CHAPTER-5

Productivity and nitrogen biogeochemistry in the Northern Arabian Sea during the last 34.6 ka

Nitrate is a vital nutrient for the biological productivity in the ocean. Though dissolved nitrogen is omnipresent in oceanic water, its bioavailable form (mainly nitrate) is rare in the surface layer that exert control on marine biogeochemistry (Galloway et al., 2004). Nitrogen fixation by micro-organisms is the major source of nitrate in the surface ocean with minor inputs from river and atmospheric systems (Altabet, 2007). However the removal of oceanic nitrate is significantly influenced by denitrification and autotrophic assimilation (Altabet, 2006; Sigman et al., 2009; Galbraith et al., 2013). Denitrification occurs in the water column as well as at sediment water interface in continental margins and significantly affects the earth's climate by altering the radiative properties of the atmosphere, through the production of N_2O (Ravishankara et al., 2009) from nitrate. Hence understanding oceanic nitrogen cycle is very important in the context of biological sequestration of CO_2 as well as production of N_2O; both have been recognized as important drivers of climate variability. Every process in the nitrogen cycle produces distinct isotopic composition of the product and the substrate (Sigman et al., 2009). Isotopic composition of organic nitrogen present in the marine sediments has been widely used in the recent decades to understand the influence of individual processes on the nitrogen cycle during the past (Altabet et al., 1995; Gruber and Sarmiento, 1997; Altabet et al., 1999; Sigman et al., 2000; Bange et al., 2005; Brunner et al., 2013).

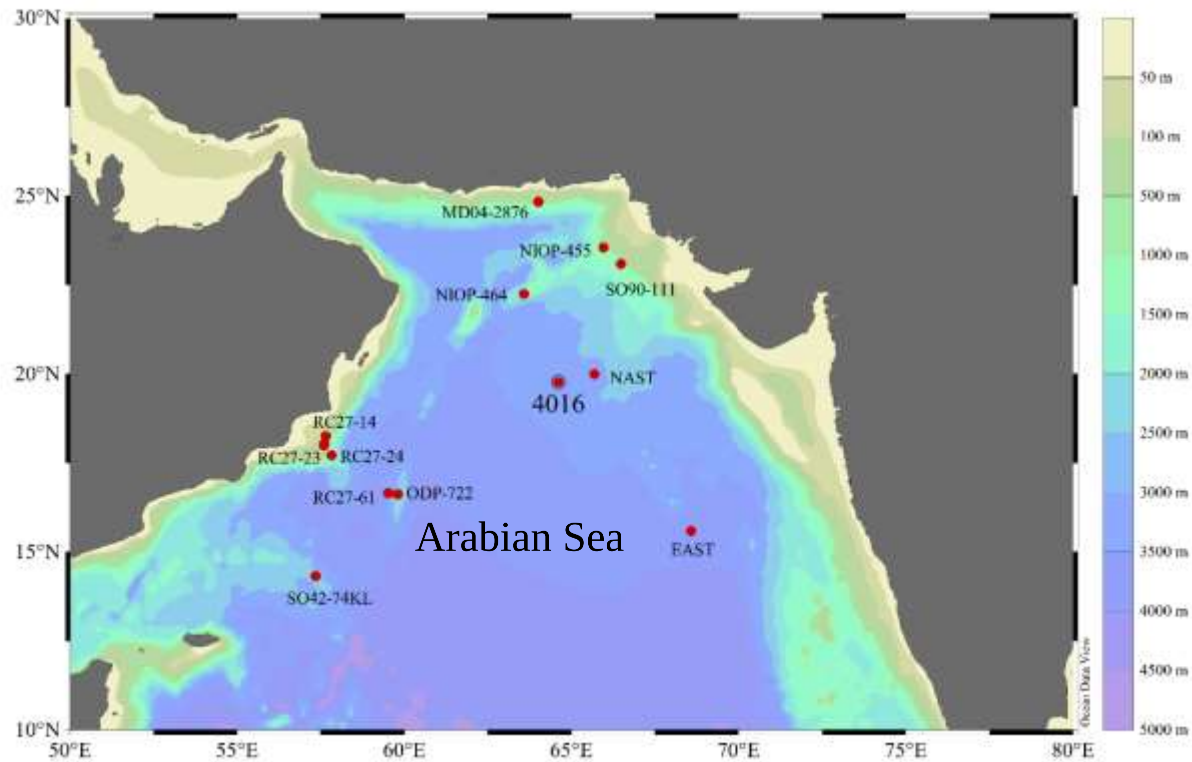

Figure 5.1: Location of sediment core 4016 along with other records discussed in this chapter: MD04-2876 (Pichevin et al., 2007), NIOP-455, NIOP-464 (Reichart et al., 1998), NAST, SO42-74KL, SO90-111 (Suthhof et al., 2001), EAST (Mobius et al., 2011), RC27-24, RC27-61 (Altabet et al., 1995), ODP-722 (Altabet et al., 1999), RC27-14, RC27-23 (Altabet et al., 2002).

The Arabian Sea is one among the three regions in the modern ocean with intense pelagic denitrification and well-developed Oxygen Minimum Zone (OMZ; Naqvi, 1987; Deutsch et al., 2007). High surface productivity during monsoon seasons and supply of low oxygenated water to intermediate depths were envisaged as reasons for the perennial OMZ in the Arabian Sea (Naqvi, 1987). A number of studies have been carried out from the coastal regions of northern part for understanding the palaeoclimate, productivity and denitrification processes (Altabet et al., 1995;

Reichart et al., 1998; Suthhof et al., 2001; Altabet et al., 2002; Pichevin et al., 2007; Mobius et al., 2011; Kao et al., 2015). However the present core has been collected from the open Arabian Sea at 3242m water depth (Figure 5.1). The purpose of the study is to understand the glacial-interglacial variations in the productivity and nitrogen cycling in Arabian Sea based on the nitrogen isotope variations and also address the issue of change in denitrification pattern in coastal to open ocean temporal records.

5.1 Results

The biogenic proxies such as organic carbon and nitrogen were measured at selected depth intervals (Table 5.1). The proxy concentrations were converted to flux using the mass accumulation rate. Organic carbon concentration and flux records follow similar trend depicting high values at 21 ka B.P. and low values at pre and post 21 ka with minor increase during the last 5 ka (Figure 5.3a). Nitrogen concentration and flux variations were synchronous with organic carbon record. Though the nitrogen concentrations were high, the flux was low during the last 5 ka (Figure 5.3b). A negative shift in C/N ratio (Figure 5.3c) has been noticed around 16 ka B.P. All biogenic proxies depict a prominent shift at around 16 ka B.P. indicating a major change in biogeochemistry of the Arabian Sea during that period.

