Temporal and spatial variation in tetraether membrane lipids of marine Crenarchaeota in particulate organic matter: Implications for TEX_{86} paleothermometry

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[1] The TEX_{86} is a new temperature proxy which is based on the number of cyclopentane moieties in the glycerol dialkyl glycerol tetraether (GDGT) lipids of the membranes of Crenarchaeota that occur ubiquitously in oceans and shelf seas. This proxy was calibrated by core top sediments, but it is as yet not clear during which season and at which depth in the water column the GDGT signal used for TEX_{86} paleothermometry is biosynthesized. Here we analyzed >200 particulate organic matter (POM) samples from 11 different marine settings for TEX_{86}. This revealed that the GDGTs occur seasonally in surface waters and occur in higher abundances during the winter and spring months. The depth distribution showed that GDGTs generally appeared in higher amounts below 100 m depth in the water column. However, the TEX_{86} values for waters below the photic zone (150–1500 m) did not correlate with the in situ temperature but rather correlated linearly with surface temperature. The TEX_{86} for POM from the upper 100 m showed a linear correlation with in situ temperature, which was nearly identical to the previously reported core top equation. The correlation of all POM samples with surface temperature was also strikingly similar to the core top correlation. These findings demonstrate that the GDGT signal which reaches the sediment is mainly derived from the upper 100 m of the water column. This may be caused by the fact that GDGTs from the photic zone are much more effectively transported to the sediment by grazing and repackaging in large particles than GDGTs from deeper waters.

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1. Introduction

[2] Organic components in sediments are useful tools to reconstruct paleoenvironments and climates. The most prominent example is sea surface temperature (SST) reconstruction using C_{37} alkenones. Alkenones are produced by marine haptophytes including the cosmopolitan coccolithophorids such as *Emiliania huxleyi* [*Volkman et al.*, 1980] and *Geophyrocapsa oceanica* [*Volkman et al.*, 1994]. In these algae the ratio of diunsaturated and triunsaturated C_{37} alkenones (expressed in the U^K_{37} ratio) changes as a function of temperature [*Brassell et al.*, 1986].

[3] A new organic geochemical SST proxy, the TetraEther Index of lipids with 86 carbon atoms (TEX_{86}) was recently introduced [*Schouten et al.*, 2002]. This proxy is based on the number of cyclopentane moieties in the tetraether membrane lipids of marine Crenarchaeota. Marine Crenarchaeota are Prokaryotes that belong to the domain of Archaea. Molecular biological work using ribosomal DNA and the analysis of membrane lipids showed that marine Archaea are ubiquitously distributed in the world's ocean and occur in polar as well as in tropical regions [*Fuhrman et al.*, 1992; *DeLong*, 1992; *Hoefs et al.*, 1997; *Sinninghe Damsté et al.*, 2002a]. Recent molecular biological work revealed that the group of the marine Crenarchaeota makes up about 20% of the picoplankton in the world's ocean [*Karner et al.*, 2001]. The membrane lipids of Archaea consist of isoprenoid glycerol dialkyl glycerol diethers and glycerol dibipytanyl glycerol tetraethers (GDGTs) [*DeRosa and Gambacorta*, 1988]. Marine Crenarchaeota biosynthesize a specific GDGT, named crenarchaeol, which contains four cyclopentane ring and one cyclohexane ring, in addition to some more generally occurring GDGTs (Figure 1) [*Sinninghe Damsté et al.*, 2002b]. It has been suggested that marine Crenarchaeota have evolved from hyperthermophilic Crenarchaeota by building an additional "kink" in their membrane lipid, i.e., the cyclohexane ring [*Sinninghe Damsté et al.*, 2002b]. This

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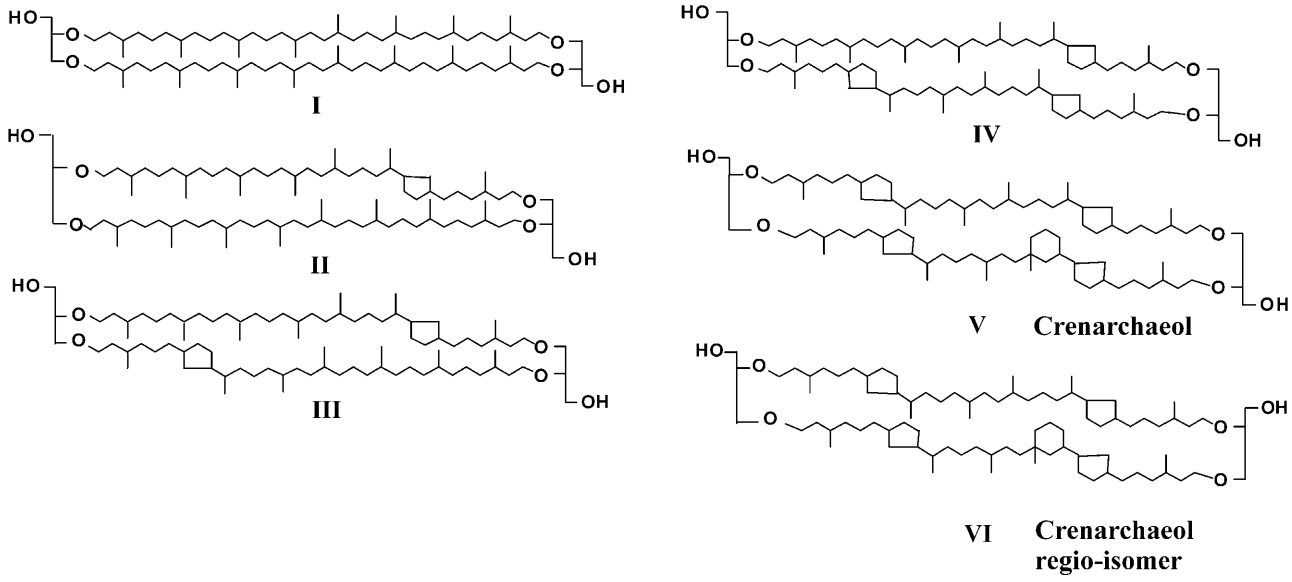

