

This discussion paper is/has been under review for the journal Biogeosciences (BG).
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Amino acid composition and $\delta^{15}\text{N}$ of suspended matter in the Arabian Sea

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Received: 13 June 2013 – Accepted: 16 July 2013 – Published: 12 August 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Sedimentation in the ocean is fed by large aggregates produced in the surface mixed layer that sink rapidly through the water column. These particles sampled by sediment traps have often been proposed to interact by disaggregation and scavenging with a pool of fine suspended matter with very slow sinking velocities and thus a long residence time. We investigated the amino acid composition and stable nitrogen isotopic ratios of suspended matter sampled during the late SW monsoon season in the Arabian Sea and compared them to those of sinking particles to investigate organic matter degradation/modification during passage through the water column. We found that amino acid (AA) composition of mixed layer suspended matter corresponds more to fresh plankton and their aggregates, whereas AA composition of suspended matter in the sub-thermocline water column deviated progressively from mixed layer composition. We conclude that suspended matter in deep waters and in the mixed layers of oligotrophic stations is dominated by fine material that has a long residence time and organic matter that is resistant to degradation. Whereas SPM in areas of high primary productivity is essentially derived from fresh plankton and thus has a strong imprint of the subsurface nitrate source, SPM at oligotrophic stations and at subthermocline depths appears to exchange amino acids with the DOC pool influencing also the $\delta^{15}\text{N}$ values.

1 Introduction

Most planktonic organisms and the mineral particles transported into the deep ocean are very small and have very low sinking velocities, so that oceanic sedimentation depends mainly on the formation and settling of large particles (Degens and Ittekkot, 1987; McCave, 1984). These are, generally, formed in surface water involving biological processes. Fecal pellets are a minor proportion of sinking particles (Pilskaln and Honjo, 1987), whereas macroscopic aggregates of organic and inorganic matter, the so called

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marine snow, are the major means of transport of material to the sediments (Aldredge and Silver, 1988). Contrary to the large sinking particles small suspended particles with low sinking velocities remain suspended for months to years if not scavenged by the rare sinking particles (McCave, 1984). Whereas sediment traps, deployed over days or weeks in the water column, are suitable to sample sinking aggregates, filtration of conventional water samples collects the fine grained suspended matter (SPM) which does not sink (Silver et al., 1998). There is evidence that in-situ filtration systems sample both fine and large particles so that their composition is intermediate between that of material intercepted by sediment traps and that obtained by filtration of water samples (Abramson et al., 2011; Bishop et al., 1985).

Total organic matter concentrations as well as labile constituents of organic matter in sinking particles intercepted by sediment traps decrease with increasing water depth (Haake et al., 1993a, 1992; Lee et al., 2000). This suggests that degradation proceeds on large aggregates while sinking in the water column despite their rapid sinking speeds of $10\text{--}150\text{ m d}^{-1}$ (McDonnell and Buesseler, 2010). Studies of organic constituents such as pigments, amino acids, and fatty acids suggest that organic matter in SPM is less degraded than that of sinking particles (Abramson et al., 2011; Lee et al., 1983; Rontani et al., 2011; Wakeham and Canuel, 1988). This is somewhat counterintuitive, as the much longer residence time of fine particles in the water column would imply stronger degradation of organic matter (Degens and Ittekkot, 1987; McCave, 1984). Based on these observations, models of particle aggregation and disaggregation with differential settling of labile and refractory matter have been formulated (Abramson et al., 2011; Lee et al., 1983; Wakeham and Canuel, 1988) with a central concept of photo-oxidation of lipids to radicals in SPM of surface waters that makes them resistant towards biotic degradation (Rontani et al., 2011).

Amino acids are frequently used to characterize and quantify the degradation state of organic matter. Indicators are amino acid concentrations, especially their contributions to organic carbon (AA-C %) or nitrogen (AA-N %) (Cowie and Hedges, 1994) as well as specific changes in amino acid monomer distribution. Ratios of individual

amino acids such as Asp/ β -Ala and Glu/ γ -Aba (Cowie and Hedges, 1994; Ittekkot et al., 1984b; Lee and Cronin, 1984), or the more complex Reactivity Index (RI; Jennerjahn and Ittekkot, 1997) and Degradation Index (DI; Dauwe and Middelburg, 1998; Dauwe et al., 1999) have been established to classify organic matter degradation (Ingalls et al., 2003; Möbius et al., 2010; Pantoja et al., 2004; Unger et al., 2005). These biogeochemical indicators of organic matter quality were essentially developed for marine sinking particles and sediments. They are of limited use in other sample sets and materials, such as marine SPM and samples from fresh and brackish waters, so that individual and adapted indices (usually derived from statistical analyzes of compositional data by principal components analysis PCA) must be developed to differentiate states of degradation (Abramson et al., 2011; Gaye et al., 2007; Goutx et al., 2007; Menzel et al., 2013; Sheridan et al., 2002).

To contribute to the understanding of oceanic particle dynamics and organic matter degradation we collected particulate matter from the Arabian Sea by filtration of large volumes of water (i) from conventional samplers and (ii) by in situ pumps and analyzed the particles for amino acid composition and stable nitrogen isotopic ratios ($\delta^{15}\text{N}$). These data are compared to data from long-term trap investigations in the Arabian Sea (Gaye-Haake et al., 2005; Haake et al., 1992, 1996; Rixen et al., 2009; Schäfer and Ittekkot, 1993, 1995). Nutrient data and $\delta^{15}\text{N}_{\text{NO}_3}$ values are available from the sampling sites (Gaye et al., 2013; Rixen et al., 2013) and permit an evaluation of $\delta^{15}\text{N}$ values of SPM ($\delta^{15}\text{N}_{\text{PN}}$) in relation to the dissolved nitrate source. This serves to test whether SPM influences and contributes to the $\delta^{15}\text{N}$ signal exported from the mixed layer into the deep ocean.

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2 Material and methods

2.1 Study area

The Arabian Sea is highly productive due to monsoon-driven upwelling of thermocline nutrients along the western margins off Oman and Somalia (Fischer et al., 1996; Wiggert et al., 2005; Woodward et al., 1999). It also hosts one of the worlds' major oxygen deficient zones (ODZ) situated between 100 m and about 1200 m water depth. There, about one third of the global oceanic nitrogen loss occurs (Gruber, 2008; Gruber and Sarmiento, 1997) mostly due to heterotrophic denitrification (Bulow et al., 2010; Ward et al., 2009). This process has a strong isotopic effect of 20–30‰ (Altabet et al., 1999a; Brandes et al., 1998; Cline and Kaplan, 1975), so that $\delta^{15}\text{N}$ values of nitrate ($\delta^{15}\text{N}_{\text{NO}_3}$) in the upper ODZ of the Arabian Sea are high and reach up to > 20‰ (Yoshinari et al., 1997). Upwelling off Oman occurs during the SW monsoon from June to September, when Ekman pumping brings water from 150 m water depth to the surface (Morrison et al., 1998). ^{15}N enriched nitrate from the top of the ODZ then reaches the euphotic zone and is further converted into particulate matter by primary producers.