Stable isotope composition of nitrogen is used to know the biogeochemical processes in marine environments (Lehmann et al., 2002). Stable isotopes of nitrogen were analysed at chosen depth intervals and the data is tabulated in table 5.1. The δ^{15}N values were plotted against Nitrogen concentration (Figure 5.2) to check the influence of diagenesis on the δ^{15}Nvalue. The lack of correlation between concentration and isotopic composition indicates that the diagenesis had no influence on down core δ^{15}N variation. However the nitrogen isotopic values (δ^{15}N) were corrected for bottom depth effect (related to oxygen exposure time) using constant correction factor of 0.6‰/km (1.945‰ for 4016 water depth of 3242m).This correction factor is less than proposed for world oceans that is 0.75‰/km (Robinson et al., 2012; Galbraith et al., 2013). Kao et al. (2015) noted that the depth effect in Arabian sea is less than the world ocean and proposed three different correction factors of 0.55, 0.70 and 0.64 ‰/km for Modern, Holocene and Glacial time periods respectively.

Depth (cm)	Age cal. a B.P.	Carbon (%)	Nitrogen (%)	C/N	Carbon flux ($g/cm^2/ka$)	Nitrogen flux ($g/cm^2/ka$)	Age cal. a B.P.	Depth corrected $\delta^{15}N$ (‰)
0.75	1366	0.46	0.07	6.3	0.51	0.08	1366	9.2
5.25	3563	0.52	0.08	6.5	0.61	0.09	3563	9.5
6.75	4296	0.51	0.07	6.9	0.61	0.09	4296	8.9
8.25	5028	0.30	0.05	6.2	0.38	0.06	6493	8.7
11.25	6493	0.34	0.05	7.5	0.45	0.06	7348	8.3
13.00	7348	0.30	0.05	6.5	0.41	0.06	8324	8.3
15.00	8324	0.27	0.05	5.8	0.38	0.06	10277	8.9
17.00	9301	0.23	0.03	7.6	0.30	0.04	11779	7.6
19.00	10277	0.23	0.03	7.0	0.29	0.04	12305	8.3
29.00	13356	0.26	0.04	6.2	0.59	0.10	13356	7.4
31.00	13881	0.27	0.04	6.3	0.61	0.10	13881	8.6
35.00	14932	0.25	0.04	6.1	0.52	0.08	14932	7.1
37.00	15458	0.28	0.04	7.2	0.54	0.08	15458	6.7
41.00	16509	0.29	0.04	6.9	0.57	0.08	16509	5.3
43.00	17034	0.30	0.04	7.3	0.59	0.08	17034	5.5
47.00	17662	0.37	0.04	8.7	1.27	0.15	17662	6.6
51.00	18290	0.44	0.05	8.1	1.47	0.18	18290	5.2
53.00	18604	0.51	0.06	9.2	1.67	0.18	18604	6.0
55.00	18918	0.53	0.07	8.0	1.92	0.24	18918	5.9
59.00	19546	0.64	0.07	9.7	2.30	0.24	19546	6.8
63.00	20173	0.68	0.07	10.0	2.48	0.25	20173	6.7
65.00	20444	0.71	0.08	9.4	2.98	0.32	20444	6.8
67.00	20715	0.69	0.07	9.3	2.86	0.31	20715	7.0
73.00	21527	0.59	0.06	9.3	2.45	0.26	21527	6.8
77.00	22068	0.55	0.06	8.7	2.25	0.26	22068	6.3
79.00	22339	0.58	0.07	8.8	2.39	0.27	22339	6.5
83.00	22881	0.63	0.06	9.9	2.45	0.25	22881	7.3
85.00	23199	0.51	0.06	8.7	1.75	0.20	23199	8.0
87.00	23518	0.45	0.05	9.0	1.56	0.17	23518	7.1
89.00	23836	0.40	0.04	9.1	1.34	0.15	23836	7.8
93.00	24474	0.42	0.05	8.7	1.44	0.17	24474	6.1
95.00	24792	0.42	0.05	8.2	1.39	0.17	24792	6.5
99.00	25430	0.45	0.05	9.5	1.46	0.15	25430	7.0
103.00	26067	0.49	0.05	9.3	1.58	0.17	26067	5.6
107.00	26758	0.63	0.07	9.3	1.90	0.20	26758	7.0

Depth (cm)	Age cal. a B.P.	Carbon (%)	Nitrogen (%)	C/N	Carbon flux ($g/cm^2/ka$)	Nitrogen flux ($g/cm^2/ka$)	Age cal. a B.P.	Depth corrected $\delta^{15}N$ (‰)
109.00	27103	0.55	0.06	8.5	1.70	0.20	27103	7.4
111.00	27448	0.53	0.06	8.8	1.65	0.19	27448	6.6
115.00	28139	0.42	0.05	8.8	1.28	0.14	28139	5.3
119.00	28830	0.39	0.04	9.2	1.16	0.13	28830	4.6
123.00	29521	0.46	0.05	10.2	1.34	0.13	29521	5.1
125.00	30026	0.46	0.06	8.2	0.93	0.11	30026	6.5
127.00	30530	0.41	0.05	9.2	0.84	0.09	30530	4.9
131.00	31540	0.43	0.05	8.0	0.90	0.11	31540	7.8
135.00	32549	0.40	0.05	8.3	0.83	0.10	32549	6.7
137.00	33054	0.42	0.05	7.6	0.84	0.11	33054	7.1
143.50	34568	0.37	0.04	8.4	0.79	0.09	34568	6.9

Table 5.1: Organic productivity proxy's concentration and nitrogen isotopic concentration of 4016 sediment core.

However, a constant value for correction factor was applied for the present study with an assumption that the use of different correction factors for different time gaps may introduce false variation in proxy data. The depth corrected $\delta^{15}N$ values varied between 4.58 to 9.49‰ during the last 34.6 ka B.P. Two sets of $\delta^{15}N$ values were observed in 4016 core record with an abrupt change at around 16 ka B.P. (Figure 5.4). The first set has an average value of 6.4‰ and persisted between 34.6 to 16 ka B.P. while the second set with the average value of 8.3‰ was observed during the last 16 ka B.P.

