Supplementary information

Section 6.3 ‘Biomarkers’

Tab. S1 Compilation of biomarker proxies indicative of oxygen-limited conditions.

proxy (compound or compound ratio)	source organism(s)	metabolism	environmental implication	reference
nitrogen cycling				
bacteriohopanetetrol-x (BHT-x)	‘Ca. Scalindua profunda’	anammox	hypoxia/anoxia, O_2 <20µmol	Schwartz-Narbonne et al., 2020
BHT-x/[BHT+BHT-x]) ≥ 0.2	‘Ca. Scalindua profunda’ / bacteria	anammox	O_2 <50 µmol	van Kemenade et al. (2022)
3-Me-bacteriohopanehexol	Ca. Methylomirabilis oxyfera	n-damo	anoxia	Kool et al., 2014
3Me-bacteriohopanepentol	Ca. Methylomirabilis oxyfera	n-damo	anoxia	Kool et al., 2014
22,29,30-trisnorhopan-21-ol	Ca. Methylomirabilis oxyfera	n-damo	anoxia	Smit et al., 2019
3Me-22,29,30-trisnorhopan-21-ol	Ca. Methylomirabilis oxyfera	n-damo	anoxia	Smit et al., 2019
3Me-22,29,30-trisnorhopan-21-one	Ca. Methylomirabilis oxyfera	n-damo	anoxia	Smit et al., 2019
sulfur cycling				
isorenieratene	green sulfur bacteria (Chlorobiaceae)	sulfide oxidation	photic zone euxinia	Summons and Powell (1987), French et al. (2015)
isorenieratane	green sulfur bacteria (Chlorobiaceae)	sulfide oxidation	photic zone euxinia	Summons and Powell (1987), French et al. (2015)
2,3,6-trimethyl aryl isoprenoids			photic zone euxinia	Schwark and Frimmel (2004)
chlorobactene	green sulfur bacteria (Chlorobiaceae)	sulfide oxidation	photic zone euxinia	Schaeffer et al. (1997)
chlorobactane	green sulfur bacteria (Chlorobiaceae)	sulfide oxidation	photic zone euxinia	Schaeffer et al. (1997)

okenone	purple sulfur bacteria (Chromatiaceae)	sulfide oxidation	photic zone euxinia	Brocks and Schaeffer (2008)
okenane	purple sulfur bacteria (Chromatiaceae)	sulfide oxidation	photic zone euxinia	Brocks and Schaeffer (2008)
bacteriochlorophyll-c,d,e	green sulfur bacteria	sulfide oxidation	photic zone euxinia	Grice et al. (1996)
3-isobutyl-4-methylmaleimide	green sulfur bacteria	sulfide oxidation	photic zone euxinia	Grice et al. (1996), Naeher et al. (2013)
monoalkyl glycerol ethers (MAGEs)	sulfate reducing bacteria	sulfate reduction	anoxia	Bradley et al. (2009)
dialkyl glycerol ethers (DAGEs)	sulfate reducing bacteria	sulfate reduction	anoxia	Bradley et al. (2009)
^{13}C-depleted C16:1ω5 cy-C17:0ω5,6 C17:1ω6 alkanoic acids	sulfate reducing bacteria	sulfate reduction	anoxia	Niemann and Elvert (2008)
carbon cycling				
GDGT-0/crenarchaeol >2	methanogenic Euryarchaeota	methanogenesis	anoxia	Blaga et al. (2009)
coenzyme F430	methanogenic Euryarchaeota	methanogenesis	anoxia	Kaneko et al. (2021)
crocetane (tetramethylhexadecane)	ANME archaea	anaerobic methanotrophy	anoxia	Elvert et al. (1999)
(unsaturated) PMI (pentamethylicosane)	ANME archaea	anaerobic methanotrophy	anoxia	Elvert et al. (1999)
hydroxyarchaeol	ANME archaea	anaerobic methanotrophy	anoxia	Hinrichs et al. (2000; 2003)
aminopentol, methylcarbamate-bacteriohopanepentol	Type I methanotrophic bacteria	aerobic methanotrophy	methane-rich environment	Rush et al. (2016)
methylene-ubiquinone $MQ_{8:7}$	Type I methanotrophic bacteria	aerobic methanotrophy	methane-rich environment	Nowicka and Kruk (2010)
methylcarbamate-bacteriohopanetetrol	Type II methanotrophic bacteria	aerobic methanotrophy	methane-rich environment	Rush et al. (2016)

