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The marine sedimentary nitrogen isotope record

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Abstract

A global database of nitrogen isotope data from marine sediments is presented, including both seafloor and sub-seafloor sediment samples. The data synthesis reveals regionally and globally consistent patterns and trends, with good agreement between neighbouring seafloor sites. The spatial coverage of seafloor δ^{15}N data is heterogenous, with excellent coverage in the eastern tropical Pacific, South China Sea and Arabian Sea, while large regions of the globe remain unsampled. The sub-seafloor δ^{15}N records are mostly from the late Pleistocene, with >90 coeval records during the last ~10 kiloyears (kyr), before which the number of records at any time decreases, with <10 coeval records at any time prior to 300 kyr. There is a good correlation between seafloor and shallow-subseafloor δ^{15}N measurements within a 100 km radius, which suggest a reliable translation of sediments into the buried sediment record. We suggest that regional discrepancies between seafloor and late Holocene subseafloor δ^{15}N indicate nitrogen cycle changes during the late Holocene period, rather than systematic diagenetic changes.

1 Introduction

Nitrogen is a critical nutrient element in marine ecosystems, and its supply is currently being modified anthropogenically in multiple ways (Gruber and Galloway, 2008). Future changes in the nitrogen cycle have the potential to significantly impact the oceanic nutrient regime, with significant implications for the marine ecosystem, but uncertainty remains regarding how sensitive the nitrogen cycle will prove to be.

Measurements of nitrogen isotopes in marine sediments provide a unique way of understanding the past and present marine nitrogen cycle and its relationship to climate change. The nitrogen isotope ratio (^{15}N/^{14}N) in a sample is expressed relative to the nitrogen isotope composition of a standard, conventionally, atmospheric nitrogen gas ($\delta^{15}\mathrm{N} = ([^{15}\mathrm{N}/^{14}\mathrm{N}]_{\mathrm{sample}}/[^{15}\mathrm{N}/^{14}\mathrm{N}]_{\mathrm{air}} - 1) \times 1000$ ‰). Over the past two decades, the

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systematics of δ^{15}N have become increasingly well understood, and they show great potential in helping us to gain better insight into the marine nutrient cycle (Altabet, 2006; Galbraith et al., 2008a).

To date, δ^{15}N measurements have been published as they became available, generally at individual core sites or within defined ocean regions. However, variations in δ^{15}N are the result of many factors, including water column denitrification, nitrate utilization and nitrogen fixation, which can result in complex spatial patterns (Somes et al., 2010). Thus, looking at single records in isolation can be insufficient when attempting to understand past variations, which may include overlapping effects from multiple factors (e.g., Galbraith et al., 2008b; Robinson et al., 2009). The database presented here is intended to aid in deciphering these overlapping factors while answering a call for more thorough data management within the geoscience community at large (Parsons et al., 2010).

Here, we present the first iteration of a global database of published marine bulk sediment δ^{15}N measurements, including both seafloor and sub-seafloor downcore sediments. This compilation aims to include all published δ^{15}N records from marine sediments of any age retrieved from anywhere in a modern ocean basin (i.e., not including marine sediments now found on land). Some unpublished data are also included in the database. The current database includes only bulk sedimentary δ^{15}N, which represents the isotopic composition of all combustible nitrogen in the sediment. Additional types of δ^{15}N measurements, such as species-specific δ^{15}N measurements (diatom, foraminifera, etc.), could be added in future. We anticipate that by assembling all δ^{15}N records previously presented in the literature, the patterns of multiple nitrogen cycling processes will become clearer, local discrepancies will become more obvious, data gaps will be highlighted, and progress will be more efficiently made toward quantifying the fidelity with which sedimentary δ^{15}N tracks sinking and sedimented organic matter.

To evaluate the translation from surface to subseafloor sediments, we also present a comparison of late Holocene (LH) and surface sedimentary δ^{15}N. This provides a first link between the surface sediment data and δ^{15}N records and informs us about spatial variability in δ^{15}N, potential climatic trends in the Holocene and post-depositional alterations (parochially known as diagenesis).

The sedimentary δ^{15}N database is available for use by the scientific community to assist in further research and analysis by download from the PAGES website (http://www.pages-igbp.org/workinggroups/nicopp). The database will be updated as new records become available, and the authors welcome additional contributions.

2 Database description

The sources of data are listed in Table 1. All data represent measurements of dry, homogenized bulk sediment, typically combusted using an Elemental Analyzer, coupled to a GC-IRMS with a Go-Flo apparatus and using He as a carrier gas, with local air as the standard. The combusted material is dominated by marine organic matter at most locations, although there is significant contamination by clay-bound inorganic (Kienast et al., 2005) and terrigenous nitrogen (Schubert and Calvert, 2001) in some locations. Given the known problems with acidification of samples (Brodie et al., 2011) we flagged samples that had been acidified where possible, though acidification is not always reported. Reported errors for the bulk combustion method are generally better than ±0.3 ‰ for replicates.