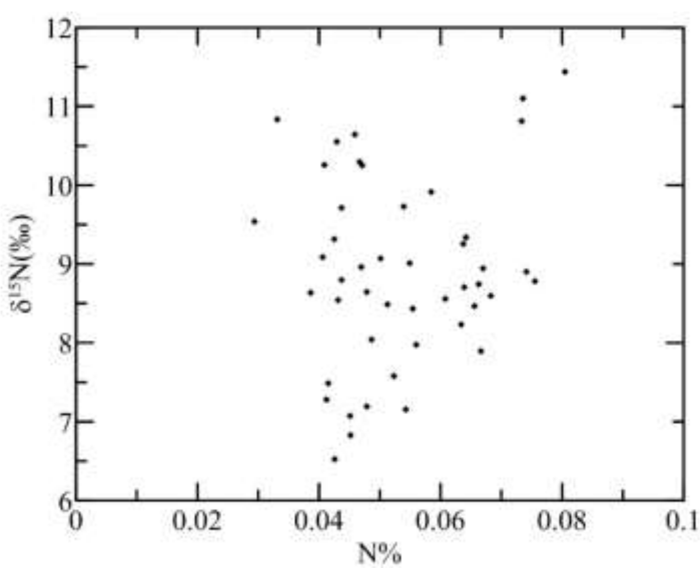

Figure 5.2. Concentration versus isotopic composition of organic nitrogen in 4016 sediment core.

5.2 Discussion

5.2.1 Temporal fluctuations in surface productivity

Organic productivity proxies (OC and N) demonstrate noticeable variations during the last 34.6 ka B.P. (Figure 5.3). Organic matter flux is influenced either by changes in surface productivity or preservation. However Reichart et al. (1998) have shown that the organic carbon flux in the northern Arabian Sea is primarily controlled by surface productivity. The location of the present sediment core 4016 is in the Indus submarine fan, which could raise question about the source of organic matter preserved in the sediments. The C/N ratio of the 4016 sediment core samples point to marine organic matter and this denies the possibility of source induced (Indus River derived) changes in flux and isotopic composition of organic matter observed in the present record. However a prominent negative shift in the C/N ratio from 9 to 6 has been noticed at around 16 ka B.P. This shift in C/N ratio might have been caused by the changes in the nutrient availability (more nitrate) and increased intake of nitrogen by marine phytoplankton. High C/N values were observed in the modern marine organic matter from the oceanic regions with nitrate limiting conditions i.e. high inorganic carbon and low nitrate pools (Mari et al., 2001).

The observed variations in the organic carbon (Figure 5.3a) and nitrogen (Figure 5.3b) in 4016 sediment record show four different sets of value at separate time periods marking variation in surface productivity. The surface productivity did not vary significantly during 34.6 to 31 ka B.P. indicating stable conditions in nutrient supply and hydrography in the northern Arabian Sea. The surface productivity was higher during 31 to 27 ka B.P. signifying increased nutrient supply to the euphotic zone. The cause for the observed increase in productivity could have been either by vertical advection of nutrient or nitrogen fixation as discussed in the next section. The surface productivity slowly declined from 27 to 23 ka B.P.

Surface productivity was at its maximum in the study area during LGM period as indicated by the high concentration of organic carbon and nitrogen (Figure 5.3). In the modern scenario, the annual productivity maximum in the study area is observed during the southwest monsoon period and the second highest productivity is noticed during the northeast monsoon.

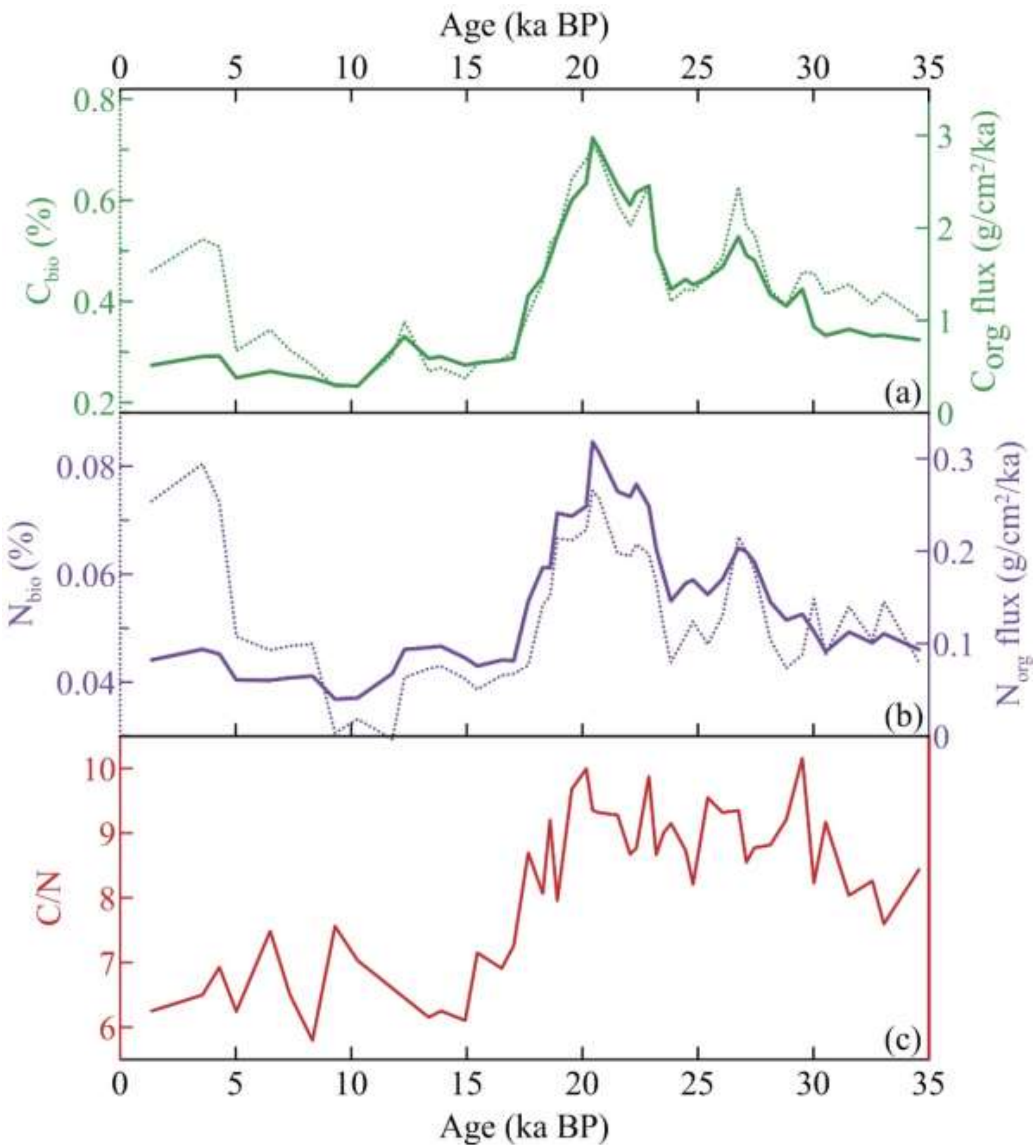

Figure 5.3. Temporal plot of concentration and flux of productivity proxies in 4016 sediment core. Solid lines in plot (a) and (b) are the flux values and the dotted lines are concentrations.

