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# VARDA (VARved sediments DAtabase) – providing and connecting proxy data from annually laminated lake sediments

**Arne Ramisch, Alexander Brauser, Mario Dorn, Cecile Blanchet, Brian Brademann, Matthias Köppl, Jens Mingram, Ina Neugebauer, Norbert Nowaczyk, Florian Ott, Sylvia Pinkerneil, Birgit Plessen, Markus J. Schwab, Rik Tjallingii, and Achim Brauer**

GFZ German Research Center for Geoscience, Section Climate Dynamics and Landscape Evolution, Telegrafenberg, 14473 Potsdam, Germany

**Correspondence:** Arne Ramisch (arne.ramisch@gfz-potsdam.de)

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**Abstract.** Varved lake sediments provide climatic records with seasonal to annual resolution and low associated age uncertainty. Robust and detailed comparison of well-dated and annually laminated sediment records is crucial for reconstructing abrupt and regionally time-transgressive changes as well as validation of spatial and temporal trajectories of past climatic changes. The VARved sediments DAtabase (VARDA) presented here is the first data compilation for varve chronologies and associated palaeoclimatic proxy records. The current version 1.0 allows detailed comparison of published varve records from 95 lakes. VARDA is freely accessible and was created to assess outputs from climate models with high-resolution terrestrial palaeoclimatic proxies. VARDA additionally provides a technical environment that enables us to explore the database of varved lake sediments using a connected data model and can generate a state-of-the-art graphic representation of a multisite comparison. This allows the reassessment of existing chronologies and tephra events to synchronize and compare even distant varved lake records. Furthermore, the present version of VARDA permits the exploration of varve thickness data. In this paper, we report in detail on the data-mining and compilation strategies for the identification of varved lakes and assimilation of high-resolution chronologies, as well as the technical infrastructure of the database. Additional palaeoclimatic proxy data will be provided in forthcoming updates. The VARDA graph database and user interface can be accessed online at https://varve.gfz-potsdam.de (last access: 15 September 2020), all datasets of version 1.0 are available at https://doi.org/10.5880/GFZ.4.3.2019.003 (Ramisch et al., 2019).

## 1 Introduction

A major challenge in simulating climate change is validating model outputs with palaeoclimatic data. Model–data comparisons on regional to global scales require the integration of palaeoclimatic data from single sites into multisite networks (e.g. Franke et al., 2017). Annually laminated lake sediments provide reliable data for such networks because they offer palaeoclimatic information in high temporal resolution with low associated age uncertainty. Due to their annual to seasonal resolution, multisite networks of varved lake sediments enable investigations of abrupt and regionally time-transgressive climate change on the continents (e.g. Lane et al., 2013; Rach et al., 2014), which are fundamental to understanding past climates, especially that of the last glacial cycle (Clement and Peterson, 2008), and to better assess spatial and temporal trajectories of future climate changes. Networks of varved lake sediments also provide means to test contrasted proxy responses to climate change (e.g. Ott et al., 2017; Ramisch et al., 2018; Roberts et al., 2016), further enhancing the robustness of palaeoclimatic reconstructions. However, despite their usefulness for the generation of highly resolved multisite networks, a global synthesis of varve-related palaeoclimatic data is still not available.

Various data providers have been developed which offer free access to palaeoclimatic and palaeoenvironmental information including high-resolution terrestrial archives. These include (1) large-scale data repositories, such as PANGAEA (http://www.pangaea.de, last access: 15 September 2020), the National Oceanic and Atmospheric Administration's (NOAA) World data service for palaeoclimatology archives (http://www.ncdc.noaa.gov, last access: 15 September 2020) and Neotoma (http://www.neotomadb.org, last access: 15 September 2020, Williams et al., 2018), and (2) proxy- or time-slice-specific databases like the ACER (Sánchez Goñi et al., 2017), the European Pollen database (Fyfe et al., 2009), the SISAL database (Atsawawaranunt et al., 2018), or the PAGES2k Global 2000 Year Multiproxy Database (Pages 2k consortium, 2017). However, the distribution of information between data providers makes a custom generation of multisite networks from varved sediments inefficient and time-consuming. Moreover, continuous geochronological development results in frequent updates of fundamental methods such as calibration curves (e.g. Reimer et al., 2004, 2009, 2013) and age–depth modelling algorithms (e.g. Bronk Ramsey, 2008; Blaauw and Christen, 2011). Incorporating such changes into existing varve-related datasets requires an interactive approach that is not offered by fixed data structures of standard relational database management systems. To overcome these limitations, we developed a new and state-of-the-art graph database especially (but not exclusively) for varved sediment records. The database was developed within the German climate modelling initiative PalMod (Latif et al., 2016), to validate the output of comprehensive Earth system models with reliable proxy data from terrestrial and marine (Jonkers et al., 2020) archives. We compiled all available and published varved sediment records and developed criteria for how these data are integrated in this database.

## 2 Data and methods

### 2.1 Data mining

We assessed varve-related publications aided by the literature database of the PAGES varve working group (http://www.pastglobalchanges.org/download/docs/working_groups/vwg/Varvepublications.pdf, last access: 15 September 2020) to identify lake archives exhibiting varved sediments and to compile suitable core-related palaeoclimatic proxy time series. A comprehensive set of lake sediment records was identified, for which proxy data from continuous or floating varve sequences were previously published. All data were collected as raw data from freely available online sources, either from online data repositories (PANGAEA, NOAA, and Neotoma) or data archives within the supplementary materials section of online publications. For a permanent and definite assignment of the compiled datasets within the database to their respective original publication, the digital object identifier (DOI) of the publication or the data provider (if available) was additionally collected and stored.

### 2.2 Data compilation

To ensure an unambiguous identification of a lake record corresponding to a given dataset, we collected and reviewed the required information of lake names and geographic coordinates from the published literature. Table 1 lists required and additional information for lake records included in VARved sediments DAtabase (VARDA). To facilitate searches for lakes in an alphabetically ordered list, the string "Lake" was removed from the name if the string appeared in the beginning of the lake name (e.g. "Lake Ammersee" was changed to "Ammersee"). However, exceptions were made if the string "Lake" is an essential feature of the lake name (e.g. "Lake of the Clouds") or if the reference is in non-English language (e.g. "Lac d'Annecy"). Lake locations were stored as WGS84-referenced geographical coordinates in decimal degrees with four decimal places, which corresponds to a precision of $\sim 10$ m. This even allows a reliable location of small lakes with a surface area $< 1$ ha and is especially useful for dense lake distributions common in large lake districts such as those in Canada or Scandinavia. Since the required precision was not available in most publications, we reassessed the published geographical location using ArcGIS and Google Earth. All lake locations refer to the approximate lake centre and are independent from coring locations.

Sediment composite profiles that were collected from primary literature sources (see Table 2) only require a unique identifier (e.g. MON for Lago Grande di Monticchio) within the VARDA database that links a profile to a corresponding lake (Table 2). Additional information encompasses the geographical coordinates of coring location (fields: latitude, longitude), coring methods (e.g. piston corer), a coring date, water depths at the core location, and the total length of the sediment composite profile with an upper (field: depth start) and lower (field: depth end) depth.

