Biostratigraphy and environment of the Holocene marine transgression in the Heligoland Channel, North Sea

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Konradi, P.B. 2000–09–18: Biostratigraphy and environment of the Holocene marine transgression in the Heligoland Channel, North Sea. *Bulletin of the Geological Society of Denmark*, Vol. 47, pp. 71–79. Copenhagen. https://doi.org/10.37570/bgsd-2000-47-05

A 51 m deep borehole in the outer Heligoland Channel, south-eastern North Sea, penetrated 17 m of marine Holocene, laminated, clayey silt and silty fine sand followed by 34 m of Pleistocene, fluvial sand. Samples from the two units were investigated for their content of foraminifers. The fluvial sand yielded only reworked foraminifers and, based on these is divided into two parts that can be related to differences in lithology. Based on the study of the foraminiferal assemblages in 20 samples, the marine unit is divided in five foraminiferal assemblage zones reflecting the marine inundation into this part of the North Sea after the last glaciation. The basal part of the unit is strongly influenced by freshwater and the lowermost part is dated to *c.* 11.0 cal. ka BP. The freshwater influence diminishes uphole with deposition of beds characteristic of a tidal flat environment in an estuarine setting with slowly increasing sedimentation depth. A subsequent sudden change in the fauna indicating higher salinity and a more open-marine environment is interpreted to reflect a change in the hydrographic situation. The basal part of this zone is dated to *c.* 8.6 cal. ka BP. A continuation of this trend is observed in the following zones with further increasing sedimentation depth. The fauna in the topmost assemblage zone indicates an environment comparable to the present conditions in this area of the North Sea.

Key words: Foraminifera, biostratigraphy, environment, radiocarbon dating, sea level, Quaternary, Holocene, North Sea

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As part of a joint research project on the Quaternary development and stratigraphy of the southern North Sea (Fannin 1992) run by the geological surveys in United Kingdom, Belgium, the Netherlands, Germany and Denmark, a coring was undertaken in the outer Heligoland Channel, German Bight, south-eastern North Sea in 1989 (Fig. 1).

The Heligoland Channel is a valley-like structure in the south-eastern part of the North Sea, surrounded to the north-west by the Dogger Bank and its north-eastern extension the Tail End. This high is connected to the mainland to the south through a sill including a.o. the Weisse Bank and the Nordschill Grund. To the east of the channel, the ground rises gradually towards the Jutland peninsula and to the north it is semi-enclosed by the Turbot Bank (Fig. 1).

Seismic investigations in the area revealed a meandering channel-like feature, probably an erosional scour formed by the paleo-Elbe. The seismic data show several sub-parallel reflectors, indicating a multiple infill during the Pleistocene and Holocene (H. Heinrich, pers. comm. 1989). To investigate these strata, the drill site at 55°49′N and 5°17′E was chosen. This paper deals with the environmental interpretation of the sediments in the borehole based on its foraminiferal assemblages.

Methods and materials

The borehole BH 89/8 (Fig. 1) was drilled on a muddy seabed at 55 m water depth. The coring was performed with the BGS Marine Wireline Corebarrel drilling system. In coherent sediments 3 m coring intervals was used, and in sandy sediments hammer sampling was performed every 1 or 2 m. The cores as well as the hammer samples had a diameter of 3″. The drilling was undertaken with the dynamically positioned drill ship M/V "*Bucentaur*". The borehole reached a total depth of 51 m below sea floor (b.s.f.). The upper 22 m was cored with a recovery of 72% in interbed-

