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

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Abstract. Varved lake sediments provide long climatic records with high temporal 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 to explore the database of varved lake sediments using a connected data-model and can generate a state-of-the-art graphic representation of multi-site comparison. This allows to reassess existing chronologies and tephra events to synchronize and compare even distant varved lake records. Furthermore, the present version of VARDA permits to explore 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 paleoclimate 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, all datasets of version 1.0 are available at http://doi.org/10.5880/GFZ.4.3.2019.003 (Ramisch et al., 2019).

1 Introduction

A major challenge in simulating climate change of the last glacial cycle is validating model outputs with paleoclimatic data. Model-data comparisons on regional to global scale require the integration of paleoclimatic data from single sites into multi-site networks (e.g. Franke et al., 2017). Annually laminated lake sediments provide reliable nodes for such networks because they offer paleoclimatic information in high temporal resolution with low associated age uncertainty. Due to their annual to seasonal resolution, multi-site 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 is fundamental to understand climates of the last glacial cycle (Clement and Peterson, 2008) and to better assess spatial and temporal trajectories of future

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climate changes. Networks of varved lake sediments also provide means to test differentiated proxy responses to climate change (e.g. Ott et al., 2017; Ramisch et al., 2018; Roberts et al., 2016), further enhancing the robustness of paleoclimatic reconstructions. However, despite their usefulness for the generation of highly resolved multi-site networks, a global synthesis of varve-related paleoclimatic data is still not available.

Various data providers have been developed which offer free access to palaeoclimatic and paleoenvironmental information including high resolution terrestrial archives. These include (1) large scale data repositories such as Pangaea (www.pangaea.de), the National Oceanic and Atmospheric Administration's (NOAA) World data service for Paleoclimatology archives (www.ncdc.noaa.gov) and Neotoma (www.neotomadb.org, 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 2,000 Year Multiproxy Database (Pages 2k consortium, 2017). However, the distribution of information in between data providers make a custom generation of multi-site 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 et al., 2007; Blauuw 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. We compiled all available and published varved sediment records and developed criteria 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/Varve%20publications.pdf) to identify lake archives exhibiting varved sediments and to compile suitable core related paleoclimatic 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 data sets 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

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additional information for lake records included in 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 degree with 4 decimal places, which corresponds to a precision of ~ 10 m. This even allows a reliable location of small lakes with a surface area < 1 ha and especially useful for dense lake distributions common in large lake districts such as in Canada or Scandinavia. Since the required precision was not available in most publications, we re-assessed the published geographical location using ArcGIS and Google Earth.

Sediment profiles that were collected from primary literature sources (see Tab. 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 (Tab.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 as well as an upper (field: depth start) and lower (field: depth end) depth of the sediment profile.

2.2.1 Lake and sediment profile meta information

The data compilation followed the basic strategy to collect proxy data associated with a published sediment profile and information about age-depth models and event layers. A sediment profile may either consist of a single core section or several overlapping core sections combined to a composite profile. 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 sediment profile with a corresponding age and to b) uniquely identify a lake, sediment 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 intercomparable data formats. Tables 1 to 7 provide an overview of data categories and required and additional information properties including the default units.

Table 2

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 et al. (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 paleoclimatic community, leading to variations in reported information and data gaps. The required information encompasses from left to right (i) the sampling depth (field: sediment profile 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).

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The required sampling position refers to the depth within the sediment 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) δ13C data; (v) the measurement method (field: method) as e.g. AMS ^{14}C; (vi) the organic carbon content of a sample (field: %C) and (vii) C/N ratios.

Table 3

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 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.

Table 4

VARDA version 1.0 includes published chronologies that are available in public data repositories. Table 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 profile as well as the corresponding data and publication DOI. Additional information will enable rapid reassessments of original chronologies.

Table 5

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 layer 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 profile to an age estimate and, if available, an uncertainty range expressed as minimum and maximum estimate (2 sigma as default). If depth information for a sediment profile was not provided, we either reconstructed an auxiliary sediment profile 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 mm to avoid

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excessive decimal places in depth reporting. The default age scale unit was set to years BP (1950 CE). 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 multi-site networks. Furthermore, the identification of layers corresponding to dated events such as e.g. 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 profiles included in the database. Table 6 provides an overview of required and additional information of published tephra layers in VARDA. The required information (sediment profile depth, age, age error and dating method) are essential to assign a tephra layer to a given depth in a sediment profile and to store 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/Calibration". The required field "Dated in profile?" provides information if the age of the tephra layer originates from the corresponding sediment 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.

