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World Atlas of late Quaternary Foraminiferal Oxygen and Carbon Isotope Ratios

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Abstract. We present a global atlas of downcore foraminiferal oxygen and carbon isotope ratios available at https://doi.pangaea.de/10.1594/PANGAEA.936747 (Mulitza et al., 2021). The database contains 2,108 published and previously unpublished stable isotope downcore records with 362,067 stable isotope values of various planktonic and benthic species of foraminifera from 1,265 sediment cores. Age constraints are provided by 6,153 uncalibrated radiocarbon ages from 598 (47%) of the cores. Each stable isotope and radiocarbon series is provided in a separate netCDF file containing fundamental meta data as attributes. The data set can be managed and explored with the free software tool PaleoDataView. The atlas will provide important data for paleoceanographic analyses and compilations, site surveys, or for teaching marine stratigraphy. The database can be updated with new records as they are generated, providing a live ongoing resource into the future.

https://doi.org/10.5194/essd-2021-337
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1 Introduction

Stable oxygen and carbon isotope ratios measured on foraminiferal shells are often regarded as the foundation of Marine Geology and Paleoceanography. The importance of these proxies stems from their broad applicability in time and space, their established and efficient analytical methods and their great value for stratigraphy and paleoceanographic reconstructions (see review by (Pearson, 2012). Since the pioneering work of (Urey, 1947), millions of foraminiferal isotope measurements have been performed representing time slices from the Middle Jurassic (e.g. Vetoshkina et al., 2014) into the Anthropocene (e.g, (McGregor et al., 2007). Foraminiferal isotopes have substantially contributed to the reconstruction and understanding of the global climate evolution since the Early Cretaceous (Cramer et al., 2009) including the validation of the orbital theory of the ice ages (Hays et al., 1976), reconstructions of ice volume (Shackleton and Opdyke, 1973; Waelbroeck et al., 2002) and water mass structure, ocean circulation and carbon cycling (Curry et al., 1988; Duplessy et al., 1988; Boyle and Keigwin, 1987).

Despite their importance for the understanding of the Earth System, foraminiferal isotope data have not been systematically catalogued or stored in a database in a consistent and standardized format. Foraminiferal isotope data are usually available in arbitrary data formats and scattered across different data repositories, which hinders an automated analysis. Harmonized data collections have the advantage that (i) information about data coverage can be immediately accessed and visualized, for example in the planning phase of research projects, (ii) data can be quickly compared for verification/quality control or to separate local signals from global signals and (iii) that customized software can be used to visualize and analyse the data.

Here we present the first global atlas of foraminiferal stable isotope data (with uncalibrated radiocarbon ages where available). The data are stored in netCDF format (Rew and Davis, 1990) and can be directly analysed and visualized with the free software tool PaleoDataView (PDV, Langner and Mulitza, 2019). In PDV, age information for a specific sediment core is linked to any downcore proxy series imported for that core within the same collection. This strategy ensures the long-term maintainability and consistency of the age models across different proxy records (e.g. stable isotope records of different species) in the same collection. The netCDF format also allows the data to be analysed using programming languages such as MATLAB, R, Fortran, C++ and Python.

2 Data sources and harmonisation

The database is provided as a collection of 2,108 netCDF files with $\delta^{18}O$ and $\delta^{13}C$ data of species-specific foraminiferal carbonate and 598 netCDF files with raw radiocarbon ages (see references in Table A1). A detailed description of the attributes and variables in the netCDF files is provided in Supplements S1 and S2. About 79% of the files containing stable isotope records were derived from data downloaded either from PANGAEA (www.pangaea.de) or NOAA's National Centers for Environmental Information (NCEI, www.ncdc.noaa.gov). The remaining 21% of the stable isotope files are based on data obtained directly from a stable isotope laboratory by one of the co-authors (8%), or have been digitized from tables provided

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Preprint. Discussion started: 25 November 2021

in papers, or paper supplements (6%), or through personal communication (7%). Radiocarbon data are not as frequently archived in public databases as stable isotope data. Only 62% of the files containing radiocarbon data were obtained from NOAA or PANGAEA, whereas data in 32% of the files were copied from tables in papers or paper supplements. 5% of the files are based on data directly obtained from laboratories, while only 1% was obtained through personal communication. The data set also includes 105 previously unpublished species-specific stable isotope downcore records including both δ^{18}O and δ^{13}C values and 45 species-specific isotope downcore records for which either δ^{13}C or δ^{18}O was previously unpublished (Supplement S3). A tabulated text file containing all data sources is available from Zenodo (https://doi.org/10.5281/zenodo.5552329).

To generate the netCDF files, meta data, isotope data and radiocarbon ages (if available) were first assembled in species- and site-specific Excel files in the format required by PDV. The species names were preserved as used in the original publication. If more than one stable isotope record of the same species was available for the same core, we added a suffix (e.g., size class or version) to the species name. The Excel files were than edited for units (mainly conversion from "cm" to "m" and years to kiloyears) and meta data were added. Unavailable data fields were filled with "NaN". Finally, the Excel files were converted to netCDF files using the PDV import tool. Stable isotope data and radiocarbon data were saved in separate files to allow the radiocarbon file to link to several proxy records from the same core via the core label. After import the data were inspected and quality controlled in PDV. Every row of the downcore data fields is associated with a "use-flag" indicating whether the values should be included in an analysis (use flag = 1) or not (use flag = 0). This flag can be used to exclude outliers (e.g. due to turbidites) or radiocarbon reversals in a later analysis of the data, while maintaining the original data in the file. Isotope values without replicates were imported with a use-flag set to "1". For replicate stable isotope measurements the use flags were set to "0" and an average of the replicates (use flag = 1) was added to the series with a comment "Mean of multiple measurements" in the same row. Raw radiocarbon ages were generally imported with a use-flag set to "0" since the data are uncalibrated. Most of the data are archived with original downcore depth of the samples. If a composite depth scale was used (e.g., for International Ocean Discovery Program (IODP) and its predecessors Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP) cores), a comment was added and care was taken that available radiocarbon dates were imported on the same depth scale. The data is stored as raw data, with all documented corrections removed from the data. This includes a previously subtracted reservoir age and corrections applied to the stable isotope values (e.g., to account for species offsets). Variables to store downcore radiocarbon reservoir and stable isotope corrections that may be applied to the data at a later stage are already included in the netCDF files. These variables have been imported with default values of 0.4 ka (± 0.1) for all radiocarbon reservoir ages and a stable isotope correction of "0" for all oxygen and carbon isotope ratios. Both, reservoir ages and stable isotope corrections can be edited within PDV.

https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

3 Data distribution

3.1 Spatial and vertical coverage

Stable isotope records are available from all major ocean basins (Fig. 1), but tend to cluster along continental margins, where higher sedimentation rate, and thus higher temporal resolutions, can be found compared to mid-ocean ridges or deep abyssal basins. About 65% of the downcore records are from coring locations within 400 km of the coastline (Fig. 2). The deepest record in the atlas is from 5,105 m water depth (EN066-29PG, eastern tropical Atlantic, (Curry and Lohmann, 1983), the shallowest record from 50 m water depth (GeoB9503-5, Senegal Mudbelt, Mulitza, unpublished). However, the availability of records decreases above about 400 m (Fig. 3), where more dynamic sedimentation regimes exist, and below 4200 m due to carbonate dissolution which often prevents the production of reliable, continuous foraminiferal stable isotope records.

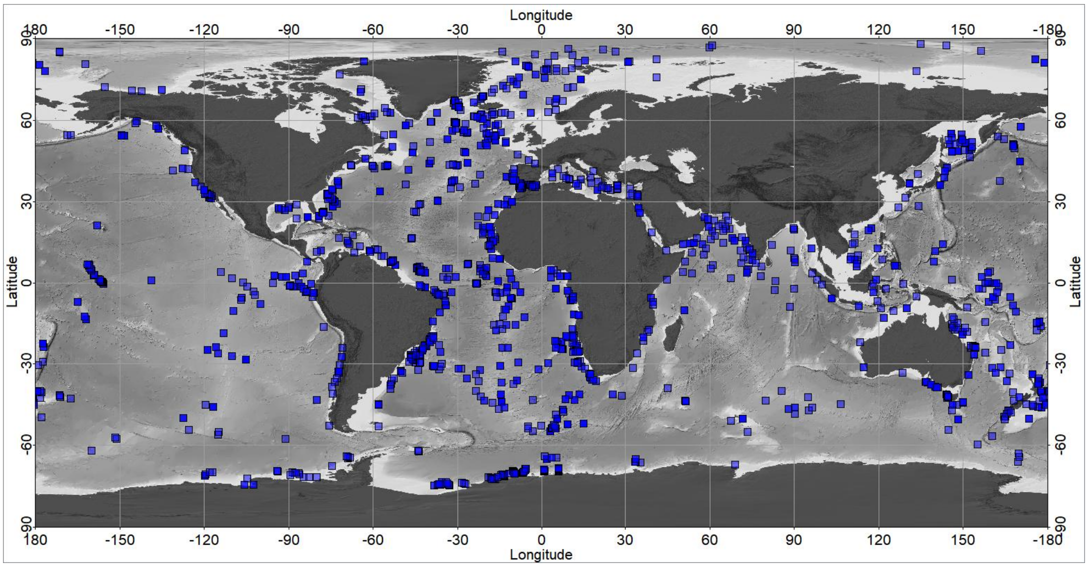

Figure 1: Spatial distribution of stable isotope records available in this atlas. The map has been generated with PaleoDataView (Langner and Mulitza, 2019)

Records are available in all oceanic 5° latitude bands with the highest number in trpical latitudes and decreasing numbers towards high latitudes (Fig. 3). The largest fraction (~47%) of the stable isotope records was measured on material from the Atlantic whereas about 9% are from the Southern Ocean (Fig. 4). However, with 21 cores/million km^2, the Mediterranean has the highest density of cores followed by the Arctic Ocean (7.8 cores/million km^2) and the Atlantic (7.5 cores/million km^2). The Pacific and Indian Oceans are currently only covered by 2 and 2.1 cores/million km^2.