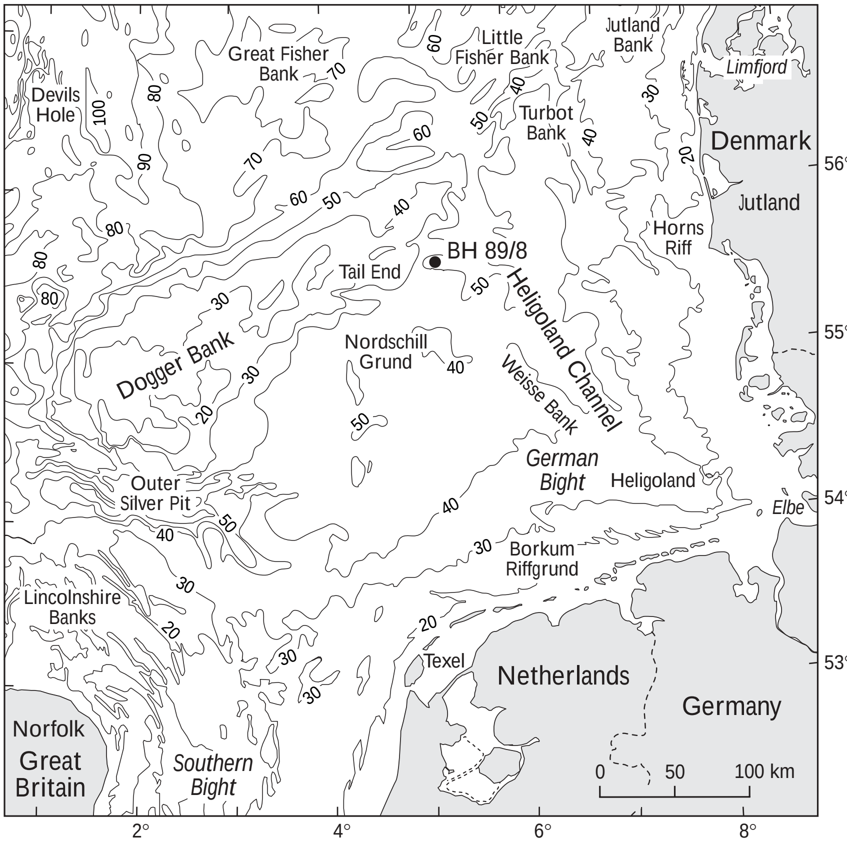


Fig. 1. Recent morphology of the sea floor of the south-eastern North Sea (after Denton 1979). The Heligoland Channel is indicated. It forms a valley-like structure in the sea floor between Jutland and the shoals Tail End, Nordschill Grund and Weisse Bank. The position of the investigated borehole BH 89/8 is indicated just south-east of Tail End.

ded and interlaminated silty clay and fine sand, reaching down to 17.15 m b.s.f., whereas recovery was only 6% in the underlying sand between 17.15 and 22 m. In the hammer sampled sandy section below 22 m b.s.f. recovery was 26%.

The content of foraminifers was investigated in 38 samples from the borehole. A total of 20 samples, each consisting of a 1 cm slice of the core, with an average dry weight of 70 g, were taken at selected intervals in the upper silty section. Additional 18 samples, with an average dry weight of 90 g, were taken from the lower sandy section. The samples were treated according to standard procedures (Knudsen 1998) and the microfossils in the 0.1 to 1.0 mm fraction were concentrated using heavy liquid flotation ($\rho = 1.8$ g / cm^3). Where possible, at least 300 specimens were identified from this fraction.

The lower sand section

The lower section of the borehole, below 17.15 m b.s.f., consists of sand (Fig. 2). In this section the number of microfossils is generally less than 100 / 100 g sediment.

It is concluded to be non marine based on the low content of Pleistocene foraminifers, their bad state of preservation, and the high number of reworked, pre-Pleistocene specimens. The Pleistocene foraminifers are therefore regarded also to be reworked. These sediments are presumably of fluvial origin, and can be divided into two lithological subunits.

In the lower subunit, from 51 m to 38 m b.s.f., the sediment consists of sand, fine to very fine, slightly silty with disseminated fine lignite. The number of pre-Pleistocene foraminifers in this subunit is about 10 times that of the Pleistocene specimens.

The upper subunit, from 38 m to 17.15 m b.s.f., consists of upwards fining sand, predominantly medium, gravely at the base and with scattered clasts, including rounded mollusc fragments. In this subunit there is about an equal number of pre-Pleistocene and Pleistocene foraminifers. Compared to the lower subunit, the higher content of reworked Pleistocene foraminifers in the upper subunit probably indicates that the river, which transported these, as well as the mollusc fragments, must have eroded into a marine Pleistocene deposit. Such deposits are found in northwestern Germany around the present mouth of the river Elbe (Knudsen 1988, 1993). The sparse reworked Pleistocene foraminiferal faunas nevertheless can not with certainty be referred to any known Quaternary marine deposit.

