

# Biomarkers as organic-carbon-source and environmental indicators in the Late Quaternary Arctic Ocean: problems and perspectives

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## Abstract

In order to examine the variation in marine and terrigenous sources of the organic matter during the last 15,000 Cal. yr BP, hydrogen index values, C/N ratios, and specific biomolecules (short- and long-chain *n*-alkanes, short-chain fatty acids, sterols, alkenones, and pigments) were determined in three sediment cores from the Laptev Sea continental margin. The results show that the interpretation of the biomarker data is much more complicated and less definitive in comparison to similar data sets from low-latitude open-ocean environments. This is mainly caused by the complexity of the Arctic Ocean system, which is characterized by a high seasonality of sea-ice cover and primary productivity, sea-ice sediment transport and a high fluvial supply of freshwater (aquatic) organic matter. A combination of organic geochemical, organic petrographic and micropaleontological data may yield to a more precise identification of organic-carbon sources for these complex systems. On the Laptev Sea shelf (cores KD9502-14 and PS2725-5), terrigenous organic-carbon input controlled by river discharge seems to be predominant during the last about 10,000 Cal. yr BP. Maximum supply of terrigenous organic carbon was reached in the Early Holocene (i.e., about 9000–10,000 Cal. yr BP). Further offshore at the upper continental slope (core PS2458-4), a major change in organic-composition occurred near 10,000 Cal. yr BP. During this period hydrogen indices as well as the amounts of short-chain *n*-alkanes, short-chain fatty acids, dinosterol and brassicasterol significantly increased, indicating increased relative proportions of marine organic matter preserved in the later time interval. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* marine and terrigenous organic carbon; biomarker; paleoproductivity; Laptev Sea; Arctic Ocean

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## 1. Introduction

The present state of the Arctic Ocean and its influence on the global climate system strongly depends on river discharge (see Stein (1998) for re-

view). The freshwater balance of the Arctic Ocean, which receives 10% of the global runoff (Aagaard and Carmack, 1989), plays a key role in controlling sea-ice extent and intermediate/bottom water formation in the Northern Hemisphere, as well as Arctic Ocean surface-water conditions. The major Arctic rivers also supply huge amounts of suspended inorganic (detrital) and organic matter to the shelves and the detrital component of Arctic shelf sediments,

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thus, largely consists of riverine material. The annual discharge of suspended sediments by the Lena River, for example, is presently  $17.6 \times 10^6$  tons (Martin et al., 1993). Concerning the sources and fate of organic matter within the Arctic system, Arctic rivers which discharge large quantities of terrigenous organic matter, but also nutrients, into the system, are of considerable importance. Dissolved and particulate organic matter supplied by the Lena River is estimated at  $3.6 \times 10^6$  tons/yr and  $1.3 \times 10^6$  tons/yr, respectively (Rachold et al., 1996). The riverine nutrient supply may cause enhanced surface-water productivity. This is reflected by elevated chlorophyll *a* concentrations and phytoplankton cell numbers in the Lena River plume (Heiskanen and Keck, 1996). The concentrations of dissolved silica are high throughout the year within the Lena River (43–108  $\mu\text{M}$ ), whereas nitrate and phosphate are low (1.4–16  $\mu\text{M}$  and 0.1–0.8  $\mu\text{M}$ , respectively) (Létolle et al., 1993; Cauwet and Sidorov, 1996; Gordeev et al., 1996). Within the Lena River phytoplankton productivity, thus, seems to be limited by nutrients other than silica (Heiskanen and Keck, 1996). This may suggest that the linkage between riverine nutrient supply and enhanced productivity is not necessarily a simple direct relationship.

Most of the organic matter accumulates in coastal zones; however, significant amounts of this material are transported further offshore by different processes such as sea-ice, ocean currents, and turbidity currents (Stein and Korolev, 1994; and further references therein). Eolian input is only of very minor importance for the sedimentary budget of the Arctic Ocean. Macdonald et al. (1998) estimated the eolian flux in the Mackenzie shelf area, reaching  $1.4 \times 10^4$  tons/yr. Based on studies of snow samples from the western central Arctic Ocean an eolian flux of 3.3–14.0  $\mu\text{g}/\text{cm}^2$  and year was calculated (Darby et al., 1974, 1989). Even if all this material would be released during summer melting and would reach the sea floor (which is not very realistic), this would result in an average sedimentation rate of 0.02–0.09 mm/kyr, i.e., about 1–5% of the bulk sedimentation rate. In our study area, the Laptev Sea continental margin where Holocene bulk sedimentation rates increase to values of about 15 to 800 cm/kyr (Stein and Fahl, 1998), the eolian input then becomes even much less important.

Comparison of sedimentological and organic-geochemical proxies in surface sediments reflecting the surface water productivity and terrigenous organic-carbon flux with physical and biological parameters provides a means to identify the most important processes controlling the organic-carbon accumulation in the Arctic Ocean (e.g., Fahl and Stein, 1997; Schubert and Stein, 1997; Stein et al., 1998). Interpretation of vertical profiles in sediment cores in the context of these findings will then yield information on changes in the organic-carbon cycle of the Arctic Ocean through time. These data may, in turn, yield important insights into the role of the Arctic Ocean during global climate change.

The use of specific organic-geochemical tracer compounds (biomarkers) as (paleo-) environmental proxies is a well established tool in low- and mid-latitude open-ocean areas (e.g., Farrimond et al., 1990; ten Haven et al., 1990; Prah et al., 1994; Hinrichs et al., 1995). When using biomarkers as (paleo-) indicators of spatial and temporal changes in organic-carbon sources for high-latitude ice-covered regions, such as the Laptev Sea continental margin and adjacent deep sea, it is important to consider the complex factors controlling the organic-carbon flux in these areas. First, the strong fluvial supply may provide freshwater (aquatic) organic matter as well as terrestrial organic matter. Second, due to the more or less closed sea-ice cover, phytoplankton productivity in the Arctic Ocean is very low and represents a mixed signal of surface-water productivity and productivity of sea-ice communities. Third, the organic matter deposited on the Laptev Sea shelf, which is a mixture of terrigenous higher plant material, freshwater organic material and, to a limited extent, marine organic matter, may be incorporated into the sea-ice and further transported offshore. Thus, terrigenous organic matter may be deposited far away from the source area.

The major goal of this study is (1) to discuss the problems of using biomarkers as organic-carbon-source indicators in Arctic Ocean sediments, (2) to identify organic-carbon sources (i.e., marine vs. aquatic vs. terrigenous), and (3) to reconstruct changes in composition and flux of organic carbon in relation to climate change and sea-level rise at the Laptev Sea continental margin during the last  $\sim 15,000$  Cal. yr BP.

## 2. Sediments and stratigraphy

The three sediment cores described in this study, PS2458-4, PS2725-5, and KD9502-14 (Fig. 1, Table

1), were obtained during RV *Polarstern* Expedition ARK-IX/4 1993 (Fütterer, 1994), RV *Polarstern* Expedition ARK-XI/1 1995 (Rachor, 1997), and TRANSDRIFT-III Expedition 1995 with RV *Kapi-*

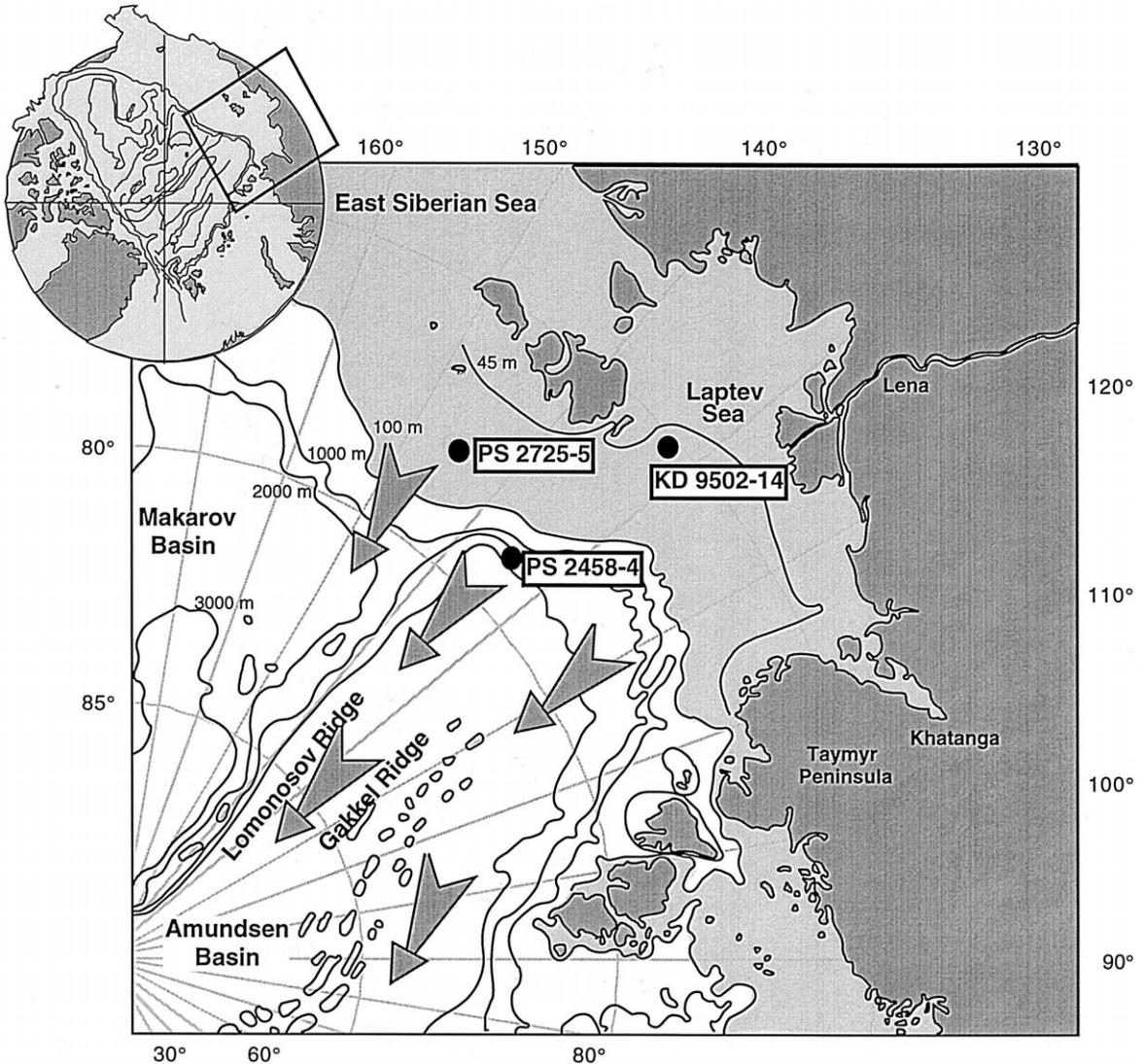


Fig. 1. Location of cores KD9502-14, PS2725-5, and PS2458-4 from the Laptev Sea and the continental margin. Grey arrows indicate the Transpolar Drift System (Pfirman et al., 1989).

