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Low impact sampling of speleothems – reconciling scientific study with cave conservation

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Abstract: Speleothems are increasingly valued as important paleoclimate archives and yet the removal of samples from caves can come at a cost to natural heritage, impacting delicate environments with limited mechanisms for repair. Conservation of cave environments is a key responsibility for scientists and, with this in mind, we are working to develop and implement techniques that allow us to extract valuable scientific data, with minimal impact. In this study, we demonstrate the utility of low-impact reconnaissance dating surveys on caves in southern Tasmania and southwest Western Australia as a precursor to the removal of stalagmites for paleoclimate reconstruction. Small flakes of calcite were discretely extracted from the base and tip of fallen stalagmites and dated using U-Th techniques. We specifically targeted stalagmites that have naturally fallen or been previously broken by human interference, to further reduce our impact on the caves. This approach provides maximum and minimum age constraints for each stalagmite and valuable information of growth frequencies without the need to remove whole samples from the cave. Selecting the most appropriate samples to analyze based on reconnaissance ages greatly reduces the quantity of speleothem material to be removed from a cave to locate a desired interval of past time, mitigating the impacts of the research. Moreover, the reconnaissance age data enable us to build an archive of speleothem ages from the cave for future scientific research and to provide information on the age and nature of cave development, useful for cave management purposes and other studies. To assess the accuracy of this method we compared the reconnaissance age with the results of a detailed age evaluation on a small number of stalagmites removed from the caves. We have found this method to be effective and has allowed us to successfully identify several stalagmites suitable for our scientific objectives.

Keywords: Speleothem, stalagmite, cave conservation, sampling, paleoclimate

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INTRODUCTION

Speleothems (secondary cave carbonate deposits) are valued resources in Quaternary studies, offering many advantages as archives of past environmental change. They are readily amenable to precise and accurate radiometric dating, most commonly through U-Th techniques which extend well beyond the limits of other techniques such as radiocarbon dating (Richards & Dorale, 2003). As speleothems are often protected within a cave, they are not subject to the same degree of physical and chemical weathering which affects preservation of other surface records. In this regard, speleothems are often long, encompassing tens of thousands of years, which allows researchers

to study climate changes on orbital and millennial time scales (e.g., Cheng et al., 2009; Wang et al., 2018).

There are, however, legitimate concerns regarding the use of speleothem archives for scientific research. Caves are unique environments that, in themselves, hold significant value to environmental, geological and archaeological sciences. They are also highly regarded by the wider community for their aesthetic and cultural heritage values, and as a source of economic income through show cave tourism and recreation. The importance of speleothems to scientific research must therefore be weighed against the environmental impact of such studies, since removing these formations leaves an indelible impact on the cave environment. Ethical practices require that scientists balance the impact of

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their research to preserve the natural heritage of caves (Frappier, 2008; Antić et al., 2020).

These conflicting positions are most obviously apparent in the commonly employed methods for cave sampling. Traditionally, whole stalagmites have been favored for constructing paleoclimate records, but until they can be dated, their temporal suitability for a particular research objective cannot be determined, resulting in the collection of many samples which are potentially of limited value or remain unused in research group archives. In addition, long, straight 'candlestick' stalagmites tend to be most attractive to researchers due to their long temporal coverage, simple internal growth structures and relatively fast growth (e.g., McDermott et al., 2006); yet removal of these formations can have the most significant impact on the aesthetic appearance of a cave.

Due to their heritage value, many caves are managed within dedicated conservation reserves such as national parks and some are also world heritage areas. The speleothems in these caves are protected by law and their collection is strictly regulated by land managers. In applying for permission to destructively sample speleothems in protected areas, scientists may be asked to demonstrate that their field methods do not unnecessarily impact caves by sampling more than the minimum amount of material required to address the research question. Land managers are less likely to approve research applications unless the sampling technique conforms to a model of current best practice; yet, few peer reviewed studies address this issue directly.

Finally, speleothems can be subjected to numerous processes that may render them unsuitable for paleoclimate research. Diagenetic alteration or other forms of open-system behavior, contamination by detrital materials and stable isotopic disequilibrium with source waters at the time of formation, for example, may all influence the suitability of speleothems for paleoclimate studies (Ortega et al., 2005; Lachniet et al., 2012). Such phenomena can be difficult or impossible to recognize in the field. Frappier (2008) presents a selection system that utilizes characteristics that can be recognized or inferred from field observations in order to reduce harvesting of unsuitable speleothems. Yet, selecting specimens without prior knowledge of their internal features and an emphasis on collecting additional specimens to test for replication, can easily result in over-collection (Spötl & Matthey, 2012). For these reasons, there is an increasing imperative for scientists to develop methods which only target specimens that meet the specific requirements of the research objectives under consideration when removing speleothems from caves.