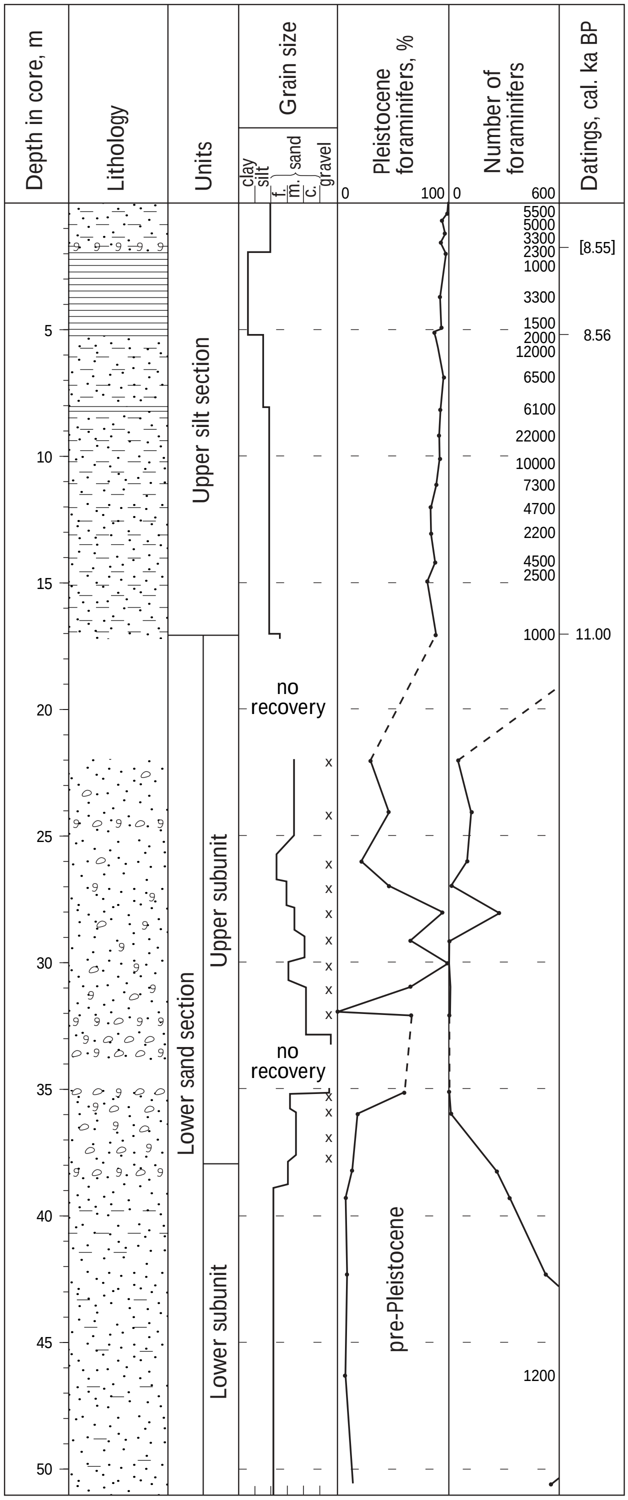


Fig. 2. Lithology of borehole BH 89/8. The figure also indicates the subdivision of the borehole, the percentage of Pleistocene foraminifers in the samples, the number of foraminifers in the samples and the radiocarbon datings.

The upper silt section

This section constitute the upper 17.15 m of the borehole. The sediment consists of interlaminated silt, clayey or fine sandy, and of sand, fine and often silty (Fig. 2). The section from 5.35 m to 1.85 m b.s.f., however, is made up of silty clay. The sediments contain a relatively rich and diverse benthic foraminiferal fauna (Fig. 3), indicating that the sediments are deposited in a marine environment.

Radiocarbon dating

Mollusc or mollusc fragments from three samples were submitted for radiocarbon dating at the AMS ^{14}C Dating Laboratory at The University of Aarhus, Denmark. The results are presented in Table 1.

The sample AAR-4458 from 1.82–1.83 m depth in the core gives an age of the same magnitude as the one of sample AAR-4459 from 5.17–5.18 m depth in the core. The date is thought to be too old for the strata, as the sample AAR-4458 is taken in a shell horizon. The horizon apparently includes reworked shells, eroded from older strata.

Foraminiferal zones

A total of 58 Quaternary benthic foraminiferal species have been identified in the marine deposit. All samples, except for the uppermost, are dominated by the species *Elphidium excavatum* as the boreal forma *selseyensis* (Feyling-Hanssen 1972) which constitutes between 35 and 82% of the fauna and indicates a boreal inner neritic environment. This is also indicated by the persistent occurrence with a few percentages of *Elphidium gerthi.*

Planktic specimens were only present in one sample (1.07–1.08 m), (six possibly *in situ)* out of 423 counted specimens. Reworked pre-Pleistocene specimens were also seen in the marine deposits, with a frequency of 17% in the lower samples, and decreasing upwards through the borehole to less then 1% in the uppermost samples.

The marine deposit is divided into 5 foraminiferal assemblage zones (for brevity in the following called zones), and some characteristics from each of the five zones (Zones A–E) are given below.

Zone E includes two samples. The lower sample, 17.03–17.05 m, is made up of sand, mostly fine, with lumps of clayey silt with shell fragments. This is probably a mixture of the top of the lower sand section

Table 1. AMS Radiocarbon ^{14}C dates of mollusc shells from 3 samples from borehole BH 89/8

