

# **LATE EOCENE-OLIGOCENE DINOFLAGELLATE PROVINCIALISM IN THE NORTH ATLANTIC OCEAN**

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## **ABSTRACT**

Diverse Eocene-Oligocene dinoflagellate assemblages occur in about four hundred and forty samples from twenty-three North Atlantic Deep Sea Drilling Project (DSDP) sites. The most complete sections are in the Priabonian, Rupelian and Chattian intervals, represented by samples from eleven coreholes on which the present study is based. Localities were grouped into five geographic regions: southwest North Atlantic (DSDP 540, 612; Alabama core); Newfoundland Basin (DSDP 112); Norwegian-Greenland Basin (DSDP 338, 345); Rockall Plateau-Porcupine Trough (DSDP 116, 117, 406, 549A); and offshore northwest Africa (DSDP 369A, 547A).

Using this spatial and temporal framework, we have related species occurrences to paleoclimatic and paleoceanographic models for the Paleogene. The distribution of species occurring in the Priabonian appears to be influenced by both paleocurrents and paleolatitude. The existence of the proto-North Atlantic Current is supported by the relatively high percentage of species (20 %) which occur in all regions except the Newfoundland Basin, which was located north of the presumed path of the current. Priabonian species diversity decreases from low to high latitudes. The Rupelian has the highest percentage of species (64 % of the total assemblage) restricted to low latitudes. Middle- and high-latitude assemblages are notably less diverse, indicating a southward migration of taxa during this time; this is interpreted as a response to the cooling event which took place across the Eocene-Oligocene boundary. In the Chattian, there is an increase in the number of cosmopolitan taxa, and the lowest species diversity occurs in the middle latitudes.

## INTRODUCTION

Dinoflagellates are protists which today inhabit a wide range of aqueous environments but are dominantly marine, planktonic, unicellular organisms. A typical dinoflagellate life cycle includes both a thecate (motile) stage and an encysted ('resting') stage, but only about 10 % of the 2,000 known living species produce preservable cysts (Dale, 1992).

Dinoflagellates are extremely useful for detailed biostratigraphic control, especially in those sediments derived from shelf and slope environments (e.g. Williams and Bujak, 1985; Haq *et al.*, 1987; Powell, 1992; Williams *et al.*, 1993). Despite considerable progress in the interpretation of dinoflagellate paleoecology (e.g. Wrenn and Kokinos, 1986; Jarvis *et al.*, 1988; Edwards and Andrie, 1992; Brinkhuis and Biffi, 1993), there have been relatively few studies published concerning regional or oceanwide assemblages and species distribution patterns as related to paleoclimate, paleoprovincialism and paleoceanography (e.g. Norris, 1975; Davies and Norris, 1980; Lentin and Williams, 1980; Williams *et al.*, 1990; Mudie *et al.*, 1990; Mudie, 1992). There are several comprehensive studies, however, which indicate that modern dinoflagellate cysts in the North Atlantic show both onshore-offshore and latitudinal trends in assemblage composition (e.g. Wall *et al.*, 1977; Harland, 1983).

The present study is based on over four hundred samples from eleven Deep Sea Drilling Project (DSDP, now Ocean Drilling Program, ODP) holes, and one onshore site, a corehole in Baldwin County, Alabama, U.S.A. (Figures 1 and 2). We have focused on the Late

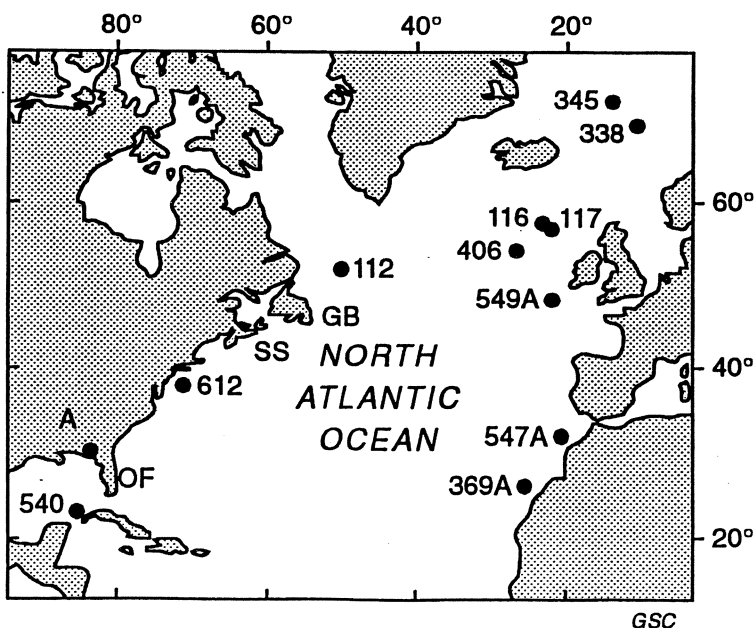


Figure 1. Index map of the North Atlantic Ocean, showing location of DSDP cores (numbered), Baldwin County, Alabama core (A) and other localities referred to in text (base map after Harland, 1983). GB = Grand Banks, SS = Scotian Shelf, OF = offshore Florida (see section on dinoflagellate provincialism; from Williams *et al.*, 1990).

35				30				Ma	DSDP Sites
EOCENE				OLIGOCENE				Epoch	
PRIABONIAN				RUPELIAN		CHATTIAN		NP Zones	
19	19	20	21	22	23	24	25		
●	●	●	●	●	●	●	●	A	Alabama
●	●	●	●	●	●	●	●	540	Offshore West Florida
	●	●	●					612	New Jersey Slope
	●	●		●		●		112	Newfoundland Basin
						●		338	Norwegian-Greenland Basin
●				●		●		345	
	●	●	●				●	116	Rockall Plateau
						●	●	117	
●	●					●	●	406	Porcupine Trough
	●	●	●	●		●	●	547A/547A/359A	
●	●	●	●	●				547A/547A/359A	Offshore Northwest Africa
	●	●	●	●		●	●		

Figure 2. Priabonian, Rupelian and Chattian sample coverage for DSDP cores, North Atlantic Ocean, included in this study. The Alabama locality (A) is an onshore core from Baldwin County, Alabama, U.S.A. The Alabama locality and those from offshore west Florida and the New Jersey slope are collectively referred to in text as 'southwestern North Atlantic'. Time scale after Haq *et al.* (1987).

