

20293

# New Faunal and Isotopic Evidence on the Late Weichselian—Holocene Oceanographic Changes in the Norwegian Sea<sup>1</sup>

HANS PETTER SEJRUP,\* EYSTEIN JANSEN,\* HELMUT ERIENKEUSER,† AND HANS HOLTEDAHL\*

\*Geological Institute, Department B, University of Bergen, Allegt. 41, 5000 Bergen-University, Norway, and †Institute of Nuclear Physics, <sup>14</sup>C-Laboratory, University of Kiel, Olshausenstr. 40-60, D-2300 Kiel, West Germany

Received December 14, 1982

Downcore studies of planktonic and benthonic foraminifera and  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  in the planktonic foraminifer *Neoglobobulimina pachyderma* (sin.) in two piston cores from the southern part of the Norwegian Sea suggest large changes in the oceanic circulation pattern at the end of oxygen-isotope stage 2 and in the early part of stage 1. Prior to oxygen-isotope Termination IA (16,000–13,000 yr B.P.), an isolated watermass with lower oxygen content and temperature warmer than today existed below a low salinity ice-covered surface layer in the Norwegian Sea. Close to Termination IA, well-oxygenated deep water, probably with positive temperatures, was introduced. This deep water, which must have had physical and/or chemical parameters different from those of present deep water in the Norwegian Sea, could have been introduced from the North Atlantic or been formed within the basin by another mechanism than that which forms the present deep water of the Norwegian Sea. A seasonal ice cover in the southern part of the Norwegian Sea is proposed for the period between Termination IA and the beginning of IB (close to 10,000 yr B.P.). The present situation, with strong influx of warm Atlantic surface-water and deep-water formation by surface cooling, was established at Termination IB.

## INTRODUCTION

The faunal and isotopic records in sediment cores from the Norwegian–Greenland Sea and the North Atlantic Ocean clearly indicate that the oceanographic regime in the Norwegian–Greenland Sea has undergone broad changes between glacial and interglacial stages and appears to be sensitively linked with variations of the earth's climate (Schnitker, 1974; Duplessy *et al.*, 1975; Kellogg, 1977, 1980; Kellogg *et al.*, 1978; Duplessy *et al.*, 1980; Belanger, 1982). Today, warm saline Atlantic surface water enters the Norwegian–Greenland Sea over the sills between Iceland and the Shetland Islands. At latitudes between Svalbard and Jan Mayen (Fig. 1), the Atlantic water becomes so dense from surface

cooling that it sinks and fills the abyss of the Norwegian–Greenland Sea and Arctic Ocean. This deep water then flows south into the North Atlantic through the Denmark Strait and beneath the North Atlantic current over the sills between the Shetland Islands and Iceland. It is the main constituent of North Atlantic deep water (NADW), which occupies much of the deep-water sphere of the Atlantic Ocean. The Norwegian Sea and areas around Antarctica, where deep water is formed by sea-water freezing, are today the most important deep-water sources for the world oceans.

Downcore variations of planktonic foraminifera composition in Norwegian Sea sediments (Kellogg, 1977, 1980) indicate that the subpolar fauna linked to warm Atlantic water entered the Norwegian Sea only two times during the last 440,000 yr: at the peak of interglacial oxygen-isotope

<sup>1</sup> Contribution No. 414 of the Sonderforschungs-ber-  
reich 95 "Interaction Sea–Sea Bottom" from the Uni-  
versity of Kiel.



stage 5e (Eemian) and at stage 1 (Holocene). It has also been shown by means of benthonic foraminifera that the typical NADW as known today was not present in the Atlantic during much of the last glaciation (Streeter, 1973; Schnitker, 1974, 1979). Studies of oxygen isotopes in foraminiferal tests from cores from the Norwegian Sea and the North Atlantic (Duplessy *et al.*, 1975, 1980) support the faunal evidence that deep-water formation was limited or did not take place in the glacial Norwegian Sea. Weyl (1968) and Newell (1974) have proposed models which link climatic fluctuations through the Quaternary with the circulation in the deep-water sphere by considering possible alterations of either the characteristics of deep-water sources or their locations. Investigating the changes in deep-water formation in the Norwegian-Greenland Sea through glacial-interglacial transitions may shed light on the feedback mechanisms governing the interaction of

the earth's climate subsystems and may greatly aid in understanding and evaluating the role of the ocean in climatic variations.

#### MATERIALS AND CHRONOSTRATIGRAPHIC FRAMEWORK

This paper will focus on the foraminiferal stratigraphy in two piston cores from the southeastern slope of the Norway Basin in the Norwegian Sea (Fig. 1). A detailed description of the lithostratigraphy in these cores is given in Jansen *et al.* (in press). Core 31-36 (2620 m depth) is 530 cm long. Its lower 526 cm consists of a nonsorted sediment (diamicton) which is interpreted to be of glaciomarine origin. The top 4 cm consists of  $\text{CaCO}_3$ -rich foraminiferal ooze. Core 31-33 (1580 m depth) is 575 cm long and reveals the following lithological units: diamicton, 575-60 cm, pelitic sediment, 60-5 cm, and foraminiferal ooze, 5-0 cm. In both cores a volcanic ash zone was re-