2.1 Seafloor sediments

Thus far, the collection of seafloor sediment δ^{15}N contains more than 2300 sites, which include only real sediment measurements from any depth and region of the ocean seafloor (Fig. 1). Most of these sites (ca. 90 %) are multicores, giant-box cores, or core-tops of piston and gravity cores. There is some uncertainty about what time range the seafloor sediment samples represent. Very few seafloor δ^{15}N values have been associated with an actual age measure, but we can assume that in low sedimentation regions samples represent a much longer time scale (order 10^3 yr) compared with high-sedimentation sites (order 10^2 yr).

The seafloor δ^{15}N values range from 2.5 to 16.6 ‰ (Fig. 1, inset). The average isotopic composition is 6.7 ‰, higher than the average isotopic composition of nitrate in the ocean (~5 ‰, Sigman et al., 1997; 1999). However, the dataset is positively skewed towards lower δ^{15}N, such that a majority of sites have values between 4 and 6 ‰ (Fig. 1, inset). Given the highly irregular sampling pattern (Fig. 1), a significant spatial bias is likely, and may contribute to the elevated mean value. In addition, alteration of the δ^{15}N during sinking and sedimentation is likely to produce higher values in the sediment (Altabet and Francois, 1994).

The global map of seafloor δ^{15}N (Fig. 1) reveals regionally-consistent patterns, aligned with large-scale oceanic features. In some regions there are strong gradients of surface δ^{15}N, such as in the eastern Arabian Sea, where gradients as large as 4.5 ‰ occur within ~1° of latitude/longitude. This variance could be due to oceanic fronts, sedimentary processes, or even to discrepancies in measurement techniques. In order to more clearly identify regions of pronounced small-scale variability, we analyzed the similarity of neighbouring seafloor samples within 100 km of each other (not shown). The average difference between neighbouring surface samples is less than 1 ‰ in most of the ocean, with significant differences occurring at only a few sites, found in the eastern Arabian Sea, central equatorial Pacific, and the Benguela Current.

2.2 Sub-seafloor

The sub-seafloor database includes δ^{15}N measurements and corresponding sediment depths, as well as (where available) a published age model, nitrogen content (% N), total organic carbon content (% C) and dry bulk density. We identified 173 sub-seafloor records for which bulk sedimentary δ^{15}N data exist (Table 1). We obtained δ^{15}N data for 147 core sites, while we could only obtain a complete set of ancillary measurements (% N, % C, dry bulk density) for 14 of those core sites, while an additional 74 core sites have at least % N or % C. Age models were entered as published in the original references with no alteration (with a few exceptions where the age model was unavailable and needed to be regenerated from the original age control data).

The majority of sub-seafloor records are situated along the coast, where sedimentation rates are high and there has been greater confidence in the fidelity of sediment δ^{15}N (Thunell et al., 2004; Altabet et al., 1999). In addition, records are concentrated at regions of interest, including those associated with coastal upwelling and/or suboxic conditions with water-column denitrification. Thus, the database has a high degree of spatial bias. In particular, as illustrated in Figs. 2 and 3a, a considerable number of records are from the Arabian Sea (17 %), the South China Sea (13 %), the Eastern Equatorial Pacific (19 %), the west coasts of North (12 %) and South America (14 %), and the southwest coast of Africa (11 %). As in the case of surface sediment sampling (Fig. 1) we have vast regions of the ocean, especially in the Southern Hemisphere, where the spatial coverage of δ^{15}N records is very poor. For example, there were no published downcore records found in the Bay of Bengal, the Southwest Pacific or most of the North Atlantic (Fig. 2).

The temporal coverage of the available δ^{15}N records shows, unsurprisingly, a strong bias toward the more recent timescales of the Holocene and late Pleistocene periods. We find the maximum number of records between 5 and 20 kyr before present (BP) (Fig. 3b). As one might expect, most of the records that go beyond the last glacial-interglacial cycle (i.e., the last ∼120 kyr), have the disadvantage of being considerably coarser in resolution. In fact, the average sampling frequency for the most recent times is as high as 5 measurements per kyr, dropping to less than one measurement per kyr by about 65 kyr, and to one measurement every 4 kyr by 100 kyr BP. To compare these unequally spaced time series of δ^{15}N records quantitatively, we created a common age axis by interpolating all δ^{15}N records.

3 Relationships between LH and neighbouring seafloor sedimentary δ^{15}N

It was shown above that the δ^{15}N of neighbouring seafloor sediment samples is consistent within a 100 km radius for most of the oceans. To better understand the translation of nitrogen isotopes in this seafloor material to what we observe in sub-seafloor records, we compared seafloor samples with sub-seafloor sediments of late Holocene age (LH, 0–5 kyr BP). In general, one would expect the average LH δ^{15}N of a sediment record to be about the same as the δ^{15}N of the surrounding surface sediments, assuming that the δ^{15}N of sinking organic nitrogen has been constant over this time period (Thunell et al., 2004).

To test this hypothesis, we examine the correlation between the average LH subseafloor δ^{15}N and the average δ^{15}N of neighbouring seafloor samples within a radius of 100 km. First, we examine LH-surface correlation within the Eastern Equatorial Pacific, since there is relatively good coverage of both seafloor and sub-seafloor data, and large-amplitude δ^{15}N gradients. We average the core-top δ^{15}N that fall within a 100 km radius of a chosen core site (see large circles, Fig. 4) and plot them against the LH average of that site (Fig. 5a). The LH and seafloor averages correlate well ($r = 0.81$) and show the same trend of lower δ^{15}N along the equator and coastline and increased δ^{15}N toward higher latitudes (Fig. 4). Interestingly, the line of best fit is shifted, nearly parallel to the 1:1 line, suggesting a small, uniform δ^{15}N enrichment from LH to seafloor values. We used a non-parametric bootstrap resampling of the data to test the consistency of the regression coefficients; this showed that the y-intercept has much higher uncertainty than the slope.

