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The SISAL database: a global resource to document oxygen and carbon isotope records from speleothems

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Abstract: Stable isotope records from speleothems provide information on past climate changes, most particularly information that can be used to reconstruct past changes in precipitation and atmospheric circulation. These records are increasingly being used to provide "out-of-sample" evaluations of isotope-enabled climate models. SISAL (Speleothem Isotope Synthesis and Analysis) is an international working group of the Past Global Changes (PAGES) project. The working group aims to provide a comprehensive compilation of speleothem isotope records for climate reconstruction and model evaluation. The SISAL database contains data for individual speleothems, grouped by cave system. Stable isotopes of oxygen and carbon ($\delta^{18}O$, $\delta^{13}C$) measurements are referenced by distance from the top or youngest part of the speleothem. Additional tables provide information on dating, including information on the dates used to construct the original age model and sufficient information to assess the quality of each data set and to erect a standardized chronology across different speleothems. The metadata table provides location information, information about the full range of measurements carried out on each speleothem and information about the cave system that is relevant to the interpretation of the records, as well as citations for both publications and archived data. The compiled data are available at http://dx.doi.org/10.17864/1947.139 .

1. Introduction

Speleothems are inorganic carbonate deposits (mostly calcite and aragonite) growing in caves that form from super-saturated cave waters with respect to $CaCO_3$. Speleothems are highly suitable for radiometric dating using uranium-series disequilibrium techniques. Since they form through continuous accretion, speleothems can provide a highly resolved record of environmental conditions, generally with a temporal resolution from seasonal to 100 years, depending on sampling resolution.

Speleothem records are widely used to reconstruct past changes in climate. Speleothem growth is, of itself, an indicator of precipitation availability (Ayliffe et al., 1998; Wang et al., 2004) and variations in annual growth increments have been interpreted as an index of precipitation amount (Fleitmann et al., 2004; Polyak and Asmerom, 2001; Trouet et al., 2009). Many different types of measurements have been made on speleothems, but the most common are the stable isotopes of oxygen and carbon ($\delta^{18}O$, $\delta^{13}C$). Although the interpretation of such records can be complicated, for samples which are deposited close to equilibrium, changes in $\delta^{18}O$ are primarily a signal of changes in precipitation amount and source, precipitation temperature, as well as cave temperature (Affek et al., 2014; Hu et al., 2008; McDermott, 2004; Wang et al., 2008) and have been widely used to reconstruct changing atmospheric circulation patterns (e.g. Bar-Matthews et al., 1999; Cai et al., 2012, 2015; Luetscher et al., 2015; Spötl and Mangini, 2002; Trouet et al., 2009). Changes in $\delta^{13}C$ are a more indirect signal of precipitation changes. If not affected by non-equilibrium deposition (Baker et al., 1997), $\delta^{13}C$ can reflect the changing abundance of C_3 and C_4 plants above the cave (Baldini et al., 2008; Dorale et al., 1998) or the availability of soil CO_2 during the dissolution of limestone (Genty et al., 2003; Hendy, 1971; Salomons and Mook, 1986). Speleothem records are widely distributed geographically, and this makes them an ideal type of archive for regional climate reconstructions.

An increasing number of climate models explicitly simulate water isotopes as a tool for characterizing and diagnosing the atmospheric hydrological cycle (e.g. Schmidt et al., 2007; Steen-Larsen et al., 2017; Sturm et al., 2010; Werner et al., 2011; Haese et al., 2013). Such models are evaluated against modern observations of the isotopic composition of rainwater (see e.g. Yoshimori et al., 2008; Steen-Larsen et al., 2017). However, evaluations against palaeo-records such as the $\delta^{18}O$ records from speleothems can be used to provide an “out-of-sample” test (Schmidt et al., 2014) of these models. Thus, in addition to their use for climate reconstruction, speleothem records are a useful additional to the tools that are used for climate-model evaluation.

More than 500 speleothem datasets have been published to date, 70% of which have been published in the decade since 2007. There have been some attempts to provide syntheses of speleothem data, particularly in the context of providing climate reconstructions or data sets for model evaluation (e.g. Bolliet et al., 2016; Caley et al., 2014; Harrison et al., 2014; Shah et al., 2013). However, these compilations generally lack sufficient information to allow careful screening of the records to ensure the reliability of the climate interpretation or the quality of the dating of the record. Furthermore, none of them provide a comprehensive coverage of the globe.

SISAL (Speleothem Isotope Synthesis and Analysis) is an international working group set up in 2017 under the auspices of the Past Global Changes (PAGES) programme (http://www.pastglobalchanges.org/). The aim of the working group is to compile the many hundreds of speleothem isotopic records worldwide, paying due attention to careful screening, the construction of standardised age models, and the documentation of measurement and age-model uncertainties, in order to produce a public-access database that can be used for palaeoclimate reconstruction and for climate-model evaluation. In this paper, we document the first publically available version of the SISAL database, focusing on describing its structure and contents including the information that has been included to facilitate quality control.

2. Data and Methods

2.1 Compilation of data

The database contains stable carbon and oxygen isotope measurements made on speleothems, and supporting metadata to facilitate the interpretation of these records. All available speleothem data is included, and no attempt was made to screen records on the basis of the time period covered, the resolution of the records, of the quality of the data or age models. Adequate metadata are provided to allow database users to select the records that are suitable for a particular type of analysis. The raw data were either provided by members of the SISAL working group or extracted from data lodged in PANGAEA or from the National Centres for Environmental Information. Additional information about the records was compiled from publications as necessary. All the records in the current version of the database (SISAL_v1) are listed and described in Table 1.

2.2 Structure of the database

The data are stored in a relational database (MySQL), which consists of 14 linked tables. Specifically: Site, entity, sample, dating, dating lamina, gap, hiatus, original chronology, d13C, d18O, entity link reference, references, composite link entity. Figure S1 shows the relationships between these tables. A detailed description of the structure and content of each of the tables is given below. The details of the pre-defined lists for all fields can be found in Table S1.