Strongest denitrification is not encountered in the most productive region off Oman but in the north eastern Arabian Sea as reflected in maximum nitrite accumulation in the oxygen-deficient water column interval (Naqvi, 1987, 1991; Yoshinari et al., 1997). This spatial decoupling of the productivity and denitrification maxima is related to the circulation in the basin. The oxygenated Indian Central Water (ICW) enters the Arabian Sea from the SW and becomes oxygen and nitrate depleted on its way to the east (Böning and Bard, 2009; Morrison, 1997; Morrison et al., 1998). Local source of mid-water re-oxygenation are the Persian Gulf Water and the Red Sea Water in the western Arabian Sea (Mantoura et al., 1993; Prasad et al., 2001), and a seasonal (SW-monsoonal) undercurrent from the Bay of Bengal flowing north along the Indian margin (Naqvi et al., 2005).

Sediment trap studies in offshore areas and at the Pakistan margin (Gaye-Haake et al., 2005; Schäfer and Ittekkot, 1993) reveal that $\delta^{15}\text{N}$ of sinking particles sampled

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in bimonthly to monthly resolution range from 5 to 9‰ with inter-annual averages ranging from 5.8–7.8‰. Early diagenetic processes and diagenetic enrichment at the sediment water interface prior to burial further increases the $\delta^{15}\text{N}$ of surface sediments to values > 12‰ in the central Arabian Sea (Gaye-Haake et al., 2005; Möbius et al., 2011).

2.2 Sampling

Water samples were taken at 14 stations with a *Seabird SBE 32 Water Sampler* equipped with 10 L PVC sample bottles during cruise R/V *Meteor 74/1b* in 2007 (Fig. 1). Between 3 L and 45 L of water were filtered on pre-combusted (450 °C overnight) and *Whatman* GF/F glass fibre filters (47 mm diameter) at water depths between 0 m (surface) and 450 m. At five stations in-situ pumps (*McLane WTS LV*) were used which filtered between 200 L and 950 L water on pre-combusted (450 °C overnight) *Whatman* GF/F filters (142 mm diameter). Samples were dried at 40 °C for two days and the dry weight was used to determine total suspended matter concentrations (SPM) in mg L^{-1} . Samples from in-situ pumps were only used for $\delta^{15}\text{N}$ analyzes as filters were not pre-weighed.

2.3 Analyses

Total carbon and nitrogen were measured by a Carlo Erba Nitrogen Analyser 1500 (Milan, Italy). Organic carbon (POC) was determined after three acid treatments of samples to remove carbonate. Precision of this method is 0.05 % for carbon and 0.005 % for nitrogen. Organic matter (OM) was calculated by multiplying the organic carbon content with 1.8 (Müller et al., 1986). Carbonate carbon is the difference between total and organic carbon.

Ratios of $^{15}\text{N}/^{14}\text{N}$ of particulate nitrogen ($\delta^{15}\text{N}_{\text{PN}}$ values) were determined using a Delta Plus XP isotope ratio mass spectrometer connected with a ConFlo-III interface after high-temperature flash combustion in a Thermo Finnigan Flash EA 1112 at

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1050 °C. Isotope ratios are reported in ‰ using the delta-notation

$$\delta^{15}\text{N}_{\text{sample}} = \left(\frac{^{15}\text{N}/^{14}\text{N}}{(^{15}\text{N}/^{14}\text{N})_{\text{reference}}} - 1 \right) \cdot 1000 \quad (1)$$

Pure tank N₂ calibrated against the reference standards IAEA-N1 (ammonium sulfate, δ¹⁵N = +0.4 ‰) and IAEA-N2 (ammonium sulfate, δ¹⁵N = +20.3 ‰) of the International Atomic Energy Agency was used as a working standard. δ¹⁵N is given as the per mil deviation from the N-isotope composition of atmospheric N₂. Duplicate measurements of samples differ by less than 0.15 ‰. The laboratory's long-term 2σ standard deviation for IAEA-N1 standard is 0.09 ‰.

Nutrient concentrations in filtered water samples were determined by a *Skalar Auto-analyser* and δ¹⁵N of nitrate were determined using the "denitrifier method" (Casciotti et al., 2002; Sigman et al., 2001); data are taken from Rixen et al. (2013) and Gaye et al. (2013).

Total hydrolysable amino acids and hexosamines (AA) were analysed with a *Biochrom 30 Amino Acid Analyser* after hydrolysis of ca. 1–2 mg for suspended particulate matter (collected on GF/F filters) with 6 N HCl for 22 h at 110 °C under a pure argon atmosphere. A particle free aliquot was three times evaporated to dryness in order to remove the remaining acid; the residue was taken up in an acidic buffer (pH: 2.2). After injection and subsequent separation with a cation exchange resin, the individual monomers were post-column derivatized with o-phthaldialdehyde in the presence of 2-mercaptoethanol and detected with a *Merck Hitachi L-2480* fluorescence detector. Duplicate analysis of a standard solution according to this method results in a relative error of 0.1 to 1.3 % for the concentrations of individual AA monomers and 0.2 to 3.0 % for individual AA monomers of SPM samples. Molar percentages of individual monomers are used to calculate the reactivity index (RI) and the degradation index (DI). The RI is the ratio of the labile amino acids Tyr and Phe divided by the sum of the non-protein amino acids β-Ala and γ-Aba. (Jennerjahn and Ittekkot, 1997). The DI assesses the diagenetic alteration of a sample by comparing it to a set of 28 samples of different degradational states and environments compiled by Dauwe and

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Middelburg (1998) and Dauwe et al. (1999). Molar percentages of individual AA are standardised by the mean and standard deviations of the 28-sample data set. The DI then integrates the AA weighed by the factor coefficients for the first axis of the principal component analyses (PCA) of Dauwe et al. (1999) according to the formula:

$$DI = \sum \left[\frac{\text{var}_i - \text{AVGvar}_i}{\text{STDvar}_i} \right] \cdot \text{fac.coef.}_i \quad (2)$$

where var_i is the original mole percentage of each AA_i , AVGvar_i and STDvar_i are the mean and standard deviations, respectively, and fac.coef._i is the factor coefficient of the first axis of the PCA of Dauwe et al. (1999). The DI thus represents the cumulative deviation of the 14 amino acids with respect to an assumed average molar composition.

Higher (lower) values of RI and DI indicate less (more) degradation.