Sample identific.	Sample depth	Conventional ^{14}C Age BP	Reservoir corrected ^{14}C Age	Calibrated age ± 1std v.	$\delta^{13}C$(‰ PDB	)$\Delta^{18}O$(‰) PDB
AAR-4458	1.82–1.83 m b.s.f.	8230 ± 80	7830 ± 80 (Res. Age: 400)	6600 BC, BC 6700–6500	1°	
AAR-4459	5.17–5.18 m b.s.f.	8250 ± 75	7850 ± 75 (Res. Age: 400)	6610 BC, BC 6760–6550	+1.3	+1.8
AAR-4460	17.00–17.10 m b.s.f.	10250 ± 90	9850 ± 90 (Res. Age: 400)	9050 BC, BC 9130–9020	–7.4	–3.7

and the basal part of the upper silt section caused by the drilling process. This mixture is also believed to have caused the comparatively low foraminiferal frequency in that sample. The upper sample, 14.95–14.96 m, consists of clayey silt with lamina of fine sand. The fauna in Zone E is dominated by *Elphidium excavatum* and characterised by the comparatively high content of *Elphidium albiumbilicatum* (10 and 20%). Other important species are *Elphidium magellanicum* and *Ammonia beccarii* and in the upper sample also *Elphidium williamsoni*. The content of *Elphidium albiumbilicatum* (Rottgard 1952, as *Elphidium* (*Elphidiella*) *asklundi*; Lutze 1965, as *Cribrononion asklundi*) and of *Elphidium williamsoni* (Lutze 1965, as *Cribrononion* cf. *alvarezianum*) in this zone points to an environment with lowered salinity. The high number of pre-Pleistocene specimens (11–17%) indicates reworking into the sedimentation basin presumably by fluvial transportation.

Zone D includes 9 samples from the interval 14.26–5.50 m. The sediment is silt, clayey or fine sandy, interbedded with lamina of fine sand. The fauna is dominated by *Elphidium excavatum* and characterised by the comparatively high frequency of *Elphidium magellanicum* (23–10%), which is normally second in frequency. The accessory species, *Elphidium albiumbilicatum*, *Haynesina germanica* and *Cassidulina reniforme*, (up to 9%) are found in most of the zone, whereas *Ammonia beccari* and *Elphidium williamsoni* (2–6%) are mainly seen in the lower part. In the middle part, the samples at 10.21 m and 9.25 m, *Elphidium excavatum* strongly dominates with 76 and 82% and the species diversity, 5 and 6, is the lowest in the zone. This indicates an extreme environment. The accessory species *Elphidium incertum* (up to 6%) is primarily found in the upper part of the zone and indicates increasing water depth. The faunal assemblages of Zone D indicate a tidal flat to subtidal environment (Voorthuysen 1960, Haake 1962, Richter 1964) with severe environmental conditions in the middle part. In the upper part the fauna indicates slightly increasing sedimentation depth. The comparatively high content of *Elphidium albiumbilicatum* and of reworked pre-Pleistocene specimens points to influence from fluvial water throughout the zone.

In Zone C, samples from 5.25–2.00 m, the sediment consists of silty, laminated clay. The faunas in the four samples from this zone are also dominated by *Elphidium excavatum*, 35–67%, and *E. magellanicum* is still frequent. However, new species such as *Quinqueloculina seminulum* (15–5%) and *Haynesina depressula* are introduced in the faunas. The appearance of these two species and of the open North Sea variant *batavus* of *Ammonia beccarii* (Haake 1962) suggests an increase in salinity and in sedimentation depth. This is also confirmed in the sudden drop in the frequencies of the low-salinity tolerating species *Elphidium albiumbilicatum*, followed by a diminishing number of fluvial transported pre-Pleistocene specimens.

The sediment in the three samples of the overlying Zone B, 1.83 m to 1.07 m, is an interlaminated silt and silty fine sand. The sedimentological shift is initiated by a shell-rich horizon at 1.85m. *Elphidium excavatum*, *E. magellanicum* and *Ammonia beccarii* var. *batavus* are still frequent. *Haynesina depressula* increases in frequency, 11 to 4%, and becomes a characteristic element of the fauna. The two species *Bulimina marginata* and *Buliminella elegantissima* appear each reaching 2% frequency. In zone B, the number of species as well as the diversity rises compared to zone C. This indicates an increasing water depth and a more open-marine environment, probably caused by a change in hydrography.

Zone A includes the two uppermost samples of the core, 0.40 m and 0.05 m, with a similar sediment type as in zone B. The fauna is strongly dominated by the agglutinating species *Eggerelloides scabrus*, 25 and 48% respectively. Other important species in this zone are *Elphidium excavatum*, *Ammonia beccarii* var. *batavus*, *Bulimina marginata* and *Buliminella elegantissima*. This faunal assemblage is close to the present foraminifer fauna at this location in the North Sea (Jarke 1961; Murray 1992).