2.2.1 Site metadata (table name: site)

A site is defined as the cave or cave system from which speleothem records have been obtained. A site may therefore be linked to several speleothem records, where each record is treated as a separate entity. The site table contains basic metadata about the cave or cave system, including: site id, site name, latitude, longitude, elevation, geology, rock age, monitoring (see Table S2). The elevation is that of the cave itself, not the elevation of the land surface above the cave, and is included because it is required in order to make a lapse rate correction for oxygen isotopes for high-elevation sites (Bowen and Wilkinson, 2002). The description of the geology and the age of the rock formation (rock_age) is given because this is important for understanding the degree of permeability of the material above the cave. Primary porosity decreases, and fracture flow increases, as rocks age, which in turn affects the likely speed at which water flows through the host rock and reaches the cave system. The geology field is also useful because it gives an indication of whether the cave is formed in Mg-rich rocks (e.g. dolomite) and thus if the speleothems are likely to be formed of aragonite, which would require special consideration in terms of oxygen and carbon isotope comparisons with that of calcite (see also Table S3). Only a limited number of descriptive terms are allowed for each field. The age of rock formation follows the standard era, period, epoch terminology as defined by the International Commission on Stratigraphy in 2015 (Cohen et al., 2015). The database includes information of whether the cave site has been monitored: positive returns in this field mean that monitoring of in-cave environmental parameters (e.g. cave air temperature) and/or cave drip chemistry has been carried out for at least a season (as opposed to single measurements of environmental conditions within the cave having been made when the speleothem was collected). The database does not contain monitoring data, but inclusion of this field facilitates researchers being able to contact the original data providers about monitoring information, which can be useful in understanding if a cave is likely to contain speleothems which have deposited close to isotopic equilibrium.

2.2.2. ***Entity metadata (table name: entity)***

Each speleothem (or composite speleothem record) has a unique identifier and a unique name. The entity metadata table (Table S3) provides information about the cave environment that can affect speleothem formation. This includes the thickness of the cover above the speleothem, which might affect the time taken for water to reach the drip site feeding the speleothem and hence the responsiveness of the record to individual rain events or seasonal patterns of precipitation (Fairchild and Baker, 2012). The distance of the speleothem from the cave entrance is provided, which depending on the morphology of a cave, can be a useful indicator of cave ventilation (direct air advection). Ventilation is important as it can control cave air temperature, humidity, evaporation and pCO_2 levels (Fairchild and Baker, 2012; Frisia et al., 2011; Spötl et al., 2005; Tremaine et al., 2011). The entity table also contains a field to document whether any tests have been made to establish whether there is oxygen and carbon isotope quasi-equilibrium between the drip water (CO_2-H_2O system) and the speleothem ($CaCO_3$). There are several such tests (see e.g. Hendy, 1971; Johnston et al., 2013; Mickler et al., 2006; Tremaine et al., 2011), but no attempt is made to identify which test has been applied in the database. The drip type (e.g. seepage flow, seasonal drip, vadose flow, Smart and Friederich, 1987) also provides useful hydrological information: seepage flow shows a small inter-annual variability of discharge and the speleothem record will therefore more likely reflect a long-term average state over several years; other drip types, such as seasonal drip, will indicate the potential to record seasonal individual rainfall events.

The main focus of the SISAL database is stable isotope measurements, but the entity metadata table also contains information about the kinds of measurements that have been made on a specific speleothem. Only the stable isotope measurements are

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currently archived in the database. However, listing the range of data available from any speleothem will facilitate researchers wishing to undertake analyses across multiple types of record and the incorporation of such data within the SISAL database framework at a later stage. The entity metadata table contains two fields to facilitate data traceability: the name of the person who was responsible for collating the data and a DOI or URL for the original data. Information about original publications on specific speleothems is given in the references table (see section 2.2.11).

2.2.3. ***Sample metadata (table name: sample)***

The sample metadata table (Table S4) contains information on the location of the sample with respect to a reference point, where the reference point can be either the top or the base of the speleothem. It also provides information on the thickness and mineralogy (calcite, secondary calcite, aragonite, vaterite, mixed, not known) of each sample. Since some samples may have mixed mineralogy, it also provides information on whether a correction for aragonite has been applied to $\delta^{18}O$ or $\delta^{13}C$.

2.2.4. ***Dating information (table name: dating)***

The dating information table (Table S5) provides information about the radiometric dates used to construct the original age model for each of the speleothem entities, including type of radiometric date (e.g. U-series), depth of dated sample, thickness of dated sample and sample weight. Dates that are used to anchor sequences that are dated by lamina counting (see Section 2.2.5) are included in the dating information table and identified in date type as an event (i.e. the start or end of a laminated sequence). The degree of precision varies between different dating methods and techniques, for e.g. MC-ICP-MS U/Th dating generally produces a more precise age than Alpha U/Th. So the inclusion of the dating method provides a basic measure of the reliability, in terms of analytical precision, of any given date. Sample thickness also influences the dating uncertainty, because thicker samples will integrate more material of different age. Similarly, sample weight can influence precision: samples with a low U content need more sample material for accurate dating as well as younger material to ensure there is sufficient ^{230}Th (which accumulates over time from the decay of ^{238}U and ^{234}U) present. However, larger samples can also increase detrital material (if present and/or abundant), thus increasing age uncertainties when correcting for it. The content of ^{232}Th is included in the dating information table because this value is used for the detrital correction of initial ^{230}Th. Sample mineralogy is also included because this affects the reliability of individual dates (e.g. samples from secondary calcite are not reliable because of the loss of U, Bajo et al., 2016).

We provide both the original uncorrected age and the corrected age for each date. The corrected U/Th age is adjusted for detrital contamination; the corrected calibrated ^{14}C age is adjusted for dead carbon. The correction factors used to derive the corrected U/Th or ^{14}C age are included in the dating information table. The decay constant used to calculate the U/Th ages is given because the values used have changed through time (Cheng et al., 2000, 2013; Edwards et al., 1987; Ivanovich and Harmon, 1992). The calibration curve used to convert radiocarbon ages to calendar years in the original publication is also given. Several different standards have been used in the original publications for the modern reference state (e.g. BP(1950), b2k, CE/BCE or the year when U/Th chemistry was completed) but all of these have been converted to BP(1950) in the database.

Some of the dates listed for a given entity were not used in the original age model, for example because the dating sample was contaminated with organic material or because of age inversions. The dates excluded from the original age model are flagged in the database (date_used) but the other information about these dates is nevertheless included in the dating information table to ensure transparency.

The geochemical characteristics of the sample provide information that is required to assess the quality or reliability of these dates. The ratio of $^{230}Th/^{232}Th$, for example, is a measure of detrital thorium concentration in the sample and thus provides an initial quality control on each date. A ratio >300 is considered a good indicator of a reliable date (Hellstrom, 2006); a higher ratio indicates a cleaner sample with higher accuracy. The thorium corrected errors are also included to provide an indication of the magnitude of the correction related to detrital thorium contamination.