We then extended this analysis to the global dataset (Fig. 5b). The correlation for the global ocean is even stronger than in the Eastern Equatorial Pacific ($r = 0.92$, $R_{1:1}{}^2 = 0.80$–0.83), with little deviation from the 1:1 line. There are a number of outliers, but these are either from regions with large variability between neighbouring seafloor measurements (large vertical whiskers, Fig. 5b), or with only one neighbour (no vertical whiskers). This correlation is highly encouraging for the use of bulk sedimentary nitrogen isotope measurements as a record of past changes in the sinking flux of organic nitrogen.

Despite the small magnitude of the discrepancies between seafloor and shallow sub-seafloor sediments, it is worthwhile considering their occurrence. Surprisingly, the relationship between surface and LH values, $\delta^{15}N_{seafloor} - \delta^{15}N_{LH}$, shows some spatial coherence, with clear contrasts between oceanic regions (Fig. 6). The $\delta^{15}N_{seafloor} - \delta^{15}N_{LH}$ is consistently negative on the western coast of Africa, consistent with observations made by Freudenthal et al. (2001) who argued that down-core increases of $\delta^{15}N$ in sediments near Mauritania reflected diagenetic enrichment. However, the picture is reversed along the western coasts of South and North America, where no sites show significant negative $\delta^{15}N_{seafloor} - \delta^{15}N_{LH}$. Elsewhere in the Pacific and Indian Oceans, the changes between LH and surface $\delta^{15}N$ are generally minor or mixed.

We can conceive of two possibilities to explain these contrasts. One, that post-depositional alteration of $\delta^{15}N$ varies between basins, due to changes in sediment characteristics, organic matter composition, or seafloor biota. Given that similar seafloor environments show opposite patterns (for example, the Benguela and Peruvian upwellings), while different environments within the same region show similar patterns (for example, Angola and the Mediterranean), this explanation seems unlikely. The second, more likely explanation, is that the $\delta^{15}N$ of sinking organic matter changed significantly over the late Holocene. If this is true, it implies that the fidelity with which seafloor $\delta^{15}N$ is transferred into the sedimentary record is somewhat better than would be indicated by our seafloor-LH comparison (Fig. 5), since our assumption of temporal invariance is incorrect.

The sense of change between the LH and seafloor sediments, with decreasing $\delta^{15}N$ in the Atlantic and increasing $\delta^{15}N$ in the Pacific, would be consistent with an increase of water column denitrification (dominantly in the Indo-Pacific) and/or an increase of N_2 fixation rates (the isotopic imprint of which is stronger in the Atlantic) over this time period. We leave the resolution of this observation to future work.

4 Conclusions

Sedimentary δ^{15}N data from the ocean are now available in a single database in order to quantitatively compare observations with each other and with biogeochemical ocean models. The variability in seafloor δ^{15}N is small over spatial scales of 100 km for most regions. However, a few places do exist where strong oceanographic and/or sedimentary gradients lead to elevated spatial variance in the surface δ^{15}N.

The spatial coverage of seafloor δ^{15}N data is poor in vast regions of the oceans, such as the southern Indian Ocean, the subtropical gyres of the Pacific, and the North Atlantic. The clustered spatial distribution is even more prevalent in the collection of sub-seafloor sediment records, with most sites located on the continental shelves and slopes of the Pacific, Arabian Sea and southeastern Atlantic.

We tested the fidelity of sedimentary δ^{15}N as a tracer of organic matter by comparing the available surface data with the LH average from the upper parts of sub-seafloor records. We found strong correlations between seafloor and sub-seafloor δ^{15}N, which suggest reliable translation of sedimented δ^{15}N into the buried sediment record.

We also discern relatively weak, but regionally coherent patterns of change between LH and seafloor sediments, suggestive of an acceleration of the marine nitrogen cycle over the late Holocene period (i.e. greater rates of water column denitrification and/or N_2 fixation).

Further studies with the synthesized dataset will help to improve our understanding of the marine nitrogen cycle, and thus of ocean biogeochemical dynamics in general. The database will continue to grow as new sedimentary δ^{15}N records become available.

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Table 1. List of δ^{15}N records in the NICOPP database (as of 03/2012).

