SISALv2: a comprehensive speleothem isotope database with multiple age-depth models

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SISALv2: a comprehensive speleothem isotope database with multiple age–depth models

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Abstract. Characterizing the temporal uncertainty in palaeoclimate records is crucial for analysing past climate change, correlating climate events between records, assessing climate periodicities, identifying potential triggers and evaluating climate model simulations. The first global compilation of speleothem isotope records by the SISAL (Speleothem Isotope Synthesis and Analysis) working group showed that age model uncertainties are not systematically reported in the published literature, and these are only available for a limited number of records (ca. 15 %, \( n = 107/691 \)). To improve the usefulness of the SISAL database, we have (i) improved the database’s spatio-temporal coverage and (ii) created new chronologies using seven different approaches for age–depth modelling. We have applied these alternative chronologies to the records from the first version of the SISAL database (SISALv1) and to new records compiled since the release of SISALv1. This paper documents the necessary changes in the structure of the SISAL database to accommodate the inclusion of the new age models and their uncertainties as well as the expansion of the database to include new records and the quality-control measures applied. This paper also documents the age–depth model approaches used to calculate the new chronologies. The updated version of the SISAL database (SISALv2) contains isotopic data from 691 speleothem records from 294 cave sites and new age–depth models, including age–depth temporal uncertainties for 512 speleothems. SISALv2 is available at https://doi.org/10.17864/1947.256 (Comas-Bru et al., 2020a).

1 Introduction

Speleothems are a rich terrestrial palaeoclimate archive that forms from infiltrating rainwater after it percolates through the soil, epikarst and carbonate bedrock. In particular, stable oxygen and carbon isotope (\( \delta^{18}O, \delta^{13}C \)) measurements made on speleothems have been widely used to reconstruct regional and local hydroclimate changes.

The Speleothem Isotope Synthesis and Analyses (SISAL) working group is an international effort under the auspices of Past Global Changes (PAGES) to compile speleothem isotopic records globally for the analysis of past climates (Comas-Bru and Harrison, 2019). The first version of the SISAL database (Atsawawaranunt et al., 2018a, b) contained 381 speleothem records from 174 cave sites and has been used for analysing regional climate changes (Braun et al., 2019a; Burstyn et al., 2019; Comas-Bru and Harrison, 2019; Deininger et al., 2019; Kaushal et al., 2018; Kern et al., 2019; Lechleitner et al., 2018; Oster et al., 2019; Zhang et al., 2019). The potential for using the SISAL database to evaluate climate models was explored using an updated version of the database (SISALv1b; Atsawawaranunt et al., 2019) that contains 455 speleothem records from 211 sites (Comas-Bru et al., 2019).

SISAL is continuing to expand the global database by including new records (Comas-Bru et al., 2020a). Although most of the records in SISALv2 (79.7 %; Fig. 1a) have been dated using the generally very precise, absolute radiometric \( ^{230}\text{Th}/^{238}\text{U} \) dating method, a variety of age-modelling approaches were employed (Fig. 1b) in constructing the original records. The vast majority of records provide no information on the uncertainty of the age–depth relationship. However, many of the regional studies using SISAL pointed to the limited statistical power of analyses of speleothem records because of the lack of temporal uncertainties. For example, these missing uncertainties prevented the extraction of underlying climate modes during the last 2000 years in Europe (Lechleitner et al., 2018). To overcome this limitation, we have developed additional age–depth models for the SISALv2 records (Fig. 2) in order to provide robust chronologies with temporal uncertainties. The results of the various age–depth modelling approaches differ because of differences in their underlying assumptions. We have used seven alternative methods: linear interpolation, linear regression, Bchron (Haslett and Parnell, 2008), Bacon (Blaauw and Christen, 2011; Blaauw et al., 2019), OxCal (Bronk Ramsey, 2008, 2009; Bronk Ramsey and Lee, 2013), COPRA (Breitenbach et al., 2012) and StalAge (Scholz and Hoffmann, 2011). Comparison of these different approaches provides a robust measure of the age uncertainty associated with any specific speleothem record.

2 Data and methods

2.1 Construction of age–depth models: the SISAL chronology

We attempted to construct age–depth models for 533 entities in an automated mode. For eight records, this automated construction failed for all methods. For these records we provide
Figure 1. Summary of the dating information on which the original age–depth models are based (a) and the original age–depth model types (b) present in SISALv2.

Figure 2. Cave sites included in the version 1, 1b and 2 of the SISAL database on the World Karst Aquifer Map (WOKAM; Goldscheider et al., 2020).
manually constructed chronologies where no age model previously existed and added a note in the database with details on the construction procedure. Age models for 21 records were successfully computed but later dropped in the screening process due to inconsistent information or incompatibility for an automated routine. In total, we provide additional chronologies for 512 speleothem records in SISALv2.

The SISAL chronology provides alternative age–depth models for SISAL records that are not composites (i.e. time series based on more than one speleothem record), that have not been superseded in the database by a newer entity and which are purely $^{230}$Th/$^{234}$U dated. We therefore excluded records for which the chronology is based on lamina counting, radiocarbon ages or a combination of methods. This decision was based on the low uncertainties of the age–depth models based on lamina counting and the challenge of reproducing age–depth models based on radiocarbon ages. We made an exception with the case of entity_id 163 (Talma et al., 1992), which covers two key periods – the mid-Holocene and the Last Glacial Maximum – at high temporal resolution. In this case, we calculated a new SISAL chronology based on the provided $^{230}$Th/$^{234}$U dates but did not consider the uncorrected $^{14}$C ages upon which the original age–depth model is based. We also excluded records for which isotopic data are not available (i.e. entities that are part of composites) and entities that are constrained by less than three dates. Additionally, the dating information for 23 entities shows hiatuses at the top and bottom of the speleothem that are not constrained by any date. For these records, we partially masked the new chronologies to remove the unconstrained section(s). Original dates were used without modification in the age–depth modelling.

To allow a comprehensive cross-examination of uncertainties, seven age–depth modelling techniques were implemented here across all selected records. Due to the high number of records ($n = 533$), all methods were run in batch mode. A preliminary study using the database version v1b demonstrated the feasibility of the automated construction and evaluation of age–depth models using a subset of records and methods (Roehfeld and Rehfeld, 2019). Further details on the evaluation of the updated age–depth models are provided in Sect. 3.2. The seven different methods are briefly described below. All methods assume that growth occurred along a single growth axis. For one entity, where it was previously known that two growth axes exist, we added an explanatory statement in the database. All approaches except StalAge produce Monte Carlo (MC) iterations of the age–depth models. We aimed to provide 1000 MC iterations for each new SISALv2 chronology at https://doi.org/10.5281/zenodo.3816804 (Rehfeld et al., 2020), but this was not always possible because some records ($n = 12$) yield a substantial number of non-monotonic ensembles that were not kept.

Major challenges arise through hiatuses (growth interruptions) and age reversals. We developed a workflow to deal with records with known hiatuses that allowed the construction of age–depth models for 20% of the records with one or more hiatuses (Roehfeld and Rehfeld, 2019: details below for each age–depth modelling technique). Regarding the age reversals, we distinguish between tractable reversals (with overlapping confidence intervals) and non-tractable reversals (i.e., where the 2-sigma dating uncertainties do not overlap) following the definition of Breitenbach et al. (2012). Details such as the hiatus treatment and outlier age modification are recorded in a log file created when running the age models. We followed the original author’s choices regarding date usage. If an age was marked as “not used” or “usage unknown”, we did not consider this in the construction of the new chronologies except in OxCal, where dates with “usage unknown” were considered.

1. Linear interpolation ($\text{lin\_interp\_age}$) between radiometric dates is the classic approach for age–depth model construction for palaeoclimate archives and was used in 32.1% of the original age–depth models in SISALv2. Here, we extend this approach and calculate the age uncertainty by sampling the range of uncertainty of each $^{230}$Th/$^{234}$U age 2000 times, assuming a Gaussian distribution. This approach is consistent with the implementation of linear interpolation in CLAM (Blaauw, 2010) and COPRA (Breitenbach et al., 2012). Linear interpolation was implemented in R (R Core Team, 2019), using the $\text{approxExtrap()}$ function in the $\text{Hmisc}$ package. We included an automated reversal check that increases the dating uncertainties until a monotonic age model is achieved, similar to that of StalAge (Scholz and Hoffmann, 2011). Hiatuses are modelled following the approach of Roehfeld and Rehfeld (2019), where rather than modelling each segment separately, synthetic ages with uncertainties spanning the entire hiatus duration are introduced for use in age–depth model construction. These synthetic ages are removed after age–depth model construction. Linear interpolation was applied to 80% ($n = 408/512$) of the SISAL records for which new chronologies were developed.

