Late Mesozoic and Cenozoic sediment flux to the central North Atlantic Ocean

Jörn Thiede & Werner U. Ehrmann

SUMMARY: A history of Mesozoic and Cenozoic palaeoenvironments of the North Atlantic Ocean has been developed based on a detailed analysis of the temporal and spatial distribution of major pelagic sediment facies, of hiatuses, of bulk sediment accumulation rates, and of concentrations and fluxes of the main deep-sea sediment components. The depositional history of the North Atlantic can be subdivided into three major phases: (a) Late Jurassic and Early Cretaceous phase: clastic terrigenous and biogenic pelagic sediment components accumulated rapidly under highly productive surface water masses over the entire ocean basin; (b) Late Cretaceous to Early Miocene phase: relatively little terrigenous and pelagic biogenic sediment reached the North Atlantic Ocean floor, intensive hiatus formation occurred at variable rates, and wide stretches of the deep-ocean floor were covered by slowly accumulating terrigenous muds; (c) Middle Miocene to Recent phase: accumulation rates of biogenic and terrigenous deep-sea sediment components increased dramatically up to Quaternary times, rates of hiatus formation and the intensity of deep-water circulation inferred from them seem to have decreased. However, accumulation rate patterns of calcareous pelagic sediment components suggest that large scale reworking and displacement of deep-sea sediments occurred at a variable rate over wide areas of the North Atlantic during this period.

Over 150 drill holes have partly or completely penetrated the deep-sea sediment layer in the central and North Atlantic; they enable us to describe temporal and spatial patterns of sediment fluxes to this ocean basin during the past 150 million years. As one of a series of syntheses of the history of the main sub-basins of the World Ocean we have now analysed information available from the North Atlantic (see van Andel *et al.* 1977, for a comparable study of the South Atlantic). The bulk of the information obtained from the North Atlantic study has been published by Ehrmann & Thiede (1985); and only a few essential aspects are highlighted in this paper.

In this study the authors point out temporal relationships between hiatus formation and sediment fluxes to the North Atlantic Ocean during the past 150 Ma. Data hitherto available seemed to suggest a strong correlation between the fluxes of individual North Atlantic deep-sea sediment components, and a negative correlation between the intensity of hiatus formation and sediment accumulation rates. Here these relationships are traced in more detail than previously, because they seem to document some important properties of the North Atlantic deep-sea depositional environment.

Ways of quantifying sediment fluxes

The authors have used methods developed by van Andel *et al.* (1975) to estimate temporal distributions of hiatuses and calculate bulk sediment and component accumulation rates for all central and North Atlantic deep-sea drill sites (Figs. 1–3). The presence of hiatuses has been assumed where bulk sediment accumulation rates fell below 100 g $cm^{-2}Ma^{-1}$, or where stratigraphies suggested the absence of sediments representing time spans longer than 2 Ma. Identified hiatuses have not been included in the calculation of sedimentation rates. The resultant data have been used to reconstruct sediment fluxes to the North Atlantic deep-sea floor, displaying them as time series or synoptic time slices both for individual sub-basins and for the entire ocean. The palaeogeographic and palaeobathymetric movements of the individual data points were backtracked by using the methods of Sclater *et al.* (1977) and Berger (1972). It is clear from Fig. 1 and Fig. 2 that both the temporal and spatial coverage of the North Atlantic's depositional history is inhomogeneous, and that the early part of this history is poorly documented. However, despite these deficiencies these data provide a basis for mapping sediment fluxes on palinspastic maps such as Fig. 4.

For each of the individual drill sites it has been possible to calculate the vertical movements (almost always subsidence) of the sediment surface with time. This has enabled the authors to compile information on the nature of the sediments on age versus palaeodepth diagrams for the central and North Atlantic Ocean and its major sub-basins (Fig. 5). These diagrams comprise data for all drill sites available from the region

From SUMMERHAYES, C.P. & SHACKLETON, N.J. (eds), 1986, *North Atlantic Palaeoceanography*, Geological Society Special Publication No. 21, pp. 3–15.

