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Palaeo-Oceanography, Margin Stratigraphy and Palaeophysiography of the Tertiary North Atlantic and Norwegian--Greenland Seas

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Palaeo-oceanography, margin stratigraphy and palaeophysiography of the Tertiary North Atlantic and Norwegian–Greenland Seas

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The Tertiary was a period of dramatic changes of the palaeo-oceanography of the world's oceans in general and of the North Atlantic in particular. These changes were caused by (1) the bathymetric evolution of ocean basins and intrabasin pathways (opening of the Norwegian–Greenland Seas and of the pathway to the Arctic Ocean, interruption of the circumglobal equatorial seaway); (2) the geographical development of the oceans and adjacent marginal basins in the context of rapid and intensive eustatic sea level fluctuations; and (3) the deterioration of the global climate throughout the Tertiary (change from a non-glacial to a glacial world, causing major changes in circulation of the surface and deep water).

A biostratigraphy of Tertiary sediments deposited close to the continental margins has been developed by using remains of planktonic floras and faunas. Their presence in these sediments and their usefulness for long distance correlations of margin sediments, depend upon the circulation pattern and hydrographic gradients of the oceanic surface and deep water masses, the climatic regime over the continental border zones, and the probability of their post-depositional preservation.

1. Introduction

The biogenic components of marine sediments along continental margins respond to a complicated network of boundary conditions, including the evolutionary trends of individual fossil groups, shifting palaeoenvironments due to vertical tectonic movements, changes of the palaeogeography, climatic fluctuations, and palaeo-oceanographic revolutions (Berggren & Hollister 1977).

Continental margin sediment sections are not easily correlated with corresponding records of the open ocean because of the presence of distinct coastal water masses with a range of salinity and temperature fluctuations, which exceed those of the open ocean at the corresponding latitude. Steep hydrographic gradients result in fewer species of marine organisms being able to occupy the water masses over the continental margins; this applies especially to the oceanic plankton (figure 1) which has been widely used to erect the biostratigraphy of Mesozoic and Cainozoic marine sections along and/or close to continental margins and in epicontinental seas. Why the preservation of the opaline and calcareous microfossils in the hemipelagic sediments, under the fertile surface water masses of such regions, follows different rules from in the pelagic environment, has not yet been elucidated completely. The palaeo-oceanography of the Tertiary North Atlantic, and its implications for the corresponding continental margin sediments, can only be discussed in the light of changes of the physiography of the ocean basin itself, and of its epicontinental seas, and also of variations of the palaeoclimate which controls circulation in this marine environment.

2. Palaeobathymetry and palaeogeography

The palaeogeographic and palaeobathymetric evolution of the Cainozoic North Atlantic Ocean is shown in figure 2. The six time slices represent late Maastrichtian – early Palaeocene (65 Ma B.P., anomaly 29), late Palaeocene – early Eocene (53 Ma B.P., anomaly 22), late Eocene – early Oligocene (38 Ma B.P., anomaly 13), early Miocene (21 Ma B.P., anomaly 6), late Miocene (10 Ma B.P., anomaly 5) and Recent times. In this figure, the palaeobathymetry of the ocean basin has been adapted from Sclater *et al.* (1977). Although the tectonic history of aseismic ridges has recently been studied in considerable detail (Detrick *et al.* 1977; Thiede 1977), major problems usually arise in such areas because the timing of the origin, the nature and the morphology of the underlying volcanic edifice are not known in enough detail. This problem is particularly pertinent to the Cainozoic North Atlantic because the dominant structural high comprises the aseismic Iceland–Faeroe Ridge which has inhibited the exchange of surface as well as bottom water masses between the Norwegian–Greenland Seas and the North Atlantic Ocean throughout the Cainozoic.