Table 1

Position, water depth and recovery of sediment cores taken during the 1993 and 1995 RV *Polarstern* and *Kapitan Dranitsyn* cruises

Core	Gear	Position	Water depth (m)	Recovery (m)
KD9502-14	Vibro corer	Inner Laptev Sea	46	2.30
		76°11.52' N      133°06.99' E		
PS2725-5	Gravity corer	Western East Siberian Sea	77	4.78
		78°39.36' N      144°08.1' E		
PS2458-4	Kastenlot	Eastern Laptev Sea	983	8.00
		78°09.95' N      133°23.86' E		

*tan Dranitsyn* (Kassens, 1997), respectively. The sampling was carried out using a Kastenlot, gravity corer, and vibro corer.

### 2.1. Inner Laptev Sea shelf

Core KD9502-14 from the Laptev Sea shelf east of the New Siberian Islands (Table 1) consists of olive gray silty clay (Kassens, 1997). Based on AMS-<sup>14</sup>C dating, the sedimentary sequence probably represents the last ~ 8000 Cal. yr BP (Bauch et al., 1996).

### 2.2. East Siberian Sea

Core PS2725-5 was obtained from the shelf of the western East Siberian Sea, north of the New Siberian Islands (Table 1). The 4.8 m long sedimentary sequence is dominated by very dark gray, dark olive, and black silty clay with common to abundant black spots/layers between 30 and 178 cmbsf (Rachor, 1997). The lowermost 40 cm contain significant amounts of sand. Based on AMS-<sup>14</sup>C dating performed on bivalves, the sediments represent the last ~ 10,000 Cal. yr BP (Stein and Fahl, 1998).

### 2.3. Eastern Laptev Sea

Core PS2458-4 taken from the upper eastern Laptev Sea continental slope (Table 1), consists of a 8 m long sedimentary sequence of very dark olive-gray silty clay of dominantly terrigenous origin (Fütterer, 1994). The upper 25 cm are of dark brown to very dark brown color. Small bivalves occasionally occur, and these bivalves were used for AMS-<sup>14</sup>C dating (Spielhagen et al., 1996). Based on these dates, the sediments of core PS2458-4 represent the

last ~ 15,000 Cal. yr BP. At a depth of 100 cmbsf, there is evidence of a hiatus lasting 6–8000 years; the upper 100 cm are probably not older than 100–200 Cal. yr BP (Spielhagen et al., 1996).

## 3. Methods

The bulk parameters (total nitrogen and organic-carbon contents) were determined by means of a Heraeus CHN-analyzer (for details concerning the method see Stein, 1991). C/N ratios were calculated as 'total organic carbon/total nitrogen ratios' based on weight percentage. The Rock-Eval parameters hydrogen index (HI in mg HC/g TOC) and oxygen index (OI in mg CO<sub>2</sub>/g TOC) were determined as described by Espitalié et al. (1977).

For the lipid analyses the sediment samples were stored at –80°C or in dichloromethane:methanol (2:1, by vol.) at –23°C until further treatment. The sediment (8 g) was homogenised, extracted and purified as recommended by Folch et al. (1957) and Bligh and Dyer (1959). An aliquot of the total extract was used for analyzing *n*-alkanes, sterols and alkenones.

### 3.1. *n*-Alkanes

The alkanes were separated from the other fractions by column chromatography using hexane as eluent. The composition of this fraction was analysed with a Hewlett Packard gas chromatograph (HP 5890, column 50 m × 0.25 mm; film thickness 0.25 μm; liquid phase: HP 1) using a temperature program as follows: 60°C (1 min), 150°C (rate: 10°C/min), 300°C (rate: 4°C/min), 300°C (45 min isothermal). The injection volume was 1 μl (Cold Injection Sys-

tem: 60°C (5 s), 300°C (60 s), rate: 10°C/s). Helium was used as carrier gas. The composition was verified by comparison with a standard mixture; for the quantification squalane was added before any analytical step.

### 3.2. Alkenones

The alkenones were separated from the other fractions by column chromatography using hexane: ethylacetate (95:5 and 90:10, by vol.) as eluent. A saponification step with 1 M potassium hydroxide in 95% methanol for 2 h at 90°C followed. The fraction was analysed by means of a Hewlett Packard gas chromatograph (as described for the *n*-alkane analysis) using a temperature program as follows: 60°C (1 min), 270°C (rate: 20°C/min), 320°C (rate: 1°C/min), 320°C (20 min isothermal). The injection volume was 1 µl (Cold Injection System: 60°C, 105°C (rate: 3°C/s), 320°C (rate: 10°C/s), 320°C (60 s isothermal). The identification of the alkenones was carried out by means of retention time. For quantification octacosanoic acid methyl ester was used as an internal standard.

### 3.3. Fatty acids

An aliquot of the total extract was used for preparing fatty acid methyl esters and free alcohols by transesterification with 3% concentrated sulfuric acid in methanol for 4 h at 80°C. After extraction with hexane, the composition was analysed with a Hewlett Packard gas chromatograph (HP 5890, column 30 m × 0.25 mm; film thickness 0.25 µm; liquid phase: DB-FFAP) using a temperature program as follows: 160°C, 240°C (rate: 4°C/min), 240°C (15 min isothermal) (modified according to Kattner and Fricke, 1986). The injection volume is 1 µl. The fatty acids and alcohols were identified by a standard mixture (Marinol standard was kindly made available by J.R. Sargent, Scotland). For quantification, an internal standard (19:0 fatty acid methyl ester) was added.

### 3.4. Sterols

An aliquot of the total extract was silylated with 100 µl BSTFA (bis-trimethylsilyl-trifluoroacet-

amide) (60°C for 2 h). After extraction with hexane, the composition was analysed by GC/MS, which consists of a gas chromatograph (HP 5890, column 30 m × 0.25 mm; film thickness 0.25 µm; liquid phase: HP 5) and a mass spectrometer (MSD, HP 5972, 70 eV electron-impact-ionisation, Scan 50–650 m/z, 1 scan/s, ion source temperature 175°C). GC analysis was performed with the following temperature program: 60°C (1.55 min), 200°C (rate: 20°C/min), 300°C (rate: 5°C/min). The injection volume is 1 µl (splitless). Helium was used as carrier gas (1.2 ml/min at 60°C). The identification of the sterols was carried out on basis of GC retention time and MS fragmentation pattern. For quantification, cholest-5-en-3β-ol-2,2,3,4,4,6-*d*<sub>6</sub> (internal standard) was added before any analytical step. Note that only the 4α-23,24-trimethyl-5α-cholest-22 *E*-en-3β-ol (dinosterol) and 24-methylcholesta-5,22 *E*-dien-3β-ol (brassicasterol) were used for interpretation.

### 3.5. Pigments

The tetrapyrrolic pigments have been determined by measuring the absorbance of their solvent extract (90% acetone) at a wavelength of 410 nm (Rosell-Melé, 1994; Rosell-Melé and Koc, 1997). Additionally, the measurement was carried out at 645 and 663 nm to determine chlorophyll abundances. The turbidity factor (absorbance at 750 nm) has been subtracted.

### 3.6. Carbon-reference-index (CPI)

The relation of odd-to-even chain length of the *n*-alkanes as an estimate for the thermal maturity of the terrigenous organic matter was calculated as  $CPI = (C_{21} + C_{23} + C_{25} + C_{27} + C_{29} + C_{31}) / (C_{22} + C_{24} + C_{26} + C_{28} + C_{30} + C_{32})$  (after Bray and Evans, 1961).

## 4. Biomarkers as organic-carbon source and environmental indicators

Several biomolecules are frequently used as biomarkers indicative for the origin of organic matter in sediments in order to derive information about the

(paleo-) environmental conditions. The distribution and significance of these molecular fossils are quite well established in temperate low and mid-latitude regions and oceanic areas subject to minor fluvial influence (e.g., Farrimond et al., 1990; ten Haven et al., 1990; Prahl et al., 1994; Hinrichs et al., 1995). When using biomarkers in the Laptev Sea and the adjacent Arctic Ocean, the different transport processes, which are dominated by river discharge, sea-ice transport, downslope transport, and vertical and lateral transport through the water column, have to be considered. The unambiguous importance of the Siberian rivers is reflected by the high input of terrigenous (higher-plant and aquatic) organic matter onto the shelf and into the adjacent slope and deep sea area. Accordingly, up to 98% of the TOC represents terrigenous organic carbon on the Laptev Sea shelf (Boetius et al., 1996), with this proportion decreasing offshore where marine productivity—especially at the ice margin—becomes more important (Fahl and Stein, 1997). The interpretation of the biomarker signals are thus much more complex than in low-latitude regions characterized by minor fluvial input and the lack of sea-ice influence. In these latter areas the complex mixing of lipids from diverse sources typical for our study area, can be largely excluded.