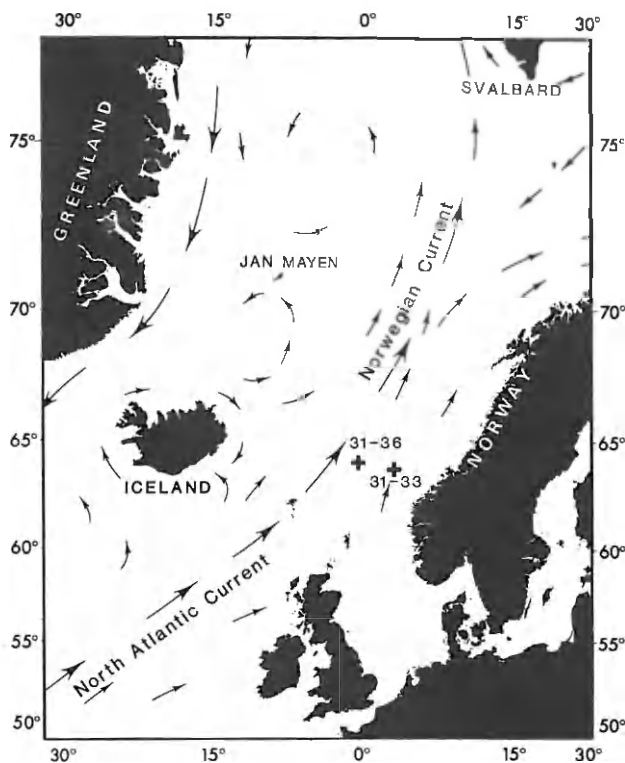


FIG. 1. Map of the Norwegian Sea showing locations of the investigated cores.

corded slightly below the ooze. This ash zone, which is situated between 7 and 9 cm in core 31–36 and between 5 and 7 cm in core 31–33, has been recorded at the same stratigraphic level in several other cores from the continental shelf and slope off western Norway (Jansen *et al.*, in press). Both cores were examined with X rays and no signs of turbidites were found.

To provide information on the paleocirculation both at the surface and in the deeper part of the Norwegian Sea, planktonic and benthonic foraminifera have been analyzed in the two cores. The results of these analyses, together with the oxygen- and carbon-isotope records of the planktonic foraminifer *Neogloboquadrina pachyderma* (sin.), are shown in Figures 2 and 3. The isotope data are also given in Tables 1 and 2. The time framework for the cores is based on three lines of evidence.

### 1. Oxygen-Isotope Stratigraphy

Both cores display a stepwise change from heavy glacial isotopic values to the light values found in the postglacial unit. The heaviest  $\delta^{18}\text{O}$  values of *N. pachyderma* (sin.) in core 31–36 are found just below this transitional zone and are close to those found by Kellogg *et al.* (1978) for this species in isotope stage 2 in sediments from central parts of the Norway Basin. The glacial extreme of the  $\delta^{18}\text{O}$  value is slightly lighter (about 0.5‰) in the shallower-lying core 31–33 which also shows a less distinct downcore pattern in both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  compared with core 31–36. Glacial reworking and downslope transport of older interglacial and meltwater-influenced material from shelf areas could account for this feature. Plankton tows and calculations of isotopic temperatures indicate a deep habitat for *N. pachyderma* (Kellogg *et al.*, 1978). Mean temperature for the upper 300 m of the water column over the coring sites is between 7° and 9°C (Sælen, 1963; Mosby, 1959). Using the paleotemperature equation of Shackleton (1974), we obtain an isotopic temperature of 9.4°C for the top

sample of core 31–33, which is close to the expected Holocene value, whereas the top sample of core 31–36 only gives 3.8°C. A slow sedimentation rate and loss of the top sediment during coring may have prevented the top sample of core 31–36 from fully attaining the expected Holocene level. Both cores display a two-step trend in  $\delta^{18}\text{O}$  values which also have been recorded at the transition from stage 2 to 1 in the Atlantic (Berger, 1978; Jones and Ruddle, 1982). However, we note that the values at the plateau between the two steps are about 1‰ lighter in core 31–33 than in 31–36. This feature is difficult to explain as the two cores are situated quite close to each other. Differences in input of redeposited planktonic foraminifera and (or) strong gradients in the upper water masses may be possible explanations. However, correlations both to foraminiferal markers and to the ash layer show that the two steps occur at the same stratigraphic level. Therefore we correlate our two steps with Termination IA and IB in the Atlantic (Duplessy *et al.*, 1981) and use them for timing foraminiferal events. Detailed dating of cores from the North Atlantic (Duplessy *et al.*, 1981) and off West Africa (Sarnthein *et al.*, in press) indicates that Termination IA, the first deglacial step, took place between 16,000 and 13,000 yr B.P. The second step, Termination IB, occurred between 10,000 and 8000 yr B.P. The substages of Termination I appear to be quite synchronous within the resolution of the  $^{14}\text{C}$ -age determinations in the west African and North Atlantic cores. With regard to the southerly position of the coring sites in the Norwegian Sea and their proximity to the North Atlantic, we will assume that the basic isotopic signals follow the same time schedule without any major time lag.