Core name	Latitude	Longitude	Depth (m)	Core type	Reference
AII 125-8 GGC-55	27.47	−112.11	820	Gravity	Pride et al. (1999)
AII 125-8 JPC-44	27.90	−111.66	655	Piston	Pride et al. (1999)
AII 125-8 JPC-48	27.94	−111.80	530	Piston	Pride et al. (1999)
AII 125-8 JPC-56	27.47	−112.10	818	Piston	Pride et al. (1999)
A1C1					Altabet (2007)
B1 GGC1					Altabet (2007)
BJ8-03-102GGC	1.00	127.72	377	Gravity	Langton et al. (2008)
CD 38-02	−14.93	−77.07	2525	Piston	Ganeshram et al. (2000)
CD 38-17	−1.60	−90.43	2590	Piston	Pichevin (unpublished)
CH07-98 GGC-19	36.87	−74.57	1049	Piston	Altabet (2007)
CR-2	14.90	74.00	45	Gravity	Agnihotri et al. (2008b)
DR-13	53.16	177.32	3930	Piston	Nakatsuka et al. (1995b)
DR-16	54.50	−176.04	3750	Piston	Nakatsuka et al. (1995b)
DSDP 41-367	12.49	−20.05	4748	Drilling	Rau et al. (1987)
DSDP 75-530	−19.19	9.39	4629	Drilling	Rau et al. (1987)
DSDP 93-603	35.49	−70.03	4633	Drilling	Rau et al. (1987)
E11-2	−56.05	−115.07	3094	Piston	Robinson et al. (2005)
FR-03/96 GC-4	−12.29	121.93	2069	Gravity	Müller and Opdyke (2000)
FR-03/96 GC-5	−12.37	122.20	1462	Gravity	Müller and Opdyke (2000)
GeoB 1008	−6.58	10.32	3124	Gravity	Holmes et al. (1997)
GeoB 1016	−11.77	11.68	3411	Gravity	Holmes et al. (1997)
GeoB 3910	−4.25	−36.35	2362	Gravity	Dupont et al. (2008)
GeoB 3911	−4.61	−36.64	828	Gravity	Jennerjahn et al. (2004)
GeoB 3912	−3.67	−37.72	772	Gravity	Jennerjahn et al. (2004)
GeoB 4216	30.63	−12.40	2324	Gravity	Freudenthal et al. (2002)
GeoB 4223	29.02	−12.47	775	Gravity	Freudenthal et al. (2002)
GeoB 4234	28.89	−13.23	1360	Multi	Freudenthal et al. (2001)
GeoB 4240	28.89	−13.23	1358	Gravity	Freudenthal et al. (2002)
GeoB 4501	−22.58	14.17	97	Multi	Struck et al. (2002)
GeoB 4502	−23.14	13.17	370	Multi	Struck et al. (2002)
GeoB 7139	−30.20	−71.98	3269	Gravity	De Pol-Holz et al. (2007)
GeoB 8903	38.63	−9.51	102	Gravity	Alt-Epping et al. (2009)
GGC27	49.60	150.18	995	Gravity	Brunelle et al. (2010)
HLY 0202 JPC17	53.93	178.70	2209	Piston	Brunelle et al. (2007)
JPC-22	28.25	−74.41	4712	Piston	Altabet et al. (2005)
JT96-09	48.90	−126.88	920	Piston	McKay et al. (2004)

Table 1. Continued.

Core name	Latitude	Longitude	Depth (m)	Core type	Reference
KC01B	36.25	17.74	3643	Gravity	Struck et al. (2001)
KH-92-1 3bPC	8.02	139.64	2831	Piston	Nakatsuka et al. (1995a)
KH-92-1 5bPC	3.54	141.86	2279	Piston	Nakatsuka et al. (1995a)
MD 76-131	15.53	72.57	1230	Piston	Ganeshram et al. (2000)
MD 84-527	−43.83	51.32	3269	Piston	Francois et al. (1993)
MD 84-552	−54.92	73.83	1780	Piston	Francois et al. (1997)
MD 84-641	33.03	32.63	1375	Piston	Calvert et al. (1992)
MD 88-773	−52.92	109.87	2460	Piston	Francois et al. (1997)
MD 96-2080	−36.27	19.48	2488	Piston	Rau et al. (2002)
MD 96-2084	−31.74	15.52	1408	Piston	Rau (2002)
MD 96-2086	−25.81	12.13	3606	Piston	Pichevin et al. (2005)
MD 96-2087	−25.60	13.38	1029	Piston	Pichevin et al. (2005)
MD 96-2098	−25.59	12.63	2909	Piston	Pichevin et al. (2005)
MD 97-2101	−43.50	79.84	3145	Piston	Crosta (unpublished)
MD 97-2146	20.12	117.38	1727	Piston	Kienast et al. (2005)
MD 98-2162	−4.68	117.90	1855	Piston	M. Kienast (unpublished)
MD 98-2177	1.40	119.67	968	Piston	M. Kienast (unpublished)
MD 98-2181	6.30	125.82	2114	Piston	Kienast et al. (2008)
MD 01-2386	1.13	129.79	2816	Piston	Jia and Li (2011)
MD 01-2392	9.85	110.21	1966	Piston	Jia and Li (2011)
MD 01-2403	25.07	123.28	1420	Piston	Kao et al. (2008)
MD 01-2404	26.65	125.81	1397	Piston	Kao et al. (2008)
MD 01-2416	51.27	167.73	2317	Piston	Galbraith et al. (2008b)
MD 02-2496	48.97	−127.04	1243	Piston	Chang et al. (2008)
MD 02-2519	22.52	−106.65	955	Piston	Arellano-Torres (2010)
MD 02-2520	15.67	−95.30	719	Piston	Pichevin et al. (2010)
MD 02-2524	12.01	−87.91	863	Piston	Pichevin et al. (2010)
MD 02-2550	26.95	−91.35	2249	Box	Meckler et al. (2011)
MD 03-2601	−66.05	138.56	746	Piston	Denis et al. (2009)
MD 03-2603	−64.29	139.38	3290	Piston	Presti et al. (2011)
MD 03-2621	10.68	−64.97	850	Piston	Meckler et al. (2007)
MD 04-2876	24.84	64.01	828	Piston	Pichevin et al. (2007)
MD 06-3067	6.52	126.50	1574	Piston	Kienast et al. (2008)
MD 06-3075	6.48	125.87	1878	Piston	Kienast et al. (2008)
ME0005A-03JC	15.65	−95.28	740	Piston	Thunell and Kepple (2004)
ME0005A-11PC	15.71	−95.29	574	Piston	Hendy and Pedersen (2006)