Figure 1. Structures of glycerol dibiphytanyl glycerol tetraethers (GDGT) membrane lipids of marine pelagic Crenarchaeota. From *Wuchter et al.* [2004].

component is thought to have lowered the transition point of the membrane lipids and allowed the Crenarchaeota to live in temperate environments. Culture experiments and field studies have shown that membrane lipids of hyperthermophilic Archaea change their relative distribution of cyclopentane moieties as a function to temperature [*Gliozzi et al.*, 1983; *Ward et al.*, 1985; *DeRosa and Gambacorta*, 1988; *Uda et al.*, 2001]. With this mechanism Archaea keep their cytoplasm membrane at a liquid crystalline state and reduce their proton permeation rate [*Albers et al.*, 2000]. Recent mesocosm studies confirmed that the GDGT composition of marine Crenarchaeota is also determined by temperature [*Wuchter et al.*, 2004]. The membrane lipids of marine Crenarchaeota are relatively stable components, and are found in sediments up to 140 million years old [*Kuypers et al.*, 2001; *Carrillo-Hernandez et al.*, 2003].

[4] *Schouten et al.* [2002] showed that the distribution of crenarchaeotal GDGTs in core top sediments derived from different geographic locations correlate with SST. In cold areas the GDGT distribution is dominated by GDGT I (see Figure 1 for structures) and crenarchaeol (V). In warmer regions the GDGT distributions differ substantially as crenarchaeol is the most abundant GDGT and higher amounts of 1–3 cyclopentane-containing GDGTs (II–IV) and a region-isomer of crenarchaeol (VI) are detected (Figure 1). The relative GDGT distribution can be expressed as an index of GDGT isomers, which was named the TEX_{86} and is defined as follows:

$$TEX_{86} = (III + IV + VI)/(II + III + IV + VI). \quad (1)$$

This index is correlated with the annual mean SST [*Schouten et al.*, 2002]:

$$TEX_{86} = 0.015 * T + 0.28 \quad (2)$$

($r^2 = 0.92$) with T = annual mean SST (in °C).

[5] The observed correlation of TEX_{86} with annual mean SST suggests that marine Crenarchaeota are mainly present in surface waters throughout the whole year. However, this seems in contradiction to ribosomal DNA work from *Massana et al.* [1997] and *Murray et al.* [1998, 1999], who observed a seasonal occurrence of marine Crenarchaeota in Santa Barbara Channel surface waters and coastal Antarctic surface waters. In addition, cell counts at the tropical Pacific revealed that marine crenarchaeotal cell numbers are relatively invariant throughout the water column during the annual cycle and cell numbers only drop below 250 m [*Karner et al.*, 2001]. In contrast, crenarchaeotal GDGT concentrations are actually higher below the photic zone in the Arabian Sea [*Sinninghe Damsté et al.*, 2002a].

[6] These different observations show that it is as yet not clear when and at which depth in the water column the GDGT signal for TEX_{86} paleothermometry is produced. To answer this question, we investigated the GDGT composition of particulate organic matter (POM) from different oceanic regimes. We analyzed surface water time series and depth profiles to shed more light on the seasonal and spatial distribution of the marine crenarchaeotal GDGTs and how this affects TEX_{86} values.

2. Material and Methods

[7] To study the seasonal GDGT abundance in surface waters we analyzed particulate organic matter (POM) from time series of two different locations, i.e., Bermuda Atlantic Time-series Study (BATS) and shallow coastal North Sea waters. The vertical GDGT distribution was studied by analyzing POM from depth profiles from three different locations, i.e., the equatorial Pacific, eastern North Pacific (vertical transport and exchange (VERTEX 5)) and Santa Monica Basin. In addition, TEX_{86} values were calculated for depth profiles from Arabian Sea and Cariaco Basin which were investigated previously [*Sinninghe Damsté et*

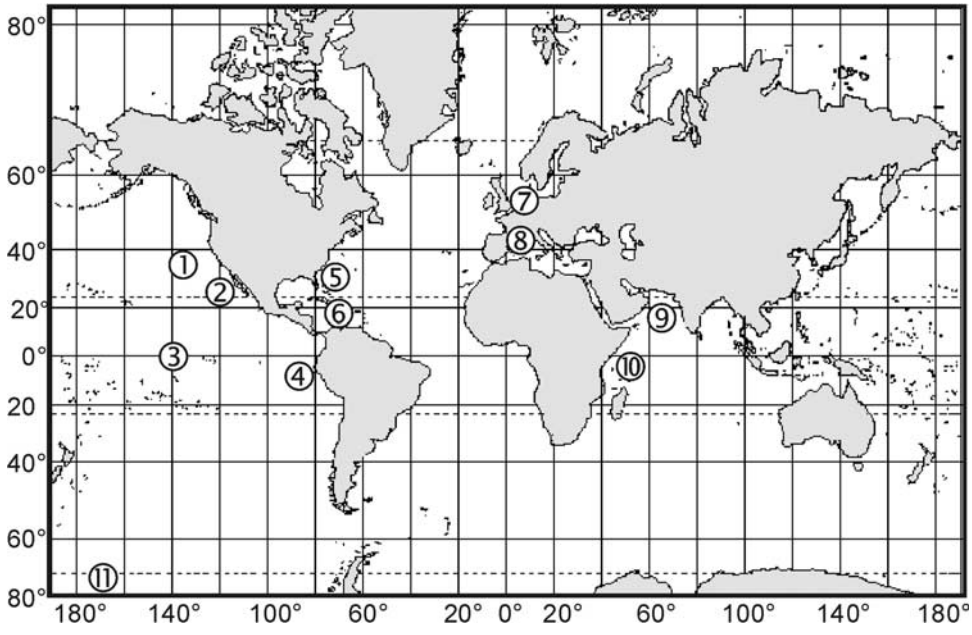

Figure 2. Sampling locations of particulate organic matter (POM) analyzed in this study: 1, northeastern Pacific (vertical transport and exchange (VERTEX 5)); 2, Santa Monica Basin; 3, equatorial Pacific; 4, Peru upwelling region; 5, Bermuda Atlantic Time-series Study (BATS); 6, Cariaco Basin; 7, shallow coastal North Sea waters; 8, Mediterranean Sea (DYFAMED); 9, Arabian Sea; 10, Seychelles; and 11, Southern Ocean. See Table 1 for further sampling details.

