RADIOCARBON DATING OF SHELLS AND FORAMINIFERA FROM THE SKAGEN CORE, DENMARK: EVIDENCE OF REWORKING

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ABSTRACT. We report on 69 radiocarbon dates of mollusk shells and benthic foraminifera from the upper 132 m of the marine shelf sediments of the Skagen Core (220 m total length). The dated sequence covers the Late Glacial and the Holocene (from 15 ka BP to Recent). Sedimentation rates range from 1 to 70 m ka^{-1}. The macrofossil shell dates follow a smooth curve constituting an age model for dating the sediments. The foraminiferal dates fall into two groups: those that agree exactly with the mollusk shells and those that deviate substantially, always being older than the shells by as much as 5 ka. One mixed foraminiferal sample consisted of members from both groups, and as a result, the age deviation of the sample turned out to be some weighted average. The data indicate that the age deviations are due to admixtures of reworked older foraminifera.

INTRODUCTION

Since the introduction of accelerator mass spectrometry (AMS), it has been possible to radiocarbon-date marine sediment cores by using samples of foraminifera, either single species or mixed faunas (Broecker *et al.* 1984). Compared to conventional ^{14}C dating of bulk sediment carbonate, one would expect AMS dating of foraminifera to be more reliable and give improved resolution limited only by the degree of bioturbation. However, data show problems other than bioturbation in using foraminifera as a dating material. Reports appear in the literature of age inversions, high core-top ages (Jones *et al.* 1989) and deviating ^{14}C ages for sample pairs of different (planktonic) foraminiferal species (Broecker *et al.* 1988, 1989; Bard *et al.* 1989; Jones *et al.* 1989). It seems that the reliability of foraminifera as a dating tool in establishing sediment chronologies has not been tested as thoroughly as "traditional" dating samples, such as mollusk shells and wood—often due to the absence of such reference material for cross-checking. Thus, it is often difficult to distinguish between possible causes of observed age anomalies as, *e.g.*, carbonate dissolution effects or reworking in high-deposition-rate, deep-sea cores (Broecker *et al.* 1989).

In a series of dates on coastal or shallow marine cores from Danish waters (Core 95, Limfjorden; Core PC10-1, Kattegat), we observed large deviations among ^{14}C age profiles determined on foraminifera as compared to mollusk shells (Nielsen 1992; Seidenkrantz and Knudsen 1993). However, two fossil types from Cores B and E, Bjørnsholm Bay, Limfjorden, agreed well (Kristensen, Heier-Nielsen and Hylleberg 1995).

To clarify the extent to which foraminifera can be trusted as a dating medium, we chose a core from North Denmark with a uniquely high sedimentation rate (on the order of 10 m ka^{-1}) and many macrofossil shells. We argue that the macrofossil shells yield the true age of the sediment and can be used as an absolute reference for dating foraminifera. The high sedimentation rate eliminates bioturbation effects, and the macrofossils are less likely to be geologically disturbed by reworking. We report 69 ^{14}C dates, for which we observed many substantial age differences between foraminifera and macrofossil shells. We address the question whether these discrepancies are of experimental or geological origin.

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METHODS

The Skagen Core location is onshore (1 m above sea level) at the Skaw Spit (Skagen Odde), near the northernmost point of the peninsula of Jutland (Fig. 1). The 35-km-long coastal spit—one of the largest in the world of its kind—has gradually grown north during the last 8 ka. The sediments forming the spit are mainly derived from the southern and eastern North Sea and transported with the Jutland Current to the accumulation area that can be regarded as a giant natural sediment trap.