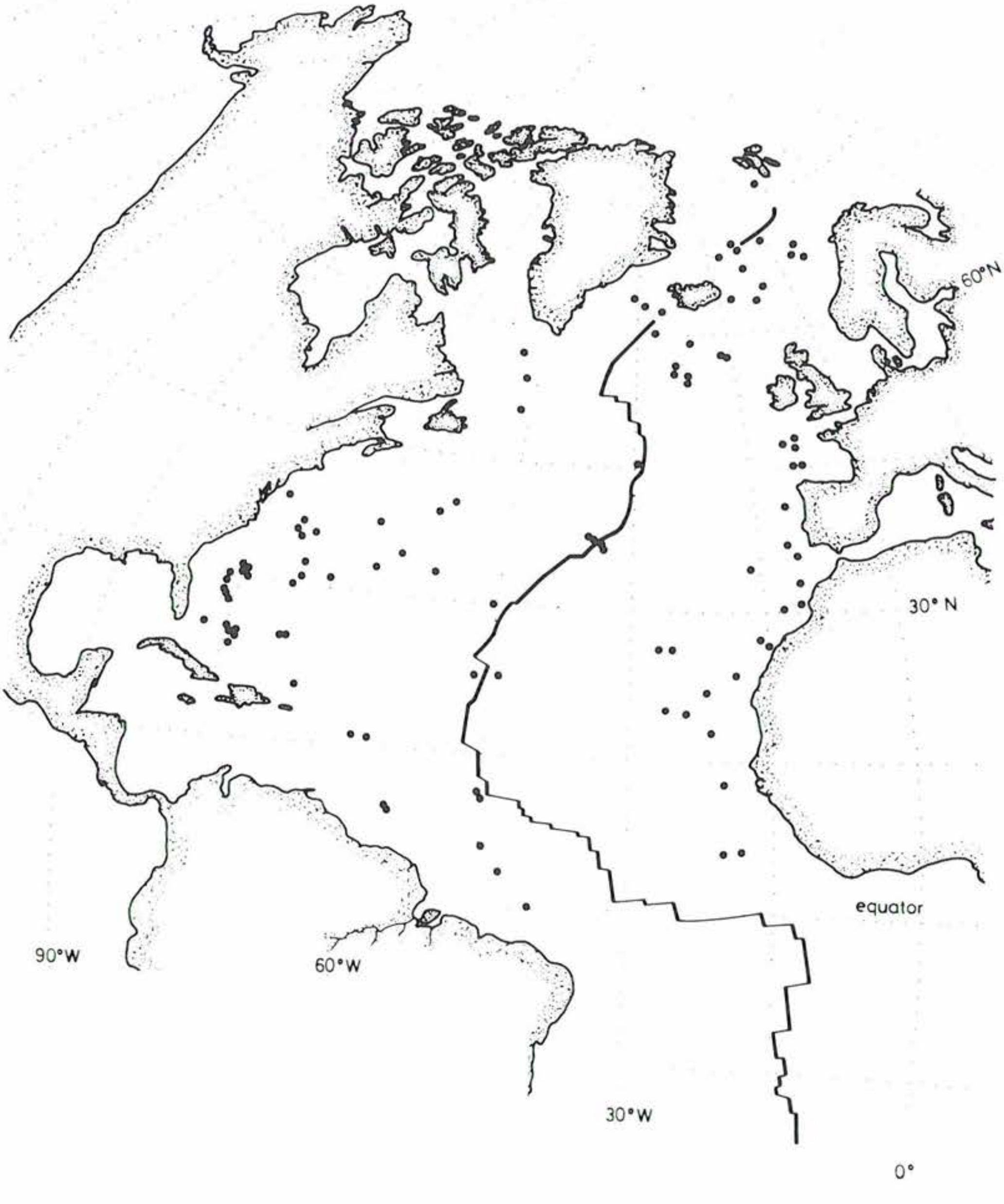

FIG. 1. Distribution of Deep-Sea Drilling Project drill sites analysed for this sudy.

under study, and provide the best regional coverage presently attainable. The bulk sediment accumulation rate data thus compiled have also been used to establish time series of average values of sediment fluxes for 1 Ma time increments, and of hiatus frequencies in the North Atlantic Ocean.

The information required for this study has been extracted from the Initial Reports of the Deep-Sea Drilling Project (DSDP), and from the shipboard site reports. The quality of the data in the DSDP Initial Reports is highly variable. Also, drill site density varies with distance from the adjacent continents, and is particularly low in the

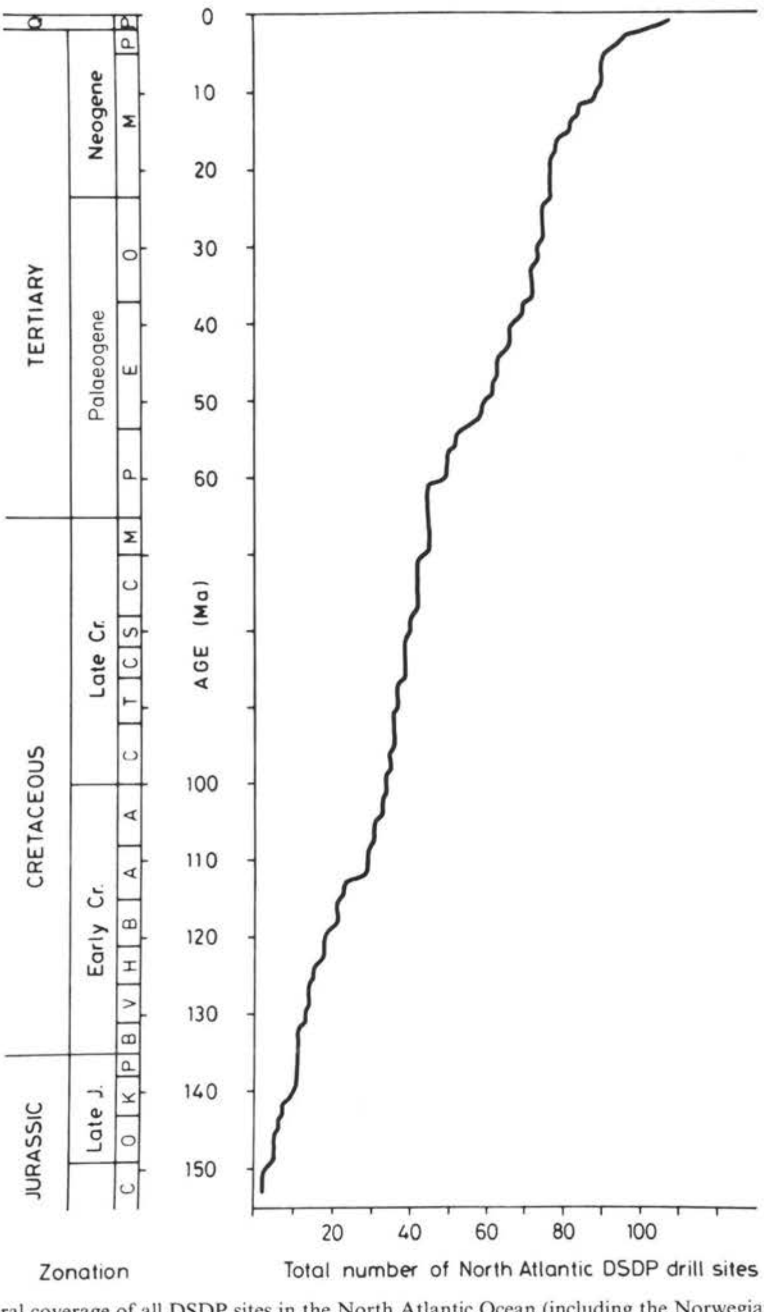

FIG. 2. Temporal coverage of all DSDP sites in the North Atlantic Ocean (including the Norwegian-Greenland Sea). The absolute time-scale (in Ma) is based on available biostratigraphic zonations (van Hinte 1976, 1978; van Couvering & Berggren 1977; Berggren *et al.* 1978); absolute ages of stratigraphic boundaries as used in this study are indicated in this figure.

central parts of the east and west North Atlantic. Most drill sites were chosen to address a specific problem or feature; only a few were selected to obtain a record of normal oceanic basement and its sediment cover. Therefore, many of the records may be documenting atypical depositional environments.