As a contribution to ongoing efforts to establish 'best practice' sampling methods for caves (e.g., Truebe, 2013) here we present a simple and effective minimal impact reconnaissance dating technique to determine the suitability of individual stalagmites for research purposes on the basis of chronology. This method can be used to assess the suitability of the calcite to dating and mitigate the likelihood

of collecting samples with significant hiatuses when approximate growth rates are known. The method can also offer insights into the ages of particular features, chambers, and cave systems which are of use in understanding speleogenesis and landscape history, which are of additional interest to cave managers in producing outreach materials.

Our proposed sampling procedure aims to survey the ages of previously broken stalagmites, leaving them *in situ* and, as a result, having an almost negligible impact on the cave itself. In many situations (e.g., dating of associated faunal remains, karst formation ages, etc.) complete removal is unnecessary. Alternatively, for paleoclimate studies, after the reconnaissance dating has been undertaken, a highly focused follow-up sampling campaign can then be implemented in the knowledge that only materials of immediate interest are removed. Working together with cave managers, our aim has been to develop and implement techniques that allow us to undertake scientific research in a more sustainable manner with minimal environmental and aesthetic impact.

Our case study focused on two Southern Hemisphere mid-latitude locations in which research programs are being developed to explore regional expression of abrupt climate change. The primary aim was to locate stalagmites suitable for constructing paleoclimate records over glacial terminations and exploring the regional response to millennial-scale climate events. We surveyed six caves between 33–43° South: Mammoth Cave, Jewel Cave, and Ngilgi Cave in the Margaret River region of southwest Western Australia; Exit Cave and Newdegate Cave in southern Tasmania; and Kubla Khan Cave in northern Tasmania. These studies were undertaken in association with National Parks personnel and with all appropriate permits in place. Here we assess the efficacy of this technique and provide recommendations on sampling practices.

EXISTING LOW IMPACT APPROACHES TO CAVE SAMPLING

A number of different approaches and techniques for mitigating the impact of speleothem research on caves have been discussed in the literature. Coring practices have been utilized as a low impact pre-screening technique and an alternative approach to removing whole formations, e.g., Gascoyne et al. (1979); Burney et al. (1994); Hellstrom et al. (1998). Spötl & Matthey (2012) provided detailed instruction on the practice of drilling and extracting cores from flowstones and *in situ* stalagmites and using small horizontal cores for reconnaissance dating. A speleothem growth profile can be obtained through vertical coring, significantly reducing the overall amount of material to be collected whilst leaving the remainder of the formation in place. Paleoclimate studies have been conducted on flowstones, stalagmites and subaqueous speleothems (e.g., Verheyden et al., 2006; Columbu et al., 2019; Drysdale et al., 2020) using these methods. Nevertheless, in samples with a complex growth history, a vertically aligned core

may not achieve optimal sampling of growth layering (Whittaker, 2008).

Alternatively, Scroxton et al. (2016) produced a model of stalagmite growth and attrition and provided insights into Late Quaternary paleoclimate conditions using a population of stalagmite basal ages obtained through mini-coring. Powder samples and 16 mm diameter cores were drilled horizontally at the base of the stalagmites to determine a maximum age constraint. Similarly, larger (25 mm diameter) basal core samples were utilized by Whittaker (2008) to pre-screen stalagmites for further study. The cores extracted were of sufficient size to perform a U-Th analysis and to assess the suitability of the calcite for paleoclimate studies. This approach allowed for the detection of unfavorable characteristics such as diagenesis and growth hiatuses. By obtaining this information prior to collection, only stalagmites deemed suitable were removed, significantly lowering the chance of collecting specimens unsuitable for research goals and reducing the overall number of formations removed.

Coring methods, being minimally destructive (especially if plugged with matching rock caps), go some way to minimizing cave impacts. Nevertheless, they remain objectionable to many cave managers, especially in high throughput tourist locations. In addition, the requirement for water-cooled drilling apparatus, and pollution from the resultant carbonate-charged slurries that such processes generate, can be impracticable in remote or sensitive locations, respectively.