3 Results

3.1 SPM, POC, and nitrogen

SPM concentrations between $1.3\text{--}8.2 \text{ mg L}^{-1}$ in Arabian Sea surface waters were encountered at the western stations off Oman (#944–947) (Fig. 2a). POC concentrations were elevated ($140\text{--}860 \mu\text{g L}^{-1}$) in the surface mixed layer of these stations, and also along the southern transect (#948–951; Fig. 2b), and both SPM and POC concentrations decreased with depth at these stations (Fig. 2a, b, Table 1). $\text{SPM} \leq 0.5 \text{ mg L}^{-1}$ and $\text{POC} \leq 100 \mu\text{g L}^{-1}$ occurred along the northern transect (#953–958) in surface waters and below 100 m at all locations (Table 1).

C/N ratios of SPM on filters are between 5 and 10 with no apparent depth trend. Organic carbon weight percentages vary between 3 and 27 % (Table 1). Lowest percentages were observed in the samples from the western Arabian. Some of these stations have considerably elevated POC concentrations in surface SPM. Samples of the northern transect and most deep samples have POC percentages between 15 and

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25% with no apparent depth related trend. Carbonate percentages are relatively low with values between 0 and 12.6 %.

3.2 $\delta^{15}\text{N}$ ratios of particulate nitrogen

$\delta^{15}\text{N}_{\text{PN}}$ are between 4.5 and 9.3 ‰ in waters < 100 m depth of the Arabian Sea (Fig. 3a), between 8.5 and 9.6 ‰ at 100–150 m depth and between 6.9 and 9.4 ‰ at \geq 200 m water depth, respectively (Fig. 3; Table 1). The $\delta^{15}\text{N}_{\text{PN}}$ of samples from deep sea pumps are slightly depleted compared to SPM from water samplers in samples at 15–50 m. The observed difference are quite small and may as well be due to spatial variations in $\delta^{15}\text{N}_{\text{PN}}$ of the Arabian Sea rather than to the two different techniques.

3.3 Amino acids

In the Arabian Sea total hydrolysable amino acid concentrations are significantly correlated with POC ($R^2 = 0.64$; $n = 40$) and with N concentrations ($R^2 = 0.82$; $n = 40$). Amino acids and hexosamines concentrations are between 28 and 297 mg g^{-1} of dry SPM, between 27 and 597 $\mu\text{g L}^{-1}$, and comprise 20–60% of total organic carbon and between 50 and 100% of nitrogen, respectively. The non-protein amino acids are present only in trace amounts so that Asp/ β -Ala and Glu/ γ -Aba ratios are > 100 in most samples. The DI values are around 1 and the RI values are between 9 and 55, respectively (Table 1). Similar to POC, amino acid concentrations and percentage contribution of amino acid carbon and nitrogen of total organic carbon and nitrogen have no depth trend at stations #951–958.

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4 Discussion

4.1 SPM concentration and composition

High SPM and organic carbon concentrations with maxima at stations #944 and #946 were observed in the western Arabian Sea where upwelling was still active in late September 2007 (Fig. 2). The negative correlation between sea surface temperature (SST) and organic POC concentrations in surface waters ($R^2 = -0.81$, $n = 14$) suggests a close relationship between upwelling related primary productivity and surface water POC concentrations. SPM concentrations are also negatively correlated with SST, but the correlation is less significant. The reason is, probably, a dilution caused by the dust input from the Arabian Peninsula which is very high during the SW monsoon (Ramaswamy et al., 1991). SPM concentrations drop immediately below the thermocline to values below 0.5 mg L^{-1} equivalent to those in surface water along the northern oligotrophic transect. Concentrations below 0.5 mg L^{-1} thus represent the standing stock of subthermocline SPM in the Arabian Sea. Elevated SPM concentrations in the surface mixed layer are evidently due to seasonally or locally enhanced productivity, when biomass material adds to the standing stock. Minima of SPM and POC concentrations are $\sim 0.2 \text{ mg L}^{-1}$ and $\sim 40 \mu\text{Cg L}^{-1}$, respectively. The mass of POC extrapolated over a water column of 3000–4000 m is between $120\text{--}160 \text{ g C m}^{-2}$. Annual average export production of the Arabian Sea is $\sim 90 \text{ g C m}^{-2} \text{ a}^{-1}$ (Rixen et al., 2005) and the available estimate of the mean residence time water in the ODZ is about 11 ± 4 yr (Olson et al., 1993). The exchange between sinking and suspended POC may, thus, be quite limited.

4.2 Source of organic matter as indicated by amino acid spectra

Amino acid composition of SPM deviates from Arabian Sea plankton, sinking particles and surface sediments. Whereas sinking particles (intercepted by sediment traps) and sediments have patterns dominated by Gly > Asp > Glu > Ala (Haake et al., 1992),

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SPM is dominated by Gly > Glu > Asp > Ser. SPM samples have lower Mol-% non-protein AA (β -Ala and γ -Aba) and considerably higher amino acid carbon percentages than sinking particles and sediments (Haake et al., 1996), which would suggest that organic matter in SPM is less degraded. Also, commonly used indicators such as Asp/ β -Al and Glu/ γ -Aba ratios, and the more complex indicators DI and RI reveal no trend with depth, which would imply that the SPM pool below the surface mixed layer is entirely homogeneous (Table 1; see methods for explanation). But these indicators were developed to trace mineralisation and organic matter degradation of sinking particles and sediments (Cowie and Hedges, 1994; Dauwe and Middelburg, 1998; Dauwe et al., 1999; Ittekkot et al., 1984a, b; Jennerjahn and Ittekkot, 1997; Lee, 1988), and are likely unsuitable or too coarse to track changes in SPM. To recognise compositional differentiation of SPM, we carried out a Principal Component Analysis (PCA) of amino acid Mol-% for the SPM sample set. The highest positive factor loadings were contributed by the amino acids Asp, Thr, Ala, Val, Ile, Leu and Phe of which most are abundant in fresh plankton (Gaye et al., 2007; Ingalls et al., 2006; Lee, 1988). The amino acids with negative factor loadings (Ser, Glu, Gly and Arg) are some of those considered as typical for carbonaceous and siliceous frustules (Cowie and Hedges, 1992; Hecky et al., 1973), but have so far not been encountered to group in amino acid PCAs (Gaye et al., 2007; Ingalls et al., 2006) (Table 2). This factor thus distinguishes samples based on the presence or absence of fresh plankton. In consequence the scores of individual samples have a clear trend with depth from high scores in shallower samples to low scores in deep samples. Moreover, samples from the mixed layers and the sub-thermocline of high production sites have higher F1 scores than those from less productive sites (Table 2). The basic trend is an enrichment of Glu, Gly and Ser in deep SPM and in low-productivity surface waters, whereas mixed-layer SPM in productive areas resembles fresh plankton (Fig. 4).