Table 1. Continued.

Core name	Latitude	Longitude	Depth (m)	Core type	Reference
ME0005A-24JC	0.02	−86.46	2941	Gravity	Dubois et al. (2011)
ME0005A-27JC	−1.85	−82.79	2203	Gravity	Dubois et al. (2011)
ME33-EAST	15.59	68.58	3820	Gravity	Möbius et al. (2011)
ME33-NAST	20.00	65.68	3167	Gravity	Suthhof et al. (2001)
MR98-05-3	50.00	164.98	5507	Piston	Shigemitsu et al. (2008)
MR06-04 PC24A	60.26	−179.42	852	Piston	Kim et al. (2011)
MW8708-PC2	−15.10	−75.70	270	Piston	Agnihotri et al. (2006); Chazen et al. (2009)
NAM1	−22.67	14.00	125	Box	Struck et al. (2002)
NH8P	22.39	−107.08	1018	Piston	Ganeshram et al. (1995)
NH15P	22.68	−106.48	420	Piston	Ganeshram et al. (2000)
NH22P	22.52	−106.52	2025	Piston	Ganeshram et al. (1995)
NIOP 455	23.55	65.95	1002	Piston	Reichart et al. (1998)
NIOP 464	22.25	63.58	1470	Piston	Reichart et al. (1998)
NIOP 905	10.01	51.01	1586	Piston	Ivanochko et al. (2005)
ODP 722	16.62	59.80	2028	Advanced Piston	Altabet et al. (1999)
ODP 723	18.05	57.61	808	Advanced Piston	Higginson et al. (2004)
ODP 882	50.35	167.58	3244	Advanced Piston	Sigman et al. (2004); Galbraith et al. (2008b)
ODP 887	54.37	−148.45	3647	Advanced Piston	Galbraith et al. (2004)
ODP 893	34.29	−120.04	577	Advanced Piston	Emmer and Thunell (2000)
ODP 964	36.26	17.75	3770	Advanced Piston	Higgins et al. (2010)
ODP 967	34.07	32.73	2550	Advanced Piston	Struck et al. (2001)
ODP 969A	33.84	24.88	2212	Advanced Piston	Higgins et al. (2010)
ODP 969E	34.23	29.87	2400	Advanced Piston	Milder et al. (1999)
ODP 974	40.36	12.14	3454	Advanced Piston	Milder et al. (1999)
ODP 999	12.75	−78.73	2827	Advanced Piston	Ren et al. (2009)
ODP 1002	10.71	−65.17	893	Advanced Piston	Haug et al. (1998); Meckler et al. (2007)
ODP 1012	32.28	−118.40	1772	Advanced Piston	Liu et al. (2008)
ODP 1017	34.54	−121.27	955	Advanced Piston	Hendy et al. (2004)
ODP 1019	41.68	−124.93	977	Advanced Piston	Ivanochko and Pedersen (2004)
ODP 1033	48.59	−123.50	345	Advanced Piston	Calvert et al. (2001)
ODP 1078	−11.92	13.40	426	Advanced Piston	Galbraith (unpublished)
ODP 1082	−21.10	11.82	1280	Advanced Piston	Robinson and Meyers (2002); Etourneau et al. (2009)
ODP 1084	−25.52	13.02	1992	Advanced Piston	Robinson and Meyers (2002)
ODP 1090	−42.91	8.90	3702	Advanced Piston	Etourneau et al. (2009)
ODP 1096	−67.57	−76.97	3152	Advanced Piston	Sigman et al. (2004)
ODP 1144	20.05	117.42	2037	Advanced Piston	Higginson et al. (2003)

Table 1. Continued.