Another methodology suggested is the selection and removal of only speleothems that have previously been broken by unintentional human interaction, vandalism, or natural causes such as seismic activity or collapse. The use of these materials is preferred since they arguably contribute little to the cave aesthetic and thus lessen the impact of scientific sampling. This methodology is increasingly being reported (e.g., Liu et al., 2020; Weij et al., 2020) and often has particular applications to show caves. Here, during the original constructional phases, formations were commonly damaged or removed to make way for infrastructure and occasionally this material was entirely removed from the cave or stored out of sight. These samples represent an opportunity to exercise conservative scientific sampling with a significantly reduced impact on the cave. Weij et al. (2020) studied this methodology in detail proposing the use of speleothem “rubble” (i.e., fragments of broken speleothem material, often abundant in caves) to assess speleothem ages and climate proxies that do not require the use of whole specimens (e.g., episodes of speleothem growth, palynology and clumped isotope palaeotemperatures). Engel et al. (2020) used a similar approach to construct an uplift history for the Buchan cave region in southeastern Australia.

An alternative approach to cave conservation is to replicate or replace stalagmites that have been extracted for scientific research, as well as broken or vandalized formations. Walczak et al. (2015) utilized non-destructive computed tomography (CT) scanning

and U-Th dating, which allowed a paleoclimate record to be developed without sectioning the stalagmite. The stalagmite was subsequently reinstated in its original location in the cave. Stefánsson (2010) reinstalled almost 40 recreated and repaired lava stalagmites that were damaged or looted from lava caves in Iceland. This approach was an attempt to remediate historic damage to the cave, however, similar methods have also been employed by researchers to reduce their impact, and to bridge the gap between conservation and scientific research. For example, Baeza et al. (2018) constructed life-like replica stalagmites cast using epoxy resin, dyed to color-match the surface appearance of the original specimen, and reinstalled them into their natural positions. They provide detailed instructions on casting techniques for different sized stalagmites and anchoring replicas into position. Similarly, Scroxton et al. (2021) created a concrete replica stalagmite using a latex mold. The application of 3D printing speleothems has been described by du Preez et al. (2018), who used Micro-computed tomography (Micro-CT) scanning to reproduce an enlarged stalagmite replica to allow for physical inspection of the complex microscopic structure. Recent and ongoing advancements in 3D printing technology will likely result in more durable and cost-effective applications of speleothem replication in the future, highlighting the potential of modern technological advances in reducing the impacts of cave research.

The multiple practices adopted so far by researchers to reduce the impact of scientific sampling of speleothems may not be feasible or practical in all circumstances. In this light, Truebe (2013) surveyed cave paleoclimate scientists and cave stakeholders to develop a series of mutually accepted “best practice” guidelines for scientific sampling. The findings of the surveys, based on 40 scientists and over 100 stakeholder respondents from several countries, suggest that both parties value various methods of scientific sampling, yet a general consensus has not yet been established. Further work into developing the conservation and scientific dialogue between researchers and cave stakeholders is still required to appease both parties and align common interests (Truebe, 2016).

An additional consideration is the use of existing samples in scientific archives to reduce the number of speleothems being removed from caves in the future. The importance of archiving speleothem samples for future scientific studies has been outlined by Fairchild & Baker (2012) who have provided recommended protocols for archiving speleothem samples and data. To date, current practices in archiving speleothems are not consistent across the field, and there are not yet any large global or national repositories for existing speleothem collections. The recent initiation of the online SISAL (Speleothem Isotope Synthesis and Analysis working group) database is a publicly accessible compilation of hundreds of speleothem isotopic records from around the world (Atsawawaranunt et al., 2018). Such openly available endeavors allow for the use of existing speleothem

records to be the basis of future scientific studies. If this practice can be widely adopted, together with archiving of collected specimens, it is anticipated to result in a significant reduction in the overall need to acquire new speleothem specimens in the future.

NEW METHODOLOGY

The current study exclusively sampled broken and fallen stalagmites to reduce our impact on the caves. Our approach is made possible by ongoing improvements in the U-Th method which now allow the acquisition of relatively large (tens to hundreds of samples) datasets in a short period of time (e.g., Hellstrom, 2003; Hellstrom et al., 2020). We collect small calcite chips of as little as 50 mg from the outer surfaces of fallen stalagmites using a small chisel or similar tool and return these to the laboratory for U-Th age determination. No specialized tools (e.g., drills, cooling water) are required for this approach and whole cave systems can be sampled in a relatively short period of time. This is often an advantage so as not to disrupt tourist activities in show caves and can also be beneficial in remote locations where provision of drills or water may be difficult, or time underground is limited for logistical reasons.