Paleogene because of: (1) the widespread geographic distribution of productive samples; (2) the relatively high species diversity; (3) the interest in the nature of the Eocene-Oligocene transition— the so-called 'Terminal Eocene Event' (Wolfe, 1978; Pomeroy and Premoli-Silva, 1986; Berggren and Prothero, 1992; Miller, 1992).

Our analysis has been carried out within the framework of three time slices: Priabonian (NP 18–20; 39.4–36.0 Ma), Rupelian (NP 21–23; 36.0–30.0 Ma) and Chattian (NP 24–25; 30.0–25.2 Ma), where stratigraphic and geographic coverage is most complete in our data set. Stratigraphic control, as presented in Damassa *et al.* (1990), was based on the nannofossil zonation of Martini (1971). At the beginning of this study, age assignments were obtained directly from the **Initial Reports** of each DSDP leg. Later modification of some age assignments was based on Williams *et al.* (1993). Our objectives are: to evaluate the temporal and spatial distribution of Late Eocene-Oligocene dinoflagellates in the North Atlantic; to delineate latitudinal and regional differentiation of assemblages, i.e. to characterize dinoflagellate provinces; to place our results into the context of the paleoceanographic history of the North Atlantic Ocean.

## DINOFLAGELLATE PROVINCIALISM

Recognition of paleoprovincialism in North Atlantic Tertiary dinoflagellate assemblages by Williams *et al.* (1990) was based on qualitative regional differences. The authors noted that the Paleogene dinoflagellates of the Scotian Shelf were in many ways more comparable to coeval assemblages from offshore Florida [Joint Oceanographic Institutions Deep Earth Sampling (JOIDES) coreholes 1-2, 5] than to those of the nearby Grand Banks; the latter comparing more closely with those of southern England. Regional differences evident in the Eocene became more pronounced in the late Oligocene, with certain, apparently warmer-water, species disappearing from the Grand Banks. Coeval assemblages from the Labrador Shelf were similar to those of the North Sea, but differed from coeval Grand Banks and Scotian Shelf assemblages. These differences were attributed to provincialism.

Head and Norris (1989) suggested that the mixed warmer and colder water dinoflagellate assemblages in Eocene-Oligocene strata at Ocean Drilling Program (ODP) Hole 647A, the Labrador Sea, reflected an active proto-Gulf Stream beginning in the middle Eocene. This interpretation was based on the presence of species such as *Histiocysta* sp. and *Elytrocysta* sp. (of Goodman and Ford, 1983), known elsewhere only from the southwestern Atlantic, eastern United States, Norwegian-Greenland Sea, Belgium and Australasia. Head and Norris (1989) inferred northward transport of these species via the proto-Gulf Stream. A cooling trend in the Late Eocene-Oligocene was indicated by the influx of colder water taxa (including protoperidiniaceans), and the absence of such warmer water species such as *Tuberculodinium vancampoe* (Rossignol, 1962) Wall 1967 and *Polysphaeridium zoharyi* (Rossignol, 1962) Bujak *et al.*, 1980 (Wall *et al.*, 1977). The late Eocene-Oligocene changes at ODP Hole 647A suggest increased availability of nutrients in an area of upwelling (Head and Norris, 1989), which may have resulted from an influx of colder water, the proto-Labrador Current, from the Arctic.

## METHODS AND RESULTS

To compare assemblages in the North Atlantic, we grouped our localities into the following geographic regions (Fig. 3): (1) southwestern North Atlantic – including the Alabama (Baldwin County) core, offshore western Florida (DSDP 540), and the New Jersey Slope (DSDP 612); (2) Newfoundland Basin (DSDP 112); (3) Norwegian-Greenland Basin (DSDP 338, 345); (4) Rockall Plateau and Porcupine Trough (DSDP 116, 117, 406, 549A); (5) offshore northwest Africa (DSDP 369A, 547A).

Geographic and latitudinal provinces were defined (Figs. 3 and 4) on the basis of species occurrences within these regions. A species restricted to the southwestern North Atlantic and/or offshore northwest Africa would be defined as belonging to the low-latitude province. Mid-latitude species are those present in the Newfoundland Basin and/or Rockall Plateau-Porcupine Trough, which are considered to have been in the middle latitudes during the late Paleogene. High latitude species are those restricted to the Norwegian-Greenland Basin. We also recognized western and eastern North Atlantic assemblages: the former included species restricted to the southwestern Atlantic and/or Newfoundland Basin; the latter included species restricted to the Norwegian-Greenland Basin, Rockall Plateau-Porcupine



















<div>PROVINCES</div> <div>GEOGRAPHIC REGIONS</div>	LOW LATITUDE	MID. LATITUDE	HIGH LATITUDE	W.N. ATLANTIC	E.N. ATLANTIC	NORTH ATLANTIC CURRENT	COSMOPOLITAN
S.W. NORTH ATLANTIC A, 540, 612							
NEWFOUNDLAND BASIN 112							
NORWEGIAN- GREENLAND BASIN 338, 345							
ROCKALL PLATEAU- PORCUPINE TROUGH 116, 117, 406, 549A							
N.W. AFRICA 369A, 547A							

Figure 3. Geographic regions for North Atlantic DSDP localities and dinoflagellate provinces, as characterized by species distribution patterns here represented as bars (e.g. low latitude species = those species occurring in localities in the southwestern North Atlantic and/or offshore northwest Africa = low latitude province); refer to text for definition of additional provinces in terms of species occurrences. DSDP cores included in each geographic region are listed above.

Trough, and/or northwest Africa. An additional category was recognized for those species whose distributions are along the inferred path of the proto-North Atlantic-Portugal Currents; that is, everywhere except in the Newfoundland Basin. Although we realize that all the cores included in this study (except DSDP 112, from the Newfoundland Basin) are located within the regions most likely to have been affected by the proto-North Atlantic Current, these cores were the only productive sections for Late Eocene-Oligocene dinoflagellates in the sites sampled (Damassa *et al.*, 1990). A 'cosmopolitan' species is here defined as one that occurs in at least one locality from each of the five defined regions. Several species in each time interval could not be assigned to a geographic or latitudinal province, because their distribution patterns did not fit into any of the categories defined above. These are included in Table 1 as 'non-diagnostic' species, and are elsewhere ignored.