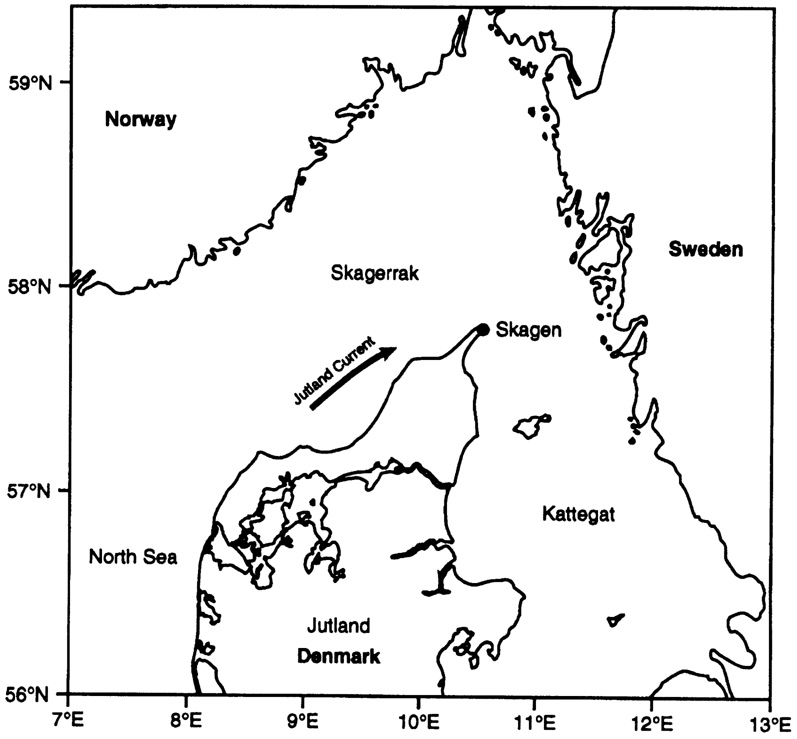

Fig. 1. Locality map

The core penetrates 200 m of Quaternary sediments, the upper 132 m of which are continuous marine deposits of Late Glacial and Holocene age (from 15 ka BP to Recent) (Knudsen 1994). Lithologically, the sequence is divided into three broad zones: 132–81 m is clayey; 81–*ca.* 30 m is silty-sandy; the top 30 m consists of coarse sand.

The core was taken with rotating drilling equipment in subcores 1.50 m long and 10 cm in diameter. The main core (Skagen 3) was supplemented with a parallel core (Skagen 4), which was taken with different equipment to produce an intact record also for the top 30 m of coarse sand. Foraminifera were extracted from bulk sediment subsamples covering 2- or 5-cm intervals. To avoid downcore contamination with younger material, we removed the outer 1 cm of the sediment ("core bark") prior to processing of the samples. Conradsen and Heier-Nielsen (1995) gave a detailed description and paleoenvironmental interpretation of the core, based on foraminiferal analysis. From local coastline displacement data and global sea-level history (Fairbanks 1989), we estimated that the water depth at the time of deposition of a given sediment level is of the same order as its depth in the core.

We processed the sediment samples using standard techniques (Feyling-Hanssen *et al.* 1971), *i.e.*, wet sieving followed by density separation in CCl_4 (ρ=1.59 g cm^{-3}) of the fraction for 0.1–1.0 mm. We saw no evidence of contamination effects from the carbon content in CCl_4. Benthic foraminifera were subsequently hand-picked from the light fraction. Samples of macrofossil shells or shell fragments for ^{14}C dating were mostly taken from the >1 mm fraction after wet sieving. The fragments often came from whole shells crushed as a result of sediment compaction.

For the macrofossil shell samples, we followed the standard mollusk-rinsing procedure (Olsson and Blake 1961; Andersen 1968). To eliminate any possible surface contamination, the outer 25% of the sample was removed by etching in 1 M HCl. Any organic carbon was removed by treatment with a $KMnO_4$ solution for 16–20 h at 80°C. The CO_2 was liberated with ~100% phosphoric acid in an evacuated vial at 25°C. Part of the CO_2 was used for $\delta^{13}C$ measurements. The rest was converted to graphite for AMS ^{14}C measurements by reduction with H_2 by using cobalt as a catalyst. We used small reaction volume and a high initial pressure of the reacting gases (Vogel *et al.* 1984).

The foraminifera were pretreated similarly, but surface etching and organic carbon removal were omitted. If present, surface contamination would be difficult to eliminate because foraminiferal shells are so thin that they are virtually "all surface". We have good reasons to believe that the surfaces were not contaminated, at least in the present core. The exact agreement observed between several foraminiferal samples—monospecific as well as mixed—and the corresponding shells support this. Further, we compared the ^{14}C ages of etched and untreated foraminifera and found no difference. It is interesting to note that analogous experiments with shells gave the same result. In most cases the etching step could probably be omitted for macrofossil shells as well.

All ^{14}C measurements were performed on the Aarhus EN tandem accelerator (Andersen *et al.* 1989) and the $\delta^{13}C$ measurements were performed on the mass spectrometer at the Science Institute, Reykjavík, Iceland. The quoted uncertainties are based on ion-counting statistics. A series of $^{14}C/^{13}C$ measurements with statistical uncertainties of 0.25–0.75% submitted to the Third International Radiocarbon Intercalibration (TIRI) indicate that this is the dominant source of uncertainty.