The task of standardizing and in part revising and correcting the North Atlantic data base, which had been accumulated during 15 years of deep-sea drilling, was difficult and time consuming. It was necessary: (1) to check the stratigraphic data and their validity; (2) to generate a lithologic data base which allowed comparison of sediment data from sites drilled during the early days of deep-sea drilling with those obtained from the latest North Atlantic deep-sea drill sites; (3) to collect the physical property data needed for the calculation of bulk sediment accumulation rates and of individual sediment component accumulation rates; and (4) to assess the importance and length of hiatuses.

Temporal and spatial variability of sediment fluxes

Figures 3–6 show that the sediment flux to the North Atlantic deep-sea floor has been highly variable in space and time. As an example of the variability at one location data from Site 369 are presented (Fig. 3). Sediment flux at this and other sites has been sporadic, and the continuity of sedimentation has been interrupted by numerous, sometimes long hiatuses. Intervals inbetween hiatuses have maximal bulk accumulation rates. A sporadic, discontinuous influx of sediments seems to have been the rule, rather than the exception in the North Atlantic during the Late Mesozoic and Cenozoic. Similar observations have been made about other oceans (Moore *et al.* 1978), but the hiatus records of the different ocean basins have yet to be compared.

Figure 4 (a and b) presents data from two Palaeogene time slices plotted onto the corresponding palinspastic maps to show the spatial variability of bulk accumulation rates. These examples illustrate that sediment fluxes have been low for most parts of the deep central and North Atlantic, values usually being 500 g $cm^{-2}Ma^{-1}$. Only a few areas, mostly close to the continental margins (proximal), received sediment at rates which exceeded 3000–5000 g $cm^{-2}Ma^{-1}$, and which are up to an order of magnitude higher than in the central ocean basin (distal).

The use of sediment traps to measure bulk sediment accumulation rates in modern oceans (Honjo 1978, 1982) has revealed rates many

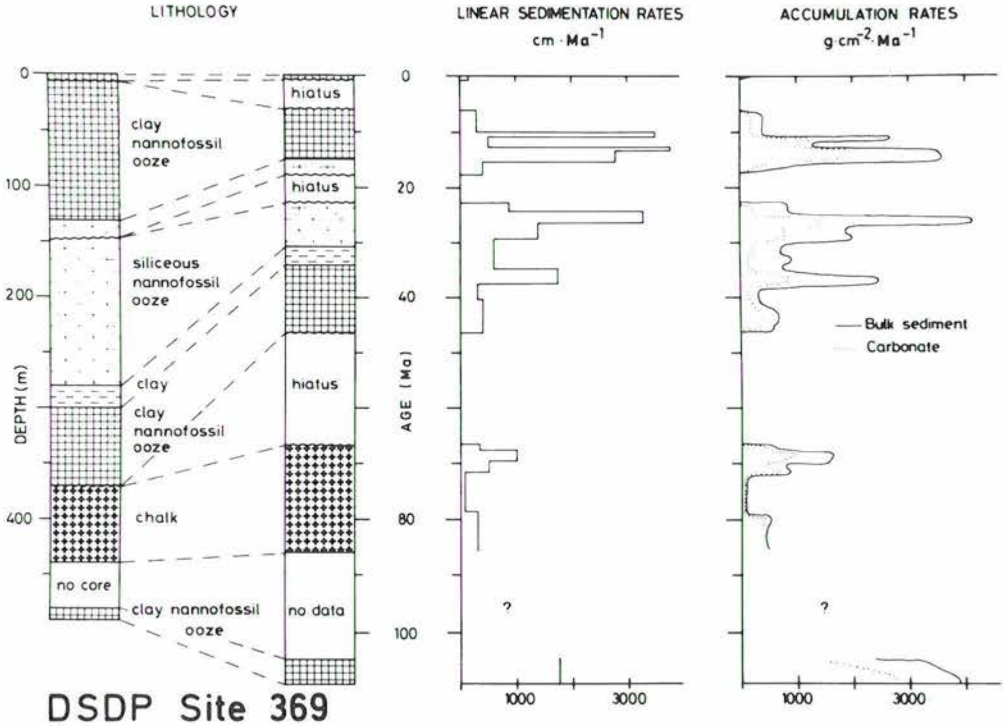

FIG. 3. Graphical example of the authors' data processing: the left column provides the lithostratigraphic information (simplified), as found in the Initial Reports of the Deep-Sea Drilling Project; in the second column lithology is plotted versus age. By correcting linear sedimentation rates for compaction the accumulation rates for every million year time interval have been calculated.

orders of magnitude higher than those determined for North Atlantic deep-sea sediments. Thus, it seems likely that other processes than the original vertical sediment flux are documented in the bulk sediment accumulation rates which have been reconstructed for North Atlantic DSDP sites.

The regional differentiation described above (Fig. 4) cannot be observed in the Jurassic to mid-Cretaceous time slices while the North Atlantic was part of the Tethyan ocean regime (Bernoulli 1984). At this time the (poorly documented) depositional environment seems to have been quite uniform throughout the entire basin. Since mid-Cretaceous times high sediment fluxes have been restricted to isolated centres like those shown in Fig. 4, although the importance and the position of these centres have often changed (Ehrmann & Thiede, 1985).

To assess the average sediment flux to the North Atlantic during the past 150 Ma the accumulation rate data have been plotted onto

FIG. 4. Accumulation rates of bulk sediment in the North Atlantic in Palaeogene times (g $cm^{-2}Ma^{-1}$, averaged). The data have been plotted onto palinspastic maps taken from Thiede (1979). DSDP Sites: ● = data; ○ = hiatus; × = no data. (a) 50–46 Ma; (b) 30–26 Ma.

FIG. 4 (b).

palaeodepth versus age diagrams (Fig. 5). To make these diagrams the North Atlantic was divided into eastern and western parts along the mid-Atlantic ridge, excluding Norwegian-Greenland Sea sites. This approach oversimplifies the regional variability by implying that the sediment flux of both basins was uniformly distributed throughout the basin. Thus Fig. 5 (a and b) reveals only major temporal and spatial distribution patterns, and obscures much of the small scale variability.