2. Linear regression ($\text{lin\_reg\_age}$) provides a single best-fit line through all available radiometric ages assuming a constant growth rate. Linear regression was used in 6.7% of the original SISALv2 age models. As with linear interpolation, age uncertainties are based on randomly sampling the U-series dates to produce 2000 age–depth models (i.e. ensembles). Temporal uncertainties are then given by the uncertainty of the median-based fit to each ensemble member. If hiatuses are present, the segments in-between were split at the depth of the hiatus without an artificial age. The method is implemented in R using the $\text{lm()}$ function from the base package. Linear regression was applied to 36% ($n = 185/512$) of the SISAL records for which new chronologies were developed.
3. Bchron (Bchron_age) is a Bayesian method based on a continuous Markov processes (Haslett and Parnell, 2008) and is available as an R package (Parnell, 2018). This method was originally used for only one speleothem record in SISALv2. Since Bchron cannot handle hiatuses, we implemented a new workflow that adds synthetic ages with uncertainties spanning the entire hiatus duration (Roesch and Rehfeld, 2019), as performed with linear interpolation, StalAge and our implementation of COPRA. Bchron provides age–depth model ensembles, of which we have kept the last 2000. We calculate the age uncertainties from the spread of the individual ensembles. Here we use the function `bchron()` with `jitter.positions = true` to mitigate problems due to rounded-off depth values. This method has been applied to 83% (n = 426/512) of the SISAL records for which new chronologies were developed.

4. Bacon (Bacon_age) is a semi-parametric Bayesian method based on autoregressive gamma processes (Blaauw and Christen, 2011; Blaauw et al., 2019). It was used in three of the original chronologies in SISALv2. The R package rBacon can handle both outliers and hiatuses, and apart from giving the median age–depth model, it also returns the Monte Carlo realizations (i.e., ensembles), from which the median age–depth model is calculated. During the creation of the SISAL chronologies, the existing rBacon package (version 2.3.9.1) was updated to improve the handling of stalagmite growth rates and hiatuses. We use this revised version, available on CRAN (https://cran.r-project.org/web/packages/rbacon/index.html, last access: 31 January 2020), to provide a median age–depth model and an ensemble of age model realizations for 65% (n = 335/512) of the SISAL records for which new chronologies were developed.

5. OxCal (Oxcal_age) is a Bayesian chronological modelling tool that uses Markov chain Monte Carlo (Bronk Ramsey, 2009). This method was used in 4.1% of the original SISALv2 chronologies. OxCal can deal with hiatuses and outliers and accounts for the non-uniform nature of the deposition process (Poisson process using the P_Sequence command). Here we used the analysis module of OxCal version 4.3 with a default initial interpolation rate value of 1 and an initial model rigidity (k) value of k₀ = 1 with a uniform distribution from 0.01 to 100 for the range of k/k₀ (log10(k/k₀) = (−2, 2)) (Christopher Bronk Ramsey, personal communication, 2019). The initial value of the interpolation rate determines the number of points between any two dates for which an age will be calculated. We subsequently linearly interpolated the age–depth model to the depths of individual isotope measurements. Where multiple dates are given for the same depth for any given entity, the date with the smallest uncertainty was used to construct the SISAL chronology. In the case of asymmetric uncertainties in the dating table, the largest uncertainty value was chosen. We kept the last 2000 realizations of the age–depth models for each entity. We calculate the age uncertainties from the spread of the individual ensembles. Details of the workflow used to construct these chronologies are available in Amirnezhad-Mozhdehi and Comas-Bru (2019). OxCal chronologies are available for 21% (n = 106/512) of the SISAL records for which new chronologies were developed.

6. COPRA (copRa_age) is an approach based on interpolation between dates (Breitenbach et al., 2012) and was used for 9.7% of the original SISALv2 chronologies. COPRA is available as a MATLAB package in Rehfeld et al. (2017) with a graphical user interface (GUI) that has interactive checks for reversals and hiatuses. The MATLAB version can handle multiple hiatuses and (to some extent) layer-counted segments. However, age reversals can occur near short-lived hiatuses. To overcome this, we implemented a new workflow in R that adds artificial dates at the location of the hiatuses and prevents the creation of age reversals (Roesch and Rehfeld, 2019) as done with linear interpolation, StalAge and Bchron. Additionally, we also incorporated an automated reversal check similar to that already embedded into StalAge (Scholz and Hoffmann, 2011). This R version, copRa, uses the default piecewise cubic Hermite interpolation (pchip) algorithm in R without consideration of layer counting. We calculate the age uncertainties from the spread of the individual ensembles. This approach was used for 76% (n = 389/512) of the SISAL records for which new chronologies were developed.

7. StalAge (StalAge_age) fits straight lines through three adjacent dates using weights based on the dating measurement errors (Scholz and Hoffmann, 2011). Age uncertainties are iteratively obtained through a Monte Carlo approach, but ensembles are not given in the output. StalAge was used to construct 13.1% of the original SISALv2 chronologies. The StalAge v1.0 R function has been updated to R version 3.4, and the default outlier and reversal checks were enabled to run automatically. Hiatuses cannot be entered in StalAge v1.0, but the updated version incorporates a treatment of hiatuses based on the creation of temporary synthetic ages following Roesch and Rehfeld (2019). In contrast to other methods, mean ages instead of median ages are reported for StalAge, and the uncertainties are internally calculated and based on iterative fits considering dating uncertainties. StalAge was applied to 62% (n = 320/512) of the SISAL records for which new chronologies were developed.
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Figure 3. The structure of the SISAL database version 2. Fields and tables marked with (*) refer to new information added to SISALv1b; see Tables 1 and 2 for details. The colours refer to the format of that field: Enum, Int, Varchar, Double or Decimal. More information on the list of predefined menus can be found in Atsawawaranunt et al. (2018a).

2.2 Revised structure of the database

The data are stored in a relational database (MySQL), which consists of 15 linked tables: site, entity, sample, dating, dating_lamina, gap, hiatus, original_chronology, d13C, d18O, entity_link_reference, references, composite_link_entity, notes and sisal_chronology. Figure 3 shows the relationships between these tables and the type of each field (e.g. numeric, text). The structure and contents of all tables except the new sisal_chronology table are described in detail in Atsawawaranunt et al. (2018a). Here, we focus on the new sisal_chronology table and on the changes that were made to other tables in order to accommodate this new table (see Sect. 2.3). Details of the fields in this new table are listed in Table 1.

Changes were also made to the dating table (dating) to accommodate information about whether a specific date was used to construct each of the age–depth models in the sisal_chronology table (Table 2). We followed the original authors’ decision regarding the exclusion of dates (i.e. because of high uncertainties, age reversals or high detrital content). However, some dates used in the orig-
Table 1. Details of the sisal_chronology table. All ages in SISAL are reported as years BP (before present), where present is 1950 CE.

| Field label           | Description                                                                 | Format  | Constraints      |
|-----------------------|-----------------------------------------------------------------------------|---------|------------------|
| sample_id             | Refers to the unique identifier for the sample (as given in the sample table) | Numeric | Positive integer |
| lin_interp_age        | Age of the sample in years, calculated with linear interpolation between dates | Numeric | None             |
| lin_interp_age_uncert_pos | Positive 2-sigma uncertainty of the age of the sample in years, calculated with linear interpolation between dates | Numeric | Positive decimal |
| lin_interp_age_uncert_neg | Negative 2-sigma uncertainty of the age of the sample in years, calculated with linear interpolation between dates | Numeric | Positive decimal |
| lin_reg_age           | Age of the sample in years, calculated with linear regression                | Numeric | None             |
| lin_reg_age_uncert_pos | Positive 2-sigma uncertainty of the age of the sample in years, calculated with linear regression | Numeric | Positive decimal |
| lin_reg_age_uncert_neg | Negative 2-sigma uncertainty of the age of the sample in years, calculated with linear regression | Numeric | Positive decimal |
| Bchron_age            | Age of the sample in years, calculated with Bchron                           | Numeric | None             |
| Bchron_age_uncert_pos | Positive 2-sigma uncertainty of the age of the sample in years, calculated with Bchron | Numeric | Positive decimal |
| Bchron_age_uncert_neg | Negative 2-sigma uncertainty of the age of the sample in years, calculated with Bchron | Numeric | Positive decimal |
| Bacon_age             | Age of the sample in years, calculated with Bacon                            | Numeric | None             |
| Bacon_age_uncert_pos  | Positive 2-sigma uncertainty of the age of the sample in years, calculated with Bacon | Numeric | Positive decimal |
| Bacon_age_uncert_neg  | Negative 2-sigma uncertainty of the age of the sample in years, calculated with Bacon | Numeric | Positive decimal |
| OxCal_age             | Age of the sample in years, calculated with OxCal                            | Numeric | None             |
| OxCal_age_uncert_pos  | Positive 2-sigma uncertainty of the age of the sample in years, calculated with OxCal | Numeric | Positive decimal |
| OxCal_age_uncert_neg  | Negative 2-sigma uncertainty of the age of the sample in years, calculated with OxCal | Numeric | Positive decimal |
| copRa_age             | Age of the sample in years, calculated with copRa                            | Numeric | None             |
| copRa_age_uncert_pos  | Positive 2-sigma uncertainty of the age of the sample in years, calculated with copRa | Numeric | Positive decimal |
| copRa_age_uncert_neg  | Negative 2-sigma uncertainty of the age of the sample in years, calculated with copRa | Numeric | Positive decimal |
| Stalage_age           | Age of the sample in years, calculated with StalAge                          | Numeric | None             |
| Stalage_age_uncert_pos | Positive 2-sigma uncertainty of the age of the sample in years, calculated with StalAge | Numeric | Positive decimal |
| Stalage_age_uncert_neg | Negative 2-sigma uncertainty of the age of the sample in years, calculated with StalAge | Numeric | Positive decimal |
Table 2. Changes made to the dating table to accommodate the new age models. These changes are marked with (*) in Fig. 3.