Dates are reported as conventional ^{14}C ages in years BP (before 1950), based on the measured $^{14}C/^{13}C$ ratio corrected for the natural isotopic fractionation by normalizing the result to the standard $\delta^{13}C$ value of –25‰ PDB (Stuiver and Polach 1977; Andersen *et al.* 1989). ^{14}C dates of marine samples were corrected for the apparent age of modern marine water (reservoir effect). A standard reservoir age of 400 yr (Krog and Tauber 1974; Nielsen *et al.* 1994) is subtracted from the conventional ^{14}C age to obtain the reservoir-corrected ^{14}C age. It is used throughout the text and figures to facilitate comparison with terrestrial ^{14}C dates.

RESULTS AND DISCUSSION

Table 1 lists the ^{14}C dating results for shells and mixed/monospecific foraminifera samples from the Late Glacial and Holocene part of the Skagen Core (132 m and upwards) together with the measured $\delta^{13}C$ values. The same data are plotted in Figures 2 and 3. Table 1 also lists age limits for 5 shells from a greater depth (175–137 m), as well as 2 dates of the carbonate content of the <63 μm grain-size fraction of the bulk sediment (80 and 104 m depth). The shell dates show a smooth, consistent age profile. In contrast, the ages of the foraminifera show a jagged profile with age inversions and large discrepancies between mixed and monospecific samples. The observed age differences are of the order of several thousand years.

TABLE 1. ^{14}C Dates Obtained from Skagen Core

Depth (m)	Sample type	Species	^{14}C age (yr BP)	Rcorr. BP*	$\delta^{13}C$	Calibrated age	Lab no. (AAR-)	Age excess
12.75	Shell	*Spisula subtruncata*	1255 ± 60	855	+1.1	AD 1070–1260	1482	
15.75	Shell	*Spisula subtruncata*	1295 ± 60	895	+1.2	AD 1040–1220	1483	
16.75	Shell	*Spisula subtruncata*	1335 ± 60	935	+1.2	AD 1020–1190	1484	
16.75	Shell	*Donax vittatus* (reworked)	1900 ± 60	1500	+1.6	AD 540–640	1485	600
19.75	Shell	*Spisula subtruncata*	1410 ± 60	1010	+1.2	AD 990–1150	1486	
25.25	Shell	*Spisula subtruncata*	1360 ± 55	960	+1.4	AD 1020–1160	1487	
30.25	Shell	*Spisula subtruncata*	1500 ± 65	1100	+1.9	AD 890–1010	1488	
31.50	Shell	Fragment	1430 ± 130	1030	+1.5	AD 890–1170	864	
33.00	Shell	Fragment	1430 ± 130	1030	+0.1	AD 890–1170	865	
34.28	Foraminifera	Mixed	4810 ± 80	4410	0†	3290–2920 BC	1322	3250
34.28	Shell	Echinoid fragment	2025 ± 80	1625	−1.1	AD 350–540	1028	450
38.22	Shell	Fragment	1630 ± 80	1230	+1.7	AD 680–890	1033	
38.22	Foraminifera	Mixed	3240 ± 140	2840	−0.9	1250–830 BC	1323	1600
53.12	Shell	Fragment	2520 ± 120	2120	+0.1	360 BC–AD 10	1319	
53.12	Foraminifera	Mixed	3560 ± 80	3160	0†	1510–1320 BC	1324	1050
69.43	Shell	Fragment	3570 ± 100	3170	−0.4	1520–1320 BC	1320	
69.43	Foraminifera	Mixed	5800 ± 90	5400	−0.4	4340–4090 BC	1325	2150
69.43	Foraminifera	*Ammonia beccarii*	4660 ± 75	4260	+0.3	2920–2700 BC	1326	1050
70.33	Foraminifera	Mixed	6030 ± 90	5630	−0.3	4540–4360 BC	1134	2300
70.33	Shell	Echinoid fragment	3760 ± 80	3360	−0.1	1740–1520 BC	1030	
78.28	Foraminifera	*Bulimina marginata*	5500 ± 90	5100	+1†	3980–3780 BC	1595	0
78.28	Foraminifera	Miliolidae	8780 ± 120	8380	+0.8	7530–7290 BC	1597	3200
78.28	Shell	Echinoid fragment	5540 ± 120	5140	−0.5	4070–3790 BC	1596	
c. 80	Bulk sediment	Carbonate <63μm	27,200 ± 270	--	+0.5		1577	
80.02	Foraminifera	Mixed	8020 ± 160	7620	0†	6560–6230 BC	1327	2400
80.02	Shell	Fragment	5590 ± 105	5190	+2.5	4220–3820 BC	1034	
80.82	Shell	Fragment	5800 ± 120	5400	0†	4350–4050 BC	1321	
80.82	Foraminifera	Mixed	8520 ± 110	8120	−1.2	7260–6820 BC	1328	2700