However previous studies show that the southwest monsoon was very weak or absent during the LGM period due to the southward shift of ITCZ (Sirocko et al., 2000; Ivanochko et al., 2005; Balaji et al., 2018). There could be two reasons for the observed high productivity during LGM, 1) nutrient flux to the euphotic zone through convective mixing, 2) increase in atmospheric deposition of bioavailable nutrients. Dahl and Oppo (2006) noticed that the SST in the Arabian

Sea was 2-4° C lower during LGM period. Surface cooling during LGM might have caused nutrient enrichment in the euphotic zone through convective mixing and thickened mixed layer. The atmospheric deposition of nutrients also has influenced the productivity due to the fact that the LGM period was arid and dusty. Sirocko et al. (2000) have indicated that high dust flux originated from Arabia and Persian Gulf regions to the Arabian Sea during LGM. Hence the high productivity during LGM was caused by both the factors, the nutrient enrichment by convective mixing and high aeolian flux. Importance of the high productivity noticed in the Arabian Sea during LGM period for the drawdown of atmospheric CO_2 needs attention. The LGM was followed by long phase (18-10 ka B.P.) of comparatively low surface productivity indicated by low concentrations of organic carbon and nitrogen. However the period between 15 to 13 ka B.P. was marked by a slightly increased productivity based on total nitrogen concentration and flux. The 2 ka period is synchronous with the Bolling-Allerod (B/A) event. Moderately high productivity during 15-13 ka has also been reported in other parts of the Arabian Sea (Balaji et al., 2018 and reference therein). The deglacial intensification of southwest monsoon at ~15 ka B.P. seems to be the reason for the observed productivity during B/A. From 13 to 10 ka B.P. the productivity in the northern Arabian Sea was decreased to the minimal levels in the last 34.6 ka B.P. mainly caused by reduced supply of nutrients to the euphotic zone. The timing of this low productivity period chronologically matches with the Younger Dryas. Since 10 ka B.P. the surface productivity in the Northern Arabian Sea was increased. However the increase in productivity during Holocene (last 10 ka) shows a step like pattern with lower productivity between 10-5 ka B.P. and higher productivity in the last 5 ka B.P. Intensified southwest monsoon during Holocene (Tiwari et al., 2010) and entrainment of nutrients through advection from Omani coast may be the most probable reasons for the high productivity during the Holocene (since 10 ka B.P.).

5.2.2 $\delta^{15}N$ variations during the last 34.6 ka B.P.

There are several processes, external as well as internal, that can influence the $\delta^{15}N$ of oceanic nitrate and subsequently the $\delta^{15}N$ of the organic matter that is produced at the surface. Riverine and aeolian nitrate fluxes are the external contributors to the marine nitrogen cycle. Riverine contribution to the new production in the study area is negligible owing to the fact that ~83% of riverine dissolved inorganic nitrogen flux is removed in the estuaries and the rest being used in the coastal Arabian Sea (Singh and Ramesh, 2011). The aeolian nitrate flux is another contributor to the oceanic new production and subsequently to the $\delta^{15}N$ of organic matter. However the recent study by Singh et al., 2012 noted that the Aeolian flux of nitrate is a minor contributor to the new production in the Arabian Sea. Only the eastern Arabian Sea gets a maximum contribution of Aeolian nitrate flux to surface production (up to 3% production). The above arguments clearly indicate that the $\delta^{15}N$ of organic matter in the study area is not affected by the external contribution and is mainly controlled by the internal processes like productivity, Nitrogen fixation, internal mixing and denitrificaton.

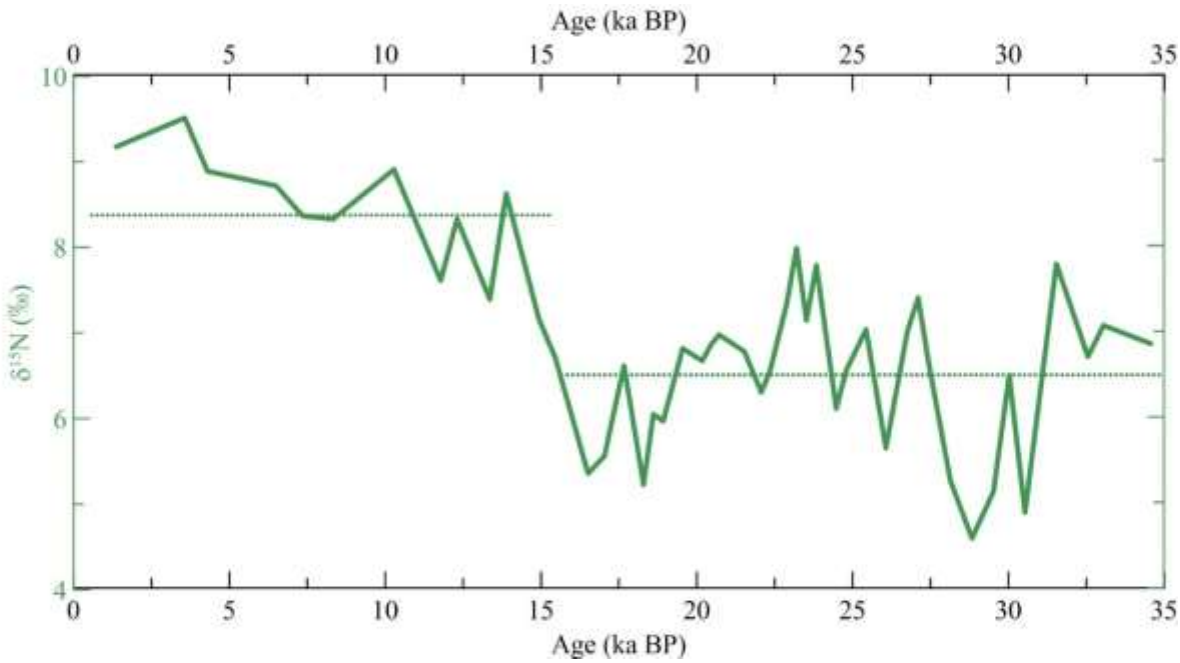

Figure 5.4. Temporal variation in Nitrogen isotopic composition of organic matter in 4016 sediment core. Horizontal dotted lines marks the different set of values with the average of 6.4 and 8.3 ‰ during the intervals of 34.6-15 and 15-1.3 ka B.P. respectively.