In the Laptev Sea continental margin and similar environments biomarkers such as short-chain *n*-alkanes, alkenones, short-chain fatty acids, sterols, and pigments may derive from aquatic (freshwater) algae as well as from marine phyto- and zooplankton (see Table 2). Consequently a pronounced algal signature is not necessarily marine in origin, and all data have

to be interpreted cautiously. Whereas the long-chain fatty acids are almost exclusively of terrigenous origin, derived from specific terrestrial higher plants (Eglinton and Hamilton, 1963; Madureira et al., 1995), the short-chain (saturated and mono/poly-unsaturated) compounds are commonly related to a marine source (e.g., Kates and Volcani, 1966; Ackman et al., 1968; Harrington et al., 1970; Pohl and Zurheide, 1979; Falk-Petersen et al., 1987; Fraser et al., 1989; Volkman, 1989; Fahl and Kattner, 1993). Specific fatty acid compositions have been described for marine diatoms, different ice algae (Kates and Volcani, 1966; Fahl and Kattner, 1993), marine Dinophyceae (Mayzand et al., 1976; Fraser et al., 1989; Ahlgren et al., 1992), as well as Haptophyceae (Sargent et al., 1985, Conte et al., 1994). Short-chain fatty acids, however, are also found in lacustrine/freshwater environments (Ahlgren et al., 1992; Léveillé et al., 1997). As a result, short-chain fatty acids cannot be used to distinguish between aquatic and marine inputs (Table 2). The same is true for pigments (Table 2), short-chain *n*-alkanes (e.g., Eglinton and Hamilton, 1963; Venkatesan et al., 1987; Madureira et al., 1995) and the investigated sterols. 4 $\alpha$ -23,24-Trimethylcholest-22 *E*-en-3 $\beta$ -ol (dinosterol) is well known as a biosynthetic product of dinoflagellates (Boon et al., 1979; de Leeuw et al., 1983) and other marine sources (Nichols et al., 1990; Volkman et al., 1993), but also occurs in lacustrine organisms (Table 2) and aquatic environments (Yunker et al., 1995). Robinson et al. (1984) and Thiel (1993), for example, determined high concentrations of dinosterol in the water column as well as in the sediments of Lake Van (Turkey) and Lake

Table 2

List of different biomarkers from marine and freshwater origin

Compounds	Marine	Freshwater/non-marine
Short-chain <i>n</i> -alkanes (C <sub>15</sub> + C <sub>17</sub> + C <sub>19</sub> )	Hinrichs et al., 1995	McKirdy et al., 1986
Long-chain <i>n</i> -alkanes (C <sub>27</sub> + C <sub>29</sub> + C <sub>31</sub> )		Yunker et al., 1995
Short-chain fatty acids (C <sub>12</sub> to C <sub>24</sub> )	Fahl and Kattner, 1993	Kates and Volcani, 1966
	Nichols et al., 1984	Ahlgren et al., 1992
4 $\alpha$ -23,23-Trimethyl-5 $\alpha$ -cholest-22 <i>E</i> -en-3 $\beta$ -ol (Dinosterol)	Nichols et al., 1984	Taylor, 1987
		Thiel, 1993
24-Methylcholesta-5,22 <i>E</i> -dien-3 $\beta$ -ol (Brassicasterol)	Nichols et al., 1984	Taylor, 1987
		Thiel, 1993
		Yunker et al., 1995
Long-chain alkenones (C <sub>37:4</sub> + C <sub>37:3</sub> + C <sub>37:2</sub> )	Conte et al., 1994	Thiel et al., 1997
Chlorophyll <i>a</i> , <i>b</i> , <i>c</i>	Stryer, 1987	Stryer, 1987

Priest Pot (England). High contents of 24-methylcholesta-5,22 *E*-dien-3 $\beta$ -ol (brassicasterol) were also measured in this lacustrine/freshwater environment (Thiel et al., 1997; Table 2), reflecting the presence of diatoms, dinoflagellates or haptophytes (Conte et al., 1994). For the long-chain *n*-alkanes a terrigenous origin from higher plants is generally accepted (Salasoo, 1987; Villanueva et al., 1997). The synthesis of long-chain *n*-alkanes by some special sulfate-reducing bacteria seems to be of minor importance for the marine environments (Davis, 1968). The lithology of the investigated cores displays a change from dark brown (oxic) to dark olive colours between 20 and 30 cmbsf indicating a reducing milieu in the lower core section. Thus, the influence of sulfate-reducing bacteria cannot be excluded. Even the long-chain unsaturated alkenones, usually regarded as a prominent marine coccolithophorid indicator (e.g., Volkman et al., 1980; Brassell et al., 1986; Prahl et al., 1989; Farrimond et al., 1990; Sikes et al., 1991; Jasper and Gagosian, 1993), were also detected in lacustrine sediments (e.g., Thiel et al., 1997). In our study area, however, the alkenones are present only in low abundances (Fahl and Stein, 1997; Stein et al., 1998).

In the Mackenzie river estuary (Canadian Arctic) the biomarker distribution also indicates a significant aquatic contribution (Yunker et al., 1995) as suggested for the Lena River.

Based on the arguments outlined above it appears to be clear that the exclusive use of biomarkers to distinguish between marine and terrigenous/aquatic sources is questionable, especially in the Laptev Sea and the adjacent continental slope. In order to solve this problem and to allow more precise statements about the organic-carbon origin and its (paleo-) environmental significance, it is necessary to combine the organic-geochemical results with micropaleontological and sedimentological data. In addition, future work on stable carbon isotopic composition of biomarkers could yield more information about the origins of organic carbon and its deposition.

## 5. Biomarker records in the Laptev Sea continental margin area

In order to understand the sedimentary processes controlling organic-carbon deposition, as well as the

(paleo-) environmental changes in the Laptev Sea and the adjacent continental margin through time, the three sediment cores, KD9502-14, PS2725-5 and PS2458-4, were investigated for the distribution of bulk parameters (TOC, HI values, and C/N ratios) and biomarkers (long/short-chain *n*-alkanes, short-chain fatty acids, dinosterol, brassicasterol, and pigments).

The depth profiles of the two shelf cores KD9502-14 and PS2725-5, which span the last ~ 8000–1000 Cal. yr BP, show TOC contents between 1 and 1.6% (Figs. 2 and 3). HI values of < 100 mg HC/g TOC occur throughout the entire records. In a HI vs. OI ('van-Krevelen-type') diagram, all data points plot into the 'Krevelen-type III' field (Fig. 4A and B), reflecting the high proportion of immature/fresh terrigenous organic carbon. The biomarker composition supports the predominantly terrigenous character of the organic carbon in both cores (Figs. 2 and 3). In general, the concentrations of long-chain *n*-alkanes (C<sub>27</sub> + C<sub>29</sub> + C<sub>31</sub>) are high (300–400  $\mu$ g/g TOC), comprising more than 50% of the total *n*-alkanes. The concentrations of the corresponding short-chain *n*-alkanes (10  $\mu$ g/g TOC) and pigments are rather low on the shelf as expected. In general, the *n*-alkane composition showing a terrigenous predominance is similar to the ice-free New England continental margin (Venkatesan et al., 1987), the Gulf of Mexico (Jasper and Gagosian, 1993), and the coastal zone off Washington State influenced by Columbia River supply (Prahl and Muehlhausen, 1989), as well as for the permanent ice-covered Arctic Ocean (Schubert and Stein, 1996). In all these environments the ratio of long- to short-chain *n*-alkanes ranges between 25 and 40. The CPI is high, varying between 1.8 and 4.3, which also supports the predominance of fresh terrigenous material in the cores (cf. Bray and Evans, 1961). According to Brassell et al. (1978) and Hollerbach (1985), fresh terrigenous organic matter shows a CPI of 3 to 10, whereas fossil material varies around 1 depending on the state of decomposition and thermal alteration.