Table 6

2.2.5 Proxy data

The technical infrastructure of VARDA is intended to attribute a down-profile record of paleoclimatic proxy data to the corresponding chronology of the sediment profile. Therefore, the required information for proxy data sequences is the sample 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 in September 2019). Therefore, all proxy records will be broadly categorized into biological, sedimentological 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 XRF records will be included in forthcoming versions of VARDA.

Table 7

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3. Database

3.1 Database design

VARDA is intended to offer a flexible generation of multi-site 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") 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 (also see 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).

Figure 1

The integration of paleoenvironmental datasets from varved lakes into a graph database resulted in a flexible data structure, which allows for connected paleoenvironmental datasets within a single lake as well as in between different lakes. Fig. 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 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 Tab. 1 to 7) which 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 which is described in more than one lake, as for example 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 which 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 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 which has raised attention in the developer community since its launch in 2014 due to its versatility and runtime performance. It is also less opinionated and easier to learn than many similar frameworks. 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 being 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 being checked, minified and bundled using WebPack for use in the browser.

The web application offers a user interface with optional filters to explore and visualize multi-site 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.

Figure 2

We add the iconic NGRIP oxygen -isotope (δ18O) 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 paleoclimate 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 to exhibit 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 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. Tab. 8 lists all identified lakes with name, geographical coordinates and available data sets including the corresponding literature reference.

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Fig. 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 ~56% located in Europe, ~26% in North America, ~8% in Asia, ~ 5% in Middle and South America, ~3% in Africa, and ~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 3

Fig. 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 yrs (from -60 to 27 BP) for Lake Woserin (Czymzik et al., 2016) and a maximal age range of 1,208,643 yrs (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 multi-site networks to effectively cover long time periods for environmental reconstructions. For network synchronization purposes, 146 individual tephra layers reported for sediment profiles in 36 lakes were identified from the published literature. Thirty tephra layers are reported to occur in more than one lake and are therefore suitable for synchronization.

Figure 4

5. Data availability

All datasets are available online at http://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 it´s accurate depiction of the VARDA data model, including the relationships in 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 URL: https://varve.gfz-potsdam.de.

6. Conclusion and future developments

VARDA offers a user-friendly and time efficient way to explore the multitude of paleoenvironmental 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 paleoenvironmental information. These multi-site networks can be used e.g. to explore and analyze leads and lags of regional climate change, large scale patterns in environmental variability or differentiated proxy responses within and between archives. Forthcoming updates of VARDA will include additional proxy data such as stable isotopes, pollen or geochemical proxies.

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Author contribution

AR coordinated manuscript writing and wrote most parts except chapter 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 as well as 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