#### 2.2.1 Lake and sediment composite profile meta-information

The data compilation followed the basic strategy of collecting proxy data associated with a published sediment composite profile and information about age–depth models and event layers. A sediment composite profile may either consist of a single core section or several overlapping core sections combined to a composite profile. The depth scale within a sediment composite profile is referred to as composite depth. Since data and meta-information availability greatly varied in between different publications, we classified the available information into required and additional information. The category required encompasses all information that is necessary to (a) associate a proxy value at a given depth in a

**Table 1.** VARDA v01 data sheet for lake information (green field: required information; yellow field: additional information).

| Attribute: | Name | Latitude | Longitude | Elevation | Max depth | Surface area | Catchment area |
|---|---|---|---|---|---|---|---|
| Default units: | String | Decimal degrees (four-digit scale) | | m a.s.l. | m | $m^2$ | $m^2$ |

**Table 2.** VARDA v01 data sheet for sediment composite profile information (green field: required information; yellow field: additional information).

| Attribute: | Label | Latitude | Longitude | Coring method | Drill date | Water depth | Depth start | Depth end |
|---|---|---|---|---|---|---|---|---|
| Default units: | String | Decimal degrees (four-digit scale) | | String | dd/mm/year | m | mm | mm |

sediment composite profile with a corresponding age and to (b) uniquely identify a lake, sediment composite profile, and original publication for a given dataset. The category additional encompasses all information that extends the data pool for more comprehensive analyses and therefore improves reproducibility, the ability to filter data by specific properties and, in addition, the quantification of methodological uncertainties. We converted all datasets to default units to provide standardized and thus inter-comparable data formats. Tables 1–7 provide an overview of data categories and required and additional information properties including the default units.

### 2.2.2 Radiocarbon dates

Uncalibrated radiocarbon measurements were collected from the published literature and adapted to the $^{14}C$ data reporting standards of Millard (2014). This allows efficient reassessments of published chronologies by calibration, age–depth modelling, and age uncertainty estimation (see Table 3). However, reporting standards are not yet fully adapted in the palaeoclimatic community, leading to variations in reported information and data gaps. The required information encompasses from left to right (i) the sampling depth (field: composite depth); (ii) the uncalibrated age (field: age uncalibrated); (iii) the associated measurement error (field: error); (iv) the error type (e.g. 1 sigma); and (v) the dated material (e.g. wood remains). The required sampling position refers to the depth within the sediment composite profile, whereas the sampling position within the individual core sections can be attributed as additional information. If available, we collected additional information on (i) the corresponding core section label (field core section); (ii) section depth (field: section depth); (iii) the lab code; (iv) $\delta^{13}C$ data; (v) the measurement method (field: method), e.g. AMS $^{14}C$; (vi) the organic carbon content of a sample (field: % C); and (vii) C / N ratios.

### 2.2.3 Age–depth models and chronologies

Chronologies for varved lake sediments are commonly based on a combination of different dating methods (Brauer et al., 2014), such as varve counting, radiometric dating (e.g. $^{14}C$, $^{137}Cs$, or $^{210}Pb$) and event age-equivalent dating (e.g. correlation to dated volcanic eruptions). Age–depth models provide the time frame for down-core sequences of sediment composite profiles and allow transformations of sediment proxy records into time series. Initially, most researchers constructed age–depth models by simple linear interpolation between individual chronological points. However, age–depth modelling algorithms such as the OxCal P-Sequence (Bronk-Ramsey, 2007) or Bacon (Blaauw and Christen, 2011) have become more common and perform more complex statistical interpolations.

VARDA version 1.0 includes published chronologies that are available in public data repositories. Tables 4 and 5 provide an overview of the required and additional meta-information for storing chronologies in VARDA and the resulting chronological data sheet, respectively. The required information includes a label for the associated sediment composite profile and the corresponding data and publication DOI. Additional information will enable rapid reassessments of original chronologies.

Additional information reports (i) on age uncertainty; (ii) presence, type, and age of anchor points for floating chronologies (e.g. sediment surface for continuous varve chronologies, $^{14}C$ dates, or elsewhere-dated tephra layers for floating chronologies); (iii) the applied dating methods (e.g. varve counting, radiometric dating, or event layers); (iv) the interpolation method (e.g. linear interpolation or Bayesian age–depth modelling, such as OxCal P-sequence or Bacon); (v) the applied $^{14}C$ calibration curve (e.g. IntCal09); and (vi) the resulting median resolution of the chronology.

Ideally, the chronological data sheet associates a given depth of a sediment composite profile to an age estimate and, if available, an uncertainty range expressed as minimum and

**Table 3.** VARDA v01 data sheet for $^{14}C$ information (green field: required information; yellow field: additional information).

| | | | | | | |
|---|---|---|---|---|---|---|
| Attribute: | Sediment composite profile | Lab code | Section depth | Composite depth | Age uncalibrated | Error |
| Default units: | String | String | mm | mm | a BP | ± a |
| Attribute: | Error type | Dated material | $\delta^{13}C$ | Method | % C | C / N ratio |
| Default units: | 1 sigma [%] | String | ‰ | String | % | dimensionless |

**Table 4.** VARDA v01 data sheet for chronological meta-information (green field: required information; yellow field: additional information).

| | | | | | | |
|---|---|---|---|---|---|---|
| Attribute: | Sediment composite profile | Data DOI | Publication DOI | Has uncertainty? | Uncertainty type | Anchored? |
| Default units: | String | String | String | Boolean | String | Boolean |
| Attribute: | Anchor point type | Anchor point age | Dating method | Interpolation method | $^{14}C$ calibration curve | Median resolution |
| Default units: | String | a BP | String | String | String | a |

maximum estimate as additional information (2 sigma as a default). If depth information for a sediment composite profile was not provided, we either reconstructed an auxiliary composite depth by cumulative sums of continuous varve thickness measurements (if available) or excluded the corresponding chronology from the present data compilation because such time series without corresponding core depth are not updatable. The default depth scale unit was set to millimetres to avoid excessive decimal places in depth reporting. The default age scale unit was set to a BP (year before present) with 1950 CE as zero age. The default age unit was restricted to annual precision and ages are reported in integer numbers (without usage of decimal places).

### 2.2.4 Isochronous event layers

Isochronous event layers provide precise tie points for the synchronization of proxy time series from regionally different locations and facilitate the construction of multisite networks. Furthermore, the identification of layers corresponding to dated events such as volcanic eruptions or geomagnetic excursions provide additional information for the construction of robust chronologies. For the first version of VARDA, we collected information on reported tephra layers in the sediment composite profiles included in the database. Table 6 provides an overview of required and additional information of published tephra layers in VARDA. The required information (composite depth, age, age error, and dating method) is essential for assigning a tephra layer to a given depth in a sediment composite profile and storing information on the age of the layer as it has been reported. Since standards for age reporting of tephra layers greatly vary in between different studies (e.g. uncalibrated vs. calibrated), information on the dating method and calibration are required for the field "dating method or calibration". The required field "dated in profile?" provides information on whether the age of the tephra layer originates from the corresponding sediment composite profile itself (field = true) or if the age was adapted from the literature (field = false). If the age was adapted from the literature, a DOI from the original publication is required. Further event layers such as geomagnetic excursions will be included in forthcoming versions of VARDA.