In contrast to the short-chain *n*-alkanes, the contents of the short-chain fatty acids 16:0, 16:1(*n*-7), 16:1(*n*-5), 18:0, 18:1(*n*-9), and 18:1(*n*-7) are surprisingly high (300  $\mu$ g/g TOC; Figs. 2 and 3, Table 3). These values are similar to those from the Santa Barbara Basin and the New England continental

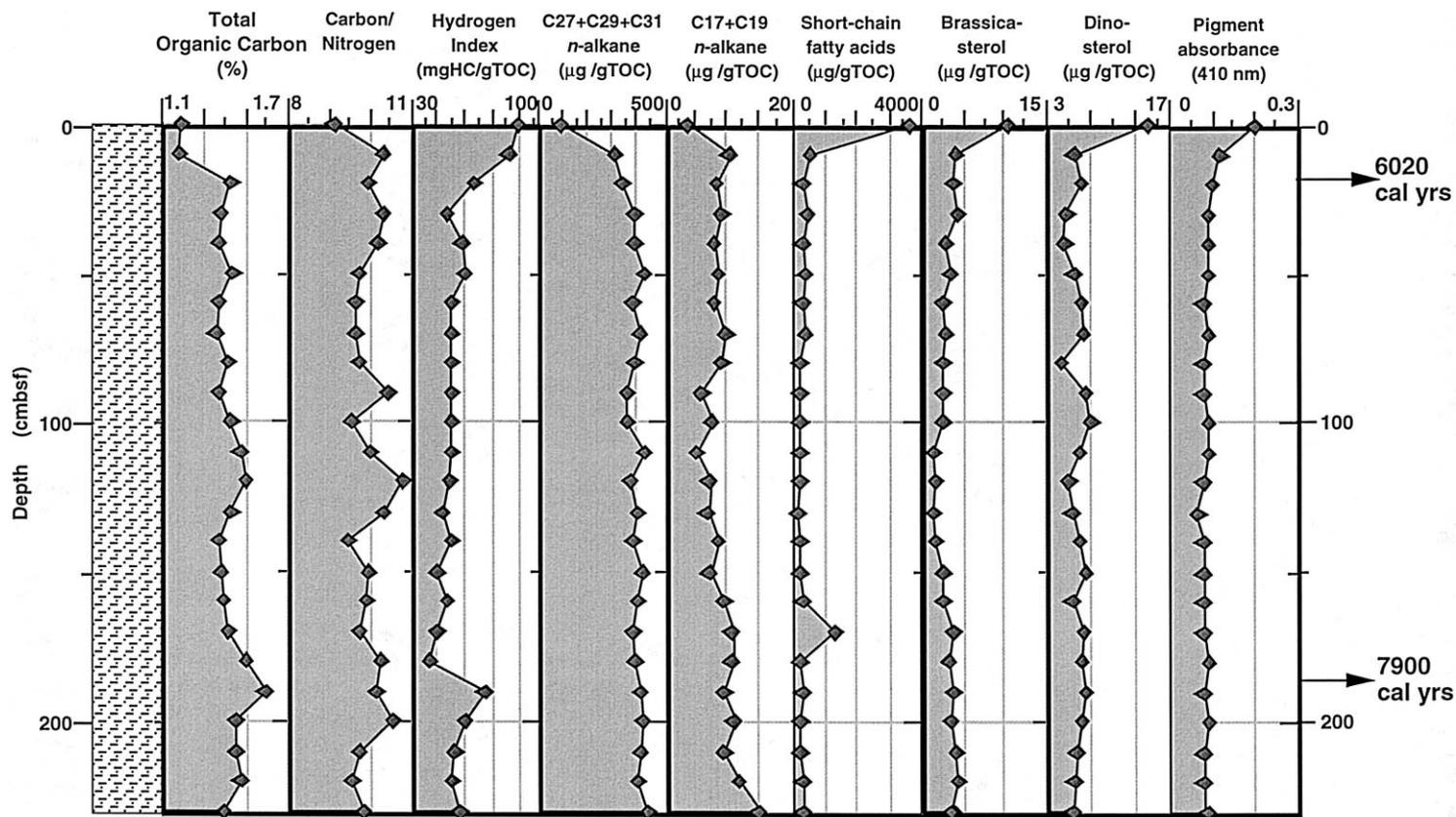


Fig. 2. Organic-geochemical bulk parameters and specific biomarkers in the sedimentary sequence of core KD9502-14: total organic-carbon contents (%), total organic carbon/total nitrogen (C/N) ratios, hydrogen index values (mg HC/g TOC), long- and short-chain *n*-alkanes (μg/g TOC), short-chain fatty acids (μg/g TOC), brassicasterol (μg/g TOC), dinosterol (μg/g TOC), and pigment absorbance values. AMS-<sup>14</sup>C ages according to Bauch et al. (1996).

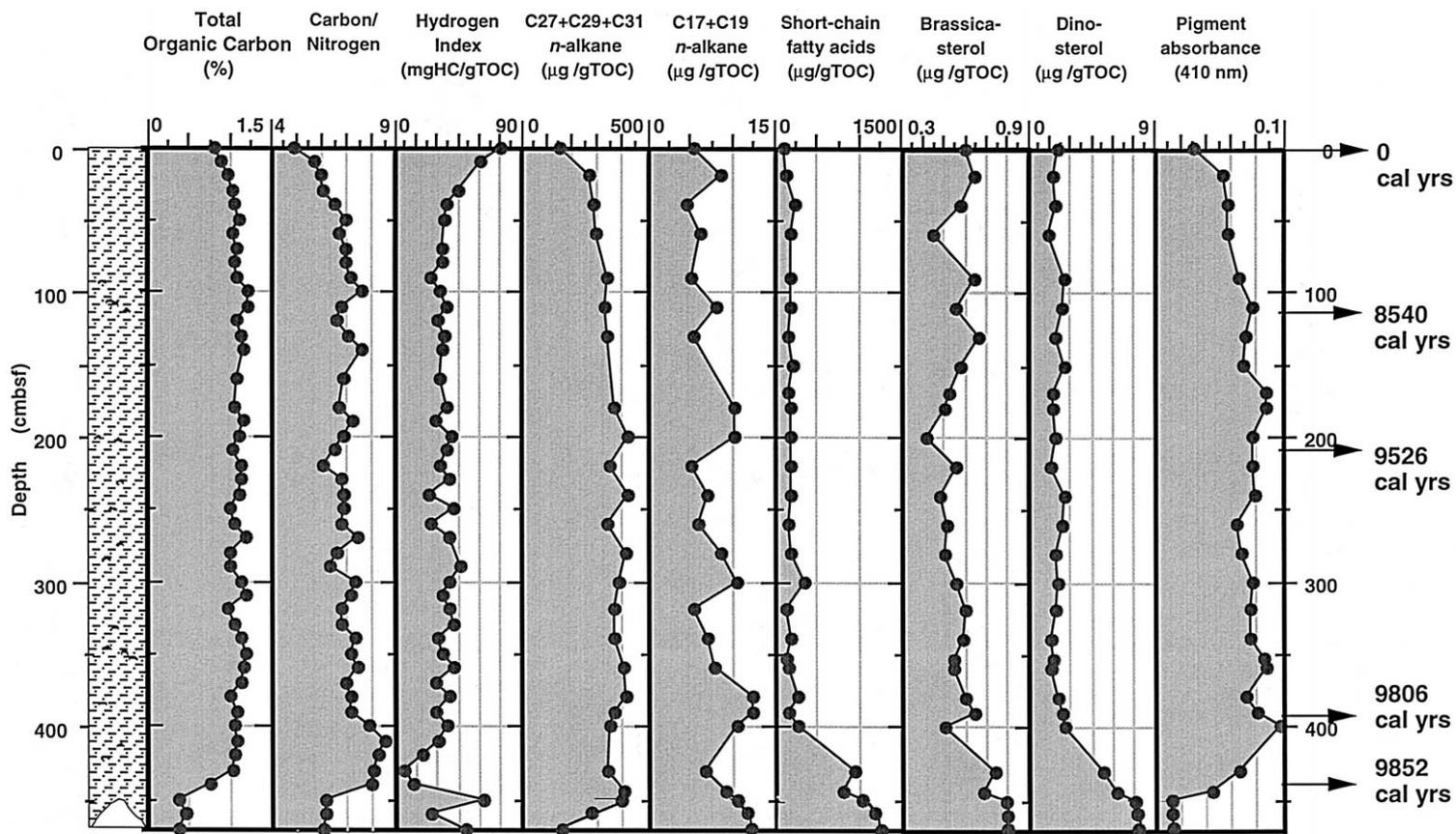


Fig. 3. Organic-geochemical bulk parameters and specific biomarkers in the sedimentary sequence of core PS2725-5: total organic-carbon contents (%), total organic carbon/total nitrogen (C/N) ratios, hydrogen index values (mg HC/g TOC), long- and short-chain *n*-alkanes (µg/g TOC), short-chain fatty acids (µg/g TOC), brassicasterol (µg/g TOC), dinosterol (µg/g TOC), and pigment absorbance values. AMS-<sup>14</sup>C ages according to Stein and Fahl (1998).