Pelagic denitrification in Arabian Sea occurs at mid-depth (200-1000m) where perennial Oxygen Minimum Zone is present (Naqvi, 1994). In the present scenario, the $\delta^{15}N$ value of nitrate in the Arabian Sea varies with depth, it increases from 6‰ in the mixed layer to >10‰ in the OMZ (Naqvi et al., 1998) due to the presence perennial denitrification. Previous studies noted that the $\delta^{15}N$ of organic matter in the Arabian Sea is mainly influenced by the variations in the intensity of denitrification (Altabet, 2006). Several sedimentary nitrogen isotopic studies have been carried out in the last few decades at different parts of the Arabian Sea to understand the past variations in nitrogen cycle (Altabet et al., 1995; Altabet et al., 2007; Kao et al., 2015 and references therein).

The nitrogen isotopic composition in the 4016 core shows two distinct sets of nitrogen isotopic composition before and after 16 ka B.P. (Figure 5.4). The first set has an average value of 6.4‰ and persisted between 34.6 to 16 ka B.P. while the second set with the average value of 8.3‰ was observed during the last 16 ka B.P. Both the sets have variation in the scale of 3 to 5 ka indicating the changes were closely related with the oceanic residence time of combined Nitrogen, 3 ka (Altabet, 2007). The observed values of $\delta^{15}N$ were stable around 7‰ during the period between 34.6 to 31 ka B.P. (Figure 5.4) probably indicates the productivity at this period was fuelled by invariable source of nitrate with more or less constant $\delta^{15}N$ value. The invariant surface productivity during 34.6 to 31 ka B.P. (Figure 3) also supports the above inference. Comparing the observed low in $\delta^{15}N$ value during 34.6-31 ka B.P. with core-top values indicates reduced pelagic denitrification due to weak/absence of OMZ in northern Arabian Sea. The time period between 31-27 ka B.P. marks the lowest $\delta^{15}N$ values (<5‰) in the 4016 sediment core record with a single high at 30 ka B.P. (6.4‰). If we consider the fractionation factor associated with phytoplankton uptake of surface nitrate was ~2.5‰ (7 out of 12 species in Needoba et al., 2003) or 1‰ (Galbraith et al., 2013) and add it to the observed value of ~4.5‰ then the $\delta^{15}N$ of oceanic nitrate that was consumed during 31 to 27 ka B.P. would turn out to be around 5.5-7‰. The average $\delta^{15}N$ value of modern oceanic nitrate is approximately 5‰ (Galbraith et al., 2013); value above this means intense pelagic denitrification and below 5‰ means intense nitrogen fixation. This clearly indicates reduced pelagic denitrification due to weakened OMZ in the northern Arabian Sea during 31 to 27 ka B.P. The occurrence of well stratified ocean also seems to have equal importance in the observed $\delta^{15}N$ at this time period. Stratified ocean inhibits the vertical advection of nutrients, rich in ^{15}N due to denitrification, and can produce organic matter with low $\delta^{15}N$ values.

Similar $\delta^{15}N$ values observed in the Bay of Bengal (stratified oceanic basin) at multiple climatic phases (Pattan et al., 2013) supports the possibility of water column stratification. However the observed productivity increase during this period (Figure 5.3) might have been supported by the nitrogen fixation rather than vertical advection of nutrient. Therefore it has been suggested that the low $\delta^{15}N$ values observed during 31 to 27 ka B.P. were a result of water column stratification and/or reduced denitrification in the northern Arabian Sea.

