KEYWORDS: ***230Th/234U dating – Speleothem skin – Fossil bone – Rock painting – Reproducibility***

THE DATING OF ROCK ART AND BONE BY THE URANIUM–THORIUM METHOD

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Abstract. A review of the history of uranium-series dating of fossil bone and calcite skins related to rock paintings reveals significant limitations to the credibility of many such results. The 'closed system' conditions required do not seem to apply to many ancient faunal remains and may be lacking in many cases also in the types of speleothems frequently used to secure minimum or maximum ages for cave paintings or petroglyphs. The studies comparing ^{14}C dates with U–Th results from such reprecipitated carbonates, particularly of the Pleistocene, suggest that the latter tend to be much higher. Recent testing of the method implies that the taphonomy of most such deposits is far too complex to allow the determination of age-governed $^{230}Th/^{234}U$ ratios. The U concentrations in coeval calcite skins vary significantly on a millimetre scale, and in some cases, apparent ages can be hundreds of times greater than actual ages. Tests also reveal that results obtained by different laboratories from the same samples differ greatly. The lack of reproducibility and testability of such results, combined with the interventional method of obtaining samples, excludes it from sustainable approaches to rock art dating.

Introduction

The first analytical investigations in Malangine Cave, conducted in December 1979 and January 1980, ushered in the 'direct dating' of rock art (Bednarik 1984). The cave is located near Mount Gambier in the far southeast of South Australia, in a karst region featuring hundreds of caves. It was one of the first two sites of that area to reveal cave art, occurring in the form of three physically separated petroglyph traditions on the cave's ceiling (Fig. 1). The earliest of these consists of finger flutings, followed by deeply engraved motifs of the Karake genre range. These percussion markings became concealed by a laminar speleothem deposit of around 15–20 mm thickness. That reprecipitated calcite skin, in turn, bears a third form of rock art, consisting of shallow engravings made with single incised strokes.

As the cave's speleothem deposits began drying out in response to the 19th-century clearing of the vegetation above, the laminar sheets effectively separating the last two petroglyph generations began to exfoliate from the ceiling, and several kilograms of the speleothem sheets fell to the floor. Appreciating that this material is datable by both ^{14}C and $^{230}Th/^{234}U$ age determination and that its age must be between those of the second and third petroglyph traditions, we secured age estimates from the substantial speleothem lamina (Bednarik 1984, 1985, 1986, 1998, 1999, 2012).

The 'direct' dating of rock art involves a direct physical relationship of a rock art motif and the dating criterion utilised, and the potential of falsifying prop-

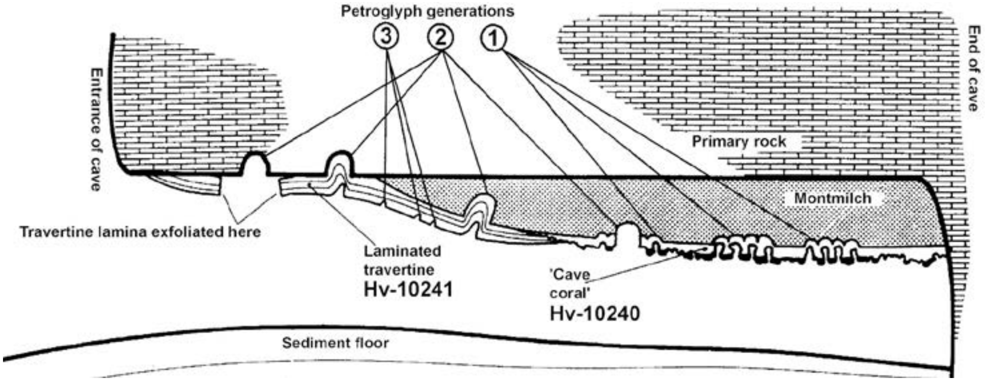

Figure 1. *Schematic longitudinal section of Malangine Cave, showing the relationships between three petroglyph phases and two ceiling speleothem deposits (after Bednarik 1984).*

ositions about that relationship. The 'criterion' can be of a wide variety of types, ranging from lichen thallus sizes to the sizes of micro-wanes on fractioned rock crystals, from organic components of paint residues to those found in mud-wasp nests. In most cases, the numerical age result is not the age of the rock art concerned but provides a minimum or maximum age only, although very few methods used offer actual 'target events' (*sensu* Dunnell and Readhead 1988). The emphasis in 'direct' dating of rock art is on the falsifiability of propositions about how the result precisely relates to the age of the rock art, and it is here that many attempts to provide such data fail.

In the case of the data from Malangine Cave, it was indisputable that the reprecipitated calcite lamina was younger than the petroglyphs it concealed and older than those executed on its surface. The ^{230}Th/^{234}U method yielded an estimate of 28.0±2.0 ka, but the radiocarbon analysis of a sub-sample delivered a date of 5550±55 yrs bp (Hv-10241) (Fig. 1). To confuse the issue further, another, stratigraphically earlier coralline speleothem from the same cave ceiling, separating the oldest rock art tradition from the second, produced a ^{230}Th/^{234}U age of 4.3±0.5 ka and a corresponding ^{14}C date of 4425±75 yrs BP (Hv-10240). Two problems arose from these four results: the first pair of dates was impossible to reconcile, one being about five times greater than the other, while the other pair corresponded perfectly but should have been greater than the first. Consequently, the uranium-series dates remained unreported for several years, while an explanation was sought to account for the significant difference of results.