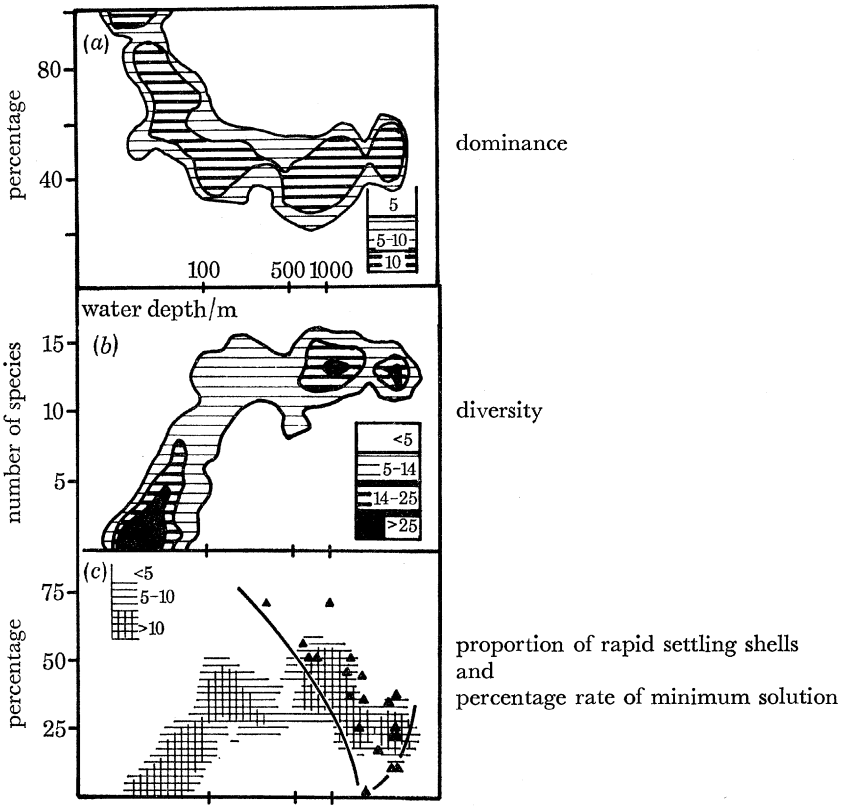

Figure 1. (*a*) Dominance and (*b*) diversity of planktonic foraminiferal surface sediment assemblages from the north-western Gulf of Mexico (after Thiede 1972). The data have been taken from Phleger 1951 and consist of 380 samples from 13 traverses. The lowermost diagram (*c*) describes the qualitative percentage distribution of rapid settling species. Percentages of species relatively resistant against calcium carbonate solution (but only data from one traverse, each symbol for one station) are marked by black triangles. The concentration of the samples is given in the diagrams as number of samples per square unit (as indicated).

The palaeogeography of the epicontinental seas around the North Atlantic Ocean has been compiled from a multitude of sources. The bulk of the palaeogeographic information published about this region has been averaged over long intervals (in general over whole stages such as Palaeocene, Eocene, etc.) because of inadequate stratigraphic information resulting in a reduced regional resolution. Since much detail is not easily accessible because of being published in little known local journals, and because a high accuracy of regional detail was not really needed for the purpose of this paper, a number of recent compilations have been consulted for guidance (Krömmelbein 1976; Mintz 1972; Papp 1959). Invaluable sources of information were found in Nairn & Stehli (1973, 1974, 1975) as well as in Cook & Bally (1975). Because of the questionable palaeodepth information available around the North Atlantic Ocean during the Tertiary, only the former coastline and the 2 and 4 km depth contours are drawn in this paper.