Both sub-basins of the North Atlantic are

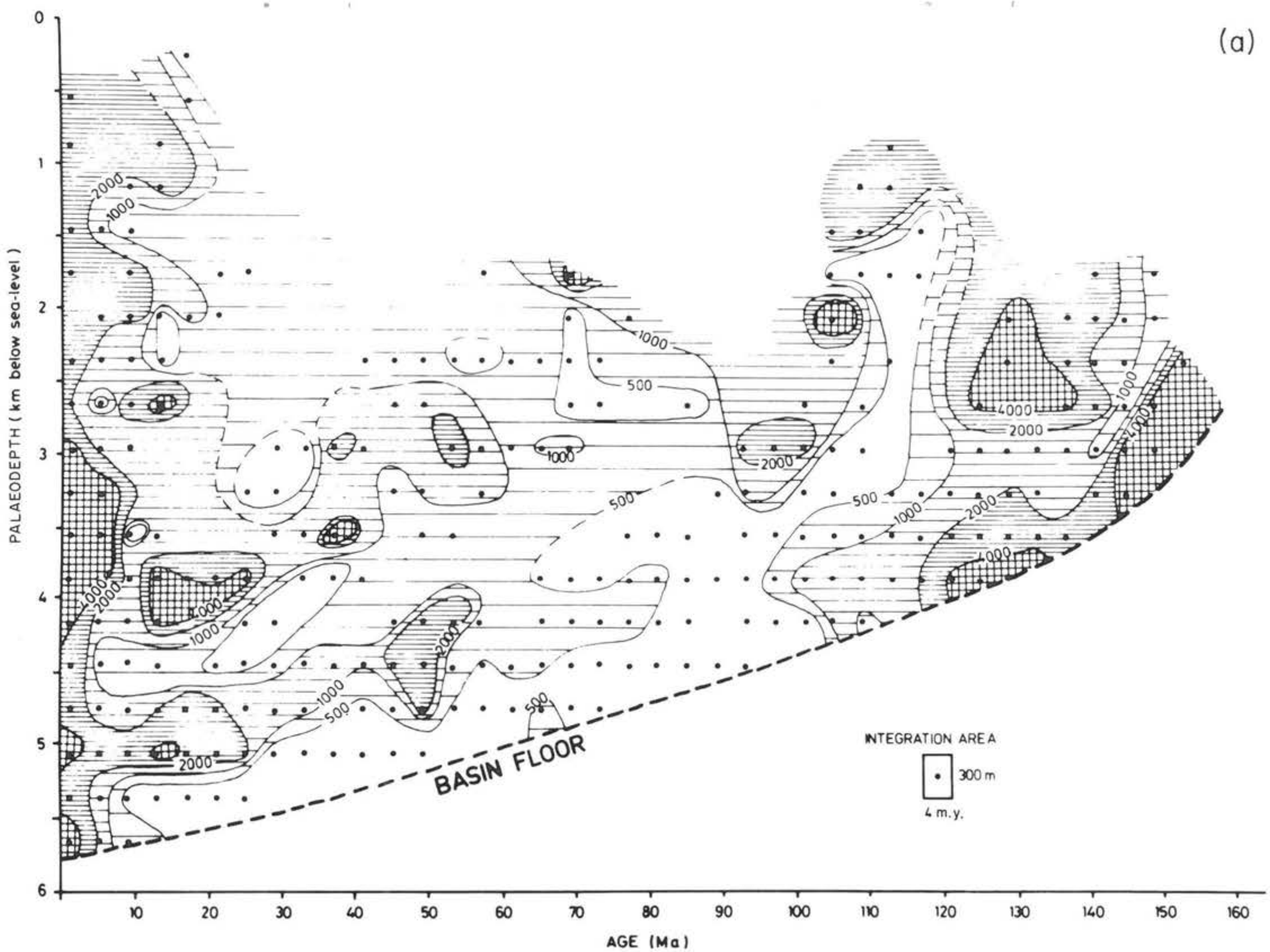

FIG. 5. Accumulation rates (g $cm^{-2}Ma^{-1}$) of bulk sediment plotted versus age and palaeodepth for (a) the western, and (b) the eastern basins of the North Atlantic Ocean.