Our approach depends on the ability to later relocate the source speleothems for individual dated calcite chips. Accordingly, we make detailed field notes during the initial sampling and collect digital images and video. We also physically tag *in situ* sampled speleothems by attaching plastic flagging tape annotated with sample numbers. Where visible markers are considered undesirable, for example in show caves, markers can be placed under broken speleothems or otherwise concealed from view (here we suggest small, long-lasting, customized speleothem tags which can act as an indicator that the stalagmite is of known age). These measures enable us to confidently identify sampled speleothems months to years after initial chip sampling.

Sixty-five stalagmites were sampled inside the six caves surveyed during fieldwork between 2017 and 2020. The Exit Cave and Newdegate Cave sites in southern Tasmania were selected for this research as they are known to contain abundant broken

speleothem material. During the first field survey in 2017 to Exit Cave and Newdegate Cave, small fragments of calcite were chipped off the broken surface closest to the base of the stalagmites. The calcite samples were retrieved using a small hammer and chisel and sampled as close to the central axis of the stalagmite as possible to give the best chance of deriving a maximum age of each stalagmite.

This simple reconnaissance sampling technique was further developed during fieldwork in Western Australia in 2019. Basal samples were collected using the same approach, but an additional sample was also collected from near the top or stratigraphically youngest part of the stalagmite. This approach for a maximum and minimum age constraint provides additional information of the growth period for each stalagmite. When sampling the youngest growth surface of the stalagmites, the outer layer or crust of the stalagmite was removed to expose fresh crystalline calcite more appropriate for U-Th dating. Freshly exposed surfaces on stalagmites were remediated by applying small amounts of local cave sediment as appropriate to color-match the surface and leave minimal visual evidence of sampling. The methodology has minimal impact on the stalagmite surfaces, with sampled regions typically ca. 1 cm² in extent (Fig. 1) and, as such, is less invasive again than mini-core drilling. Where possible sample locations were on hidden surfaces and, where moved during sampling, the stalagmites were returned to their original positions and any footprints or other markings erased.

A subsample of approximately 10-200 mg of visibly clean calcite was extracted from each of the field samples for U-Th dating. The subsamples were cleaned under running water to remove any detrital matter, and any weathered or altered calcite was removed using a dental drill. An additional cleaning step was taken with some of the Kubla Khan Cave samples to remove any trace of an aragonite crust which was present in the nearby surrounds of the cave. This involved cleaning the surface layer in a bath of dilute HNO₃ for approximately one minute, followed by repeated rinses of ultra-pure water. As aragonite is U-rich, this additional step was undertaken to reduce the likelihood of age contamination by even small amounts of younger speleothem overgrowth.

Fig. 1. Minimally impacted stalagmites after sampling for reconnaissance dating. These images highlight the overall impact of this sampling technique which has an almost negligible impact on the aesthetics of the cave.

Chemistry and mass spectrometry procedures followed Hellstrom (2003). The samples were taken into a HEPA-filtered clean laboratory where they were dissolved in HNO_3 , spiked with synthetic U and Th isotope tracers ^{236}U – ^{233}U – ^{229}Th and refluxed overnight to equilibrate. U and Th isotopes were separated from the calcite matrix using TRU-Spec™ polymer ion exchange resin in columns washed with 1.5 M HNO_3 and 4 M HCl , eluted together using a mix of 0.1 M HCl + 0.2 M HF . The extracted U and Th cut was dried down overnight then introduced in a run solution of 5% HNO_3 and 0.5% HF to a Nu Instruments Plasma multi-collector inductively coupled plasma mass spectrometer (MC ICP-MS) for analysis. Ages were calculated accounting for the presence of detrital Th at the time of speleothem formation, using initial $^{230}\text{Th}/^{232}\text{Th}$ values determined using the stratigraphic constraint method of Hellstrom (2006). A global default $^{230}\text{Th}/^{232}\text{Th}$ value of 1.5 ± 1.5 was used to calculate ages of base and tip samples, and this value was later refined when initial $^{230}\text{Th}/^{232}\text{Th}$ could be determined for individual stalagmites with higher resolution dating.

To assess the accuracy of this method, 21 of the stalagmites that produced age determinations suitable for our objectives were subsequently collected from five caves and dated at higher resolution. Age-depth models were developed using the Finite Positive Growth Rate model (Drysdale et al., 2005; Corrick et al., 2020). The minimum and maximum age determinations produced through the age modelling were then compared with the reconnaissance base and tip ages to assess how closely the ages replicated.