### 2.2.5 Proxy data

The technical infrastructure of VARDA is intended to attribute a down-profile record of palaeoclimatic proxy data to the corresponding chronology of the sediment composite profile. Therefore, the required information for proxy data sequences is the composite depth and a corresponding proxy measurement, while additional information further describes proxy specific measurement standards. We adapted the variable controlled vocabulary of the PaST thesaurus for proxy data (World Data Service for Paleoclimatology, https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/past-thesaurus, last access: 15 September 2020). Therefore, all proxy records will be broadly categorized into biological, sedimentological,

**Table 5.** VARDA v01 chronology data sheet (green field: required information; yellow field: additional information).

| Attribute: | Sediment composite profile | depth | Age | Age min | Age max |
|---|---|---|---|---|---|
| Default units: | String | mm | a BP | a BP | a BP |

**Table 6.** VARDA v01 data sheet for tephra layers (green field: required information; yellow field: additional information).

| Attribute: | Lab code | Composite depth | Age | Error | Dating method or calibration |
|---|---|---|---|---|---|
| Default units: | String | mm | a BP | ± a | String |

| Attribute: | Correlated to event | Source locality | Major element data available | Trace element data available | Dated in profile? | Age transfer reference |
|---|---|---|---|---|---|---|
| Default units: | String | String | Boolean | Boolean | Boolean | DOI |

and geochemical proxy data. In the present version of the database, we included varve thickness data that were found in public data repositories. Table 7 lists the required and additional information concerning varve thickness records. Further proxy data such as stable-isotope, pollen, or X-ray fluorescence (XRF) core scanning records will be included in forthcoming versions of VARDA.

## 3 Database

### 3.1 Database design

VARDA is intended to offer a flexible generation of multisite networks with complex data relations for storing and organizing the collected information. To store and organize datasets from varved lake archives, we use a graph database. Graph technology in computer science has evolved as part of the NoSQL movement (meaning "not only SQL"; SQL: Structured Query Language) and is based on graph theory, a mathematical concept of expressing objects as interconnected entities, which dates back to the early works of Leonard Euler in the 18th century (Euler, 1741). In contrast to fixed data schemes required by relational database management systems (RDBMS), a graph explicitly models relations between data by representing entities as nodes (or vertices) described by properties and connected through edges as shown in Fig. 1 (see also the property graph model). To categorize the nature of a particular entity, one or more labels can be added to the node. Edges can be distinguished by their type and may have properties just like nodes. The ability to add new labels, edges, and properties to any entity at all times enables developers to quickly adapt the data model to changing scientific or technical requirements. Neo4j's native query language Cypher is used to read and update the contents in the graph. It allows for an intuitive and flexible generation of queries that are short and readable even for complex patterns (many relationships, circular structures, variable-length paths).

The integration of palaeoenvironmental datasets from varved lakes into a graph database resulted in a flexible data structure, which allows for connected palaeoenvironmental datasets within a single lake as well as in between different lakes. Figure 1 illustrates the VARDA property graph model schematically and visualizes connections between nodes. The VARDA data model associates each lake with one or more sediment composite profiles, which are connected to one or more datasets. Datasets, in turn, are connected to a publication, a category (chronology, tephra layer, radiocarbon date, or varve thickness record in version 1.0) and various category-specific attributes (as listed in Tables 1–7) that further describe a dataset. All these connections provide the necessary meta-information to the actual data points, which are included in a given data set. Data points from the category tephra layer can additionally connect to an event that is described in more than one lake, e.g. the Laacher See tephra. The event node offers the possibility to connect datasets between different lakes for, e.g. synchronization.

### 3.2 Application design

VARDA provides fast access to palaeoclimatic data from varved lakes, irrespective of a user's technical background or operating system. Therefore, the user interface (UI) was designed to be intuitive and reactive with self-explanatory forms and components that immediately respond to the user's actions. It is implemented as an online service, which can be accessed permanently using a web browser.

Overall, the application consists of the web client, a server-side Neo4j graph database and an Application Programming Interface (API) for communication of the client with

**Table 7.** VARDA v01 data sheet for varve thickness (Green field: *required* information, yellow field: *additional* information).

| | | | | | | |
|---|---|---|---|---|---|---|
| Attribute: | Sediment composite profile | Varve number | Composite depth (varve top) | Composite depth (varve bottom) | Age | Varve thickness |
| Default unit: | String | Integer | mm | mm | a BP | mm |

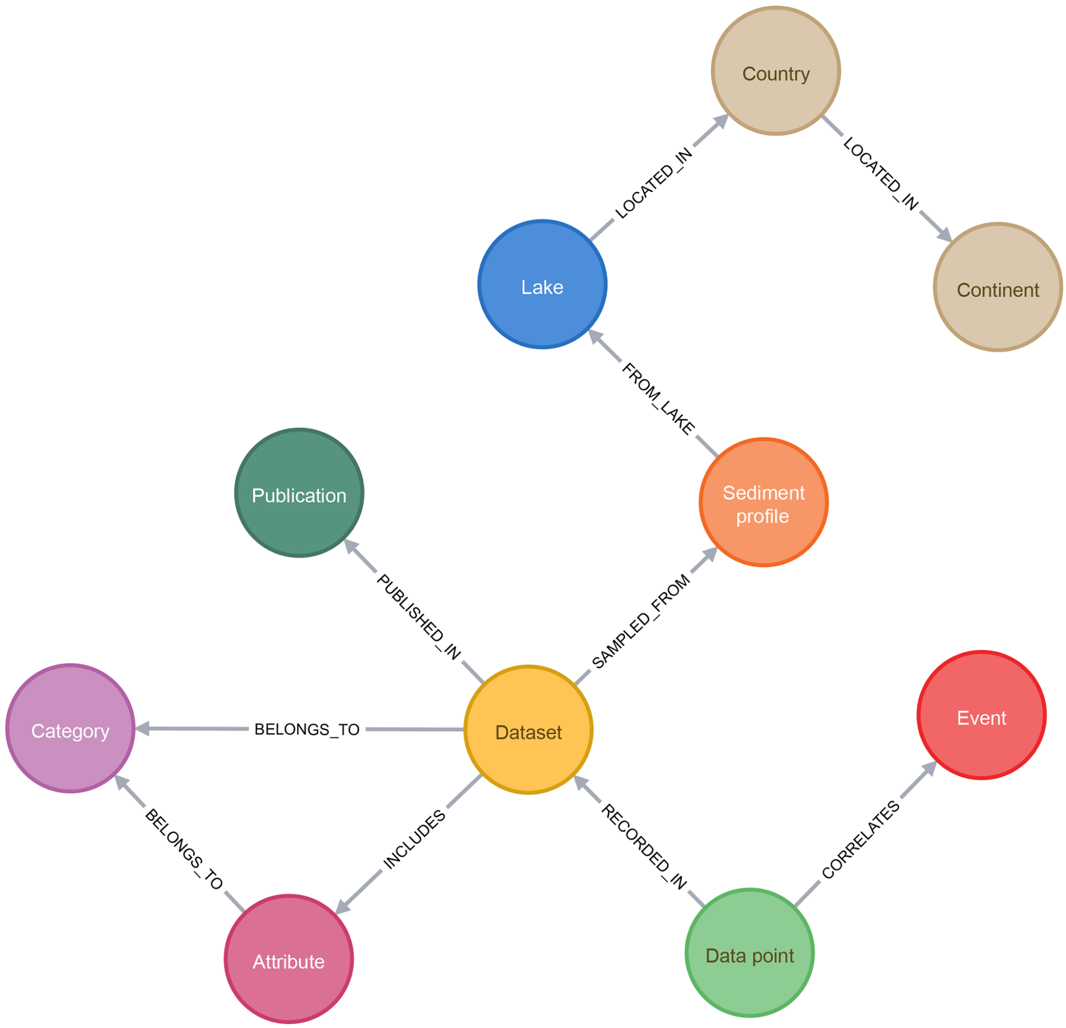


**Figure 1.** VARDA property graph model. Coloured circles represent nodes, and grey arrows represent edges between nodes. For an explanation, see the text.

the database. All software libraries that are integrated into VARDA have licenses that are free and permissive. The client is built with Vue.js, a JavaScript UI framework that has gained attention in the developer community since its launch in 2014 due to its versatility and runtime performance. Some features of VARDA integrate other well-documented third-party libraries, such as D3.js for data visualization and OpenLayers for rendering maps (e.g. from OSM) among vector layers with spatial data. The client state (e.g. user data and entity cache) and any transactions with the database are handled with Apollo GraphQL, a framework for API communication and state management. The client's component-oriented architecture enables fast development of new features with little interference with existing modules. All lines of source code required by the client are checked, minified, and bundled using WebPack for use in the browser.