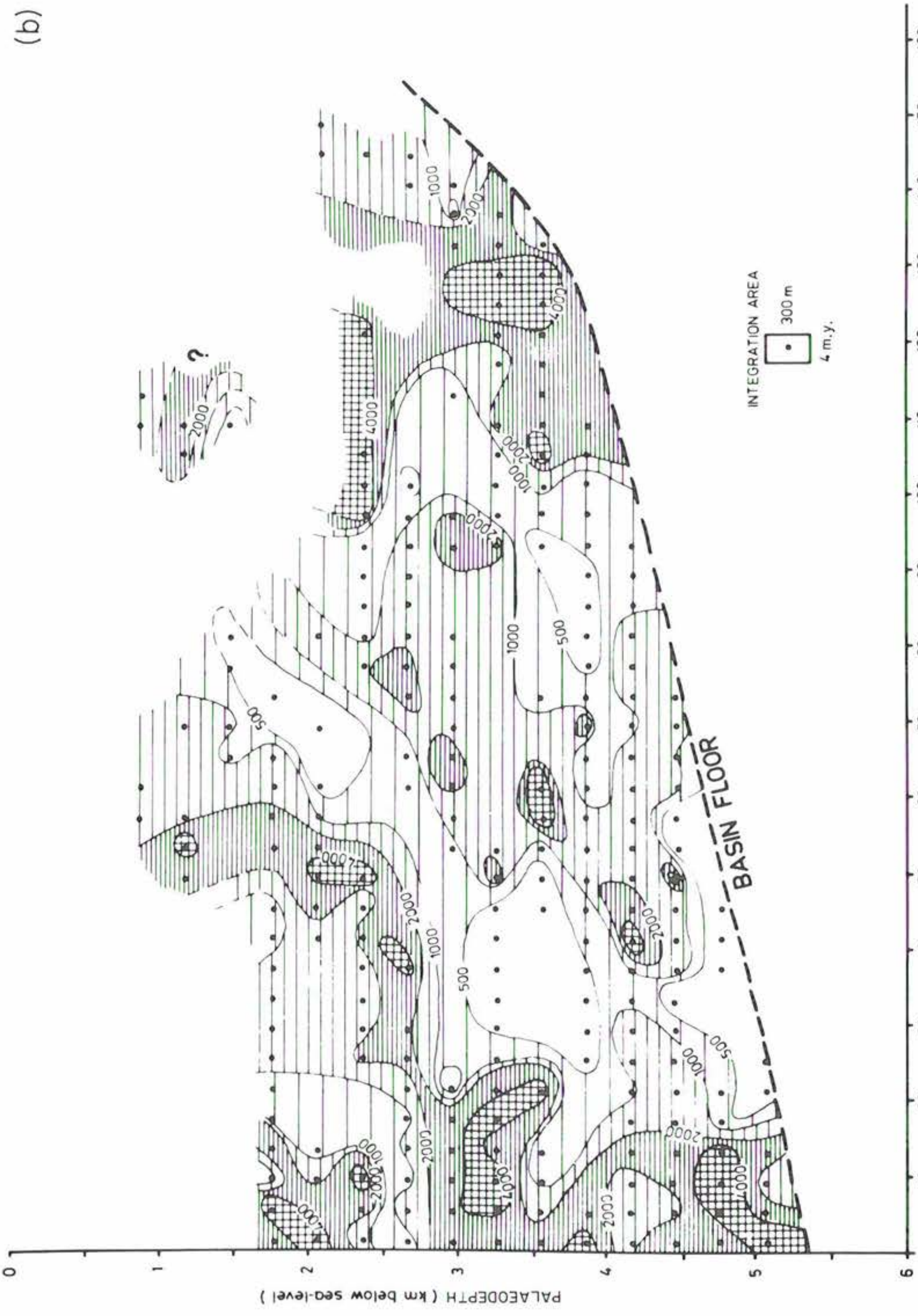
(b)
AGE (Ma)
PALAEODEPTH (km below sea-level)
BASIN FLOOR
INTEGRATION AREA
300 m
4 m.y.

FIG. 5 (b).

characterized by high bulk sediment accumulation rates during their early history, ending approximately 100–110 Ma ago and apparently extending throughout the entire water column (Fig. 5). This early phase is succeeded by a long interval of variable, but generally low, bulk sediment accumulation rates, which also seem to suggest a distinct vertical zonation in the sediment flux. At about 10–20 Ma ago bulk sediment accumulation rates gradually rose again in both basins to similar or even higher values than those reached in the early North Atlantic phase. This last phase seems to have started somewhat earlier in the east than in the west North Atlantic basins.

The palaeodepth distribution of the bulk sediment accumulation rates also reveals a distinct pattern, although the North Atlantic DSDP drill sites only permitted the description of palaeodepth intervals in water depths > 1500 m. The early high bulk accumulation rate phase can be traced across the entire water column, with no suggestions of any depth stratification. Even though the ensuing phases of low and high bulk sediment accumulation rates are highly variable in detail, between the east and west North Atlantic sub-basins, as well as within the same basin, they seem to suggest some stratification and henceforth some type of vertical zonation of the rate of preservation of the sedimentary record reflecting the action of different water masses. The authors believe that this difference is highly significant and that it represents a signal of some basic characteristic of the oceanic water column. The authors also note that the early 'non-depth stratified' phase of high bulk sediment accumulation rates coincided with the repeated develop-

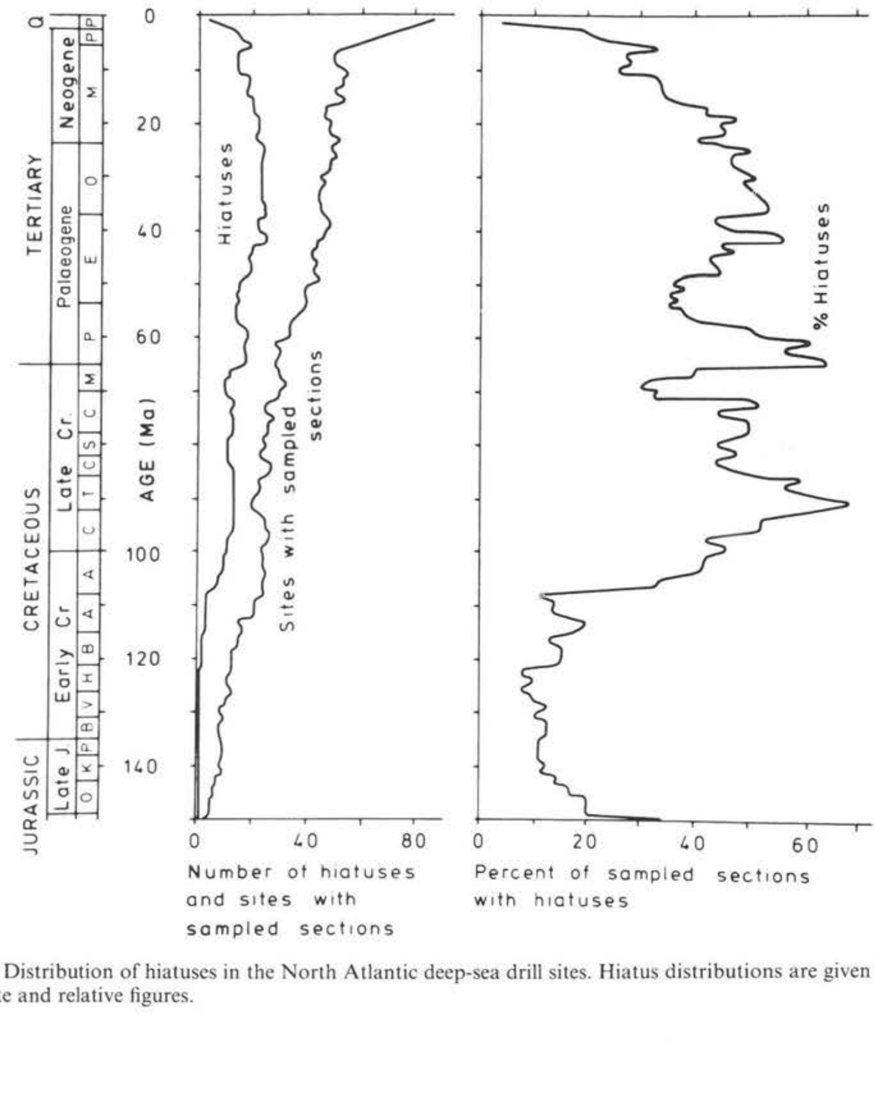

FIG. 6. Distribution of hiatuses in the North Atlantic deep-sea drill sites. Hiatus distributions are given in absolute and relative figures.

ment of oxygen deficient depositional environments (de Graciansky *et al.* 1984; Arthur & Dean, in press).