| Action       | Field label     | Description                                                                 | Format          | Constraints                                      |
|--------------|-----------------|------------------------------------------------------------------------------|-----------------|--------------------------------------------------|
| Field added  | date_used_lin_age | Indication whether that date was used to construct the linear age model     | Text            | Selected from predefined list: “yes”, “no”       |
| Field added  | date_used_lin_reg | Indication whether that date was used to construct the age model based on linear regression | Text            | Selected from predefined list: “yes”, “no”       |
| Field added  | date_used_Bchron | Indication whether that date was used to construct the age model based on Bchron | Text            | Selected from predefined list: “yes”, “no”       |
| Field added  | date_used_Bacon  | Indication whether that date was used to construct the age model based on Bacon | Text            | Selected from predefined list: “yes”, “no”       |
| Field added  | date_used_OxCal  | Indication whether that date was used to construct the age model based on OxCal | Text            | Selected from predefined list: “yes”, “no”       |
| Field added  | date_used_copRa  | Indication whether that date was used to construct the copRa-based age model | Text            | Selected from predefined list: “yes”, “no”       |
| Field added  | date_used_StalAge| Indication whether that date was used to construct the age model based on StalAge | Text            | Selected from predefined list: “yes”, “no”       |

inal age–depth model were not used in the SISALv2 chronologies to prevent unrealistic age–depth relationships (i.e. age inversions). Information on whether a particular date was used for the construction of specific type of age–depth model is provided in the dating table under columns labelled date_used_lin_interp, date_used_lin_reg, date_used_Bchron, date_used_Bacon, date_used_OxCal, date_used_copRa and date_used_StalAge (Table 2).

The dating and the sample tables were modified to accommodate the inclusion of new entities in the database. Specifically, the predefined option lists were expanded, options that had never been used were removed, and some typographical errors in the field names were corrected; these changes are listed in Table 3.

3 Quality control

3.1 Quality control of individual speleothem records

The quality control procedure for individual records newly incorporated in the SISALv2 database is based on the steps described in Atsawawaranunt et al. (2018a). We have updated the Python database scripts to provide a more thorough quality assessment of individual records. Additional checks of the dating table resulted in modifications in the 230Th_232Th, 230Th_238U, 234U_238U, ini230Th_232Th, 238U_content, 230Th_content, 232Th_content and decay constant fields in the dating table for 60 entities. A summary of the fields that are both automatically and manually checked before uploading a record to the database is available in the Supplement.

Analyses of the data included in SISALv1 (Braun et al., 2019a; Burstyn et al., 2019; Deininger et al., 2019; Kaushal et al., 2018; Kern et al., 2019; Lechleitner et al., 2018; Oster et al., 2019; Zhang et al., 2019) and SISALv1b (Comas-Bru et al., 2019) revealed a number of errors in specific records that have now been corrected. These revisions include, for example, updates in mineralogies (sample.mineralogy), revised coordinates (site.latitude and/or site.longitude) and addition of missing information that was previously entered as “unknown”. The fields affected and the number of records with modifications are listed in Table 4. All revisions are also documented in Comas-Bru et al. (2020a).

3.2 Automation and quality control of the age–depth models in the SISAL chronology

We used an automated approach to age–depth modelling in R because of the large number of records. Roesch and Rehfeld (2019) have described the basic workflow concept and tested it using all of the age-modelling approaches used here except OxCal. The basic workflow involves step-by-step inspection and formatting of the data for the different methods, and the use of predefined parameter choices is specific to each method. Each age-modelling method is called sequentially. An error message is recorded in the log file if a particular age-modelling method fails, and the algorithm then progresses to the next method. If output is produced for a par-
Table 3. Changes made to tables other than the sisal_chronology since the publication of SISALv1 (Atsawawaranunt et al., 2018a, b).

| Table name | Action | Field label | Reason | Format | Constraints |
|------------|--------|-------------|--------|--------|-------------|
| Dating     | Removed “sampling gap” option | date_type | Option never used | Text | Selected from predefined list |
|           | The “others” option changed to “other” | decay_constant | Correction of typo | Text | Selected from predefined list |
|           | Added “other” option | calib_used | Option added to accommodate new entities | Text | Selected from predefined list |
|           | Added “other” option | date_type | Option added to accommodate new entities | Text | Selected from predefined list |
| Sample     | Added “other” option | original_chronology | Option added to accommodate new entities | Text | Selected from predefined list |
|           | Added “other” option | ann_lam_check | Option added to accommodate new entities | Text | Selected from predefined list |

Figure 4. Visual summary of quality control of the automated SISAL chronology construction. The evaluation of the age–depth models for each method (x axis) is given for each entity (y axis) that was considered for the construction (n = 533). Black lines mark age–depth models that could not be computed. Age–depth models dropped in the automated or expert evaluation are marked by grey lines. Age–depth models retained in SISALv2 are scored from 1 (only one criterion satisfied) to 3 (all criteria satisfied) in shades of blue. For 503 records alternative age–depth models with uncertainties are provided (green lines) in the “success” column.

ticular age-modelling method, these age models are checked for monotonicity. Finally, the output standardization routine writes out, for each entity and age-modelling approach, the median age model, the ensembles (if applicable) and information of which hiatuses and dates were used in the construction of the age models. These outputs are then added to the sisal_chronology table (Table 2). All functions are available at https://github.com/paleovar/SISAL.AM (last access: 23 July 2020).

The general approach for the OxCal age models was similar, and step-by-step details and scripts are provided at https://doi.org/10.5281/zenodo.3586280 (Amirnezhad-Mozhdehi and Comas-Bru, 2019). The quality control parameters obtained from OxCal were compared with the rec-
Table 4. Summary of the modifications applied to records already in version 1 (Atsawawaranunt et al., 2018b) and version 1b (Atsawawaranunt et al., 2019) of the SISAL database. Mistakes in previous versions of the database were identified as outlined in the Supplement and through analysing the data for the SISAL publications.