**Table 8.** Identified lakes, updated geographic coordinates, and datasets included in VARDA 1.0. Letters indicate data availability in data repositories. Table also includes varved lake sites without publicly available data (without letters and references).

| Lake name | Latitude | Longitude | Chrono-logies | Tephra layers | $^{14}$C | Varve thick. | References |
|---|---|---|---|---|---|---|---|
| A | 83,0004 | −75,4247 | | | | | |
| Ahvenainen | 60,8263 | 28,1254 | | | | | |
| Albano | 41,7461 | 12,6695 | | | | | |
| Alimmainen Savijärvi | 61,7442 | 24,4016 | | | | | |
| Ammersee | 47,9983 | 11,1218 | A | | B | | A: Grafenstein (1999);<br>B: Czymzik et al. (2013) |
| Angulinao | 41,3500 | 114,3833 | | | | | |
| Anterne | 45,9910 | 6,7983 | A | | | | A: Giguet-Covex et al. (2011) |
| Arendsee | 52,8900 | 11,4759 | | | | | |
| Arreo | 42,7784 | −2,9911 | | | | | |
| Aspevatnet | 69,7503 | 19,9608 | | | A | | A: Bakke et al. (2005) |
| Avigliana | 45,0654 | 7,3870 | | | | | |
| Ayr Lake | 70,4590 | −70,0860 | A | | | A | A: Thomas et al. (2012) |
| Baldeggersee | 47,1979 | 8,2614 | | | | | |
| Barrine | −17,2504 | 145,6356 | | | A | | A: Head et al. (1994) |
| Bear Lake (Canada) | 75,4838 | −85,1900 | | | | | |
| Bear Lake (USA) | 41,9950 | −111,3382 | | A | | | A: Colman et al. (2009) |
| Belau | 54,1006 | 10,2524 | A | B | B | | A: Garbe-Schönberg et al. (1998);<br>B: Dörfler et al. (2012) |
| Berrington Pool | 52,6605 | −2,7042 | | | | | |
| Big Round Lake | 69,8648 | −68,8548 | A | | | A | A: Thomas and Briner (2008) |
| Big Watab Lake | 45,5526 | −94,4524 | | | | | |
| Bled | 46,3616 | 14,0953 | | A | | | A: Lane et al. (2011) |
| Blue Lake | 68,0870 | −150,4652 | A | | A | A | A: Bird et al. (2008) |
| Bosumtwi | 6,5014 | −1,4113 | | | | | |
| Bourget | 45,7262 | 5,8673 | | | | | |
| Bow Lake | 51,6644 | −116,4486 | | | A | | A: Leonard and Reasoner (1999) |
| Bramant | 45,1999 | 6,1759 | | | A | | A: Guyard et al. (2007) |
| Brownie Lake | 44,9676 | −93,3243 | | | | | |
| Butrint | 39,7803 | 20,0313 | | | A | | A: Morellón et al. (2016) |
| C2 | 82,8276 | −77,9860 | | | A | A | A: Lamoureux and Bradley (1996) |
| Challa | −3,3168 | 37,7040 | A | | B | C | A: Verschuren et al. (2009);<br>B: Blaauw et al. (2011);<br>C: Wolff et al. (2011) |
| Cheakamus | 50,0080 | −122,9179 | | | | | |
| Constance | 47,6017 | 9,4218 | | | | | |
| Crawford Lake | 43,4684 | −79,9488 | A | | | | A: Yu and Eicher (1998) |
| Crevice | 45,0006 | −110,5784 | | | A | | A: Whitlock et al. (2012) |
| Czechowskie | 53,8740 | 18,2370 | A | B; C | | | A: Dietze et al. (2019);<br>B: Wulf et al. (2016);<br>C: Wulf et al. (2013) |
| Dead Sea | 31,5352 | 35,4909 | A; B | | A | | A: Migowski et al. (2004);<br>B: Neugebauer et al. (2015) |
| Deep Lake | 47,6830 | −95,3993 | | | A | B | A: Hu et al. (1997);<br>B: Hu et al. (1999) |
| Diss Mere | 52,3754 | 1,1075 | | | | | |
| Donard | 66,6625 | −61,7875 | A | | B | B | A: Moore et al. (2001);<br>B: Moore et al. (2001) |
| DV09 | 75,5744 | −89,3094 | A | | A | A | A: Courtney Mustaphi and Gajewski (2013) |

**Table 8.** Continued.

| Lake name | Latitude | Longitude | Chrono-logies | Tephra layers | $^{14}C$ | Varve thick. | References |
|---|---|---|---|---|---|---|---|
| East Lake | 74,8882 | −109,5342 | A | | | A | A: Cuven et al. (2011) |
| Eklutna | 61,4053 | −149,0259 | A | A | A | A | A: Fortin et al. (2019) |
| Elk Lake | 47,1891 | −95,2179 | | | A | B | A: Smith et al. (1997); B: Dean and Megard (1993) |
| Ellesmere Mere | 52,9088 | −2,8843 | | | | | |
| Erlongwan | 42,3026 | 126,3806 | | | | | |
| Foy Lake | 48,1662 | −114,3599 | A | B | | | A: Stone and Fritz (2006); B: Shuman et al. (2009) |
| Frängsjön | 64,0228 | 19,7376 | | | | | |
| Frías | −41,0617 | −71,7990 | | | A | | A: Ariztegui et al. (2007) |
| Frickenhäuser See | 50,4029 | 10,2373 | | | | | |
| Fukami | 35,3256 | 137,8195 | | | | | |
| Furskogstjärnet | 59,3802 | 12,0801 | | A | | | A: Zillén et al. (2002) |
| Geneva | 46,4392 | 6,5164 | | | | | |
| Glacier Lake | 40,0230 | −105,5027 | | | | | |
| Gosciaz | 52,5829 | 19,3398 | | | | | |
| Gölcük | 31,6270 | 40,6547 | | A | | | A: Sullivan (1988) |
| Green Lake | 43,8110 | −89,0002 | | | | | |
| Greifen | 47,3500 | 8,6794 | | | | | |
| Grimselsee | 46,5680 | 8,3092 | | | | | |
| Gropviken | 58,3376 | 16,6678 | | A | | | A: Macleod et al. (2014) |
| Gyltigesjön | 56,7567 | 13,1754 | | | A; B | | A: Mellström et al. (2013); B: Snowball et al. (2013) |
| Hämelsee | 52,7596 | 9,3107 | | A | | | A: Jones et al. (2017) |
| Hancza | 54,2647 | 22,8126 | A | | A | | A: Lauterbach et al. (2010) |
| Hännisenlampi | 62,0750 | 30,2096 | | | | | |
| Hector Lake | 51,5881 | −116,3643 | | A | A | | A: Leonard and Reasoner (1999) |
| Hell's Kitchen Lake | 46,1868 | −89,7025 | | | | | |
| Holzmaar | 50,1193 | 6,8787 | A | B | B | | A: Zolitschka et al. (2000); B: Prasad and Baier (2014) |
| Hoya La Alberca | 20,3889 | −101,2009 | | | | | |
| Hoya Rincón de Parangueo | 20,4311 | −101,2495 | | | A | | A: Park et al. (2010) |
| Huron | 44,6418 | −82,3580 | | | | | |
| Hvítárvatn | 64,6101 | −19,8401 | A | A | | A; B | A: Larsen et al. (2011); B: Larsen et al. (2013) |
| Iceberg Lake | 60,7880 | −142,9589 | A | | B | A; B | A: Loso (2008); B: Diedrich and Loso (2012) |
| Järlasjön | 59,3020 | 18,1515 | | | | | |
| Judesjön | 62,8337 | 17,7728 | | | | | |
| Jyväsjärvi | 62,2385 | 25,7771 | | | | | |
| Kälksjön | 60,1531 | 13,0559 | | | | | |
| Kallio Kourujärvi | 62,5600 | 27,0030 | A | B | | A | A: Saarni et al. (2015a); B: Kalliokoski et al. (2018) |
| Kalliojärvi | 63,2261 | 25,3678 | A | | | A | A: Saarni et al. (2015b) |
| Kassjön | 63,9254 | 20,0100 | | | | | |
| Kissalammi | 61,2556 | 24,3549 | | | | | |
| Koltjärnen | 62,9526 | 18,3043 | | | | | |
| Kongressvatnet | 78,0212 | 13,9605 | | | | | |
| Kortejärvi | 63,6236 | 28,9341 | | | | | |
| Korttajärvi | 62,3373 | 25,6903 | | | | | |
| Lac Brulé | 45,7192 | −75,4422 | A | | A | A | A: Lafontaine-Boyer and Gajewski (2014) |