RESULTS

The U-Th age determinations of the stalagmite base and tip samples produced a wide distribution of ages, from 3.97 ± 1.69 to 792 ± 102 ka (1950 BP) (Fig. 2). Older cave development was observed in the Tasmanian sites, with some ages beyond the suitable limits of U-Th dating. The ages for the southern Tasmanian sites ranged >650 ka to 57.88 ± 0.34 ka at Exit Cave and from >650 ka to 38.16 ± 0.81 ka at Newdegate Cave. The maximum ages of samples from Kubla Khan Cave were much younger, ranging from 136.0 ± 1.0 to 77.40 ± 0.52 ka.

The distribution of ages from southwest Western Australia displayed younger cave development with ages concentrated during the last 150 kyr. Jewel Cave had the oldest cave development of the three Western Australian sites with ages spanning from 436 ± 57 ka to 3.97 ± 1.69 ka, whereas Ngilgi Cave and Mammoth Cave did not produce ages beyond the penultimate glaciation, with maximum ages of 158.8 ± 2.2 ka and 110.4 ± 2.9 ka.

This approach has enabled us to identify several stalagmites potentially corresponding to the periods of interest and thus for meeting our scientific objectives, but importantly has also identified specimens that are not appropriate to our present research questions. Of the 65 dated stalagmites, we selected ten from the Western Australian caves and 11 from the Tasmanian caves that met our criteria for higher resolution paleoclimate analysis. Appropriate permit applications could then be enacted with cave management authorities in the confident knowledge that only materials likely to be appropriate to our study were being targeted.

Fig. 2. Age distribution of reconnaissance base and tip samples from Tasmania and Western Australia for each stalagmite. U-Th ages are plotted with the 2σ uncertainty range. Shaded bands indicate the temporal periods of interest to our study. Stalagmites highlighted in pink were collected from Tasmanian caves and stalagmites highlighted in blue were collected from Western Australian caves. All other stalagmites remain in the caves in the positions in which they were found.

DISCUSSION

Accuracy of the targeting method

It is clearly of primary importance to determine whether this 'minimalist' reconnaissance methodology provides an accurate picture of speleothem age ranges. To this end, for a small number of samples collected after the initial reconnaissance phase, we compare the results of the reconnaissance study with detailed age evaluation of the same samples back in the laboratory obtained through higher-resolution U-Th dating and age-depth modelling, using the Finite Positive Growth Rate Model (for convenience we term these 'true' ages).

Figure 3 demonstrates how the reconnaissance basal ages compare with the true ages for samples collected from the Tasmanian sites. In general, the reconnaissance ages are consistent with the true ages with some minor variations. Of the 11 stalagmites collected from the Tasmanian sites, nine reconnaissance ages fall within 5% of the true ages with an average relative error of 0.74%. Slight discrepancies can be observed in some samples between the reconnaissance and true ages, in some cases due to the location from which the reconnaissance samples were taken in the field relative to the absolute base of the stalagmite determined after sectioning.

Fig. 3. Basal reconnaissance ages (using basal sampling method) plotted against true ages determined through higher resolution U-Th dating and age depth modelling for stalagmites collected from southern Tasmania. Reconnaissance ages are largely consistent with true ages. Stalagmite NG-17-7 has been excluded from the age evaluation as it was deemed unsuitable for further study due to diagenesis.

Similarly, the expected duration of growth relative to the true duration of the stalagmites collected from Western Australia (Fig. 4) demonstrates consistencies between the ages. The true ages largely fall within the

2 σ uncertainties of the reconnaissance ages, with a few exceptions. Slight age offsets are present, again likely due to sampling locations on exterior portions of stalagmites in the field.

Fig. 4. Expected growth interval (orange) and true growth interval (purple; determined using age-depth modelling of multiple U-Th ages) for stalagmites collected from Western Australian caves. Field samples were collected using base and tip sampling method.

Where the reconnaissance samples produced anomalous age determinations that were disproved by the true ages, the cause was mostly identified after sectioning and higher-resolution dating of the stalagmites. Examples of some of these causes have been highlighted in Figure 5.