On the relationship between hiatuses and bulk sediment fluxes

To investigate further the temporal variability of sediment fluxes the hiatus frequencies (Fig. 6) and average bulk sediment accumulation rates (Fig. 7) versus time only have been re-plotted. Although these data were generated independently, both data sets seem to support a threefold subdivision in the depositional history of the North Atlantic.

Hiatuses are rare in sediments older than 100–110 Ma in both the eastern and western sub-basins of the North Atlantic (Fig. 6). The time span from 100 Ma to about 20 Ma is generally characterized by high, but variable hiatus frequencies. Pronounced maxima occur close to 90 Ma, 65 Ma, and 40 Ma. After 40 Ma, and clearly after 20 Ma, hiatus frequencies decreased to their modern minimum. The maxima are separated from each other by equally pronounced minima at 70 Ma and 50–60 Ma. The authors interpret these data as showing that the erosion of deep-sea sediments has fluctuated extensively through

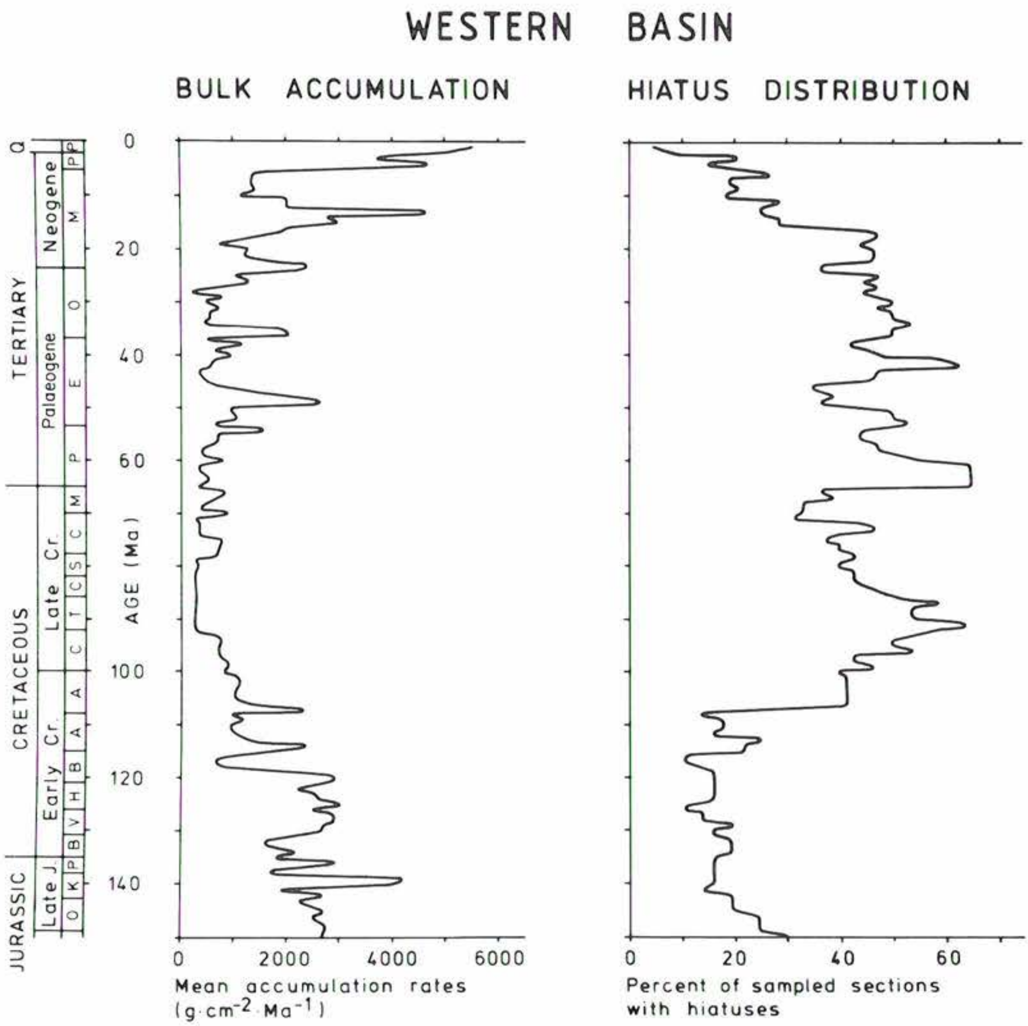

FIG. 7. Average bulk sediment accumulation rates and hiatus distributions versus time in the western sub-basin of the North Atlantic.

time. This has already been pointed out by Moore *et al.* (1978) for the Cenozoic pelagic deposits of most major ocean basins. For the North Atlantic it is now possible to use hiatus distributions to precisely pinpoint intervals of strengthening and weakening of deep-sea erosion. As outlined by Ehrmann & Thiede (1985), approximately 30–50% of the time which might be represented by North Atlantic deep-sea deposits cannot be documented properly because of the development of hiatuses. At present it is difficult to know where the sediment representing the hiatus intervals is situated.

Evaluating the importance of hiatuses is complicated by the fact that bulk sediment fluxes were high during times of low hiatus frequencies, and generally low during times of high hiatus frequencies. In Fig. 7 and Fig. 8 data have been plotted representing average values for 1 Ma time increments for bulk sediment accumulation rates, and hiatuses versus time. Previously it has been pointed out that hiatuses identified and represented in the hiatus plots, have been excluded when calculating bulk sediment accumulation rates. Despite these precautions an inverse relationship between sediment flux and hiatus formation can still be seen.