The depth-related change in amino acid composition of SPM found in this PCA is different from that observed in sinking particles. Bacterial degradation of sinking fresh plankton and attached bacteria of similar amino acid composition (Cowie and Hedges,

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1992) progresses with depth and shifts the amino acid composition to typical degradation products of proteinogenic amino acids, such as the non-protein amino acids β -Ala, γ -Aba and Orn (Cowie and Hedges, 1994; Lee and Cronin, 1982, 1984). SPM from the euphotic zone in our sample set is similar to sinking particles caught at 1000–3000 m depth, whereas SPM in samples deeper than ≥ 100 m is different (Fig. 4; data from Haake et al., 1992, 1996). Results of a second PCA of all SPM amino acid spectra from this data set, average values for sediment trap deployments between 1986 and 1990, and plankton samples from the Arabian Sea corroborate that SPM on the one hand and plankton/sinking materials on the other hand are compositionally different (Fig. 5). The first factor (53% of the total variance) has positive loadings of Val, Ala, Thr, Lys, Met, Tyr, Asp, His, β -Aba and γ -Aba, and negative factor loadings of Ser, Glu, Ile and Leu. Scores of individual samples on this factor clearly separate SPM (negative scores) from plankton and trap samples (positive scores). The second factor (23% of the total variance) reveals modifications related to water depth. High scores mark trap and SPM samples from shallow depths, and low scores SPM samples from sub-thermocline depths and deeper traps. Negative scores of trap samples are related to the enrichment of degradation products Orn and the non-protein amino acids, as well as His and Gly. Negative scores of deep SPM are mainly due to the negative loadings of Ser and Gly. The second factor produces a similar order of SPM samples in the expanded data set including sinking matter and fresh plankton, as the factor analyses carried out using SPM only (Table 2). These results illustrate the difference between sinking and suspended particles and show that amino acid spectra of SPM and sinking particles depart from plankton and further diverge with depth.

Diverging amino acid composition of SPM and sinking particles may be related to the difference in source and bulk composition. SPM from the euphotic zone contains aggregated coccolithophorids and diatoms, which are also present in sediment trap samples (H. Schulz, personal communication, 2012). SPM from the surface layer thus is probably a mixture of fresh plankton, biogenic aggregates and fine non- or very

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1995). The high concentrations of organic matter in SPM may not be explained by sorption of dissolved moieties to mineral surfaces only, but may indicate that dissolved organic matter is transferred into the particulate organic matter pool by aggregation (Chin et al., 1998). Studies by McCarthy et al. (2004) and McCarthy et al. (1997) found relatively undegraded dissolved organic nitrogen of an autotrophic origin in the deep ocean which may have been protected from degradation by a gel-matrix structure (Chin et al., 1998).

Sinking particles on the other hand are sites of bacterial decomposition of plankton-derived organic matter and accumulate degradation products such as non-protein amino acids (Alldredge et al., 1986; Alldredge and Silver, 1988; Lee and Cronin, 1982; Silver et al., 1998). Larger particles escape faster from the euphotic zone due to the “ballast-effect” of biogenic frustules and rapidly transport labile organic matter to the deep sea and to the sediments (Klaas and Archer, 2002; Salter et al., 2010). Due to their fast escape from the photic zone they contain less free radicals that are assumed to prevent microbial degradation (Rontani et al., 2011).

4.3 Nitrate assimilation and $\delta^{15}\text{N}_{\text{PN}}$

Arabian Sea subsurface waters have $\delta^{15}\text{N}_{\text{NO}_3}$ values between 7–8 ‰ (Gaye et al., 2013). This enrichment relative to deep ocean nitrate ($\delta^{15}\text{N}_{\text{NO}_3} = 4.8 \text{ ‰}$; Sigman et al., 2000) may be related to upward mixing and diffusion of isotopically enriched nitrate from the upper ODZ, or to recycling of the ^{15}N -enriched particulate organic matter from upwelling areas where nitrate from the ODZ can reach the surface waters.

Assimilation of nitrate in surface waters follows the “Rayleigh closed system” model, if the substrate is not replenished. In this case the $\delta^{15}\text{N}_{\text{NO}_3}$ of the nitrate substrate can be calculated according to Mariotti et al. (1981):

$$\delta^{15}\text{N}_{\text{substrate}} = \delta^{15}\text{N}_{\text{initial.substrate}} - \epsilon \{ \ln(f) \} . \quad (3)$$

Values for f (the fraction of nitrate + nitrite remaining) are calculated according to

$$f = ([\text{NO}_3] + [\text{NO}_2]) / ([\text{NO}_3] + [\text{NO}_{3\text{def}}]) \quad (4)$$

where $\text{NO}_{3\text{def}}$ is the nitrate deficit calculated from the stoichiometric relationship established from Arabian Sea JGOFS data that accounts for a preformed nitrate deficit (Codispoti et al., 2001)

$$\text{NO}_{3\text{def}} = \left(14.89 \cdot \left([\text{PO}_4^{3-}] - 0.28 \right) - \left([\text{NO}_3^-] + [\text{NO}_2^-] + [\text{NH}_4^+] \right) \right) \cdot 0.86 . \quad (5)$$

The isotopic effect of assimilation can be obtained from the slope of the linear regression of $\ln(f)$ against the $\delta^{15}\text{N}_{\text{NO}_3.\text{substrate}}$. This regression carried out for all $\delta^{15}\text{N}_{\text{NO}_3}$ from depths ≤ 100 m results in $^{15}\epsilon = 4.1$ ‰ with a correlation coefficient of $R^2 = 0.89$ ($n = 16$). The calculated isotopic effect is slightly lower than the isotopic effect of $^{15}\epsilon \sim 5.0$ ‰ commonly assumed for assimilation (Sigman et al., 1999; Wada, 1980). Subsurface $\delta^{15}\text{N}_{\text{NO}_3}$ is about 8 ‰ ($= \delta^{15}\text{N}_{\text{initial.substrate}}$).

Organic matter produced by assimilation should be depleted in ^{15}N relative to the substrate following the calculation of the instantaneous product

$$\delta^{15}\text{N}_{\text{inst.product}} = \delta^{15}\text{N}_{\text{substrate}} - ^{15}\epsilon . \quad (6)$$

The accumulated product should have a $\delta^{15}\text{N}$ according to

$$\delta^{15}\text{N}_{\text{acc.product}} = \delta^{15}\text{N}_{\text{initial.substrate}} + ^{15}\epsilon \{ f / (1 - f) \} \ln(f) . \quad (7)$$

We would expect the $\delta^{15}\text{N}_{\text{PN}}$ to be in the range of the instantaneous product rather than the accumulated product because we know from sediment trap studies that productivity signals from surface water are transferred into the deep ocean (1000–3000 m) with a delay of only two weeks (Haake et al., 1996; Rixen et al., 2000).

While $\delta^{15}\text{N}_{\text{NO}_3}$ in the mixed layer can be explained by Rayleigh fractionation during assimilation, many of the measured $\delta^{15}\text{N}_{\text{PN}}$ do not plot close to the $\delta^{15}\text{N}_{\text{inst.product}}$ of

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Rayleigh fractionation (Fig. 6). Samples from the nitrate-depleted oligotrophic stations (lowest f) are lower than the expected $\delta^{15}\text{N}_{\text{inst.product}}$. Samples with $\delta^{15}\text{N}_{\text{PN}}$ above the $\delta^{15}\text{N}_{\text{inst.product}}$ are from the upwelling areas and from depths in the lower euphotic zone.