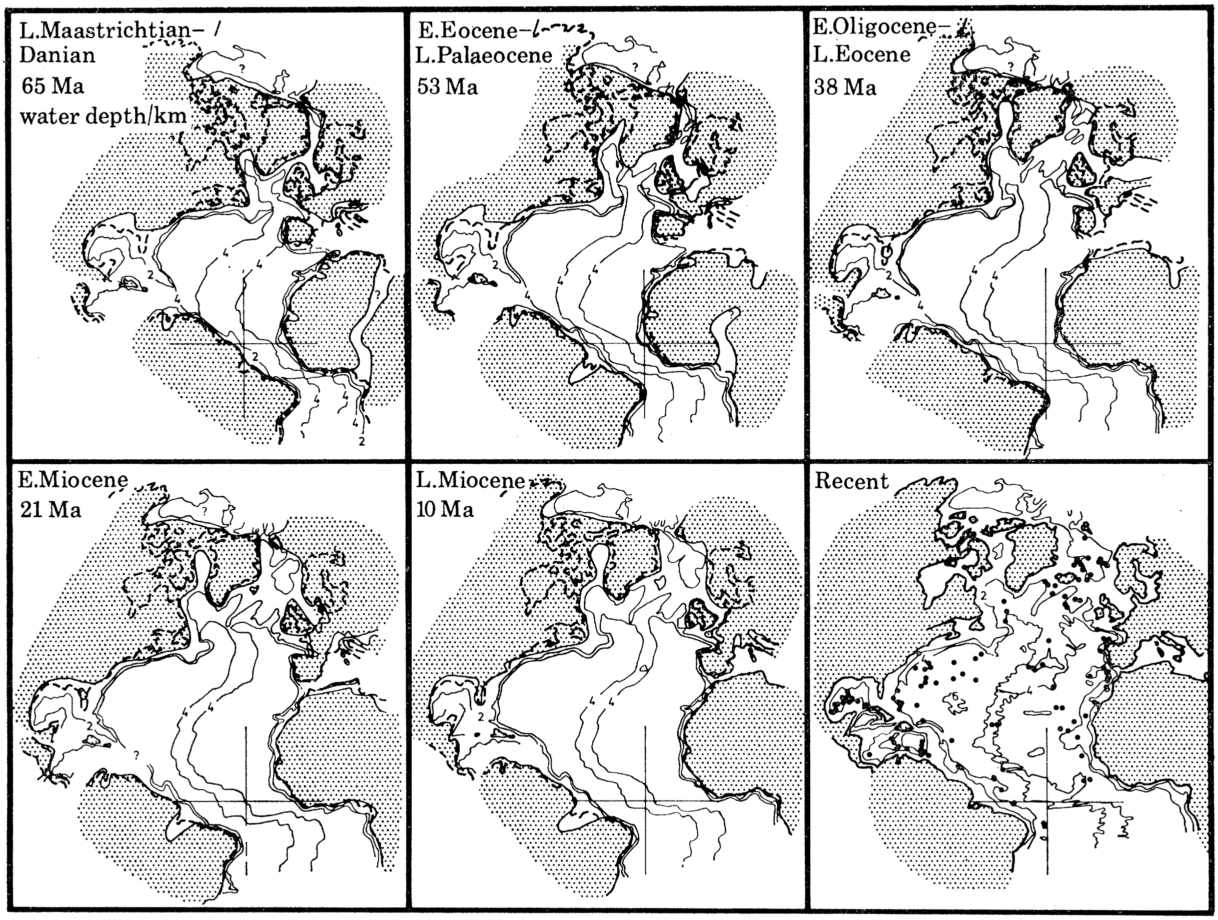

FIGURE 2. Palaeobathymetric and palaeogeographic evolution of the North Atlantic Ocean, the Norwegian–Greenland Seas and their epicontinental seas during the last 65 Ma. For references and sources see text. The dots in the Recent ocean represent sites of the Deep Sea Drilling Project which have been drilled between 1968 and 1977.

At the end of the Mesozoic era the North Atlantic comprised an ocean which was several thousand kilometres wide. The floor of the eastern and western basins had subsided to more than 5 km water depth (Sclater *et al.* 1977). A deep water connection to the South Atlantic had probably been established during Maastrichtian – early Palaeocene times, 60–70 Ma ago (van Andel *et al.* 1977). During that time, openings existed in the east and west to a circum-equatorial seaway commonly known as Tethys (Laubscher & Bernoulli 1977; Donelly 1975). However, the temporal and spatial history of these openings (especially their width and water depth) and the impact of the access of the then circumglobal equatorial surface current system to the oceanography of the North Atlantic are not understood at present (Berggren & Hollister 1974).

During the Late Mesozoic, the North Atlantic was virtually closed at the north because the Norwegian–Greenland Seas did not exist as a deep ocean basin during that time.

The main developments of the Cainozoic North Atlantic consist of the breakup and widening of the Norwegian–Greenland Seas during Palaeocene–Eocene times, the establishment of a deep water connection to the Arctic Ocean during Oligocene–Miocene times, the closure of the circumequatorial Tethys seaway between Europe and Africa and between both Americas, and major changes of the palaeogeography of the epicontinental seas in western Europe, western Africa and in the southern part of North America.

The Early Palaeocene deep North Atlantic consisted of an eastern and western basin which were divided diagonally by the mid-ocean ridge (figure 2). The deep water environment continued as a relatively narrow appendix to the North branching into the Labrador Basin which had opened during Late Cretaceous (Laughton 1975; Vogt & Avery 1974*b*), and into the Rockall Trough which had developed during late Jurassic – early Cretaceous times (Roberts 1975). A shallow shelf sea probably covered a relatively narrow corridor between Europe and Greenland and the North Sea was attached to this seaway (Pegrum *et al.* 1975). The Mediterranean exchanged its water masses with the North Atlantic via the Aquitaine basin, through a gap between Africa and Europe and by way of much disputed seaway across the central Sahara (Machens 1973; Reyment *et al.* 1976; Kogbe 1972; Murat 1972). The Caribbean and the Gulf of Mexico were open to the southwestern North Atlantic since marine Palaeocene sediments have been found to cover the whole southern rim of the North American continent in considerable thickness (Cook & Bally 1975).