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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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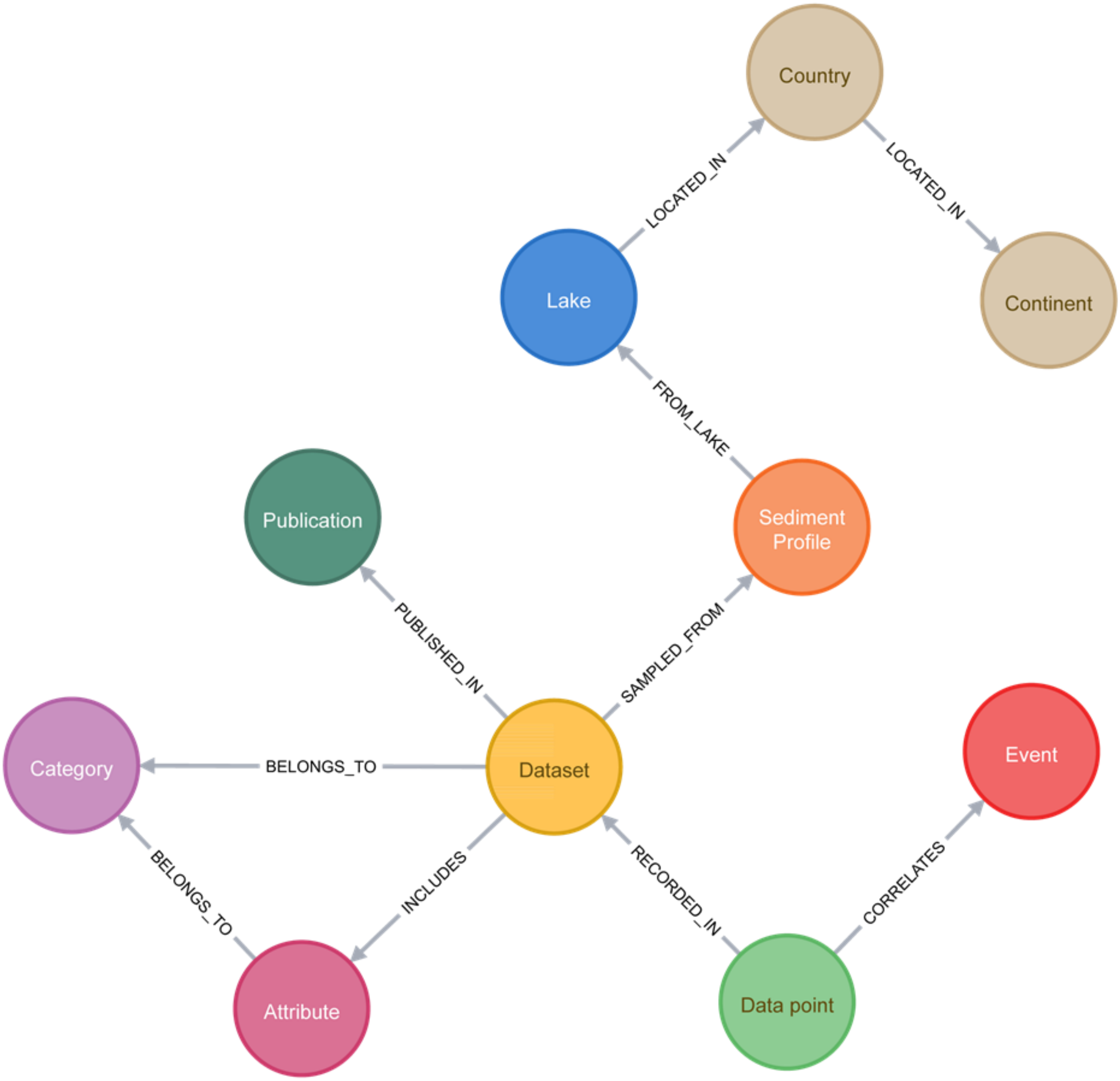

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Figure 1: VARDA property graph model. Coloured circles represent nodes, grey arrows represent edges between nodes. For explanation see text.