TABLE 1. (Continued)

Depth (m)	Sample type	Species	^{14}C age (yr BP)	Rcorr. BP*	δ^{13}C	Calibrated age	Lab no. (AAR-)	Age excess
81.00	Shell	*Cerastoderma* sp.	5970 ± 140	5570	+1.5	4540–4260 BC	863	
90.42	Shell	Echinoid fragment	7110 ± 110	6710	−0.8	5670–5480 BC	1031	
90.42	Foraminifera	Mixed	9200 ± 110	8800	+1†	7970–7640 BC	1598	2100
90.42	Foraminifera	*Uvigerina mediterranea*	7180 ± 110	6780	−0.0	5710–5530 BC	1135	0
96.18	Shell	Echinoid fragment	7780 ± 100	7380	−0.3	6360–6050 BC	1032	
c. 104	Bulk sediment	Carbonate <63μm	30,650 ± 460	--	+0.6		1578	
103.82	Foraminifera	Miliolidae	13,290 ± 160	12,890	+0.3	13,590–13,010 BC	1283	4850
104.50	Foraminifera	Mixed	11,070 ± 160	10,670	+0.4	10,820–10,470 BC	1136	2550
104.50	Shell	Echinoid fragment	8520 ± 80	8120	−0.8	7250–7010 BC	1027	
104.62	Foraminifera	*Bulimina marginata*	8510 ± 110	8110	0†	7260–6820 BC	1282	0
111.67	Foraminifera	Mixed	9230 ± 100	8830	0†	8000–7700 BC	1114	0
111.67	Shell	Echinoid fragment	9170 ± 80	8770	−0.4	7940–7640 BC	1029	
114.67	Foraminifera	Mixed	11,410 ± 150	11,010	−1.0	11,130–10,830 BC	1207	1150
114.67	Foraminifera	*Nonionellina labradorica*	11,060 ± 120	10,660	−1.2	10,770–10,500 BC	1208	800
114.67	Shell	Fragment	10,230 ± 125	9830	+1.4	9240–9000 BC	1102	
114.76	Shell		10,450 ± 100	10,050	+0.1	9940–9060 BC	1115	
114.81	Foraminifera	Mixed	10,550 ± 130	10,150	−1.1	10,180–9180 BC	1209	150
114.81	Foraminifera	*Nonionellina labradorica*	10,550 ± 120	10,150	−1.0	10,200–9170 BC	1210	150
115.05	Shell		10,700 ± 85	10,300	+0.3	10,360–10,000 BC	1103	
115.05	Foraminifera	*Nonionellina labradorica*	11,320 ± 140	10,920	−2.1	11,030–10,750 BC	1211	650
115.11	Shell		10,820 ± 130	10,420	+0.6	10,540–10,160 BC	1503	
115.17	Foraminifera	*Nonionellina labradorica*	11,340 ± 140	10,940	−1.9	11,050–10,770 BC	1212	550
115.22	Shell		10,800 ± 110	10,400	+1.5	10,500–10,160 BC	1117	
115.32	Shell		10,850 ± 110	10,450	−2.6	10,550–10,240 BC	1104	
115.32	Foraminifera	*Nonionellina labradorica*	11,480 ± 90	11,080	0†	11,140–10,940 BC	1205	550
115.93	Shell	Fragment	12,120 ± 140	11,720	+2.4	11,910–11,540 BC	1219	
115.93	Foraminifera	*Nonionellina labradorica*	12,370 ± 140	11,970	−0.6	12,220–11,810 BC	1213	250
115.97	Shell		12,070 ± 230	11,670	+0.2	11,940–11,390 BC	1119	
115.97	Foraminifera	*Nonionellina labradorica*	12,550 ± 190	12,150	−0.7	12,510–11,970 BC	1214	350
116.86	Shell		13,560 ± 130	13,160	−1.0	13,950–13,500 BC	1120	

TABLE 1. (Continued)