### 2. Volcanic Ash Zone

The volcanic ash zone, which must record a large volcanic event somewhere in the Norwegian Sea area, is a good stratigraphic marker in cores from the Norwe-

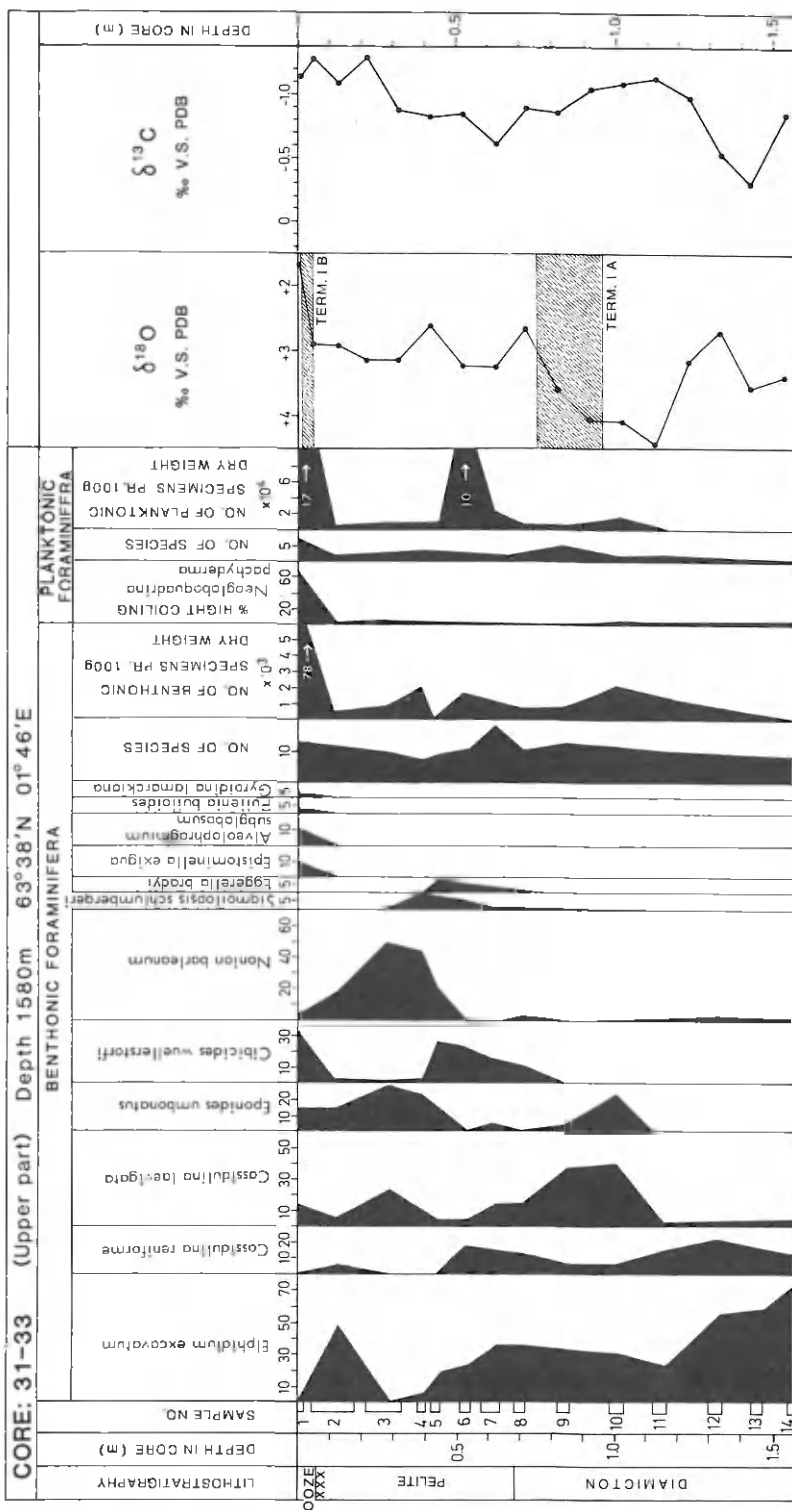


FIG. 2. Distribution of selected taxa of benthonic and planktonic foraminifera in the upper 1.5 m of core 31-33. The measurements of δ<sup>18</sup>O and δ<sup>13</sup>C have been performed on *N. pachyderma* (sm.). XXX indicates the position of the volcanic ash zone.