| Modification | V1 to v1b | V1b to v2 |
|--------------|-----------|-----------|
| **Site table** |           |           |
| Number of new sites | 37 | 82 |
| Sites with new entities | 11 | 32 |
| Sites with altered site.site_name altered | 3 | 15 |
| Sites with changes in site.latitude | 4 | 29 |
| Sites with changes in site.longitude | 6 | 32 |
| Sites with changes in site.elevation | 13 | 11 |
| Sites with site.geology updated | 7 | 6 |
| Sites with site.rock_age info updated | 3 | 8 |
| Sites with site.monitoring info updated | 0 | 13 |
| **Entity table** |           |           |
| Number of new entities | 74 | 236 |
| How many entities were added to pre-existing sites? | 17 | 84 |
| Entities with revised entity_name | 2 | 25 |
| Entities with updated entity.entity_status | 1 | 10 |
| Entities with altered entity.corresponding current | 0 | 11 |
| Entities with altered entity.depth_ref? | 0 | 1 |
| Entities with altered entity.cover_thickness | 1 | 3 |
| Entities with altered entity.distance_entrance | 0 | 3 |
| Entities with revised entity.speleothem_type | 14 | 4 |
| Entities with revised entity.drip_type | 10 | 2 |
| Entities with altered entity.d13C | 1 | 0 |
| Entities with altered entity.d18O | 1 | 0 |
| Entities with altered entity.d18O_water_equilibrium | 4 | 6 |
| Entities with altered entity.trace_elements | 1 | 2 |
| Entities with altered entity.organics | 1 | 2 |
| Entities with altered entity.fluid_inclusions | 1 | 3 |
| Entities with altered entity.mineralogy_petroleum_fabric | 1 | 2 |
| Entities with altered entity.clumped_isotopes | 1 | 3 |
| Entities with altered entity.noble_gas_temperatures | 1 | 2 |
| Entities with altered entity.C14 | 1 | 2 |
| Entities with altered entity.ODL | 1 | 2 |
| Entities with altered entity.Mg_Ca | 1 | 2 |
| Entities with altered entity.contact (mostly correction of typos) | 7 | 32 |
| Entities with altered entity.Data.DOI.URL (revision mostly to permanent links) | 134 | 14 |
| **Dating table** |           |           |
| Entities with changes in the dating table | 70 | 269 |
| Addition of “Event: hiatus” to an entity | 0 | 3 |
| How many hiatuses had their depth changed? | 2 | 7 |
| Entities with the depths of “Event: start/end of laminations” changed | 0 | 5 |
| Entities with altered dating.date_type | 11 | 30 |
| Entities with altered dating.depth_dating | 14 | 45 |
| Entities with altered dating.dating_thickness | 14 | 37 |
| Entities with altered dating.material_dated | 5 | 62 |
| Entities with altered dating.min_weight | 13 | 56 |
| Entities with altered dating.max_weight | 19 | 36 |
| Entities with altered dating.uncorr_age | 18 | 48 |
| Entities with altered dating.uncorr_age_uncert_pos | 12 | 53 |
| Entities with altered dating.uncorr_age_uncert_neg | 12 | 40 |
| Entities with altered dating.14C_correction | 17 | 36 |
Table 4. Continued.

| Modification                                      | V1 to v1b | V1b to v2 |
|---------------------------------------------------|-----------|-----------|
| Entities with altered dating.calib_used           | 13        | 32        |
| Entities with altered dating.date_used            | 4         | 51        |
| Entities with altered dating.238U_content         | 11        | 47        |
| Entities with altered dating.238U_uncertainty     | 16        | 29        |
| Entities with altered dating.232Th_content        | 15        | 46        |
| Entities with altered dating.232Th_uncertainty    | 14        | 50        |
| Entities with altered dating.230Th_content        | 11        | 40        |
| Entities with altered dating.230Th_uncertainty    | 15        | 38        |
| Entities with altered dating.230Th_232Th_ratio    | 5         | 60        |
| Entities with altered dating.230Th_232Th_ratio_uncertainty | 14    | 49        |
| Entities with altered dating.230Th_238U_activity  | 19        | 40        |
| Entities with altered dating.230Th_238U_activity_uncertainty | 17    | 49        |
| Entities with altered dating.234U_238U_activity   | 12        | 40        |
| Entities with altered dating.234U_238U_activity_uncertainty | 11    | 40        |
| Entities with altered dating.ini_230Th_232Th_ratio | 15        | 41        |
| Entities with altered dating.ini_230Th_232Th_ratio_uncertainty | 8    | 49        |
| Entities with altered dating.decay_constant       | 17        | 55        |
| Entities with altered dating.corr_age             | 17        | 36        |
| Entities with altered dating.corr_age_uncert_pos  | 13        | 47        |
| Entities with altered dating.corr_age_uncert_neg  | 9         | 52        |

Sample table

|                      |          |          |
|----------------------|----------|----------|
| Altered sample.depth_sample | 0        | 15       |
| Altered sample.mineralogy   | 0        | 20       |
| Altered sample.arag_corr   | 11       | 20       |
| How many entities had their d18O time series altered (i.e. changes in depth and/or isotope values as in duplicates)? | 13 | 96       |
| How many entities had their d13C time series altered (i.e. changes in depth and/or isotope values as in duplicates)? | 8    | 64       |

Original chronology

|                      |          |          |
|----------------------|----------|----------|
| Entities with altered original_chronology.interp_age | 1        | 42       |
| Entities with altered original_chronology.interp_age_uncert_pos | 0    | 14       |
| Entities with altered original_chronology.interp_age_uncert_neg      | 0        | 14       |

References

|                      |          |          |
|----------------------|----------|----------|
| How many entities had their references changed (changes/additions/removals)? | 6        | 16       |
| How many citations have a different pub.DOI? | 2        | 16       |

Notes

|                      |          |          |
|----------------------|----------|----------|
| Sites with notes removed | 7        | 5        |
| Sites with notes added    | 32       | 68       |
| Sites with notes modified                 | 21        | 33       |

ommended values of the agreement index \((A) > 60\%\) and convergence \((C) > 95\%\) in accordance with the guidelines in Bronk Ramsey (2008), both for the overall model and for at least 90\% of the individual dates. OxCal age–depth models failing to meet these criteria were not included in the sisal_chronology table (Table 2).

An overview of the evaluation results for the age–depth models constructed in automated mode is given in Fig. 4. Three nested criteria are used to evaluate them. Firstly, chronologies with reversals (Check 1) are automatically rejected (score \(-1\)). Secondly, the final chronology should flexibly follow clear growth rate changes (Check 2) such that 70\% of the dates are encompassed in the final age–depth model within 4-sigma uncertainty (score \(+1\)). Thirdly, temporal uncertainties are expected to increase between dates and near hiatuses (Check 3). This criterion is met in the automated screening (score \(+1\)) if the interquartile range (IQR) is higher between dates or at hiatuses than at dates. Only
Table 5. Information on new speleothem records (entities) added to the SISAL_v2 database from SISALv1b (Comas-Bru et al., 2019). There may be multiple entities from a single cave, here identified as the site. Latitude (Lat) and Longitude (Long) are given in decimal degrees north and east, respectively.