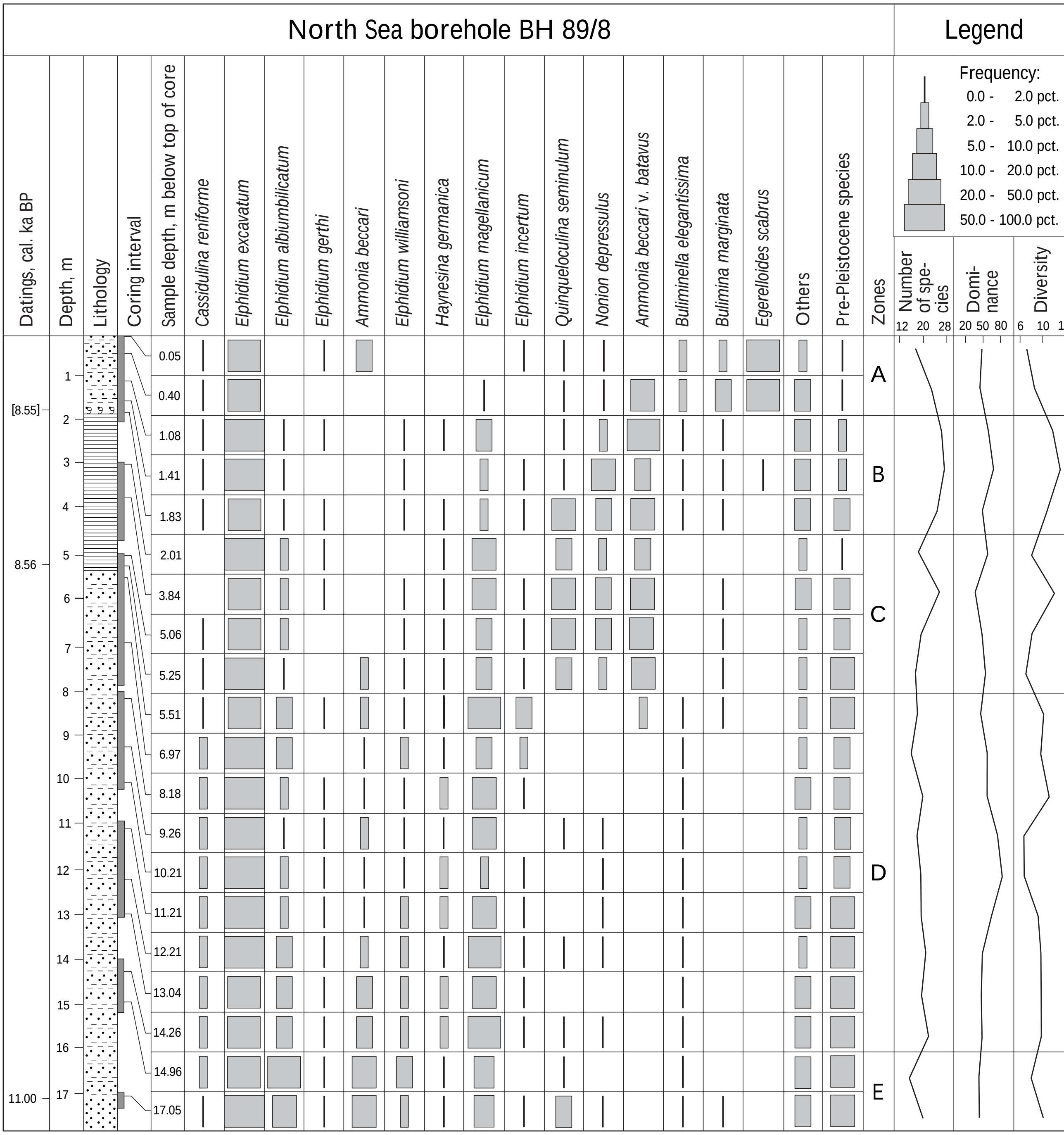


Fig. 3. Range chart of selected foraminiferal species in the marine section of borehole BH 89/8. The relative frequencies of 15 selected species, e.g. species with a frequency of at least 2 % in two samples, are presented together with the group: others, and the group: pre-Pleistocene species. The foraminiferal zones, the number of species, the faunal diversity and the dominance (Walton 1964) are illustrated as well as the position of the datings. The group Others include unidentified specimens, and the group pre-Pleistocene is given as percentage compared to the number of Pleistocene specimens.

Interpretation

The lower sand section, from 51 to 17 m, is interpreted to be fluvial sediments. Based on the seismic profiles, the upper subunit was presumably deposited in an erosion channel, formed into the lower subunit by the river draining the southern rim of the Weichselian ice sheet, the "Elbe-Urstrom" (Figge 1980).

The ^{14}C datings show that the marine upper silt unit, from 17 to 0 m in the borehole, is of Holocene age. Zone E represents the start of the Holocene marine transgression into the valley of the glacial Elbe River. The fresh water out-flow from the Elbe River strongly influenced the environment of the sedimentation basin. This also accounts for the high content of reworked pre-Pleistocene specimens. A sample from the lowermost marine part of the core, 17.0–17.10 m b.s.f., is AMS ^{14}C dated to 10250 ± 90 y BP = 11.0 cal. ka BP. This sample bears the first witness of the marine inundation in this part of the North Sea after the Weichselian glacial period. The foraminifer fauna is a shallow water fauna and the level, about 72 m below present sea level, is regarded to indicate the relative sea level at that time.