2.2.5. ***Lamina dating information (table name: dating_lamina)***

Variations in the dripwater geochemistry and/or quantity or cave conditions may occur at regular intervals, forming laminae of a range of thicknesses usually linked to

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surface seasonal climate variations (Fairchild and Baker, 2012). A high-resolution chronology can be established for such records by lamina counting, provided an absolute date is available for either the start or the end of the laminated sequence (e.g. because U/Th dates have been obtained or because the stalagmite was actively growing when collected). The identification of individual lamina can be difficult if they are very thin or of varying width, so best practice is to provide an estimate of the counting uncertainty that propagates from the absolute anchor dates. The lamina dating information table (Table S6) provides the age of each lamina in the sequence and the uncertainty on this dating; the absolute dates used as anchor points are given in the dating information table and identified in the date type field there as an event (see Section 2.2.4).

It should be noted that laminae can be formed on a variety of timescales, depending on the frequency that the thresholds for the formation of specific fabrics/mineralogies are crossed. Annual laminations are more likely in regions where there is a clear seasonality in climate or cave environment. In other regions, the lamination may be a result of lower-or higher-frequency variations in, for example, hydrologically effective precipitation (e.g. infiltrated waters) or soil CO_2 production. It is imperative to demonstrate that the laminations are annual (see Table S7) before using lamina counting for dating.

2.2.6 *Hiatus place mark information (table name: hiatus)*

A prolonged cessation of speleothem growth can occur under unfavourable environmental conditions leading to, for example, undersaturation of dripwater or cessation of dripping. Growth hiatuses can often be recognized from structural or mineralogical features, or inferred based on absolute dating. Growth hiatuses have to be taken into account in the construction of age models and thus the hiatus place mark table (Table S7) provides information about the location of such features. The hiatus is referenced to the specific depth at which it occurs, and this depth is considered as an imaginary sample which then appears with a specific sample_id in the sample table.

2.2.7. *Gap place mark information (table name: gap)*

When a composite record is created based on more than one individual speleothem from the same cave system there may be discontinuities in the overlapping time of the individual records. These gaps are not growth hiatuses, but must be identified to facilitate plotting of the records. The gap place mark information table (Table S8) provides information about the location of sample gaps. The gap is referenced to the specific depth at which it occurs, and this depth is considered as an imaginary sample which then appears with a specific sample_id in the sample table. In composite records where sample depths are not given, the location of a gap can be derived from the sample ordering and the absence of isotopic information for a given sample. In point of fact, this table is empty in version 1 of the database.

2.2.8. ***Original chronology (table name: original_chronology)***

The original chronology table (Table S9) provides an estimate of the age, and age uncertainty, according to the original published age model for each sample on which stable isotope measurements have been made. The table also provides information on the type of age model (e.g. linear interpolation between dates, polynomial fit, Bayesian, StalAge (Scholz and Hoffmann, 2011), COPRA (Breitenbach et al., 2012), OxCal (Bronk Ramsey, 2001, 2008)) used in the original publication. The fields ann_lam_check and dep_rate_check are included for quality assurance purposes, since they indicate that the assumption that laminae are truly annual has been explicitly tested.

2.2.9. ***Carbon isotope data (table name: d13C)***

The carbon isotope data table (Table S10) contains the carbon isotope measurements. It also provides information on the laboratory precision of each measurement and the standard (PDB or Vienna-PDB) used as a reference.

2.2.10 ***Oxygen isotope data (table name: d18O)***

The oxygen isotope data table (Table S11) contains the oxygen isotope measurements. It also provides information on the laboratory precision of each measurement and the standard (PDB or Vienna-PDB) used as a reference.

2.2.11 ***Publication information (table name: references)***

This table (Table S12) provides full bibliographic citations for the original references documenting the speleothems, their isotopic records, and/or their age models. References on monitoring of the cave may also be provided. There may be multiple publications for a single speleothem record, and all of these references are listed. For convenience, there is also a table (Table S13) that links the publications to the specific entity.

2.2.12 ***Link composite and entity information (table name: composite_link_entity)***

Multiple speleothem records showing a temporal overlap (and a similar signal) can be combined to create a composite record of changes through time. The composite record is treated as a distinct entity in the database. The link composite and entity information table (Table S14) is provided in order to be able to link this composite record to the individual speleothem records from which it has been derived. Thus any single composite entity (composite_entity_id) is linked to multiple single entities (single_entity_id)

2.2.13 ***Notes (table name: notes)***

The notes table (Table S15) is provide in order to record additional information regarding the site which cannot be recorded in the fields of the table; this may also include entity specific information.

2.3 Quality Control

Individual records in the SISAL database were compiled either by the original authors or from published and open-access material by specialists in the collection and interpretation of speleothem records. In this latter case, the data compilers made every attempt to contact original authors to check that the compiled data were correct. The name of the person who compiled the data is included in the database (entity table, contact) so that they can be consulted in the future about queries or corrections. Individual records for the database were subsequently checked by a small number of regional coordinators, to ensure that records were being entered in a consistent way. Prior to entry in the database, the records were automatically checked using specially designed database scripts (in Python) to ensure that the entries to individual fields were in the format expected (e.g. text, decimal numeric, positive integers) or were selected from the pre-defined lists provided for specific fields. In defining both the formats and the pre-defined lists, the SISAL working group has taken especial care to ensure that the entries are unambiguous. Null values for metadata fields were identified during the checking procedure, and checks were made with the data contributors whenever possible to ensure that null fields genuinely corresponded to missing information.

The database contains a large amount of information designed to allow an assessment of the quality of an individual record. Thus, the entity metadata table contains information about e.g. the distance of the speleothem from the cave entrance in order to allow the user to assess whether cave temperatures are driven by advection of air or conduction through the bedrock. There are several other factors that can affect ventilation, for example the contrast between the cave and external climates, and cave morphology such as the size of the entrance or the number of entrances. Information on these factors is only rarely given in publications; we assume that this information would be more likely to be available if the original authors thought that ventilation was a significant influence on the speleothem record. Including information about distance from the cave mouth is therefore being regarded as a minimal indicator for record quality. Other fields that are included to allow the user to select appropriate records include: geology, rock age, speleothem type and drip type.

The database also contains information to allow an assessment of the reliability of the dates used in constructing the original age model. The most important of these fields are the information about the sample geochemistry (see Section 2.2.4), which allows the user to determine whether the samples were sufficiently large and sufficiently pure to yield good U/Th dates. The database also gives information on sample weight, which also addresses this issue. The information about the corrections employed, dating uncertainties and whether the original authors considered the date reliable (and therefore used it in constructing an age model) also provide insights into the reliability of individual chronologies.

The SISAL database is an ongoing effort and continuing efforts to update the records will include updating missing data fields for individual records. Analysis of the data is also useful for verification purposes and may result in corrections of some data. Any such changes to sites and entities included in v1 of the database will be documented in subsequent updates. The SISAL working group also aims to provide new chronologies in future versions of the database based on Bayesian approaches, namely OxCal (Bronk Ramsey, 1995, 2008), COPRA (Breitenbach et al., 2012), and StalAge (Scholz and Hoffmann, 2011).