There are several explanations feasible for the deviation of $\delta^{15}\text{N}_{\text{PN}}$ from the calculated $\delta^{15}\text{N}_{\text{inst.product}}$. Under the oligotrophic late- to post-monsoon conditions along the northern transect and at the eastern locations the isotopic effect of assimilation may be smaller than $^{15}\epsilon = 4\text{‰}$ due to nutrient limitation. Uptake of regenerated ammonium may also be significant and reduce the $\delta^{15}\text{N}_{\text{PN}}$ (Waser et al., 1998). The value for $\delta^{15}\text{N}_{\text{initial.substrate}}$ is possibly higher at the near coastal stations as upwelling from 150 m depth would entrain water with a $\delta^{15}\text{N}_{\text{NO}_3} \sim 11\text{‰}$. Also, most of the assimilation may have taken place at shallower depths where the f ratio is lower.

Although some of the expected patterns such as high $\delta^{15}\text{N}_{\text{PN}}$ at upwelling stations are found, $\delta^{15}\text{N}_{\text{PN}}$ cannot be explained by Rayleigh assimilation, whereas the $\delta^{15}\text{N}_{\text{NO}_3}$ and also the $\delta^{15}\text{N}$ of sinking particles fit the Rayleigh model (Fig. 6). As described in earlier studies, processes such as aggregation, disaggregation, consumption as well as vertical mixing processes complicate the interpretation of $\delta^{15}\text{N}$ from SPM (Altabet, 1988, 1989; Voss et al., 1996). In addition to possible reasons for a deviation of individual samples described above, we believe that an important contribution to the observed deviation of the $\delta^{15}\text{N}_{\text{PN}}$ from the Rayleigh model is the fact that SPM contains not only fresh plankton and aggregates, but also fine material with a very long residence time in the ocean. We know little about source and decomposition processes of the organic matter in SPM. As SPM from the euphotic zone contains fresh plankton and aggregates it includes the signal of the nitrogen source of plankton, especially when productivity is high.

Our highest $\delta^{15}\text{N}_{\text{PN}}$ from the two stations of active upwelling are elevated compared to the non-upwelling stations. A study from the spring intermonsoon period revealed the influence of seasonal nitrogen fixation reducing $\delta^{15}\text{N}_{\text{PN}}$ to 4‰ in surface waters around 10°N in the central Arabian Sea (Montoya and Voss, 2006). In contrast, deep

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$\delta^{15}\text{N}_{\text{PN}}$ as well as $\delta^{15}\text{N}_{\text{PN}}$ sampled under oligotrophic conditions appears to be dominated by organic matter attached to fine, probably, very slowly sinking mineral particles. This organic matter is amino acid rich with 30–50 % of POC and 50–85 % of total nitrogen contributed by amino acids. We hypothesize that due to the long residence time of fine particles in the ocean and their possible exchange with the more homogenous dissolved organic matter pool the regional differences in $\delta^{15}\text{N}_{\text{PN}}$ of deep SPM must be much smaller than that in surface SPM, sinking particles and underlying sediments. The differences observed between $\delta^{15}\text{N}_{\text{PN}}$ in the surface mixed layer and the subthermocline depths may be due to this difference in organic matter source (Altabet, 1988, 1989; Altabet et al., 1999b; Montoya and Voss, 2006; Voss et al., 1996).

4.4 Preservation of the $\delta^{15}\text{N}$ signal of the nitrogen source in sediments

Our snapshot of surface SPM from the late SW-monsoonal upwelling off Oman produced $\delta^{15}\text{N}_{\text{PN}}$ values of 8.7 and 9.2 % under active upwelling conditions derived from a $\delta^{15}\text{N}_{\text{NO}_3}$ source of $\sim 11\%$. This difference is due to the isotopic effect of assimilation and confirms that nutrients are not completely utilized in the upwelling areas, but are advected into the central Arabian Sea (Naqvi, 2008). Surface sediments from stations #944 and #945 had $\delta^{15}\text{N}$ values of 9.4 and 8.8 %, respectively, which is remarkably close to the observed $\delta^{15}\text{N}_{\text{PN}}$ in surface waters. This is in line with the assumption that slope sediments from the ODZ preserve the primary $\delta^{15}\text{N}$ signal of the N source without a diagenetic enrichment (Altabet et al., 1999b; Möbius et al., 2011) and are thus very good sedimentary archives for the reconstruction of the upwelling and denitrification history. However, in contrast to the core denitrification zone in the northern and north eastern Arabian Sea where $\delta^{15}\text{N}_{\text{NO}_3}$ values at 150 m are enriched to $> 20\%$ (Gaye et al., 2013), the western Arabian Sea subsurface and upper ODZ waters are ventilated by oxygen rich ICW as well as branches of the Persian Gulf and Red Sea Water (Morrison, 1997; Prasad et al., 2001). This inflow leads to locally depleted $\delta^{15}\text{N}_{\text{NO}_3}$

with dissolved amino acids. We suggest that exchange with the dissolved pool could be an important process modulating organic matter on SPM. This suggested mechanism needs more detailed investigations and its role in the global cycling of elements and their documentation in sediment records needs to be assessed.

5 *Acknowledgements.* We thank Udo Hübner for operating the CTD and water samplers as well as captain Uwe Pahl and crew of R/V *Meteor* (M 74-1b) for their excellent technical support. We are grateful to Marcel M. M. Kuypers for letting us use his deep sea pumps. Jürgen Möbius helped with his suggestions and many discussions. Financial support for the Meteor cruise came from the Deutsche Forschungsgemeinschaft (DFG Grant No. GA 755/4-1).

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Table 1. Continued.