We have determined species diversities for each time interval studied, and for each latitudinal and regional province, and have related these to climatic change in the Late Paleogene. Previous studies of dinoflagellate species diversity have related these patterns to the evolutionary history of the group (Tappan and Loeblich Jr., 1971; 1973; Bujak and Williams, 1979). More recently, MacRae *et al.* (1993) have generated plots of total species diversity for all Mesozoic and Cenozoic dinoflagellate records. Their curve shows diversity peaks in the Late Cretaceous (Maastrichtian) and Early Eocene (Ypresian).

There has been only minimal use of species diversity data to delineate regional or latitudinal differences in the living dinoflagellate flora. Harland's (1983) results indicated that

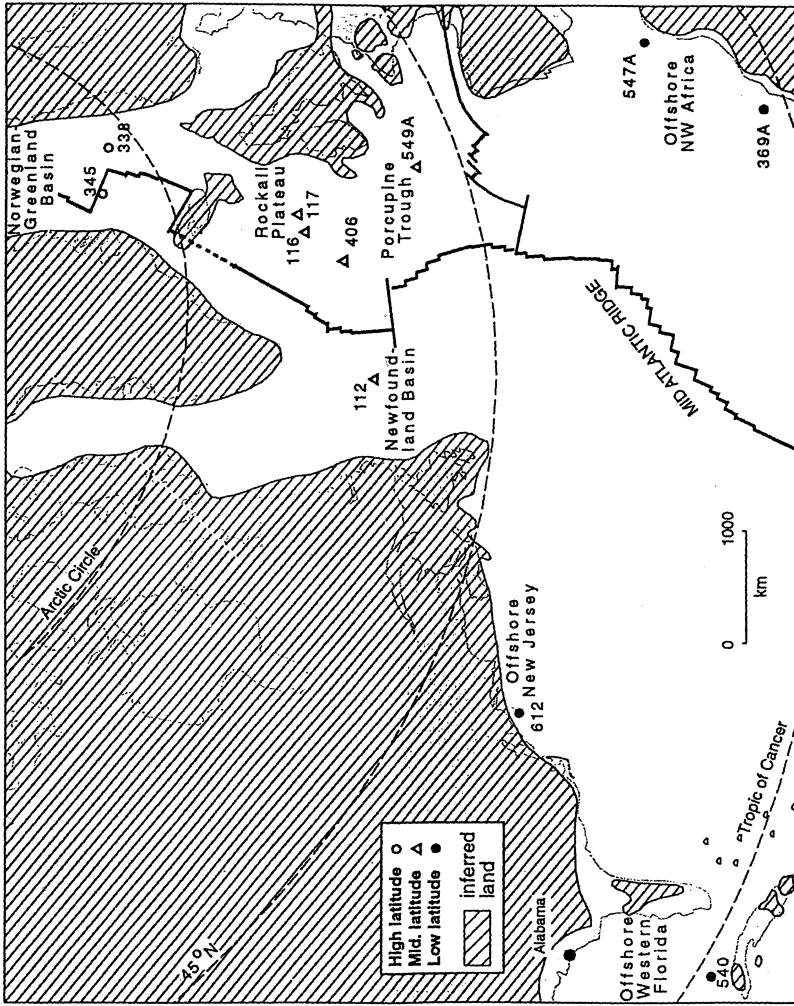


Figure 4. Latitudinal classification of DSDP localities (and Alabama core) in the North Atlantic Ocean for Priabonian-Chattian dinoflagellate assemblages. Geographic regions as for Figures 2 and 3. Paleogeographic reconstruction after Tucholke and McCoy (1986, pl. 10, fig. J).

<div> <div>AGE</div> <div>PROVINCE</div> </div>	NORTH ATLANTIC - DSDP					
	PRIABONIAN		RUPELIAN		CHATTIAN	
	# spp. = 104	% total spp.	# spp. = 103	% total spp.	# spp. = 98	% total spp.
LOW LATITUDE	25	24.0	66	64.0	21	21.4
MID. LATITUDE	18	17.3	8	7.7	9	9.1
HIGH LATITUDE	8	7.6	5	4.8	18	18.3
W. N. ATLANTIC	18	17.3	19	18.4	11	11.2
E. N. ATLANTIC	25	24.0	33	32.0	20	20.4
NORTH ATLANTIC CURRENT	20	19.2	3	2.9	7	7.1
COSMOPOLITAN	27	25.9	6	5.8	31	31.6
NON-DIAGNOSTIC	34	32.6	16	15.5	12	12.2

Table 1. Dinoflagellate provinces for the Priabonian-Chattian interval, North Atlantic DSDP and Alabama cores, showing species diversity and relative percentage for each stage and province. In the 'non-diagnostic' category are included those species whose geographic distribution does not permit assignment to any of the provinces, as defined in the text. Note that column totals do not add to 100 %, due to species occurrences in more than one province.

dinoflagellate cyst diversity was greatest for the temperate regions of the North Atlantic Ocean. In contrast, Dodge and Harland (1991) stated that there was a greater cyst diversity in higher latitudes, as well as an increase in diversity from the oceanic to neritic environments.

#### PRIABONIAN (NP 18–20, 39.4–36.0 Ma)

**Provincialism.** In the Priabonian, twenty-five species (24 %) are restricted to low latitudes; eighteen (17.3 %) to middle latitudes; but only eight (7.6 %) to high latitudes (Fig. 5A). Thus, slightly more than 50 % of the species in this interval show a broad latitudinal distribution. This, plus the comparatively high percentage of cosmopolitan species (25.9 %), correlates well with models which indicate a more equable climatic regime in the Priabonian than exists at the present day. The relatively high number of species (20, or 19.2 %) which occur in all regions except the Newfoundland Basin, defined here as the North Atlantic Current Province (Fig. 3), suggests that assemblage composition and species distribution were in part influenced by the proto-North Atlantic Current.