The fresh-water influence in the sedimentation basin is also registered in the overlying Zone D where the faunas indicate a tidal flat to subtidal environment. Based on interpretation of seismic profiles (H. Heinrich, pers. comm. 1990) both zone E and zone D are suggested to have been deposited in an estuary, filling the valley of the Elbe-Urstrom east and south-east of the Dogger Bank (Fig. 4). The marine access to the lengthy, fjord-like, shallow basin was limited and thought to have occurred in the depression between Tail End and the Turbot Bank. During deposition of the upper part of zone D the sedimentation depth was slightly increasing.

The fauna of Zone C indicates a relatively abrupt change in the marine environment that became more saline, most probably because the fluvial outflow ceased to strongly influence the area. This change is believed to be reflected in the change to laminated clays at 5.35 m. The hydrografic change was presumably caused by the rising sea level. This rise allowed the open-marine water from the Outer Silver Pit area to pass freely over the sill between the paleo-Dogger Bank and the mainland to the south, in the area north-west of the Nordschill Grund, and into the basin of the former paleo-Elbe estuary. Figge (pers. comm. 1995) expects that the base of the Holocene in the area between Nordschill Grund and Tail End is found around –48 m, which is in agreement with Gans et al. (1993). This event happened shortly before 8.56 cal ka BP. The probable extension of land and sea during deposition of zone C is sketched in Figure 5.

Zone B starts with a horizon rich in shells at 1.80–1.85 m. The horizon includes reworked Holocene shells, and it is interpreted to be caused by an extensive change in the hydrography, including erosion, of the southern North Sea basin. The fauna in the rest of the zone and the following zone A reflects ongoing gradual changes in the environment with increase in water depth before eventually reaching modern environmental conditions.

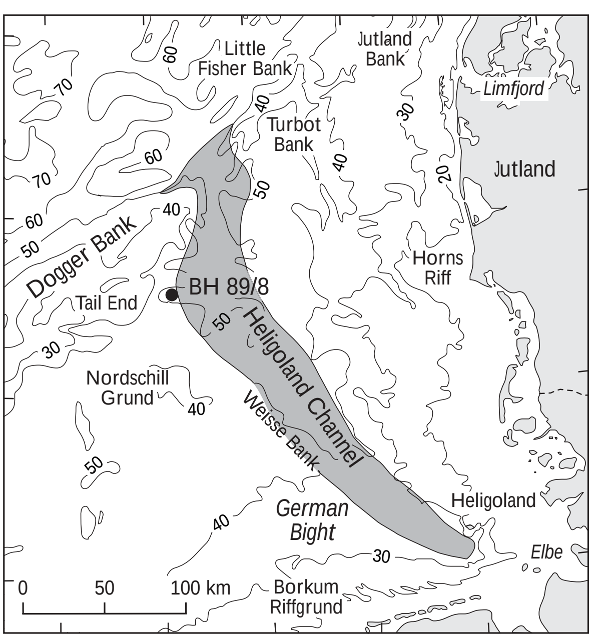


Fig. 4. Suggested extension (in grey) of the estuary in the paleo Elbe River in the foraminiferal zone D at the first part of the Holocene transgression, indicated on part of the map of Fig. 1. (Partly after unpublished data from Figge1995 and Heinrich 1990).

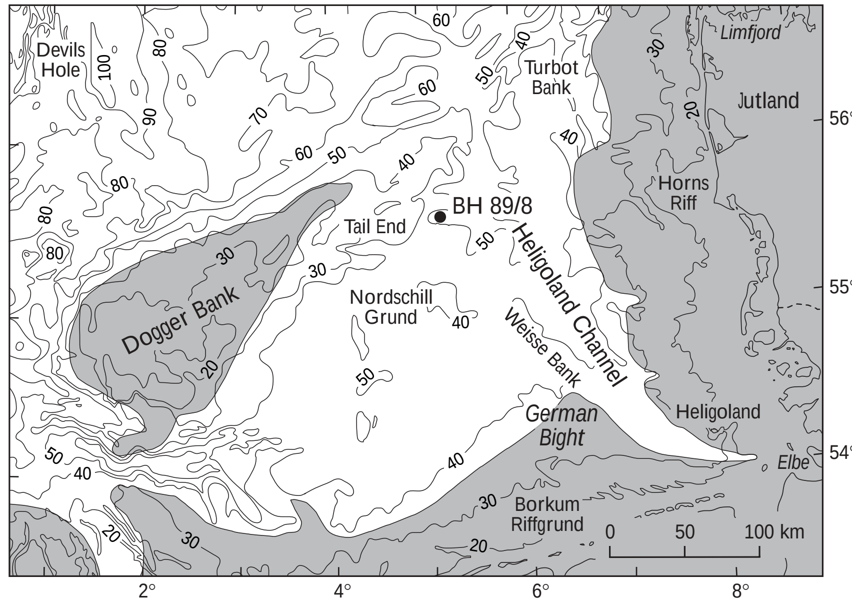
Comparisons

The date *c.* 11.0 cal. ka BP for the marine inundation, 17.00-17.10 m or about 72 m below present sea level, is in agreement with the North Sea sea-level curve of Streif (1990), if this curve is extended back to 11 ka BP.