Station No.	Depth [m]	NO ₃ [μmol]	δ ¹⁵ N _{NO₃} [‰]	δ ¹⁵ N _{PN} [‰]	Susp. [mg L ⁻¹]	POC [μg L ⁻¹]	POC [%]	OM [%]	N [%]	C/ N _{mol}	Carbo- nate [%]	AA+HA [μg L ⁻¹]	AA+HA [mg g ⁻¹ sed.]	ASP/ b-ALA	GLU/ g-ABA	RI	DI	AA-C [%]	AA-N [%]	
951	0			9.12	0.79	174.6	22.2	40.0	3.81	6.8	0.0	175.3	222.9	160.2	112.0	33.7	0.94	43.7	71.3	
	15			9.25	1.14	152.3	13.4	24.1	2.67	5.9	2.4	148.8	130.7	23.4	89.1	9.3	0.72	42.3	59.7	
	50				0.24	52.1	21.4	38.6	3.76	6.7		48.8	200.9	122.8	131.7	33.5	0.97	40.3	73.4	
	100			8.69	0.23	46.9	20.1	36.2	4.22	5.6		56.1	240.7	156.1	173.8	35.3	0.89	50.7	80.1	
	300			8.99	0.24	48.2	20.3	36.6	3.5	6.7		46.6	196.2	188.7	94.9	28.6	0.90	41.0	78.6	
953	0	0.52		6.47	0.96	253.1	26.3	47.4	3.37	9.1	12.6	100.5	104.6	97.3	102.6	24.9	1.04	17.2	42.7	
	5	0.59																		
	15	0.49																		
	25	0.83																		
	50	2.93	9.06																	
	75	13.98	7.52																	
	99	22.68	8.32																	
	125	25.35		8.96*																
	225	21.70		8.68*																
	954	0	1.18		6.73	0.26	58.6	22.2	39.9	3.67	7.0	4.4	45.6	172.8	165.5	79.2	27.8	1.11	33.9	65.2
5		1.15																		
10		1.18																		
15		1.95																		
35																				
50		5.51		7.20	0.30	80.4	26.6	47.8	5.5	5.6	10.5	89.8	297.0	239.3	152.1	53.5	0.98	48.6	74.3	
75		23.41																		
100		25.48		9.63	0.18	40.3	22.9	41.2	4.20	6.3	1.5	38.8	220.2	983.7	126.3	54.6	1.30	41.5	73.4	
300				8.89	0.18	47.4	25.8	46.4	4.46	6.8	5.0	39.3	213.5	204.1	121.9	34.7	0.96	35.1	67.5	
955		0	0.56		6.60	0.25	62.0	24.9	44.9	4.72	6.2	4.0	63.9	256.6	186.6	203.5	52.3	1.08	44.6	75.5
	5	0.54																		
	15	0.55		4.53*																
	25	1.06																		
	50	3.19	7.41	5.86*																
	75	16.65	8.13																	
	125	21.65		9.59*																
	200	18.47	21.46	8.07*																
	956	0			7.48	0.33	72.4	22.1	39.8	3.64	7.1	1.8	56.8	173.3	165.8	112.0	30.4	1.01	33.6	66.2
		25			7.30	0.42	75.1	17.9	32.2	2.64	7.9	0.0	67.4	160.5	155.1	186.0	41.2	1.13	39.0	84.0
50				0.45	92.8	20.7	37.3	3.13	7.7			79.1	176.4	109.7	159.6	31.7	0.98	36.6	63.4	
100				9.43	0.20	36.1	17.7	31.9	3.29	6.3	3.7	39.1	191.6	150.4	209.4	40.2	0.97	45.9	86.2	
300				8.85	0.26	40.6	15.7	28.3	3.85	4.8	8.2	36.2	140.5	358.6	139.5	39.9	0.96	37.9	60.0	
957		0	0.18		7.23	0.28	64.4	22.8	41.1	3.85	6.9	4.1	50.3	178.4	46.8	116.0	18.0	1.03	33.7	63.6
		5	0.16																	
		10	0.17		5.71*															
		15	0.17																	
		25	2.46																	
	50	18.50		5.01*																
	75	22.06	8.11																	
	200	16.98		9.41*																
	958	0			7.55	0.24	52.2	21.9	39.4	4.02	6.4	2.4	52.7	221.2	113.2	113.9	30.9	1.10	43.9	75.5
		25			7.43	0.27	62.9	23.2	41.8	4.04	6.7	3.9	54.1	199.9	159.1	141.9	38.9	0.97	37.1	68.3
40				7.25	0.31	64.6	20.9	37.6	4.17	5.8		60.9	197.0	168.2	129.8	39.7	1.02	41.0	64.6	
100				8.75	0.23	33.8	14.6	26.3	2.74	6.2	3.7	33.3	144.2	134.9	124.4	30.5	0.99	42.0	73.7	
300				8.70	0.21	36.6	17.7	31.8	3.36	6.1	6.4	32.0	154.6	178.0	103.7	29.8	0.98	37.1	64.9	

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Table 2. Factor loadings of individual amino acids of a PCA carried out with all analyzed amino acids in Mol % of all SPM samples and a PCA of Mol % of all amino acids carried out of SPM, plankton and trap samples. Factor scores of individual SPM samples of the two PCAs sorted by the factor scores of the first factor (F1) of the PCA of SPM only. The sorting is very similar to that of the factor F2 of the PCA which includes SPM, plankton and trap samples (see text for explanation).

Amino Acid	PCA SPM			PCA SPM + Plankton + Traps			
	F1 Loading	F1 Loading	F2 Loading	F1 Score	F1 Score	F2 Score	
Asp	0.098	0.091	0.002	944-S	1.77	-0.321	1.998
Thr	0.107	0.087	0.125	946-S	1.44	-0.132	1.283
Ser	-0.100	-0.084	-0.129	944-20m	1.40	-0.238	1.612
Glu	-0.080	-0.099	0.024	950-S	1.34	-0.413	1.594
Gly	-0.107	-0.021	0.231	945-20m	1.33	-0.118	1.263
Ala	0.105	0.068	0.175	951-15m	1.06	-0.335	1.331
Val	0.106	0.057	0.195	949-S	0.95	-0.723	1.343
Met	0.014	0.086	0.011	951-S	0.91	-0.299	1.245
Ile	0.102	-0.07	0.170	945-S	0.86	-0.426	1.225
Leu	0.070	-0.089	0.117	946-15m	0.82	-0.469	1.235
Tyr	0.032	0.092	-0.004	944-120m	0.74	-0.444	0.566
Phe	0.097	-0.052	0.188	948-S	0.74	-0.434	0.763
β -Ala	0.048	0.094	-0.069	958-40m	0.62	-0.575	0.943
γ -Aba	0.045	0.089	-0.059	958-S	0.56	-0.615	0.749
His	0.018	0.084	-0.044	954-S	0.53	-0.686	0.738
Orn	0.031	0.028	-0.029	954-35m	0.50	-0.424	0.675
Lys	0.069	0.08	0.008	953-S	0.38	-0.833	0.800
Arg	-0.023	-0.029	0.005	957-S	0.31	-0.762	0.384
				956-25m	0.25	-0.882	0.606
				955-S	0.19	-0.773	0.394
				946-125m	0.13	-0.743	0.244
				958-25m	-0.05	-0.848	0.176
				951-50m	-0.11	-0.834	0.100
				956-50m	-0.15	-0.920	-0.017
				948-300m	-0.48	-0.969	-0.347
				946-300m	-0.53	-0.976	-0.565
				956-S	-0.54	-1.075	-0.370
				944-450m	-0.55	-0.875	-0.640
				947-100m	-1.00	-1.178	-0.921
				958-100m	-1.03	-1.198	-0.999
				956-300m	-1.15	-1.276	-1.089
				954-100m	-1.20	-1.033	-1.228
				951-300m	-1.26	-1.107	-1.541
				951-100m	-1.39	-1.356	-1.248
				958-300m	-1.40	-1.230	-1.418
				954-300m	-1.40	-1.261	-1.489
				956-100m	-1.46	-1.330	-1.393
				948-100m	-1.48	-1.375	-1.309
				947-300m	-1.63	-1.401	-1.561