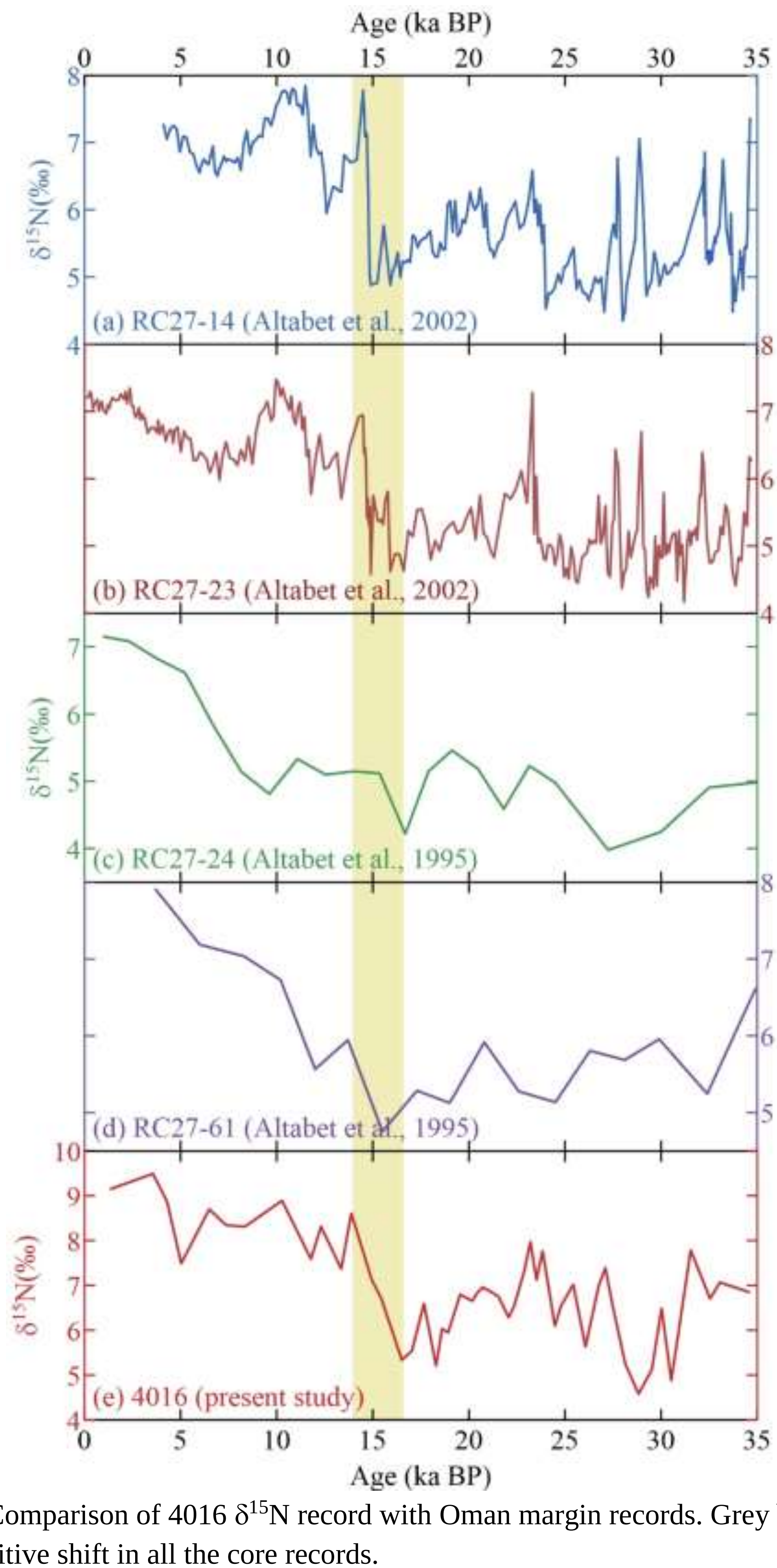

Figure 5.5: Comparison of 4016 $\delta^{15}N$ record with Oman margin records. Grey bar indicates the timing of positive shift in all the core records.

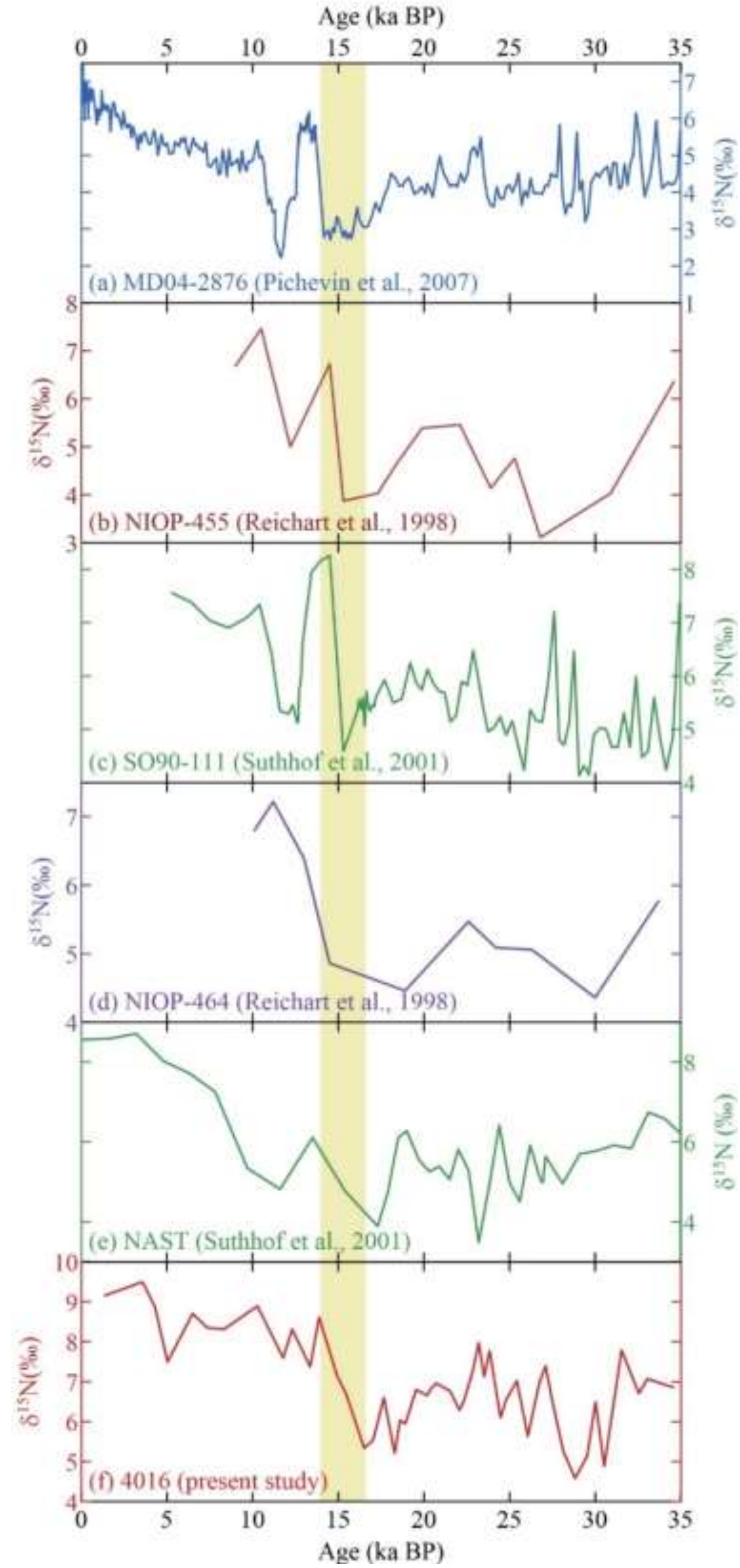

Figure 5.6: Comparison of 4016 $\delta^{15}N$ record with Northeast Arabian Sea records.