2.4 Overview of contents

The first version of the SISAL database contains 195,619 $\delta^{18}O$ measurements and 124,355 $\delta^{13}C$ measurements from 366 speleothem records (of which 19 are resampled versions of an existing record) and 10 composites from 172 cave systems. This represents approximately 57% of published speleothem records we have identified. The database also contains 5 records that have not been published.

The distribution of sites is global in extent (Figure 1). The majority (31%) of the sites are from Europe (53 sites) and there is currently less good representation of sites from other regions.

The temporal distribution of records is excellent for the past 2,000 years (Figure 2a) and good for the past 22,000 years (Figure 2b). Altogether, 144 entities record some part of the past 2,000 years, 87 of which have a resolution ≤ 10 years between samples on average. There are 254 entities recording some part of the past 22,000 years, including 154 of which have a resolution of ≤ 100 years between samples on average. The database contains 42 entities from the Last Interglacial (115,000 to 130,000 years before present), 41 of which have a resolution of ≤ 1000 years between samples on average (Figure 2c).

3. Data availability: The database is available in SQL format from http://dx.doi.org/10.17864/1947.139.

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4. Conclusions

The SISAL database is based on a community effort to compile isotopic measurements from speleothems to facilitate palaeoclimate analysis. Considerable effort has been made to ensure that there is adequate metadata and quality control information to allow the selection of records appropriate to answer specific questions and to document the uncertainties in the interpretation of these records. The database is public access.

The first version of the SISAL database contains 195,619 $\delta^{18}O$ measurements and 124,355 $\delta^{13}C$ measurements from 366 individual speleothem records, and 10 composites from 172 cave systems. The distribution of sites is global in extent. The temporal distribution is excellent for the past 2,000 years and good for the past 22,000 years. There are also records that span the Last Interglacial.

The format of the database is designed to facilitate the use of the data for regional to continental-scale analyses, and in particular to facilitate comparisons with and evaluation of isotope-enabled climate model simulations. The SISAL working group will continue to expand the coverage of the SISAL database and will provide new chronologies based on standardised age models; subsequent versions of the database will be made freely available to the community.

Author contributions

LCB is the coordinator of the SISAL working group. KA, SPH, LCB, MD, AB designed the database, drawing on discussions with participants at the first SISAL workshop. KA, SPH, LCB, SAM were responsible for the database construction. NK, SMA, MA, YAB, PB, KB, YB, SC, WD, IGH, JH, ZK, IL, ML, FL, AL, CP-M, RP and NS coordinated the regional data collection. TA and DG contributed original unpublished data to the database. The first draft of the paper was written by KA, SPH, LCB, MB, AB and NK and all authors contributed to the final version. The SISAL Working Group members contributing data to this paper are: Tim Atkinson, Avner Ayalon, James Baldini, Miriam Bar-Matthews, Juan Pablo Bernal, Sebastian Breitenbach, Ronny Boch, Andrea Borsato, Yanjun Cai, Stacy Carolin, Hai Cheng,

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Figure 1: Map of the location of sites in the database. Note that some sites include records for multiple individual speleothems, which are treated as separate entities in the database itself. The sites are coded with different shapes to indicate whether they provide records only for oxygen isotopes, or for both oxygen and carbon isotopes.

Figure 2: Plot showing the temporal coverage of individual entities in the database. The uppermost panel (a) shows records covering the past 2,000 years (2kyr BP), the middle panel (b) shows records covering the past 22,000 years (22kyr BP), and the bottom panel (c) shows records that cover the Last Interglacial (130,000 to 115,000 years before present, 130-115kyr BP).

Table 1: Information on speleothem records (entities) in the SISAL_v1 database

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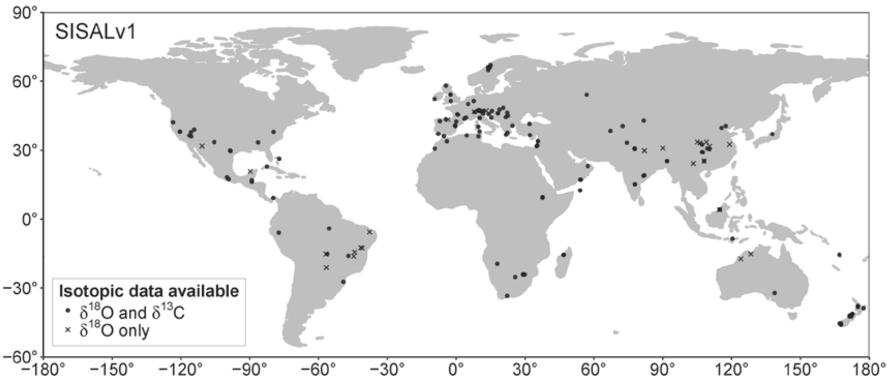

Figure 1: Map of the location of sites in the database. Note that some sites include records for multiple individual speleothems, which are treated as separate entities in the database itself. The sites are coded with different shapes to indicate whether they provide records only for oxygen isotopes, or for both oxygen and carbon isotopes.