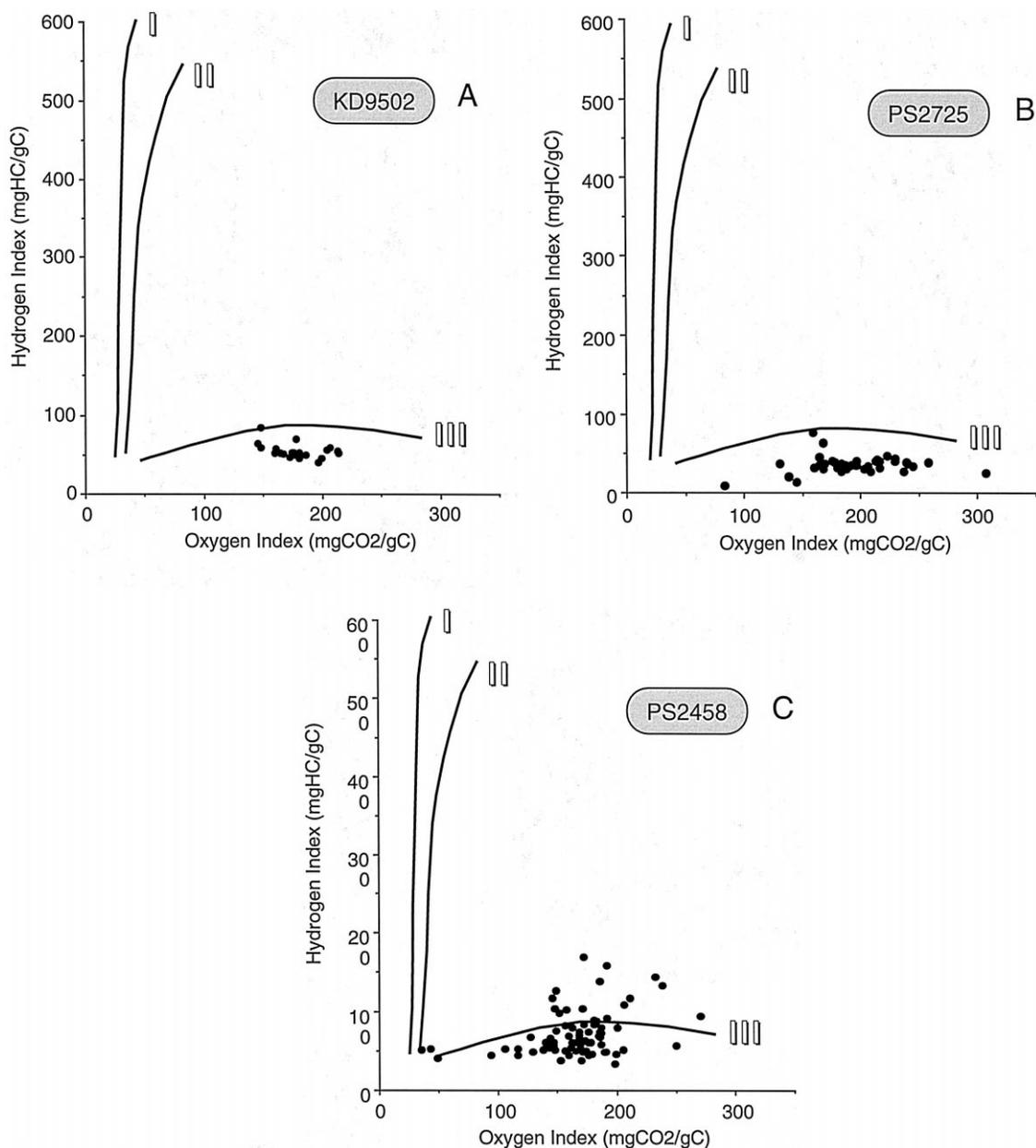


Fig. 4. Hydrogen index vs. oxygen index ('van-Krevelen-type') diagram of cores KD9502-14 (A), PS2725-5 (B) and PS2458-4 (C). Roman numbers mark different kerogen types: I and II marine, III terrigenous organic matter (classification after Espitalié et al., 1977; Peters, 1986).

margin (Table 3), where they have been interpreted as a marine organic-carbon source indicators. The same interpretation was published by ten Haven et al. (1990) for the upwelling area off Peru, but there

the concentrations of the short-chain fatty acids are 10 times higher than in the Laptev Sea (Table 3), as expected for high-productivity environments characterized by high marine organic-carbon flux. Ze-

Table 3  
Concentrations of biomarkers in sediments from different environments

Area		Type of environment
Lake Van, Turkey (Thiel, 1993)		Freshwater environment (water depth: 451 m)
Long-chain <i>n</i> -alkanes	362 $\mu\text{g/g}$ TOC	
Dinosterol	128 $\mu\text{g/g}$ TOC	
Brassicasterol	380 $\mu\text{g/g}$ TOC	
Columbia River (Prah and Muehlhausen, 1989)		High fluvial supply
Long-chain <i>n</i> -alkanes	277 $\pm$ 87 $\mu\text{g/g}$ TOC	
Gulf of Mexico (Jasper and Gagosian, 1993)		High fluvial supply, hemipelagic environment (water depth: 2260 m)
Long-chain <i>n</i> -alkanes (odd)	164 $\mu\text{g/g}$ TOC	
Peru Upwelling Area (Farrimond et al., 1990; ten Haven et al., 1990)		High productivity upwelling environment (water depth: 461 m)
Long-chain <i>n</i> -alkanes	51 $\mu\text{g/g}$ TOC *	
Short-chain <i>n</i> -alkanes	8 $\mu\text{g/g}$ TOC *	
Short-chain fatty acids	5000 $\mu\text{g/g}$ TOC	
Dinosterol	34 $\mu\text{g/g}$ TOC *	
Brassicasterol	235 $\mu\text{g/g}$ TOC *	
Santa Barbara Basin (Hinrichs et al., 1995; Stein and Rack, 1995)		Semi-closed basin with high surface- water productivity and suboxic bottom water (water depth: 577 m)
Long-chain <i>n</i> -alkanes	91 $\mu\text{g/g}$ TOC	
Short-chain <i>n</i> -alkanes	31 $\mu\text{g/g}$ TOC	
Short-chain fatty acids	140–250 $\mu\text{g/g}$ TOC	
Dinosterol	42 $\mu\text{g/g}$ TOC	
Brassicasterol	40 $\mu\text{g/g}$ TOC	
Cont. margin, New England (Venkatesan et al., 1987)		Continental margin, ice-free (water depth: 1280 m)
Long-chain <i>n</i> -alkanes	60.6 $\mu\text{g/g}$ TOC	
Short-chain <i>n</i> -alkanes	2.4 $\mu\text{g/g}$ TOC	
Fatty acids (C12–C32)	454 $\mu\text{g/g}$	
Dinosterol	136 $\mu\text{g/g}$ TOC	
North Atlantic, Biscay Abyssal Plain (Madureira et al., 1995)		Open ocean, ice-free (water depth: 4105 m)
Long-chain <i>n</i> -alkanes	75 $\mu\text{g/g}$ TOC	
Total sterols	150 $\mu\text{g/g}$ TOC	
Arctic Ocean (Schubert and Stein, 1996)		Open ocean, permanent sea-ice cover (water depth: 1500–4000 m)
Long-chain <i>n</i> -alkanes	400–700 $\mu\text{g/g}$ TOC	
Short-chain <i>n</i> -alkanes	10–20 $\mu\text{g/g}$ TOC	
Laptev Sea shelf (This paper, average values)		Shelf, seasonal sea-ice cover, high fluvial supply (water depth: 46 m)
Long-chain <i>n</i> -alkanes	355 $\mu\text{g/g}$ TOC	
Short-chain <i>n</i> -alkanes	9 $\mu\text{g/g}$ TOC	
Short-chain fatty acids	300 $\mu\text{g/g}$ TOC	
Dinosterol	4 $\mu\text{g/g}$ TOC	
Brassicasterol	7 $\mu\text{g/g}$ TOC	

Table 3 (continued)

Area		Type of environment
Laptev Sea continental slope (This paper, average values)		Continental slope, seasonal sea-ice cover, high fluvial supply (water depth: 948 m)
799–360 cmbsf		
Long-chain <i>n</i> -alkanes	196 $\mu\text{g/g}$ TOC	
Short-chain <i>n</i> -alkanes	7 $\mu\text{g/g}$ TOC	
Short-chain fatty acids	17 $\mu\text{g/g}$ TOC	
Dinosterol	9 $\mu\text{g/g}$ TOC	
Brassicasterol	22 $\mu\text{g/g}$ TOC	
360–0 cmbsf		
Long-chain <i>n</i> -alkanes	150 $\mu\text{g/g}$ TOC	
Short-chain <i>n</i> -alkanes	86 $\mu\text{g/g}$ TOC	
Short-chain fatty acids	50 $\mu\text{g/g}$ TOC	
Dinosterol	45 $\mu\text{g/g}$ TOC	
Brassicasterol	100 $\mu\text{g/g}$ TOC	

\* Calculated with 3.5% TOC content (Suess et al., 1988).

Values are normalized to TOC content.

gouagh et al. (1996) assumed that the high amounts of short-chain fatty acids they measured in surface sediments from the Lena Delta and further offshore in the Laptev Sea (SPASIBA 2 Expedition, 1991) are marine in origin. However, based on the above arguments and the positive correlation with the high concentration of long-chain *n*-alkanes, as well as low hydrogen index values, we infer that the high concentration of short-chain fatty acids in our records probably derives from freshwater/aquatic algae (cf. Ahlgren et al., 1992; L  veill   et al., 1997).

The relative abundances of 4 $\alpha$ -23,24-trimethyl-5 $\alpha$ -cholest-22*E*-en-3 $\beta$ -ol (dinosterol) and 24-methylcholesta-5,22*E*-dien-3 $\beta$ -ol (brassicasterol) reach concentrations of 6  $\mu\text{g/g}$  TOC in both cores. These compounds are often used as indicators of marine inputs (e.g., Nichols et al., 1984), but here their presence also seems to be due to freshwater algae (Tayler, 1987; Thiel, 1993). First results of micropaleontological investigations and maceral analysis support this assumption. Low but significant amounts of freshwater algae occur throughout both shelf cores without high variabilities (Matthiessen, personal communication, 1997). In comparison with other oceanic regimes (Table 3), the concentrations of dinosterol and brassicasterol are rather low. Thus, in general, the organic-geochemical data of both cores indicate that the organic carbon which accumulates on the Laptev Sea shelf is mainly of terrigenous/

aquatic origin, most probably controlled by fluvial (Lena) discharge.