In a core about 20 km to the north-north-west of core BH 89/8 H. Heinrich (Pers. comm. 1995) has dated a rootlet to 9.225 ^{14}C y BP. most probably indicating the time of the marine inundation at this position around 54 m below present sea level. This date fits well with Jelgersma's (1979) curve, and reasonably wells with Streif's (1990) curve.

Rose *et al.* (1993) gives dates of 12.200–10.500 radiocarbon y BP of samples from 64.3–65.5 m below

Fig. 5. Suggested extension of the North Sea in the foraminiferal zone C, indicated on the map of Fig. 1. Land areas are indicated in a grey tone. The coastline of the former North Sea is sketched. The Dogger Bank was an island at that time as the base of the Holocene is around –30 m (Jeffery et al. 1990).



present sea surface from a core situated to the north of Tail End. The sediments in this core comprise of brackish-water deposits, filling a fluvial erosionel depression presumably associated with the now submerged estuary of the Elbe River. In order to explain the deviation from general models of eustatic sea-level change the ages of these sediments indicate that local tectonic movements, caused by glacio-isostatic release, must have occurred in the area after the glaciation.

According to the sea-level curves of Jelgersma (1979) and of Streif (1990), the flooding of the pre-Holocene base of the Dogger Bank would have occurred around 8000 ^{14}C y BP. This event would have created a new configuration of the sea floor as well as of the whole southern rim of the North Sea. When the sea level some time after had risen sufficient for the sea to move freely across the palaeo Dogger Bank, this must have resulted in a significant change in the general hydrography of the southern North Sea. This may have led to the establishment of the modern hydrographical circulation, including the palaeo Jutland Current.

In a borehole at Skagen, northernmost tip of Jutland, a hydrographic change is documented in the sediments as well as in the microfauna at 7600 ^{14}C y BP or *c.* 8.4 cal. ka BP. (Conradsen & Nielsen 1995). This change is thought to have been caused by the formation of a palaeo Jutland Current, and it is suggested that this date pinpoint the change to the present hydrographic pattern of the North Sea. Using Jelgersma's (1979) and Streif's (1990) curves of sea-level rise, the event would have occurred when sea level was around 20 m below the present level. It is assumed that this event is reflected in the shell horison at the base of Zone B in the present borehole.

Based on present-day bathymetry of the North Sea, Austin (1991) suggested that modern hydrographic conditions in the North Sea were established when the eustatic sea level was between 10 and 15 m below present. Using the sea-level curves of Jelgersma (1979) and Streif (1990) this would be dated to 6500–7200 ^{14}C y BP. Jeffery et al. (1990) state that the Holocene sediment accumulation on the Dogger Bank has a maximum of 16 m. Further, they demonstrate that the base of the Holocene is situated around the –30 m level in the area. It is suggested that if data on the base of the Holocene were used for bathymetry in Austin's model [15], the change to the present hydrographic situation would have occurred somewhat earlier than inferred by him. It could probably have occurred at 7600 ^{14}C y BP, as indicated by Conradsen & Nielsen (1995).

The sill separating the Southern Bight from the North Sea proper in the Norfolk Banks area is situated around –35 to –40 m (Cameron et al. 1986, Harrison et al. 1987). According to the sea-level curves (Jelgersma 1979, Steif 1990) this sill would have been transgressed around 8.200–8.700 ^{14}C y BP. For the above reasons the "opening of the English Channel" (references in Nordberg 1991) most probably is not the only reason for hydrographic changes in the North Sea in this period.

Conclusion

Investigations of foraminiferal assemblages, found in samples from the borehole BH 89/8 in the outer Heligoland Channel, south-eastern North Sea, in combination with lithology and seismic profiles reveal the development of the Heligoland Channel. At first, fluvial sand is deposited in a glacial erosional depression. With the Holocene marine transgression, dated at around 11.0 cal. ka BP, the depression is transformed into a fjord-like estuary with a tidal flat or subtidal environment influenced by fresh water from the Elbe River. As sea level continued to rise, the southeastern part of the North Sea south of the Dogger Bank was flooded, and a new hydrographic regime was established. This resulted in a change in the environment to fully marine conditions. This event is suggested to have occurred shortly before *c.* 8.6 cal. ka BP. With the continued rise in sea level the Pleistocene Dogger Bank was flooded and the present hydrographic situation of the North Sea was established. This is suggested to have occurred at 8.4 cal. ka BP. These changes are mirrored in the gradual change in the foraminiferal fauna to that of the present day North Sea at this locality.