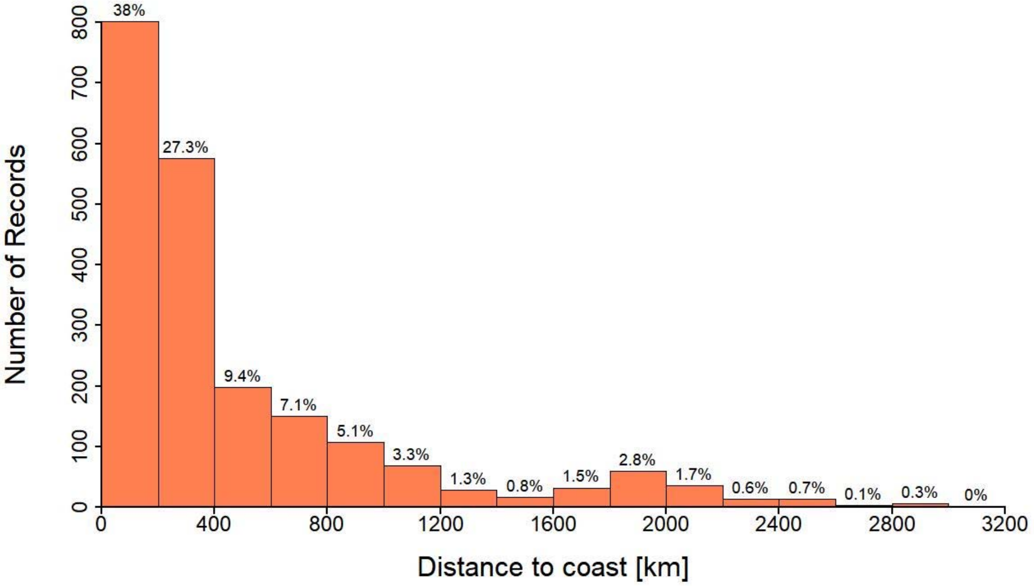

Figure 2: Number of isotope records available in this atlas versus distance to the coastline in 200 km bins. The global coastline was created with the free vector and raster map data from www.naturalearthdata.com.

3.2 Species distribution

The majority (61%) of all stable isotope values available in this compilation were measured on planktic foraminifera (see individual percentages for carbon and oxygen isotopes in Fig. 5). Among the planktic species, *Globigerinoides ruber* (37%) and *Neogloboquadrina pachyderma* (28%) are the most commonly used species, followed by *Globigerina bulloides* (17%) and *Globigerinoides sacculifer* (6%). Isotope measurements on other (mostly deep-dwelling) planktic species (summarized under “other planktics”) constitute about 12% of all values in the atlas (Fig. 5). 75% of the included planktic oxygen isotope values and 88% of the included benthic oxygen isotope values are reported together with the corresponding carbon isotope value. Most of the benthic isotope values (70%) were obtained from the epi-faunal genus *Cibicides/Cibicidoides*. Isotope values from the in-faunal genus *Uvigerina* constitute about 18% of all benthic isotope values in the atlas. The grouping of the original species names into species/genus names used in Fig. 5 and Fig. 6 is provided in Supplement S4.

https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

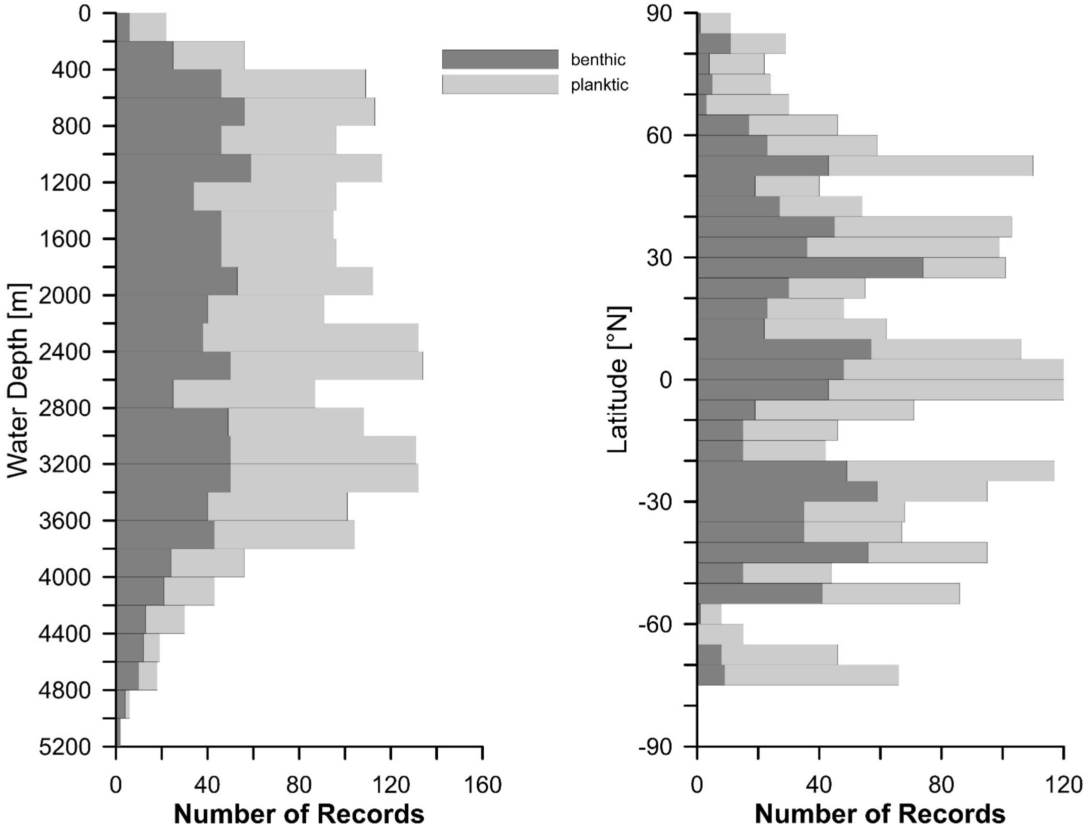

Figure 3: Distribution of stable isotope records with water depth in 200 m bins (left) and with latitude in 5° bins (right).

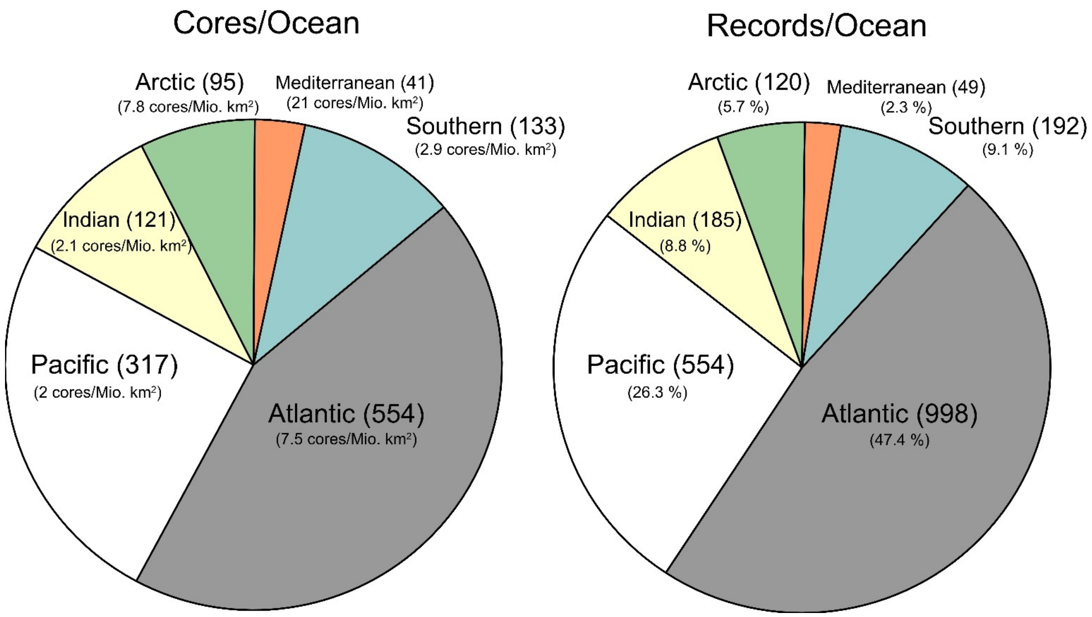

Figure 4: Number of cores (left) and records (right) for major ocean basins. A record is a downcore series of paired oxygen and carbon isotope measurements on a foraminiferal species or species group stored in a single netCDF file. Several records can exist for a single core. The counts include records/cores for which either $\delta^{18}O$ or $\delta^{13}C$ is missing. Numbers in small letters indicate density of cores in 10^6 km² (left) and percentage from the total number of records in the atlas (right) in each basin. Ocean basins follow the definitions in the World Ocean Atlas 2001 (Stephens et al., 2002). Pacific includes the Sea of Japan and the Indian Ocean includes the Bay of Bengal. 8 records from four Red Sea cores are not shown.