al., 2002a; *Wakeham et al.*, 2004]. Finally, a number of surface and depth samples from Peru upwelling region, Seychelles, Southern Ocean and Mediterranean Sea (collected at the French DYFAMED site) were analyzed. For further detailed information about the sampling locations and the collection of the samples, see Figure 2 and Table 1.

2.1. Sampling and Extraction

[8] POM was collected by large volume filtration systems through extracted 50 μm Nitex screen and precombusted glass fiber filters (GF) with a nominal pore size of 0.7 μm. The filters were wrapped in clean aluminum foil and kept frozen at −20°C until extraction. Filters were Soxhlet extracted with dichloromethane (DCM) and methanol (2:1 by volume) at Skidaway Institute of Oceanography.

[9] Coastal North Sea surface waters were sampled for POM at about 1 m depth in weekly intervals from August 2002 to July 2003 at the NIOZ jetty. Twenty liters of water collected at high tide were filtered through ashed 3 μm and 0.7 μm GF filters. The filters were wrapped in clean aluminum foil and stored at −20°C until further analyses. The GF filters were freeze-dried and ultrasonically extracted with methanol, methanol/DCM (1:1 by volume) and three times with DCM at NIOZ.

2.2. Lipid Analysis

[10] An aliquot of the total lipid extract was cleaned over an activated Al_2O_3 column by eluting with methanol/DCM (1:1 by volume). For analysis of intact GDGTs, the solvent was removed under a stream of nitrogen and the residue was dissolved by sonication (5 min) in hexane/propanol (99:1 by volume). The resulting suspension was filtered through a 0.45 μm pore size, 4 mm diameter Teflon filter prior to injection. The intact GDGTs were analyzed by high-performance liquid chromatography (HPLC)–atmospheric pressure positive ion chemical ionization mass spectrometry (APCI-MS) by applying conditions slightly modified from *Hopmans et al.* [2000]. Analyses were performed using an HP (Palo Alto, California, USA) 1100 series LC-MS equipped with an autoinjector and Chemstation chromatography manager software. Separation was achieved on a Prevail Cyano column (2.1 × 150 mm, 3 μm; Alltech, Deerfield, IL, USA), maintained at 30°C. Injection volumes were 15 μL. GDGTs were eluted isocratically with 99% A and 1% B for 5 min, followed by a linear gradient to 1.8% B in 45 min, where A = hexane and B = propanol. Flow rate was 0.2 mL/min. After each analysis the column was cleaned by back flushing hexane/propanol (90:10, by volume) at 0.2 mL/min for 10 min. Detection was achieved using APCI-MS of the eluent. Conditions for APCI-MS were as follows: nebulizer pressure 60 psi, vaporizer temperature 400°C, drying gas (N_2) flow 6 L/min and temperature 200°C, capillary voltage −3 kV, corona 5 μA (~3.2 kV). GDGTs were detected by single ion monitoring of their $[M + H]^+$ ions (dwell time 237 ms). For TEX_{86} calculation the peak areas of GDGTs I–VI were integrated and TEX_{86} values were calculated according to equation (1). For the temperature correlation only TEX_{86} values were used where all isomers of GDGTs could be detected and accurately quantified.

3. Results

[11] We analyzed 220 POM samples from different oceanic regimes to determine the GDGT occurrence and

Table 1. Sampling Information and Related References of the POM Samples Investigated in This Study

Sampling Site	Area/Station	Sampling Intervals	Cruise/Cruise Number	Sampling Depth	Sampling Size (l)	Number of Samples	Sources
Northeastern Pacific (VERTEX 5)	V5A: 33.3°N, 139.2°W; V5C: 36.1°N, 122.6°W	June 1984	R/V *Wecoma*	10–1500 m	900–5000	12	*Wakeham and Canuel* [1988] *Silver and Gowing* [1991]
Santa Monica Basin	33°75′N, 119°08′W	March 1991 to April 1992	R/V *Sea Watch* (6 cruises)	25–850 m	250–4000	15	*Bidigare et al.* [1997]
Equatorial Pacific	station 6: 140°W, 2°N; station 15: 140°W, 12°S.	February–March and August–September 1992	R/V *Thomas G. Thompson* TT007 and TT011	25–840 m	2000–17000	32	*Murray et al.* [1995] *Sheridan et al.* [2002]
Peru upwelling region	transect 12°S and 13.5°S	October 1992	R/V *Seward Johnson*	surface	70–190	20	*Pancost et al.* [1997]
Bermuda Atlantic Time-series (BATS)	32°10′N, 64°30′W (Hydrostation S)	November 1991 to January 1996	R/V *Weatherbird II* BATS 38-88	surface	1000–3000	50	*Steinberg et al.* [2001] and *Conte et al.* [2001]
Cariaco Basin	10°40′N, 65°36′W	February to March 1986	R/V *Iselin*	10–1150 m	500–5000	10	*Wakeham* [1990] *Wakeham et al.* [2004]
Shallow coastal North Seawaters	53°00′25″N, 4°78′27″E (NIOZ Jetty)	August 2002 to July 2003	—	surface	20	33	this manuscript
MedFlux (DYFAMED)	43°20′N, 7°40′W	September 2002	R/V *Tethys II*	3–150 m	550–800	6	http://www.msrc.sunysb.edu/MedFlux/ *Liu et al.* [2005]
Arabian Sea Process Study	station 2: 15°58′N, 61°29′E; station 4: 17°12′N, 59°35′E; station 5: 17°24′N, 58°49′E; station 6: 17°41′N, 57°50′E; station 7: 17°40′N, 57°41′E; station 10: 17°44′N, 57°29′E; station 13: 19°13′N, 58°31′E	May 1995	R/V *Thomas G. Thompson* TN047	30–1500 m	2400–3000	19	*Smith et al.* [1998] *Sinninghe Damsté et al.* [2002a]
Seychelles	6°12′S, 52°7′E	November 2003	R/V *Darwin*	surface	20	1	this manuscript
Southern Ocean	transect along 170°W	November–December 1996, February–March 1998	R/V *Nathaniel B. Palmer*; NBP 96-5, NBP 98-2	surface	1000–1100	22	this manuscript