**Table 8.** Continued.

| Lake name | Latitude | Longitude | Chrono-logies | Tephra layers | $^{14}$C | Varve thick. | References |
|---|---|---|---|---|---|---|---|
| Lac d'Annecy | 45,8578 | 6,1717 | | | A | | A: Brauer and Casanova (2001) |
| Lac Pavin | 45,4955 | 2,8877 | | | | | |
| Etoliko | 38,4732 | 21,3248 | A | | B | A | A: Koutsodendris et al. (2017); B: Haenssler et al. (2013) |
| Lago Buenos Aires | −46,4900 | −72,0129 | | A | | | A: Bendle et al. (2017) |
| Laguna Potrok Aike | −51,9608 | −70,3794 | A | B | B | | A: Kliem et al. (2013); B: Haberzettl et al. (2007) |
| Lake of the Clouds | 48,1426 | −91,1122 | | | | | |
| Lampellonjärvi | 61,0737 | 25,0605 | | | | | |
| Längsee | 46,7894 | 14,4242 | | A | | | A: Schmidt et al. (2002) |
| Laukunlampi | 62,6682 | 29,1564 | | | | | |
| Lavijärvi | 61,6333 | 30,5000 | | | | | |
| Lehmilampi | 63,6283 | 29,1022 | A | | | A | A: Haltiahovi et al. (2007) |
| Lillooet | 50,2425 | −122,4973 | | | | | |
| Lind | 45,7504 | −92,4354 | | | | | |
| Linné | 78,0463 | 13,8028 | | | | A | A: Werner et al. (2009) |
| Loch Ness | 57,3000 | −4,4500 | | | | | |
| Loe Pool | 50,0730 | −5,2909 | | | | | |
| Lögurinn | 65,2507 | −14,4649 | | A | | | A: Striberger et al. (2010) |
| Lower Murray Lake | 81,3328 | −69,5510 | A | | | A | A: Cook et al. (2008) |
| Lower Mystic Lake | 42,4261 | −71,1474 | | | | | |
| Lugano | 45,9203 | 8,9053 | | | | | |
| Malawi | −11,5486 | 34,5376 | A; B | | C | | A: Sánchez Goñi et al. (2017); B: Ivory et al. (2016); C: Pilskaln and Johnson (1991) |
| Mascardi | −41,3157 | −71,5757 | | | A | | A: Hajdas et al. (2003) |
| McCarrons | 44,9981 | −93,1131 | | | | | |
| Meerfelder Maar | 50,1010 | 6,7570 | A | B; C | D | A; B; E; F | A: Martin-Puertas et al. (2012); B: Engels et al. (2015); C: Lane et al. (2015); D: Brauer et al. (2000); E: Brauer et al. (2008); F: Litt et al. (2009) |
| Mina | 45,8878 | −95,4788 | | | | | |
| Mirror Lake | 62,0305 | −128,2840 | | | | | |
| Mondsee | 47,8157 | 13,3819 | A | | B | | A: Lauterbach et al. (2011); B: Swierczynski et al. (2013) |
| Montcortés | 42,3306 | 0,9951 | | | A | | A: Corella et al. (2010) |
| Monticchio | 40,9313 | 15,6050 | A; B | C; D; E | F; G; H | | A: Martin-Puertas et al. (2014); B: Allen et al. (1999); C: Huntley et al. (1999); D: Wulf et al. (2012); E: Wulf et al. (2004); F: Hajdas et al. (1997); G: Watts (1996); H: Zolitschka (1996) |
| Mötterutstjärnet | 59,6394 | 12,6675 | | A | | | A: Zillén et al. (2002) |
| Murray Lakes | 81,3555 | −69,5436 | | | | | |
| Nar Gölü (Lake) | 38,3403 | 34,4560 | | | | | |
| Nautajärvi | 61,8052 | 24,6782 | | | | | |
| Nedre Heimredalsvatnet | 68,2990 | 13,6547 | | | A | | A: Balascio et al. (2011) |
| Nedrefloen | 61,9306 | 6,8664 | | | A | | A: Vasskog et al. (2012) |
| Nicolay Lake | 77,7670 | −94,6529 | | | | | |