3.3 Species-specific and latitudinal distribution of oxygen and carbon isotope values

In the current version, the atlas contains a total of 201,652 $\delta^{18}O$ values. The lowest $\delta^{18}O$ values (-7.51 ‰) are observed in the species *G. ruber white* (Fig. 6) from the Gulf of Mexico core LOUIS1924 (Aharon, 2003) under the influence of Mississippi freshwater discharge. The highest planktic $\delta^{18}O$ values (6.31 ‰) can be observed in the tropical species *G. ruber* from core M31_2-78_PC6 (Red Sea, Geiselhart and Hemleben, 1998b). With latitude, planktic $\delta^{18}O$ values follow the typical bell-shaped curve as expected from a dominant influence of sea surface temperature (Fig. 7). Benthic $\delta^{18}O$ values range from -2.85 ‰ from *Cibicides corpulentus* in core OC205-2-108GGC (Slowey and Curry, 1995) to 6.46 ‰ from *Creseis acicula* from Red Sea site M31_2-84_PC6 (Geiselhart and Hemleben, 1998a). Vertically, the $\delta^{18}O$ of predominantly endobenthic and epibentic foraminiferal species increases with water depth over the upper 800 m as expected from decreasing temperatures within the main thermocline (Fig. 8). Planktic $\delta^{18}O$ values do not show clear visual trends with water depth (not shown). Planktic and benthic $\delta^{18}O$ values converge towards polar regions as expected from the decreasing temperature stratification with increasing latitude (Fig. 7).

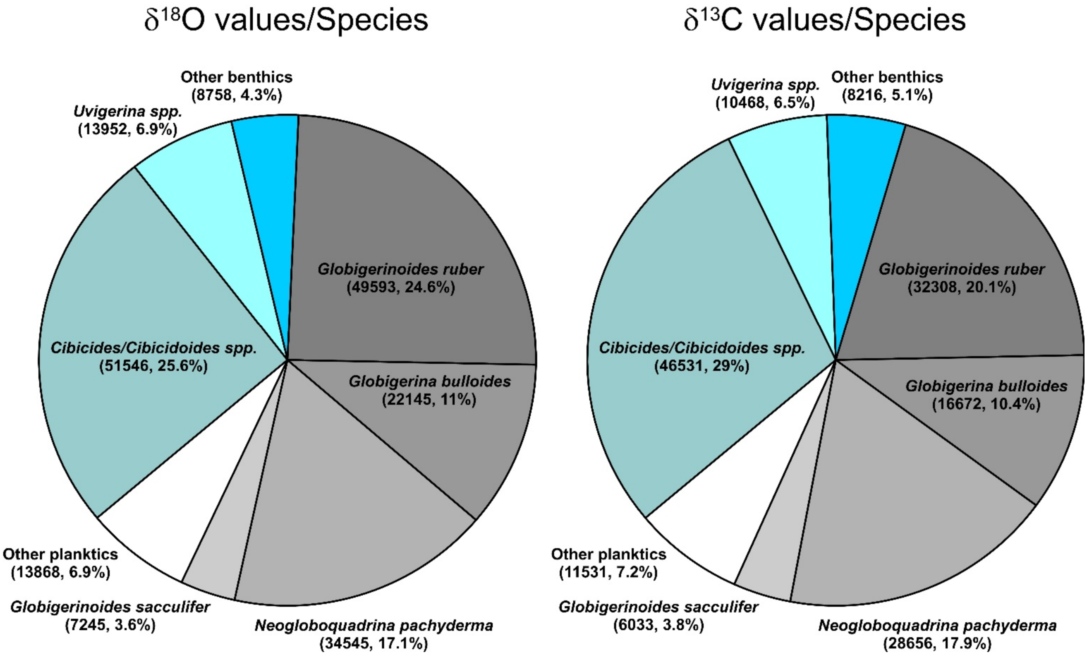

Figure 5: Fraction of oxygen (left) and carbon (right) isotope values measured on benthic (blue) and planktic (grey) species/species groups. Numbers in small letters indicate absolute number of values and percentage from the total number of $\delta^{18}O$ (left) or $\delta^{13}C$ (right) values in the atlas. See Supplement S4 for the categorisation of the individual species names from the original publications.

The data set contains 160,415 $\delta^{13}C$ values. Shallow-dwelling planktic foraminifera from tropical latitudes show the highest $\delta^{13}C$ values (Fig. 9) of up to 3.53 ‰ in shells of the species *G. ruber* from the Red Sea core M31_2-78_PC6 (Geiselhart and Hemleben, 1998b). Planktic $\delta^{13}C$ values get as low as -17.7 ‰ on *N. pachyderma sinistral* (Fig. 6) in core LV28-4-4 from the Sea of Okhotsk (Kaiser, 2001), which might be related to a potential contribution from authigenic carbonate minerals that form with the anaerobic oxidation of methane (Cook et al., 2011). Benthic foraminiferal $\delta^{13}C$ gets as low as -7.99 ‰ in *Elphidium batialis* from western North Pacific core KT90-9_21 (Oba and Murayama, 2004) and as high as 3.57 ‰ in *Creseis acicula* from Red Sea core M31_2-84_PC6 (Geiselhart and Hemleben, 1998b). In contrast to endobenthic species, epibenthic species show a clear trend toward decreasing $\delta^{13}C$ values in the deep ocean (Fig. 8), as expected from the global distribution of $\delta^{13}C$ in dissolved ΣCO_2 (Kroopnick, 1985).

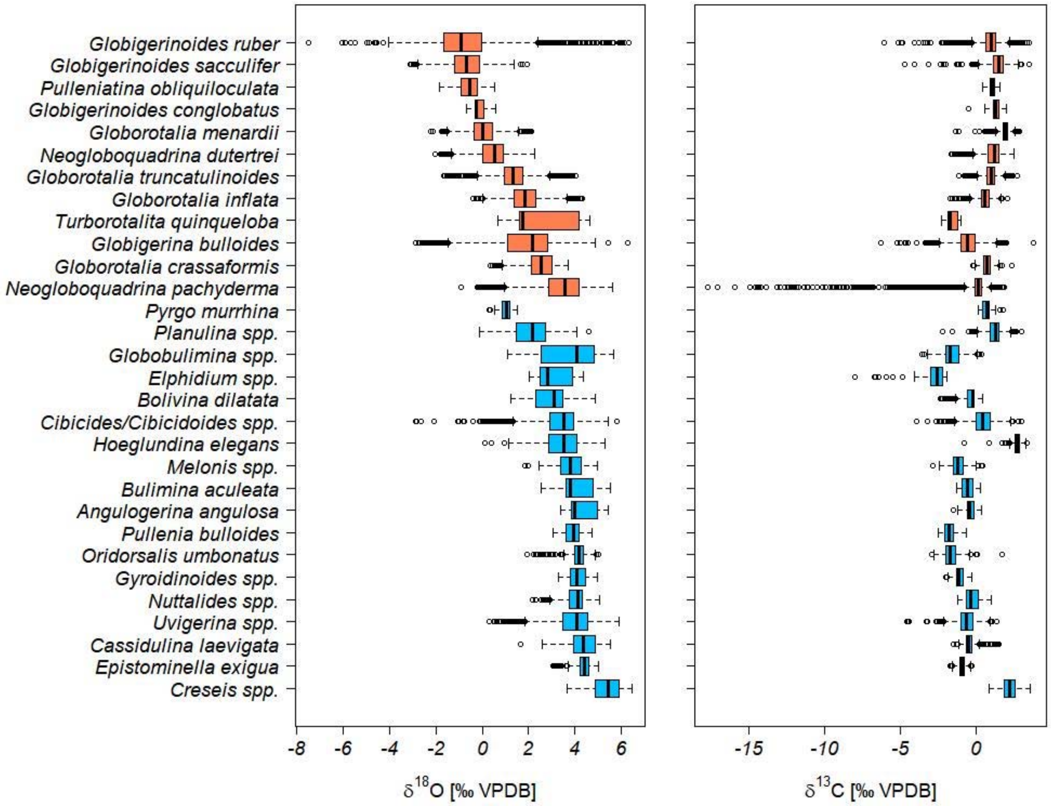

Figure 6: Box-whisker plot of oxygen (left) and carbon (right) stable isotope values of planktic (orange) and benthic (blue) foraminifera at the species or genus level. The vertical line shows the median, left and right margins of the box indicate the 25th and 75th percentiles. The whiskers (the horizontal dashed lines) indicate the maximum/minimum values, or in case of outliers (open circles), highest/lowest data point that is less than 1.5 times above/below the interquartile range. The plot has been created with R's boxplot() function (R Core Team, 2017).