| Site ID | Site name           | Lat (N) | Long (E) | Region    | Entity ID | Entity name | Reference                       |
|---------|---------------------|---------|----------|-----------|-----------|-------------|---------------------------------|
| 2       | Kesang cave         | 42.87   | 81.75    | China     | 620       | CNKS-2      | Cai et al. (2017)               |
|         |                     |         |          |           | 621       | CNKS-3      | Cai et al. (2017)               |
|         |                     |         |          |           | 622       | CNKS-7      | Cai et al. (2017)               |
|         |                     |         |          |           | 623       | CNKS-9      | Cai et al. (2017)               |
| 6       | Hulu cave           | 32.5    | 119.17   | China     | 617       | MSP         | Cheng et al. (2006)             |
|         |                     |         |          |           | 618       | MSX         | Cheng et al. (2006)             |
|         |                     |         |          |           | 619       | MSH         | Cheng et al. (2006)             |
| 12      | Mawmluh cave        | 25.2622 | 91.8817  | India     | 476       | ML-1        | Kathayat et al. (2018)          |
|         |                     |         |          |           | 477       | ML-2        | Kathayat et al. (2018)          |
|         |                     |         |          |           | 495       | KM-1        | Huguet et al. (2018)            |
| 13      | Ball Gown cave      | −17.03  | 125      | Australia | 633       | BGC-5       | Denniston et al. (2013b, 2017)  |
|         |                     |         |          |           | 634       | BGC-10      | Denniston et al. (2013b, 2017)  |
|         |                     |         |          |           | 635       | BGC-11_2017 | Denniston et al. (2013b, 2017)  |
|         |                     |         |          |           | 636       | BGC-16      | Denniston et al. (2013b, 2017)  |
| 14      | Lehman caves        | 39.01   | −114.22  | United States | 641     | CDR3      | Steponaitis et al. (2015)        |
|         |                     |         |          |           | 642       | WR11       | Steponaitis et al. (2015)        |
| 15      | Baschg cave         | 47.2501 | 9.6667   | Austria   | 643       | BA-5        | Moseley et al. (2020)            |
|         |                     |         |          |           | 644       | BA-7        | Moseley et al. (2020)            |
| 23      | Lapa grande cave    | −14.37  | −44.28   | Brazil    | 614       | LG12B       | Stríkis et al. (2018)           |
|         |                     |         |          |           | 615       | LG10        | Stríkis et al. (2018)           |
|         |                     |         |          |           | 616       | LG25        | Stríkis et al. (2018)           |
| 24      | Lapa sem fim cave   | −16.1503 | −44.6281 | Brazil    | 603       | LSF15      | Stríkis et al. (2018)           |
|         |                     |         |          |           | 604       | LSF3_2018   | Stríkis et al. (2018)           |
|         |                     |         |          |           | 605       | LSF15      | Stríkis et al. (2018)           |
|         |                     |         |          |           | 606       | LSF11      | Stríkis et al. (2018)           |
|         |                     |         |          |           | 607       | LSF9       | Stríkis et al. (2018)           |
| 27      | Tamboril cave       | −16     | −47      | Brazil    | 594       | TM6        | Ward et al. (2019)              |
| 39      | Dongge cave         | 25.2833 | 108.0833 | China     | 475       | DA_2009    | Cheng et al. (2009)             |
| 54      | Sahiya cave         | 30.6    | 77.8667  | India     | 478       | SAH-2       | Kathayat et al. (2017)          |
|         |                     |         |          |           | 479       | SAH-3       | Kathayat et al. (2017)          |
|         |                     |         |          |           | 480       | SAH-6       | Kathayat et al. (2017)          |
| 65      | Whiterock cave      | 4.15    | 114.86   | Malaysia (Borneo) | 685     | WR12-01    | Carolin et al. (2016)           |
|         |                     |         |          |           | 686       | WR12-12     | Carolin et al. (2016)           |
| 72      | Ascunsa cave        | 45      | 22.6     | Romania   | 582       | POM1       | Staubwasser et al. (2018)        |
| 82      | Hollywood cave      | −41.95  | 171.47   | New Zealand | 673     | HW-1       | Williams et al. (2005)          |
| 86      | Modric cave         | 44.2568 | 15.5372  | Croatia   | 631       | MOD-27     | Rudzka-Phillips et al. (2013)   |
|         |                     |         |          |           | 632       | MOD-21     | Rudzka et al. (2012)            |
| 105     | Schneckenloch cave  | 47.4333 | 9.8667   | Austria   | 663       | SCH-6      | Moseley et al. (2020)           |
| 113     | Paixao cave         | −12.6182| −40.0184 | Brazil    | 611       | PX5        | Stríkis et al. (2015)           |
|         |                     |         |          |           | 612       | PX7_2018   | Stríkis et al. (2018)           |
| 115     | Höllöch im Mahdial  | 47.3781 | 10.1506  | Germany   | 664       | HOL-19     | Moseley et al. (2020)           |
| 117     | Bunker cave         | 51.3675 | 7.6647   | Germany   | 596       | Bu2_2018   | Weber et al. (2018)             |
| 128     | Buckeye creek       | 37.98   | −80.4    | United States | 681     | BCC-9      | Cheng et al. (2019)             |
|         |                     |         |          |           | 682       | BCC-10_2019 | Cheng et al. (2019)             |
|         |                     |         |          |           | 683       | BCC-30     | Cheng et al. (2019)             |
| 135     | Grotte de Piste     | 33.95   | −4.246   | Morocco   | 464       | GP5        | Ait Brahim et al. (2018)        |
|         |                     |         |          |           | 591       | GP2        | Ait Brahim et al. (2018)        |
| 138     | Moomi cave          | 12.55   | 54.2     | Yemen (Socotra) | 481     | M1-2       | Mangini, Cheng et al. (unpublished data); Burns et al. (2003, 2004) |
| Site ID | Site name         | Lat (N) | Long (E) | Region   | Entity ID | Entity name     | Reference                  |
|---------|-------------------|---------|----------|----------|-----------|-----------------|----------------------------|
| 140     | Sanbao cave       | 31.667  | 110.4333 | China    | 482       | SB3             | Wang et al. (2008)         |
|         |                   |         |          |          | 483       | SB-10_2008      | Wang et al. (2008)         |
|         |                   |         |          |          | 484       | SB11            | Wang et al. (2008)         |
|         |                   |         |          |          | 485       | SB22            | Wang et al. (2008)         |
|         |                   |         |          |          | 486       | SB23            | Wang et al. (2008)         |
|         |                   |         |          |          | 487       | SB24            | Wang et al. (2008)         |
|         |                   |         |          |          | 488       | SB25-1          | Wang et al. (2008)         |
|         |                   |         |          |          | 489       | SB25-2          | Wang et al. (2008)         |
|         |                   |         |          |          | 490       | SB-26_2008      | Wang et al. (2008)         |
|         |                   |         |          |          | 491       | SB34            | Wang et al. (2008)         |
|         |                   |         |          |          | 492       | SB41            | Wang et al. (2008)         |
|         |                   |         |          |          | 493       | SB42            | Wang et al. (2008)         |
|         |                   |         |          |          | 494       | TF              | Wang et al. (2008)         |
| 141     | Sofular cave      | 41.4167 | 31.9333  | Turkey   | 456       | SO-2            | Badertscher et al. (2011)  |
|         |                   |         |          |          | 687       | SO-4            | Fleitmann et al. (2009);   |
|         |                   |         |          |          | 688       | SO-6            | Göktürk et al. (2011)      |
|         |                   |         |          |          | 689       | SO-14B          | Badertscher et al. (2011)  |
|         |                   |         |          |          |           |                 | Badertscher et al. (2011)  |
| 145     | Antro del Corchia | 43.9833 | 10.2167  | Italy    | 665       | CC-1_2018       | Tzedakis et al. (2018)     |
|         |                   |         |          |          | 666       | CC-5_2018       | Tzedakis et al. (2018)     |
|         |                   |         |          |          | 667       | CC-7_2018       | Tzedakis et al. (2018)     |
|         |                   |         |          |          | 668       | CC-28_2018      | Tzedakis et al. (2018)     |
|         |                   |         |          |          | 669       | CC_stack        | Tzedakis et al. (2018)     |
|         |                   |         |          |          | 670       | CC27            | Isola et al. (2019)        |
| 155     | KNI-51            | −15.3   | 128.62   | Australia| 637       | KNI-51-1        | Denniston et al. (2017)    |
|         |                   |         |          |          | 638       | KNI-51-8        | Denniston et al. (2017)    |
| 160     | Soreq cave        | 31.7558 | 35.0226  | Israel   | 690       | Soreq-composite185| Bar-Matthews et al. (2003)|
| 165     | Ruakuri cave      | −36.27  | 175.08   | New Zealand| 674       | RK-A            | Williams et al. (2010)     |
|         |                   |         |          |          | 675       | RK-B            | Williams et al. (2010)     |
|         |                   |         |          |          | 676       | RK05-1          | Whittaker (2008)           |
|         |                   |         |          |          | 677       | RK05-3          | Whittaker (2008)           |
|         |                   |         |          |          | 678       | RK05-4          | Whittaker (2008)           |
| 177     | Santo Tomas cave  | 22.55   | −83.84   | Cuba     | 608       | CM_2019         | Warken et al. (2019)       |
|         |                   |         |          |          | 609       | CMA             | Warken et al. (2019)       |
|         |                   |         |          |          | 610       | CMb             | Warken et al. (2019)       |
| 179     | Closani cave      | 45.10   | 22.8     | Romania  | 390       | C09-2           | Warken et al. (2018)       |
| 182     | Kotumnsr cave     | 19      | 82       | India    | 590       | KOT-I           | Band et al. (2018)         |
| 192     | El Condor cave    | −5.93   | −77.3    | Peru     | 592       | ELC-A           | Cheng et al. (2013)        |
|         |                   |         |          |          | 593       | ELC-B           | Cheng et al. (2013)        |
| 198     | Lianhua cave, Hunan| 29.48  | 109.5333 | China    | 496       | LH-2            | Zhang et al. (2013)        |
| 213     | Tausooare cave    | 47.4333 | 24.5167  | Romania  | 457       | 1152            | Staubwasser et al. (2018)  |
| 214     | Cave C126         | −22.1   | 113.9    | Australia| 458       | C126-117        | Denniston et al. (2013a)   |
|         |                   |         |          |          | 459       | C126-118        | Denniston et al. (2013a)   |
| 215     | Chaara cave       | 33.9558 | −4.2461  | Morocco  | 460       | Cha2_2018       | Ait Braham et al. (2018)   |
|         |                   |         |          |          | 588       | Cha2_2019       | Ait Braham et al. (2019)   |
|         |                   |         |          |          | 589       | Cha1            | Ait Braham et al. (2019)   |
| 216     | Dark cave         | 27.2    | 106.1667 | China    | 461       | D1              | Jiang et al. (2013)        |
|         |                   |         |          |          | 462       | D2              | Jiang et al. (2013)        |
| 217     | E’mei cave        | 29.5    | 115.5    | China    | 463       | EM1             | Zhang et al. (2018b)       |
| 218     | Nuanhe cave       | 41.3333 | 124.9167 | China    | 465       | NH6             | Wu et al. (2012)           |
|         |                   |         |          |          | 466       | NH33            | Wu et al. (2012)           |
| Site ID | Site name                  | Lat (N) | Long (E) | Region   | Entity ID | Entity name | Reference                          |