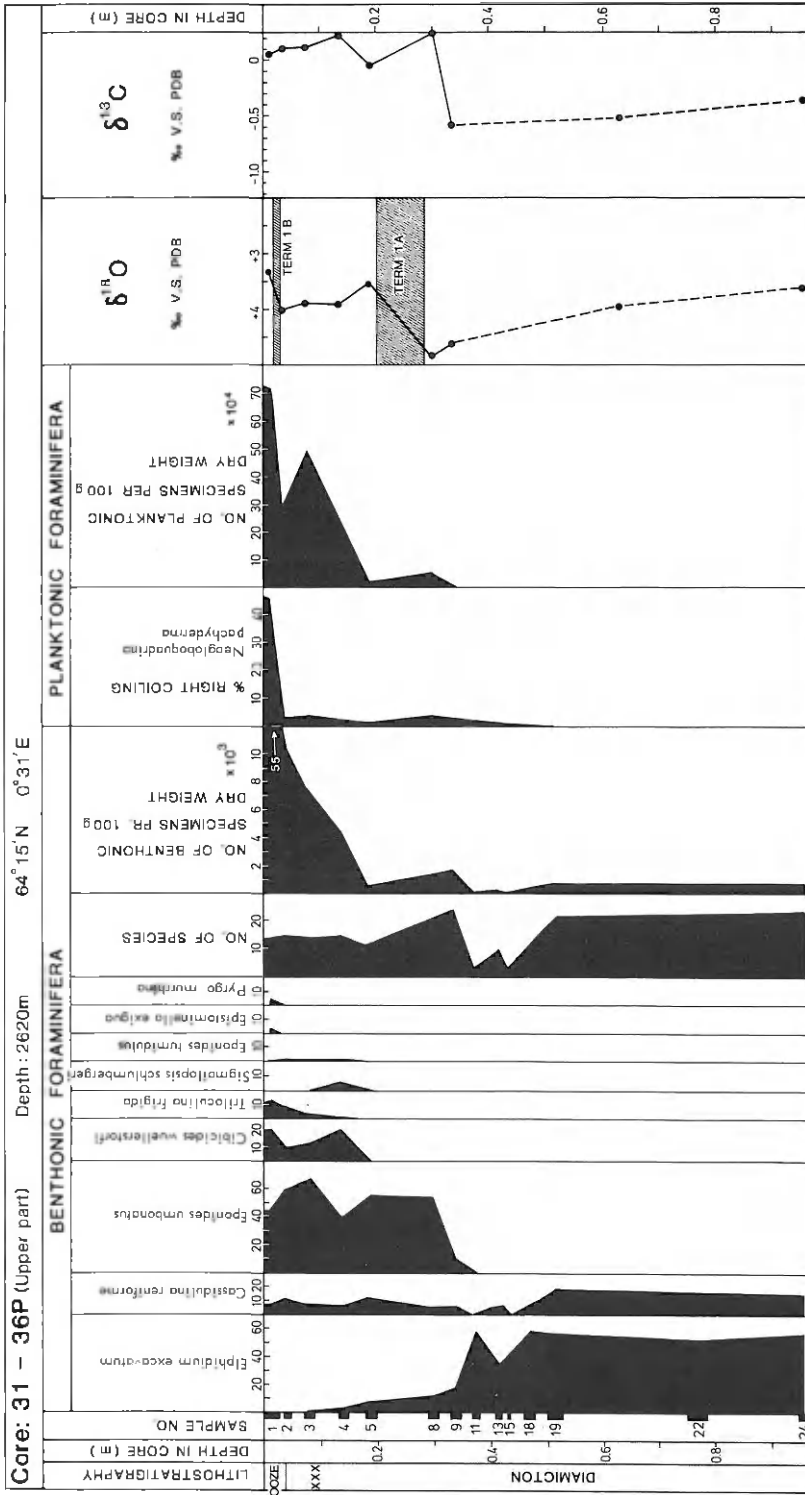


FIG. 3. Distribution of selected taxa of benthonic and planktonic foraminifera in the upper 90 cm of core 31-36. The measurements of  $\delta^{18}O$  and  $\delta^{13}C$  have been performed on *N. pachyderma* (sin.). XXX indicate the position of the volcanic ash zone.

TABLE 1. OXYGEN AND CARBON ISOTOPE DATA IN *N. pachyderma* (SIN.) FROM CORE 31-36

Sample No.	Depth in core (cm)	$\delta^{18}\text{O}$ (‰ vs PDB)	$\delta^{13}\text{C}$ (‰ vs PDB)
1	0-2	+3.32	+0.06
2	3-4	+4.00	+0.11
3	8-10	+3.97	+0.12
4	13-15	+3.90	+0.23
5	17-19	+3.54	-0.04
8	29-31	+4.88	+0.24
9	34-35	+4.62	-0.59
21	65-67	+3.99	-0.52
24	95-96	+3.51	-0.35

gian Sea and the Norwegian continental margin. Radiocarbon dates of marine mollusks found in cores from the continental margin off western Norway indicate that deposition of the ash took place just prior to 10,000 yr B.P. (Jansen *et al.*, in press). In cores 31-33 and 31-36, the ash layer is situated just below Termination IB, the beginning of which is dated to about 10,000 yr B.P. Mangerud *et al.* (in press) have recorded an ash horizon in lake deposits in western Norway with  $^{14}\text{C}$  dates indicating an age close to 10,600 yr B.P. Geochemical analyses indicate that the ash in the marine

cores and in the limnic sediments record the same volcanic event on Iceland. Thus the ash zone can be used for stratigraphic correlation.

### 3. Correlation with $^{14}\text{C}$ -Dated Cores

Cores 31-36 and 31-33 have been correlated by means of biostratigraphic criteria with  $^{14}\text{C}$ -dated cores from the continental shelf and slope in the same area (Jansen *et al.*, in press). These dates also support the chronostratigraphy of the two cores suggested by the oxygen-isotope record and by the age of the ash layer.