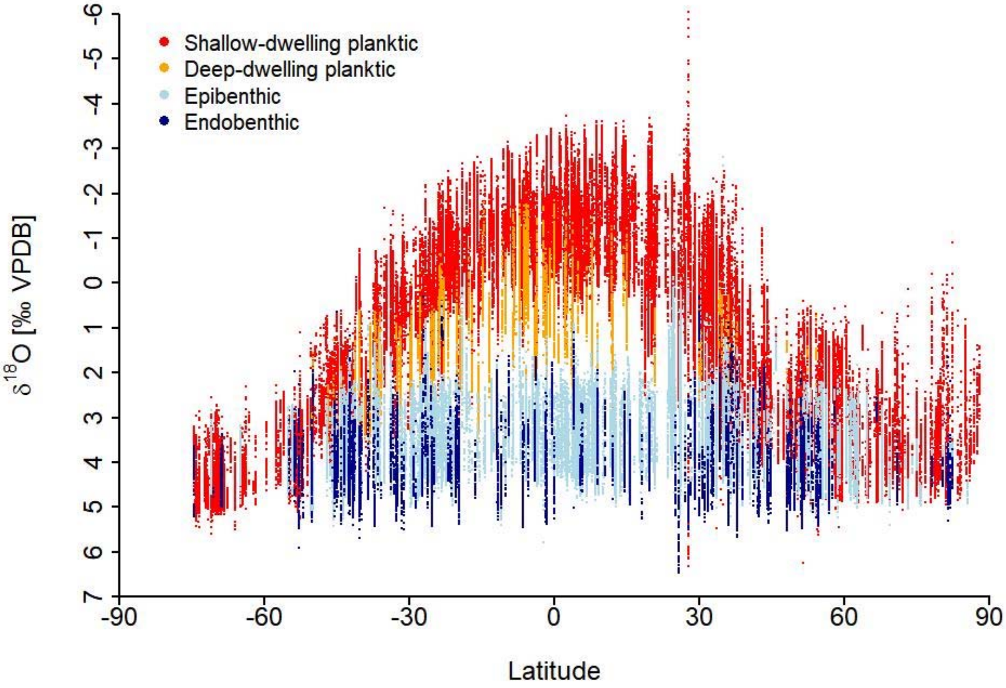

Figure 7: Distribution of δ^{18}O values with latitude. Red/orange: planktic foraminifera, light/deep blue: benthic foraminifera.

https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

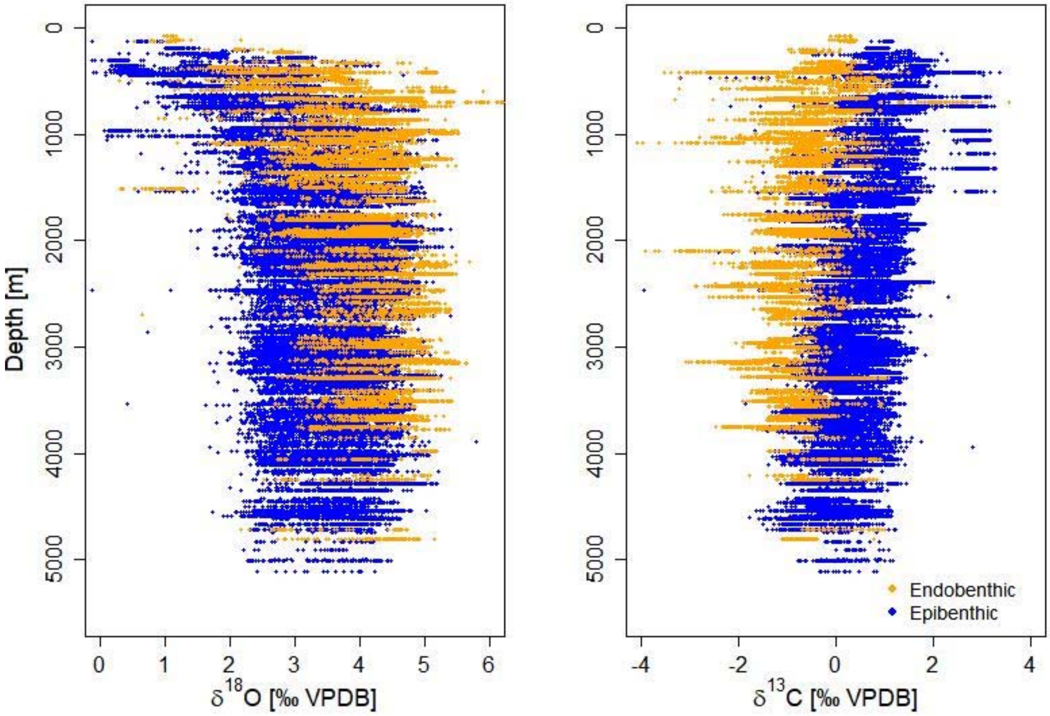

Figure 8: Distribution of benthic oxygen ($\delta^{18}O$, left) and carbon ($\delta^{13}C$, right) isotope values with water depth. Extreme values outside the axis ranges are not shown. Orange: endobenthic species, light/deep blue: epibenthic species.

https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

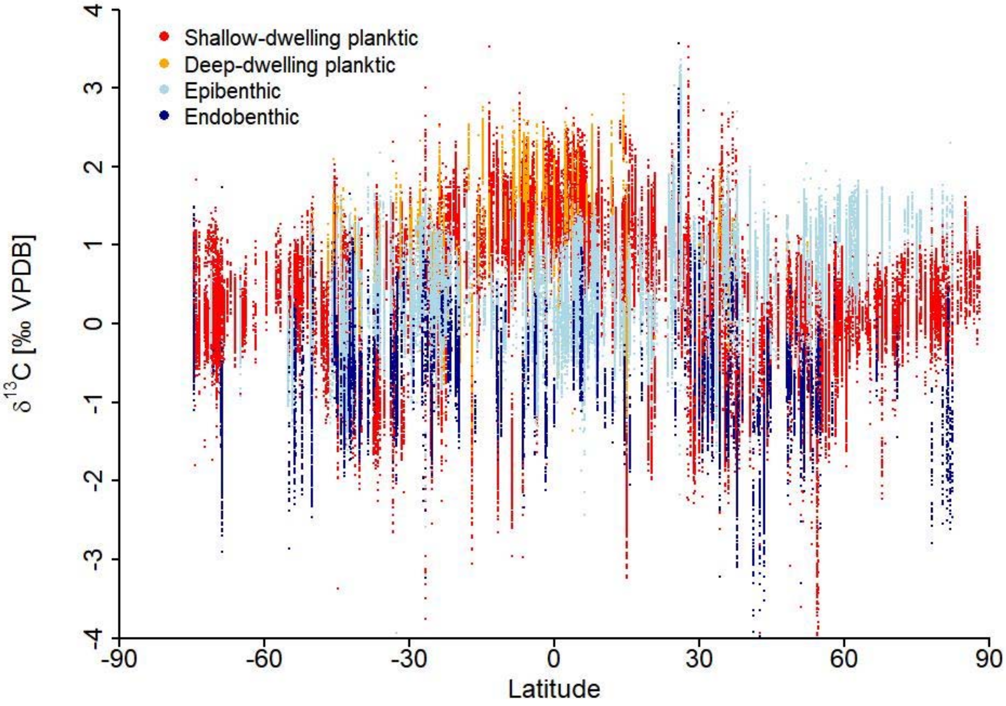

Figure 9: Distribution of δ^{13}C values with latitude. Red/orange: planktic foraminifera, blue: benthic foraminifera. Extreme values outside the axis ranges are not shown.

3.4. Distribution of radiocarbon ages

The data set contains 6,153 individual radiocarbon ages with a maximum age of about 56 ka. About 47% of the cores are associated with at least one radiocarbon date. Most of the radiocarbon-dated cores are from the Atlantic (44%) followed by the Pacific (28%) and the Arctic Ocean (12%) (Fig. 10). The temporal distribution of the radiocarbon ages (Fig. 11) shows that deglacial sequences have been preferentially dated which is likely a consequence of the stratigraphic extent and the scientific attention focussed on this period. The fraction of reversals is higher for the deglacial and glacial periods, where the the higher sampling density increases the likelihood of reversals.

