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# Glacial–interglacial records of the reflectance of sediments from the Norwegian–Greenland–Iceland Sea (Nordic seas)

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**Abstract** The reflectance of sediments (gray level) were measured on 11 sediment cores from the Norwegian–Greenland–Iceland Sea (Nordic seas). The analyzed time interval covers the past five glacial–interglacial cycles. Although the results demonstrate that the gray-level method has a potential for stratigraphic purposes, it is indicated that gray-level changes in the Nordic seas are not necessarily driven by variations in the content of biogenic calcite. A detailed comparison of gray-level values with contents of total $CaCO_3$ (carbonate) and total organic carbon (TOC) reveals no overall causal link between these proxies. However, specific glacial core sections with layers containing organic-rich sediment clasts as a consequence of iceberg-rafting seem to correlate well with law gray-level values. Of those cores which show relatively high and comparable carbonate values in the last three main interglacial intervals (stages 11, 5.5, and 1), stage 11 is always marked by the highest gray-level values. A close inspection of the surface structure of the foraminiferal tests as well as the conduction of reflectance measurements on these tests leads to the conclusion that enhanced carbonate corrosion occurred during stage 11. The test corrosion not only affected the reflectance of the tests by making them appear whiter, it also seems responsible for the comparatively high gray-level values of the total sediment in stage 11. In contrast, the relatively low gray-level values found in stages 5.5, and 1 are not associated with enhanced test corrosion. This observation implies that variable degrees of carbonate corrosion can have a profound effect on total sediment reflectance.

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**Key words** Marine sediments · Glacial–interglacial change · Sediment gray-level reflectance · Biogenic carbonate · Organic carbon · Calcite dissolution · Nordic seas

## Introduction

The color of fresh marine sediments contains information about the climatic, oceanographic, and sedimentologic conditions during the time of their deposition (Merrill and Beck 1995). Changes in sedimentation patterns are often recognized as changes in sediment color. To deduce further information from these colors, the factors determining the color should be identified. Until a few years ago, conventional color descriptions of marine sediments were made by visual description using the Munsell Rock Color Chart. But to some extent, the Munsell system is biased in that it depends on the individual and, most of all, leads only to qualitative results.

Different technical systems are now available which offer quantitative and comparable results to determine the sediment color of various marine environments. These systems are being widely used also in paleoceanographic studies (e.g., Merrill and Beck 1995; Mix et al. 1992, 1995; Schaaf and Thurow 1994, 1995). Recent investigations on late Pleistocene glacial–interglacial sediments from the North Atlantic have shown a good correlation between carbonate content and sediment reflectance (Cortijo et al. 1995; Grousset et al. 1993). Apparently, this correlation depends on increased carbonate bioproductivity during warmer intervals (higher reflectance) and less productivity together with the increased content of terrigenous materials (IRD) derived from melting icebergs during colder intervals (lower reflectance).

In comparison with the lower latitudes, the deposition of glacial and interglacial sediments in the subpolar North Atlantic, the Norwegian–Greenland–Iceland Sea (Nordic seas), is of a different

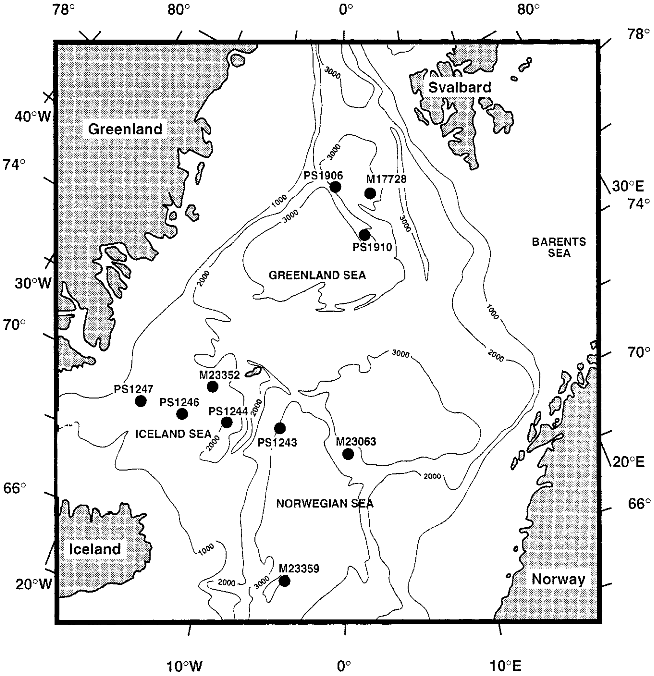


**Fig. 1** Overview of work area and position of studied sites

**Table 1** List of all sites and cores studied. Number behind the dash indicates different cores: *BC* box core; *KC* kasten core; *GC* gravity core; *PC* piston core

| Core | Corer | Water depth (m) | Position | |
|---|---|---|---|---|
| | | | Latitude | Longitude |
| M17728-1 | BC | 2473 | 76°31.2′N | 03°57.5′E |
| M17728-2 | KC | 2485 | 76°31.1′N | 03°57.3′E |
| M23063-2 | BC | 2302 | 68°44.8′N | 00°00.3′W |
| M23063-3 | PC | 2299 | 68°45.0′N | 00°00.0′E |
| M23352-2 | BC | 1822 | 70°00.5′N | 12°25.5′W |
| M23352-3 | KC | 1819 | 70°00.4′N | 12°25.8′W |
| M23359-2 | BC | 2821 | 65°31.8′N | 04°09.0′W |
| M23359-4 | KC | 2820 | 65°31.7′N | 04°09.6′W |
| PS1243-2 | BC | 2716 | 69°22.5′N | 06°31.3′W |
| PS1243-1 | GC | 2710 | 69°22.3′N | 06°32.4′W |
| PS1244-1 | BC | 2122 | 69°22.0′N | 08°40.0′W |
| PS1244-2 | GC | 2162 | 69°22.0′N | 08°31.3′W |
| PS1245-1 | GC | 1750 | 69°23.0′N | 10°47.0′W |
| PS1246-2 | BC | 1861 | 69°23.0′N | 12°55.0′W |
| PS1246-4 | GC | 1902 | 69°23.0′N | 12°55.0′W |
| PS1247-2 | BC | 1400 | 69°29.5′N | 17°07.0′W |
| PS1247-1 | GC | 1400 | 69°29.5′N | 17°07.0′W |
| PS1906-1 | BC | 2990 | 76°50.5′N | 02°09.0′W |
| PS1906-2 | KC | 2939 | 76°50.1′N | 02°09.1′W |
| PS1910-1 | BC | 2448 | 75°37.0′N | 01°19.0′E |
| PS1910-2 | KC | 2454 | 75°37.0′N | 01°20.0′E |

temporal variability. In this region, relatively long intervals with hemipelagic sedimentation dominate over much shorter periods which are characterized by a deposition of pelagic components (Baumann et al. 1995; Henrich 1998). This is due to the proximity of this area to the Scandinavian landmass, which became repeatedly glaciated and deglaciated during the Pleistocene. During colder climate conditions, this caused a deposition of predominantly lithogenic sediments in the marine environment via iceberg rafting (Wolf and Thiede 1991).