Near constant $\delta^{15}N$ values (~6.5±0.5‰) were observed for a prolonged period between 27 to 19 ka B.P. with an intermittent positive high around 23 ka B.P. However the nitrogen isotopic composition of organic matter during 27-19 ka B.P. is comparable to the values during 34.6-31 ka B.P. and indicates similar condition. The increase in vertical mixing of water column after 27 ka B.P. and increase of denitrification in the northern Arabian Sea seems to be the reasons for the observed $\delta^{15}N$ value during 27-19 ka B.P. The cause for the increase in vertical mixing may have been either convective mixing or related with upwelling, and needs to be further studied. However a comparison of present dataset with other climatic records may provide some insight. Along with sedimentary $\delta^{15}N$, the productivity proxies also show an increase at 23 ka B.P. (Figure 3), but the high productivity continued up to 19 ka B.P. The co-occurrence of positive shift in $\delta^{15}N$ and productivity clearly indicates increased supply of nitrate with high δ^{15} value. This could have been caused by the abrupt increase in vertical transport of nutrient from denitrifying layer at 23 ka B.P. and continued till 19 ka B.P. This further suggests that the vertical transport of nutrients was initiated at 27 ka B.P., and intensified at 23 ka B.P. This prolonged mixing might have increased sub-surface ventilation and reduced the intensity of denitrification. Though the nutrient supply continued till 19 ka B.P., the reduction in denitrification lowered $\delta^{15}N$ of nitrate and subsequently the $\delta^{15}N$ of produced organic matter.

The $\delta^{15}N$ values further decreased to below 6‰ after 19 ka B.P. and remained low upto16 ka B.P. (Figure 5), demonstrating that the vertical advection of nitrate with enriched ^{15}N from sub-surface (denitrifying layer) ceased. The decrease in surface productivity at 19 ka B.P. also indicates reduction in nutrient supply to euphotic layer. Therefore it has been inferred that the northern Arabian Sea was stratified and the productivity was primarily supported by nitrogen fixation during the period between 19-16 ka B.P. After 16 ka B.P. the $\delta^{15}N$ of organic matter in 4016 core record abruptly increased more than 2‰ within 2 ka period and reached to ~8.5‰ at around 14 ka B.P. Similar changes in $\delta^{15}N$ of marine organic matter were observed in all oceanic basins around 15 ka B.P. and it has been attributed to increase in pelagic denitrification (Galbraith et al., 2013). Other records from the Arabian Sea also show an abrupt change in $\delta^{15}N$ at around 16 ka B.P. (Figures 5.5 and 5.6). However the abrupt change in $\delta^{15}N$ in the northern Arabian Sea could have been caused by 1) increase in pelagic denitrification, 2) increased supply of sub-surface nitrate with high $\delta^{15}N$ due to upwelling, and 3) lateral advection of upwelling nutrients. Former was the primary driver for the abrupt change which has been observed throughout the basin. The last two cases arise due to the observed post-glacial onset of southwest monsoon in the Arabian Sea from several records (Sirocko et al., 2000; Boll et al., 2015). Prior to 16 ka B.P. the northern Arabian Sea region experienced stratified condition for around 3 ka preceded by prolonged high productive period. High productivity followed by stratified conditions might have accumulated subsurface nitrate with enriched ^{15}N. Onset of southwest monsoon at ~16 ka B.P. brought up the sub-surface nutrient through coastal upwelling and subsequent transport by lateral advection to study area. Pelagic denitrification, upwelling and lateral advection are actually interconnected processes, denitrification and lateral advection has control on $\delta^{15}N$ value and the upwelling process connects them. Following the shift a minor decrease in $\delta^{15}N$ value has been observed during Younger Dryas. Weakened southwest monsoon during Younger Dryas was observed in the Indian monsoon region from various palaeoclimatic records (Altabet et al., 2002; Ivanochko et al., 2005). Lowest productivity also observed at 11 ka B.P. indicates a reduced supply of nitrate, however, it was rich in ^{15}N. Reduction in upwelling and lateral advection due to weaker southwest monsoon caused the observed $\delta^{15}N$ value at this interval. Since 11 ka B.P. the $\delta^{15}N$ shows an increasing trend with two millennial scale positive events at 10 and 3.5 ka B.P. (Figure 5). Productivity is also observed to have increased during the last 10 ka (Figure 5) and attributed to enhanced nutrient supply from upwelling region. Intensification of pelagic denitrification in the Northern Arabian Sea caused by increase in surface productivity, subsequent export flux and over-consumption of oxygen due to organic matter remineralization at mid-depth and upwelling of this mid-depth waters were the reasons for the observed increase in the $\delta^{15}N$ during the last 11 ka B.P.

5.2.3 Variation in sedimentary $\delta^{15}N$ records of coastal to open ocean

In the modern scenario the surface productivity in the Northern Arabian Sea during southwest monsoon is fuelled by the nutrient supply from Oman coastal upwelling region through lateral advection (Kumar et al., 2001). The advection of upwelled water influences the upper – ocean heat budget in Arabian Sea and is also important in the meridional transport of heat (Fischer et al., 2002). Comparison of present $\delta^{15}N$ record with Oman margin record can throw some light on past changes in the lateral advection of nutrients to the northern Arabian Sea. If the variation in $\delta^{15}N$ was caused by pelagic denitrification alone then the depth corrected $\delta^{15}N$ of coastal and open ocean records should be similar within the error limits. The comparison plot of present record with two records from the Oman coastal area (Figure 5.7; sediment cores RC27-14 and RC27-23 from

Altabet et al., 2002) is presented in the Figure 5.8. The $\delta^{15}N$ data for the coastal sediment cores (Altabet et al, 2002) were downloaded from the NICOPP database. The$\delta^{15}N$ fluctuations in coastal and open ocean records are synchronous and indicate the basin wide presence of causative process. The short term variations were not comparable as the data points were not similar in the $\delta^{15}N$ records. Overall, the open ocean $\delta^{15}N$ values were little higher than the coastal records. Both the records show similar $\delta^{15}N$ values (difference is $\leq$ 1‰) between 34.6 to 15 ka B.P. with minor variations at 31, 29, 27-23 and 21 ka B.P. The difference in $\delta^{15}N$ records during 31, 29, 27 to 23 and 21 ka B.P. may be caused by short spells of advection of coastal waters with partially utilized nutrients. However it requires further studies to understand the causative process. Since 15 ka B.P., the $\delta^{15}N$ values of the open ocean record are clearly distinguishable from coastal records which have been >1‰ higher.