|-------|---------------------------|---------|----------|----------|-----------|-------------|-----------------------------------|
| 219   | Shennong cave             | 28.71   | 117.26   | China    | 467       | SN17        | Zhang et al. (2018a)               |
| 220   | Baeg-nyong cave           | 37.27   | 128.58   | South Korea | 468   | BN-1        | Jo et al. (2017)                   |
| 221   | La Vierge cave            | −19.7572| 63.3703  | Rodrigues | 469       | LAVI-4      | Li et al. (2018)                   |
| 222   | Patate cave               | −19.7583| 63.3864  | Rodrigues | 470       | PATA-1      | Li et al. (2018)                   |
| 223   | Wanxiang cave             | 33.32   | 105      | China    | 471       | WX42B       | Zhang et al. (2008)               |
|       |                           |         |          |          | 679       | WXSM-51     | Johnson et al. (2006)             |
|       |                           |         |          |          | 680       | WXSM-52     | Johnson et al. (2006)             |
| 224   | Xianglong cave            | 33      | 106.33   | China    | 472       | XL16        | Tan et al. (2018a)                |
|       |                           |         |          |          | 473       | XL2         | Tan et al. (2018a)                |
|       |                           |         |          |          | 474       | XL26        | Tan et al. (2018a)                |
| 225   | Chillonkhalaka cave       | −18.1222| −65.7739 | Bolivia  | 497       | Boto 1      | Apaestegui et al. (2018)          |
|       |                           |         |          |          | 498       | Boto 3      | Apaestegui et al. (2018)          |
|       |                           |         |          |          | 499       | Boto 7      | Apaestegui et al. (2018)          |
| 226   | Cueva del Diamante        | −5.73   | −77.5    | Peru     | 500       | NAR-C       | Cheng et al. (2013)               |
|       |                           |         |          |          | 501       | NAR-C-D     | Cheng et al. (2013)               |
|       |                           |         |          |          | 502       | NAR-C-F     | Cheng et al. (2013)               |
|       |                           |         |          |          | 503       | NAR-D       | Cheng et al. (2013)               |
|       |                           |         |          |          | 504       | NAR-F       | Cheng et al. (2013)               |
| 227   | El Capitan cave           | 56.162  | −133.319 | United States | 505   | EC-16-5-F  | Wilcox et al. (2019)             |
| 228   | Bat cave                  | 32.1    | −104.26  | United States | 506   | BC-11       | Asmerom et al. (2013)             |
| 229   | Actun Tunichil Muknal     | 17.1    | −88.85   | Belize   | 507       | ATM-7       | Frappier et al. (2002, 2007); Jamieson et al. (2015) |
| 230   | Marota cave               | −12.6227| −41.0216 | Brazil   | 508       | MAG         | Strikis et al. (2018)             |
| 231   | Pacupahuain cave          | −11.24  | −75.82   | Peru     | 509       | P09PH2      | Kanner et al. (2012)              |
| 232   | Rio Secreto cave system   | 20.59   | −87.13   | Mexico   | 510       | Itzamna     | Medina-Elizalde et al., (2016, 2017) |
| 233   | Robinson cave             | 33      | −107.7   | United States | 511   | KR1         | Polyak et al. (2017)              |
| 234   | Santana cave              | −24.5308| −48.7267 | Brazil   | 512       | St8-a       | Cruz et al. (2006)                |
|       |                           |         |          |          | 513       | St8-b       | Cruz et al. (2006)                |
| 235   | Cueva del Tigre Perdido   | −5.9406 | −77.3081 | Peru     | 514       | NC-A        | van Breukelen et al. (2008)       |
|       |                           |         |          |          | 515       | NC-B        | van Breukelen et al. (2008)       |
| 236   | Toca da Boa Vista         | −10.1602| −40.8605 | Brazil   | 516       | TBV40       | Wendt et al. (2019)               |
|       |                           |         |          |          | 517       | TBV63       | Wendt et al. (2019)               |
| 237   | Umayajalanta cave         | −18.12  | −65.77   | Bolivia  | 518       | Boto 10     | Apaestegui et al. (2018)          |
| 238   | Akalagavi cave            | 14.9833 | 74.5167  | India    | 519       | MGY         | Yadava et al. (2004)              |
| 239   | Baluk cave                | 42.433  | 84.733   | China    | 520       | BLK12B      | Liu et al. (2019)                 |
| 240   | Baratang cave             | 12.0833 | 92.75    | India    | 521       | AN4         | Laskar et al. (2013)              |
|       |                           |         |          |          | 522       | AN8         | Laskar et al. (2013)              |
| 241   | Gempa bumi cave           | −5      | 120      | Indonesia (Sulawesi) | 523   | GB09-03     | Krause et al. (2019)              |
|       |                           |         |          |          | 524       | GB11-09     | Krause et al. (2019)              |
| 242   | Haozhu cave               | 30.6833 | 109.9833 | China    | 525       | HZZ-11      | Zhang et al. (2016)               |
|       |                           |         |          |          | 526       | HZZ-27      | Zhang et al. (2016)               |
| 243   | Kailash cave              | 18.8445 | 81.9915  | India    | 527       | KG-6        | Gautam et al. (2019)              |
| 244   | Lianhua cave, Shanxi      | 38.1667 | 113.7167 | China    | 528       | LH1         | Dong et al. (2018)                |
|       |                           |         |          |          | 529       | LH4         | Dong et al. (2018)                |
|       |                           |         |          |          | 530       | LH5         | Dong et al. (2018)                |
|       |                           |         |          |          | 531       | LH6         | Dong et al. (2018)                |
|       |                           |         |          |          | 532       | LH9         | Dong et al. (2018)                |
|       |                           |         |          |          | 533       | LH30        | Dong et al. (2018)                |
| Site ID | Site name          | Lat (N) | Long (E) | Region                  | Entity ID | Entity name | Reference                        |
|--------|--------------------|---------|----------|-------------------------|-----------|-------------|-----------------------------------|
| 245    | Nakarallu cave     | 14.52   | 77.99    | India                   | 534       | NK-1305     | Sinha et al. (2018)               |
| 246    | Palawan cave       | 10.2    | 118.9    | Malaysia (northern Borneo)| 535       | SR02        | Partun et al. (2015)              |
| 247    | Shalaii cave       | 35.1469 | 45.2958  | Iraq                    | 536       | SHC-01      | Marsh et al. (2018); Amin Al-Mannii et al. (2019) |
|        |                    |         |          |                         | 537       | SHC-02      | Marsh et al. (2018); Amin Al-Mannii et al. (2019) |
| 248    | Shenqi cave        | 28.333  | 103.1    | China                   | 538       | SQ1         | Tan et al. (2018b)                |
|        |                    |         |          |                         | 539       | SQ7         | Tan et al. (2018b)                |
| 249    | Shigao cave        | 28.183  | 107.167  | China                   | 540       | SG1         | Jiang et al. (2012); Jiang et al. (2012) |
|        |                    |         |          |                         | 541       | SG2         | Jiang et al. (2012); Jiang et al. (2012) |
| 250    | Wuya cave          | 33.82   | 105.43   | China                   | 542       | WY27        | Tan et al. (2015)                 |
|        |                    |         |          |                         | 543       | WY33        | Tan et al. (2015)                 |
| 251    | Zhenzhu cave       | 38.25   | 113.7    | China                   | 544       | ZZ12        | Yin et al. (2017)                |
| 252    | Andriamaniloke     | −24.051 | 43.7569  | Madagascar              | 545       | AD4         | Scroxton et al. (2019)            |
| 253    | Hoq cave           | 12.5866 | 54.3543  | Yemen (Socotra)         | 546       | Hq-1        | Van Rampelbergh et al. (2013)    |
|        |                    |         |          |                         | 547       | STM1        | Van Rampelbergh et al. (2013)    |
|        |                    |         |          |                         | 548       | STM6        | Van Rampelbergh et al. (2013)    |
| 254    | PP29               | −34.2078| 22.0876  | South Africa            | 549       | 46745       | Braun et al. (2019b)             |
|        |                    |         |          |                         | 550       | 46746-a     | Braun et al. (2019b)             |
|        |                    |         |          |                         | 551       | 46747       | Braun et al. (2019b)             |
|        |                    |         |          |                         | 552       | 138862.1    | Braun et al. (2019b)             |
|        |                    |         |          |                         | 553       | 138862.2a   | Braun et al. (2019b)             |
|        |                    |         |          |                         | 554       | 142828      | Braun et al. (2019b)             |
|        |                    |         |          |                         | 555       | 46746-b     | Braun et al. (2019b)             |
|        |                    |         |          |                         | 556       | 138862.2b   | Braun et al. (2019b)             |
| 255    | Mitoho             | −24.0477| 43.7533  | Madagascar              | 557       | MT1         | Scroxton et al. (2019)            |
| 256    | Lithophagus cave   | 46.828  | 22.6     | Romania                 | 558       | LFG-2       | Lauritzen and Onac (1999)         |
| 257    | Akcakale cave      | 40.4498 | 39.5365  | Turkey                  | 559       | 2p          | Jex et al. (2010, 2011, 2013)     |
| 258    | B7 cave            | 49      | 7        | Germany                 | 560       | STAL-B7-7   | Niggemann et al. (2003b)          |
| 259    | Cobre cave         | 42.98   | −4.37    | Spain                   | 561       | PA-8        | Osete et al. (2012); Rossi et al. (2014) |
| 260    | Crowassa Azzurra   | 39.28   | 8.48     | Italy                   | 562       | CA          | Columbu et al. (2019)             |
| 261    | El Soplao cave     | 43.2962 | −4.3937  | Spain                   | 563       | SIR-1       | Rossi et al. (2018)               |
| 262    | Bleiberg cave      | 50.4244 | 11.0203  | Germany                 | 564       | BB-1        | Breitenbach et al. (2019)         |
|        |                    |         |          |                         | 565       | BB-3        | Breitenbach et al. (2019)         |
| 263    | Orlova Chaika cave | 43.5937 | 25.9597  | Bulgaria                | 566       | ocz-6       | Pawlak et al. (2019)              |
| 264    | Strašna peč cave   | 44.0049 | 15.0388  | Croatia                 | 567       | SPD-1       | Lončar et al. (2019)             |
|        |                    |         |          |                         | 568       | SPD-2       | Lončar et al. (2019)             |
| 265    | Coves de Campanet  | 39.7937 | 2.9683   | Spain                   | 569       | CAM-1       | Dumitrut et al. (2018)            |
| 266    | Cueva Victoria     | 37.6322 | −0.8215  | Spain                   | 570       | Vic-III-4   | Budsky et al. (2019)              |
| 267    | Gruta do Casal da Lebre | 39.3 | −9.2667  | Portugal                | 571       | GCL6        | Denaisston et al. (2018)          |
| 268    | Pere Noel cave     | 50      | 5.2      | Belgium                 | 572       | PN-95-5     | Verheyden et al. (2000, 2014)     |
| 269    | Gejkar cave        | 35.8    | 45.1645  | Iraq                    | 573       | Gej-1       | Floro et al. (2017)               |
| 270    | Gol-E-Zard cave    | 35.84   | 52       | Iran                    | 574       | GZ14-1      | Carolin et al. (2019)             |
| 271    | Jersey cave        | −35.72  | 148.49   | Australia               | 575       | YB-F1       | Webb et al. (2014)                |
| 272    | Metro cave         | −41.93  | 171.47   | New Zealand             | 576       | M-1         | Logan (2011)                      |
| 273    | Crystal cave       | 36.59   | −118.82  | United States           | 577       | CRC-3       | McCabe-Glynn et al. (2013)        |
### Table 5. Continued.