In the continental slope core PS2458-4 representing the last  $\sim 15,000$  Cal. yr BP (Spielhagen et al., 1996), the sedimentary regime seems to be different. Although the TOC values are in the same range as those determined in the shelf cores (1–1.5%; Fig. 5), the composition of the organic carbon is much more variable, as indicated by the HI values, C/N ratios and the biomarker distributions. In the lower core section (790 to 360 cmbsf) low HI values and rather high concentrations of long-chain *n*-alkanes (C<sub>27</sub> + C<sub>29</sub> + C<sub>31</sub>) (Fig. 5) indicate terrigenous organic matter. In general, also the high CPI indices of 2 to 3.5 and a position in the ‘Krevelen-type III’ field of HI vs. OI diagram (Fig. 4C) support the high content of fresh terrigenous organic material. The upper core section (360 to 0 cmbsf), on the other hand, is characterized by relatively high HI values (up to 200 mg HC/g TOC) suggesting a more marine character of the organic material. In the HI vs. OI diagram, these data points plot above the ‘Krevelen-type III’ line (i.e., a mixture of marine/terrigenous organic matter with, however, still a dominance of terrigenous organic material). The more marine character is also supported by higher concentrations of short-chain fatty acids, dinosterol, and brassicasterol, which are mainly derived from diatom and/or dinoflagellates (e.g., Kates and Volcani, 1966; Boon et al.,

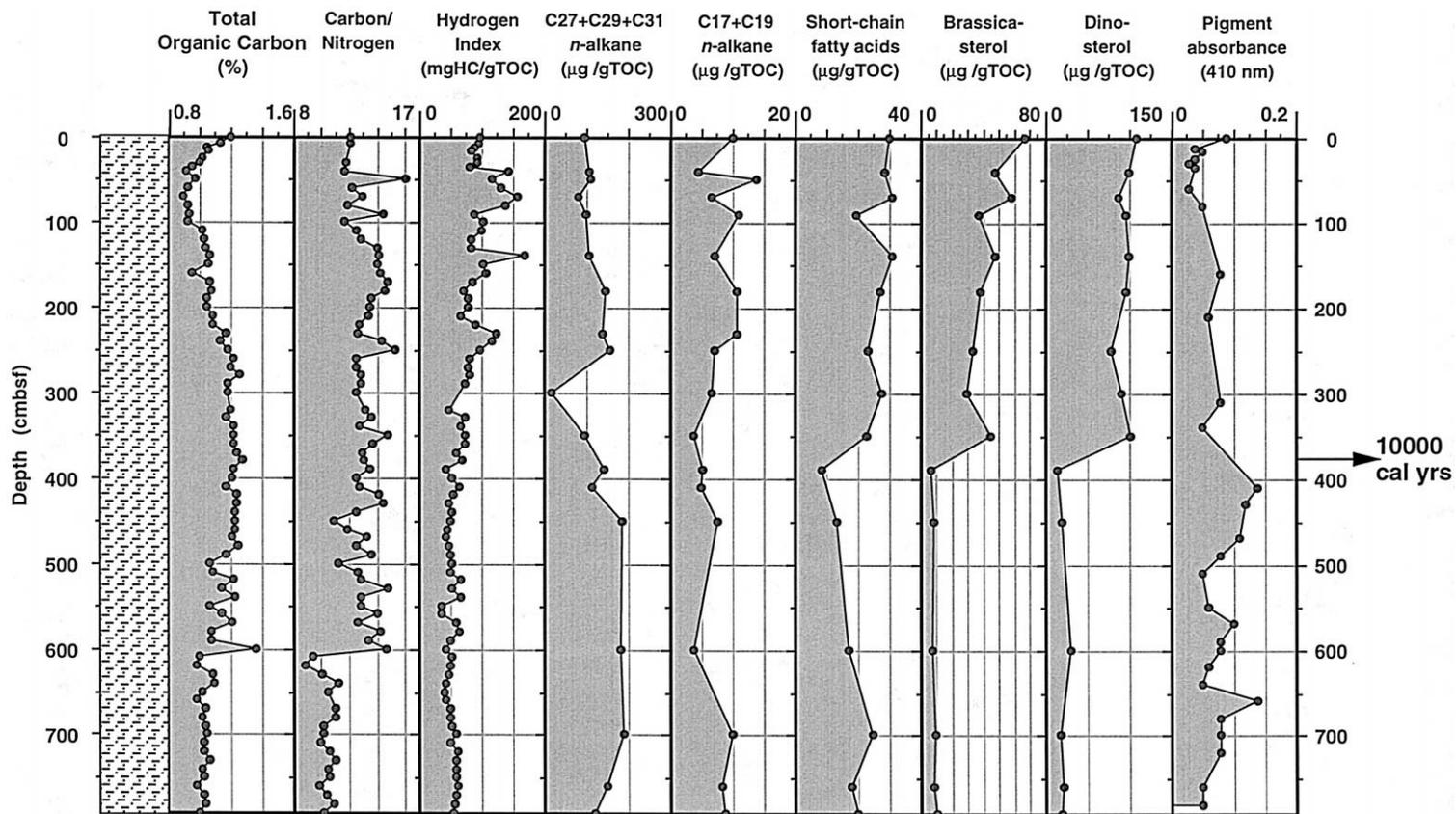


Fig. 5. Organic-geochemical bulk parameters and specific biomarkers in the sedimentary sequence of core PS2458-4: total organic-carbon contents (%), total organic carbon/total nitrogen (C/N) ratios, hydrogen index values (mg HC/g TOC), long- and short-chain *n*-alkanes (μg/g TOC), short-chain fatty acids (μg/g TOC), brassicasterol (μg/g TOC), dinosterol (μg/g TOC), and pigment absorbance values. AMS-<sup>14</sup>C age according to Spielhagen et al. (1996).

1979; de Leeuw et al., 1983; Nichols et al., 1990; Fahl and Kattner, 1993; Volkman et al., 1993). The correlation coefficient ( $r^2$ ) of 0.624 (for short-chain fatty acids) and 0.495 (for dinosterols) indicates a well supported correlation between the hydrogen index and these two biomarkers (Fig. 6A and B). The ratio of long- to short-chain *n*-alkanes, which reaches values of 2 to 6, is comparable to the calculated ratios from high-productivity upwelling areas, including the Santa Barbara Basin (Table 3). A high proportion of marine organic carbon is confirmed by micropaleontological and maceral data. Marine par-

ticulate organic matter (lamalginites and dinoflagellate cysts) occur in significant amounts in this interval of core PS2458-4 (Boucein, personal communication, 1997). This relative increase in the proportion of marine organic matter at the Laptev Sea continental slope occurred near 10,000 Cal. yr BP (Fig. 5), i.e., near the end of the last major post-glacial sea-level rise (cf. Fairbanks, 1989) when the Laptev Sea shelf became widely flooded. Since that time, the modern environmental situation appears to have been established.

Large volumes of sediments and associated organic matter, supplied by the major rivers such as the Lena, have accumulated on the Laptev Sea shelf. Modern (Holocene) accumulation rates of terrigenous organic matter reach high values of 0.2–2 g C cm<sup>-2</sup> kyr<sup>-1</sup> at the location of core PS2725-5 (Stein and Fahl, 1998). During a short interval in the Early Holocene (i.e., near 9000–10,000 Cal. yr BP) when the Laptev Sea shelf became flooded and coastal erosion and/or river discharge distinctly increased, these values may have even reached 10–15 g C cm<sup>-2</sup> kyr<sup>-1</sup> (Stein and Fahl, 1998). Significant proportions of terrigenous organic matter, however, are also incorporated into the sea-ice and further transported offshore within the Transpolar Drift System (cf. Fig. 1). During melting processes, the organic (as well as inorganic) matter becomes released and settles to the deep-sea floor. Thus, in areas of the central Arctic Ocean characterized by very low phytoplankton productivity due to the more or less closed sea-ice cover (Subba Rao and Platt, 1984), the majority organic matter in the surface sediments may be of terrigenous origin (Stein et al., 1994; Schubert and Stein, 1996; Stein and Schubert, 1996). The *n*-alkane concentration in the central Arctic Ocean surface sediments, for example, are very similar to those determined in the Laptev Sea shelf sediments (Table 3).

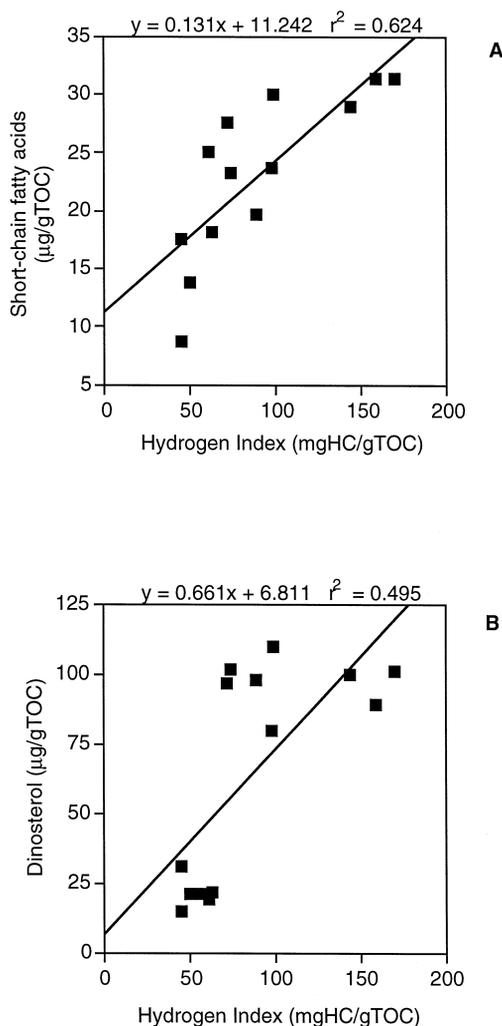


Fig. 6. Hydrogen index (mg HC/g TOC) vs. short-chain fatty acids (μg/g TOC) and hydrogen index (mg HC/g TOC) vs. dinosterol (μg/g TOC) diagrams of core PS2458-4.

## 6. Conclusion

\* Total organic carbon, hydrogen index, C/N and biomarker records from the Laptev Sea continental margin provide information about variation in the input of terrigenous and marine organic carbon during the last 10,000–15,000 Cal. yr BP.

\* On the Laptev Sea shelf, (fluvial) terrigenous organic matter supply was most important throughout the last about 10,000 Cal. yr BP, with maximum values reached in the Early Holocene (i.e., 9000–10,000 Cal. yr BP).