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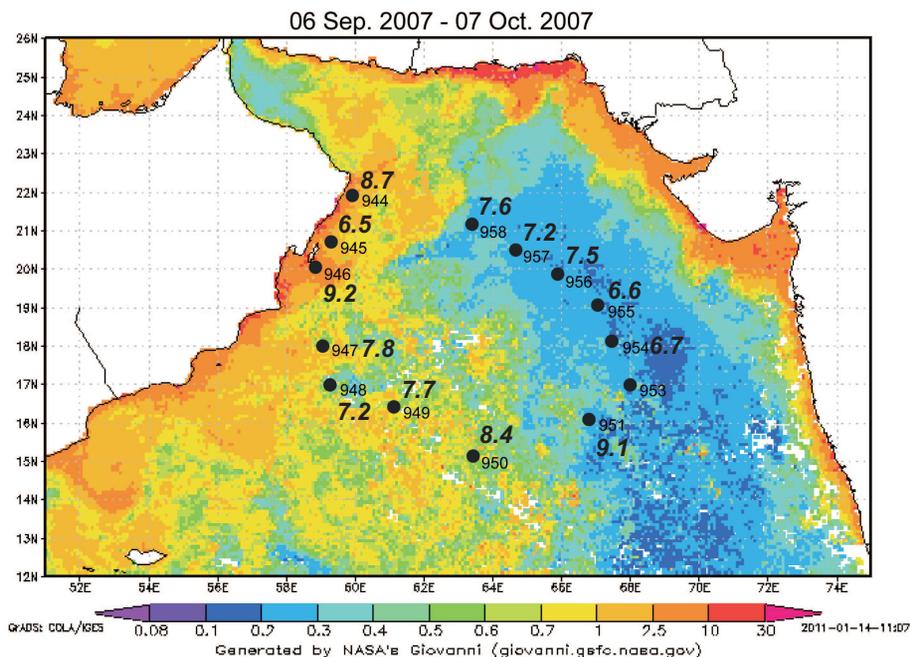


Fig. 1. Sampling locations in the Arabian Sea (location number in small letters). Bold numbers indicate $\delta^{15}\text{N}_{\text{PN}}$ in ‰ of surface SPM. Colours indicate chl_a concentrations in mg m^{-3} from satellite observations between 6 September and 7 October, 2007 available from http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=ocean_month.

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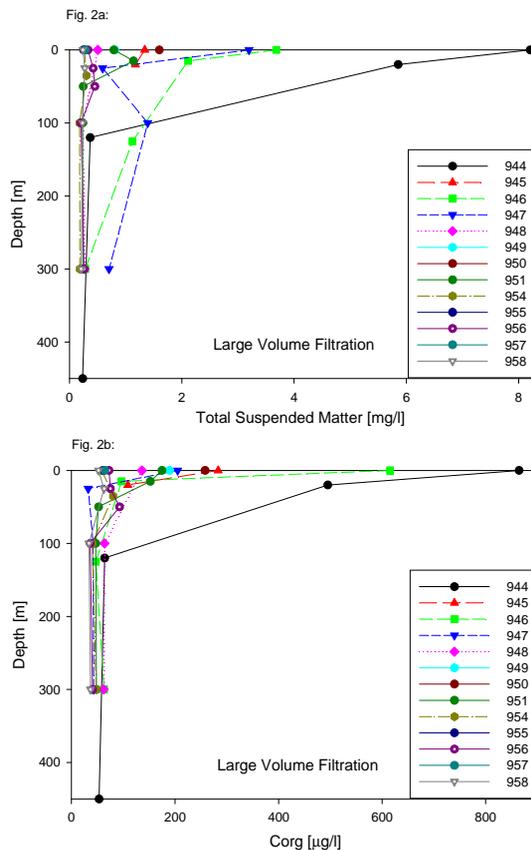


Fig. 2. Total suspended matter concentrations in mgL^{-1} (a) and organic carbon concentrations (POC) in μgL^{-1} (b) vertical profiles from the Arabian Sea. Station numbers are indicated in Fig. 1.

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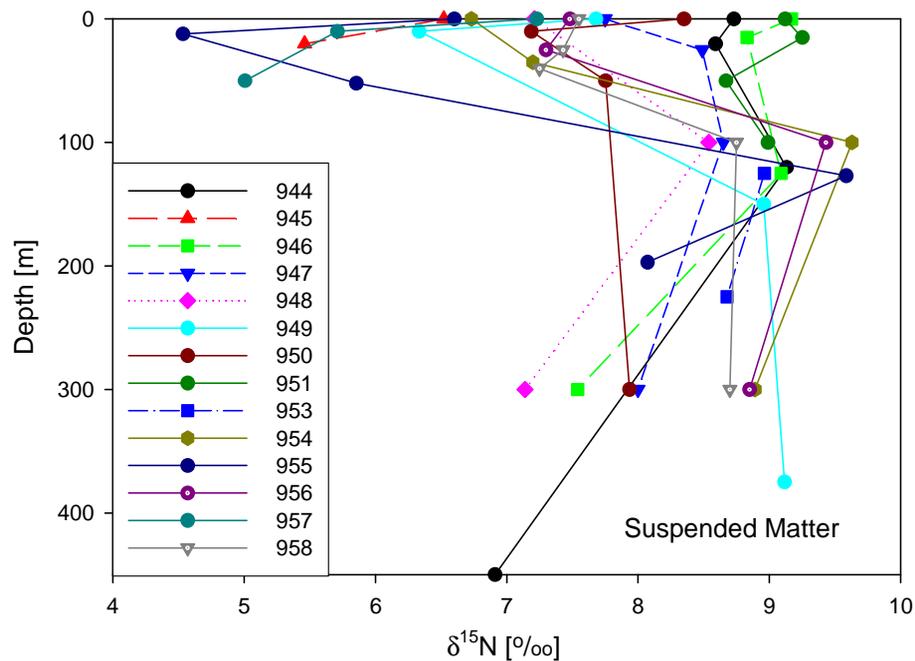


Fig. 3. Vertical profiles of $\delta^{15}\text{N}_{\text{PN}}$ in ‰ in large volume filtration samples from conventional water samples and in situ pumps.