With some stalagmites, the match between the reconnaissance and true ages were less consistent. The reconnaissance tip age of stalagmite M19-12 was 8.8 ± 3.1 ka, incongruously younger than the true age of 15.59 ± 0.73 ka. This reconnaissance sample contained high detrital Th which is likely explained by the contamination of younger material. NGI19-3 and NGI19-4 grew over significantly older intervals than implied by the reconnaissance ages and on sectioning these stalagmites unconformable growth layers were identified in both samples (Fig. 5A, D). These layers were up to 5 mm thick, largely encapsulating the older parts of both stalagmites, and were inadvertently sampled in the field. Evidence of localized dissolution was discovered at the top of stalagmite NGI19-4 once it was sectioned (Fig. 5C), invalidating the use of reconnaissance U-Th dating at this location. Diagenesis was also observed in one stalagmite from Tasmania, NG-17-7, in which the higher resolution dating produced an age determination significantly older than the reconnaissance age. Evidence of significant diagenetic alteration was revealed upon sectioning (Fig. 5B), likely the result of aragonite-

calcite inversion, causing open-system U loss and the generation of a significantly older apparent age. For this reason, NG-17-7 was deemed unsuitable for further U-Th dating and paleoclimate proxy analysis, although this could not have been recognized solely based on field observation or reconnaissance dating. Finally, stalagmites M19-4 and M19-9 both produced coeval growth durations based on the reconnaissance ages, with tip ages consistent with the true ages, yet both reconnaissance basal ages failed to replicate the true ages. However, it is worth noting that both reconnaissance basal ages produced concurrent age determinations of 41.5 ± 2.5 ka and 41.7 ± 5.7 ka. The coincidentally similar ages may imply that a common perturbation was responsible for producing age determinations significantly younger than the true ages. Both samples contained high detrital Th and were situated only meters apart, suggesting a single generation of overgrowth.

In general, this method has provided reconnaissance ages that are more often than not consistent with ages produced through higher resolution U-Th dating and age-depth modelling. The success rate for obtaining samples that fell within our anticipated temporal range was 76%, though 90% of stalagmites collected are still considered useful for our objectives, compared to a likely success rate of ca. 30% had we removed all 65 fallen stalagmites from the caves without the use of reconnaissance dating.

Fig. 5. A) Younger layers of calcite were identified after sectioning stalagmite NGI19-3, which produced significantly younger reconnaissance ages. B) Diagenetic alteration of stalagmite NG-17-7 identified after sectioning. C and D) Stalagmite NGI19-4 displays evidence of dissolution at the top and a younger unconformable layer at the base of the stalagmite.

Limitations of the technique

In hindsight, it became clear that our initial method of exclusively sampling the base of stalagmites for reconnaissance dating did not provide enough temporal information to allow us to confidently select stalagmites for our objectives. This approach did however provide constraints on the timing of cave development and could be of immediate benefit to studies of karst/cave evolution, regional landscape history and vertebrate paleontology without any further removal of material. Although this method was the least invasive, basal ages could only provide limited information to evaluate the extent of the growth periods covered by any given sample. In many caves growth rates are variable or unknown, however, this method may still provide useful constraints where growth rates are known to be reasonably consistent. The addition of sampling the tip or youngest growth surface of the stalagmites enabled us to constrain the growth period and determine the suitability of the stalagmite, at the cost of a slight increase in impact on the cave environment.

It is also important to note that the application of this technique is only suited to broken or fallen stalagmites as basal sampling cannot easily be applied to standing specimens, as this requires more invasive *in-situ* core drilling as utilized by Scroxton et al. (2016) and Spötl & Matthey (2012). Determining a maximum age constraint requires material to be sampled at or near the central growth axis at the base of the stalagmite which is not accessible on standing stalagmites. As such, attempts to produce maximum age constraints using this method on standing stalagmites will not provide a true basal age and a tip age alone is not usually informative.

One of the major contributors to successful dating relies on the quality of the calcite sampled: ideally dense, microcrystalline calcite (Richards & Dorale, 2003). Dirty samples containing a high detrital content result in ages with high uncertainties. Where possible, we aimed to sample calcite which was visibly unaffected by detrital matter and diagenetic alteration; however, at times the quality of the sampled material was compromised. To reduce our impact and evidence of sampling, we took a very conservative approach to ensure no visible evidence of sampling remained in show caves (Fig. 1) where stalagmites were in direct view, and in some instances the amount of material collected was only sufficient for a single age determination attempt. The importance of these stalagmites to the integrity of the cave outweighed any scientific potential they may have held, and in this regard, ages contribute to the overall knowledge of cave ages and not to assess their paleoclimate potential. Moreover, some samples that appeared to be free of detritus were affected by elevated $^{232}\text{Th}/^{238}\text{U}$ and required repeat analyses which is only possible where sufficient material has been collected. To satisfy U-Th analytical and precision requirements, we recommend extracting large enough samples to allow for sufficient cleaning of outer surface layers either physically or through rapid dissolution.