The above coincidence has been investigated by calculating correlation coefficients between bulk sediment accumulation rates and hiatus frequencies (Tables 1 and 2). The authors discovered that (a) phases of high correlation between these two parameters alternated with phases of low or no correlation; (b) correlations

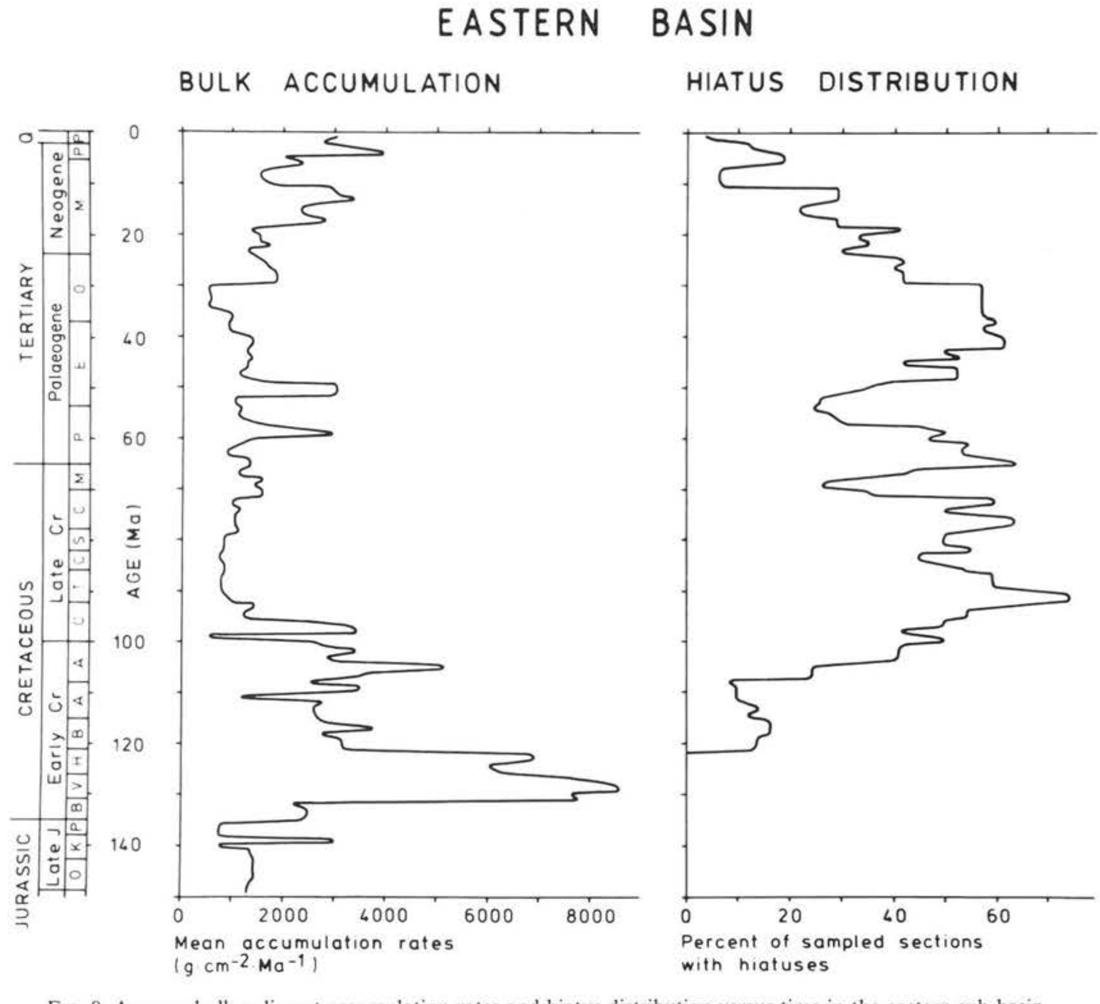

FIG. 8. Average bulk sediment accumulation rates and hiatus distribution versus time in the eastern sub-basin of the North Atlantic.

TABLE 1. *Correlation of bulk sediment accumulation rates (BAR) and hiatuses (correlation coefficients)*

Time span	(Ma)	Correlation coefficients	
		Western basin	Eastern basin
Total record		−0.69 (1–150 Ma)	−0.62 (1–120 Ma)
Tertiary	2–65	−0.73	−0.57
Neogene	2–24	−0.54	−0.14
Palaeogene	24–65	−0.53	−0.41
Late Cretaceous	65–100	−0.34	−0.30
Early Cretaceous	100–135	−0.43	0.17
Jurassic	135–150	0.06	—
Miocene	5–24	0.25	0.05
Oligocene	24–37	0.39	−0.92
Eocene	37–54	−0.56	−0.38
Palaeocene	54–65	0.50	0.08
Maastrichtian-Coniacian	65–86	−0.40	−0.52
Turonian-Albian	86–108	−0.77	−0.74
Aptian-Barremian	108–121	0.33	0.37
Hauterivian-Berriasian	121–135	−0.58	—

TABLE 2. *Correlation between the eastern and western sub-basins of the North Atlantic Ocean in respect to accumulation of bulk sediment and hiatus occurrence*

Time span	(Ma)	Correlation coefficients	
		Bulk sediment	Hiatuses
Total record		0.53 (1–139 Ma)	0.82 (1–121 Ma)
Tertiary	2–65	0.64	0.76
Neogene	2–24	0.73	0.79
Palaeogene	24–65	0.13	0.35
Late Cretaceous	65–100	0.53	0.75
Early Cretaceous	100–135	0.63	0.85
Jurassic	135–150	—	—
Miocene	5–24	0.59	0.78
Oligocene	24–37	0.18	0.72
Eocene	37–54	0.28	0.05
Palaeocene	54–65	−0.21	0.87
Maastrichtian-Coniacian	65–86	0.37	0.64
Turonian-Albian	86–108	0.69	0.90
Aptian-Barremian	108–121	0.19	−0.32
Hauterivian-Berriasian	121–135	0.65	—

between these parameters were variable, but similar in both sub-basins of the North Atlantic during the time spans prior to 65 Ma, and (c) correlations between these parameters were variable, but quite different from each other in the east and west Atlantic sub-basins over the past 65 Ma. The authors interpret these observations to suggest a relationship between the depositional processes controlling the bulk sediment flux to the ocean floor, and hiatus formation.