Priabonian assemblages also exhibit some differences between the western and eastern North Atlantic (Fig. 5B). Twenty-five species (24 %) occur only in the eastern ocean, whereas eighteen (17.3 %) are restricted to the western North Atlantic; these differences are considerably less than those for the Oligocene.

Figure 5A

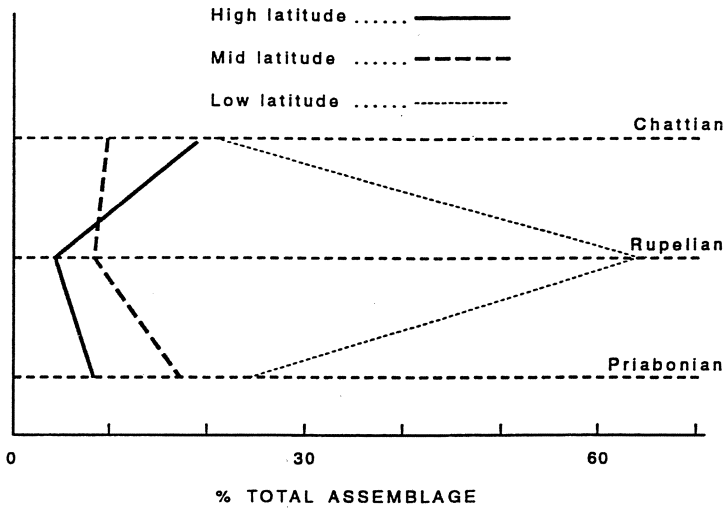


Figure 5B

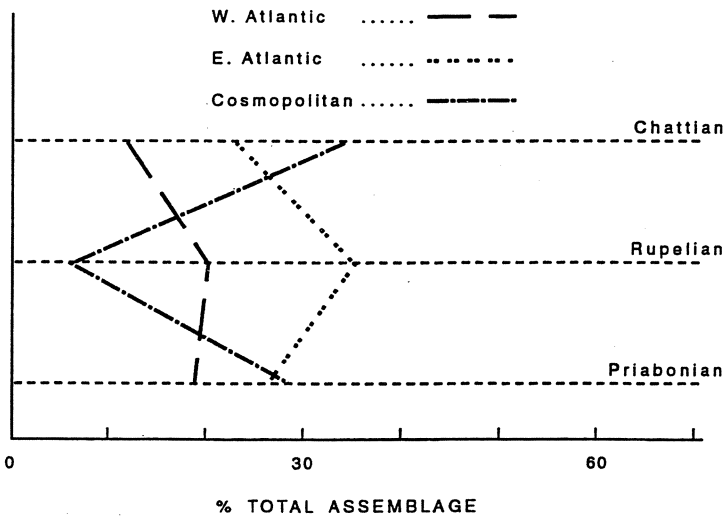


Figure 5. Summaries of species diversity data for Priabonian-Chatian dinoflagellate provinces (see Table 1). **5A** – Priabonian-Chatian dinoflagellate assemblages: latitudinal variations in species diversity (as percentage of total assemblage) in the North Atlantic Ocean, based on DSDP and Alabama cores. Figures plotted are for species restricted in distribution to each latitudinal province. **5B** – Priabonian-Chatian dinoflagellate assemblages: regional variations in species diversity, based on DSDP and Alabama cores, for western North Atlantic, eastern North Atlantic, 'Cosmopolitan' and North Atlantic Current. Figures plotted are for species restricted in distribution to each province, as defined in text.



**Species diversity.** The total cyst species diversity recorded in Priabonian samples is 104 (Table 1). Species diversity varies from a low of 11 at DSDP 540, offshore west Florida, to a high of 60 at DSDP 612, on the New Jersey slope (Fig. 6); however, diversities are generally high throughout the North Atlantic for all of the included localities.

#### **RUPELIAN (NP 21–23, 36.0–30.0 Ma.)**

**Provincialism.** In the Rupelian, the number of species restricted to lower latitudes reaches a maximum of 66 (or 64 % of the total assemblage), and is far greater than that for the Priabonian (Fig. 5A). This increase is accompanied by a decrease in the number and percentage of species restricted to middle and high latitudes: 8 (7.7 %) and 5 (4.8 %), respectively. These changes suggest more pronounced latitudinal temperature gradients in the Rupelian and agree with temperature models for the late Paleogene (Berggren and Prothero, 1992) which indicate a decrease in temperature in the Rupelian.

In the Rupelian, the differences in assemblages between the eastern and western North Atlantic are more marked than in the Priabonian (Fig. 5B). Thirty-three species (32 %) occur only in the eastern Atlantic, whereas only nineteen species (18.4 %) are restricted to the western Atlantic. The number of species whose distribution pattern would suggest influence of the North Atlantic Current is too small (2.9 %) to be of significance.

**Species diversity.** Total species diversity (103) in the Rupelian remains high (Table 1), being almost identical to that for the Priabonian. This disagrees with MacRae *et al.* (1993), who recorded a dramatic decline from 700 species in the Priabonian to 620 species in the Rupelian, a decrease of more than 10 %. Species diversities for the North Atlantic DSDP assemblages in the Rupelian vary from a minimum of 5 at Hole 549A, Porcupine Trough, to a maximum of 49 at 369A, offshore northwest Africa (Fig. 7).

#### **CHATTIAN (NP 24–25, 30.0–25.2 Ma)**

**Provincialism.** The number of cosmopolitan species (31, or 31.6 %) is somewhat higher than for the Priabonian and much higher than for the Rupelian (Fig. 5B). Variations in the composition of low, middle and high latitude assemblages are less extreme than in the Rupelian and compare more favorably with the Priabonian. Twenty-one species (21.4 %) are restricted to low latitudes; nine species (9.1 %) to middle latitudes, and eighteen (18.3 %) to high latitudes. This suggests an ameliorating climate from Rupelian to Chattian time.

Differences in species diversity between the western and eastern Atlantic are less than in the Rupelian, but slightly greater than in the Priabonian. Twenty species (20.4 %) are found only in the eastern Atlantic, whereas eleven (11 %) occur only in the western Atlantic. As for the Rupelian, species whose distributions are thought to have been influenced by the North Atlantic Current are low in number, comprising only 7.1 % of the total assemblage.