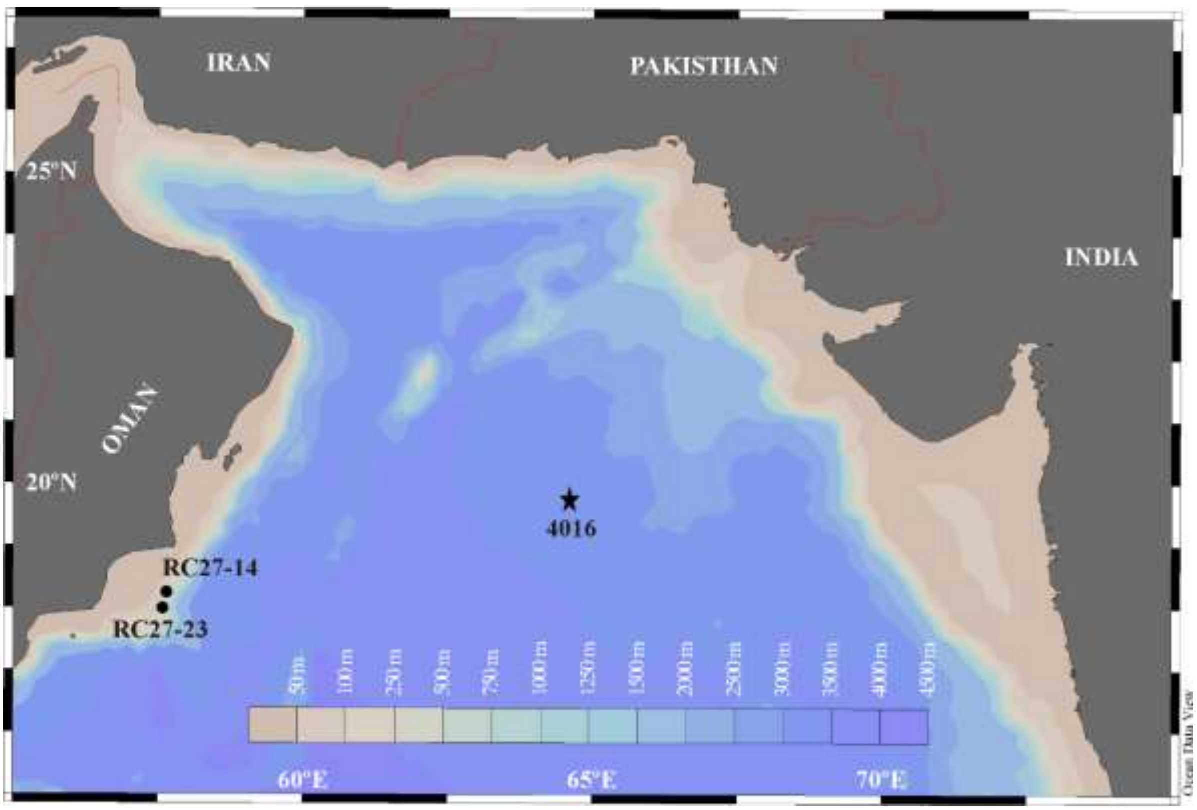

Figure 5.7. Location of 4016 sediment core in Arabian Sea (star). Also shown are the coastal sites. Map has been plotted using licensed copy of Ocean Data View (https://odv.awi.de/).

The primary cause for the increase in organic $\delta^{15}N$ was the de-glacial intensification of pelagic denitrification (Galbraith et al., 2013) and southwest monsoon, subsequent supply of nutrient from subsurface i.e. OMZ. However the $\delta^{15}N$ difference between coastal and open ocean indicates the presence of secondary process. The lateral advection of upwelled waters seems to be the secondary process which increases the open ocean $\delta^{15}N$ value. Upwelling in the Oman coastal region is too intense and causes partial nutrient utilization prior to upwelled waters (nutrients) being laterally advected away (Hitchcock et al., 2000) resulting into an increase in the $\delta^{15}N$ value of remaining nitrate.

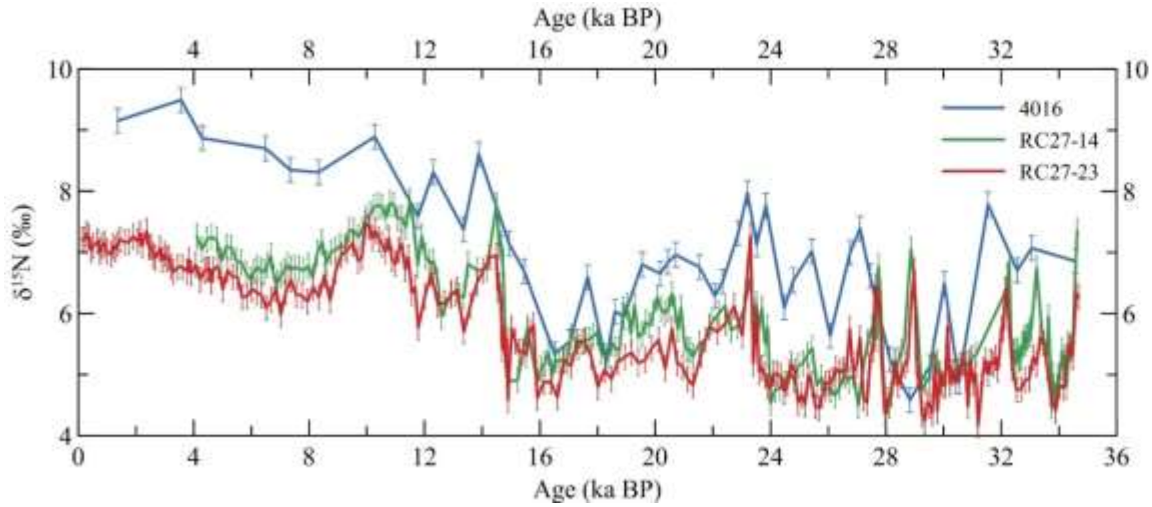

Figure 5.8. Comparison of coastal and open ocean $\delta^{15}N$ (‰) records. Red and green plots are coastal records from Altabet et al., 2002. Blue plot is open ocean record (present core; 4016).

However this gradient in $\delta^{15}N$ can vary with the intensity of lateral advection; high advection causes low gradient and vice versa because low advection allows more nutrient consumption during its path from the upwelling zone to the core location and leaves nitrate being highly enriched in ^{15}N. The increase in the intensity of lateral advection was the cause for similar $\delta^{15}N$ values in coastal and open ocean records at 15-14 and 11-10 ka B.P. The gradient in $\delta^{15}N$ steadily increased during the Holocene from 1‰ at 10 ka B.P. to 2‰ in late Holocene. A decline in the intensity of lateral advection during the southwest monsoon season caused the observed increase in $\delta^{15}N$ gradient. However the remaining nutrients were substantial to help the productivity. Based on evidence for the presence of lateral advection of upwelled water, it can be further surmised that the southward meridional transport of heat in the northern Arabian Sea has continued since 15 ka B.P.