**Table 8.** Continued.

| Lake name | Latitude | Longitude | Chrono-logies | Tephra layers | $^{14}C$ | Varve thick. | References |
|---|---|---|---|---|---|---|---|
| Nikkilänlampi | 63,1745 | 30,9479 | | | | | |
| Ni no Megata | 39,9524 | 139,7284 | | A | | | A: Yamada et al. (2010) |
| Nylandssjön | 62,9458 | 18,2826 | | | | | |
| Oeschinen | 46,4984 | 7,7274 | A | | A | | A: Amann et al. (2015) |
| Ogac | 62,8432 | −67,3401 | | | | | |
| Ohrid | 41,0371 | 20,7181 | A; B; C; D | E; F | F | | A: Vogel et al. (2010a); B: Wagner et al. (2008); C: Francke et al. (2016); D: Wagner et al. (2010); E: Leicher et al. (2016); F: Vogel et al. (2010b) |
| Ojibway | 48,4739 | −79,2801 | | | | | |
| Pääjärvi | 61,0625 | 25,1307 | | | | | |
| Pavin | 45,4957 | 2,8879 | A | | B | | A: Stebich et al. (2005); B: Chassiot et al. (2016) |
| Perespilno | 51,4269 | 23,5695 | | | | | |
| Pettaquamscutt | 41,5030 | −71,4506 | | | A | | A: Hubeny et al. (2008) |
| Pitkälampi | 62,2543 | 30,4679 | | | | | |
| Plomo | −47,0047 | −72,9122 | A | | | | A: Elbert et al. (2015) |
| Pohjajärvi | 62,8157 | 28,0332 | | | | | |
| Polvijärvi | 63,1614 | 28,9700 | | | | | |
| Prespa | 40,8967 | 21,0050 | | A; B | A | | A: Wagner et al. (2012); B: Wagner et al. (2010) |
| Puyehue | −40,6667 | −72,4667 | | | A | | A: Bertrand et al. (2008) |
| Pyhäjärvi | 60,7167 | 26,0000 | | | | | |
| Rehwiese | 52,4280 | 13,1996 | A | A | | A | A: Neugebauer et al. (2012) |
| Rostherne Mere | 53,3543 | −2,3862 | | | | | |
| Rõuge Suurjärv | 57,7282 | 26,9223 | | | | | |
| RS29 | 73,1400 | −95,2780 | | | A | | A: Paull et al. (2017) |
| Rudetjärn | 62,3662 | 16,9975 | | | | | |
| Sacrower See | 52,4432 | 13,0991 | | A | A | | A: Enters et al. (2009) |
| Saky | 45,1224 | 33,5612 | | | | | |
| San Pueto | 41,2856 | 13,4080 | | | | | |
| Sanagak Lake | 70,2095 | −93,6355 | | | | | |
| Sarsjön | 64,0387 | 19,6008 | | | | | |
| Sawtooth | 79,3494 | −83,9235 | | | | A | A: Francus et al. (2002) |
| Schleinsee | 47,6122 | 9,6348 | | A | | | A: Clark et al. (1989) |
| Seebergsee | 46,5773 | 7,4433 | | | | | |
| Sihailongwan | 42,2865 | 126,6019 | A | A | | | A: Mingram et al. (2018) |
| Silvaplana | 46,4487 | 9,7923 | | | | | |
| Skilak Lake | 60,4107 | −150,3386 | | | | | |
| Soppensee | 47,0901 | 8,0803 | | A | B | | A: Hajdas and Michczyński (2010); B: Gierga et al. (2016) |
| Sotkulampi | 61,4964 | 29,0894 | | | | | |
| Starnberger See | 47,9000 | 11,3167 | | | | | |
| Steel Lake | 46,9730 | −94,6834 | | | A | | A: Tlan et al. (2005) |
| Storsjön | 63,2149 | 14,3146 | A | | A | | A: Labuhn et al. (2018) |
| Sugan Lake | 38,8667 | 93,9000 | A | | B | | A: Zhang et al. (2009); B: Zhou et al. (2009) |
| Suigetsu | 35,5833 | 135,8833 | | A | | | A: Smith et al. (2013) |
| Suminko | 54,1841 | 17,7970 | | | | | |
| Summit Lake | 59,6737 | −135,0958 | | | | | |

**Table 8.** Continued.

| Lake name | Latitude | Longitude | Chrono-logies | Tephra layers | $^{14}$C | Varve thick. | References |
|---|---|---|---|---|---|---|---|
| Superior | 47,7508 | −72,2719 | A | | | | A: O'Beirne et al. (2017) |
| Szurpily | 54,2291 | 22,8978 | | | | | |
| Taka-Killo | 61,0584 | 24,9477 | | | | | |
| Tanganyika | −5,8363 | 29,5976 | A; B; C; D | E | | | A: Sánchez Goñi et al. (2017); B: Tierney et al. (2010); C: Tierney et al. (2008); D: Tierney and Russell (2007); E: Williamson et al. (1991) |
| Tekapo | 35,0301 | −108,9329 | | | | | |
| Teletskoye | 51,5914 | 87,6672 | | | A | | A: Rudaya et al. (2016) |
| Tiefer See | 53,5946 | 12,5281 | A | B | | | A: Dräger et al. (2016); B: Wulf et al. (2016) |
| Tõugjärv | 57,7386 | 26,9051 | | | | | |
| Tougou-ike | 35,4775 | 133,8925 | | A | | | A: Kato et al. (2003) |
| Trübsee | 46,7942 | 8,3899 | | | | | |
| Tuborg | 80,9500 | −75,7667 | | | | | |
| Tutira | −39,2238 | 176,8923 | | A | | | A: Eden and Page (1998) |
| Upper Soper Lake | 62,9150 | −69,8784 | | | | | |
| Valkiajärvi | 61,9048 | 23,8812 | | | | | |
| Van | 38,6040 | 42,8763 | A | | | | A: Pickarski et al. (2015) |
| Vesijärvi | 61,1368 | 25,4732 | | | | | |
| Victoria | 33,19833 | −1,2317 | A; B; C | D | | | A: Stager et al. (2005); B: Stager et al. (2002); C: Berke et al. (2012); D: Lane et al. (2018) |
| Vuolep Njakajaure | 68,3419 | 18,7808 | | | | | |
| Waikopiro | −39,2351 | 176,8944 | | | | | |
| Woserin | 53,6684 | 12,0263 | A | | | A | A: Czymzik et al. (2016) |
| Xiaolongwan | 42,2999 | 126,3594 | | | | | |
| Xinluhai | 31,8485 | 99,1129 | | | | | |
| Yoa | 19,0576 | 20,5069 | | | | | |
| Żabińskie | 54,1318 | 21,9836 | | A | | | A: Żarczyński et al. (2018) |
| Zoñar | 37,4833 | −4,6897 | | | A | | A: Martín-Puertas et al. (2008) |
| Zürichsee | 47,2513 | 8,6672 | | | | | |

The web application offers a user interface with optional filters to explore and visualize multisite networks on demand (see Fig. 2). A universal search field (1 in Fig. 2) can be used to select filters either by region or proxy category. An interactive diagram (2 in Fig. 2) can be used to select a temporal filter by scrolling with the mouse or resizing the light-blue-coloured frame (3 in Fig. 2) underneath the main figure.

We add the iconic NGRIP oxygen-isotope ($\delta$18O) record with the GICC05 chronology (Vinther et al., 2006; Rasmussen et al., 2006; Andersen et al., 2006; Svensson et al., 2005) as a temporal reference curve for the user. This curve is well-known in the palaeoclimate community and thus allows an easy recognition of the time interval covered by a lake record of interest. In the present version it does not allow precise correlations between lake records with the NGRIP curve because chronological uncertainties for the latter are not shown for visual clarity. Orange circles (4 in Fig. 2) correspond to tephra layers that have been identified in sediments of at least two archives. Clicking a circle enables (or disables) the respective filter. The results will be updated immediately on the map (5 in Fig. 2) and in the result list (6 in Fig. 2) below whenever any filters have been changed. Direct selection of a lake on the map or in the result list guides users to the lake detail view with a list of corresponding core datasets. In version 1.0 all datasets of interest can be downloaded in CSV format.