Species list

The 15 most important foraminiferal species used for the interpretation of the stratigraphy and the environment at the borehole BH 89/8 are arranged alphabetically in the following list:

Ammonia beccarii (Linné 1758)
Ammonia beccarii var. *batavus* (Hofker 1951)
Buliminella elegantissima (d'Orbigny 1839)
Bulimina marginata d'Orbigny 1826
Cassidulina reniforme Nørvang 1945
Eggerelloides scabrus (Williamson 1858)
Elphidium albiumbilicatum (Weiss 1954)
Elphidium excavatum (Terquem) forma *selseyensis* (Heron-Allen & Earland 1911)
Elphidium gerthi van Voorthuysen 1957
Elphidium incertum (Williamson 1858)
Elphidium magellanicum Heron-Allen & Earland 1932
Elphidium williamsoni Haynes 1973
Haynesina germanica (Ehrenberg 1840)
Haynesina depressula (Walker & Jacobs 1798)
Quinqueloculina seminulum (Linné 1758)

Acknowledgements

This study is part of the CEC funded project: The modelling and dynamics of the Quaternary geology of the southern North Sea and their applications to environmental protection and industrial developement, in the Science Programme, contract no. SCI* 0128-C (EDB). The AMS radiocarbon datings were carried out at the University of Aarhus under supervision of Jan Heinemeier. All colleagues from the international group participating in the project who discussed my results with me are cordially thanked, especially C. Laban, K. Figge and H. Heinrich as well as K.L. Knudsen, who all commented on an early draft of the manuscript. The journal referees, H.P. Sejrup and M.-S. Seidenkrantz, are thanked for valuable criticism and many suggestions. The crew of M/V "*Bucentaur*" and technicians Birte Hammerstrøm and Gurli Ellis Hansen from GEUS are thanked for technical assistance.

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Dansk sammendrag

Der er foretaget en 51 m dyb boring i den ydre del af Helgoland Kanalen (Fig. 1), hvor seismiske undersøgelser viser forekomsten af en begravet dal. De nederste 34 m består af pleistocænt fluvialt sand og de øverste 17 m af holocænt marint, leret og finsandet silt (Fig. 2). Der er foretaget foraminifer analyser af 38 prøver fra boringen. Foraminifer indholdet i prøverne fra den nedre sandede sektion består af både kvartære og af præ-kvartære arter, der alle er omlejrede. Ud fra forholdet mellem kvartære og præ-kvartære arter kan denne del af boringen deles i en nedre del, under 38 m's dybde, og en øvre del, der svarer til de litologiske forskelle. Fra den øvre marine del af boringen er foraminifer indholdet i 20 prøver undersøgt (Fig. 3). På baggrund af foraminifer selskaberne og disses miljøkrav er det marine afsnit inddelt i 5 foraminifer zoner, der viser ændringerne i miljøforholdene ved havbunden under den marine transgression i holocæn tid. En prøve fra den dybeste del af de marine aflejringer (17,10 m's dybde) er AMS ^{14}C dateret til ca. 11.000 kalender år før nu. De nederste dele af afleringerne er afsat under stærk indflydelse af ferskvand. Denne indflydelse aftager opefter i aflejringer afsat under vadehavslignende forhold i et fjordlignende estuarie, der alene havde forbindelse med den åbne Nordsø mod nord mellem Tail End og Turbot Banke(Fig. 4). En efterfølgende markant ændring i faunaselskaberne viser nu højere saltholdighed og mere åbne marine forhold. En prøve nær bunden af disse lag (5,18 m's dybde) er dateret til ca. 8.560 kalender år. Denne ændring er tolket som en betydelig forandring i de hydrografiske forhold i aflejringbassinet. Den tænkes at være sket på det tidspunkt, hvor den stigende havstand medførte at Nordsøens åbne vand overskyllede den tidligere landbro mellem Dogger Banke og fastlandet mod syd, således at Helgoland Kanalen nu ophørte med at være en fjordarm (Fig. 5). Aflejringerne opefter i boringen viser tiltagende vanddybder og mere åbne marine forhold. Et musling fragment fra et skallag i 1.83 m dybde er dateret til ca. 8.550 kalender år før nu, dvs. jævngammelt med dateringen fra 5,18 m's dybde. Skallaget indeholder således omlejrede skaller, som kan være transporteret i forbindelse med en ny markant ændring i de hydrografiske forhold i denne del af Nordsøen, for eksempel da Dogger Bankes præ-holocæne bund i kote ca. –30 m blev overskyllet i forbindelse med den fortsatte havstigning. De øverste prøver fra boringen viser at miljøforholdene gradvist ændrer sig til de, der hersker på stedet i dag.

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