The authors have also attempted to relate their time series of hiatus frequencies and bulk sediment accumulation rates to evidence presented by Vail & Hardenbol (1979) and Vail *et al.* (1977) for relative eustatic sea-level changes during the Late Mesozoic and Cenozoic. The authors have been unable to detect any direct and easily recognizable relationship between eustatic sea-level changes, hiatus frequencies and bulk sediment accumulation rates, in contrast with previous authors (e.g. Worsley & Davies 1979).

Results and conclusions

(1) The available data allow us to subdivide the sedimentary history of the North Atlantic Ocean into three major phases, with high sediment fluxes in Late Jurassic-Early Cretaceous and late Cenozoic times, but low sediment fluxes in between.

(2) Interruptions of the sediment flux (=hiatuses) are of little importance during times of high sediment flux. They have made it difficult to document the North Atlantic's history over wide regions and for long time spans during the Late Cretaceous and the main part of the Tertiary.

(3) Regional distributions of bulk sediment accumulation rates have been highly variable. Centres of sediment fluxes have usually been located close to the continental margins of NW Africa, NW Europe, Greenland and NE America. Their location and intensity changed rapidly and frequently.

(4) An inverse correlation between sediment flux and hiatus frequencies suggests that bulk sediment accumulation rates are an expression of the rates and amount of preservation of the original sediment flux to the sea floor rather than the original sediment flux itself.

(5) The depositional environments of the east and west North Atlantic basins were very similar during the time span from 150 to 100 Ma. These basins became differentiated during the Late Cretaceous and Cenozoic.

(6) During the early high bulk sediment accumulation rate phase of the North Atlantic (150–100 Ma) the authors did not find in the sediment flux data any indications of stratified water columns. However, the sediment flux and hiatus data suggest that the deep North Atlantic was well stratified since that time.

ACKNOWLEDGMENTS: The research on which this paper is based was supported by the German Research Foundation (DFG). The data were compiled from the Initial Reports of the Deep-Sea Drilling Project.

References

ARTHUR, M.A. & DEAN, W.E., in press. Cretaceous paleoceanography. *In*: TUCHOLKE, B. & VOGT, P. (eds), *DNAG Western North Atlantic Synthesis*. Geol. Soc. Am.

BERGER, W.H. 1972. Deep sea carbonates: dissolution facies and age depth constancy. *Nature* **236,** 392–5.

BERGGREN, W.A., MCKENNA, M., HARDENBOL, J. & OBRADOVICH, J. 1978. Revised Paleogene polarity time scale. *J. Geol.* **86,** 67–81.

BERNOULLI, D. 1984. The early history of the Atlantic-Tethyan system. *Ann. Geophys.* **2** (2), 133–6.

EHRMANN, W.U. & THIEDE, J. 1985. History of Mesozoic and Cenozoic sediment fluxes to the North Atlantic Ocean. *Contr. Sediment.* **15,** 1–109.

GRACIANSKY, P.C. DE, DEROO, G., HERBIN, J.P., MONTADERT, L., MÜLLER, C., SCHAAF, A. & SIGAL, J. 1984. Ocean-wide stagnation episode in the Late Cretaceous. *Nature* **308,** 346–9.

HONJO, S. 1978. Sedimentation of materials in the Sargasso Sea at a 5,367 m deep station. *J. mar. Res.* **36** (3), 469–92.

——1982. Seasonality and interaction of biogenic and lithogenic particulate flux at the Panama Basin. *Science* **218,** 883–4.

MOORE, T.C., VAN ANDEL, TJ. H., SANCETTA, C. & PISIAS, N. 1978. Cenozoic hiatuses in pelagic sediments. *Micropaleontology* **24** (2), 113–38.

SCLATER, J.G., HELLINGER, S. & TAPSCOTT, C. 1977. The paleobathymetry of the Atlantic Ocean from the Jurassic to the Present. *J. Geol.* **85,** 509–52.

THIEDE, J. 1979: History of the North Atlantic Ocean: evolution of an asymmetric zonal paleo-environment in a latitudinal basin. *In*: TALWANI, M., HAY, W.W. & RYAN, W.B.F. (eds), *Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment*. Maurice Ewing Series 3. Am. Geophys. Union. 275–96.

VAIL, P.R., MITCHUM, R.M. & THOMPSON, S. 1977. Global cycles of relative changes of sea level. *Am. Ass. Petrol. Geol. Mem.* **26,** 63–97.

——& HARDENBOL, J. 1979. Sea level changes during the Tertiary. *Oceanus* **22,** 71–9.

VAN ANDEL, TJ. H., HEATH, G.R. & MOORE, T.C. 1975. Cenozoic history and paleoceanography of the central equatorial Pacific. *Geol. Soc. Am. Mem.* **143,** 134 pp.

——, THIEDE, J., SCLATER, J.G. & HAY, W.W. 1977. Depositional history of the South Atlantic Ocean during the last 125 million years. *J. Geol.* **85,** 651–98.

VAN COUVERING, J.A. & BERGGREN, W.A. 1977. Biostratigraphical basis of the Neogene time scale. *In*: KAUFFMAN, E.G. & HAZEL, J.E. (eds), *Concepts and Methods of Biostratigraphy*. Dowden, Hutchinson & Ross, Stroudsburg, Pa. 283–305.

VAN HINTE, J.E. 1976. A Cretaceous time scale. *Am. Ass. Petrol. Geol. Bull.* **60,** 498–516.

—— 1978. A Jurassic time scale. *Am. Assoc. Petrol. Geol. Stud. Geol.* **6,** 289–97.

WORSLEY, T.R. & DAVIES, T.A. 1979. Sea-level fluctuations and deep-sea sedimentation rates. *Science* **203,** 455–6.

JÖRN THIEDE & WERNER U. EHRMANN, Geologisch-Paläontologisches Institut und Museum, Christian-Albrechts-Universität, Olshausenstrasse 40, D-2300 Kiel, Federal Republic of Germany.