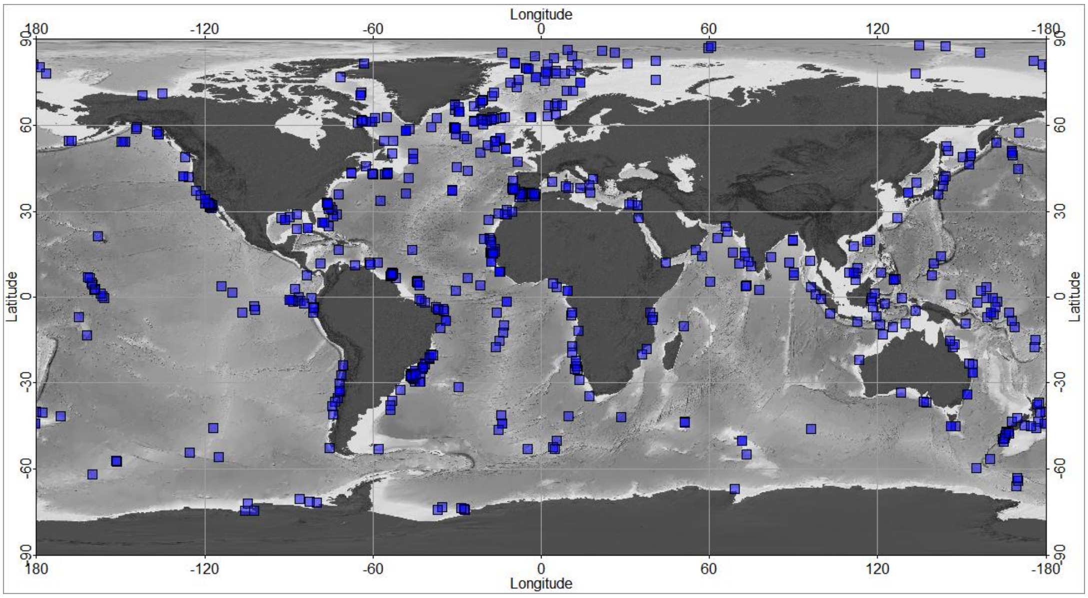

Figure 10: Spatial distribution of stable isotope records with at least one radiocarbon age. The map has been generated with PaleoDataView (Langner and Mulitza, 2019).

4. Possible applications

4.1 Marine Geology and Paleoceanography

Foraminiferal oxygen isotope ratios provide one of the most reliable tools for stratigraphy in marine sediments, particularly for time periods older than the range of the radiocarbon method, or if radiocarbon is not available or associated with large uncertainties due to unknown reservoir ages. Usually oxygen-isotope stratigraphy is applied by using globally (Imbrie et al., 1984; Prell et al., 1986; Lisiecki and Raymo, 2005) or basin-wide (Lisiecki and Stern, 2016) isotope reference curves. The collection presented here may provide the opportunity to find and align new records with the closest published isotope record measured on the same species, taking events into account that may only occur locally. Through its value for stratigraphy, our collection may also provide a foundation for the global mapping of seafloor sedimentation rates. The spatial quantitative mapping of sedimentation rates will allow the development of sediment budgets for the seafloor, including carbon burial.

Oxygen and carbon isotope ratios of foraminifera are of great value for paleoclimatology, by providing information on the history of seawater temperature and isotopic composition as well as circulation, productivity and carbon sequestration. This isotope atlas will allow for new global compilations to be undertaken to understand these processes at a global scale. Although distorted by habitat- and vital effects, there is hope that some of these effects can be represented and quantified in foraminiferal ecosystem/calcification models (e.g. Wolf-Gladrow et al., 1999; Schmidt and Mulitza, 2002; Fraile et al., 2008). Since the number of climate models containing the cycling of oxygen- and carbon isotopes is constantly growing (Marchal and Curry, 2008; Kurahashi-Nakamura et al., 2017; Tierney et al., 2020; Muglia et al., 2018; Völpel et al., 2017), foraminiferal isotopes may provide the opportunity to validate climate model experiments directly. Given this prospect and the spatial coverage, foraminiferal isotope data should be rescued, assembled and organized to secure the information for future applications as future work continues to improve our understanding of the ecological and geochemical processes that determine isotope ratios in foraminiferal shells. Depending on the scientific problem, paleoceanographic compilations usually have specific criteria (e.g. temporal resolution or the availability of radiocarbon ages) for the selection of the records to be included (e.g. Jonkers et al., 2020). An atlas product that includes the majority of the available records enables quick selection of suitable data without an extensive literature review.

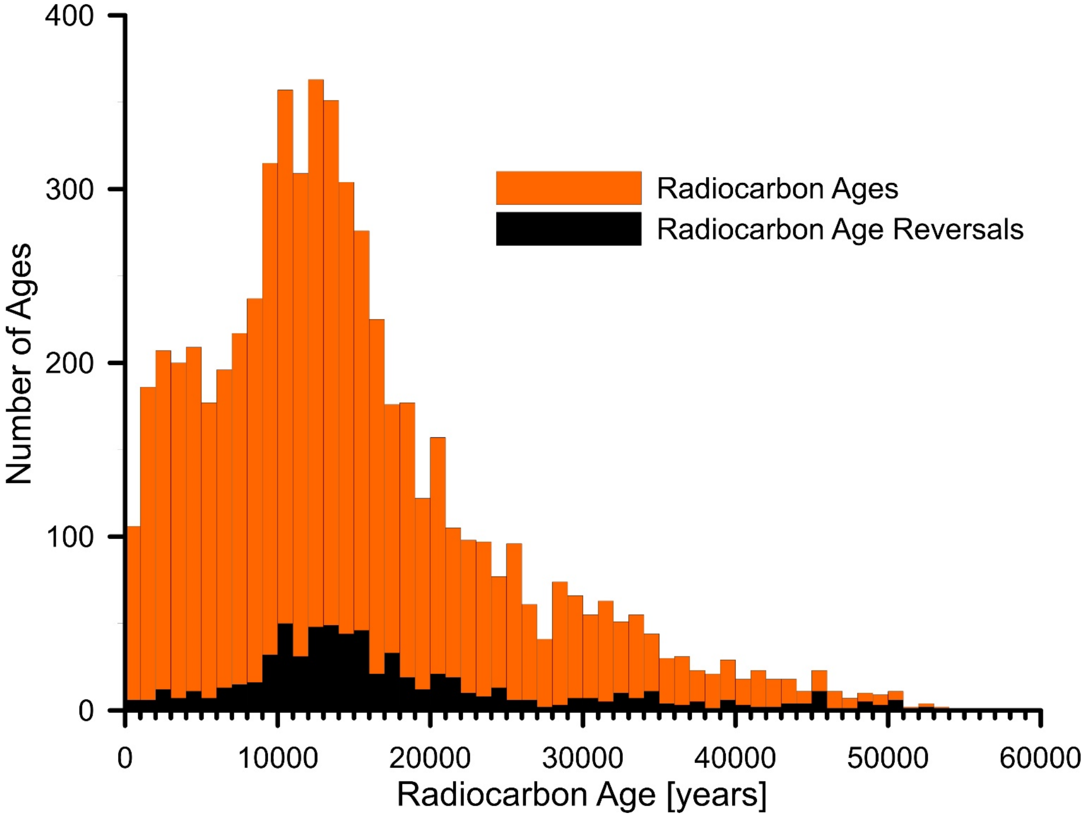

Figure 11: Distribution of radiocarbon ages in 1-kyr bins. Fraction of age reversals in black. Three negative radiocarbon ages are not included.

4.2 Expedition planning

The planning of marine coring campaigns requires prior knowledge of existing cores. Existing core locations are often resampled to get new sediment material or to extend the stratigraphic coverage with alternative coring gear that can penetrate deeper into the sediment. For example, many IODP and ODP cores are drilled on sites where short cores were previously retrieved. The knowledge of existing core locations and their stratigraphy allows identification of sampling gaps. Many aspects of marine expeditions are unpredictable, and schedules and coring plans regularly have to be adapted, often on a daily basis. The atlas we are presenting here, provides fast access to stratigraphic data and may aid the identification of suitable alternative coring locations on ocean expeditions. Both the PDV software and the atlas do not require web access and are therefore suitable to be used with a standard laptop computer.

4.3 Education

Foraminiferal oxygen isotope ratios are still the most valuable stratigraphic tool in marine sediments. The atlas covers various sedimentation regimes and therefore provides numerous examples of how factors like local hydrography, species or sedimentation rates influence the patterns of downcore isotope ratios. It therefore may be used as a resource to train students in regional isotope stratigraphy for studies in Paleoceanography, Paleoclimate and Marine Geology.