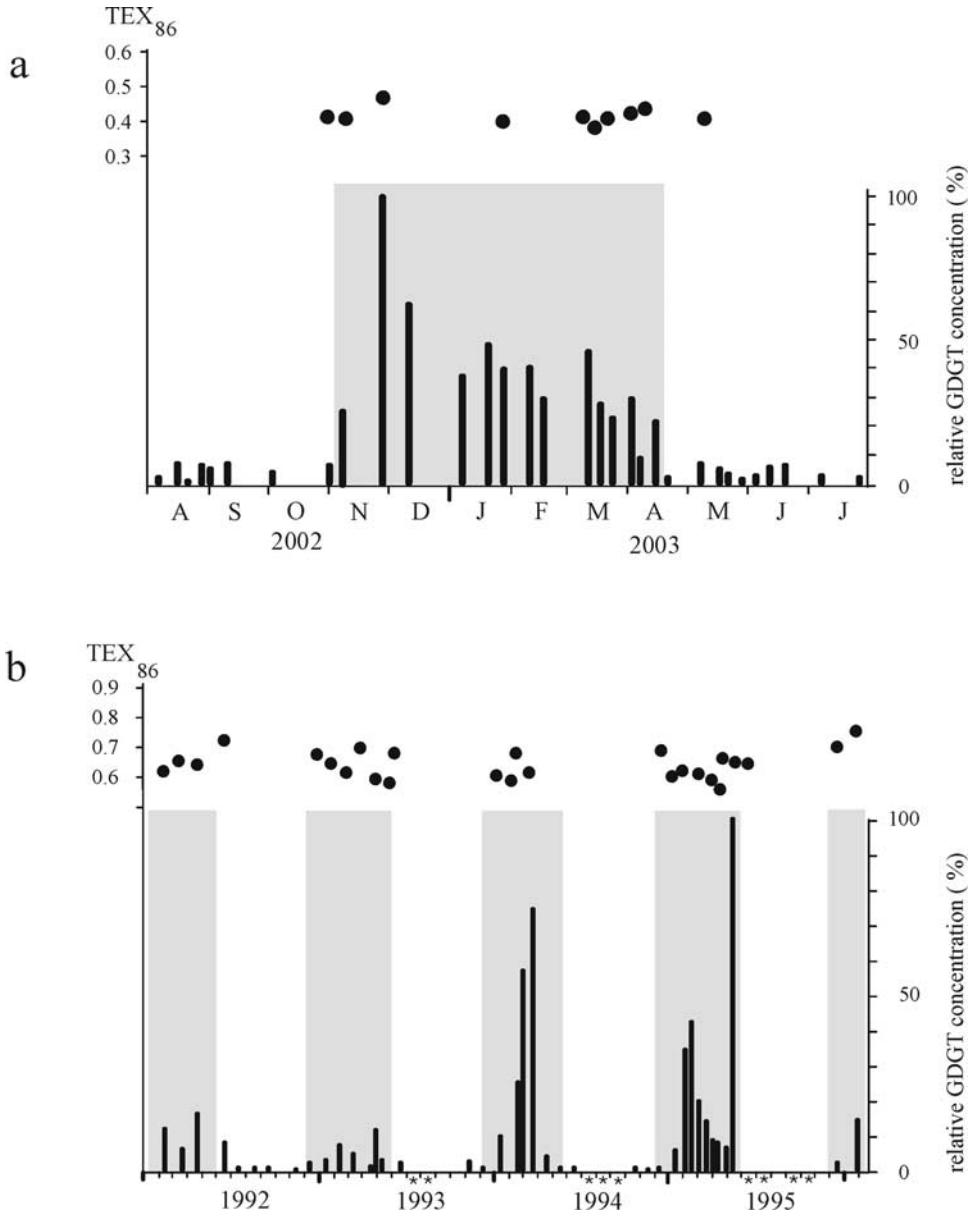

Figure 3. Relative GDGT concentrations and TEX_{86} values measured in POM of time series at two different settings: (a) shallow coastal North Sea waters time series from August 2002 until July 2003 and (b) Bermuda Atlantic Time-series Study starting from winter 1991 until winter 1995. Shaded areas correspond to winter and spring seasons. Months marked with an asterisk indicate that water samples were analyzed but GDGTs were not detected.

distribution with depth and with time. Of these, 118 POM samples contained sufficient amounts of GDGTs for reliable TEX_{86} calculation. The sampling locations ranged from shallow coastal North Sea waters to open ocean samples such as Arabian Sea, equatorial Pacific, and the Southern Ocean (see Figure 2).