In speleothems that have undergone diagenetic alteration, a loss of soluble U through mobilization

can result in a relative increase in the $^{230}\text{Th}/^{238}\text{U}$ ratio, producing older ages (Ortega et al., 2005; Lachniet, 2012). Several stalagmites in Jewel Cave that were located close to a now-drained underwater lake produced unrealistic ages. This is likely to have been caused by repeated inundation since formation, resulting in partial dissolution and associated movement of U within the calcite lattice. Caution should be exercised when sampling speleothems in similar settings, or where diagenesis is suspected, and detailed field observations should be recorded.

An important consideration affecting successful selection of stalagmites based on reconnaissance ages is the occurrence of growth hiatuses. Two of the stalagmites that were collected from Jewel Cave and Mammoth Cave based on their expected age duration contained long growth hiatuses, limiting their utility for paleoclimatic reconstruction. Stalagmites J19-3 and M19-12 produced modelled upper and lower ages that closely replicated the predicted growth duration, yet detailed dating indicated that both stalagmites experienced substantial pauses in deposition, covering much of their anticipated growth intervals. Stalagmite J19-3 contained growth hiatuses between 128-114 ka and M19-12 contained two growth hiatuses between 86-71 ka and 66-18 ka. These hiatuses were unable to be identified until the stalagmites were sectioned, and the central growth axis was exposed, highlighting a shortcoming of the reconnaissance dating technique. In some cases, the presence of significant breaks in deposition can be inferred by using the reconnaissance constraints on the duration of growth and knowledge of local average growth rates.

To avoid unnecessary sectioning of stalagmites which may not be suited for paleoclimate studies, the application of non-destructive techniques such as X-ray computed tomography (X-ray CT) and Micro-CT may be implemented (Mickler et al., 2004). In addition, Walczak et al. (2015) showed that CT scanning of stalagmites can be used as a non-destructive technique to derive paleoclimate data, enabling scientifically favorable stalagmites to be returned to the cave. Such techniques can be used to assess the presence of growth hiatuses or evidence of diagenesis prior to sectioning stalagmites and if collected and treated with sufficient care unsuitable stalagmites can be returned to the cave (Frappier 2008; Bajo et al., 2016).

Comparison with previous methodologies

Site location and accessibility may present challenges when undertaking reconnaissance fieldwork due to limiting factors such as cost or availability of permits for return visits to collect samples. If returning to a cave presents challenges or is not possible, the collection of sufficient data remains imperative, and thus the time requirements of sampling may need to be considered. Coring speleothems is relatively time consuming and can take 20-30 minutes per sample (Whittaker, 2008), in comparison base and tip sampling can be performed in less than a minute per sample. Although this method is ideally suited to caves which can be returned to once permits have been granted, this approach allows for screening a

larger population of speleothems over a short period of time. In this context, a speleothem rubble approach (Weij et al., 2020) is an alternative to generating a wide sample of speleothem ages. Rapid sampling methods such as these may be favorable or more appropriate in remote locations or where caves are not readily accessible. These methods may also be advantageous in situations where caves (outside of conservation areas) may be threatened by destructive activities such as quarrying or development. Where time and human resources may be limited, rapid sampling approaches such as these are recommended. Additionally, neither of these techniques requires the need for specialized drilling and coring equipment, and can be applied to nearly any cave, whereas coring may not always be appropriate, e.g., in show caves. The rubble approach is ideally suited for collecting information on the age and development of a cave, but it is, however, limited in the extent of paleoclimate information that can be derived. As the approach targets broken fragments of speleothems it is not suited for identifying formations for higher resolution paleoclimate studies. Furthermore, this approach is limited to producing a single age as opposed to a growth interval, which is favorable in a climatic context. Hence, the low-impact approach adopted will likely be governed by the research objectives and logistical constraints.

One of the limitations of our technique is the unintentional sampling of younger calcite overgrowths or crusts which post-dated formation of the target stalagmite surface and resulted in significantly younger age constraints. In both instances where this was encountered it was not identified until the stalagmites had been sectioned through the central axis and dated at a higher resolution. As an alternative approach, the application of mini-coring (Scroxton et al., 2016; Spötl & Matthey, 2012) is advantageous here as this technique allows for multiple dates from a single core, and would likely identify the presence of any post-depositional layers. As this approach is more intrusive and requires drilling equipment, it may not always be a practical option. In this situation, we would instead recommend extracting base and tip samples deeper into the stalagmite. Although this does have greater visual impact, it presents an improved likelihood of identifying and avoiding unconformable growth layers.