It is the objective of this study to present for the first time quantitative and comparable results of reflectance records of sediments from the Nordic seas which cover the time period of the past five glacial–interglacial cycles, i.e., back to marine oxygen isotope stage 12. As these cores were measured at close intervals yielding high-resolution records, it is tested to what extent these records can be used as a paleoceanographic tool. For this, a comparison to other standard proxy methods is made in order to define the main factors which determine the sediment reflectance in this region.

## Materials and methods

In this study a hand-held Minolta CM-2002 (Minolta, Ahrensburg, Germany) spectrophotometer was used to analyze the sediment color. For all measurements the spectrophotometer was set at an angle of 2° and the mode "normal light" $D_{65}$ was chosen. The sediments were measured using the gray-level value L* of the L*a*b* color space. The L*a*b* color space is defined by the brightness L* (scale between black = 0 and white = 100) and the chromatic coordinates a* and b*

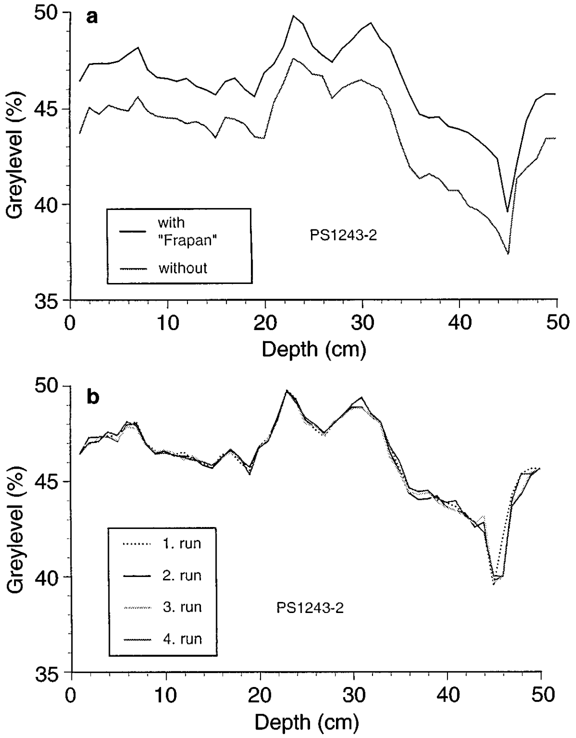
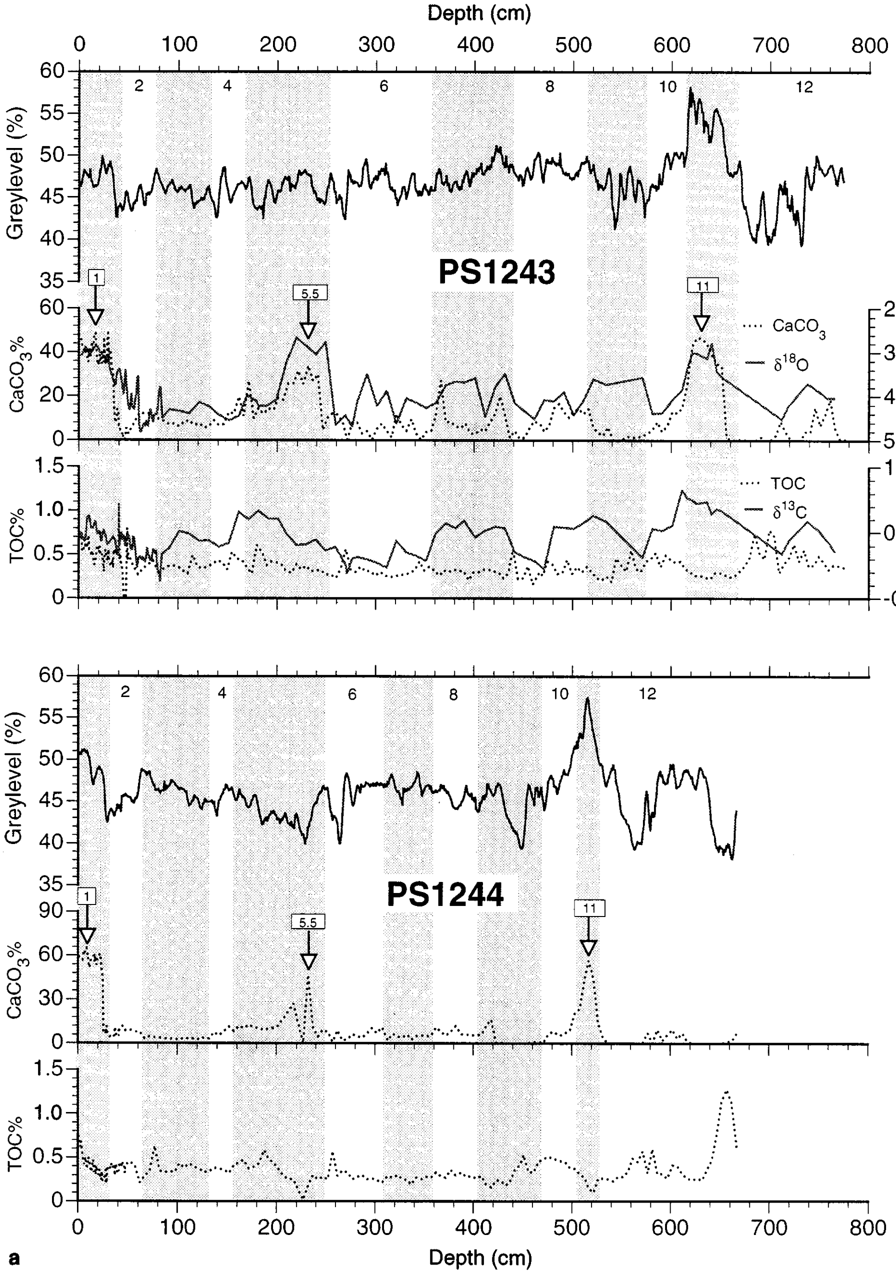


**Fig. 2** **a** Results of the sediment gray-level measurements from box core PS1243-2 with and without "Frapan". The effect of "Frapan" is a higher reflection; nevertheless, the general trend remains similar for both measurements. **b** Four separate runs of gray-level measurements

**Fig. 3a–f** Downcore comparison of sediment gray-level records (smoothed with a five-point moving average) with records of stable isotopes, carbonate, and total organic carbon (TOC)