**Species diversity.** The total cyst species diversity for the Chattian is 98 (Table 1). The decrease relative to the Rupelian is much smaller than that observed by MacRae *et al.* (1993), who noted a significant drop in diversity from the Rupelian to the Chattian. Our results, showing only a slight decline from the Priabonian through the Rupelian to the Chattian, suggest that our Rupelian and Chattian values are either abnormally high (as compared to the Priabonian), or that the Priabonian value is too low. An alternative possibility is that the total

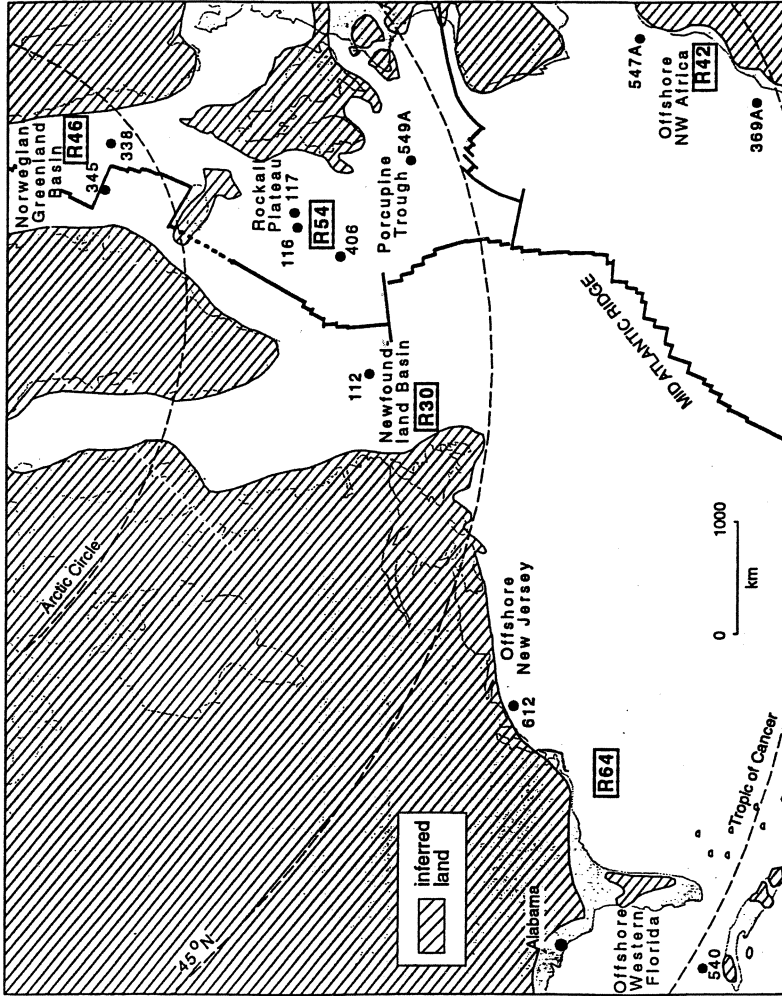


Figure 6. Regional species diversity values for Priabonian samples, North Atlantic DSDP localities and Alabama core. Numbers preceded by 'R' = regional diversities. Geographic regions as for Figure 3 and defined in text. Paleogeographic reconstruction as for Figure 4.

Priabonian species diversities for individual localities are as follows: DSDP 540 = 11; Alabama = 29; DSDP 612 = 60; DSDP 112 = 23; DSDP 345 = 41; DSDP 116/406 = 36; DSDP 549A = 20; DSDP 369A = 37; DSDP 547A = 32.

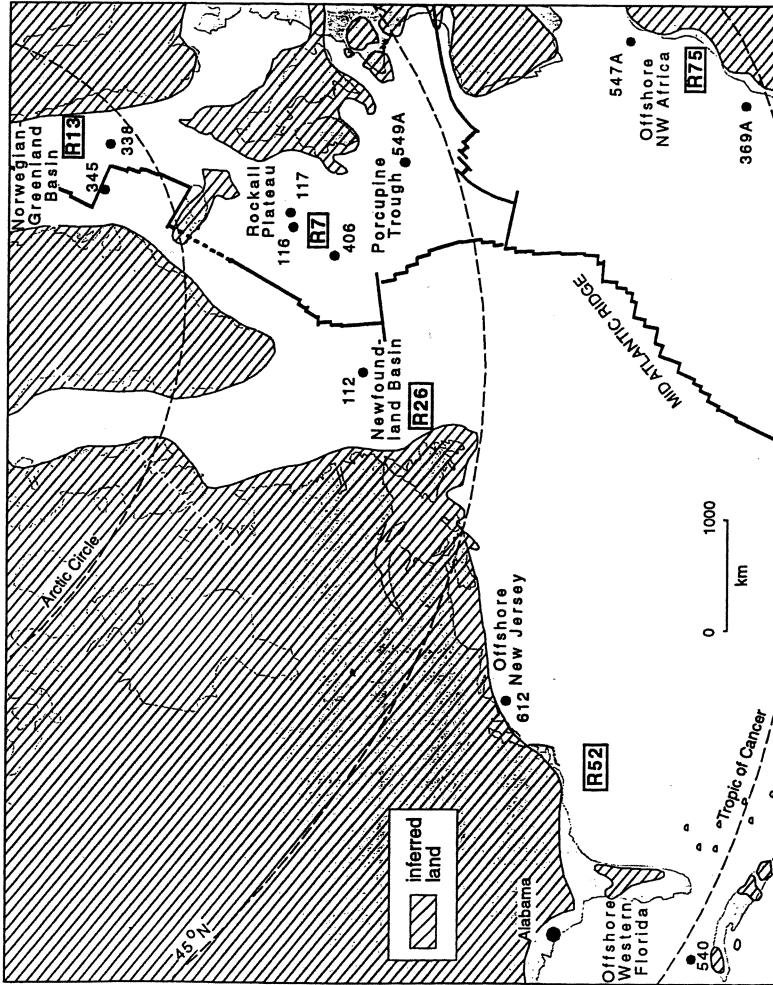


Figure 7. Regional species diversity values for Rupelian samples, North Atlantic DSDP localities and Alabama core. Numbers preceded by 'R' = regional diversities. Geographic regions as for Figure 3 and defined in text. Paleogeographic reconstruction as for Figure 4.