3.1. Surface Time Series

[12] Both time series, the BATS and the shallow coastal North Sea water, showed a seasonal occurrence of GDGTs during the annual cycle. At the shallow coastal North Sea water site the GDGTs were most abundant during the winter and early spring seasons (Figure 3a). In late spring, summer and autumn the concentration of GDGTs was <10% of that in winter. The GDGT distribution was dominated by GDGT I and, to a lesser extent crenarchaeol (V) and a relatively low amount of cyclopentane-containing GDGTs (Figure 4a). The TEX_{86} values ranged between 0.39 and 0.51 for shallow coastal North Sea waters during winter and spring (Figure 3a).

[13] At the BATS site, surface water POM samples were collected monthly [*Conte et al.*, 2001] but GDGTs were only detected in the winter and spring months (Figure 3b). During the rest of the year the GDGT concentration was

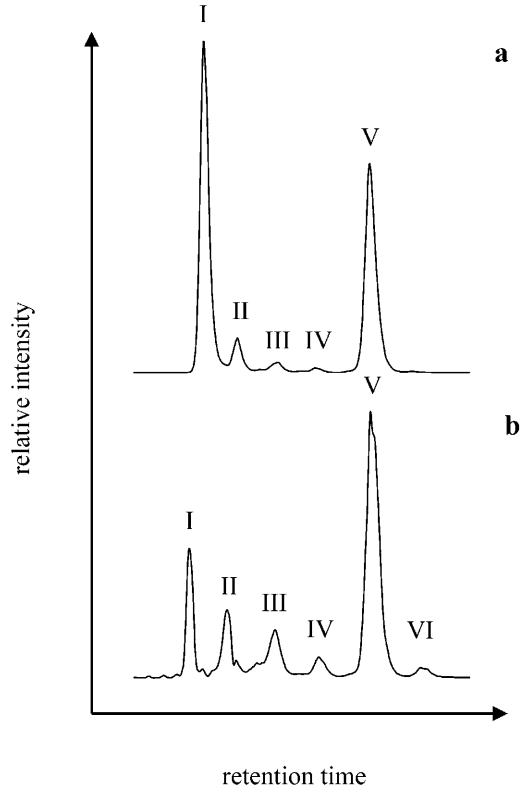

Figure 4. Partial high-performance liquid chromatography–atmospheric pressure positive ion chemical ionization mass spectrometry base peak chromatograms of POM derived from (a) shallow coastal North Sea waters and (b) surface water sampled in the Bermuda Atlantic Time-series Study. Numbers indicate structures shown in Figure 1.

near the detection limit (ca. 1 pg/l). The GDGT distribution was dominated by crenarchaeol and relatively high amounts of cyclopentane-containing GDGTs (Figure 4b). TEX_{86} values ranged between 0.56 and 0.73 (Figure 3b).

3.2. Depth Profiles

[14] All three studied depth profiles had a similar GDGT distribution throughout the water column. POM from different depths of the Santa Monica Basin were obtained in August and October 1991 and in February 1992 at four depths ranging between 25 m and 850 m. Apart from the October samples, the GDGT abundance was highest between 100 to 850 m water depths (Figure 5a). The GDGT distribution was dominated by GDGT I and to a lesser extent crenarchaeol with a relatively low amount of cyclopentane-containing GDGTs. The TEX_{86} values ranged between 0.42 and 0.53 (Figure 5a).

[15] Depth profiles were obtained from POM taken in February/March 1992 and August/September 1992 at two equatorial Pacific sampling sites at 8 sampling depths ranging from 10 to 842 m in the water column. In all instances GDGTs were more abundant below 100 m (Figure 5b) The GDGT distribution was dominated by crenarchaeol and relatively high amounts of cyclopentane-containing GDGTs and the obtained TEX_{86} values ranged between 0.63 and 0.85 (Figure 5b).

[16] The two depth profiles of the northeast Pacific setting were obtained from POM at 5 different depths ranging from 10 to 1500 m. The highest GDGT concentrations were again measured below 100 m (Figure 5c). GDGT I and crenarchaeol were present in equal amounts and substantial amounts of cyclopentane-containing GDGTs were detected. The obtained TEX_{86} values ranged between 0.47 and 0.59 (Figure 5c).

4. Discussion

4.1. Seasonality of GDGT Abundance

[17] Our data show that there is a strong seasonal contrast in the abundance of GDGTs in surface waters at the BATS and the coastal North Sea sampling station (Figure 3). GDGT concentrations peak during the spring and winter seasons, respectively. Marine Crenarchaeota are the dominant Archaea in coastal North Sea surface waters during winter (November–February) as revealed by 16S rDNA work (C. Wuchter et al., unpublished data, 2005). In contrast, chlorophyll *a* concentrations were high during late spring and early summer over the last 30 years in this area [*Cadée and Hegeman*, 2002; *Colijn and Cadée*, 2003]. This seasonal cycle was also observed in 2002–2003. The GDGT and the chlorophyll *a* concentration thus show a strong negative correlation during the annual cycle in coastal North Sea waters. This indicates that archaea are not abundant during periods of high primary production. This is consistent with previous 16S rDNA findings in the Antarctic Peninsula region and Santa Barbara Channel which showed that archaeal abundance in surface waters is negatively correlated with chlorophyll *a* concentrations [*Murray et al.*, 1998, 1999].

[18] At the BATS site, however, a positive correlation between chlorophyll *a* and archaeal lipids in surface waters is observed. In this region the passage of cold fronts erodes the seasonal thermocline and forms subtropical water during the winter season at the BATS station [*Steinberg et al.*, 2001]. Convective mixing caused by the winds results in mixed layers at 150–300 m depth and associated nutrient enrichment of the surface layers [*Steinberg et al.*, 2001]. High chlorophyll *a* concentrations in the late winter, early spring season in surface waters are associated with convective deep mixed water layers but are not sustained throughout the year [*Steinberg et al.*, 2001]. The nutrient enrichment in surface waters may also support growth of marine Crenarchaeota. Alternatively, the higher archaeal lipid abundance may be due to the water mixing when the GDGT signal originally derived from deeper waters is upwelled to the surface layer. Deeper waters generally contain higher concentrations of GDGTs (see discussion in section 4.2).