Core name	Latitude	Longitude	Depth (m)	Core type	Reference
ODP 1207	37.79	162.75	3101	Drilling	Dumitrescu and Brassell (2006)
ODP 1228	−11.06	−78.08	273	Advanced Piston	Agnihotri et al. (2006)
ODP 1233	−41.00	−74.45	838	Advanced Piston	Martinez et al. (2006)
ODP 1234	−36.22	−73.68	1015	Advanced Piston	Robinson et al. (2007)
ODP 1239	−0.67	−82.08	1414	Advanced Piston	Etourneau (unpublished)
ODP 1240	0.02	−86.46	2921	Advanced Piston	Pichevin et al. (2009)
ODP 1240	0.02	−86.46	2921	Advanced Piston	Robinson et al. (2009)
ODP 1242	7.86	−83.61	1364	Advanced Piston	Robinson et al. (2009)
P7GC	2.60	−84.00	3085		Farrell et al. (1995)
PC13	49.72	168.30	2393	Piston	Brunelle et al. (2010)
PRCK-3-2	38.54	−76.43	24	Piston	Bratton et al. (2003)
PS2163	86.24	59.22	3040	Multi	Schubert et al. (2001)
PS2170	87.60	60.90	4083	Multi	Schubert et al. (2001)
PS2178	88.02	159.59	4008	Multi	Schubert et al. (2001)
PS2185	87.50	144.48	1051	Multi	Schubert et al. (2001)
PTMC-3-1	38.03	−76.22	23	Piston	Bratton et al. (2003)
PX98-2	38.33	−76.38	9	Piston	Bratton et al. (2003)
RC13-259	−53.88	−4.93	2677	Piston	Rau and Froelich (1993); Brzezinski et al. (2002)
RC27-14	18.25	57.66	596	Piston	Altabet et al. (2002)
RC27-23	17.99	57.59	820	Piston	Altabet et al. (2002)
RC27-24	17.72	57.82	1416	Piston	Altabet et al. (1995)
RC27-61	16.66	59.52	1893	Piston	Altabet et al. (1995)
RD98-P2	38.89	−76.39	27	Piston	Bratton et al. (2003)
RR98-6	38.88	−76.45	8	Piston	Bratton et al. (2003)
SC-8	5.01	156.14	3604	Box	Nakatsuka et al. (1995a)
SK117-GC08	15.48	72.85	2500	Gravity	Banakar et al. (2005)
SK177/11	8.20	76.47	776	Gravity	Kao (unpublished)
SK126/39	12.63	73.33	1940	Gravity	Kessarkar et al. (2010)
SL226620	−22.76	14.31	81	Gravity	Emeis et al. (2009)
SO42-74KL	14.32	57.35	3212	Piston	Suthhof et al. (2001)
SO90-111KL	23.10	66.48	775	Piston	Suthhof et al. (2001)
SO95 GIK17924-3	19.41	118.85	3438	Gravity	Kienast (2000)
SO95 GIK17940-2	20.12	117.38	1727	Gravity	Kienast (2000)
SO95 GIK17954-2	14.76	111.53	1517	Gravity	Kienast (2000)

Table 1. Continued.

Core name	Latitude	Longitude	Depth (m)	Core type	Reference
SO95 GIK17961-2	8.51	112.33	1795	Gravity	Kienast (2000)
SO95 GIK17964-2	6.16	112.21	1556	Piston	Kienast (2000)
SO95 GIK17964-3	6.16	112.21	1556	Gravity	Kienast (2000)
SO115 GIK18284-3	5.54	110.54	226	Gravity	Kienast (2000)
SS3268G5	12.50	74.20	600	Gravity	Agnihotri et al. (2003)
SS4018G	13.21	53.26	2830	Gravity	Tiwari et al. (2010)
St-11	57.05	−176.96	3650	Piston	Nakatsuka et al. (1995b)
SU90-09	43.08	−31.08	3375	Piston	Huon et al. (2002)
SU94-11K	21.48	−17.95	1200	Piston	Bertrand et al. (2000)
SU94-20bK	25.03	−16.65	1445	Piston	Martinez et al. (2000)
TR163-19	2.26	−90.95	2348	Piston	Dubois et al. (2011)
TR163-22	0.52	−92.40	2830	Piston	Robinson et al. (2009)
TR163-22	0.52	−92.40	2830	Piston	Dubois and M. Kienast (unpublished)
TR163-31	−3.62	−83.97	3205	Piston	Dubois et al. (2011)
TT199-5-GC26	2.70	−86.00		Gravity	Farrell et al. (1995)
TTN013-PC72	0.11	−139.40	4298	Piston	Altabet (2001)
V34-101	17.49	67.42	3038		Altabet et al. (1999)
VNTR01-8PC	0.03	−110.48	3791		M. Kienast (unpublished)
VNTR01-13GC	−3.09	−90.82	3304	Gravity	Farrell et al. (1995)
W7706-37	−13.63	−76.85	370	Gravity	Higginson and Altabet (2004)
W7706-40	−11.25	−77.97	186	Gravity	Higginson and Altabet (2004); Agnihotri et al. (2008a)
W7706-41	−11.35	−78.12	410		Higginson and Altabet (2004)
W7706-77			540		Altabet (2007)
W8709-1 BC	41.54	−131.96	3680	Box	S. Kienast and Calvert (unpublished)
W8709-2 PC	41.35	−132.00	3684	Piston	S. Kienast and Calvert (unpublished)
W8709-8 PC	42.26	−127.68	3111	Piston	Kienast et al. (2002)
W8709-8 TC	42.26	−127.68	3111	Trigger	Kienast et al. (2002)
W8709-13 PC	42.12	−125.75	2712	Piston	Kienast et al. (2002)
Y71-6-12	−16.45	−77.57	2734		S. Kienast (unpublished)