\* On the upper continental slope a major increase in marine organic matter occurred near 10,000 Cal. yr BP, when the Laptev Sea shelf became largely flooded and the modern environmental situation established.

\* The comparison of the river-dominated shelf cores (KD9502-14 and PS2725-5) with the continental slope core (PS2458-4), where marine productivity is enhanced, provides an excellent example of the possible problems and limitations in using biomarkers as terrigenous and marine organic-carbon-source indicators.

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### References

- Aagaard, K., Carmack, E.C., 1989. The role of sea-ice and other freshwater in the arctic circulation. *J. Geophys. Res.* 94 (C10), 14485–14498.
- Ackman, R.G., Tocher, C.S., McLachlan, J., 1968. Marine phytoplankter fatty acid. *J. Fish. Res. Board Can.* 25, 1603–1620.
- Ahlgren, G., Gustafsson, I.-B., Boberg, M., 1992. Fatty acid content and chemical composition of freshwater microalgae. *J. Phycol.* 28, 37–50.
- Bauch, H.A., Cremer, H., Erlenkeuser, H., Kassens, H., Kunz-Pirung, M., 1996. Holocene Paleoenvironmental Evolution of the Northern Central Siberian Shelf Sea. Quaternary Environment of the Eurasian North (QUEEN), First Annual Workshop, Strasbourg, Abstract Volume.
- Bligh, E.G., Dyer, W.J., 1959. A rapid method of total lipid extraction and purification. *Can. J. Biochem. Physiol.* 37, 911–917.
- Boetius, A., Nöthig, E.-M., Liebezeit, G., Kröncke, I., 1996. Distribution of chlorophyll pigments as indicator for marine organic matter input in the Eurasian shelf seas and the central Arctic Ocean. In: Stein, R., Ivanov, G., Levitan, M., Fahl, K. (Eds.), Surface-Sediment Composition and Sedimentary Processes in the Central Arctic Ocean and Along the Eurasian Continental Margin. Reports on Polar Res. 212, 324 pp.
- Boon, J.J., Rijpstra, W.I.C., de Lange, F., de Leeuw, J.W., Yoshioka, M., Shimizu, Y., 1979. The Black Sea sterols—a molecular fossil for dinoflagellate blooms. *Nature* 277, 125–127.
- Brassell, S.C., Eglinton, G., Maxwell, J.R., Philip, R.P., 1978. Natural background of alkanes in the aquatic environment. In: Hutzinger, O., Lelyveld, I.H., Zoetman, B.C.J. (Eds.), Aquatic Pollutants: Transformation and Biological Effects. Pergamon Press, Oxford, pp. 69–86.
- Brassell, S.C., Eglinton, G., Marlowe, I.T., Pflaumann, U., Sarntheim, M., 1986. Molecular stratigraphy: a new tool for climate assessment. *Nature* 320, 129–133.
- Bray, E.E., Evans, E.D., 1961. Distribution of *n*-paraffins as a clue to recognition of source beds. *Geochim. Cosmochim. Acta* 22, 2–15.
- Cauwet, G., Sidorov, I., 1996. The biogeochemistry of Lena River: organic carbon and nutrients distribution. *Mar. Chem.* 53, 211–227.
- Conte, M.H., Volkman, J.K., Eglinton, G., 1994. In: Green, J.C., Leadbeater, B.S.C. (Eds.), The Haptophyte Algae, Systematics Association Special Volume. Clarendon Press, Oxford, 51, 351–377.
- Darby, D.A., Burckle, L.H., Clarke, D.L., 1974. Airborne dust on the Arctic pack ice: its composition and fallout rate. *Earth Planet. Sci. Lett.* 24, 166–172.
- Darby, D.A., Naidu, A.S., Mowatt, T.C., Jones, G., 1989. Sediment composition and sedimentary processes in the Arctic Ocean. In: Herman, Y. (Ed.), The Arctic Seas—Climatology, Oceanography, Geology, and Biology. New York, 657–720.
- Davis, J.B., 1968. Paraffinic hydrocarbons in the sulfate-reducing bacterium *Desulfovibrio desulfuricans*. *Chem. Geol.* 3, 155–160.
- de Leeuw, J.W., Rijpstra, W.I.C., Schenck, P.A., Volkman, J.K., 1983. Free, esterified, and residual bound sterols in Black Sea Unit I sediments. *Geochim. Cosmochim. Acta* 47, 455–465.
- Eglinton, G., Hamilton, R.J., 1963. The distribution of alkanes. In: Swan, T. (Ed.), Chemical Plant Taxonomy. Academic Press, London, 187–208.
- Espitalié, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Paulet, J., Boutefeu, A., 1977. Méthode rapide de caractérisation des roches mères, de leur potentiel pétrolier et de leur degré d'évolution. *Rev. Inst. Franc. Pétrol.* 32, 23–42.
- Fahl, K., Kattner, G., 1993. Lipid content and fatty acid composition

- tion of algal communities in sea-ice and water from Weddell Sea (Antarctica). *Polar Biol.* 13, 405–409.
- Fahl, K., Stein, R., 1997. Modern organic-carbon deposition in the Laptev Sea and the adjacent continental slope: surface-water productivity vs. terrigenous supply. *Org. Geochem.* 26, 379–390.
- Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342, 637–642.
- Falk-Petersen, S., Sargent, J.R., Tande, K., 1987. Lipid composition of zooplankton in relation to the sub-Arctic food web. *Polar Biol.* 8, 115–120.
- Farrimond, P., Eglinton, G., Poynter, J.G., 1990. A molecular stratigraphic study of Peru margin sediments, HOLE 686B, LEG 112<sup>1</sup>. *Proc. ODP Sci. Results* 112, 539–546.
- Folch, J., Lees, M., Sloane-Stanley, G.H., 1957. A simple method for the isolation and purification of total lipids from animal tissues. *J. Biol. Chem.* 226, 497–509.
- Fraser, A.J., Sargent, J.R., Gamble, J.C., Seaton, D.D., 1989. Formation and transfer of fatty acids in an enclosed marine food chain comprising phytoplankton, zooplankton and herring (*Clupea harengus* L.) larvae. *Mar. Chem.* 27, 1–18.
- Fütterer, D.K., 1994. The Expedition ARCTIC'93 Leg ARK IX/4 of RV 'Polarstern' 1993. Report on Polar Res. 149, 244 pp.
- Gordeev, V.V., Martin, J.M., Sidorov, I.S., Sidorova, M.V., 1996. A reassessment of the Eurasian river input of water, sediment, major elements, and nutrients to the Arctic Ocean. *Am. J. Sci.* 296, 664–691.
- Harrington, G.W., Beach, B.H., Dunham, J.E., Holz, G.G. Jr., 1970. The polyunsaturated fatty acids of marine dinoflagellates. *J. Protozool.* 17, 213–219.
- Heiskanen, A.-S., Keck, A., 1996. Distribution and sinking rates of phytoplankton, detritus, and particulate biogenic silica in the Laptev Sea and Lena River (Arctic Siberia). *Mar. Chem.* 53, 229–245.
- Hinrichs, K.-U., Rullkötter, J., Stein, R., 1995. Preliminary assessment of organic geochemical signals in sediments from Hole 893A, Santa Barbara Basin, offshore California. In: Kennett, J.P., Baldauf, J.G., Lyle, M. (Eds.), *Proc. ODP. Sci. Results* 146 (Pt. 2), 201–211.
- Hollerbach, A., 1985. *Grundlagen der organischen Geochemie*. Springer Verlag, Berlin, 190 pp.
- Jasper, J.P., Gagosian, R.B., 1993. The relation between sedimentary organic carbon isotopic composition and organic biomarker compound concentrations. *Geochim. Cosmochim. Acta* 57, 167–186.
- Kassens, H., 1997. Laptev Sea System: Expeditions in 1995. Report on Polar Res. 248, 210 pp.
- Kates, K., Volcani, B.E., 1966. Lipid components of diatoms. *Biochem. Biophys. Acta* 116, 264–278.
- Kattner, G., Fricke, H.S.G., 1986. Simple gas-liquid chromatographic method for simultaneous determination of fatty acids and alcohols in wax esters of marine organisms. *J. Chromatogr.* 361, 313–318.
- Léveillé, J.-C., Amblard, C., Bourdier, G., 1997. Fatty acids as specific algal markers in a natural lacustrine phytoplankton. *J. Plankt. Res.* 19 (4), 469–490.
- Létolle, R., Martin, J.M., Thomas, A.J., Gordeev, V.V., Gusarova, S., Sidorov, I.S., 1993. <sup>18</sup>O abundances and dissolved silica in the Lena delta and Laptev Sea (Russia). *Mar. Chem.* 43, 47–64.
- Macdonald, R.W., Solomon, S.M., Cranston, R.E., Welch, H.E., Yunker, M.B., Gobeil, C., 1998. A sediment and organic carbon budget for Canadian Beaufort Shelf. *Mar. Geol.* 144, 255–273.
- Madureira, L.A.S., Conte, M.H., Eglinton, G., 1995. *Paleoceanography* 10 (3), 627–642.
- Martin, J.M., Guan, D.M., Elbaz-Poulichet, F., Thomas, A.J., Gordeev, V.V., 1993. Preliminary assessment of the distributions of some trace elements (As, Cd, Cu, Fe, Ni, Pb and Zn) in a pristine aquatic environment: the Lena River estuary (Russia). *Mar. Chem.* 43, 185–199.
- Mayzand, P., Eaton, C.A., Ackman, R.G., 1976. The occurrence and distribution of octadecapentaenoic acids in a marine food chain. *Lipids* 11, 871–876.
- McKirdy, D.M., Cox, R.E., Volkman, J.K., Howell, V.J., 1986. Botryococcane in a new class of Australian non-marine oils. *Nature* 320, 57–59.
- Nichols, P.D., Jones, G.J., de Leeuw, J.W., Johns, R.B., 1984. The fatty acid and sterol composition of two marine dinoflagellates. *Phytochemistry* 23 (5), 1043–1047.
- Nichols, P.D., Palmisano, A.C., Rayner, M.S., Smith, G.A., White, D.C., 1990. Occurrence of novel C<sub>30</sub> sterols in Antarctic sea-ice diatom communities during a spring bloom. *Org. Geochem.* 15, 503–508.
- Peters, K.E., 1986. Guidelines for evaluating petroleum source rocks using programmed pyrolysis. *Am. Assoc. Petrol. Geol. Bull.* 70, 318–329.
- Pfirman, S.L., Gascard, J.-C., Wollenburg, I., Mudie, P., Abellmann, A., 1989. Particle-laden Eurasian Arctic sea-ice: observations from July and August 1987. *Polar Res.* 7, 59–66.
- Pohl, P., Zurheide, F., 1979. Fatty acids and lipids of marine algae and their control of biosynthesis by environmental factors. In: Hoppe, H.A., et al. (Eds.), *Marine Algae in Pharmaceutical Science* Walter de Gruyter, Berlin, 473–523.
- Prahl, F.G., Muehlhausen, L.A., 1989. Lipid biomarkers as geochemical tools for paleoceanographic study. In: Berger, W.H., et al. (Eds.), *Productivity of the Ocean: Past and Present*. Life Sci. Res. Rep. 44, 271–290.
- Prahl, F.G., de Lange, G.J., Lyle, M., Sparrow, M.A., 1989. Post-depositional stability of long-chain alkenones under contrasting redox conditions. *Nature* 330, 367–369.
- Prahl, F.G., Ertel, J.R., Goni, M.A., Sparrow, M.A., Eversmeyer, B., 1994. Terrestrial organic-carbon contributions to sediments on the Washington margin. *Geochim. Cosmochim. Acta* 58 (14), 3035–3048.
- Rachold, V., Lara, R., Hubberten, H.-W., 1996. Concentration and composition of dissolved and particulate organic material in the Lena River—organic carbon transport to the Laptev Sea. Third Workshop on Russian-German Cooperation: Laptev Sea System, October 16–19, 1996, St. Petersburg, Abstract Volume, 24–25.
- Rachor, E., 1997. Scientific Cruise Report of the Arctic Expedition ARK-XI/1 of RV 'Polarstern' in 1995. Report on Polar Res. 226, 157 pp.
- Robinson, N., Eglinton, G., Brassell, S.C., Cranwell, P.A., 1984.