Depth (m)	Sample type	Species	^{14}C age (yr BP)	Rcorr. BP*	δ^{13}C	Calibrated age	Lab no. (AAR-)	Age excess
119.22	Shell	Fragment	13,750 ± 145	13,350	−1.5	14,230–13,780 BC	1105	
119.22	Foraminifera	Mixed	14,000 ± 220	13,600	−2.2	14,640–14,030 BC	1215	250
128.40	Shell		14,420 ± 170	14,020	+0.7	15,080–14,640 BC	1106	
128.40	Foraminifera	Mixed	14,930 ± 160	14,530	−1.8	15,650–15,260 BC	1206	500
129.46	Shell	Fragment	14,850 ± 155	14,450	+0.1	15,560–15,170 BC	1107	
129.46	Foraminifera	Mixed	15,600 ± 180	15,200	−1.6	16,370–15,970 BC	1216	
137.44	Shell	Fragment	> 42000	--	+0.1		1108	
143.14	Shell		> 38000	--	+0.5		1109	
143.44	Shell		> 44000	--	+3.0		1110	
148.32	Shell		> 38000	--	+2.0		1111	
175.26	Shell	Fragment	> 37000	--	+0.1		1112	

*Rcorr. BP is the reservoir-corrected ^{14}C age BP; the reservoir age assumed to equal 400 yr.

†Standard value assumed, no measurement. Age excess is calculated as the difference between the age of a foraminifera sample and the age model. In two cases, age excess is calculated for shell results as well. Age excess values are rounded to the nearest 50. All reservoir corrected results have been calibrated using the terrestrial calibration curve based on 20-yr averages of Stuiver and Reimer (1993).

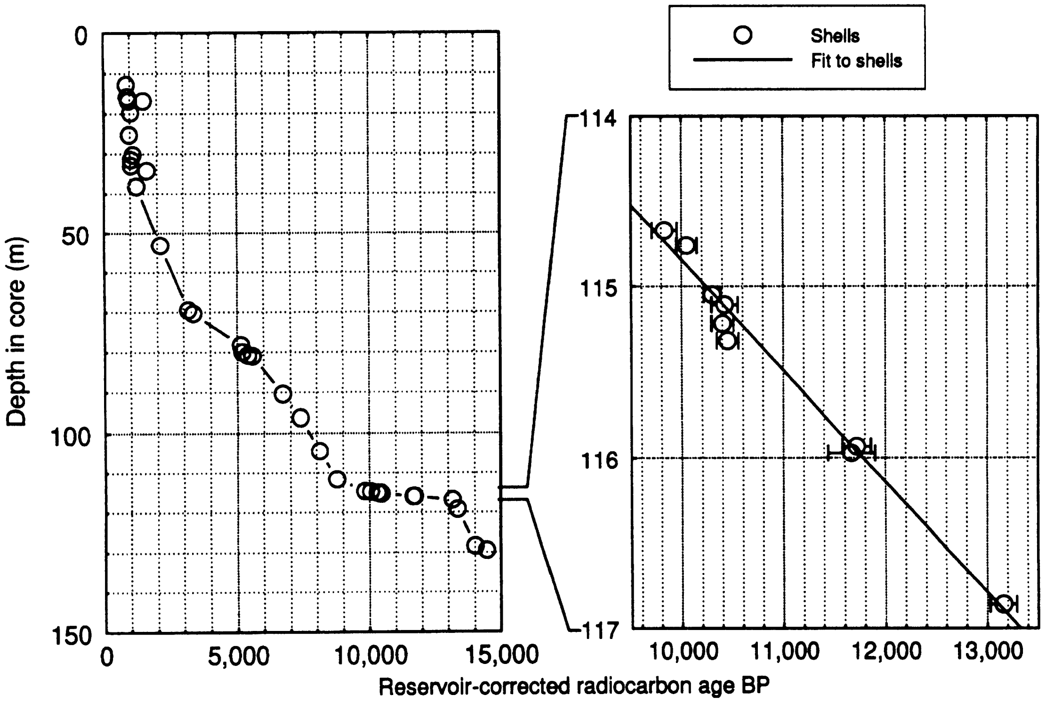

Fig. 2. Shell AMS dates of the Skagen Core. Results are given as conventional ^{14}C ages, corrected for a reservoir age of 400 yr. If experimental uncertainties are smaller than or equal to the point size, they are omitted.