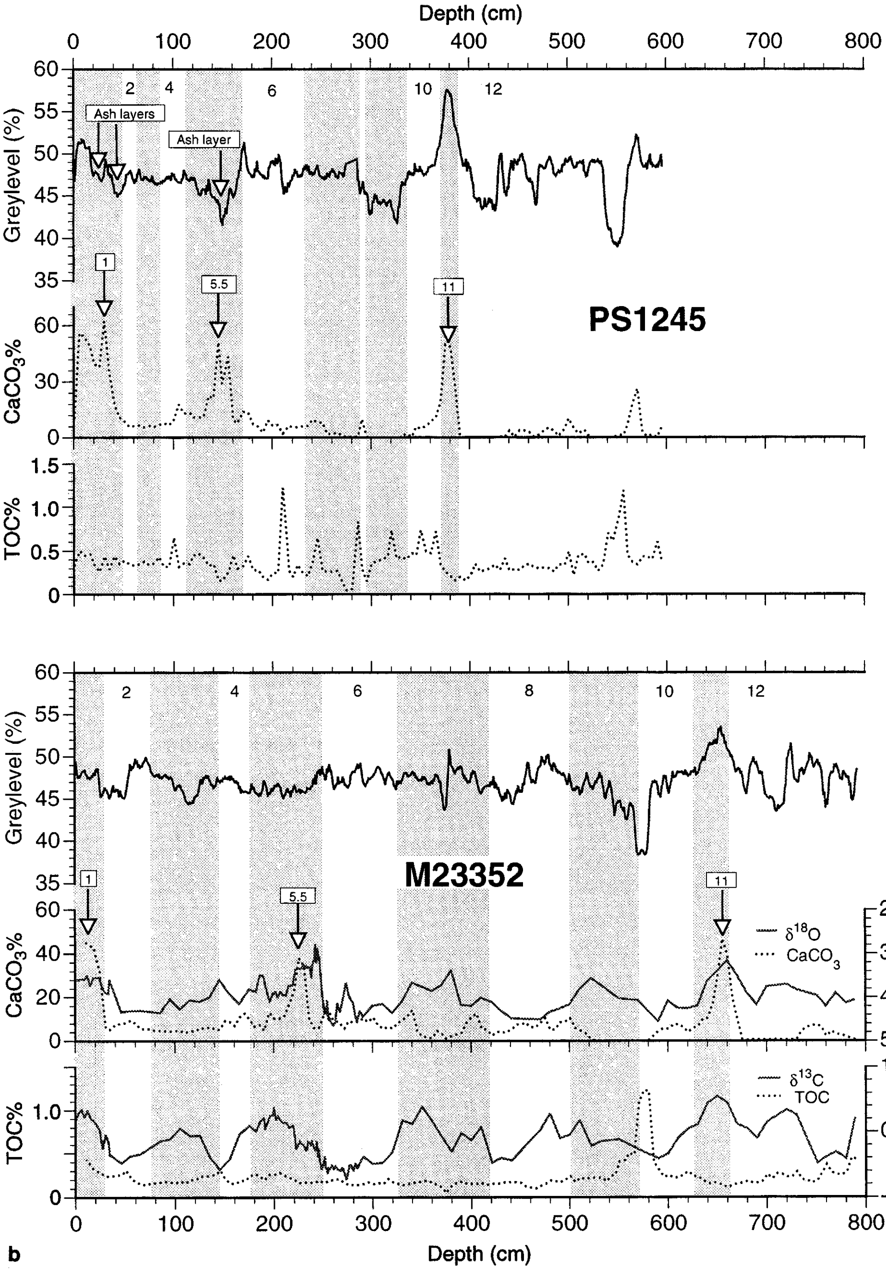
For continuation of Figure 3 please see the next pages

(between 60 and –60). The center of this color space represents a gray, which becomes more colorful towards its edge.

The method of gray-level analysis as L* was selected because in the Nordic seas, the changes in sediment brightness depends mainly on the input of biogenic carbonate, IRD, and some occasional ash layers. In the North Atlantic, which is characterized by sediment components similar to the Nordic seas, Nagao and Nakashima (1992) worked with L* (gray level), whereas others used the gray-level changes of the green channel only (Cortijo et al. 1995). But variations within either the green, blue, or red channels are minor and both methods, L* and gray level of a single color channel, yield similar trends.

In this study, long sediment cores as well as shorter box cores with undisturbed upper sediments from 11 sites in the Nordic seas were analyzed (Fig. 1; Table 1). The long cores and the box cores were spliced together at levels with prominent lithological changes. The prerequisite for selecting these sediment cores was that previous studies had already given downcore information on total $CaCO_3$ (carbonate), total organic carbon (TOC), as well as $\delta^{18}O$ and $\delta^{13}C$ analyzed on the planktic foraminifer *Neogloboquadrina pachyderma* sinistral. Although the stable isotope data were the