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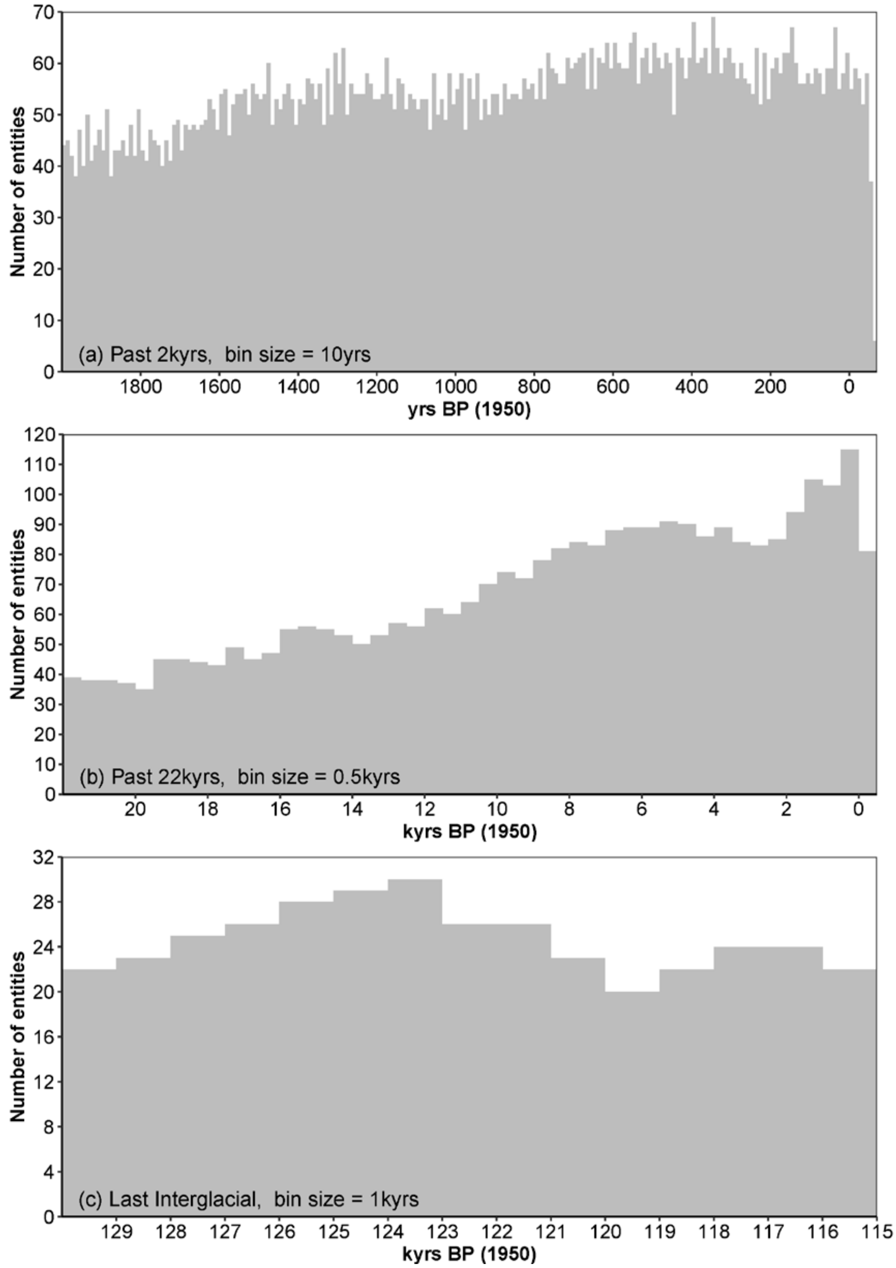

Figure 2: Plot showing the temporal coverage of individual entities in the database. The uppermost panel (a) shows records covering the past 2,000 years (2kyrs BP), the middle panel (b) shows records covering the past 22,000 years (22kyrs BP), and the

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bottom panel (c) shows records that cover the Last Interglacial (130,000 to 115,000 years before present, 130-115kyrs BP).

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Table 1: Information on speleothem records (entities) in the SISAL_v1 database. Elevation (Elev) is given in metres and latitude (Lat) and longitude (Long) in decimal degrees.

Entity name	Site name	Elev (m)	Lat (°)	Long (°)	Citations
AB-DC-01, AB-DC-03, AB-DC-12	Abaco Island cave	-45	26.23	-77.16	Arienzo et al., 2017
AB-DC-09	Abaco Island cave	-45	26.23	-77.16	Arienzo et al., 2015, 2017
ABA_1, ABA_2	Abaliget cave	209	46.13	18.12	Koltai et al., 2017
Abissal, Ale-1	Abissal cave	100	-5.6	-37.733	Cruz et al., 2009
Ach-1	Achere cave	1534	9.52	37.65	Asrat et al., 2006; 2008
AB2	Anjohibe cave	131	-15.53	46.88	Scroxton et al., 2017
AB3	Anjohibe cave	131	-15.53	46.88	Burns et al., 2016
ANJB-2, MAJ-5	Anjohibe cave	131	-15.53	46.88	Voarintsoa et al., 2017c
MA3	Anjohibe cave	131	-15.53	46.88	Voarintsoa et al., 2017a
CC-1_2004	Antro del Corchia	840	43.98	10.22	Drysdale et al., 2004
CC-1_2009, CC-5_2009, CC-7	Antro del Corchia	840	43.98	10.22	Drysdale et al., 2009
CC-28	Antro del Corchia	840	43.98	10.22	Drysdale et al., 2007
CC-5_2005	Antro del Corchia	840	43.98	10.22	Drysdale et al., 2005
POM2	Ascunsa cave	1050	45	22.6	Drăguşin et al., 2014
BGC11, BGC14, BGC6	Ball Gown cave	100	-17.3	124.1	Denniston et al., 2013b
BAR-II#B, BAR-II#L	Baradla cave	375	48.4667	20.5	Demény et al., 2017b
BA-1, BA-1b, BA-2	Baschg cave	780	47.2501	9.6667	Boch and Spötl, 2011
Bero-1	Bero cave	1363	9.31	37.64	Asrat et al., 2008; Baker et al., 2010
Keklik1	Bir-Uja cave	1435	40.4833	72.5833	Fohlmeister et al., 2017
BT-1, BT-2.1, BT-2.2, BT-2.3, BT-2.4, BT-2.5, BT-4, BT-6, BT-8, BT-9	Bittoo cave	3000	30.7903	77.7764	Kathayat et al., 2016
BT-2	Botuverá	180	-27.2247	-49.1569	Cruz et al., 2005
BTV21a	Botuverá	180	-27.2247	-49.1569	Bernal et al., 2016
BDinf	Bourgeois–Delaunay cave	100	45.6678	0.5133	Couchoud et al., 2009
BC01-07	Brown's cave	25	22.8894	-82.5186	Pollock et al., 2016
BFM-9, Boss, F2	Brown's Folly mine	150	51.38	-2.37	Baldini, 2001; Baldini et al., 2005
RL4_2006	Buca della Renella	300	44.08	10.21	Drysdale et al., 2006
RL4_2016	Buca della Renella	300	44.08	10.21	Zanchetta et al., 2016
BCC_composite, BCC-2, BCC-4, BCC-6	Buckeye creek	600	37.9825	-79.5894	Hardt et al., 2010
BCC-8, BCC-10	Buckeye creek	600	37.9825	-79.5894	Springer et al., 2014
BMS1	Bue Marino cave	0	40.2467	9.6228	Columbu et al., 2017
Buffalo Cave Flowstone	Buffalo cave	1140	-24.1428	29.177	Hopley et al., 2007a, 2007b
BA02	Bukit Assam cave	150	4.03	114.8	Carolin et al., 2013
BA03	Bukit Assam cave	150	4.03	114.8	Chen et al., 2016
BA04	Bukit Assam cave	150	4.03	114.8	Partin et al., 2007
Bu1, Bu2, Bu4, Bu6, BuStack	Bunker cave	184	51.3675	7.6647	Fohlmeister et al., 2012
Calcite	Calcite cave		-46.0172	167.7431	Lorrey et al., 2008
V3	Cango cave		-33.3925	22.2147	Vogel, 1983; Talma & Vogel, 1992; Vogel & Kronfeld, 1997
COB-01-02	Cave of the Bells		31.75	-110.75	Wagner et al., 2010
CWN4	Cave Without a Name	377	29.8852	-98.6208	Feng et al., 2014
CC-1	Ceremosnja cave	530	44.4	21.65	Kacanski et al., 2001
Chau-stm6	Chauvet cave	240	44.23	4.26	Genty et al., 2006
CHIL-1	Chilibrillo cave	60	9.2	-79.7	Lachniet, 2004
CL26	Clamouse cave	110	43.71	3.55	McDermott et al., 1999
Cla4	Clamouse cave	110	43.71	3.55	Plagnes et al., 2002
FC12-12, FC12-14, FC12-15	Clearwater cave	120	4.1	114.8333	Carolin et al., 2016
Squeeze1	Clearwater/Wind		4.1	114.83	Meckler et al., 2012