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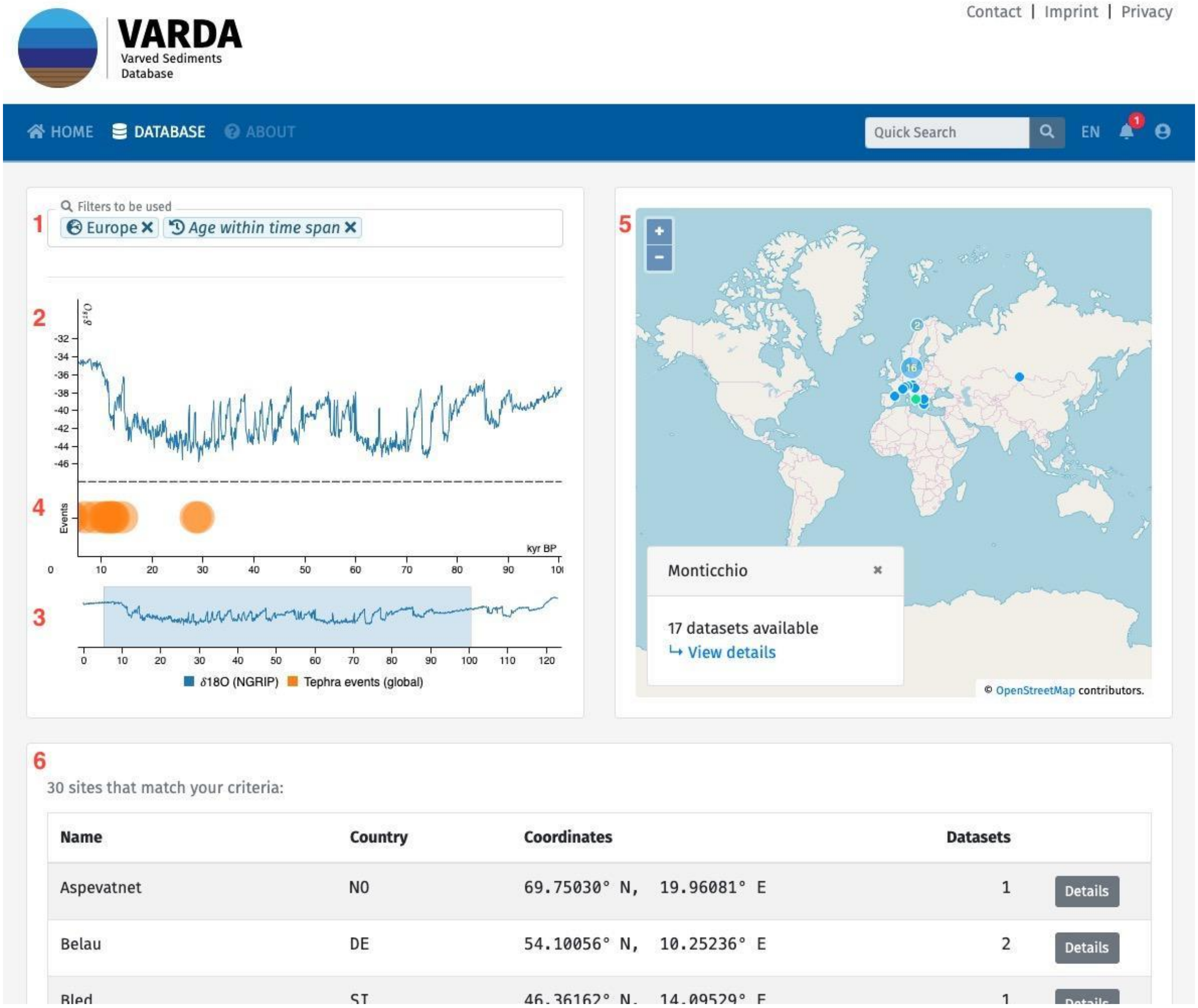

Figure 2: Screenshot of the user interface in version 1.0 available online at https://varve.gfz-potsdam.de. See text for explanation. © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.

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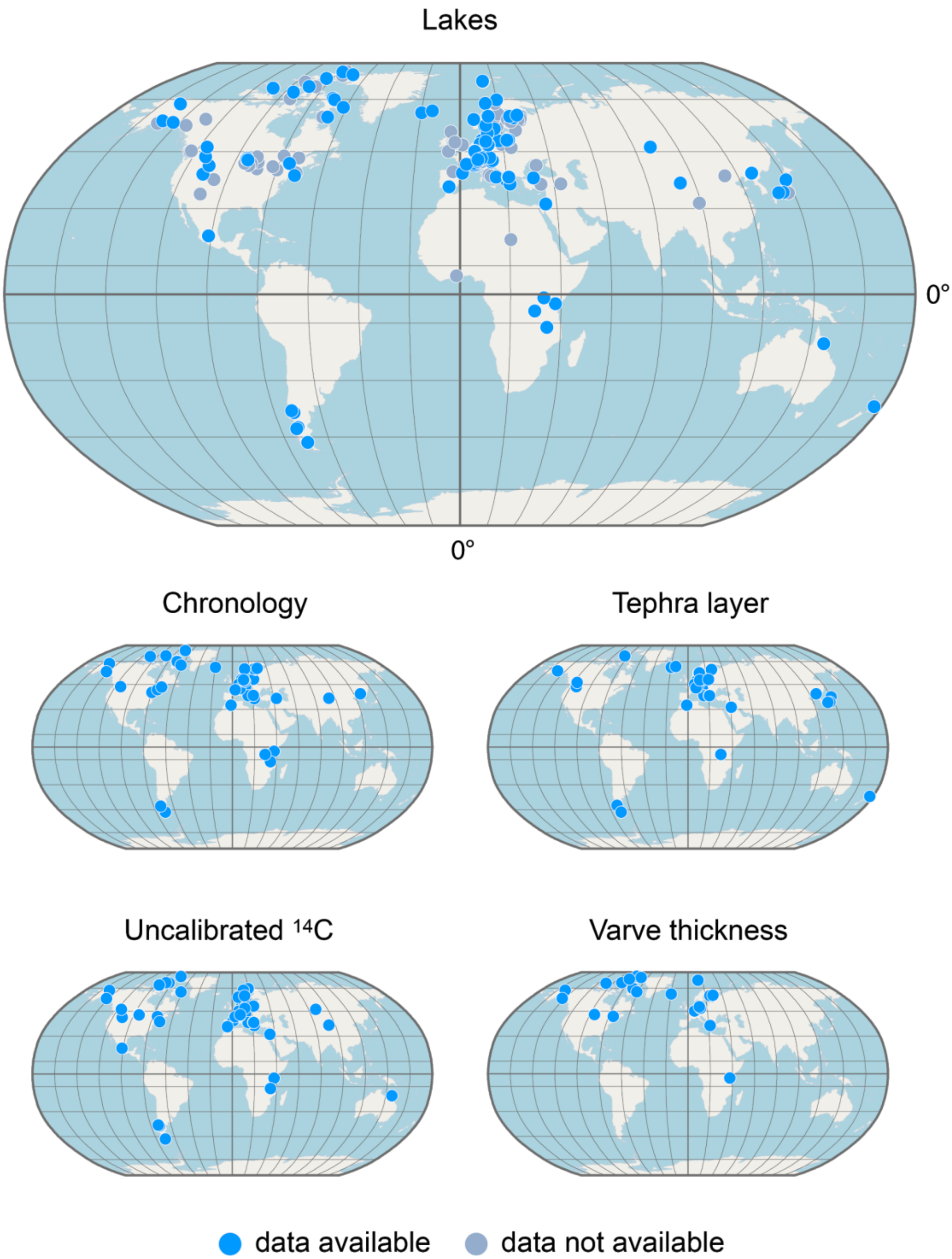