A further issue encountered with this method was the ability to identify the presence of growth hiatuses. Again, extracting a horizontal basal core from the stalagmite would allow for multiple dating aliquots to be performed and assist in identifying the presence of growth hiatuses. Powder mini-core samples (Scroxton et al., 2016) are likely to yield a true maximum age determination without encountering younger post depositional layers, however, they are limited in the chronologic information that they provide, and the presence of hiatuses cannot be determined using this method.

Although coring does offer advantages over our sampling method and the rubble approach, other factors must be taken into consideration. Coring practices, both vertical and horizontal, inevitably

produce a waste by-product that can contaminate pools and disturb the natural appearance of the surrounds. Thus, additional measures must be taken to contain and clean up effluent (Spötl & Matthey, 2012). Information that can be extracted from a core is limited by the diameter of the core barrel relative to that of the stalagmite. For instance, the cores of Whittaker (2008) were large enough to produce reconnaissance ages and assess the calcite suitability for paleoclimate work, which otherwise may have been more difficult to determine from smaller cores. Extracting cores less than 6 mm in diameter tends to result in poor recovery and disintegration of material (Spötl & Matthey, 2012). Although sampling larger diameter cores is more destructive than other approaches, the information that can be obtained may justify the impact. It should be noted that to obtain a maximum age constraint by horizontal coring, the core must intersect the central growth axis at the base of the stalagmite. As it is often undesirable to have sampling disturbances through the central axis, the size of the core diameter should be taken into consideration to suit future higher resolution analyses (e.g., stable isotopes). The potential implications to proxy analysis may deem our method as more appropriate. Furthermore, when combined with alternative approaches, such as adapted stepwise screening (Frappier, 2008) or cave monitoring (Treble et al., 2008), the paleoclimate suitability of the stalagmite may be assessed.

CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to implement and assess a simple and discrete sampling procedure for establishing the age ranges of broken stalagmites in any cave, to establish their suitability for further research. This approach has proved to be an effective and beneficial technique, which has allowed us to identify favorable stalagmites, whilst significantly mitigating environmental impact. Our success rate of 76% for obtaining stalagmites that fell within our anticipated temporal range, and 90% of collected stalagmites useful for our objectives, certainly highlights the benefit of this reconnaissance dating technique. This approach also has the added advantage of building an inventory of stalagmite ages, which is then available to inform the selection of material for future research programs.

The full value of such an inventory is unlikely to be realized unless accessible to the broader research community, potentially via initiatives such as the SISAL database (Atsawawaranunt et al., 2018). However, SISAL does not store sample location data beyond cave names and would not assist a researcher interested in re-locating a specific speleothem dated by a previous researcher using the chip method.

Fairchild & Baker (2012, p. 368-370) provide recommendations for good practice in archiving speleothems and speleothem data, stressing the importance of appropriate record keeping and storage of samples. We concur with these recommendations, noting that speleothems dated using chip samples may have no published result and no physical object to

archive following completion of laboratory procedures. This situation does not detract from the value of the work as a contribution to future targeted speleothem sampling. In the absence of an agreed data repository for field notes, images and videos collected when chip sampling speleothems, we encourage researchers to consider all available options for securing the longevity of relevant information, including lodging copies with land managers. We also encourage land managers responsible for issuing sampling permits to place conditions on these authorities to ensure that sample sites are adequately documented.

The benefit of caves to scientific research is undoubtedly clear, though the scientific value must be balanced with conserving such fragile environments. This technique has offered the opportunity to gain insightful information into the occurrence of speleothem growth, cave development and karstification, and paleoclimate interpretation whilst leaving minimal impact on the cave. We have found prior screening of speleothem ages using this technique of dating small fragments is a practical application that can significantly reduce the impact scientists have on caves. The addition of a tip sample has provided valuable information on growth duration, insights into growth rates and the presence of suspected hiatuses. Sampling too conservatively does, however, present complications and thus best judgement should be exercised to balance the environmental and cultural impact with scientific outcomes. We recommend sampling sufficient material for repeat dating aliquots to constrain initial Th and to allow the sample to be thoroughly cleaned of any detritus or diagenetically altered material. Additionally, caution should be exercised to avoid unconformable growth layers which will produce younger-than-true ages.

There are various advantages and disadvantages to the techniques previously outlined, hence there is no single best approach to reducing the impact of scientific sampling on caves. Adopting low-impact methods will likely depend on research capacity and desired outcomes, however, there are various options available to reduce the overall impact that scientific research has on cave environments. In our view, appropriately conservative speleothem chip sampling contributes to current best practice in speleothem science, where it facilitates more selective sampling of whole speleothems and thus reduces unnecessary destructive sampling.

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