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	caves connection				
T5	Cold Air cave	1420	-24	29.1833	Repinski et al., 1999
T7_1999	Cold Air cave	1420	-24	29.1833	Holmgren et al., 1999; Stevenson et al., 1999
T7_2001	Cold Air cave	1420	-24	29.1833	Lee-Thorp et al., 2001
T7_2013	Cold Air cave	1420	-24	29.1833	Sundqvist et al., 2013
T8	Cold Air cave	1420	-24	29.1833	Holmgren et al., 2003
ESP03	Cova da Arcoia	1240	42.61	-7.09	Railsback et al., 2011
CC3	Crag cave	60	52.25	-9.43	McDermott et al., 1999; McDermott, 2001
ASM, ASR	Cueva de Asiul	285	43.32	-3.59	Smith et al., 2016
CBD-2	Cueva del Diablo	1030	18.1833	-99.9167	Bernal et al., 2011
CUR4	Curupira cave	420	-15.2002	-56.7839	Novello et al., 2016
DAN-D	Dandak cave	400	19	82	Berkelhammer et al., 2010; Sinha et al., 2007
DP1_2013	Dante cave		-19.4	17.8833	Sletten et al., 2013
DP1_2016	Dante cave		-19.4	17.8833	Voarintsoa et al., 2017b
DY-1	Dayu cave	870	33.133	106.3	Tan et al., 2009
S3	Defore cave	150	17.1667	54.0833	Burns, 2002
DSSG-4	DeSoto caverns	150	33.3722	-86.3667	Aharon et al., 2013
DH2, DH2-D, DH2-E Terminal1, DH2-E Terminal2	Devils Hole	719	36.4256	-116.291	Moseley et al., 2016
Dim-E2, Dim-E3, Dim-E4	Dim cave	232	36.53	32.11	Unal-İmer et al., 2015
DV2	Diva cave	680	-12.3667	-41.5667	Novello et al., 2012
D3, D4	Dongge cave	680	25.28	108.08	Yuan, 2004
D8	Dongge cave	680	25.28	108.08	Cheng et al., 2016b
Doubtful	Doubtful Xanadu	960	-45.3735	167.0476	Lorrey et al., 2008
ARTEMISA	Ejulve cave	1240	40.45	-0.35	Pérez-Mejías et al., 2017
HOR	Ejulve cave	1240	40.45	-0.35	Moreno et al., 2017
TKS	Entrische Kirche cave	2119	47.16	13.15	Meyer et al., 2008
GEX-SPA	Excentrica cave	100	37.1	-7.77	Ponte et al., 2017; Veiga-Pires et al., 2017
ED1	Exhaleair cave	685	-41.2833	172.633	Hellstrom et al., 1998
FS2_2010	Fort Stanton cave	1864	33.5067	-105.443	Asmerom et al., 2010
FS2_2012	Fort Stanton cave	1864	33.5067	-105.443	Polyak & Asmerom, 2001
FG01	Fukugaguchi cave	170	36.9917	137.8	Sone et al., 2013
FR-0510	Furong cave	480	29.13	107.54	Li et al., 2011a
FR-5	Furong cave	480	29.13	107.54	Li et al., 2011b
GG1, GG2	Gardener's Gut	120	-37.7394	175.1033	Williams et al., 2004
GC08	Green Cathedral cave		4.2333	114.925	Meckler et al., 2012
CR1	Grotta di Carburangeli	22	38.1669	10.1608	Frisia et al., 2006; Madonia et al., 2005
ER76	Grotta di Ernesto	1167	45.9667	11.65	Scholz and Hoffmann, 2011
GP2	Grotte de Piste	1260	33.84	-4.09	Wassenburg et al., 2016
stm2, stm4	Gueldaman cave	507	36.4333	4.5667	Ruan et al., 2016
GT05-5	Guillotine cave	740	-42.3108	172.2178	Whittaker, 2008
SCH02, SSC01	Gunung-buda cave (snail shell cave)	150	4.033	114.8	Cobb et al., 2007; Moerman et al., 2013; Moerman et al., 2014; Partin et al., 2007;2013b
Han-9	Han-sur-Lesse cave	180	50.1164	5.1884	Vansteenberge et al., 2016
Han-stm1	Han-sur-Lesse cave	180	50.1164	5.1884	Genty et al., 1999
Han-stm5b	Han-sur-Lesse cave	180	50.1164	5.1884	Genty et al., 1998
HS4_2008	Heshang cave	294	30.45	110.4167	Hu et al., 2008
HS4_2013	Heshang cave	294	30.45	110.4167	Liu et al., 2013
HOL-10	Hölloch im Mahdtal	1240	47.3781	10.1506	Moseley et al., 2015
HOL-7, HOL-16, HOL-16-17, HOL-17, HOL-18, HOL-comp	Hölloch im Mahdtal	1240	47.3781	10.1506	Moseley et al., 2014
HW3	Hollywood cave	130	-41.95	171.4667	Whittaker et al., 2011
H5	Hoti cave	800	23.0833	57.35	Neff et al., 2001
HY1, HY2, HY3	Huangye cave	1650	33.5833	105.1167	Tan et al., 2010
H82, MSD, MSL, PD, YT	Hulu cave	90	32.5	119.17	Wang, 2001
IFK1	Ifoulki cave	1250	30.708	-9.3275	Ait Brahim et al., 2017