- Dinoflagellate origin for sedimentary 4 $\alpha$ -methylsteroids and 5 $\alpha$ (H)-stanols. *Nature* 308, 439–442.
- Rosell-Melé, A., 1994. Long-chain alkenones, alkyl alkenoates and total pigment abundances as climatic proxy-indicators in the Northeastern Atlantic. PhD Thesis, Bristol University, 164 pp.
- Rosell-Melé, A., Koc, N., 1997. Paleoclimatic significance of stratigraphic occurrence of photosynthetic biomarker pigments in the Nordic seas. *Geology* 25, 49–52.
- Salasoo, I., 1987. Alkane distribution in epicuticular wax of some heath plants in Norway. *Biochem. System. Ecol.* 15 (6), 663–665.
- Sargent, J.R., Eiteltsen, H.C., Falk-Petersen, S., Taasen, J.P., 1985. Carbon assimilation and lipid production in phytoplankton in northern Norwegian fjords. *Mar. Biol.* 85, 109–116.
- Schubert, C., Stein, R., 1996. Deposition of organic carbon in Arctic Ocean sediments: Terrigenous supply vs. marine productivity. *Org. Geochem.* 24, 421–436.
- Schubert, C., Stein, R., 1997. Lipid distribution in surface sediments from the eastern central Arctic Ocean. *Mar. Geol.* 138, 11–25.
- Sikes, E.L., Farrington, J.W., Keigwin, L.D., 1991. Use of the alkenone unsaturation ratio  $U_{37}^k$  to determine past sea surface temperatures: core-top SST calibrations and methodology considerations. *Earth Planet. Sci. Lett.* 104, 36–47.
- Spielhagen, R.F., Erlenkeuser, H., Heinemeier, J., 1996. Deglacial Changes of Freshwater Export from the Laptev Sea to the Arctic Ocean. Quaternary Environment of the Eurasian North (QUEEN), First Annual Workshop, Strasbourg, Abstract Volume.
- Stein, R., 1991. Accumulation of Organic Carbon in Marine Sediments. *Lect. Notes Earth Sci.* Springer Verlag Heidelberg, 34, 217 pp.
- Stein, R. (Ed.), 1998. Arctic Paleo-River Discharge (APARD): A New Research Programme of the Arctic Ocean Science Board (AOSB). *Reports on Polar Res.* 279, 128 pp.
- Stein, R., Fahl, K., 1998. Holocene Accumulation of Organic Carbon at the Laptev-Sea Continental Margin (Arctic Ocean) and its Paleoenvironmental Significance. *Paleoceanography*, submitted.
- Stein, R., Korolev, S., 1994. Shelf-to-basin sediment transport in the eastern Arctic Ocean. *Report on Polar Res.* 144, 87–100.
- Stein, R., Rack, F.R., 1995. A 160,000-year high resolution record of quantity and composition of organic carbon in the Santa Barbara Basin (Site 893). In: Kennett, J.P., Baldauf, J.G., Lyle, M. (Eds.), *Proc. ODP. Sci. Results*, 146 (Pt. 2), 125–137.
- Stein, R., Schubert, C., 1996. Organischer Kohlenstoffeintrag im spätquartären Arktischen Ozean. *Geowissenschaften* 9, 370–375.
- Stein, R., Grobe, H., Wahsner, M., 1994. Organic carbon, carbonate, and clay mineral distributions in eastern central Arctic Ocean surface sediments. *Mar. Geol.* 119, 269–285.
- Stein, R., Fahl, K., Niessen, F., Siebold, M., 1998. Late Quaternary organic carbon and biomarker records from the Laptev Sea Continental Margin (Arctic Ocean): implications for organic carbon flux and composition. In: Kassens, H., Bauch, H.A., Dmitrenko, I., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timokhov, L. (Eds.), *Land—Ocean Systems in the Siberian Arctic: Dynamics and History*. Springer Verlag, Heidelberg, in press.
- Stryer, L., 1987. *Biochemie*. Vieweg Verlag 4, Auflage, 329–330.
- Subba Rao, D.V., Platt, T., 1984. Primary production of Arctic waters. *Polar Biol.* 3, 191–201.
- Suess et al., 1988.
- Taylor, F.J.R. (Ed.), 1987. *The Biology of Dinoflagellates*. Blackwell Scientific Publications, Botanical Monographs 21, 785 pp.
- ten Haven, H.L., Littke, R., Rullkötter, Stein, R., Welte, D.H., 1990. Accumulation rates and composition of organic matter in the Late Cenozoic sediments underlying the active upwelling area off Peru. In: Suess, E., von Huene, R., et al. (Eds.), *Proc. ODP. Sci. Results*, 112, 591–606.
- Thiel, V., 1993. Untersuchungen von Biomarkern als Faziesindikatoren für limnische Ablagerungsräume. Master thesis, Hamburg University, Germany, 137 pp.
- Thiel, V., Jenisch, A., Landmann, G., Reimer, A., Michaelis, W., 1997. Unusual distribution of long-chain alkenones and tetrahymanol from the highly alkaline Lake Van, Turkey. *Geochim. Cosmochim. Acta* 61 (10), 2053–2064.
- Venkatesan, M.I., Ruth, E., Steinberg, S., Kaplan, I.R., 1987. Organic geochemistry of sediments from the continental margin off southern New England, USA: Part II. Lipids. *Mar. Chem.* 21, 267–299.
- Villanueva, J., Grimalt, J.O., Cortijo, E., Vidal, L., Labeyrie, L., 1997. A biomarker approach to the organic matter deposited in the North Atlantic during the last climatic cycle. *Geochim. Cosmochim. Acta* 61 (21), 4633–4646.
- Volkman, J.K., 1989. Fatty acids of microalgae used as feedstocks in aquaculture. In: Cambie, R.C. (Ed.), *Fats for the Future*. Ellis Horwood, Chichester, 263–283.
- Volkman, J.K., Eglinton, G., Corner, E.D.S., Forsberg, T.E.V., 1980. Long-chain alkenes and alkenones in the marine coccolithophorid *Emiliania huxleyi*. *Phytochemistry* 19, 2619–2622.
- Volkman, J.K., Barrett, S.M., Dunstan, G.A., Jeffrey, S.W., 1993. Geochemical significance of the occurrence of dinosterol and other 4-methyl sterols in a marine diatom. *Org. Geochem.* 20, 7–15.
- Yunker, M.B., Macdonald, R.W., Veltkamp, D.J., Cretney, W.J., 1995. Terrestrial and marine biomarkers in a seasonally ice-covered Arctic estuary—integration of multivariate and biomarker approaches. *Mar. Chem.* 49, 1–50.
- Zegouagh, Y., Derenne, S., Largeau, C., Saliot, A., 1996. Organic matter sources and early diagenetic alteration in Arctic surface sediments (Lena River delta and Laptev Sea, Eastern Siberia): I. Analysis of the carboxylic acids released via sequential treatment. *Org. Geochem.* 24, 841–857.