During late Palaeocene – early Eocene time the Labrador Basin widened as spreading continued. The Rockall Trough had attained roughly its present shape and size after the spreading axis had jumped to the northwest of the Rockall Plateau during Palaeocene times now separating Greenland and Rockall (Laughton 1975). Talwani & Eldholm (1977) suspect also that spreading started during that time in the Norwegian–Greenland Seas generating the first deep marine troughs between Scandinavia and Greenland. Late Palaeocene – early Eocene faunas on Svalbard (Livsič 1974) prove the existence of a seaway connecting the Arctic Ocean with the growing Norwegian–Greenland Seas and through them with the North Atlantic Ocean. Although thick semi-consolidated sediments have been reported from the Barents Sea (Sundvor 1975), their exact age is not known, and we can only suspect that an arm of the shelf sea along Svalbard stretched into the Barents Sea. The North Sea was invading the central part of northwest Europe and was probably connected to the Bay of Biscay while the pathways between the North Atlantic and the Mediterranean grew narrower.

The Labrador Basin attained its present size during late Eocene – early Oligocene. The youngest magnetic anomalies found in this area suggest that its active spreading ridge ceased by about 47 Ma B.P. (Le Pichon *et al.* 1971) or 38 Ma B.P. (Kristoffersen & Talwani 1977). The widening of the Norwegian–Greenland Seas continued and provided growing space to an oceanic palaeoenvironment which has been documented through the presence of pelagic microfossils in Eocene sediments from the Vøring Plateau (Bjørklund & Kellogg 1972) and from the Lofoten Basin (Talwani *et al.* 1976*a*). It is believed that a predecessor of the Iceland–Faeroe Ridge existed during that time although the parts above sea level might have had a much wider extension than indicated on figure 2 (see discussion below about subsidence of this ridge). The coastline around Norwegian–Greenland Seas probably roughly followed the continental margin with the possible exception of the Barents Sea. In western and middle Europe an extension of the North Sea transgressed over a wide region establishing a seaway to the eastern European epicontinental seas. A narrow seaway which connected northwest Europe with the Alpine–Mediterranean realm, however, existed only for a short time during middle Oligocene (Papp 1959). The pathways from the Mediterranean to the eastern North Atlantic continued to narrow and the Bay of Biscay was finally separated from the Tethys.

During the early Miocene spreading in the North Atlantic and in the Norwegian–Greenland Seas continued and the ocean basins both widened and deepened. The style of spreading varied between the late Eocene – early Oligocene and recent times because both the spreading axis jumped and the direction of spreading changed several times in the region north and south of Iceland (Laughton 1975). How these changes have influenced the morphologic evolution of the growing ocean basin, is not quite clear because of the exceptionally shallow depth of the oceanic basaltic basement in this region.

The early Miocene coastline seems to have followed rather closely the former continental margin along the eastern North Atlantic, with the exception of the shrinking North Sea (Spjeldnaes 1975) and relatively small epicontinental seas in western France. Both the outlet from the Mediterranean (Dewey *et al.* 1973) and the pathway to the tropical Pacific (Malfait & Dinkelman 1972) had become relatively narrow by that time, although the ostracodes observed in the western Mediterranean Oligocene indicate that the pathway was over 2 km deep (Benson 1976).

During the late Miocene the North Atlantic and the Norwegian–Greenland Seas had attained roughly their present size, shape and depth. The pathways of the circumequatorial seaway were virtually closed. The Caribbean and the southern Atlantic did not exchange their water masses with the tropical Pacific any longer (Malfait & Dinkelman 1972) and the Mediterranean dried out to give place to evaporite deposition for a brief period during Late Miocene (Hsü *et al.* 1973). A deep water connection between the Arctic Ocean and the Greenland Sea had finally been established during late Oligocene – early Miocene and continued to widen up to recent times (Talwani & Eldholm 1977). The Iceland–Faeroe Ridge, as a major barrier, inhibited the deep water exchange between the Norwegian–Greenland Seas and the North Atlantic Ocean (cf. Vogt 1972). Iceland is believed to have existed at least for the last 16 Ma (Laughton 1975; Piper 1973). The epicontinental seas in western Europe had approximately the same size as during the early Miocene, the North Sea had attained roughly its present shape and continue its regression by withdrawing from the present northwest European coastlines during Pliocene times. Minor epicontinental basins still existed in southwestern Europe and along the African continental margin.