We propose that the age profile of the shells represents the true age of the sediment, *i.e.*, the time of its deposition. The smooth interpolated age curve for the shells is taken to represent a model of the sediment age. Only two shell dates fall outside this curve. Both shells were from the top, coarse-grained 30 m of the core where the sedimentation rate reaches the extremely high value of 70 m ka^{-1}, consistent with a high-energy coastal environment. One case is a specimen of *Donax vittatus*, found at 16.8-m depth, which turned out to be 600 yr older than the sediment age. This shell showed clear signs of mechanical reworking, and was dated only because of specific interest in the history of this species. The other case is from 34.3 m where a shell fragment is 450 yr older than the interpolated age. At 34.3 m, we also recorded the largest deviation, 2700 yr, for a mixed foraminiferal sample in the whole core. These age deviations can be explained only by reworking.

From the shell age profile, we deduce sedimentation rates ranging from *ca.* 1 m ka^{-1} at 117–114 m (Late Glacial) with a steep increase to 14 m ka^{-1} in the interval 114–38 m, and up to 70 m ka^{-1} for the coarse, sandy sediment of the top 30 m of the core where hardly any foraminifera are present. This increase in sedimentation rate is associated with a decrease in water depth from *ca.* 100–0 m.

The data points for the foraminifera show an irregular pattern with large deviations from the sediment ages; yet some consistent features are important clues to the possible cause of the deviations. Several points are "normal" inasmuch as they agree closely with the age model; they are dates of monospecific samples of *Bulimina marginata, Uvigerina mediterranea, Nonionellina labradorica* and certain mixed samples occurring at core depths 78.3, 90.4, 104.5, 111.7, 114.8, 115.9 and 119.2 m. Where points deviate from the age model, the age of the foraminifera is always higher than that of the corresponding shell, and this age excess can be quite large. The dates of the foraminifera fall

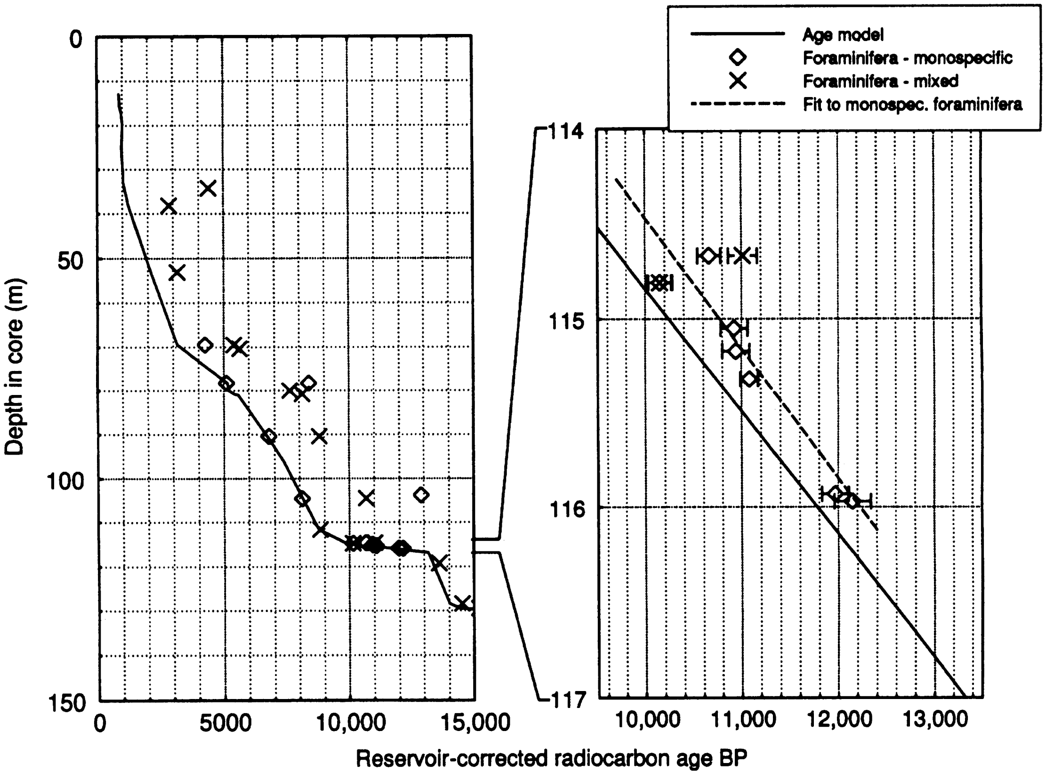

Fig. 3. Foraminiferal AMS dates of the Skagen Core. The macrofossil shell dates are indicated by the smooth curve. Results are given as conventional ^{14}C ages, corrected for a reservoir age of 400 yr. If experimental uncertainties are smaller than or equal to the point size, they are omitted.

in two distinct groups: they either agree exactly with the age model or they deviate substantially from it. There are four levels in the Holocene part of the core where the dates of foraminifera and shells agree closely. The calculated mean value of the differences, at these four levels, is 20 ± 70 yr (the uncertainty is the standard deviation of the mean computed from the statistical uncertainties in Table 1). The empirical standard deviation of the mean of the four differences is 30 yr. Where the dates of the foraminifera disagree, the difference is in the range of 1 to 5 ka.