TABLE 2. OXYGEN AND CARBON ISOTOPE DATA IN *N. pachyderma* (SIN.) FROM CORE 31-33

Depth in core (cm)	$\delta^{18}\text{O}$ (‰ vs PDB)	$\delta^{13}\text{C}$ (‰ vs PDB)
0-2	+1.64	+0.14
3-5	+2.89	+0.28
10-13	+2.90	+0.09
20-23	+3.13	+0.30
30-33	+3.14	-0.12
40-43	+2.61	-0.18
50-53	+3.23	-0.14
60-63	+3.26	-0.39
70-73	+2.66	-0.11
80-83	+3.64	-0.14
90-93	+4.09	+0.06
100-104	+4.08	+0.09
110-114	+4.44	+0.14
120-124	+3.18	-0.01
130-134	+2.62	-0.46
140-144	+3.56	-0.69

## FAUNAL AND ISOTOPIC CHANGES

### Pre-Termination IA

The lower part of both cores (Figs. 2 and 3) reveals a benthonic foraminiferal assemblage poor in the number of individuals and relatively rich in the number of species. It is dominated by *Elphidium excavatum* and other species common to arctic shelf areas and also exhibits a high percentage of pre-Quaternary species. This indicates that the assemblage is derived largely from glacial erosion on the continental shelf off Norway and by iceberg transport. Investigations from other parts of the Norwegian Sea show that the dominance of displaced benthonic species in the glacial parts of cores 31-36 and 31-33 is a regional phenomenon which in the Weichselian first occurs somewhere in oxygen-isotope stage 3 or 4

(Streeter *et al.*, 1982). Our data reveal that the Norwegian Sea was reinhabited by typical benthonic deep-sea species, such as *Cibicides wuellerstorfi* and *Eponides umbonatus*, just before or within Termination IA.

The suppression of the benthonic fauna prior to Termination IA is difficult to explain, as no analog is known from the deep oceans today. Low planktonic foraminiferal production, together with high dominance of *N. pachyderma* (sin.), indicate a year-round sea-ice cover (Kellogg, 1977). Belanger (1982) presents evidence that the productivity of the presumably ice-covered Norwegian Sea was very low during much of the last glacial stage, and he considers this an ecological factor possibly accounting for the absence of the benthonic species *C. wuellerstorfi*. On the other hand, an ice cover does not, in general, appear to suppress a typical deep-sea assemblage, as is shown for the Arctic Ocean where a rich benthonic fauna exists today under a year-round ice-covered sea (Lagoe, 1977). Also, temperature changes are unlikely to have basically affected the benthonic foraminiferal fauna, as glacial temperatures of the deep water of the Norwegian Sea cannot have been much lower than today ( $-1^{\circ}\text{C}$ ), but rather were higher by several degrees (Duplessy *et al.*, 1975).

Another and probably more crucial ecological factor is the oxygen content of the deep water. Streeter and Shackleton (1979) have considered the abundance of *C. wuellerstorfi* to be indicative of oxygen availability in the bottom water of the North Atlantic. The poorly developed benthonic foraminiferal assemblage in the Norwegian Sea might thus be explained by hypothesizing that during glacial isotope stages 2, most of 3, and part of 4 (Belanger, 1982), the deep water of the Norwegian Sea was isolated from the North Atlantic water masses. A stable thermo-haline stratification could have prevented deep-water formation, and the deep water of the Norwegian Sea hence became depleted in oxygen.

A steady outflow of meltwater from the large ice sheets draining to the Norwegian Sea and the Arctic Ocean could have created a sort of "fjord situation" characterized by a relatively low-oxygen-content water mass under a low-salinity surface layer, with the shallow ridges between Scotland and Iceland acting as sills for the "fjord ocean." The stable carbon-isotope record of the deep-dwelling *N. pachyderma* reveals lighter  $\delta^{13}\text{C}$  values for the glacial sections below Termination IA than above (average difference about 0.5‰). One explanation for this could be an enhanced accumulation in the water of  $\text{CO}_2$  from decomposition of isotopically light organic matter, thereby pointing to poor renewal of the water body and correspondingly lower  $\text{O}_2$  content, as explained by Kroopnich (1980) and by Shackleton *et al.* (in press). This view would be in accordance with the conclusions based on the composition of the benthonic foraminiferal fauna. Similar glacial-to-interglacial changes in  $\delta^{13}\text{C}$ , both in benthonic and deep-dwelling planktonic foraminifera, have been found in other basins and have been explained by enhanced accumulation of biologically fixed carbon on land (Shackleton, 1977) or in the sea (Broecker, 1981) in interglacial times. Cores from outside the Norwegian-Greenland Sea (Shackleton, 1977); from the Sierra Leone rise, eastern Atlantic and off western Australia (H. Erlenkeuser, unpublished data), show glacial-to-interglacial  $\delta^{13}\text{C}$  changes that lag behind or are synchronous with the respective  $\delta^{18}\text{O}$  transitions. In contrast, the  $\delta^{13}\text{C}$  increase at Termination IA in our cores from the Norway Basin seems to precede the deglaciation response of  $\delta^{18}\text{O}$ . Hence, this pattern may not simply reflect a worldwide glacial-to-interglacial variation in the carbon isotope ratio but rather may indicate more local changes in the oceanographic regime. It may reflect a rejuvenation of the water masses at the habitat depth of *N. pachyderma* and possibly signals temporary open-water conditions.