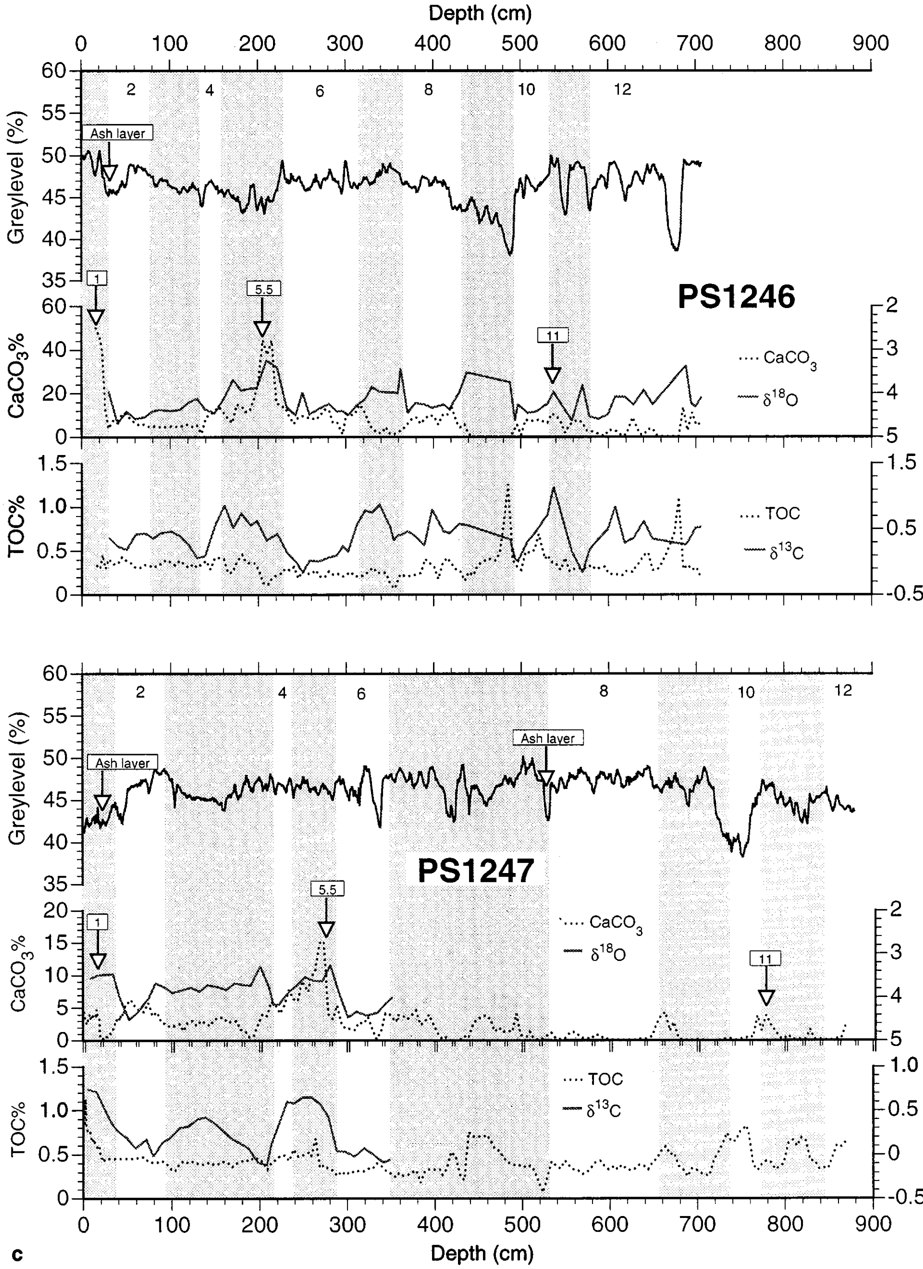
**Fig. 3b**



main basis for placing oxygen isotope stage boundaries (Imbrie et al. 1984; Martinson et al. 1987), the stratigraphic framework was further refined by also taking into account the other standard proxy records. In most cases the analyses of these standard proxies were carried out at a lower sample resolution (every 5 and 10 cm) than the gray-level measurements (every 1 cm).

It is crucial for color investigations of marine sediments that the analysis is measured on a fresh sediment surface. Since some of the used sediment cores were taken more than 10 years ago, most color measurements were made on 30-cm-long core sections which were formerly sliced from the cores for X-ray analyses. These samples were usually prepared onboard or just after the cruise. They were sealed in plastic foil under vacuum conditions. To measure the core sections the foil was removed and the sediment was directly covered with wrapping plastic foil (conventional household-type "Frapan"). With this procedure it was possible to place the spectrophotometer directly onto the sediment surface without any danger of contaminating the illumination/viewing system of the spectrophotometer (Ø = 0.8 cm). Furthermore, placing the aperture onto the sediment prevents disturbances from any ambient light. To investigate the influence of the Frapan on our analyses, the same core section was measured with and without Frapan (Fig. 2a). The results show that effect of Frapan is a higher reflection. To test the tolerance of our measurements, the same section (core PS1243-2)

Fig. 3c



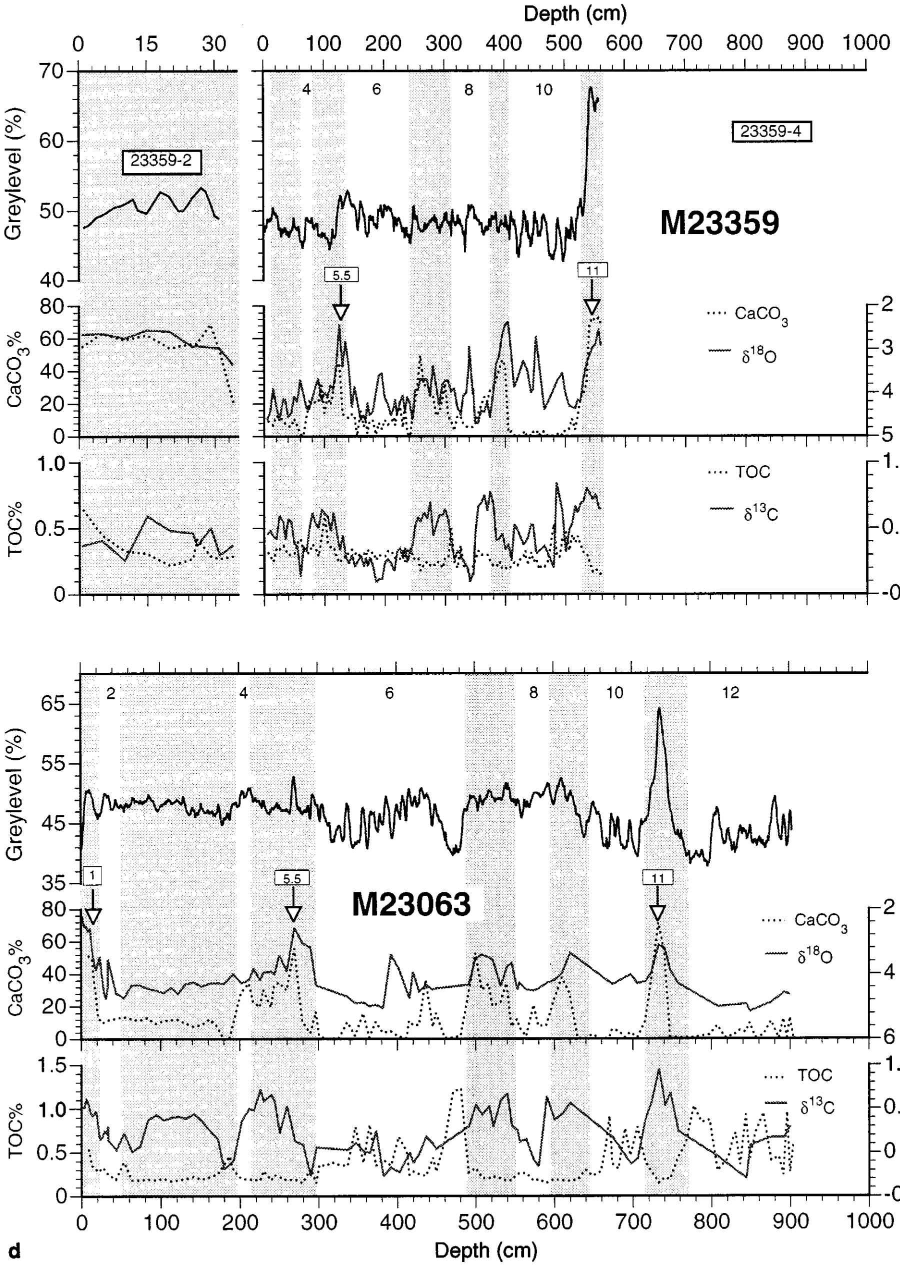
was measured on four runs (Fig. 2b). On average, these measurements deviate from the mean by ±1.5%. This is small considering that each of the four runs was executed on not exactly the same spot and that sediments can vary laterally. All downcore gray-level records shown herein were smoothed using a five-point moving average.