An illustrative example occurs at *ca.* 104.5 m, where we measured a mixed-sample age excess of 2600 yr. We measured two other samples from about the same level, a monospecific sample of *Bulimina marginata* and one of large-sized Miliolidae. The age of the latter was as much as 4900 yr older than the sediment age. Clearly, the miliolids must be responsible for a large part of the offset of the mixed sample. In contrast, the smaller-sized *Bulimina marginata* agreed exactly with the shell age within the experimental uncertainty of 100 yr.

The general pattern in the core, with a few exceptions, is that age excess increases with sedimentation rate. Between 117 and 114 m in the core (Late Glacial, Fig. 3) deposited at the lowest sedimentation rate and at water depths of the order of 100 m, the deviations are relatively small and uniform, *ca.* 600 yr. Thus, a least-squares fit to the foraminiferal ages gives a line that is displaced 600 yr toward the old side of the shell curve. During the Early Holocene (from 114 m upward, Fig. 3), with sharply increasing sedimentation rates at decreasing water depth, the deviations become larger and more erratic.

We cannot rule out *a priori* the possibility that the observed age excesses of foraminifera are caused by contamination of the microfossils with old carbon either *in situ* or in the laboratory handling of the samples. We investigated the following three possible sources of systematic uncertainty:

1. Effect of carbonaceous sediment trapped inside foraminiferal shells. We estimated that inclusions of fine-grained carbonaceous sediments in the foraminiferal chambers cannot explain the large age excesses *e.g.*, at levels 80 and 104 m. At these levels, the carbonate content of the $<63\ \mu$m grain size fraction was only 10% and dated to 27,200 and 30,500 BP, respectively. A significant apparent age increase due to contamination with dead carbonate from fine-grained sediment in the chambers would thus have revealed itself by a low CO_2 yield from the foraminiferal samples. However, the measured carbonate content was typically >80–90%, corresponding to a maximum apparent age increase of 160–80 yr. If, *e.g.*, the above-mentioned 4900-yr age excess for the large Miliolidae at 104.5 m were due to trapped sediment, the measured carbonate yield would have been 20% rather than the observed yield of 96%.
2. Exchange of carbon between foraminifera and dissolved carbonate. If this process were significant, it would be impossible to explain the fact that totally unaffected foraminiferal species with dates in exact concordance with the shell age co-exist at several levels with species having large age deviations.
3. Contamination with carbon from CCl_4 and/or tap water used in processing foraminiferal samples. Large samples, 2 near-modern and 1 background sample (Eemian) of foraminifera, handpicked without further processing, were divided into subsamples and subjected to different treatments. Figure 4 shows no significant effect of the treatment of CCl_4 or tap water in the dating results.

We conclude that contamination, *in situ* or during handling in the laboratory, cannot be responsible for the observed age excesses.

All evidence points to reworking of foraminifera as the actual cause of the age discrepancies between shells and foraminifera in the present case. The effect of bioturbation and related effects (Andrée *et al.* 1984; Broecker *et al.* 1984; Peng and Broecker 1984) is negligible here due to the extremely high sedimentation rates of the Skagen Core. Part of the foraminiferal content in the sediment was deposited by lateral transport of older fossil material. As a quantitative example, we calculate that, at the 104-m level, *ca.* 60% by weight of the foraminiferal sample (age excess 2600 yr) are reworked specimens, if we assume that all the reworked foraminifera have the same age excess (4900 yr, Late Glacial) as the dated large Miliolidae.

Sand-grain-sized foraminifera are comparable to much smaller, silt-sized quartz grains with respect to hydrodynamic transportation properties (*e.g.*, Oehmig 1993). The reason is that foraminiferal shells, with thin, water-filled structures, have much lower effective density (grain bulk density minus density of water) than quartz particles. This makes entrainment and transport of foraminifera highly probable, especially in a high-energy environment.

The foraminiferal species show very different behavior in the present study. Thus, certain species (*e.g.*, ***Bulimina marginata***) are found almost exclusively *in situ*, buried in sediment mixed with reworked older foraminiferal shells belonging to a range of other species (*e.g.*, Miliolidae).