3. Subsidence of the Iceland–Faeroe ridge

The Iceland–Faeroe Ridge is a structural high separating the Norwegian–Greenland Seas and the main basin of the North Atlantic Ocean. The subsidence of this feature (Vogt 1972; Nilsen 1978) is of utmost importance for the Tertiary palaeo-oceanography of this region, because it is the most important obstacle to the free exchange of the bottom water masses during recent times and because it has probably impeded the surface water circulation during times of low eustatic sea levels owing to its shallow main platform which lies at depths of 400–600 m. The only deep passage is a narrow channel southeast and south of the Faeroe Islands, 800–900 m deep. Talwani *et al.* (1976*b*) have documented the volcanic origin of this feature from basalts encountered under Late Eocene sediments at Site 336. This volcanic origin was presumed many

Table 1. Drill sites Leg 38 of the Deep Sea Drilling Project on the Iceland–Faeroe Ridge (from Talwani *et al.* 1976*b*)

Site no.	latitude/ °N	longitude/ °W	water depth/m	penetration/ m	depth of basement below water surface/m	age of oldest sediment	age of basement/Ma
336	63° 21.1′	07° 47.3′	811	515	1295	mid–late Eocene	43.4 ± 3.3
352	63° 39.0′	12° 28.3′	990	104	Not reached	mid Oligocene	—
352 A	63° 39.0′	12° 28.3′	990	123	Not reached		—

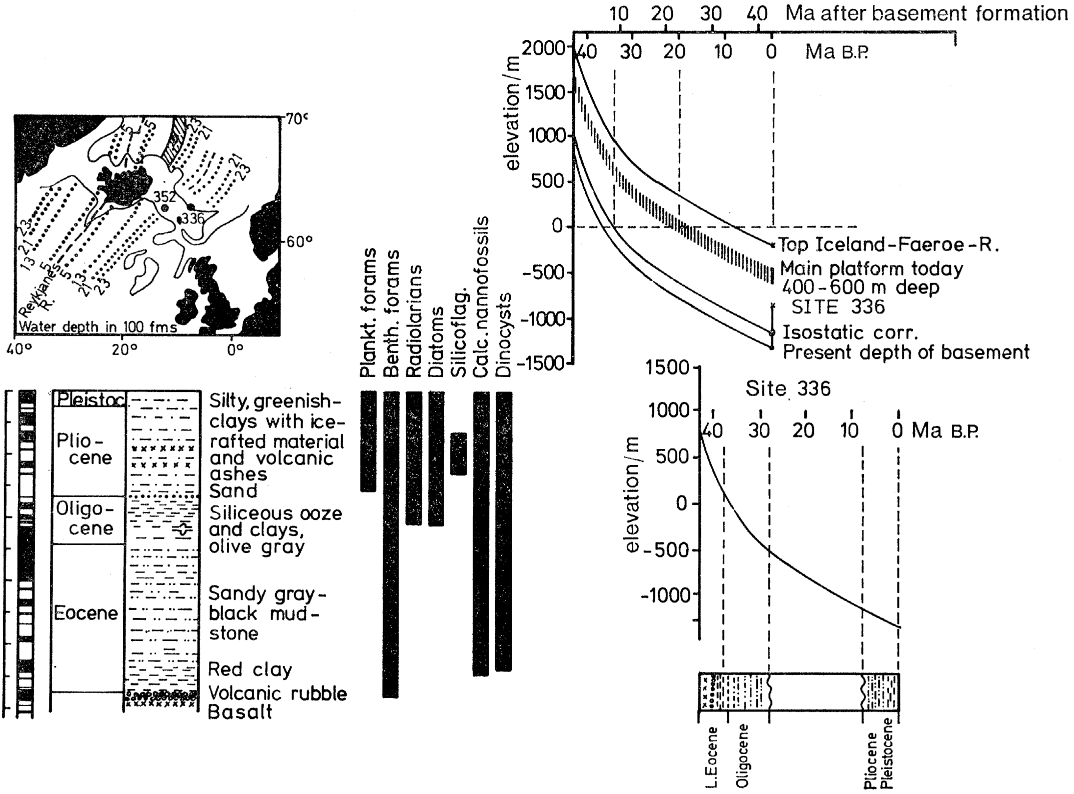

Figure 3. History and subsidence of the Iceland–Faeroe Ridge during the Cainozoic (after data from Talwani *et al.* 1976*b*). The geographic sketch map with magnetic anomalies has been drawn following Talwani & Udintsev (1976) and Talwani & Eldholm (1977).