| Site ID | Site name         | Lat (N) | Long (E) | Region     | Entity ID | Entity name | Reference                          |
|---------|-------------------|---------|----------|------------|-----------|-------------|------------------------------------|
| 274     | Terciopelo cave   | 10.17   | −85.33   | Costa Rica | CT-1      | Lachniet et al. (2009)             |
|         |                   |         |          |            | CT-5      | Lachniet et al. (2009)             |
|         |                   |         |          |            | CT-6      | Lachniet et al. (2009)             |
|         |                   |         |          |            | CT-7      | Lachniet et al. (2009)             |
| 275     | Buraca Gloriosa   | 39.5333 | −8.7833  | Portugal   | BG41      | Denniston et al. (2018)            |
|         |                   |         |          |            | BG66      | Denniston et al. (2018)            |
|         |                   |         |          |            | BG67      | Denniston et al. (2018)            |
|         |                   |         |          |            | BG61      | Denniston et al. (2018)            |
|         |                   |         |          |            | BG6LR     | Denniston et al. (2018)            |
| 276     | Beke cave         | 48.4833 | 20.5167  | Hungary    | BNT-2     | Demény et al. (2019)              |
|         |                   |         |          |            |           | Czuppon et al. (2018)             |
| 277     | Huagapo cave      | −11.27  | −75.79   | Peru       | P00-H2    | Kanner et al. (2013)              |
|         |                   |         |          |            | P00-H1    | Kanner et al. (2013)              |
|         |                   |         |          |            | P09-H1b   | Burns et al. (2019)               |
|         |                   |         |          |            | P10-H5    | Burns et al. (2019)               |
|         |                   |         |          |            | P10-H2    | Burns et al. (2019)               |
|         |                   |         |          |            | PeruMIS6Composite | Burns et al. (2019) |
| 278     | Pink Panther cave | 32      | −105.2   | United States | PP1   | Asmerom et al. (2007) | |
| 279     | Staircase cave    | −34.2071| 22.0899  | South Africa | 46322    | Braun et al. (2019b)             |
|         |                   |         |          |            | 46330-a   | Braun et al. (2019b)             |
|         |                   |         |          |            | 46861     | Braun et al. (2019b)             |
|         |                   |         |          |            | 50100     | Braun et al. (2019b)             |
|         |                   |         |          |            | 142819    | Braun et al. (2019b)             |
|         |                   |         |          |            | 142820    | Braun et al. (2019b)             |
|         |                   |         |          |            | 46330-b   | Braun et al. (2019b)             |
| 280     | Atta cave         | 51.1    | 7.9      | Germany    | AH-1      | Niggemann et al. (2003a)          |
| 281     | Venado cave       | 10.55   | −84.77   | Costa Rica | V1        | Lachniet et al. (2004)           |
| 282     | Wadi Sannur cave  | 28.6167 | 31.2833  | Egypt      | WS-5d     | El-Shenawy et al. (2018)         |
| 283     | Babylon cave      | −41.95  | 171.47   | New Zealand | BN-1      | Williams et al. (2005)           |
|         |                   |         |          |            | BN-2      | Williams et al. (2005)           |
|         |                   |         |          |            | BN-3      | Lorrey et al. (2010)             |
| 284     | Creighton’s cave  | −40.63  | 172.47   | New Zealand | CN-1      | Williams et al. (2005)           |
| 285     | Disbelief cave    | −38.82  | 177.52   | New Zealand | Disbelief | Lorrey et al. (2008)             |
| 286     | La Garma cave     | 43.4306 | −3.6658  | Spain      | GAR-01_drill | Baldini et al. (2015, 2019)       |
|         |                   |         |          |            | GAR-01_laser_d18O | Baldini et al. (2015) |
|         |                   |         |          |            | GAR-01_laser_d13C | Baldini et al. (2015) |
| 287     | Twin Forks cave   | −40.63  | 172.48   | New Zealand | TF-2      | Williams et al. (2005)           |
| 288     | Wet Neck cave     | −40.7   | 172.48   | New Zealand | WN-4      | Williams et al. (2005)           |
|         |                   |         |          |            | WN-11     | Williams et al. (2005)           |
| 289     | Gassel Tropfsteinhöhle | 47.8228 | 13.8428  | Austria    | GAS-12    | Moseley et al. (2020)            |
|         |                   |         |          |            | GAS-13    | Moseley et al. (2020)            |
|         |                   |         |          |            | GAS-22    | Moseley et al. (2020)            |
|         |                   |         |          |            | GAS-25    | Moseley et al. (2020)            |
|         |                   |         |          |            | GAS-27    | Moseley et al. (2020)            |
|         |                   |         |          |            | GAS-29    | Moseley et al. (2020)            |
| 290     | Grete-Ruth Shaft  | 47.5429 | 12.0272  | Austria    | HUN-14    | Moseley et al. (2020)            |
| 292     | Limnon cave       | 37.9605 | 22.1403  | Greece     | KTR-2     | Peckover et al. (2019)           |
| 293     | Tham Doun Mai     | 20.75   | 102.65   | Laos       | TM-17     | Wang et al. (2019)               |
| 294     | Palco cave        | 18.35   | −66.5    | Puerto Rico | PA-2b     | Rivera-Collazo et al. (2015)     |
Figure 5. Illustration of the impact of the age model choice on reconstructed speleothem chronology illustrated by the KNI-51-H speleothem record (entity_id 342; Denniston et al., 2013b). Panel (a) shows the median and mean age estimates for each downcore sample from the different age models; (b) shows the interquartile range (IQR) of the ages. Dashed horizontal lines show the depths of the measured dates; (c) shows the isotopic record using the different age models.