5 Data availability

All data included in the World Atlas of late Quaternary Foraminiferal Oxygen and Carbon Isotope Ratios can be downloaded at https://doi.pangaea.de/10.1594/PANGAEA.936747 (Mulitza et al., 2021). For use with the software PaleoDataView, the unzipped root directory ("WA_Foraminiferal_Isotopes_2021") of the collection with all its content can be copied into the "Documents/PaleoDataView/" folder (Windows) or the /PaleoDataView/ folder under "Applications" (macOS). For use with custom software, netCDF files containing stable isotopes data are stored under "WA_Foraminiferal_Isotopes_2021\Foraminiferal Isotopes\Data\" and the radiocarbon data under "WA_Foraminiferal_Isotopes_2021\Age\".

6 Future: Building a dynamic World Atlas of Marine Sediments

The amount of proxy data from marine sediments is growing fast and the demand of data sets that can constrain past states of the Earth system is increasing. The complexity of the data makes it challenging to maintain and reduce the data sets into spatially and chronologically coherent and meaningful data sets. We propose to initiate an atlas series that provides raw data in a consistent data format as a first step from data archived in public databases (as published) towards more sophisticated data products describing past states of the ocean and the seafloor (Fig. 12). Eventually, these harmonized data sets can form a continuously growing and sustainable public "database layer" where proxy-specific raw data can be queried and directly loaded into software that provides the tools to generate homogenized data products that can reach out into other disciplines, i.e., climate modelling. We present a simple file-based data collection where each file contains only one proxy record rather than all available data of the core. Paleoclimatic data are often analysed and assembled in proxy-specific collections, because proxy-specific transfer functions have to be applied in order to quantify environmental variables. Furthermore, comparisons of records from different sites are preferably done on the same proxy type to ensure comparability. A single file per proxy facilitates the composition of proxy-specific collections, avoiding the additional costs (i.e., in terms of data management and disk space) of other downcore parameters in the same file. This modularity also allows individual scientists to separate their unpublished/unvalidated data from published/validated data that are ready to be included into a proxy collection. On the other hand, it is desirable to consistently apply the same stratigraphy to all proxies from a single core. PDV will automatically apply a single age model to all proxy records with the same core label. This requires, however, that the depth scales and the core label of the different proxies are identical, when the data are imported.

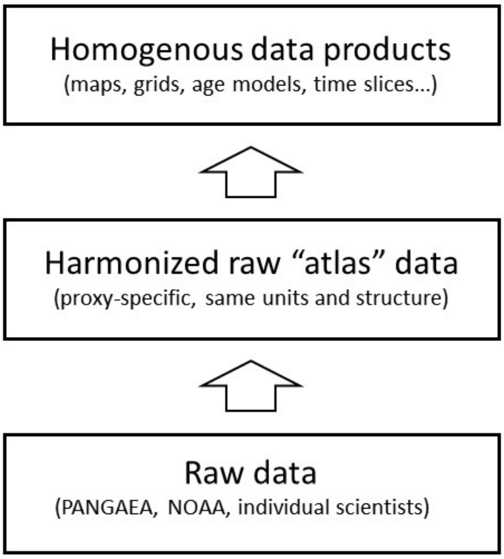

Figure 12: Potential workflow to form sustainable data products from raw databases.

Stable isotopes and radiocarbon ages usually provide the stratigraphic basis for further investigations. When collections of other proxies are added to PDV, these collections can rely on the stratigraphic data provided here and any changes in the stratigraphy will be applied to all proxy data in the collection. The efficient visualization of the data in PDV allows the identification of erroneous data and helps to improve the atlas product over time. The Excel export and import functions of PDV also ensure access to the data for individuals without strong programming skills. We hope this atlas will be a useful resource for the paleoceanography and marine geology community and will continue to grow through the contribution of new datasets as they are developed.

https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

Appendix A

Table 1: References for the included stable isotope and radiocarbon data.

Core/Site	References
12PC51	Sikes and Keigwin, 1994
3MO67	Znaidi-Rivault, 2006a
64PE-174P13	Scussolini and Peeters, 2013
75KS23	Znaidi-Rivault, 2006b
75KS5	Znaidi-Rivault, 2006c
75KS50	Znaidi-Rivault, 2006d
75KS76	Znaidi-Rivault, 2006e
75KS79	Znaidi-Rivault, 2006f
A179-15	Mix et al., 1986; CLIMAP Project Members, 2004a
A7	Sun et al., 2005
AA_GC5	Rathburn et al., 1997
AAS9_21	Govil and Naidu, 2010
AHF-11343	Mortyn et al., 1996
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Core/Site	References
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Core/Site	**References**
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CHAT10K	McCave et al., 2008; McCave et al., 2008; Maxson et al., 2019
CHAT3K	McCave et al., 2008
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Core/Site	**References**
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GeoB1032-2	Bickert and Mackensen, 2004
GeoB1032-3	Wefer et al., 1996; Bickert and Mackensen, 2004
GeoB1034-1	Bickert and Mackensen, 2004
GeoB1034-3	Bickert and Mackensen, 2004
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Core/Site	**References**
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Core/Site	References
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Core/Site	References
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JM11-FI-19PC	Hoff et al., 2016
JM96-1225_1-GC	Hagen and Hald, 2002
JM96-1225_2-GC	Hagen and Hald, 2002
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KET82-21	Colin et al., 2021
KF-12	Costa et al., 2016a
KF14	Leonhardt et al., 2015
KF16	Repschläger et al., 2015
KH94-3_LM-8	Oba and Murayama, 2004
KN07304-0003PG	Curry et al., 1988
KN166-14-11JPC	Elmore et al., 2015a; Elmore et al., 2015b
KN166-14-3GGC	Elmore et al., 2015b
KN166-14-JPC-13	Hodell et al., 2010
KNR110-43PC	Curry and Crowley, 1987
KNR110-50	Curry et al., 1988
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KNR159-5-125GGC	Lund et al., 2015; Hoffman and Lund, 2012
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KNR159-5-17JPC	Lund et al., 2015; Tessin and Lund, 2013
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KNR159-5-22GGC	Lund et al., 2015; Hoffman and Lund, 2012
KNR159-5-30GGC	Lund et al., 2015; Tessin and Lund, 2013
KNR159-5-33GGC	Lund et al., 2015; Tessin and Lund, 2013
KNR159-5-36GGC	Lund et al., 2015; Carlson et al., 2008; Sortor and Lund, 2011; Came et al., 2003
KNR159-5-42JPC	Lund et al., 2015; Hoffman and Lund, 2012
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KNR159-5-78GGC	Lund et al., 2015; Tessin and Lund, 2013
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KNR166-2-105JPC	Lynch-Stieglitz et al., 2009
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KNR166-2-113JPC	Lynch-Stieglitz et al., 2009
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KNR166-2-26JPC	Schmidt and Lynch-Stieglitz, 2011; Lynch-Stieglitz et al., 2011
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https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

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https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

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ME0005-24JC	Kienast et al., 2013; Kusch et al., 2010; Kienast et al., 2007; Dubois et al., 2011
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MG237	Giresse et al., 1982; Sarnthein et al., 1994
ML1208-06BB	Lynch-Stieglitz et al., 2015
ML1208-10GC	Lynch-Stieglitz et al., 2015
ML1208-11GC	Lynch-Stieglitz et al., 2015
ML1208-12GC	Lynch-Stieglitz et al., 2015
ML1208-13BB	Monteagudo et al., 2021; Lynch-Stieglitz et al., 2015; Costa and McManus, 2017
ML1208-15GC	Lynch-Stieglitz et al., 2015
ML1208-17PC	Lynch-Stieglitz et al., 2015
ML1208-17TC	Lynch-Stieglitz et al., 2015
ML1208-18GC	Lynch-Stieglitz et al., 2015; Monteagudo et al., 2021; Lynch-Stieglitz, unpublished
ML1208-19GC	Lynch-Stieglitz et al., 2015
ML1208-20BB	Monteagudo et al., 2021; Lynch-Stieglitz et al., 2015; Costa and McManus, 2017
ML1208-27BB	Lynch-Stieglitz et al., 2015; Monteagudo et al., 2021; Lynch-Stieglitz, unpublished
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ML1208-31BB	Lynch-Stieglitz et al., 2015; Jacobel et al., 2016; Monteagudo et al., 2021; Lynch-Stieglitz, unpublished
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https://doi.org/10.5194/essd-2021-337
Preprint. Discussion started: 25 November 2021

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OC205-103GGC	Curry et al., 1999
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OC205-2-106GGC	Slowey and Curry, 1995
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Core/Site	References
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Core/Site	References
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PS1563-2	Grobe, 2002a
PS1564-2	Grobe, 2002b
PS1565-2	Hillenbrand, 1995
PS1576-2	Brehme, 1992
PS1577-1	Brehme, 1992
PS1588-1	Grobe, 1996k