Rupelian species diversities for individual localities are as follows: DSDP 540 = 20; Alabama = 20; DSDP 612 = 31; DSDP 112 = 26; DSDP 338/345 = 13; DSDP 547A = 28; DSDP 549A = 5; DSDP 369A = 41.

number of species described from the Oligocene is far too low, and that the decline seen by MacRae *et al.* (1993) reflects our inadequate knowledge of Rupelian and Chattian assemblages. Regional species diversity for the Chattian varies from a low of 20 in Alabama to a high of 58 in the Norwegian-Greenland Basin (Fig. 8).

## DISCUSSION AND CONCLUSIONS

Dinoflagellates assemblages show major fluctuations in species diversity and distribution patterns in upper Eocene-Oligocene sediments recovered from DSDP coreholes in the North Atlantic Ocean. Analysis of these fluctuations permits recognition of regional variations and distinct latitudinal provinces (Figs. 9 and 10). The classification of late Paleogene dinoflagellate cysts by latitudinal province is similar to that of dinoflagellate cysts in the present day North Atlantic, as demonstrated by Wall *et al.* (1977) and Harland (1983). In this study we have examined Priabonian-Chattian dinoflagellates from North Atlantic DSDP cores with respect to provincialism, species diversity, and individual species distributions.

In the Priabonian, about 25 % of the cyst species are cosmopolitan, about 8 % are restricted to higher latitudes and about 24 % are restricted to low latitudes (Fig. 5A). Species diversity is generally high at all localities. Rupelian assemblages show significant latitudinal differentiation, with only 6 % cosmopolitan species and only about 5 % restricted to high latitudes, but with a dramatic increase to 64 % restricted to lower latitudes (presumably a result of 'mass' southward migration of species). Total species diversity remains high, although in some regions it is quite low (Fig. 7). In the Chattian, the percentage of cosmopolitan taxa reaches a peak of 31.6 %, and the percentage of species restricted to low latitudes decreases to 21.4 %, while species restricted to high latitudes increases to about 9 % (Fig. 5A, Table 1). Regional species diversity in the Chattian is highest in the Norwegian-Greenland Basin (Fig. 8). The latitudinal species diversities in the Priabonian-Chattian interval all show maximum values for low latitudes, especially during Rupelian time (Fig. 10). Regional species diversity in the Priabonian-Chattian interval, shown in Fig. 9, emphasizes the relative stability of Priabonian and Chattian diversity, and highlights the dramatic latitudinal and regional differences which occurred in the Rupelian. In contrast, modern assemblages in the North Atlantic show greatest cyst diversity in middle latitudes according to results of Harland (1983), and at higher latitudes, according to Dodge and Harland (1991). These differences may reflect a bias in sample coverage either for the Paleogene DSDP data or for the modern assemblages, or alternatively, may indicate a shift in the cyst-forming population from the Paleogene to the Recent.

Although ten of the eleven DSDP cores are located along the paths of inferred paleocurrents, variations in the composition of the assemblages are not easily interpreted as predominantly current-controlled. Postulated surface and deep-water currents for the early Oligocene of the North Atlantic are shown in Fig. 11 (Tucholke and McCoy, 1986). Surface and deep water current patterns altered dramatically with the development of the Circum-Antarctic Current (Shackleton and Kennett, 1975; Kennett, 1977) and the formation of the psychrosphere, the cold bottom layer of the ocean. The presence of vigorously circulating deep water at high latitudes during latest Eocene-earliest Oligocene time (Miller, 1992) is substantiated by the existence of widespread hiatuses in deep water sediments of this age.

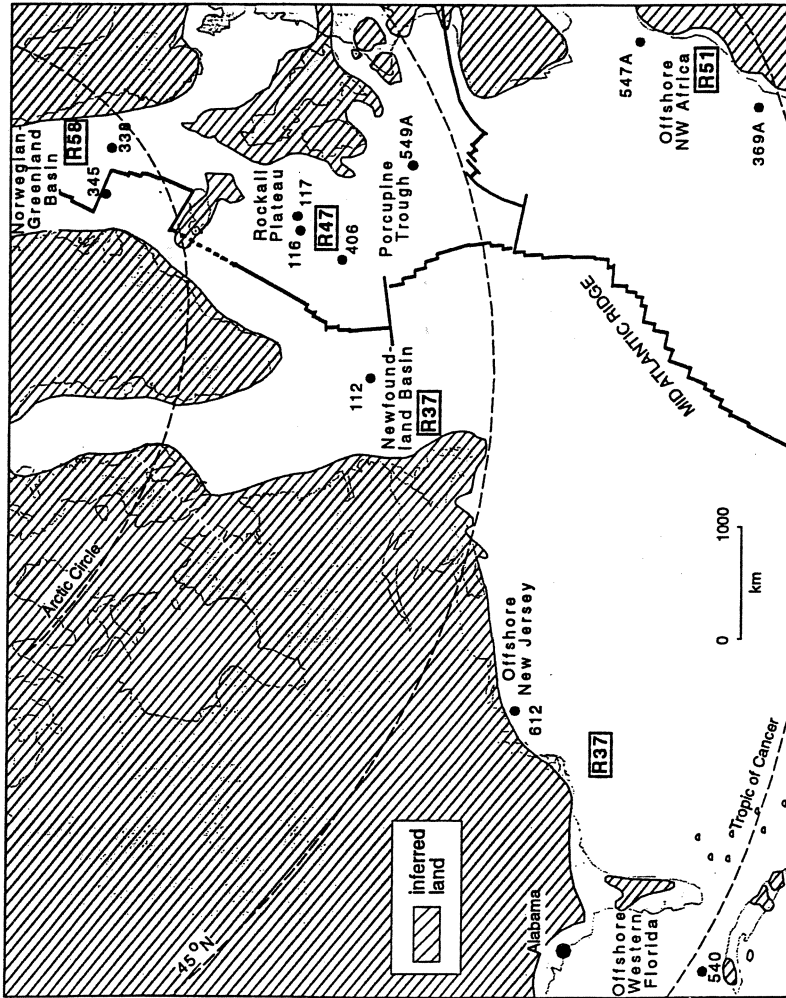


Figure 8. Regional species diversity values for Chatthian samples, North Atlantic DSDP localities and Alabama core. Numbers preceded by 'R' = regional diversities. Geographic regions as for Figure 3 and defined in text. Paleogeographic reconstruction as for Figure 4.

