995]. This will require a section which offers a complete stratigraphic representation of Chron C24r, a situation unlikely to be found in a marginal setting.

We also call attention to the widespread occurrence of unconformities around the NP9/NP10 zonal boundary, and to the need to take them into account when interpreting and comparing isotopic records from different areas. As with any other data, isotopic signatures, in particular excursions, cannot be taken at face value ; rather their significance must be determined based on biostratigraphic control. Such control demonstrates that many excursions identified in deep sea sections are pseudoevents unrelated to the CIE. Paleoceanographic interpretations would gain from the recognition of the incompleteness of the deep sea stratigraphic record, and more accurate temporal interpretations and correlations would be derived from the identification of unconformities before records are fine-tuned for comparison.

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