## Results

### Gray level vs carbonate

In Fig. 3 the gray-level results for all cores are presented in comparison with the records of carbonate, TOC, and stable isotopes. In general, the gray-level results vary between 68 and 38%. Except for cores PS1247 and M17728, maximum reflectance occurs in all cores within interglacial stage 11. In contrast, the lowest values are recognized during glacial and/or glacial–interglacial transitions, i.e., during times of major deglaciation intervals (terminations). In cores PS1243, PS1244, PS1245, M23352, M23359, and M23063, the high gray-level values found in stage 11 coincide with high amounts in carbonate content. Maximum gray-level values found in this interval range between 55 and 65%. Compared with the other two main interglacial intervals in the Nordic seas which reveal similar values in $CaCO_3$ content, the stages 5.5 (Eemian) and 1 (Holocene), absolute gray-level values are notably lower and vary between 43 and 53%

**Fig. 3d**



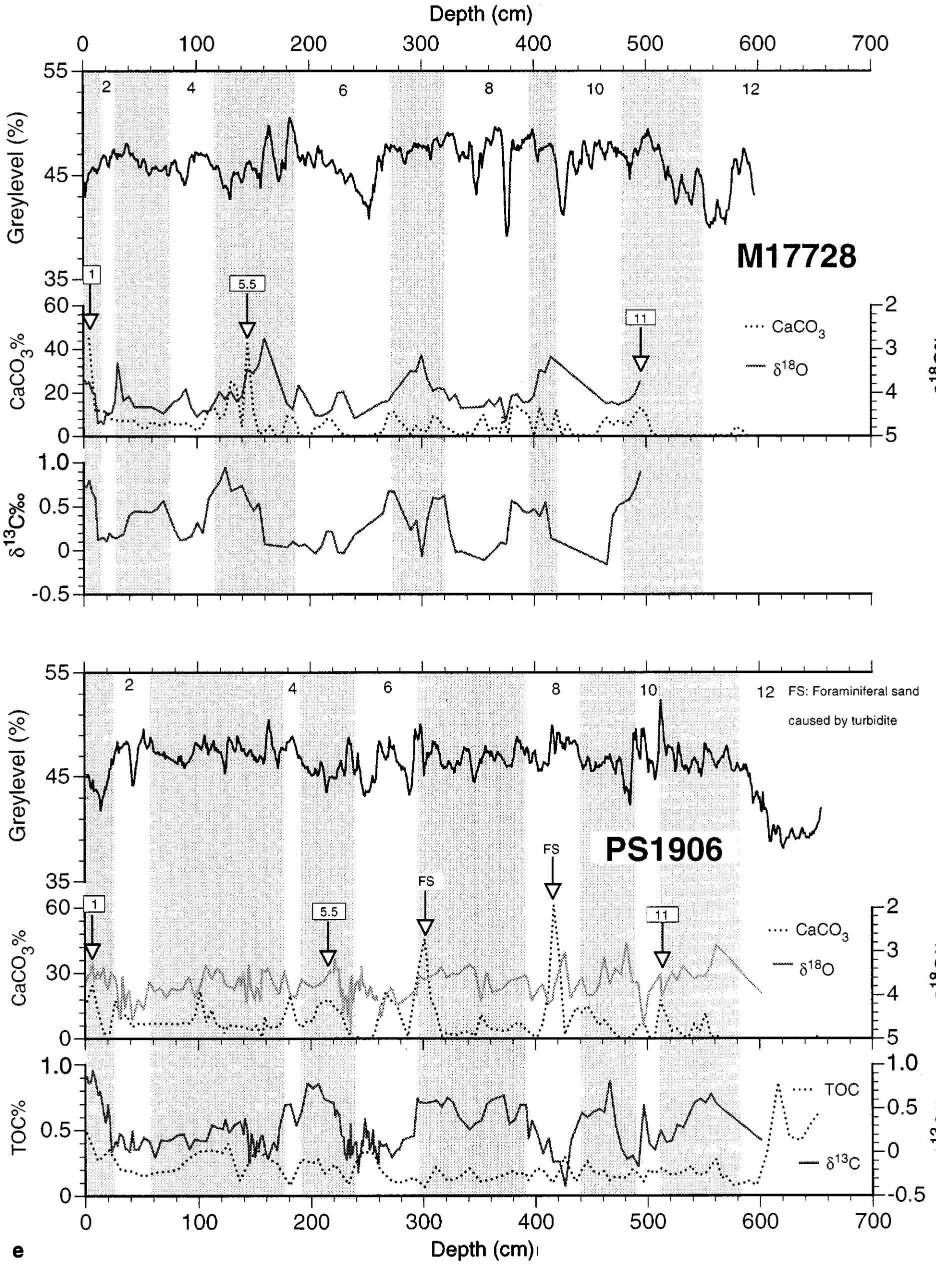
(Fig. 3). In some cores from the Iceland Sea the carbonate record in stage 5.5 peak is bimodal (cores PS1244, PS1245) due to a prominent ash layer composed of rhyolitic glass shards with darker reflectance (Birgisdottir 1991).

Although a parallel increase in gray level and carbonate content towards the end of stage 6 and into stage 5.5 is observed in some cores (M17728, M23063, PS1243, M23359), this trend is by no means consistent. In most instances, gray-level value as noted for the two warm stages 5.5 and 1 are also observed during cold stages, regardless of carbonate content. This indicates that components other than the carbonate content can also influence the gray reflectance of the sediments at high-northern latitudes.

## Gray level vs TOC

The analyses of TOC reveal that in most cores values remain below 0.5%. But cores from sites closer to the continental shelves are sporadically marked by increases in TOC of more than 1%. In such cases the steep increase in TOC corresponds to a significant decrease in gray level. Some of these darker intervals are particularly prominent during stages 6, 10, and 12, and during terminations. Interestingly, the marked decreases in gray level during stages 12 and 10 can be observed in all cores and, thus, may be used as stratigraphic markers for correlating between the cores. The dark intervals in stage 6 which correspond to enhanced TOC are particularly prominent in cores located closest