Chatthian species diversities for individual localities are as follows: DSDP 540 = 32; Alabama = 10; DSDP 112 = 37; DSDP 338/345 = 58; DSDP 116/117/406 = 47; DSDP 369A = 51.

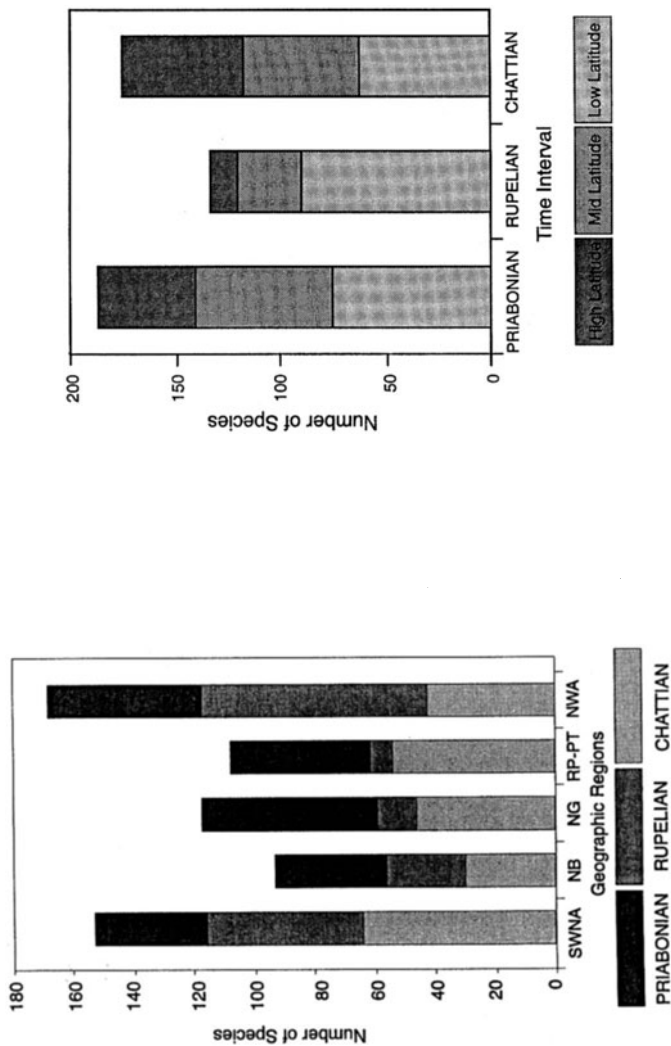


Figure 9. (Left) Bar graph showing regional species diversity of Late Eocene-Oligocene dinoflagellates, based on DSDP data only, North Atlantic Ocean (Alabama data not included). Note dramatic decrease in assemblage diversity at high latitudes (NG bar) for Rupelian. SWNA = southwestern North Atlantic; NB = Newfoundland Basin; NG = Norwegian-Greenland Basin; RP-PT = Rockall Plateau-Porcupine Trough; NWA = offshore northwest Africa. See Figure 3 for specific localities included in these regions.

Figure 10. (Right) Bar graph showing latitudinal species diversity of Late Eocene-Oligocene dinoflagellates, based on DSDP data only, North Atlantic Ocean (Alabama data not included). Note dramatic decrease in high latitude assemblage diversity, and corresponding increase in low latitude assemblage diversity, in the Rupelian. Note similarity of latitudinal diversities in Priabonian and Chattian intervals.

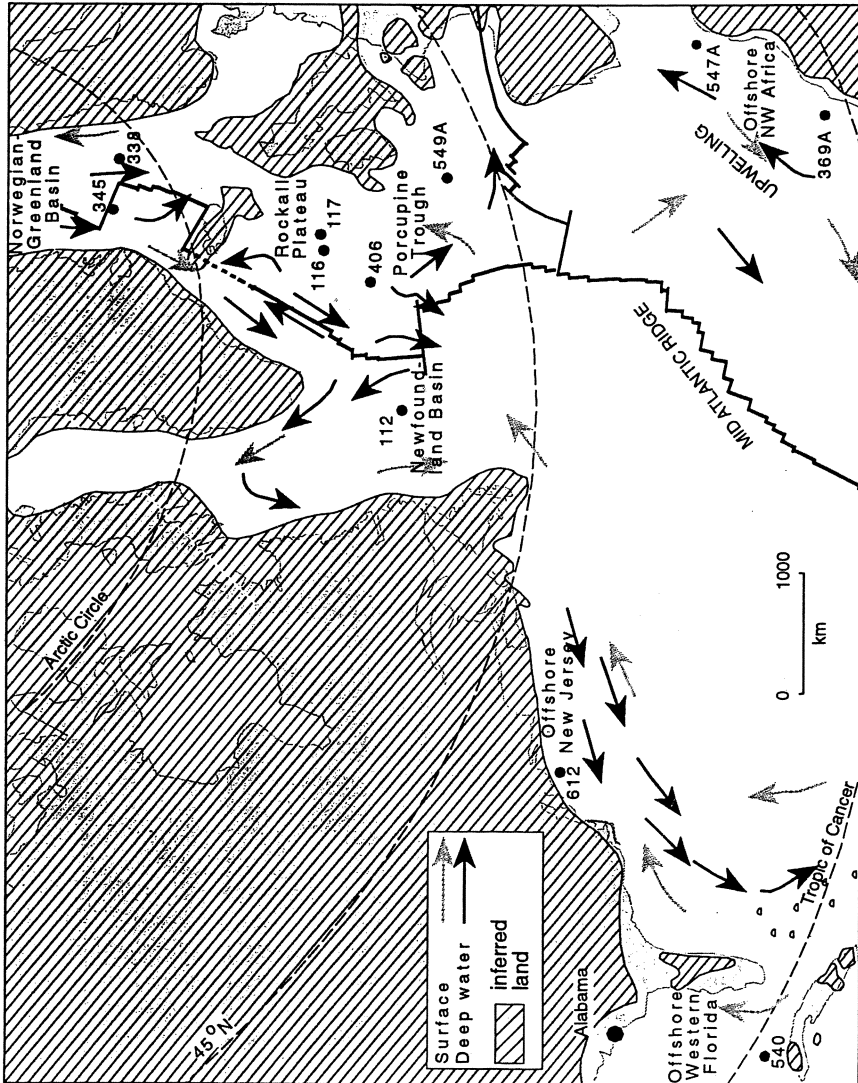


Figure 11. North Atlantic paleocurrents during Rupelian time (after Tucholke and McCoy, 1986, Pl. 10, Fig. J).