Figure 3: Spatial distribution of identified lakes and collected datasets included in VARDA 1.0. Data availability is indicated by blue coloured dots.

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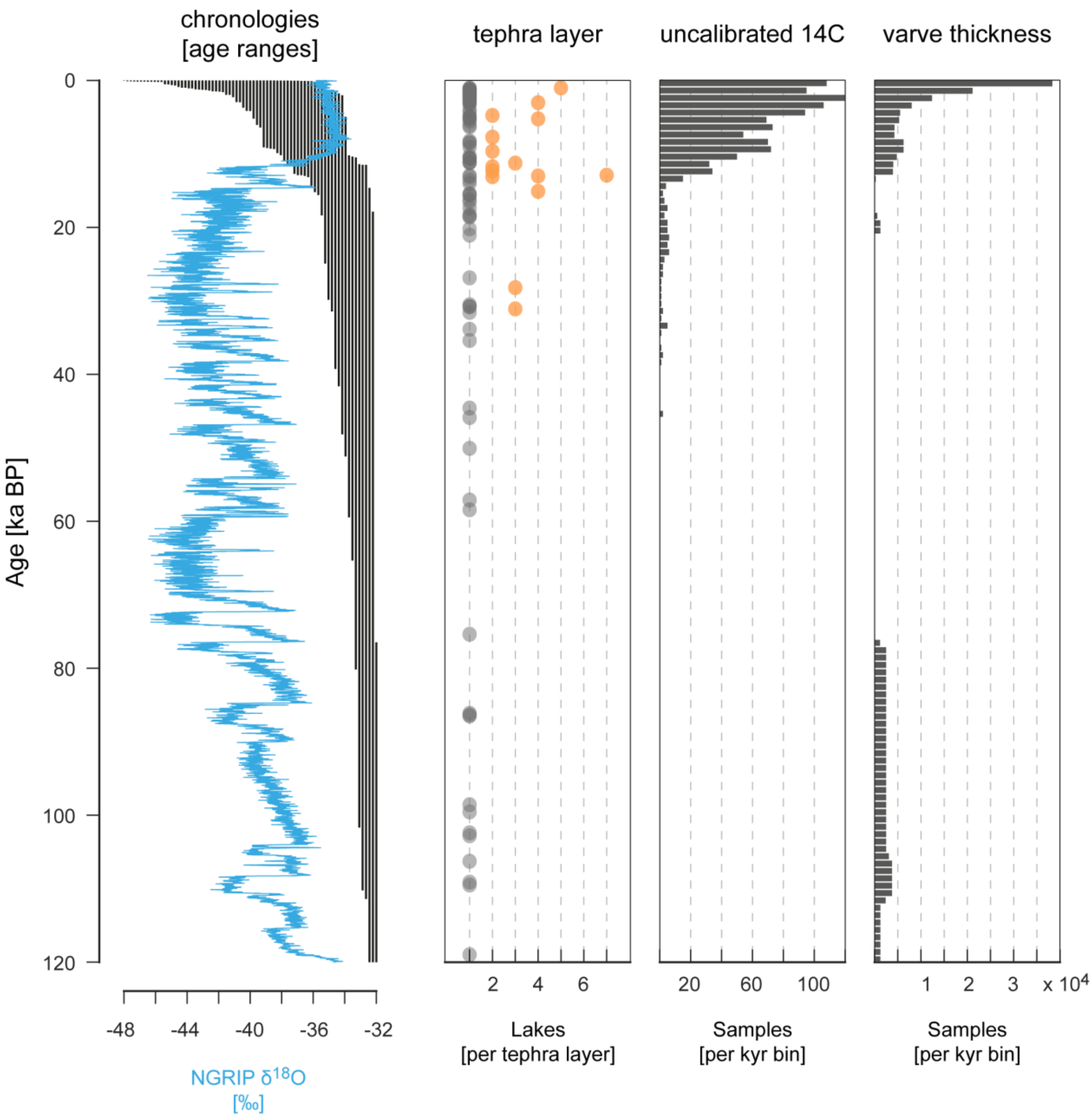