### Termination IA to IB

The composition of the benthonic fauna began to change just prior to Termination IA. The benthonic species which then immigrated into the Norwegian Sea have a wide distribution in the world's oceans today (Figs. 2 and 3). *C. wuellerstorfi* and *E. umbonatus* are the main constituents of the benthonic fauna above 40 cm in core 31–36. In core 31–33, from a 1580-m water depth, *Cassidulina laevigata* appears at the same level as *E. umbonatus*. The present depth habitat of *C. laevigata* in the Norwegian Sea (Belanger and Streeter, 1980; Sejrup *et al.*, 1981) is restricted to water depths shallower than 1600 m. The high abundance of *Nonion barleeaanum* in the pelitic sediment unit of core 31–33 corresponds to the modern habitat of this species in areas with rapid pelitic sedimentation on the slope off Norway (Sejrup *et al.*, 1981). Data from the upper slope (Jansen *et al.*, in press) also show a distinct depth zonation among the benthic organisms which migrated into the area close to Termination IA. Prior to this, the *Elphidium* assemblage dominated at all depths along the continental margin off western Norway. Elements of the *Elphidium* assemblage are still present in cores 31–36 and 31–33 but gradually decrease relative to the normal deep-sea fauna (except for one sample, apparently more affected by redeposition, in the upper part of core 31–33). The large changes in the relative abundance of *C. wuellerstorfi* and *E. umbonatus* have also been recorded by Streeter *et al.* (1982) in cores from the Norwegian Sea and were suspected to result from changes in sedimentation rate and nutrient supply. Two benthonic species, *Eggerella bradyi* and *Sigmoilopsis schlumbergeri*, appear in cores 31–36 and 31–33 and in several other cores (Jansen *et al.*, in press) between Termination IA and the ash zone. Except for one occurrence of *E. bradyi* in one sample (Sejrup *et al.*, 1981), in which it could have been derived from older units, these species have not been reported in the deep-sea

fauna of the present Norwegian Sea, the Greenland Sea, or the Arctic Ocean (Sejrup *et al.*, 1981; Belanger and Streeter, 1980; Lagoe, 1977). Both species, however, are common constituents in the recent faunas of the North Atlantic (Phleger *et al.*, 1953).

The benthonic fauna also changes just above the ash layer. *C. wuellerstorfi*, *E. umbonatus*, and *C. laevigata* are still the dominant elements but *E. bradyi* and *S. schlumbergeri* have disappeared and a number of new species such as *Triloculina frigida*, *Alveolophragmium subglobosum*, and *Epistominella exigua* appear.

The planktonic fauna shows an increase both in the number of species and in the number of individuals at the base of Termination IA, but *N. pachyderma* (sin.) is still the dominant element. This could be explained by seasonally longer ice-free periods and/or higher temperatures in the upper parts of the water column.

### Post-Termination IB

The change to a planktonic fauna dominated by *N. pachyderma* (dex.) does not take place until just after the deposition of the ash layer. This is in accordance with the observations of Sejrup *et al.* (1980), who suggested an age close to 10,000 yr for this faunal boundary, referring to <sup>14</sup>C dates on material from the continental shelf off Norway. Kellogg (1976), Ruddiman and McIntyre (1976), and Ruddiman *et al.* (1977) have used this faunal boundary to determine the paleoposition of the oceanic polar front. Using the same criteria as these authors, our data conflict with Mangerud's (1977) conclusion based on studies of littoral mollusks that the polar front attained a more northerly position in the Norwegian Sea between 12,600 and 11,000 yr B.P.

### SUMMARY AND CONCLUSIONS

The faunal data from two cores from the southeastern slope of the Norway Basin off southern Norway revealed low production rates of foraminifera under peak glacial conditions. The dominance of *N. pachy-*

*derma* (sin.), the lack of *C. wuellerstorfi* and of other common deep-water benthonic foraminifera species, and the comparatively light carbon-isotope composition of *N. pachyderma* (sin.) suggest that in glacial isotope stage 2 the Norwegian Sea was essentially isolated from North Atlantic waters and suffered from low availability of oxygen.

Shortly before Termination IA (16,000–13,000 yr B.P.), abundances of benthonic and planktonic foraminifera (relative to sediment weight) increase, but still remain at a low level until Termination IB (ca. 10,000 yr B.P.). At the same time, some of the common benthonic foraminiferal species indicative of North Atlantic deep-water recolonized the abyss of the Norwegian Sea. The enrichment of  $^{13}\text{C}$  in *N. pachyderma* (sin.) at the base of or shortly above Termination IA and the reappearance of several benthonic species slightly later point to an improved supply of oxygen-rich water to the deeper parts of the Norwegian Sea. However, the still-reduced variety of benthonic foraminifera and the lack of a sub-polar planktonic assemblage indicate that the Holocene pattern of water circulation had not yet developed in the Norwegian Sea.