years ago and this aseismic ridge had therefore been believed to be part of the Thulean basalt province (Noe Nygård 1974) which stretches from Baffin Island to the Fennoscandian border zone. Its origin has been linked to the existence of one or more hot spots which first developed in latest Cretaceous to Palaeocene times (Vogt 1974). The Iceland–Faeroe Ridge links the volcanic rocks of Iceland which are middle Miocene to recent in age (Piper 1973) with the Faeroe Islands which have been built by Early Tertiary subaerial basaltic volcanism (Noe Nygård 1974).

Talwani *et al.* (1976*b*) successfully attempted to sample the volcanic rocks underlying the Iceland–Faeroe Ridge to the north and northwest of the Faeroe Islands (table 1). At Site 336 (figure 3) basaltic rocks were obtained whose composition resembles mid-ocean ridge tholeiites Their age was dated as 43.4 ± 3.3 Ma B.P. which corresponds to the Late Eocene red clayey soil overlying them (Nilsen 1978). If it is correct that the volcanic rocks represent an aseismic ridge originating from oceanic plate volcanism, we can assume that this structure subsided at a rate similar to the surrounding normal oceanic basement, even though the rise is towering several kilometres above the surrounding sea floor (Detrick *et al.* 1977). The curve of subsidence obtained for Site 336 (figure 3) suggests that the site sank below sea level during Late Eocene times, that it crossed a neritic environment during Oligocene times, and that it did not reach water depths of around 1000 m before the Plio–Pleistocene. This subsidence is confirmed by the late Eocene red soil covering the volcanic rubble over the basalts, by Oligocene benthic foraminiferal faunas and by the Plio-Pleistocene sediments (Talwani *et al.* 1976*b*).

The subsidence of an elongate aseismic ridge can only be described completely by a whole family of different subsidence curves whose length and shape is dependent upon the age of the underlying oceanic crust. This age cannot be assessed properly at the present time (Fleischer *et al.* 1974) owing to the complicated and, in part unsolved, spreading history of the ocean basins north and south of the Iceland–Faeroe Ridge (Talwani & Eldholm 1977). However, it can be deduced from the subsidence of Site 336 (situated on the northern flank of this structural high) that the main ridge platform, which towers some 600–700 m above the basement of Site 336, did not sink below sea level before middle Miocene times. Although the ridge became 'leaky' in relation to surface water circulation during this period, the last peaks of the ridge (which lie almost 1 km above the basement at Site 336), submerged not later than the Pliocene (see figure 3). It is very interesting to note that late Oligocene to Pliocene, deposits are missing in the sedimentary record of both sites drilled on the Iceland–Faeroe Ridge. Although it cannot be estimated how long the process generating this hiatus lasted (except that it is bracketed by the ages of the overlying and underlying sediments), the coincidence of the resumption of sedimentation and of the subsidence of the highest peaks of this ridge below sea level does suggest that surface water currents were vigorously eroding sediments from the flanks of the ridge during Miocene and early Pliocene times. Thus results from Site 336 support the idea of a large subaerial aseismic ridge of volcanic origin separating the Norwegian–Greenland Seas from the main North Atlantic Ocean for a long period during early and late Cainozoic times. A primordial Iceland existed, at least twice as long as has been presumed hitherto (Laughton 1975; Talwani & Eldholm 1977). The hypothesis dating from the beginning of this century, of a Tertiary 'land bridge' between North America and Europe (Strauch 1970), can therefore be revived (cf. Vogt 1972). The presence of this barrier is also expressed in the strong Palaeogene floral and faunal gradients between the Norwegian–Greenland Seas and the North Atlantic Ocean (Talwani *et al.* 1976*b*).

4. Discussion: palaeo-oceanography and margin stratigraphy

The quality and resolution of planktonic stratigraphs, dating sediment records from continental margins and from epicontinental seas, depend upon the availability of both calcareous and siliceous pelagic guide fossils. The presence and preservation of the latter is intimately linked to the palaeo-oceanography and then to the palaeoclimate in the border zone between continent and ocean. It is known that the mode of water exchange between marginal seas and the ocean is entirely climate controlled (Seibold 1970) and that the pelagic microfaunas (and floras?) undergo typical changes with respect to their composition and to the phenotypes of their single species when entering the marginal water masses (Murray 1976; Thiede 1972).