**Fig. 3e**



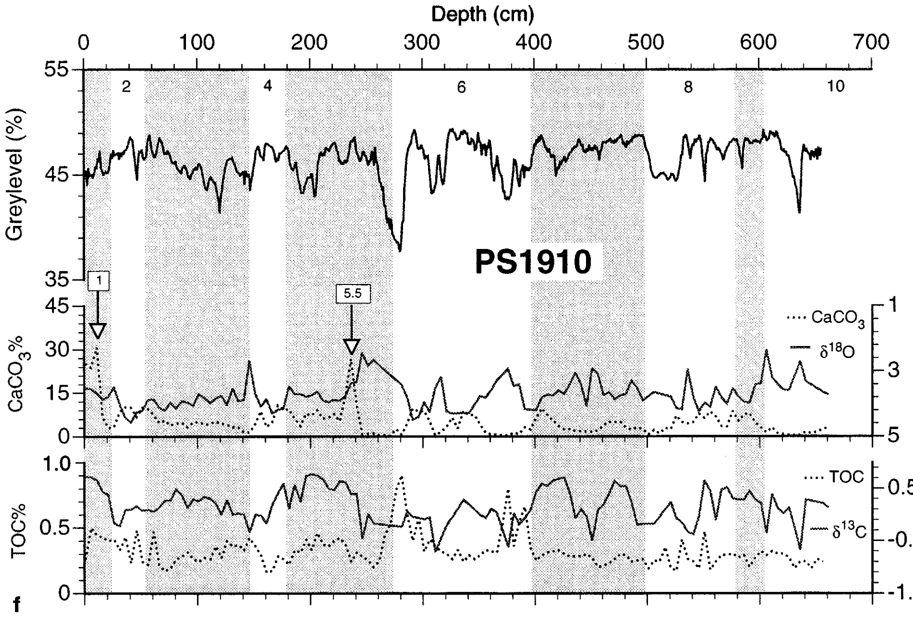
to the shelves of the Barent Sea and Norway (e.g., cores M23063, PS1910, M17728). This may imply that the sources for the TOC-rich layers during glacial stages must be sought on these continental shelves too.

The comparison of the gray-level measurements with carbonate and TOC has revealed that, at least for certain core intervals, a causal link seems to exist among these parameters. Taking all downcore measurements, the correlation coefficient between gray level and carbonate and TOC is poor (Fig. 4), meaning that most investigated cores show no linear correlation between the three different proxy tools (the exception is core M23063 which reveals a correlation coefficient of 0.59 and 0.74 for carbonate and TOC, respectively). However, a generally good correlation coefficient of 0.6 exists for carbonate if only the interval across stage 11 (between stages 12 and 9) is considered (Fig. 5).

## Discussion

In the North Atlantic region, high contents of carbonate reveal a very high correlation with sediment reflectance (Cortijo et al. 1995). But in the Nordic seas, only the high gray level in stage 11 seems to follow this general pattern. This is surprising because a similar response in gray level is not found for stages 5.5 and 1, although the total carbonate content is nearly equal or even higher than in stage 11 (e.g., cores PS1243,

**Fig. 3f**



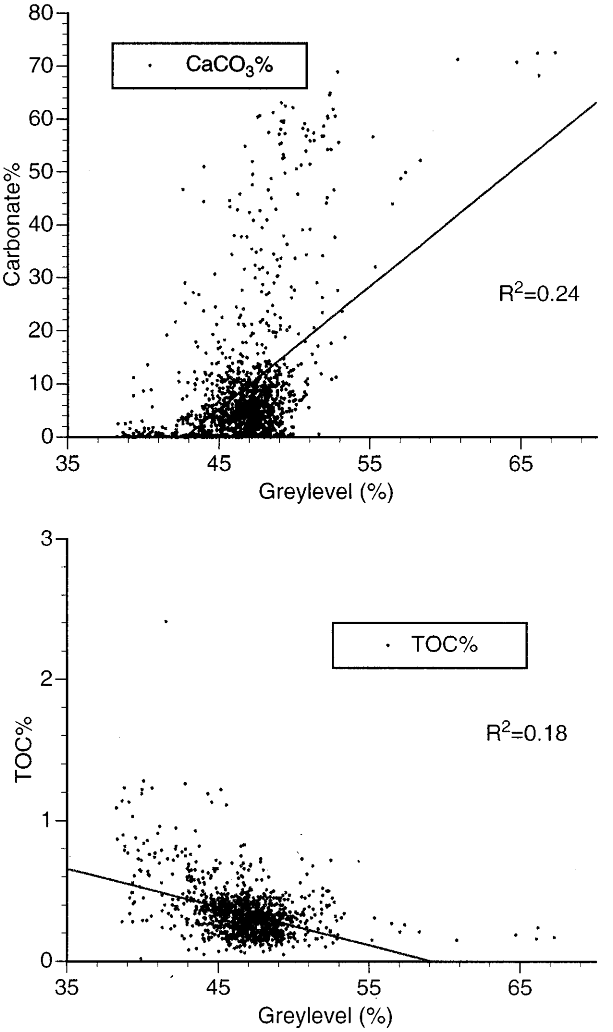


**Fig. 4** Linear correlation of sediment gray level to carbonate and TOC contents for all samples

PS1244, PS1245). The lower sample density usually applied to the carbonate record cannot be responsible for this (carbonate in stage 1 of core PS1243 was also measured at 1-cm intervals). One possible mechanism that could explain the gray-level differences between the peak interglaciations may be differences in fine carbonate content which may be attributed to variable contents of coccoliths (Baumann et al. 1995). But previous investigations in the distribution of fine and coarse carbonate (i.e., >63 and <63 μm), which was based on some of the cores shown in this study, cannot support such a link. In core M23352, for instance, the fine carbonate content in interglacial stage 1 is as high as 30%, whereas less than 5% is usually found during glacial intervals (Bauch et al. 1999). Although fine carbonate contents in stages 5.5 and 11 of this core remain below 10% (Bauch et al. 1999; Henrich 1992), stage 11 clearly exhibits the highest gray-level values. Therefore, the reason for the much brighter sediment reflectance during stage 11 than during stages 1 and 5.5 should be sought in the coarse carbonate content (>63 μm) where the main mass of foraminifera occurs. In the Norwegian and Iceland seas, stage 11 is characterized by the highest abundances of planktic foraminifera during the past 450 ka (Spiegler and Jansen 1989; Bauch 1997). Although stage 11 is barren of any IRD in this region (Birgisdottir 1991), the planktic foraminiferal assemblage is almost entirely composed of the cold-water species *Neogloboquadrina pachyderma* sinistral with only small proportions of warmer water indicating species occurring in the southern Norwegian Sea (Bauch 1997).