The occurrence in late-glacial sediments off Norway of benthonic species which are not found in the present Norwegian Sea, but are well known in the deeper parts of the North Atlantic, is likely to indicate deep-water temperatures higher than at present. Duplessy *et al.* (1981) have suggested that in the glacial periods bottom water with temperatures of about  $+1.3^{\circ}\text{C}$  was formed in the North Atlantic. Overflow of this water mass northward into the basins of the Norwegian Sea could have occurred at an increased rate between Termination IA and IB when the polar front was situated farther north and much closer to the Iceland–Faroe Ridge than during peak glacial conditions (Ruddiman *et al.*, 1977). This could explain the “Atlantic” benthonic species found in the late-glacial Norwegian Sea.

It is only since Termination IB (or the end of the Younger Dryas interval) that abundances and composition of both benthonic and planktonic foraminifera and, in particular, the dominance of the dextral-coiling *N. pachyderma*, have given evidence for the establishment of the Norwegian current and hence the modern pattern of circulation.

Our data suggest that the late-glacial circulation pattern in the Norwegian Sea was substantially different from both the full-glacial and full-interglacial regimes. It may represent “interstadial” conditions and may similarly have prevailed during parts of oxygen-isotope stages 5a–d and 4 (Belanger, 1982). Recent work on raised marine deposits in western Norway indicates a very complex history of the Weichselian, with several interstadial sequences, each one represented by a rich marine fauna and embedded between tills (Mangerud, 1981; Andersen *et al.*, 1983; Miller *et al.*, 1983). Future research will show if these interstadials are also reflected by faunas similar to those of the late glacial in the Norwegian Sea and a corresponding northerly position of the polar front in the North Atlantic.

#### ACKNOWLEDGMENTS

The figures were made by Ellen Irgens, Jane Ellingsen, and Masaoki Adachi. The manuscript was typed by Solveig Helland and Ellen Altheim. Dr. Gifford Miller, Arne Rasmussen, and Dr. Bjørn G. Andersen critically read the manuscript and made suggestions for improvements. The work was financially supported by the Norwegian Research Council for Science and Humanities (NAVF) and Deutsche Forschungsgemeinschaft (DFG). To all these persons and institutions we offer our sincere thanks.

#### REFERENCES

- Andersen, B. G., Sejrup, H. P., and Kirkhus, Ø. (1983). Eemian and Weichselian deposits at Bø on Karmøy, SW Norway: A preliminary report. *Norges Geologiske Undersøkelse* 380, 189–201.
- Belanger, P. E. (1982). Paleo-oceanography in the Norwegian Sea during the past 130,000 yr: Cocolithophorid and foraminiferal data. *Boreas* 11, 29–36.
- Belanger, P. E., and Streeter, S. S. (1980). Distribution and ecology of benthic foraminifera in the Nor-