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PS1591-1	Grobe and Fütterer, 1990
PS1599-3	Weber, 1992; Weber et al., 1994
PS1606-3	Melles, 1991
PS1607-1	Melles, 1991
PS1607-3	Melles, 1991
PS1609-3	Melles, 1991
PS1611-3	Melles, 1991
PS1612-1	Melles, 1991
PS1612-2	Melles, 1991
PS1613-2	Melles, 1991
PS1613-4	Melles, 1991
PS1640-1	Grobe and Mackensen, 1992
PS1648-1	Grobe and Mackensen, 1992
PS1649-2	Ott and Gersonde, 1997b
PS1650-1	Ott and Gersonde, 1997c
PS1650-2	Ott and Gersonde, 1997d
PS1651-1	Ott and Gersonde, 1997e
PS1651-2	Ott and Gersonde, 1997f
PS1652-1	Ott and Gersonde, 1997g
PS1652-2	Ott and Gersonde, 1997h
PS1653-1	Ott and Gersonde, 1997i
PS1653-2	Ott and Gersonde, 1997j
PS1654-1	Ott and Gersonde, 1997k
PS1654-2	Ott and Gersonde, 1997l; Bianchi and Gersonde, 2004
PS1704-4	Horwege/Spielhagen, unpublished
PS1706-1	Horwege/Spielhagen, unpublished
PS1707-1	Horwege/Spielhagen, unpublished
PS1708-1	Horwege/Spielhagen, unpublished
PS1730-2	Nam, 1997; Stein et al., 1996
PS1754-1	Niebler, 1995
PS1768-8	Mulitza et al., 1999; Gersonde et al., 2003
PS1769-1	Niebler, 1995

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PS1789-1	Weber, 1992; Weber et al., 1994
PS1790-1	Weber, 1992; Weber et al., 1994
PS1805-6	Grobe, 1996l
PS1811-8	Grobe, 1996m
PS1812-1	Grobe, 1996n
PS1812-6	Grobe, 1996o
PS1813-6	Grobe, 1996p
PS1816-1	Grobe, 1996q
PS1878-3	Nowaczyk et al., 2003; Telesiński et al., 2014a; Telesiński et al., 2014b
PS1894-7	Nørgaard-Pedersen et al., 2003; Telesiński et al., 2014a; Telesiński et al., 2014b
PS1906-1	Magnus, 2000; Nørgaard-Pedersen et al., 2003
PS1906-2	Nees, 1993; Nørgaard-Pedersen et al., 2003
PS1910-1	Telesiński et al., 2014a
PS1920-1	Stein et al., 1996
PS1927-2	Nam, 1997; Stein et al., 1996
PS1951-1	Stein et al., 1996
PS2037-3	Bonn, 1995
PS2038-2	Bonn et al., 1998
PS2039-1	Bonn, 1995
PS2040-2	Bonn, 1995
PS2045-3	Bonn, 1995
PS2046-1	Bonn, 1995
PS2047-3	Bonn, 1995
PS2049-4	Bonn, 1995
PS2050-1	Bonn, 1995
PS2055-2	Bonn, 1995
PS2056-1	Bonn, 1995
PS2076-3	Niebler, 1995
PS2082-1	Mackensen et al., 1994
PS2085-2	Niebler, 1995
PS2102-2	Niebler, 1995; Gersonde et al., 2003
PS2121-4	Müller, 1995

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PS2166-2	Nørgaard-Pedersen et al., 1998
PS2170-4	Stein et al., 1994
PS2177-1	Nørgaard-Pedersen et al., 2003; Nørgaard-Pedersen et al., 1998
PS2185-3	Spielhagen et al., 2004; Nørgaard-Pedersen et al., 1998
PS2195-4	Nørgaard-Pedersen et al., 1998
PS2200-2	Nørgaard-Pedersen et al., 1998
PS2206-4	Stein et al., 1994
PS2208-1	Stein et al., 1994; Stein and Schneider, 2003
PS2212-3	Wollenburg et al., 2001
PS2250-5	Niebler, 1995
PS2423-4	Notholt, 1998
PS2424-1	Notholt, 1998
PS2446-4	Knies and Stein, 1998b; Stein and Fahl, 2000
PS2458-4	Spielhagen et al., 2005; Spielhagen, unpublished
PS2487-6	Flores et al., 1999
PS2495-3	Mackensen et al., 2001; Gersonde et al., 2003; Niebler, 2004a; Niebler, 2004b; Niebler, 2004c
PS2498-1	Mackensen et al., 2001; Gersonde et al., 2003; Niebler, 2004d; Niebler, 2004e; Niebler, 2004f
PS2499-5	Mackensen et al., 2001; Gersonde et al., 2003
PS2539-2	Hillenbrand et al., 2003
PS2540-1	Hillenbrand et al., 2003
PS2541-2	Hillenbrand et al., 2003
PS2543-3	Hillenbrand et al., 2003
PS2547-2	Hillenbrand et al., 2003
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PS2551-1	Hillenbrand et al., 2002
PS2556-1	Hillenbrand et al., 2003

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PS2561-2	Krueger et al., 2008
PS2644-2	Voelker, 1999
PS2644-5	Voelker, 1999
PS2646-5	Voelker, 1999
PS2647-2	Voelker, 1999
PS2709-1	Flores et al., 2000
PS2819-2	Vernaleken, 1999
PS2820-1	Vernaleken, 1999
PS2837-5	Nørgaard-Pedersen et al., 2003
PS2876-1	Nørgaard-Pedersen et al., 2003
PS2876-2	Nørgaard-Pedersen et al., 2003
PS2887-1	Nørgaard-Pedersen and Spielhagen, 2000; Nørgaard-Pedersen et al., 2003
PS2887-2	Nørgaard-Pedersen, 2000b; Nørgaard-Pedersen et al., 2003
PS51_038-3	Nørgaard-Pedersen, 2006
PS51_038-4	Spielhagen et al., 2004
PS66_309-1	Winkelmann et al., 2008
PS69_251-1	Hillenbrand et al., 2017; Smith et al., 2014
PS69_912-3	Ronge, 2019b, 2019a
PS69_912-4	Ronge, 2019b, 2019a
PS72_396-3	Geibert et al., 2021
PS75_056-1	Ullermann et al., 2016
PS75_072-4	Benz et al., 2016; Tiedemann and Lembke-Jene, unpublished
PS75_073-2	Benz et al., 2016; Tiedemann and Lembke-Jene, unpublished
PS75_085-1	Benz et al., 2016; Tiedemann and Lembke-Jene, unpublished
PS75_160-1	Hillenbrand et al., 2017
PS75_167-1	Hillenbrand et al., 2017
PS75-059-2	Ullermann et al., 2016; Ronge et al., 2016
Q208	Winn, 2013a
Q585	Weaver et al., 1998
Q859	Winn and Fenner, 2013a
Q861	Winn and Fenner, 2013b

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R657	Weaver et al., 1998
RAMA44P	Keigwin, 1987
RAPiD-10-1P	Thornalley et al., 2011; Thornalley et al., 2010
RAPiD-12-1K	Thornalley et al., 2010, 2009
RAPiD-15-4P	Thornalley et al., 2010
RAPiD-17-5P	Thornalley et al., 2010
RC09-150	Bé and Duplessy, 1976
RC09-166	Tierney et al., 2017
RC10-131	Anderson et al., 1989
RC10-289	Matsumoto and Lynch-Stieglitz, 2003
RC11-120	Curry et al., 1988
RC11-238	Koutavas and Lynch-Stieglitz, 2003
RC11-83	Charles et al., 1996; Charles and Fairbanks, 1992; Piotrowski et al., 2004
RC11-86	Shackleton, 2003
RC12-109	Anderson et al., 1989
RC12-113	Anderson et al., 1989
RC12-279	Lynch-Stieglitz et al., 2006
RC12-294	CLIMAP Project Members: Stable isotope analysis on sediment core RC12-294, 2003.
RC12-339	Naqvi et al., 1994
RC12-344	Duplessy, 1982; Naqvi et al., 1994; Rashid et al., 2007
RC13-110	Lyle et al., 2002
RC13-115	Lyle et al., 2002
RC13-140	Koutavas and Lynch-Stieglitz, 2003
RC13-228	Curry et al., 1988
RC13-229	Oppo and Fairbanks, 1987
RC13-254	Charles et al., 1991
RC13-259	Shemesh et al., 1995
RC13-269	Shemesh et al., 1995.
RC14-31	Broecker et al., 2000
RC14-33	Broecker et al., 2000
RC15-93	Charles et al., 1991