One important factor that needs to be considered when evaluating gray-level analyses from the Nordic seas is, therefore, the different degrees of carbonate dissolution. Presently, foraminiferal tests are well preserved in most parts of the Nordic seas. Only along

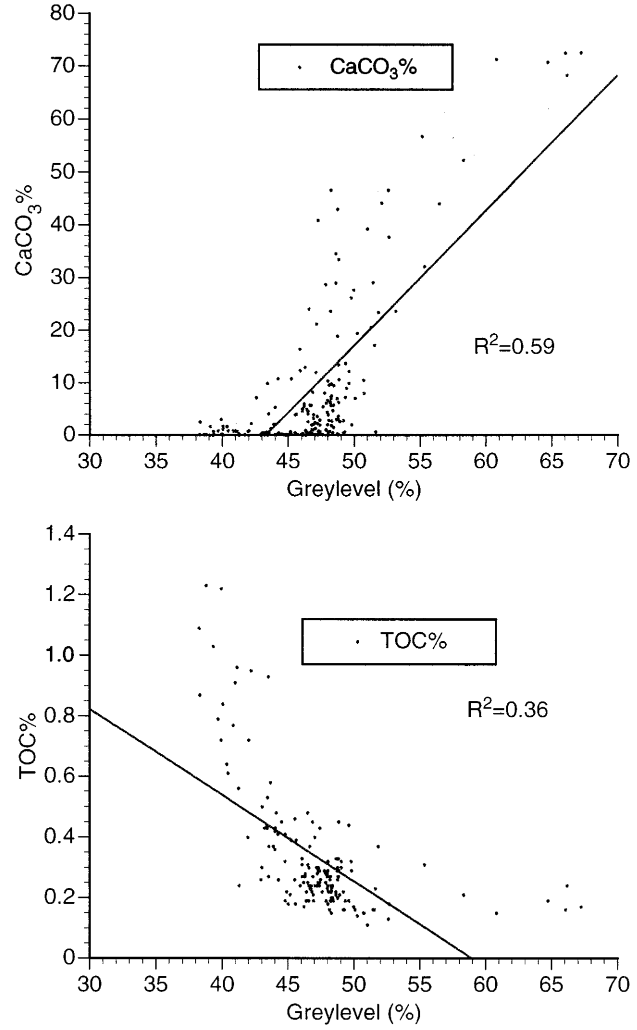


**Fig. 5** Linear correlation of sediment gray level to carbonate (cores M23063, M23352, M23359, PS1244) and TOC (cores M23063, M23352, M23359, PS1910) contents using the samples from the interval stages 12 to 9. The correlation coefficients for this specific interval is considerably higher than for the entire suite of downcore samples (see Fig. 4)

the East Greenland continental margin can severe carbonate corrosion be observed, a fact which is also reflected by very low carbonate contents in the surface sediments from this region (Baumann et al. 1993). Henrich (1986), who studied corrosional features on planktic foraminifera from the Nordic seas using a scanning electron microscope, introduced a dissolution index to distinguish between the different degrees of test corrosion. Increasing corrosion was documented by enhanced corrosional features on the surface of the tests. During our study and after the sediment samples had been washed and dried, it became apparent that in those cores with high carbonate content in stage 11 all planktic foraminiferal tests appear extremely white, essentially not showing a translucent character. Furthermore, all tests, although not perforated, were very fragile, implying intensive calcite loss through corrosion. In contrast, the planktic foraminiferal tests from stages 1 and 5.5 as well as from the glacial stages 6 and 2 appeared rigid and relatively pristine. The effect of foraminiferal test corrosion is demonstrated in Fig. 6. Corrosion obviously caused a rougher surface structure of formerly well-developed crystal faces. When comparing the tests from different stages, the strongest test corrosion is observed in stage 11, whereas the tests from stages 2 and 6 are extremely well preserved (Fig. 6). Intriguingly, the surface structure of the test from stage 5.5, although quite well preserved too, seems to show first corrosional features. Based on all these observations, we conclude that the change in the microstructure due to corrosion leads to surface enhancement and, thus, to a reduction in the transparency of the entire test, thereby making it whiter.

To further confirm the assumption that the color of planktic foraminiferal tests changes towards a brighter white with increasing carbonate dissolution, we measured the color reflectance of the washed samples (125–500 μm), i.e., the bulk of the foraminiferal tests themselves. Prior to this, the residues were closely inspected in order to avoid samples which contained components other than biogenic carbonate. All of these bulk measurements reveal a comparatively brighter reflectance of foraminiferal tests in stage 11 than in the stages 5.5 or 1 (Fig. 7).

The water depths of the cores investigated range between 2800–1800 m. Thus far, glacial–interglacial changes in the position of the calcite compensation depth (CCD) are not known from the Atlantic Ocean for such shallow water depths (Broecker and Peng 1993). The carbonate dissolution pulse observed during stage 11 may therefore be a regional phenomenon caused by a shallowing of the lysocline to water depths of at least <1800 m in the Nordic seas only. But recent studies from the Caribbean also indicate intense carbonate dissolution during stage 11 (Droxler et al. 1996), giving evidence that this paleoceanographic event was of much larger regional scale. Thus, the carbonate corrosional event in the Nordic seas may be linked to changes in the global carbon cycle.

The typical negative correlation between gray level and TOC content was noted for certain depth levels in most cores. These distinct levels are particularly obvious during glacial intervals, which in the Nordic seas were characterized by increased input of terrigenous material from icebergs (Henrich et al. 1989; Wolf and Thiede 1991; Baumann et al. 1995; Fronval and Jansen 1995; Wagner and Hölemann 1995). Wagner and Henrich (1994) pointed out that organic carbon in these sediments is mainly of allochthonous origin, which was deposited through glaciomarine sedimentation processes. It is therefore no surprise that those sites which are located nearer to the Greenland and Norwegian shelves exhibit these marked horizons with low gray-level values. Most often these horizons are typical diamictons containing high numbers of dark sediment clasts, e.g., organic-rich siltstones and shales