Although many details are missing, we can probably assume that the biostratigraphy of Tertiary pelagic sections is relatively well known. We are now close to being able to reconstruct the physiographic evolution of the ocean basins which are accompanied by passive continental margins as exemplified here by the Tertiary North Atlantic Ocean. However, the understanding of the former major water mass distributions, and thus of the palaeobiogeography of the important pelagic fossil groups as well as of the Cainozoic palaeoclimatic evolution of the northern hemisphere, is patchy at best. We are therefore unable to assess the problems of margin stratigraphy to their full extent. These missing variables will be available after samples from all oceanic drill sites have been released and after comparative investigations of epicontinental sea sections have been included in these studies.

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References (Thiede)

Asmus, H. E. & Ponte, F. C. 1973 In Nairn & Stehli (1973), pp. 87–133.
Benson, R. H. 1976 *Mar. Micropal.* **1**, 249–262.
Berggren, W. A. 1972 *Lethaia* **5**, 195–215.
Berggren, W. A. & Hollister, C. D. 1974 *Soc. Econ. Palaeont. Miner. spec. Publ.* **20**, 126–186.
Berggren, W. A. & Hollister, C. D. 1977 *Tectonophysics* **38**, 11–48.
Birkelund, T., Perch-Nielsen, K., Bridgewater, D. & Higgings, A. K. 1974 In Nairn & Stehli (1974), pp. 125–159.
Bjørklund, K. R. & Kellogg, D. E. 1972 *Micropalaeontology* **18**, 386–396.
Bott, M. H. P. 1974 In Kristjansson 1974, pp. 33–47.
Cool, T. D. & Bally, A. W. 1975 *Stratigraphic atlas of North and Central America*, Princeton University Press.
Dalland, A. 1975 *Norg. geol. Unders.* **316**, 271–287.
Dessauvagie, T. F. J. & Whiteman, A. J. 1972 *African geology*. Ibadan: University Geological Department.
Detrick, R. S., Sclater, J. G. & Thiede, J. 1977 *Earth planet. Sci. Lett.* **34**, 185–196.
Dewey, J. F., Pitman, W. C., Ryan, W. B. F. & Bonnin, J. 1973 *Bull. geol. Soc. Am.* **84**, 3137–3180.
Donelly, T. W. 1975 In Nairn & Stehli (1975), pp. 663–689.
Dunn, W. W. 1975 *Norg. geol. Unders.* **316**, 69–97.
Fleischer, U., Holzkamm, I., Vollbrecht, K. & Voppel, D. 1974 *Dt. Hydrogr. Z.* **27**, 97–113.
Hsü, K. J., Ryan, W. B. F. & Cita, M. B. 1973 *Nature, Lond.* **242**, 240–244.
Kogbe, C. A. 1972 In Dessauvagie & Whiteman (1972), pp. 219–227.
Kristjansson, L. 1974 *Geodynamics of Iceland and the North Atlantic area*, Dordrecht: Reidel.
Kristoffersen, Y. & Talwani, M. 1977 *Bull. geol. Soc. Am.* **88**, 1037–1049.
Krömmelbein, K. 1976 *Brinkmanns Abriss der Geologie*. Vol. 2. *Historische Geologie*, Stuttgart: Enke.
Laubscher, H. & Bernoulli, D. 1977 In *The ocean basins and margins*. vol. 4A: *Mediterranean* (ed. A. E. M. Nairn, F. G. Stehli & W. Kanes), pp. 1–28. New York: Plenum.
Laughton, A. S. 1975 *Norg. geol. Unders.* **316**, 169–193.
Le Pichon, X., Hyndman, R. & Pautot, G. 1971 *J. geophys. Res.* **76**, 4724–4743.
Livsič, J. J. 1974 *Norsk Polarinst. Skr.* **159**, 51 pp.
Machens, E. 1973 In Nairn & Stehli (1973), pp. 351–390.

Malfait, B. T. & Dinkelman, M. C. 1972 *Bull. Geol. Soc. Am.* **83**, 251–272.

Mintz, L. W. 1972 *Historical geology*. Columbus: Merill.

Murat, R. C. 1972 In Dessauvagie & Whiteman (1972), pp. 251–266.

Murray, J. W. 1976 *Mar. Geol.* **22**, 103–119.

Nairn, A. E. M. & Stehli, F. G. 1973 *The ocean basins and margins. The South Atlantic*. New York: Plenum.