## 4 Data inventory

We identified 186 lakes from the published literature, which are described as exhibiting continuous or floating varve sequences in their sediments. We additionally included unvarved sediments from Lake Prespa (Europe), Lake Ohrid (Europe), Laguna Potrok Aike (South America), and Bear

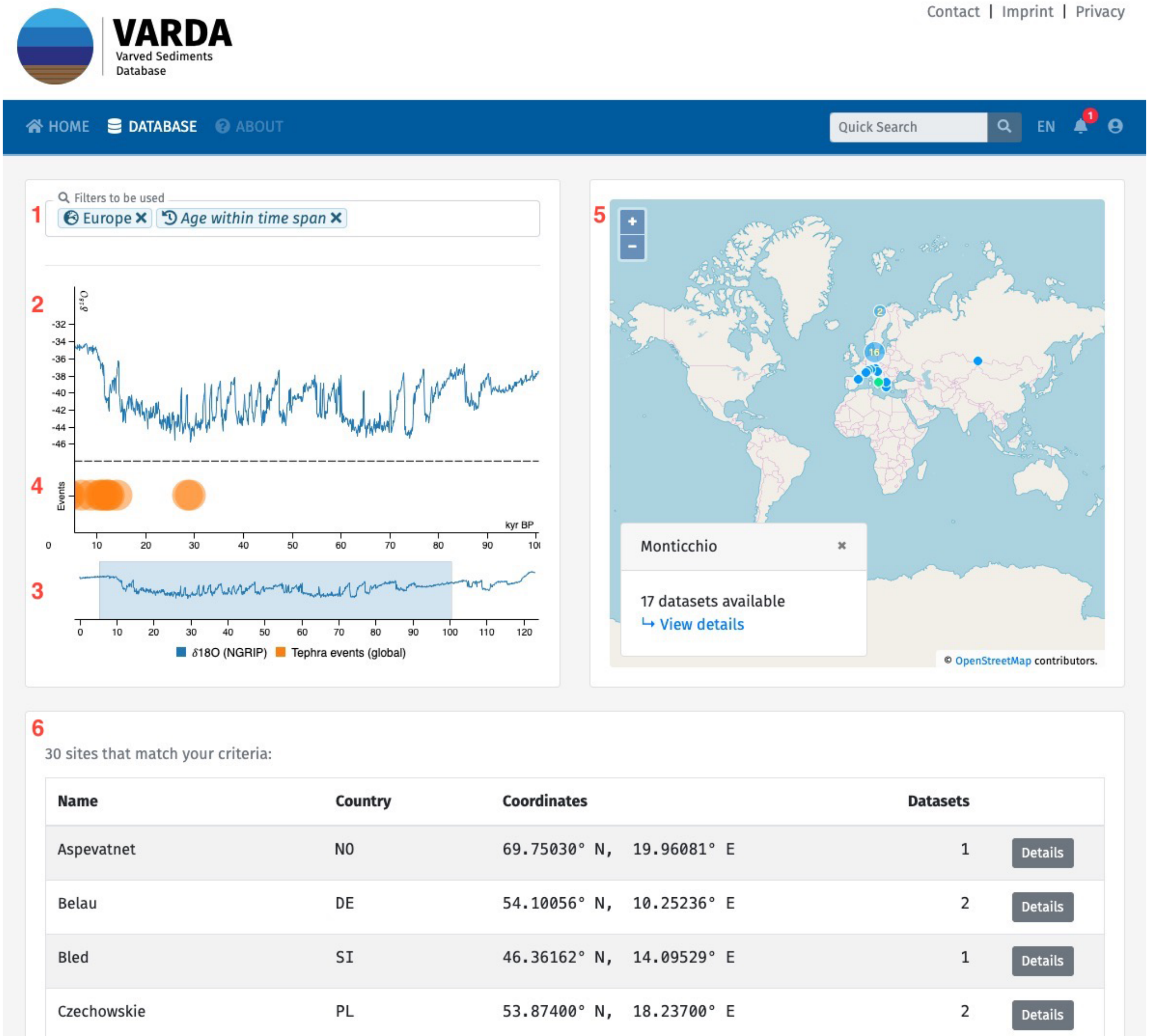


**Figure 2.** Screenshot of the user interface in version 1.0, available online at https://varve.gfz-potsdam.de (last access: 15 September 2020). See text for explanation. © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.

Lake (North America) to the compilation due to their long continuous chronologies and good age control from independent dating techniques or the frequent occurrence of tephra layers. In total, 261 datasets for 95 of the identified lakes are available (September 2019) in public data repositories and were included in VARDA version 1.0. The datasets comprise of 70 individual chronologies from 43 lakes, 146 tephra layers from 36 lakes, 118 uncalibrated $^{14}C$ records from 50 lakes, and 55 varve thickness records from 23 lakes. Table 8 lists all identified lakes with their name, geographical coordinates, and available datasets, including the corresponding literature reference.

Figure 3 presents the spatial coverage of lakes and associated datasets included in VARDA 1.0. The identified lakes are located on all continents except Antarctica, with $\sim 56\,\%$ located in Europe, $\sim 26\,\%$ in North America, $\sim 8\,\%$ in Asia, $\sim 5\,\%$ in Central America and South America, $\sim 3\,\%$ in Africa, and $\sim 2\,\%$ in Oceania. The spatial coverage shows a distinct spatial emphasis in lake distribution on the mid-latitudes of the Northern Hemisphere, especially the North Atlantic realm. In contrast, only 13 of the 190 lake archives are located on the Southern Hemisphere.

Figure 4 presents the temporal distribution of datasets included in VARDA 1.0. The combined chronologies span the entire last glacial cycle with a minimum age range of 87 years