In the late Eocene-Oligocene, the proto-North Atlantic Current should have been an efficient distributor of low-latitude taxa to higher latitudes (Fig. 11). In addition, the Portugal Current and perhaps the proto-Norwegian Current would have been effective transporters of species originating in the western North Atlantic to the eastern North Atlantic. Differences between the western and eastern North Atlantic assemblages (computed as the difference between the percentage of the assemblages restricted to the eastern versus the western North Atlantic) are more pronounced in the Rupelian than in either the Priabonian or the Chattian (Table 1, Fig. 5B). Assemblage differences between the eastern and western Atlantic during the Rupelian suggest either that the North Atlantic Current was not as effective a dispersal mechanism during that time, or that other factors were of greater importance in determining assemblage composition and species distribution.

Exchange of North Atlantic water with Arctic Ocean water, initiated by the late Eocene, would take place through both the Norwegian-Greenland Sea and Labrador Sea-Baffin Bay. The separation of Svalbard and Greenland in the Early Oligocene would also have introduced colder water into the North Atlantic (Talwani and Eldholm, 1977). Haq (1981) provided reconstructions showing Paleogene oceanic circulation and the path of what he termed the paleo-Gulf Stream. Based on the work of Gradstein and Srivastava (1980), Haq believed that there was active transfer of relatively warm Atlantic water northward into the Arctic through the Labrador Sea (Newfoundland Basin) and Baffin Bay. The high percentage of species restricted to the Newfoundland Basin during Priabonian time suggests, however, that there was not free exchange from the North Atlantic to the Labrador Sea, possibly due to the existence of a cold surface- or deep-water current flowing southwards.

By the late Oligocene, the configuration of the global surface currents was essentially similar to that of the modern ocean, and was quite different from that of the preceding Late Eocene-Early Oligocene (Haq, 1981). The high percentage of cosmopolitan dinoflagellate species in the North Atlantic by Chattian time supports the stabilization of evolving surface water circulation patterns in the North Atlantic.

Accompanying the changes in oceanic circulation patterns were dramatic decreases in global temperature across the Eocene-Oligocene boundary. Climatic trends established for the Paleogene, based on oxygen isotope analysis of foraminifera (e.g. Shackleton, 1984; Miller *et al.*, 1987 and Fig. 12), show a major reduction in temperature between the Priabonian and the Rupelian, with the minimum for the Paleogene occurring near the beginning of the Rupelian. Temperature fluctuations at the Eocene-Oligocene boundary have been the focus of several studies (e.g. Shackleton and Boersma, 1981; Miller *et al.*, 1991; Miller, 1992).

Response to decreasing temperatures is the most plausible explanation for the southward migration of many dinoflagellate species during Rupelian times, resulting in a low-latitude species diversity maximum in this interval. Climatic warming in the Chattian explains the similarity of latitudinal diversity percentages to those of the Priabonian.

Dinoflagellates are an important component of Tertiary and present day phytoplankton, and clearly contain important clues to the history of paleoclimate and paleoceanography. Dinoflagellate data routinely should be integrated with that for other microfossil groups, as well as with oxygen and carbon isotope data and evidence for oceanic circulation patterns. Unlike other forms of microplankton, they can be recovered from a wide spectrum of marine environments (estuarine to deep water) at all latitudes; in addition, because the cyst wall of most species is organic in composition, preservation is not affected by the calcium compensation depth (CCD). Dinoflagellates can thus provide reliable stratigraphic and oceanographic information from depositional environments in which other groups were not originally present or preserved.



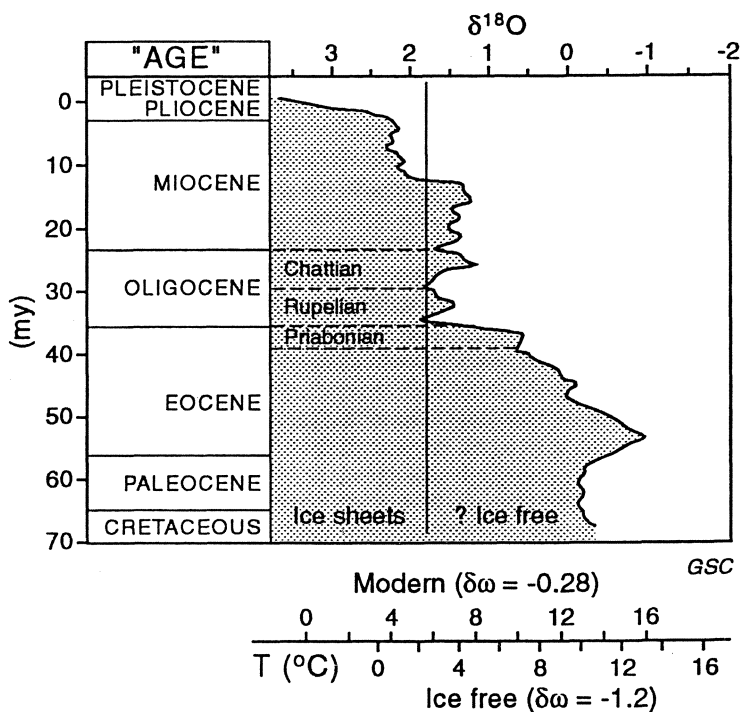


Figure 12. Composite benthic foraminiferal oxygen isotope record for Atlantic Ocean DSDP localities (after Miller *et al.*, 1987), showing Priabonian–Chattian stages.

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