Figure 6. Scatterplot of average uncertainties in the sisal_chronology table and $^{230}$Th/U mean dating uncertainties for each entity and age–depth model technique. The 1 : 1 line is shown in black.

entities that pass all three criteria are considered successful. All age–depth models that satisfied Check 1 were also evaluated in an expert-based manual screening by 10 people. If more than two experts agreed that an individual age–depth model was unreliable or inconsistencies, such as large offsets between the original age model and the dates marked as “used”, occurred, the model was not included in the SISAL chronology table. This automatic and expert-based quality control screening resulted in 2138 new age–depth models constructed for 503 SISAL entities.
4 Recommendation for the use of SISAL chronologies

The original age–depth models for every entity are available in SISALv2. However, given the lack of age uncertainties for most of the records, we recommend considering the SISAL chronologies with their respective 95 % confidence intervals whenever possible. No single age–depth modelling approach is successful for all entities, and we therefore recommend that all the methods for a specific entity are used together in visual and/or statistical comparisons. Depending on methodological choices, age–depth models compatible with the dating evidence can result in considerable temporal differences for transitions (Fig. 5). For analyses relying on the temporal alignment of records (e.g. cross-correlation), age–depth model uncertainties should be considered using the ensemble of compatible age–depth models as described in, for example, Mudelsee et al. (2012), Rehfeld and Kurths (2014) and Hu et al. (2017).

5 Code and data availability

The database is available in SQL and CSV format from https://doi.org/10.17864/1947.256 (Comas-Bru et al., 2020a). This dataset is licensed by the rights holder(s) under a Creative Commons Attribution 4.0 International License: https://creativecommons.org/licenses/by/4.0/. The code used for constructing the linear interpolation, linear regression, Bchron, BacoR and StatsAge age–depth models is available at https://github.com/paleovar/SISALv2 (last access: 23 July 2020; codes licensed by the right holder(s) under a GPL-3 license.). rBacon package (version 2.3.9.1) is available on CRAN (https://cran.r-project.org/web/packages/rbacon/index.html; last access: 31 January 2020; this package is licensed by the right holder(s) under a GPL-3 license.). The code used to construct the OxCal age–depth models and trim the ensemble output to the last 2000 iterations is available at https://doi.org/10.5281/zenodo.3586280 (Amirnezhad-Mozhdehi and Comas-Bru, 2019). These codes are licensed by the right holder(s) under a Creative Commons Attribution 4.0 International. The ensembles are available at https://doi.org/10.5281/zenodo.3816804 (Rehfeld et al., 2020). These codes are licensed by the right holder(s) under a Creative Commons Attribution 4.0 International.

6 Overview of database contents

SISALv2 contains 353,976 δ18O and 200,613 δ13C measurements from 673 individual speleothem records and 18 composite records from 293 cave sites (Table 5, Fig. 2; Comas-Bru et al., 2020a). There are 20 records included in SISALv2 that are identified as being superseded and linked to the newer records; their original datasets are included in the database for completeness. This is an improvement of 235 records from SISALv1b (Atsawawaranunt et al., 2019; Comas-Bru et al., 2019; Table 6). SISALv2 represents 72 % of the existing speleothem records identified by the SISAL working group and more than 3 times the number of speleothem records in the NCEI-NOAA repository (n = 210 as of November 2019; https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/speleothem (last access: 20 October 2020), which is the one most commonly used by the speleothem community to make their data publicly available. SISALv2 also contains nine records that have not been published or are only available in PhD theses.

The published age–depth models of all speleothems are accessible in the original_chronology metadata table, and our standardized age–depth models are available in the siscal_chronology table for 512 speleothems. Temporal uncertainties are now provided for 79 % of the records in the SISAL database. This is a significantly larger number than in SISALv1b, where most age–depth models lacked temporal uncertainties. Most speleothem records show average 230Th/U age errors between 100 and 1000 years (Fig. 6), which are only slightly changed by using age–depth modelling software. Nevertheless, when comparing the mean uncertainties of the 230Th/U ages with those of their corresponding age–depth model, the slope between both parameters is smaller than 1. This indicates that age–depth models tend to reduce uncertainties, especially when dating errors are large, while they increase uncertainties when 230Th/U age errors are small.

This second version of the SISAL database has an improved spatial coverage compared to SISALv1 (Atsawawaranunt et al., 2018b) and SISALv1b (Fig. 3; Atsawawaranunt et al., 2019). SISALv2 contains most published records from Oceania (80.2 %), Africa (73.7 %) and South America (77.6 %), but improvements are still possible in regions like the Middle East (42.3 %) and Asia (64.8 %; Table 6).

The temporal distribution of records for the past 2000 years is good, with 181 speleothems covering at least one-third of this period and 84 records covering the entire last 2000 years (−68 to 2000 years BP) with an average res-
Figure 7. Global and regional temporal coverage of entities in the SISALv2. (a) Last 2000 years, with a bin size of 10 years; (b) last 21,000 years, with a bin size of 500 years; (c) the period between 115,000 and 130,000 years BP, with a bin size of 1000 years. BP refers to “before present”, where present is 1950 CE. Regions defined as in Table 7.

Table 6. Percentage of entities uploaded to the different versions of the SISAL database with respect to the number of records identified by the SISAL working group as of November 2019. The number of identified records includes potentially superseded speleothem records. Regions are defined as: Oceania (−60° < Lat < 0°; 90° < Long < 180°), Asia (0° < Lat < 60°; 60° < Long < 130°), Middle East (7.6° < Lat < 50°; 26° < Long < 59°), Africa (−45° < Lat < 36.1°; −30° < Long < 60°; with records in the Middle East region removed), Europe (36.7° < Lat < 75°; −30° < Long < 30°; plus Gibraltar and Siberian sites), South America (S. Am.; −60° < Lat < 8°; −150° < Long < −30°), North and Central America (N./C. Am.; 8.1° < Lat < 60°; −150° < Long < −50°).

| Region       | Version 1 Entities | Version 1b Entities | Version 2 Entities |
|--------------|--------------------|---------------------|--------------------|
|              | Sites              | Sites               | Sites              |
| Oceania      | 47.7               | 36.7                | 56.8               | 51.0                | 80.2              | 69.4              |
| Asia         | 36.2               | 28.8                | 41.1               | 33.3                | 64.8              | 48.5              |
| Middle East  | 21.2               | 31.1                | 28.8               | 35.6                | 42.3              | 48.9              |
| Africa       | 63.2               | 62.5                | 63.2               | 62.5                | 73.7              | 87.5              |
| Europe       | 48.0               | 51.9                | 54.6               | 58.7                | 75.3              | 77.9              |
| S. Am.       | 30.6               | 39.5                | 40.8               | 50.0                | 77.6              | 73.7              |
| N./C. Am.    | 35.7               | 36.7                | 51.8               | 56.7                | 70.5              | 73.3              |

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olution of 20 isotope measurements in every 100-year slice (Fig. 7a). There are 182 records that cover at least one-third of the Holocene (last 11 700 years BP), with 37 of these covering the whole period with at least one isotope measurement in every 500-year period (Fig. 7b). There are 84 entities during the deglaciation period (21 000 to 11 700 years BP) with at least one measurement in every 500-year time period (Fig. 7b). The Last Interglacial (130 000 to 115 000 years BP) is covered by 47 speleothem records that record at least one-third of this period with, on average, 25 isotope measurements in every 1000-year time slice (Fig. 7c).

This updated SISALv2 database now not only provides the basis for comparing a large number of speleothem-based environmental reconstructions on a regional to a global scale but also allows for comprehensive analyses of stable-isotope records on various timescales, from multi-decadal to orbital.

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coordinated the regional data collection and the age model screening. SFMB, MB and DS provided support for COPRA, Bacon and StalAge, respectively. JF assisted in the quality control procedure of the SISAL database. Figures 1, 4 and 5 were created by CR and KR. Figures 2, 3 and 6 were created by LCB. All authors listed as “SISAL working group members” provided data for this version of the database and/or helped to complete data entry. The first draft of the paper was written by LCB with input by KR and SPH, and all authors contributed to the final version.

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