4.2. Depth Distribution of GDGTs

[19] The GDGT depth distribution at the equatorial Pacific, northeast Pacific and Santa Monica Basin sampling sites show a similar pattern. GDGT concentrations increase with depth and have maxima generally below 100 m. These findings are consistent with previous findings of GDGT depth

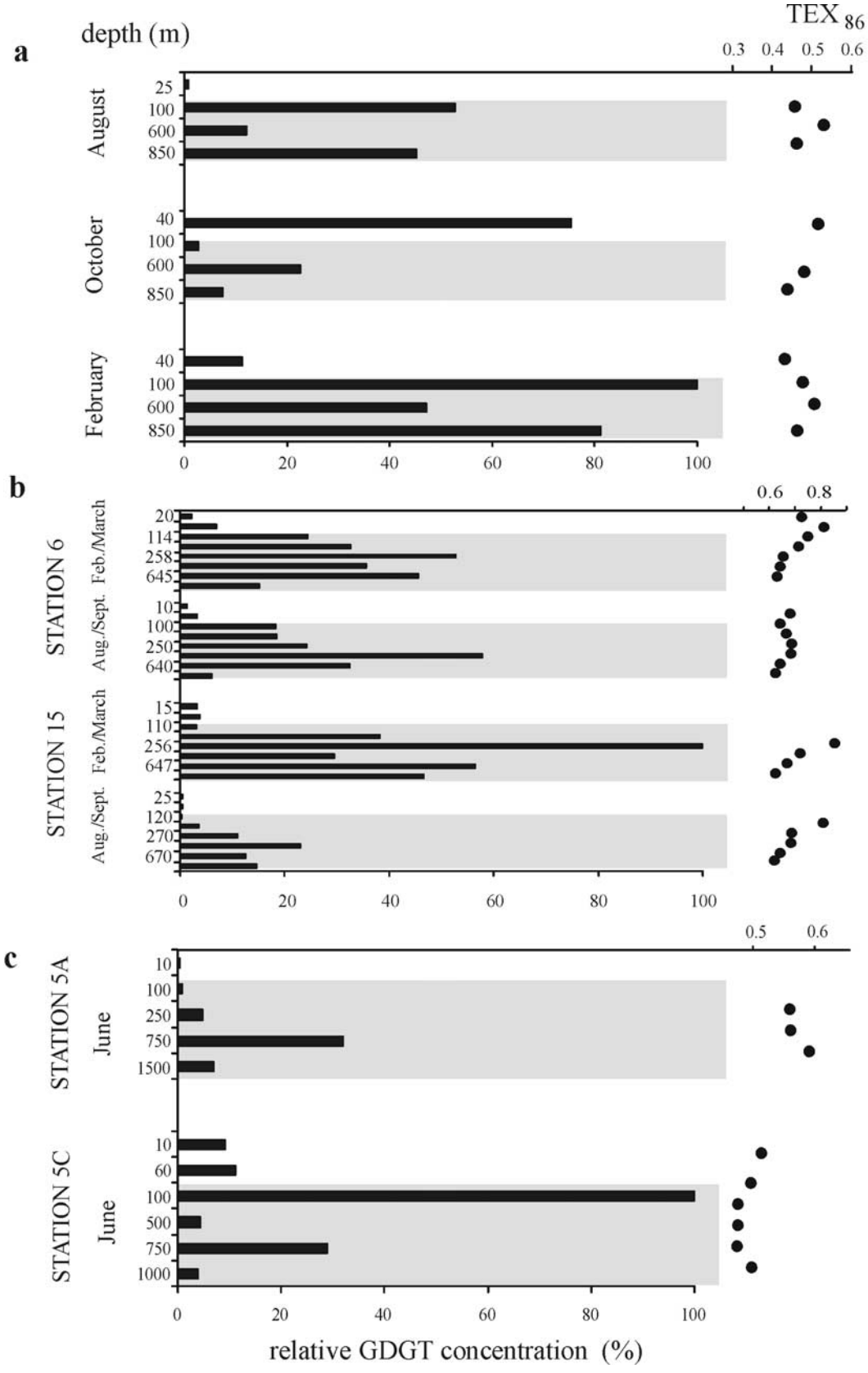

Figure 5. Relative GDGT concentrations (in percent) and TEX_{86} values measured in POM of three depth profiles: (a) Santa Monica Basin, (b) equatorial Pacific, and (c) northeastern Pacific (VERTEX 5). Shaded areas correspond to water depths below 100 m.

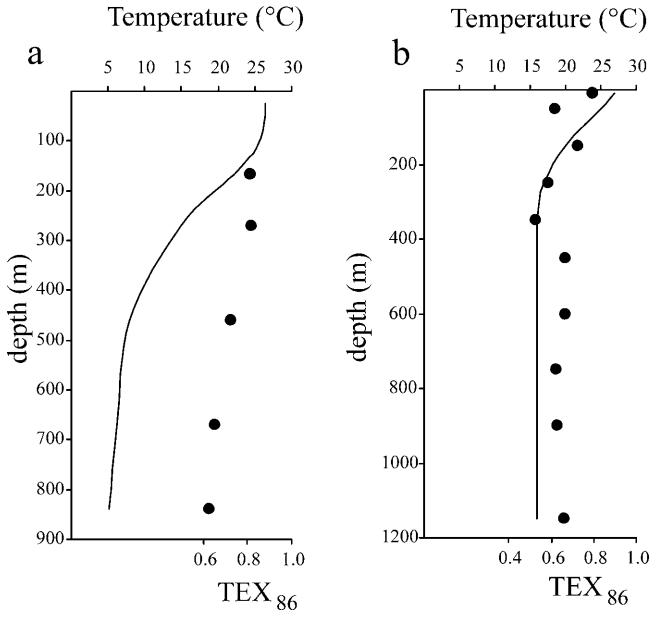

Figure 6. TEX_{86} values and in situ temperature versus depth for (a) equatorial Pacific and (b) Cariaco Basin.