redox products				
pristane/phytane <1	chlorophyll-producing organisms	abiotic	anoxia	Peters et al. (2005)
pyropheophytin	chlorophyll-producing organisms	abiotic	anoxia	Szymczak-Żyla et al. (2008)
steryl chlorin esters	chlorophyll-producing organisms	abiotic	anoxia	Szymczak-Żyla et al. (2008)
high homohopane index	bacteria	abiotic	anoxia	Peters et al. (2005)
orphan biomarkers (unknown source)				
high lycopane/C_{31} n-alkane	unknown	methanogenesis?	anoxia	Sinninghe Damsté et al. (2003)
OB-GDGTs	unknown bacteria	unknown	anoxia	Liu et al. (2014), Connock et al. (2022)

Section 6.8 ‘Benthic foraminifera carbon isotope offsets’

Data used to put together Figure 6.8.1 can be found below.

Ocean	Core name	Latitude	Longitude	Water depth	GLODAP BWO umol/kg	WOA18 BWO umol/kg	WOCE BWO umol/kg	Avg BWO	±	Comment
Atlantic	JC89-11	37.86	9.34	628	190.002	182.003	197.225	189.7	7.6	
Atlantic	JC89-10	37.84	9.51	1127	188.48	178.561	188.95	185.3	5.9	
Atlantic	JC89-13	37.94	9.59	1448	208.256	176.743		192.5	15.8	
Atlantic	JC89-09	37.83	9.82	2323	233.956	184.159		209.1	24.9	
Atlantic	JC89-08	37.78	10.05	2619	229.978	186.119		208.0	21.9	
Atlantic	JC89-06	37.56	10.14	2645	229.552	186.446		208.0	21.6	
Atlantic	JC89-13	37.94	9.59	1448	208.256	176.743		192.5	15.8	
Atlantic	JC89-09	37.83	9.82	2323	233.956	184.159		209.1	24.9	
Atlantic	JC89-08	37.78	10.05	2619	229.978	186.119		208.0	21.9	
Atlantic	JC89-06	37.56	10.14	2645	229.552	186.446		208.0	21.6	
Pacific	ODP 846	-3.09	-90.82	3295	142.073	137.298	139.928	139.8	2.4	
Pacific	ODP 1240	0.02	-86.46	2921	131.934	128.152	125.078	128.4	3.4	
Pacific	TR163-23	0.41	-92.16	2730	120.847	124.408	118.232	121.2	3.1	
Pacific	TR163-25	-1.65	-88.45	2650	122.026	124.634	118.643	121.8	3.0	
Pacific	ODP 1242	7.86	-83.61	1363.7	127.684	86.6735	91.3205	101.9	22.5	
Atlantic	RAPID 11 7B/RAF	62.30	-17.50	2126	286.577	300.161		293.4	6.8	
Atlantic	GeoB3706	-22.70	12.60	1313	189.867	173.426	181.189	181.5	8.2	
Atlantic	GeoB3708	-21.10	11.80	1283	187.783	170.818	179.975	179.5	8.5	
Atlantic	GeoB3725	-23.30	12.40	1980	229.613	210.188	221.574	220.5	9.8	
Indian	GeoB3004	-14.60	52.90	1803	148.112	146.06	148.11	147.4	1.2	
Indian	TN041-8PG/8JPC	17.80	57.50	761	8.4437	12.638	7.18298	9.4	2.9	
Atlantic	GeoB3606-1	-25.47	13.08	1785	216.136	201.987	211.187	209.8	7.2	
Atlantic	KNR197-3-24MC	7.59	-53.92	383	113.169	114.124	117.243	114.8	2.1	
Atlantic	KNR197-3-2MC	7.66	-53.82	556	114.721	114.741	118.175	115.9	2.0	
Atlantic	KNR197-3-26MC	7.72	-53.78	704	125.258	123.31	127.781	125.4	2.2	
Atlantic	KNR197-3-28MC	7.84	-53.67	962	148.777	146.589	149.333	148.2	1.5	
Atlantic	KNR197-3-17MC	7.44	-52.76	1029	152.662	155.437	152.411	153.5	1.7	
Atlantic	KNR197-3-10MC	7.94	-53.58	1107	171.421	166.881	171.917	170.1	2.8	
Atlantic	KNR197-3-33MC	8.25	-53.24	1275	198.167	193.116	196.64	196.0	2.6	
Atlantic	KNR197-3-41MC	8.38	-53.05	2052	253.88	248.203	254.556	252.2	3.5	
Atlantic	KNR197-3-37MC	8.43	-52.79	2440	254.986	250.463	256.365	253.9	3.1	
Atlantic	KNR197-3-35MC	8.47	-52.79	3328	257.601	253.102	258.674	256.5	3.0	
North Pacific	ODP1014	32.83	-119.98	1165	31.8758	32.0458	31.4944	31.8	0.3	
North Pacific	ODP1019	41.68	-124.93	980	13.1707	17.7959	12.7325	14.6	2.8	