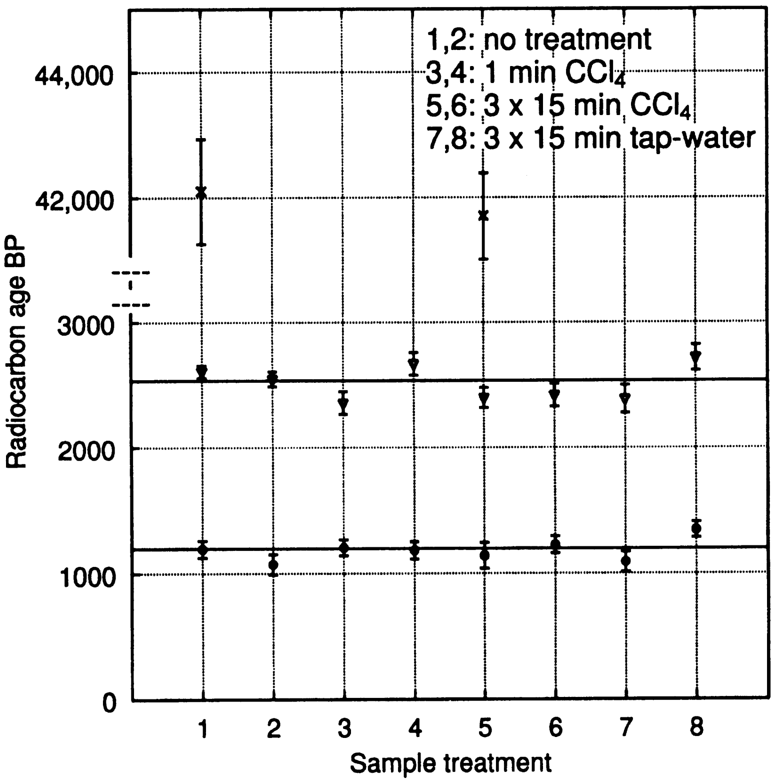

Fig. 4. Results of a test on possible carbon contamination from CCl_4 and tap-water treatments in the processing of foraminiferal samples. Three large samples of hand-picked foraminifera were divided into subsamples and subjected to different treatments. Subsamples 1 and 2 act as reference samples. Subsamples 3 and 4 were given the normal CCl_4 treatment, whereas 5 and 6 were subjected to a prolonged treatment. Subsamples 7 and 8 were washed with hot tap water for 3 × 15 min and dried under infrared light after each treatment. × is a background sample, *ca.* 42,000 BP; ▼ and ● are samples with average ages of 2500 BP and 1200 BP, respectively.

Is there a "best choice" of foraminiferal species for dating a sediment? Can we select *in-situ* species? The Skagen Core provides an example of a possible answer: We found that the species *Bulimina marginata* (at 78.3 m) and *Uvigerina mediterranea* (at 90.4 m) agreed precisely with the corresponding shell dates. These species are clearly *in situ* and are not seen as reworked fossils in the core. Thus, they are perfect dating tools for this core. This was predictable because these species are rare in the southerly source regions of the northbound Jutland Current that transported the sediments. Thus, the paleoenvironmental interpretations enabled us to select *in-situ* species.

Concordance between two species as well as a smooth age profile have been proposed as criteria for the reliability of foraminiferal dating in deep-sea cores (Broecker *et al.* 1989). We emphasize that, in the present study, these criteria are not sufficient to exclude that foraminiferal samples are influenced by reworking. For example, in dating foraminifera of a Late Glacial part of the Skagen Core, we observed concordance between monospecific and mixed samples (at 114.6 and 114.8 m, see Fig. 3) and a smooth age profile. If we had relied on this, we would have introduced an undetected age bias of 600 yr in the dating of the core.

CONCLUSION

We conclude that foraminiferal shells are well suited for ^{14}C dating because the measured age marks the true time of death of the organism. However, dating sediments *via* foraminifera may cause problems because the microfossil shells are likely to be affected by reworking, as demonstrated here. In the present shelf core, the reworked foraminifera are recognized easily from their large age excesses, in particular when the sedimentation rate is high, as in the Holocene part of the core. In a deep-sea core, reworking of foraminifera might be less frequent than in a shelf core, but may also be less easily detected due to lower resolution and the smoothing effect of bioturbation.

We plan to extend the present study of shelf sediments to cores, both from the continental slope and the deep sea, to compare the effects of reworking processes in these different environmental regimes.

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