JAR7, JAR13, JAR14	Jaraguá cave	570	-21.083	-56.583	Novello et al., 2017
Jeita-1, Jeita-2, Jeita-3	Jeita cave	100	33.95	35.65	Cheng et al., 2015
AF12	Jerusalem west cave	700	31.7833	35.15	Frumkin et al., 1999; 2000
JHU-1	Jhumar cave	600	18.8667	81.667	Sinha et al., 2011
C996-1, C996-2	Jiuxian cave	1495	33.5667	109.1	Cai et al., 2010b
JX-2, JX-10	Juxtlahuaca cave	934	17.4	-99.2	Lachniet et al., 2013
JX-6	Juxtlahuaca cave	934	17.4	-99.2	Lachniet et al., 2012
JX-7	Juxtlahuaca cave	934	17.4	-99.2	Lachniet et al., 2017
KL 3	Kalakot cave	826	33.2219	74.4258	Kotlia and Singh, 2016
Kanaan_MIS5	Kanaan cave	98	33.9069	35.6069	Nehme et al., 2015
GK-09-02	Kapsia cave	700	37.6233	22.3539	Finné et al., 2014
K1, K3	Katerloch cave	900	47.0833	15.55	Boch et al., 2011
KS06-A, KS06-A-H, KS06-B, KS08-1, KS08-1-H, KS08-2, KS08-2-H, KS08-2-MIS3, KS08-6	Kesang cave	2000	42.87	81.75	Cheng et al., 2016a
KC-1, KC-3, KC-Composite	Kinderlinskaya cave	240	54.15	56.85	Baker et al., 2017
PFU6	Klapferloch cave	1140	46.95	10.55	Boch et al., 2009
SPA_49, SPA_126	Kleegruben cave	2165	47.08	11.67	Spötl et al., 2006
KNI-51-0, KNI-51-3, KNI-51-4, KNI-51-7, KNI-51-10, KNI-51-A2-side1, KNI-51-A2-side2, KNI-51-C, KNI-51-F, KNI-51-G, KNI-51-H, KNI-51-I, KNI-51-J, KNI-51-N, KNI-51-O	KNI-51 cave	100	-15.18	128.37	Denniston et al., 2013a
KNI-51-11	KNI-51 cave	100	-15.18	128.37	Denniston et al., 2015; 2016
K11	Korallgrottan cave	540	64.88	14	Sundqvist et al., 2010
BW-1	Kulishu cave	610	39.68	115.65	Ma et al., 2012
Min-stm1	La Mine cave	975	36.03	9.68	Genty et al., 2006
L4	Labyrintgrottan cave	730	66.06	14.68	Sundqvist et al., 2007
LH-70s-1	Lancaster Hole	294	54.2209	-2.5168	Atkinson & Hopley, 2013
LH-70s-2, LH-70s-3	Lancaster Hole	294	54.2209	-2.5168	Atkinson & Hoffman, unpublished
LD12	Lapa Doce cave	680	-12.3667	-41.5667	Novello et al., 2012
LG3, LG11	Lapa grande cave	590	-14.3794	-44.2888	Strikis et al., 2011
LSF3, LSF16	Lapa sem fim cave	341	-16.1503	-44.6281	Stríkis et al., 2015
L03	Larshullet cave	400	66	14	Linge et al., 2009b
Leany	Leany cave	420	47.7	18.84	Demény et al., 2013
LC-2	Lehman caves	2080	39	-114.2	Shakun et al., 2011
LMC-14, LMC-21	Lehman caves	2080	39	-114.2	Lachniet et al., 2014
LC-1	Leviathan cave	2400	37.89	-115.58	Lachniet et al., 2014
LR06-B1_2009, LR06-B3_2009	Liang Luar cave	550	-8.53	120.43	Griffiths et al., 2009
LR06-B1_2016, LR06-B3_2016	Liang Luar cave	550	-8.53	120.43	Griffiths et al., 2016
LR06-B3_2013, LR06-C2, LR06-C3_2013, LR06-C5, LR06-C6, LL_Comp_2013	Liang Luar cave	550	-8.53	120.43	Ayliffe et al., 2013
LR06-C3_2011, LR07-E1, LR07-E1-D	Liang Luar cave	550	-8.53	120.43	Lewis et al., 2011
LR07-A8, LR07-A9, LR07-E11	Liang Luar cave	550	-8.53	120.43	Griffiths et al., 2013
LII4-1, LII4-2	Lobatse cave	1200	-25.21	25.68	Holmgren et al., 1994: 1995
ME-12	Ma'ale Efrayim cave	250	32.0833	35.3667	Vaks et al., 2003
MC01	Macal Chasm	530	16.883	-89.108	Akers et al., 2016; Webster et al., 2007
MC-S1, MC-S2	Mairs cave	475	-32.16	138.83	Treble et al., 2017
S1	Mavri Trypa cave	70	36.736	21.7596	Finné et al., 2017
KM-A	Mawmluh cave	1160	25.26	91.88	Berkelhammer et al., 2013; Breitenbach et al., 2015
MAW-6	Mawmluh cave	1160	25.26	91.88	Lechleitner et al., 2017
MWS-1	Mawmluh cave	1160	25.26	91.88	Breitenbach et al., 2015; Dutt et al., 2015