Nairn, A. E. M. & Stehli, F. G. 1974 *The ocean basins and margins. The North Atlantic*. New York: Plenum.

Nairn, A. E. M. & Stehli, F. G. 1975 *The ocean basins and margins. The Gulf of Mexico and the Caribbean*. New York: Plenum.

Nilsen, T. H. 1978 *Nature, Lond.* **274**, 786-788.

Noe Nygård, A. 1974 In Nairn & Stehli (1974), pp. 391–443.

Papp, A. 1959 *Tertiär, Grundzüge regionaler Stratigraphie*, Handb. Strat. Geol. (ed. F. Lotze), vol. 3. Stuttgart: Enke.

Pegrum, R. M., Rees, G. & Naylor, D. 1975 *Geology of the North-West European continental shelf: The North Sea*. London: Graham Trotman Dudley.

Phleger, F. B 1951 *Geol. Soc. Am. Mem.*, **46**, 88 pp.

Piper, J. D. A. 1973 In *Implications of continental drift to the Earth sciences* (ed. D. H. Tarling & S. K. Runcorn), vol. 2, pp. 635–647. London: Academic Press.

Pitman, W. C. & Herron, E. M. 1974 In Kristjansson (1974), pp. 1–15.

Ponte, F. C. & Asmus, H. E. 1976 *Anais Acad. bras. Cienc.* **48** (suppl.), 215–289.

Reyment, R. A., Bengtson, P. & Tait, E. A. 1976 *Anais Acad. bras. Cienc.* **48** (suppl.), 253–264.

Roberts, D. G. 1975 *Phil. Trans. R. Soc. Lond.* A **278**, 447–509.

Sclater, J. G., Hellinger, S. & Tappscott, C. 1977 *J. Geol.* **85**, 509–552.

Seibold, E. 1970 *Geol. Rdsch.* **60**, 73–105.

Spjeldnaes, N. 1975 *Norg. geol. Unders* **316**, 289–311.

Strauch, F. 1970 *Geol. Rdsch.* **60**, 381–417.

Sundvor, E. 1975 *Norg. geol. Unders.* **316**, 237–240.

Talwani, M. & Eldholm, O. 1977 *Bull. geol. Soc. Am.* **88**, 969–999.

Talwani, M. & Udintsev, G. 1976 *Init. Rep. D.S.D.P.* **38**, 1213–1242.

Talwani, M., Udintsev, G., Bjørklund, K. R., Caston, V. N. D., Faas, R. W., van Hinte, J. E., Kharin, G. N., Morris, D. A., Müller, C., Nilsen, T. H., Warnke, D. A., White, S. M., Løvlie, R., Manum, S. B., Raschka, H., Eckardt, F.-J. & Schrader, H.-J. 1976*a* *Init. Rep. D.S.D.P.* **38**, 151–387.

Talwani, M., Udintsev, G., Bjørklund, K. R., Caston, V. N. D., Faas, R. W., van Hinte, J. E., Kharin, G. N., Morris, D. A., Müller, C., Nilsen, T. H., Warnke, D. A., White, S. M., Løvlie, R., Manum, S. B., Raschka, A., Eckardt, F.-J. & Schrader, H.-J. 1976*b* *Init. Rep. D.S.D.P.* **38**, 23–116.

Thiede, J. 1972 *J. foram. Res.* **2**, 93–102.

Thiede, J. 1977 *Bull. Am. Ass. Petrol. Geol.* **61**, 929–940.

van Andel, T. H., Thiede, J., Sclater, J. G. & Hay, W. W. 1977 *J. Geol.* **85**, 651–698.

van Hinte, J. E. 1976*a* *Bull. Am. Ass. Petrol. Geol.* **60**, 498–516.

van Hinte, J. E. 1976*b* *Bull. Am. Ass. Petrol. Geol.* **60**, 489–497.

Vogt, P. R. 1972 *Nature, Lond.* **239**, 79–81.

Vogt, P. R. 1974 In Kristjansson (1974), pp. 105–126.

Vogt, P. R. & Avery, O. E. 1974*a* In *Marine Geology and Oceanography of the Arctic Seas* (ed. Y. Herman), pp. 83–117. New York: Springer–Verlag.

Vogt, P. R. & Avery, O. E. 1974*b* *J. geophys. Res.* **79**, 363–389.

Watts, A. B. & Ryan, W. B. F. 1976 *Tectonophysics* **36**, 25–44.