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RC16-119	Oppo and Horowitz, 2000
RC16-59	Lynch-Stieglitz, unpublished
RC16-84	Oppo and Horowitz, 2000
RC16-86	Oppo and Horowitz, 2000
RC17-176	Leech et al., 2013
RC17-69	CLIMAP Project Members, 1981
RC8-102	Koutavas and Lynch-Stieglitz, 2003
RC9-150	Wells et al., 1994
RC9-203	Oppo and Fairbanks, 1987
RECORD23	Colin et al., 2021
RNDB-11PC	Keigwin and Lehman, 2015
RNDB-13PC	Keigwin and Lehman, 2015
RR0503_125JPC	Schiraldi et al., 2014; Sikes et al., 2016
RR0503_41JPC	Sikes et al., 2016
RR0503-79JPC	Sikes et al., 2016
RR0503_83JPC	Sikes et al., 2016
RR0503_83TC	Sikes et al., 2016
RR0503-87JPC	Sikes et al., 2016
RR0503_87TC	Sikes et al., 2016
RR0503-64JPC	Schiraldi et al., 2014; Sikes et al., 2016
RR0503-79JPC	Schiraldi et al., 2014
RR0503-87JPC	Schiraldi et al., 2014
RS105_GC23	Troedson and Davies, 2001
RS105GC25	Troedson and Davies, 2001; Bostock et al., 2006
RS112GC10	Troedson and Davies, 2001
RS112GC9	Troedson and Davies, 2001; Bostock et al., 2006
RS147-GC07	Sikes et al., 2016; Sikes et al., 2009
RS67-GC13	Lynch-Stieglitz et al., 1994
RS67-GC16	Lynch-Stieglitz et al., 1994
RS67-GC27	Lynch-Stieglitz et al., 1994
RS67-GC3	Lynch-Stieglitz et al., 1994
RS67-GC52	Lynch-Stieglitz et al., 1994

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RS78-GC18	Lynch-Stieglitz et al., 1994
S794	Weaver et al., 1998
SAN-76	Toledo et al., 2007
SAT-048A	Frozza et al., 2020
SBB2012DB	Osborne et al., 2020
SCS90-36	Huang et al., 1997
SHAK06-5K	Ausín et al., 2019
SK129-CR05	Guptha et al., 2005
SK157-15	Raza et al., 2014
SK157-16	Raza et al., 2014
SK157-20	Naik and Naidu, 2016
SK157-GC04	Saraswat et al., 2005
SK200-GC17	Naik et al., 2014
SK218_1	Govil and Divakar Naidu, 2011; Govil, Naidu, Mulitza, unpublished
SK237-GC04	Saraswat et al., 2013
SK237-GC09	Saraswat et al., 2019
SL-1	Guptha et al., 2005
SL-4	Guptha et al., 2005
SN6	Tiwari et al., 2015
SO12_98	Winn, 2012
SO126_39KL	Weldeab et al., 2019
SO130_261KL	Rad et al., 2003
SO135_03GKG	Winn, 2014a
SO135_04SL	Winn, 2014b
SO135_05GKG	Winn, 2014c
SO135_21GKG	Winn, 2014f
SO135_40KL	Winn, 2014f
SO136_003GC	Ronge et al., 2015; Barrows et al., 2007
SO136-111	Crosta et al., 2004; Sturm, 2003
SO161_5_50SL	Blumberg et al., 2008
SO164-03-4	Reißig et al., 2019
SO178-13-6	Max et al., 2014; Lembke-Jene et al., 2017

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SO189-144KL	Mohtadi et al., 2014; Mohtadi, unpublished
SO189-39KL	Mohtadi et al., 2014; Mohtadi, unpublished
SO201-2-12KL	Riethdorf et al., 2013
SO201-2-85	Riethdorf et al., 2013; Max et al., 2014
SO202_1_27-6	Maier et al., 2015; Maier et al., 2018
SO213_2_60-1	Molina-Kescher et al., 2016
SO213_2_82-1	Ronge et al., 2015
SO213_2_84-1	Ronge et al., 2015
SO213-59-2	Tapia et al., 2015; Molina-Kescher et al., 2016; Nürnberg, unpublished
SO225-08-3	Raddatz et al., 2017; Nürnberg, unpublished
SO225-53-3	Raddatz et al., 2017; Nürnberg, unpublished
SO236_52-4	Bunzel et al., 2017
SO26_127KA	Winn et al., 1991
SO26_131KA	Winn et al., 1991
SO26_141KA	Sarnthein and Winn, 2013b
SO26_189KA	Sarnthein and Winn, 1991
SO26_222KA	Sarnthein and Winn, 2013a
SO26_58KA	Winn et al., 1991
SO26_90KA	Winn et al., 1991
SO28-05KL	Sirocko, 1989
SO28-11KL	Sirocko, 1989
SO28-18KL	Sirocko, 1989
SO35_2_101KL	Winn et al., 1990
SO35_2_102KL	Winn et al., 1990
SO35_3_182KL	Winn et al., 1990
SO35_3_211KL	Winn et al., 1990
SO35_3_272KL	Winn, 2013i
SO36_2_17SL	Lynch-Stieglitz et al., 1994
SO36-SL17	Lynch-Stieglitz et al., 1994
SO36-SL7	Lynch-Stieglitz et al., 1994
SO42-15KL	Sirocko, 1989

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SO42-51KL	Sirocko, 1989
SO42-57KL	Sirocko, 1989
SO42-64KL	Sirocko, 1989
SO42-70KL	Sirocko, 1989
SO42-71KL	Sirocko, 1989
SO42-74KL	Sirocko et al., 2000
SO42-82KL	Sirocko, 1989
SO42-87KL	Sirocko, 1989
SO75_3_26KL	Zahn et al., 1997
SO82_2-2	Lackschewitz et al., 1998
SO82_4-2	Lackschewitz et al., 1998; Moros et al., 1997
SO82_5-2	Jung, 1996; Lackschewitz et al., 1998; van Kreveld et al., 2000
SO82_7-2	Lackschewitz et al., 1998.
SO90_137KA	Rad et al., 1999
SO93_1_22KL	Weber, 1997
Station-8s-MC	Harada et al., 2004
Station-8s-PC	Harada et al., 2004
SU81-07	Kallel et al., 1997
SU81-18	Bard et al., 1987; Sarnthein et al., 1994; Duplessy, 1996; Bard et al., 2000; Waelbroeck et al. 2001, Waelbroeck et al. 2019; Missiaen et al., 2019
SU81-32	Sarnthein et al., 1994
SU81-44	Sarnthein et al., 1994
SU81-50	Sarnthein et al., 1994
SU90-08	Missiaen et al., 2020; Grousset et al., 1993; Elliot et al., 1998
SU90-09	Grousset et al., 2001
SU90-11	Labeyrie et al., 1995
SU90-24	Elliot et al., 2002
SU90-I02	Schulz, 1995
SU90-I03	Schulz, 1995
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SU92-21	Sarnthein et al., 1994
T86-15P	Sarnthein et al., 1994
T86-15S	Sarnthein et al., 1994
T87_2_20G	Thunell et al., 1977
TAN0803-09	Maxson et al., 2019; Bostock et al., 2015
TAN0803-27	Maxson et al., 2019
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TAN1106-15	Maxson et al., 2019
TAN1106-28	Bostock et al., 2015
TAN1106-34	Maxson et al., 2019; Bostock et al., 2015
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TAN1106-7	Maxson et al., 2019
TGS-931	Schröder et al., 2018
TR163-19	Spero et al., 2003
TR163-25T	Hoogakker et al., 2018
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TTN057-13-PC4	Kanfoush et al., 2002; Kanfoush et al., 2000; Shemesh et al., 2002
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TTR13-AT-455G	Seidenkrantz et al., 2021
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U306	Winn, 2016
U938	Weaver et al., 1998
Ulleung_C11	Kim et al., 2000
Ulleung_C21	Kim et al., 2000
UM94PC31	Corselli et al., 2002
V10-49	Kallel et al., 1997
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V12-70	Lynch-Stieglitz et al., 2006
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V21-40	Koutavas and Lynch-Stieglitz, 2003
V22-108	Charles et al., 1991
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V22-196	Sarnthein et al., 1994
V22-197	Curry et al., 1988
V22-222	Mix et al., 1986
V23-100	Sarnthein et al., 1994
V23-81	Jansen and Veum, 1990; Elliot et al., 1998
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V24-166	Anderson et al., 1989
V24-170	Anderson et al., 1989
V24-184	Anderson et al., 1989
V24-253	Oppo and Horowitz, 2000
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V25-59	Curry et al., 1988
V26-175	Matsumoto and Lynch-Stieglitz, 2003
V26-176	Sarnthein et al., 1988; Matsumoto and Lynch-Stieglitz, 2003; CLIMAP Project Members, 2004b
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V34-90	Gorbarenko et al., 2002
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VM12-107	Schmidt et al., 2012
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VM19-110	Leech et al., 2013
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VM28-233	Leech et al., 2013
VM28-234	Leech et al., 2013

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VM28-235TW	Leech et al., 2013
VM28-236	Leech et al., 2013
VM28-246	Leech et al., 2013
VM34-2	Leech et al., 2013
VNTR01_10PC	Keigwin and Lehman, 2015
W8402A-14	Jasper et al., 1994
W8709A-1	Lyle et al., 1992
W8709A-13	Lyle et al., 1992; Lund and Mix, 1998
W8709A-8	Lyle et al., 1992; Ortiz et al., 1997
W8709A-8TC	Lyle et al., 1992; Ortiz et al., 1997
WIND-28K	Kiefer et al., 2006; Johnstone et al., 2014
Y71-06-12	Shackleton, 1977a
Y71-09-101	Lyle et al., 2002
Z2108	Nelson et al., 1994
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