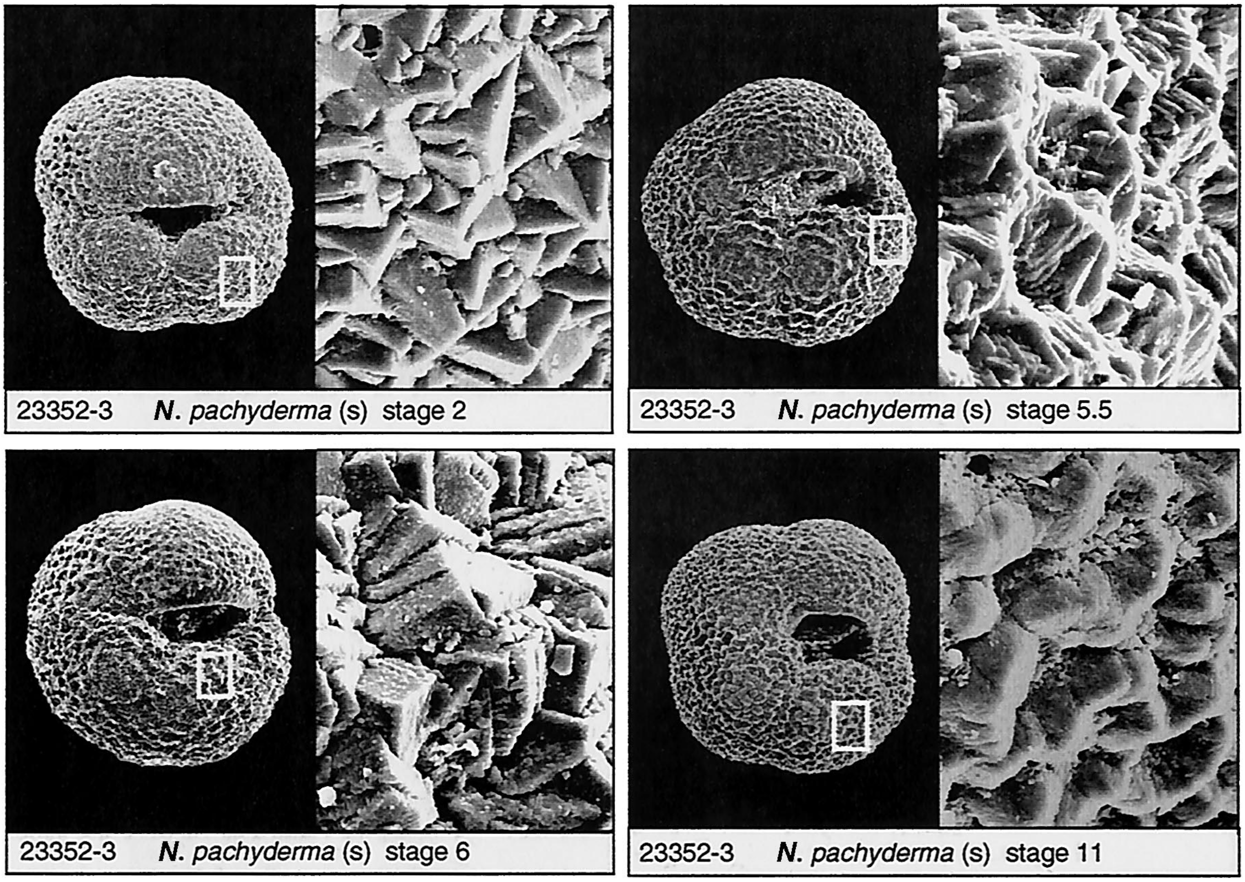


**Fig. 6** Various surface structures of the polar planktic foraminifera *N. pachyderma* sinistral taken from different climate periods. Smooth calcite ridges are observed on the test from interglacial stage 11, indicating enhanced test corrosion. In contrast, sharp-edged, well-preserved calcite crystals are found on tests from the two glacial periods (stages 2 and 6). The surface of the test from interglacial stage 5.5 seems to indicate slight corrosional features

(Henrich et al. 1989; Bischof 1994). The temporal and spatial distribution of this terrigenous material with high TOC content in the Nordic seas indicates that it derived from abrasional processes of glaciers surging on the shelves during times of lowered sea level (Wagner and Henrich 1994).

Cores from the Iceland Sea and the southern Norwegian Sea which are marked by a significant carbonate increase across the last glacial–interglacial transition, Termination I, do indeed reflect a simultaneous increase in gray level. But this feature does not seem very consistent for other terminations. During Termination II, for example, changes in gray level and carbonate content are not precisely parallel (Fig. 3). The total change in the amplitude of gray level across Termination I is usually not more than 5% (e.g., cores M23359, M23063, M23352). The relative change in gray level becomes only slightly higher where cores also document an ash layer (cores PS1243, PS1244, PS1245). Except for stage 11, major relative changes in gray level are primarily due to varying contents in the darker

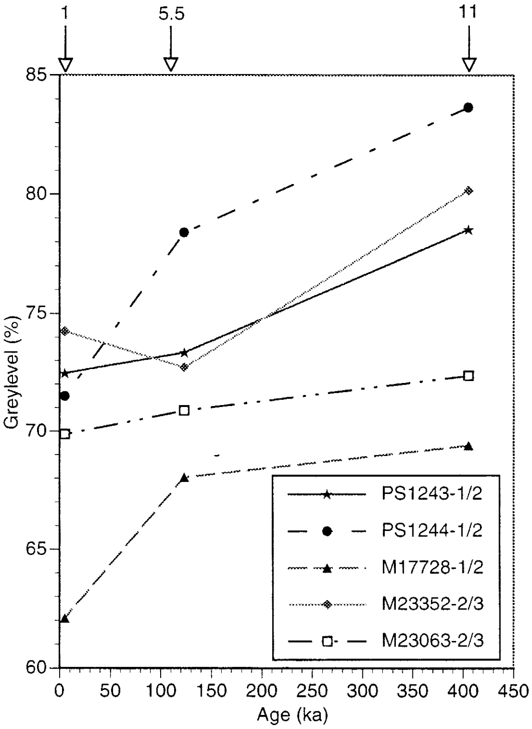


**Fig. 7** Gray-level analyses of bulk foraminiferal tests (size fraction 125–250 μm) taken from the three interglacial stages 1, 5.5., and 11. All measurements reveal highest gray-level values for stage 11, indicating that the foraminiferal tests are whiter in this interval than in the other two interglaciations

sediment components. This can be deduced from all core sections where layers with high TOC contents occur. The common increase in gray level just above a horizon with high TOC is, thus, simply a return to a sedimentary environment characterized by a reduced input of organic-rich material. The reason for the observed variability in gray level in those core sections with generally both low TOC and carbonate remains an unanswered question. These color changes are most likely caused by sediment components which are of light color also, e.g., felsic minerals such as quartz grains. These constituents are sufficiently available throughout most core intervals (Henrich et al. 1989; Birgisdottir 1991).

## Summary and conclusion

Sediment gray-level analyses were conducted on sediment cores from the Nordic seas in order to evaluate this method for studying sedimentary changes at high northern latitudes during the past five glacial–interglacial cycles. In general, the gray-level records reveal that this method has some potential for regional stratigraphy in the Nordic seas. However, it is generally concluded that gray-level variability in the Nordic seas is not necessarily driven by variations in carbonate contents alone (i.e., in the deposition of biogenic calcite vs lithogenic components) like in the North Atlantic. Based on the 11 cores studied, which go back in time to at least oxygen isotope stage 11, some characteristic changes in the gray-level records were observed and compared with other records:

1. A detailed comparison of gray-level values with contents of total carbonate (%) and TOC (%) reveal no consistent correlation between the three proxies. However, specific organic-rich layers in glacial core intervals, which were the result of iceberg rafting, seem to correlate well with low gray-level values and may be used as stratigraphic indicators.
2. Despite comparable and high carbonate values observed in the last three main interglacial intervals (stages 11, 5.5, 1) of cores from the southern Nordic seas, stage 11 is always marked by the highest gray-level values. Based on a study of the surface structure of foraminiferal tests as well as of the reflectance of these tests, it is concluded that enhanced carbonate corrosion occurred during stage 11. It is further suggested that the effect of this increased test corrosion also caused the high gray level of the total sediment in this interval.
3. Gray-level values during the other two interglaciations (stage 5.5 and 1) do not seem to differ significantly from gray levels found in glacial or interstadial intervals when the carbonate content is commonly low. For these core intervals, it is therefore believed that sedimentologic parameters other than the carbonate content also have a profound influence on sediment reflectance in the Nordic seas.

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