distributions in the Arabian Sea [*Sinninghe Damsté et al.*, 2002a] where the authors reported higher GDGT concentrations below the photic zone and the Cariaco Basin [*Wakeham et al.*, 2004] with maximum GDGT concentrations at 250 m depth. However, there is a discrepancy between the lipid data and 16S rDNA studies. While fluorescence in situ hybridization (FISH) data show that the marine crenarchaeotal absolute abundance in the tropical Pacific Ocean is relatively invariant throughout the upper 250 m of the water column and decreases at lower depth [*Karner et al.*, 2001], our lipid data show maximum GDGT concentrations generally below 100 m at the sampling sites. The FISH technique detects only living cells whereas our lipid analysis does not discriminate between living and dead crenarchaeotal cell material. Thus a substantial percentage of the GDGTs encountered at greater depth may be derived from suspended or sinking dead cell debris. This is likely due to the generally more refractory nature of lipids compared to other cell material such as DNA. GDGTs are themselves not more refractory than other membrane lipids as studies have shown that they degrade, under oxic conditions, at similar rates as other phytoplanktonic lipids [*Sinninghe Damsté et al.*, 2002c; *Schouten et al.*, 2004].

4.3. TEX_{86} and Temperature

[20] As GDGTs are found throughout the water column, it may be expected that the TEX_{86} values would reflect a large range of temperatures from surface to deep waters. However, compared to the large range of in situ temperatures, the TEX_{86} values showed only minor variation with depth (e.g., the equatorial Pacific and Cariaco Basin sites, Figure 6). Indeed, when TEX_{86} values from all sampling locations are compared with in situ temperatures only a weak correlation is observed (Figure 7a). For raw data see auxiliary information.[1] The TEX_{86} in surface sediment correlates best with annual mean SST [*Schouten et al.*, 2002], and this suggests that the TEX_{86} in POM probably also reflects mainly temperatures of the photic zone. To investigate this hypothesis, we split the POM TEX_{86} data into two sets, those derived from the upper 100 m of the water column and those from below 100 m. The correlation of TEX_{86} for POM in the upper 100 m of the water column with in situ temperature was high, with an r^2 of 0.80 (Figure 7b), and is nearly identical to the core top equation (Figure 7f). In contrast, a weak correlation is found between TEX_{86} values of POM from below 100 m depth with in situ temperature (Figure 7c). Instead, TEX_{86} values of POM below 100 m depth correlated well with surface temperatures at the time of sampling (Figure 7d). When TEX_{86} values of all POM samples are compared with actual surface temperature, a correlation is obtained (Figure 7e) that is strikingly similar to the TEX_{86} core top correlation (Figure 7f). These findings indicate that the GDGT signal in POM at all depth is mainly reflecting the temperature of the upper 100 m of the water column. Growth of marine Crenarchaeota in deeper waters may influence the TEX_{86} in POM to a minor degree as observed, for example, in the equatorial Pacific (Figure 6) where the TEX_{86} values slightly decrease with depth. It is most likely that the TEX_{86} values of deep water POM reflect a mixed GDGT signal from living but slowly growing crenarchaeotal cells, since microorganisms living in the deep ocean have a slow metabolic rate [*Tamburini et al.*, 2003], and sinking, dead crenarchaeotal cell material in which GDGTs may become enriched through their refractory nature. This is consistent with our depth profile data where GDGTs are enhanced in abundance in deeper water layers and are probably derived for a large part of dead cell material.

4.4. Origin of Sedimentary GDGT Signal

[21] The similarity of the TEX_{86} POM and the TEX_{86} core top equations (compare Figures 7e and 7f) suggests that the temperature signal that is found in the sediment must be mainly derived from the upper 100 m of the water column. The GDGTs that are found in sediments thus seems to be mainly derived from crenarchaeotal cell material derived from the photic zone and transported with fast sinking aggregates that reaches the seafloor. These findings are supported by previous work done on the Black Sea [*Wakeham et al.*, 2003]. We analyzed POM, sediment traps and surface sediment samples to investigate the GDGT distribution and isotopical signature of the biphytane skeletons contained in these GDGTs. We found high amounts of ^{13}C-depleted biphytanes in POM of the deep anoxic zone of the Black Sea (>1000 m) but could not find the corresponding ^{13}C-depleted biphytanes in the sediment traps or the underlying sediments. This led us to suggest that because of the absence of grazing in the deep anoxic zone of the Black Sea, the GDGTs from deeper waters may lack transport mechanisms (e.g., by fecal pellets) to the seafloor and that, therefore, the dominant flux of GDGTs to the surface sediments was derived from the upper part of the water column where particle packaging through grazing can

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/pa/2004PA001110.