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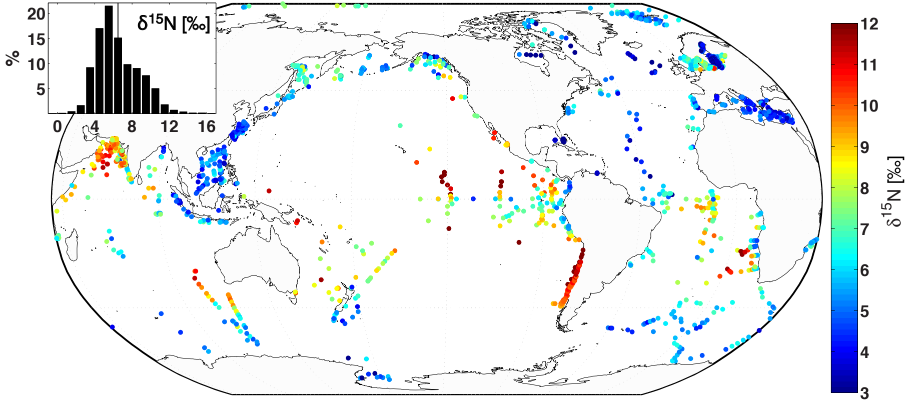

Fig. 1. Spatial distribution of surface sediment δ^{15}N samples. Inset: Histogram of surface δ^{15}N (in 1-kyr bins). The vertical line indicates the mean of 6.7 ‰, higher than the average δ^{15}N of nitrate in the ocean (∼5 ‰). The dataset is skewed towards heavier nitrogen isotopic composition.

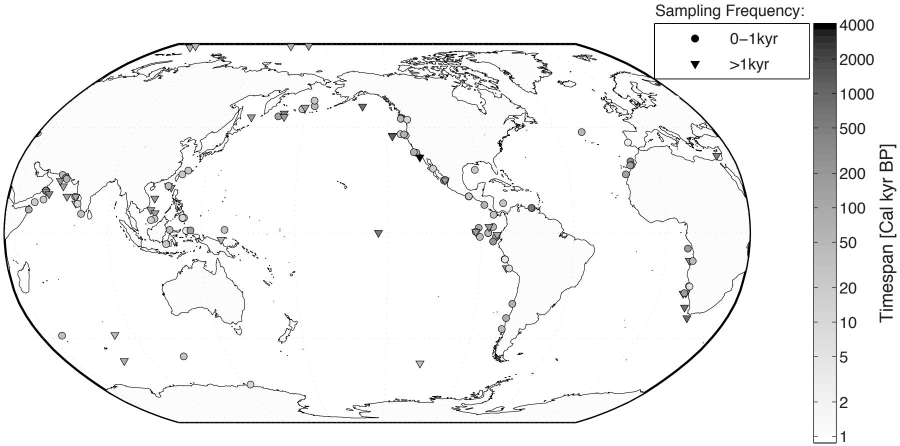

Fig. 2. Location of cores with a δ^{15}N record versus age. Each symbol represents a core site. The δ^{15}N records of each site differ both in their time ranges and in the resolution of their data. The symbols shading indicate the time range (Cal ka BP). We categorized records with high (circles) and low temporal resolution (triangles). High temporal resolution is considered to be an average sampling frequency of at least one data point every kyr, whereas low resolution is everything longer than this threshold.

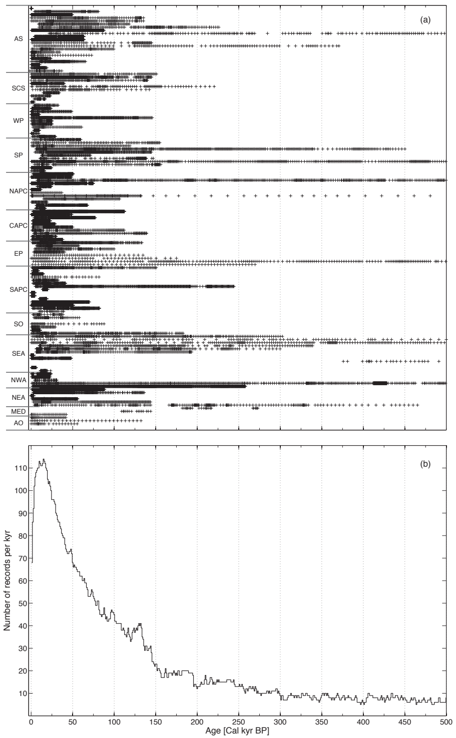

Fig. 3. Data point distribution through the last 500 kyr. **(a)** Each record is plotted horizontally, and each black cross represents a data point. Records are grouped by major oceanic regions: Arabian Sea (AS), South China Sea (SCS), West Pacific (WP), Subarctic Pacific (SP), North American Pacific coast (NAPC), Central, American Pacific coast (CAPC), Equatorial Pacific (EP), South American Pacific coast (SAPC), Southern Ocean (SO), Southeast Atlantic (SEA), Northwest Atlantic including Caribbean Sea and Gulf of Mexico (NWA), Northeast Atlantic (NEA), Mediterranean Sea (MED) and Arctic Ocean (AO). **(b)** Time series of the number of records per kyr through the last 500 kyr.