Figure 4: Temporal distribution of datasets in VARDA 1.0. a) Age range of chronologies indicated by black bars where each bar indicates the coverage of an individual chronology. The NGRIP stable oxygen record (Andersen et al., 2004) with the GICC05 chronology (Vinther et al., 2006; Rasmussen et al., 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 kyr bin of uncalibrated 14C measurements. d) Number of samples per kyr bin of individual varve thickness measurements.

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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 (4 digits scale)		m a.s.l.	m	m^2	m^2

Table 2: VARDA v01 data sheet for sediment 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 (4 digits scale)		String	dd/mm/year	m	mm	mm

Table 3: VARDA v01 data sheet for 14C information (Green field: *required* information, yellow field: *additional* information)

Attribute:	Core section	Lab code	Section depth	Sediment profile depth	Age uncalibrated	Error
Default Units:	String	String	mm	mm	a B.P.	± a

Table 3 - continued

Attribute:	Error type	Dated material	∂13C	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 profile	Data DOI	Publication DOI	Has uncertainty?	Uncertainty type	Anchored?
Default Units:	String	String	String	Boolean	String	Boolean

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Table 4 – continued

Attribute:	Anchorpoint type	Anchorpoint age	Dating method	Interpolation method	14C Curve	Calibration	Median Resolution
Default Units:	String	a BP	String	String	String		a

Table 5: VARDA v01 chronology data sheet (Green field: *required* information, yellow field: additional information)

Attribute:	Core section	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:	Core section	Lab code	Section depth	Sediment profile depth	Age	Error	Dating method / Calibration
Default Units:	String	String	mm	mm	a BP	± a	String

Table 6 - continued

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

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

Attribute:	**Sediment profile**	**Core section**	**Varve number**	**Section depth**	**Composite depth**	**Age**	**Varve Thickness**
Default Unit:	String	String	integer	mm	mm	a BP	mm

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Tab. 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	Lat	Long	Chronology	Tephra Layer	^{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; 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; 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; B:
Challa	-3,3168	37,7040	A		B	C	A: Verschuren et al., 2009; B: Blaauw et al., 2011; 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; B: Wulf et al., 2016; C: Wulf et al., 2013
Dead Sea	31,5352	35,4909	A; B		A		A: Migowski et al., 2004; B: Neugebauer et al., 2015;
Deep Lake	47,6830	-95,3993			A	B	A: Hu et al., 1997; B: Hu et al., 1999
Diss Mere	52,3754	1,1075					
Donard	66,6625	-61,7875	A		B	B	A: Moore et al., 2001; B: Moore et al., 2001;
DV09	75,5744	-89,3094	A		A	A	A: Courtney Mustaphi and Gajewski, 2013;
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		x			
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;
Lac D'Annecy	45,8578	6,1717			A		A: Brauer and Casanova, 2001
Lac Pavin	45,4955	2,8877					

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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, A., 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

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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				
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				

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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					
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

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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					