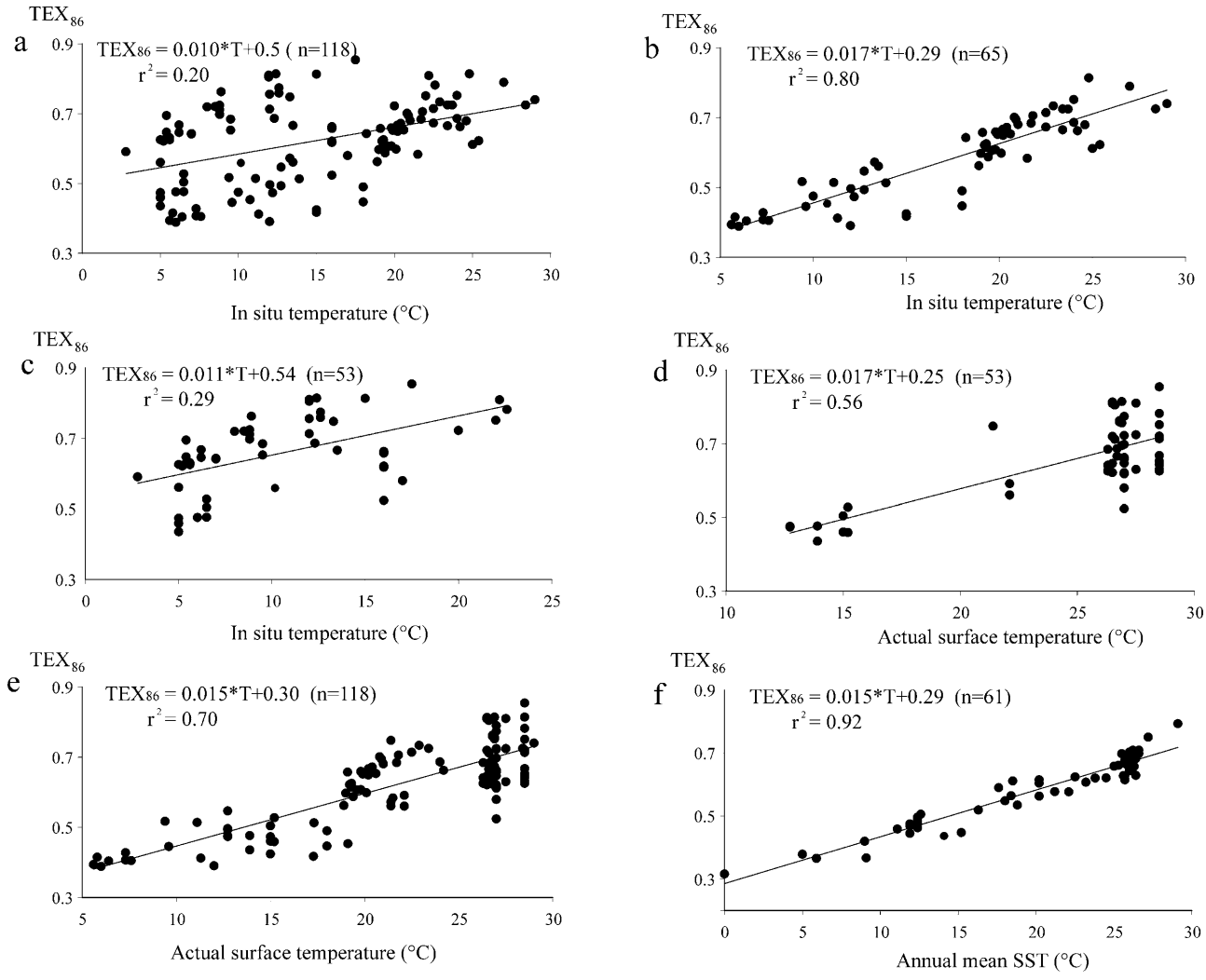

Figure 7. Cross plots of TEX_{86} and temperature for POM from (a) all depths versus the in situ temperature, (b) the upper 100 m of the water column versus in situ temperature, (c) below 100 m depth versus in situ temperature, (d) below 100 m depth versus surface temperature, (e) all depths versus surface temperature, and (f) updated TEX_{86} correlation line from surface samples versus annual mean sea surface temperature [*Wuchter et al.*, 2004]. The best linear fit is shown.

occur. A distinct compositional difference between suspended and sinking particles was also observed for other lipid classes in the Black Sea [*Wakeham and Beier*, 1991] and in oceanic settings like the eastern tropical North Pacific Ocean [*Wakeham and Canuel*, 1988; *Wakeham and Lee*, 1993]. Sediments are mainly derived from fast sinking large particles [*McCave*, 1984] which are produced by biologically mediated aggregation (e.g., grazing), and laboratory and field observations showed that fecal pellets and marine snow may sink at rates of tens to hundreds of meters per day [e.g., *Small et al.*, 1979]. Thus, owing to these mechanisms the sedimentary signal is primarily derived from the upper part of the water column where an active food web exists.

[22] Marine Crenarchaeota are generally abundant in the surface water during times when the majority of the phytoplankton is not blooming [*Murray et al.*, 1998, 1999; this study]. Therefore the GDGT signal which is biosynthesized in the upper 100 m of the water column probably reflects the temperatures at this time interval in the seasonal cycle. The TEX_{86} temperature signal which is preserved in the sedimentary record may thus mainly reflect a seasonal signal, which may explain some of the scatter in the correlation of the TEX_{86} with annual mean SST in core tops. Indeed, for surface sediments of the eastern southern Atlantic *Schouten et al.* [2002] observed that the best correlation of TEX_{86} is with austral winter SST.

5. Conclusion

[23] Our data show that the TEX_{86} of POM from different oceanic regimes correlates well with temperature at depths shallower than 100 m. TEX_{86} values of POM from deeper waters (>100 m) do not correlate with in situ temperature but with surface temperature. Thus these findings suggest

that the GDGT signal which reaches the sediment must be mainly biosynthesized in the upper 100 m of the water column. Packaging of small GDGT-containing crenarchaeal cells into fecal pellets and marine snow aggregates probably results in rapid transport from the photic zone to the sediment. Living suspended deep sea Crenarchaeota do not substantially influence the sedimentary GDGT signal probably because of the lack of aggregation processes and transport mechanisms to the seafloor. Marine Crenarchaeota appear seasonally in surface waters and the GDGT signal accumulating in the underlying sediment may mostly reflect these periods of elevated GDGT biosynthesis. The data presented here, in combination with previous studies on core tops [*Schouten et al.*, 2002], diagenetic stability [*Schouten et al.*, 2004], and mesocosm experiments [*Wuchter et al.*, 2004], show that the TEX_{86} may be used to reconstruct upper water column temperatures in ancient environments.

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