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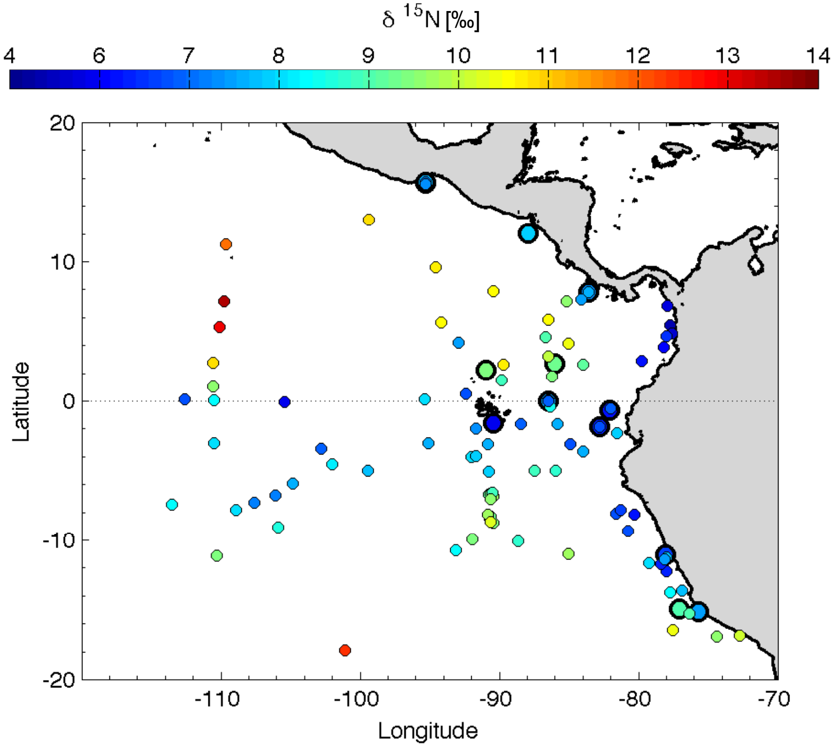

Fig. 4. Location of sediment core sites (large circles) and surface samples (smaller circles) in the Eastern Equatorial Pacific. The large circles approximately encompass the spatial range of a 100 km radius. All surface samples that fall within that range are averaged and compared to the LH average of the core site.

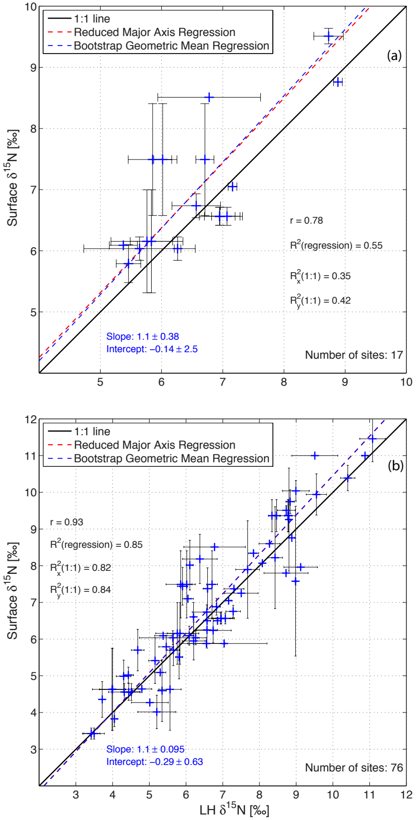

Fig. 5. LH δ^{15}N average compared with surface δ^{15}N within 100 km for **(a)** the Eastern Equatorial Pacific and **(b)** for all available records. The horizontal whiskers show the temporal variance of the LH average and the vertical whiskers indicate the spatial variance of the surface sample average.

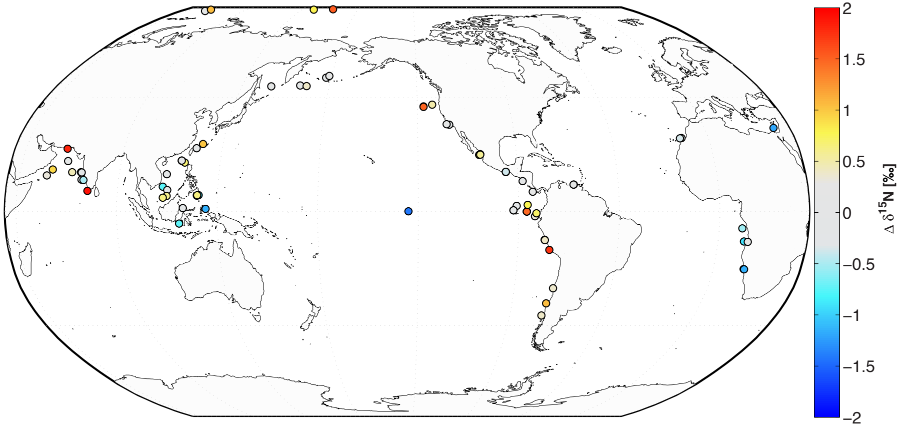

Fig. 6. Difference between surface and LH δ^{15}N. Differences are calculated as $\delta^{15}\mathrm{N}_{\mathrm{seafloor}} - \delta^{15}\mathrm{N}_{\mathrm{LH}}$.