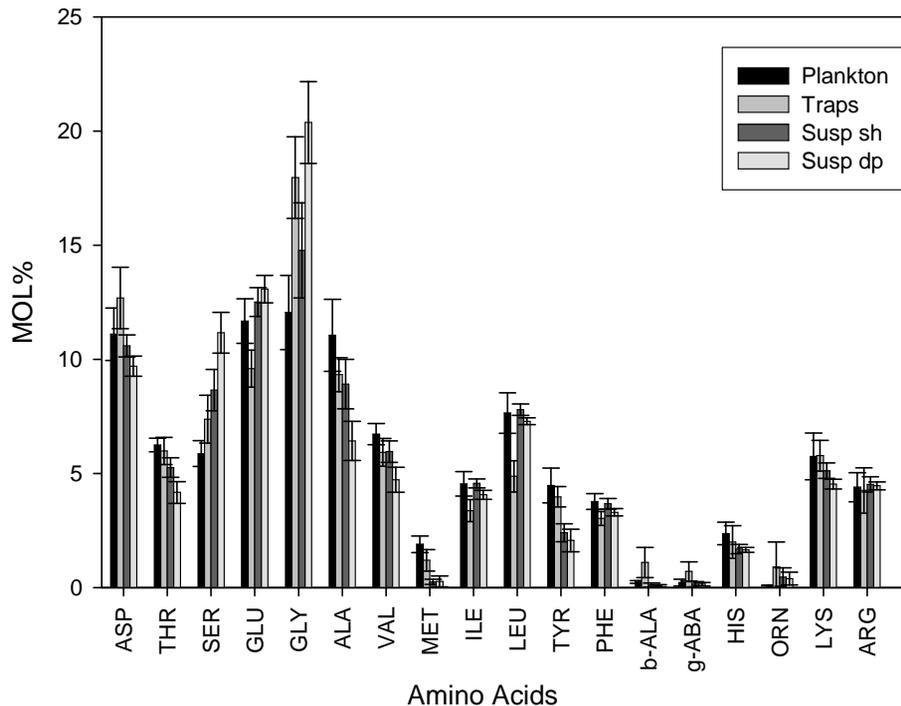


Fig. 4. Amino acid distribution in mol% averaged for plankton suspended matter from the mixed layer (Susp sh), deeper waters (Sups dp) and sediment trap samples (from Haake et al., 1992, 1996).

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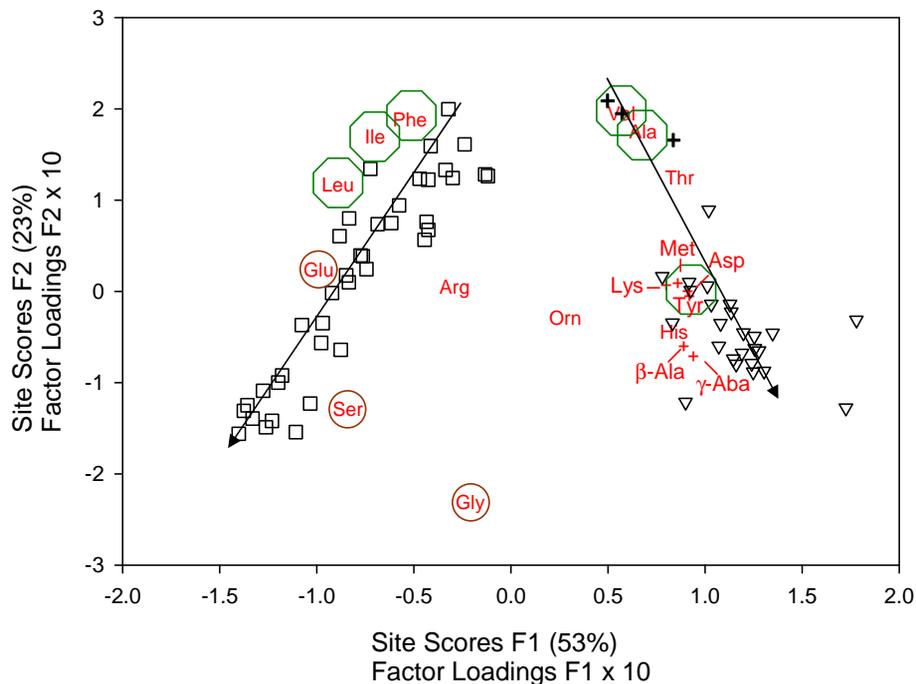


Fig. 5. Results of the PCA carried out on amino acid spectra (mol%) of SPM, plankton and trap samples from the Arabian Sea. Symbols indicate the Site scores of individual plankton (crosses), SPM (boxes), and trap samples (triangles). Factor loadings of individual amino acids multiplied by 10 are indicated by red abbreviations. Amino acids typical of fresh plankton are marked with an hexagon, amino acids enriched with depth on SPM are encircled and arrows indicate increasing sampling depths.

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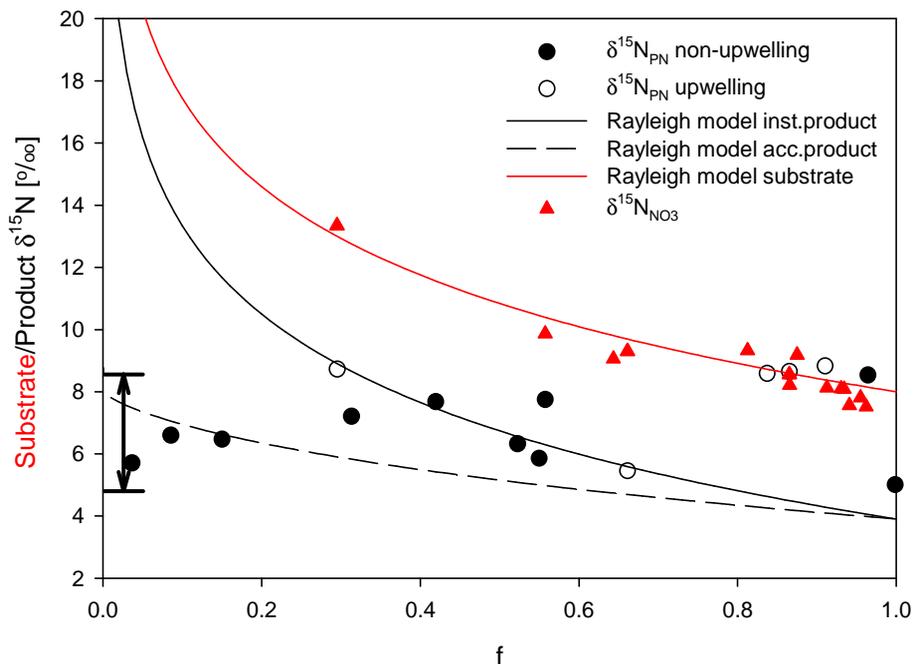


Fig. 6. Lines indicate results of the Rayleigh closed system model using the isotopic effect ε calculated for the samples of this study and the $\delta^{15}\text{N}$ of the instantaneous product found in Arabian Sea subsurface waters (see text for explanations). Symbols are measurements from the Arabian Sea surface mixed layer. Values are given in Table 1. The arrow indicates the range of $\delta^{15}\text{N}$ of sediment trap samples.