Below follows a morphological description of the benthic foraminifera used to reconstruct bottom water oxygen concentrations through $\Delta\delta^{13}C$:

The most commonly used foraminifer is *Cibicidoides wuellerstorfi* (Schwager), 1866. Following the description of Loeblich and Tappan (1988) and Holbourn et al. (2013), C. wuellerstorfi has typically a very low trochospiral, compressed and planoconvex test, eight to twelve chambers visible in the final whorl that curve back at the periphery, with an (partially) evolute spiral (umbilical) side and a keeled periphery. About ten elongated and curved chambers in the final whorl are separated by strongly curved sutures that are slightly depressed in the final chambers on the spiral side. The spiral (umbilical) side is coarsely (finely) perforated and the interiomarginal aperture of *C. wuellerstorfi* features a narrow lip. One particular sensu lato morphotype of C. wuellerstorfi has been described previously and is commonly found in southern high-latitude marine environments (Gottschalk et al., 2016; Rae et al., 2011). While it shares many characteristics with *C. wuellerstorfi*, in particular the trochospiral, plano-convex test and perforation features, it has often only seven to nine chambers in the final whorl that are wider and more inflated than in the sensu stricto morphotype of *C. wuellerstorfi*. The test of the sensu lato morphotype shows intercameral sutures that are not as strongly curved towards the periphery as seen in the sensu stricto morphotype and appears duller in reflectance.

When *C. wuellerstorfi* is absent in the sedimentary record, other foraminiferal species thought to approximate an epifaunal habitat like *Cibicides kullenbergi* (Parker), 1953 (synonymously used with *Cibicidoides mundulus* (Brady, Parker, and Jones), 1888) have also been used to reconstruct bottom water oxygen levels using the $\Delta\delta^{13}C$ proxy [e.g., Gottschalk et al., 2016a, 2020; Bunzel et al., 2017; Lu et al., 2022]. While *C. kullenbergi* specimens are similar to *C. wuellerstorfi* (i.e., showing a trochospiral test, ten to eleven chambers in the final whorl, similar perforation intensities, aperture with a thin lip, and arched sutures on the spiral side), it is biconvex in cross-section. The length to width ratio of chambers in *C. kullenbergi* is much smaller and intercameral sutures are less curved than in *C. wuellerstorfi*. However, intergrades between *C. kullenbergi* sensu stricto and *C. wuellerstorfi* sensu stricto are common, leading not only to specimen with similarity to *C. wuellerstorfi* (*C. wuellerstorfi* sensu lato) but also to specimen with resemblance to *C. kullenbergi* (C. kullenbergi sensu lato). *C. kullenbergi* sensu lato tends to show a plano-convex test and a more sub-circular test compared to the biconvex, circular *C. kullenbergi* sensu stricto. In addition, the sutures of *C. kullenbergi* sensu lato are more strongly curved towards the periphery than those of *C. kullenbergi* sensu stricto, but not as strong as in *C. wuellerstorfi* sensu stricto or sensu lato. The chamber length-to-width ratio is also slightly greater in comparison to *C. kullenbergi* sensu stricto but not as high as seen in *C. wuellerstorfi* sensu stricto or sensu lato.