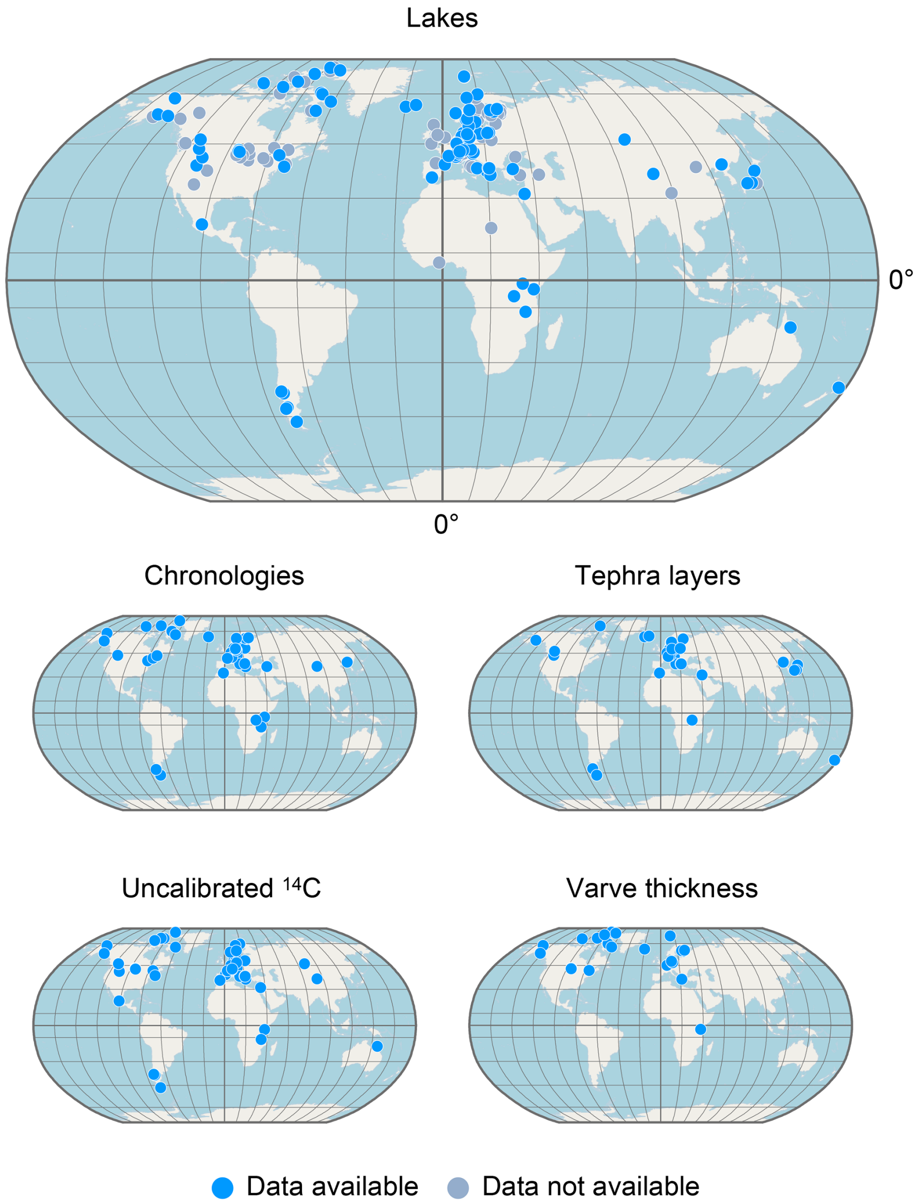


**Figure 3.** Spatial distribution of identified lakes and collected datasets included in VARDA 1.0. Data availability is indicated by blue-coloured dots.

(from −60 to 27 BP) for Lake Woserin (Czymzik et al., 2016) and a maximal age range of 1 208 643 years (from 10 475 to 1 219 118 BP) for Lake Malawi (Ivory et al., 2018). However, none of the chronologies entirely covers the last glacial cycle on its own, illustrating the need to generate multisite networks to effectively cover long time periods for environmental reconstructions. For network synchronization purposes, 146 individual tephra layers reported for sediment composite profiles in 36 lakes were identified from the published literature. A total of 30 tephra layers are reported as occurring in more than one lake and are therefore suitable for synchronization.

## 5 Data availability

All datasets are available online at https://doi.org/10.5880/GFZ.4.3.2019.003 (Ramisch et al., 2019) in JavaScript Object Notation (JSON) format. The benefit of this data format is its accurate depiction of the VARDA data model, including the relationships between data nodes. Additionally, all datasets are also available in CSV format. The VARDA graph database and the user interface can be assessed online via the following URL: https://varve.gfz-potsdam.de (last access: 15 September 2020). Support for VARDA is provided under varve@gfz-potsdam.de.

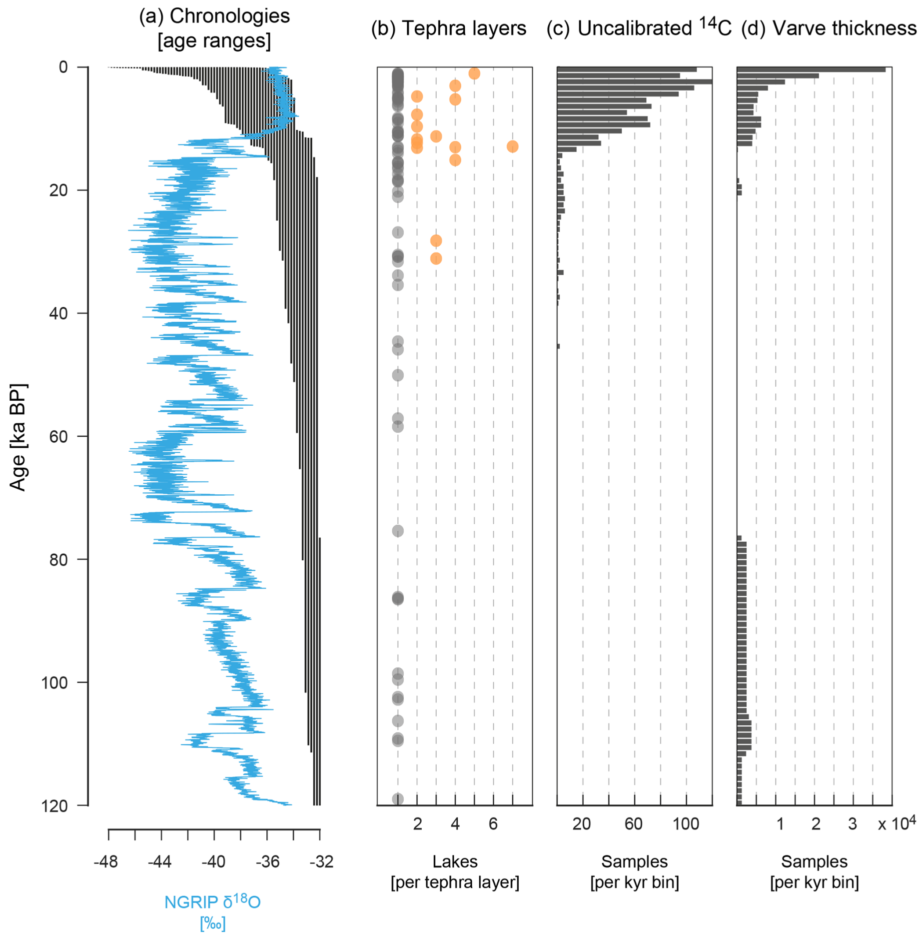


**Figure 4.** Temporal distribution of datasets in VARDA 1.0. **(a)** Age range of chronologies indicated by black bars, where each bar indicates the coverage of an individual chronology. The NGRIP stable oxygen record (Andersen et al., 2004) with the GICC05 chronology (Vinther et al., 2006; Rasmussen et al., 2006; Andersen et al., 2006; Svensson et al., 2005) is shown as a temporal reference curve. **(b)** Tephra layers associated with lakes included in VARDA. Dots indicate the number of lakes associated with a single tephra layer. **(c)** Number of samples per kiloyear bin of uncalibrated $^{14}$C measurements. **(d)** Number of samples per kiloyear bin of individual varve thickness measurements.

## 6 Conclusion and future developments

VARDA offers a user-friendly and time-efficient way to explore the multitude of palaeoenvironmental data from varved lake archives. Due to the integration of precise chronologies and isochrones from tephra event layers into a modern graph database, VARDA offers an easy way to construct regional to global networks of palaeoenvironmental information. These multisite networks can be used e.g. to explore and analyse leads and lags of regional climate change, large scale patterns in environmental variability or differentiated proxy responses within and between archives. The first version of VARDA presented here includes all technological requirements and tools for future upgrades and developments. Presently, we are working on the integration of (1) an advanced visualization tool, (2) a user-friendly import application and (3) additional proxy data such as stable isotopes and geochemical data, as priority goals for the next update. Additionally, the source code of the database application will be made available for the public in a separate contribution. In general, VARDA is intended to be community-based effort, and we welcome and encourage the participation of varve specialists and the broader palaeoenvironmental community for the further development and application of this tool.

**Author contributions.** AR coordinated the manuscript writing and wrote most parts, except Sect. 3, which was written by AlB and MD. All authors contributed to manuscript writing. AlB, AR, and AcB carried out the data compilation and designed the standardization scheme with contributions from IN, MJB, JM, and NN for tephrochronological data; RT, JM, FO, BP, and CB for $^{14}$C data and chronologies; and JM, FO, and RT for varve thickness data. AlB, MD, and AR collected meta-information with contributions from AcB, RT, IN, JM, BP, SP, and BB for the standardization of meta-information. MD and AlB designed the graphical user interface for the database. MD implemented the user client and the server application with the help of MK. All authors reviewed the database and provided valuable feedback. AcB and AR coordinated the project.

**Competing interests.** The authors declare that they have no conflict of interests.

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