MAXS	Max's cave	325	-37.7394	175.1033	Williams et al., 2004
ML1	McLean's cave	300	38.07	-120.42	Oster et al., 2015
MB-2, MB-3, MB-5, MB-6	Milchbach cave	1840	46.6167	8.083	Luetscher et al., 2011
MC3	Moaning cave	520	38.0717	-120.466	Oster et al., 2009, 2015
MOD-22	Modric cave	32	44.15	15.32	Rudzka et al., 2012
MO-1	Molinos cave	1050	40.7925	-0.4492	Moreno et al., 2017
MO-7	Molinos cave	1050	40.7925	-0.4492	Moreno et al., 2017; Muñoz et al., 2015
M1-5	Moomi cave	400	12.5	54	Shakun et al., 2007
Mun-stm1, Mun-stm2	Munagamanu cave	475	15.15	77.92	Genty et al., unpublished
NBJ	Natural Bridge caverns	306	29.69	-98.34	Wong et al., 2015
MD3	Nettlebed cave	390	-41.25	172.633	Hellstrom et al., 1998
Gib04a	New St Michael's cave	325	36.15	-5.35	Mattey et al., 2008, 2010
FM3, Oks82	Okshola cave	165	67	15	Linge et al., 2009a
OCNM02-1	Oregon caves national monument	1300	42.0981	-123.407	Ersek et al., 2012
PX7	Paixão cave		-12.6182	-41.0184	Stríkis et al., 2015
PAL3, PAL4	Palestina cave	870	-5.92	-77.35	Apaéstegui et al., 2014
PAR01, PAR03, PAR06, PAR07, PAR08, PAR16, PAR24	Paraiso cave	60	-4.0667	-55.45	Wang et al., 2017
ALHO6	Pau d'Alho cave	340	-15.2055	-56.2055	Jaqueto et al., 2016; Novello et al., 2016
Candela	Pindal cave	24	43.4	-4.53	Moreno et al., 2010; Rudzka et al., 2011
PC-1	Pinnacle cave	1792	35.97	-115.5	Lachniet et al., 2011
YD01	Pippikin Pot cave	320	54.2143	-2.5123	Atkinson & Hopley, 2013; Daley et al., 2011
POS-STM-4	Postojna cave	529	45.77	14.20	Genty et al., 1998
Q5	Qunf cave	650	17.1667	54.3	Fleitmann et al., 2007
RN1, RN4	Rainha cave	100	-5.6	-37.733	Cruz et al., 2009
Ruakuri C	Ruakuri cave	80	-38.2667	175.0667	Williams et al., 2004
Asfa-3, Merc-1	RukieSSa cave	1618	9.51	37.65	Asrat et al., 2008; Baker et al., 2007
SAH-A, SAH-AB, SAH-B	Sahiya cave	1190	30.6	77.8667	Sinha et al., 2015
SB-10, SB-26, SB-27, SB-43, SB-44, SB-49	Sanbao cave	1900	31.667	110.433	Dong et al., 2010
SB-12, SB-14, SB-32, SB-58	Sanbao cave	1900	31.667	110.433	Cheng et al., 2016b
MF-3	Schafsloch cave	1890	47.2333	9.3833	Häuselmann et al., 2015
SCH-5	Schneckenloch cave	1285	47.4333	9.8667	Moseley et al., 2015
SCH-7	Schneckenloch cave	1285	47.4333	9.8667	Boch and Spötl, 2011
SC02, SC03	Secret cave	250	4.0848	114.8503	Carolin et al., 2013
SE09-6	Seso cave	794	42.46	0.04	Bartolomé et al., 2015
7H, 7H-2, 7H-3	Sieben Hengste cave	1955	46.75	7.81	Luetscher et al., 2015
MAR_L	Skala Marion cave	41	40.6387	24.5144	Psomiadis et al., 2018
So-1	Sofular cave	700	41.42	31.93	Fleitmann et al., 2009
2-6	Soreq cave	400	31.7597	35.0264	Orland et al., 2009
2N	Soreq cave	400	31.7597	35.0264	Orland et al., 2012
Soreq-composite	Soreq cave	400	31.7597	35.0264	Grant et al., 2012
SG95	Soylegrotta cave	280	66	14	Linge et al., 2001
COMNISPA II, SPA12, SPA127, SPA128, SPA133, SPA70	Spannagel cave	2310	47.08	11.67	Fohlmeister et al., 2013
SPA121	Spannagel cave	2310	47.08	11.67	Spötl et al., 2008
SZ2	Suozi cave	700	32.43	107.17	Zhou et al., 2008
TM0, TM2	Tamboril cave	200	-16	-47	Wortham et al., 2017
Taurius	Taurius cave	230	-15.5333	167.0167	Partin et al., 2013a
Aurora	Te Anau Fiordland	320	-45.28	167.7	Lorrey et al., 2008
Te Reinga A, Te Reinga B	Te Reinga cave		-38.82	177.52	Lorrey et al., 2008
TM-18a, TM-18b	Tianmen	4800	30.9167	90.0667	Cai et al., 2012
TM-2, TM-5	Tianmen	4800	30.9167	90.0667	Cai et al., 2010a

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T1	Timta cave	1900	29.8381	82.0336	Sinha et al., 2005
TC1	Tityana cave	1470	30.6419	77.6521	Joshi et al., 2017
TON-1, TON-2	Tonnel'naya cave	3226	38.4	67.23	Cheng et al., 2016a
TR5	Torrinha cave	680	-12.3667	-41.5667	Novello et al., 2012
Trio	Trio cave	275	46.11	18.15	Demény et al., 2017a; Siklósy et al., 2009
Chaac	Tzabnah cave	20	20.73	-89.716	Medina-Elizalde et al., 2010
SU032	Uamh an Tartair	220	58.1	-4.5	Baker et al., 2012
SU967	Uamh an Tartair	220	58.1	-4.5	Baker et al., 2011
PU-2	Ursilor cave	482	46.32	22.25	Onac et al., 2002
VSPM1	Valmiki cave	420	15.15	77.8167	Raza et al., 2017
VSPM4	Valmiki cave	420	15.15	77.8167	Lone et al., 2014
Vil-car1	Villars cave	175	45.43	0.78	Wainer et al., 2011
Vil-stm1	Villars cave	175	45.43	0.78	Labuhn et al., 2015
Vil-stm11	Villars cave	175	45.43	0.78	Genty et al., 2006
Vil-stm14	Villars cave	175	45.43	0.78	Genty et al., 2010; Wainer et al., 2009
Vil-stm27	Villars cave	175	45.43	0.78	Genty et al., 2003
Vil-stm6	Villars cave	175	45.43	0.78	Genty, unpublished
Vil-stm9	Villars cave	175	45.43	0.78	Genty et al., 2003: 2010
WS-B	Wah Shikhar cave	1290	25.25	91.8667	Sinha et al., 2011
Waiau	Waiau cave	100	-46	167.73	Lorrey et al., 2008
WP-1	Wazpretti cave	100	-42.3108	171.4	Williams et al., 2005
WSC-97-10-5	White Scar cave	255	54.1656	-2.4419	Atkinson & Hopley, 2013; Daley et al., 2011
WR5	Whiterock cave		4.15	114.86	Meckler et al., 2012
W5	Wolkberg cave	1450	-24.1	29.88	Holzkämper et al., 2009
XBL-3, XBL-4, XBL-7, XBL-26, XBL-27, XBL-29, XBL-48, XBL-65	Xiaobailong cave	1500	24.2	103.36	Cai et al., 2015
XL-1	Xinglong cave	710	40.5	117.5	Duan et al., 2016
XY07-8	Xinya cave	1250	30.75	109.47	Li et al., 2017a
XY-2	Xinya cave	1250	30.75	109.47	Li et al., 2007
JFYK7	Yangkou cave	2140	29.2	107.11	Han et al., 2016; Li et al., 2017b; Zhang et al., 2017
YK5, YK12, YK23, YK47, YK61	Yangkou cave	2140	29.2	107.11	Li et al., 2014
YOKG	Yok Balum cave	336	16.2086	-89.0735	Ridley et al., 2015
YOKI	Yok Balum cave	336	16.2086	-89.0735	Kennett et al., 2012