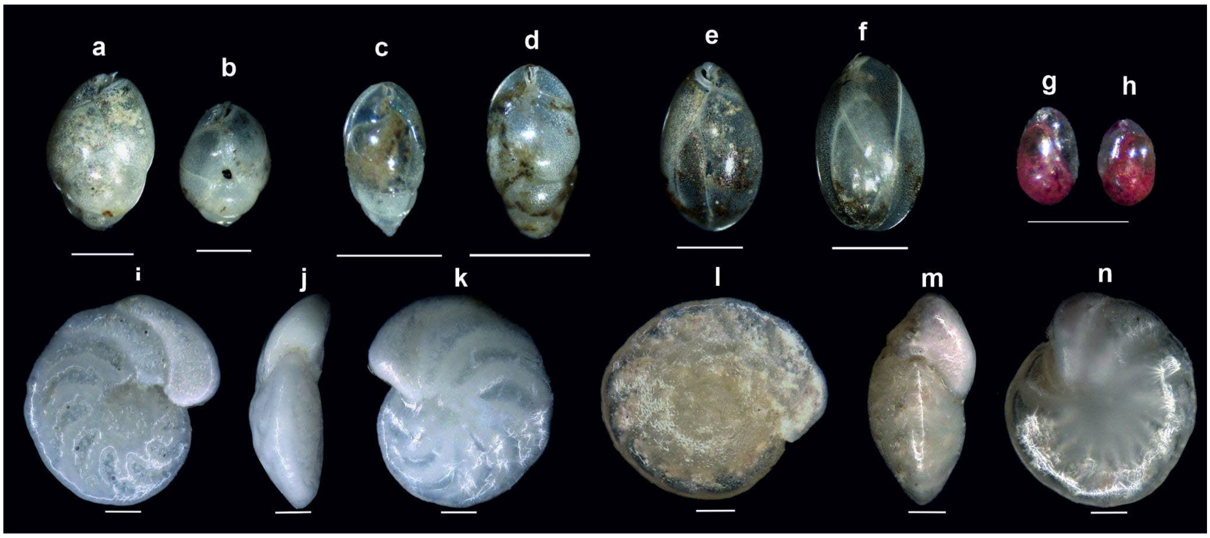

Figure 2. Overview of *Globobulimina* and *Cibicidoides/Cibicides* species that form the backbone of the $\Delta\delta^{13}C$ proxy. a, b) Lateral view of *Globobulimina auriculata* (a: ODP1014D 1H 4W, 97-99 cm; b: ODP1014D 1H 5W, 66-68 cm; scale = 1000 µm), c) lateral view of *Globobulimina affinis* (morphotype 1; ODP1014D 1H 5W, 7-9 cm; scale = 1000 µm), d) lateral view of *G. affinis* (morphotype 2; ODP1014D 1H 5W, 7-9 cm; scale = 1000 µm), e, f) lateral view of *Globobulimina pacifica* (ODP1014D 1H 4W, 129-131 cm; scale = 1000 µm), g, h) lateral view of *Globobulimina turgida* (GeoB15022-2, 1-2 cm; scale = 350 µm), i, j, k) spiral, lateral and umbilical view

of *Cibicidoides wuellerstorfi* sensu stricto (TNO57-6GC 44-46 cm; scale = 100 µm), and l, m, n) spiral, lateral and umbilical view of *Cibicides kullenbergi* sensu stricto (MD97-2100, 20-21 cm; scale = 100 µm).

Section 8 ‘Data management and transparency’

Table S1. Examples of file structure and data organization; PANGAEA and other repositories provide extensive details about which meta data is required with core submission:

File type	Necessary information that need to content and examples	name of the file
Sample location	Site name, ocean basin or sea, site name, latitude and longitude, water depth DOI code of the original publication	sitename_metadata.csv (e.g. GeoB15007-1_metadata.csv)
Sample details	Site name, depth information (details of conversions to MBSF or MCD in the case of ODP cores, unique sample number from core repository.	sitename_depth.csv
Age model	Site name (use the original name used in the expedition) (e.g. GeoB15007-1; 1014) Sample depth (m), dating technique (AMS dates, d18O stratigraphy, 210-Pb, other), age.	sitename_ageraw.csv
Foraminifera Assemblages	Site name, sample label, sample depth (m), sample size, splits and fraction, staining if applicable, foraminifera taxa, counts, example images DOI: publications	site_forams_assemblages.csv

Examples of working groups that are curating specific proxy data bases and links to websites.

FORCIS (Foraminifera response to Climatic Stress, currently active) are evaluating the biodiversity changes of calcifying zooplankton in response to multiple stressors (https://forcis.cerege.fr/). NICOPP (Global ocean sediment nitrogen isotope data base, inactive) was a joint group between PAGES and IMAGES studying nitrogen isotope dynamics from sedimentary records in the Quaternary and modern times (http://pastglobalchanges.org/science/wg/former/nicopp/). MOSAIC (Modern Ocean Sediment Archive and Inventory of Carbon, active) goal is to synthesize local, regional and global-scale of the content, source and fate of organic materials accumulating in contemporary marine sediments (http://mosaic.ethz.ch/). Finally, GLODAP (The Global Ocean Data Analysis Project) is an example of where physical and chemical hydrological data of water samples are stored (https://glodap.info/).