- wegian-Greenland Sea. *Marine Micropaleontology* **5**, 401-425.
- Berger, W. H. (1978). Oxygen-18 stratigraphy in deep-sea sediments: Additional evidence for the deglacial meltwater effect. *Deep-Sea Research* **25**, 473-480.
- Broecker, W. S. (1981). Glacial to interglacial changes in ocean chemistry. *Progress in Oceanography* **11**, 151-179.
- Duplessy, J. C., Chenouard, L., and Vila, F. (1975). Weyl's theory of glaciation supported by isotopic study of Norwegian Sea core K 11. *Science* **188**, 1208-1209.
- Duplessy, J. C., Delibiras, G., Turon, J. L., Pujol, C., and Duprat, J. (1981). Deglacial warming of the northeastern Atlantic Ocean: Correlation with the paleoclimatic evolution of the European continent. *Palaeogeography, Palaeoclimatology, Palaeoecology* **35**, 121-144.
- Duplessy, J. C., Moyes, J., and Pujol, C. (1980). Deep water formation in the North Atlantic Ocean during the last Ice Age. *Nature (London)* **286**, 479-482.
- Jansen, E., Sejrup, H. P., Fjæran, T., Hald, M., Holtedahl, H., and Skarbø, O. (in press). Late Weichselian paleoceanography of the southeastern Norwegian Sea. *Norsk Geologisk Tidsskrift*.
- Jones, G. A., and Ruddiman, W. F. (1982). Assessing the global meltwater spike. *Quaternary Research* **17**, 148-177.
- Kellogg, T. B. (1976). Late Quaternary climatic changes: Evidence from deep-sea cores of Norwegian and Greenland seas. In "Investigation of Late Quaternary Paleoceanography and Paleoclimatology" (R. M. Cline and J. E. Hays, Eds.). *Geological Society of America Memoir* **145**, 77-110.
- Kellogg, T. B. (1977). Paleoclimatology and paleoceanography of the Norwegian and Greenland seas: The last 450,000 yr. *Marine Micropaleontology* **2**, 235-249.
- Kellogg, T. B. (1980). Paleoclimatology and Paleoceanography of the Norwegian and Greenland seas: Glacial-interglacial contrasts. *Boreas* **9**, 115-137.
- Kellogg, T. B., Duplessy, J. C., and Shackleton, N. J. (1978). Planktonic foraminiferal and oxygen isotopic stratigraphy and paleoclimatology of Norwegian Sea deep-sea cores. *Boreas* **7**, 61-73.
- Kroopnich, P. (1980). The distribution of  $^{13}\text{C}$  in the Atlantic Ocean. *Earth and Planetary Science Letters* **49**, 469-484.
- Lagoe, M. B. (1977). Recent benthonic foraminifera from the central Arctic Ocean. *Journal of Foraminiferal Research* **7**, 106-129.
- Mangerud, J. (1977). Late Weichselian marine sediments containing shells, foraminifera and pollen at Ågotnes, western Norway. *Norsk Geologisk Tidsskrift* **57**, 23-54.
- Mangerud, J. (1981). The early and middle Weichselian in Norway: A review. *Boreas* **10**, 381-393.
- Mangerud, J., Lie, S. E., Furnes, H., Kristiansen, I. L., and Lømo, L. (in press). A younger Dryas ash bed in western Norway, with possible correlations to the Norwegian Sea and the North Atlantic. *Quaternary Research*.
- Miller, G. H., Sejrup, H. P., Mangerud, J., and Andersen, B. G. (1983). Amino acid ratios in Quaternary molluscs and foraminifera from western Norway: Correlation, geochronology and paleotemperatures estimates. *Boreas* **12**, 107-124.
- Mosby, H. (1959). Deep water in the Norwegian Sea. *Geofysiske Publikasjoner* **21**, 3.
- Newell, R. E. (1974). Changes in the poleward energy flux by the atmosphere and ocean as a possible cause for ice ages. *Quaternary Research* **4**, 117-127.
- Pfleger, F. B., Parker, F. L., and Peirson, J. F. (1953). North Atlantic foraminifera. *Reports of the Swedish Deep-Sea Expedition* **7**, 1-122.
- Ruddiman, W. F., and McIntyre, A. (1976). Northeast Atlantic paleoclimatic changes over the past 600,000 yr. In "Investigations of Late Quaternary Paleoceanography and Paleoclimatology" (R. M. Cline and J. D. Hays, Eds.). *Geological Society of America Memoir* **145**, 111-146.
- Ruddiman, W. F., Sancetta, C. D., and McIntyre, A. (1977). Glacial/interglacial response rate of subpolar North Atlantic waters to climatic change: The record in oceanic sediments. *Philosophical Transactions of the Royal Society of London Series B* **280**, 119-142.
- Sarnthein, M., Erlenkeuser, H., and Zahn, R. (in press). Termination I: The response of continental climate in the subtropics as recorded in deep-sea sediments. *Bulletin of the Institut de Geologie du Bassin d'Aquitaine*.
- Schnitker, D. (1974). West Atlantic abyssal circulation during the past 120,000 years. *Nature (London)* **248**, 385-387.
- Schnitker, D. (1979). The deep water of the western North Atlantic during the past 24,000 years, and the reinitiation of the western boundary undercurrent. *Marine Micropaleontology* **4**, 265-280.
- Sejrup, H. P., Fjæran, T., Hald, M., Beck, L., Hagen, J., Miljeteig, I., Morvik, I., and Norvik, O. (1981). Benthonic foraminifera in surface samples from the Norwegian continental margin between 62°N and 65°N. *Journal of Foraminiferal Research* **11**(4), 277-295.
- Sejrup, H. P., Holtedahl, H., Norvik, O., and Miljeteig, I. (1980). Benthonic foraminifera as indicators of the paleoposition of the Subarctic Convergence in the Norwegian-Greenland Sea. *Boreas* **9**, 203-207.
- Shackleton, N. J. (1974). Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina*: Isotopic changes in the ocean during the last glacial. *Centre National de la Recherche Scientifique Colloques Internationaux*, **219**.

- Shackleton, N. J. (1977). The oxygen isotope stratigraphic record of the late Pleistocene. *Philosophical Transactions of the Royal Society of London* **3280**, 169–182.
- Shackleton, N. J., Imbrie, J., and Hall, M. A. (in press). Oxygen and carbon isotope record of Core V 19-30: Implications for the formation of deep water in the late Pleistocene North Atlantic. *Earth and Planetary Science Letters*.
- Streeter, S. S. (1973). Bottom water and benthonic foraminifera in the North Atlantic: glacial–interglacial contrasts. *Quaternary Research* **3**, 131–141.
- Streeter, S. S., Belanger, P. E., Kellogg, T. B., and Duplessy, J. C. (1982). Late Pleistocene Paleooceanography of the Norwegian–Greenland sea: Benthic foraminiferal evidence. *Quaternary Research* **18**, 72–90.
- Streeter, S. S., and Shackleton, N. J. (1979). Paleocirculation of the deep North Atlantic; 150,000-Year record of benthic foraminifera and oxygen-18. *Science* **203**, 168–173.
- Sælen, O. H. (1963). Studies in the Norwegian Atlantic current, Part II: Investigations during the years 1954–1959 in an area west of Stad. *Geofysiske Publikasjoner* **23**.
- Weyl, P. K. (1968). The role of the oceans in climatic change: A theory of the ice ages. *Meteorological Monographs* **8**, 30, 37–62.