Since this first discrepancy in direct rock art dating more than 40 years ago, numerous such issues have come to light, and not only in rock art dating endeavours. They are reviewed in this paper. The conventional assumption in U–Th disequilibrium dating is that a 'pure' calcite speleothem age can be determined from the ratio of the ^{230}Th to ^{234}U contents. However, this ratio is often upset if either of these isotopes are present as detrital contaminants or are removed in that form (Schwarcz 1980). Similarly, it is of no relevance to age if uranium has been removed by moisture. It must be clarified upfront that the subsurface zones of rock also are generally ^{14}C-open systems (Bednarik 1979; Watchman 2022) and thus pose significant problems for radiocarbon-dating of rock art. Indeed, the several methods used in the quest to estimate rock art age that face taphonomic and logical challenges include also, for instance, OSL analysis of insect structures: the assumption that radiation dose rates are constant through time is unproven. Therefore, rock art age estimation continues to face many obstacles but here we will focus on those with U–Th dating.

Defining the problems with U–Th

In the years since the early 1980s, it has emerged that the cited inconsistencies in the results from Malangine Cave were perfectly predictable. Similar disparities have been reported by nearly all other researchers who have applied both methods, ^{14}C and ^{230}Th/^{234}U, to sample splits. Bard et al. (1990) used both methods to analyse corals from Barbados and detected similar discrepancies. They also found that results matched reasonably well for samples that appeared to be less than 9.0 ka (thousand years) old, but those of the early Holocene and the final Pleistocene diverged increasingly with age. At age 20 ka, the ^{230}Th/^{234}U results were 17.5% higher. Next, Holmgren et al. (1994) applied both techniques to a stalagmite in a Botswana cave and reported the deviation between results to be much greater. At 30 ka by radiocarbon, the corresponding ^{230}Th/^{234}U age was 50 ka. However, stalagmites are usually far more suitable for both methods than more porous forms of speleothem because they tend to be of much denser, more crystalline structure.

Labonne et al. (2002) then investigated the flowstone deposit sealing the Magdalenian occupation layer in Altamira Cave and found that the ^{14}C ages provided the most reliable age estimates, as per conventional dating of charcoal from the occupations. Up to the beginning of the Holocene, there was *reasonable* correspondence between radiocarbon age estimates and those derived from uranium-series analysis, just as others had found, but earlier dates of the latter method are typically too high. These results comprehensively support the findings of Bednarik, Bard et al. and Holmgren et al.

A year later, Plagnes et al. (2003) reported results from both methods that were even more similar to those secured from Malangine Cave over twenty years earlier. A speleothem lamina overlying a hand stencil in Gua Saleh, a cave in Borneo, yielded a ^{230}Th/^{234}U age of 27.32±0.21 ka, whereas its corresponding ^{14}C age was 9.90–7.84 ka BP. Just as in Malangine Cave, another sample provided concordant results from the two methods of about 9 ka.

Another study applying both methods to carbonate speleothems was conducted at the Baiyunwan rock art site in Yunnan Province, China (Taçon et al. 2012). Although most results of this investigation were of the Holocene, those acquired by ^{230}Th/^{234}U presented low ^{230}Th/^{232}Th ratios. Oddly, the U–Th dates of mineral layers above the target paint layer ranged in age from c. 7.17 ka to c. 13.96 ka, while those below it varied from c. 11.33 ka to c. 11.98 ka. The corresponding ^{14}C dates above the paint residues clustered near 4.5 ka, while those below the pigment layer were between 10 and 11 ka. Taçon et al. attempted to correct for detrital thorium and determined that the painting was between 15 ka and 3.4 ka old.

The next project combining both dating methods involved Toca da Gameleirinha in the Capivara National Park, Piauí, in north-eastern Brazil, where Fontugne et al. (2013) reported a series of ^{14}C results ranging from about 4.5 ka to 11.8 ka. The data secured from Nerja Cave, Málaga, Spain, are considerably more detailed (Quiles et al. 2014; Sanchidrián et al. 2017; Valladas et al. 2017). A thin calcite skin formed over a dot of red pigment provided a ^{230}Th/^{234}U age of between 56 and 60 ka. However, the same speleothem yielded a 27–33 ka cal BP radiocarbon age. Even more dramatic were the results obtained from two other samples from Nerja Cave, GN13-15 and GN13-17. They were collected, respectively, from speleothem skins above and below a charcoal mark. The charcoal had previously been determined by ^{14}C analysis to be between 18 ka and 20 ka old (Sanchidrián et al. 2017) and is, therefore, most unlikely to be older than that age but may still be significantly younger. From below the painting event, the older calcite sample produced a ^{230}Th/^{234}U date of 86.9 ka, while the sample younger than the charcoal mark provided a much older date of 118.9 ka BP (Pons-Branchu et al. 2020). Therefore, the U–Th ages are several times too old, but they are also stratigraphically inverted: the younger layer cannot be 37% older than the previous layer. Perhaps more clearly than any other information, the data from Nerja Cave confirm the problem long identified in a series of earlier investigated sites: most Pleistocene U–Th dates from thin speleothem skins are much too old.

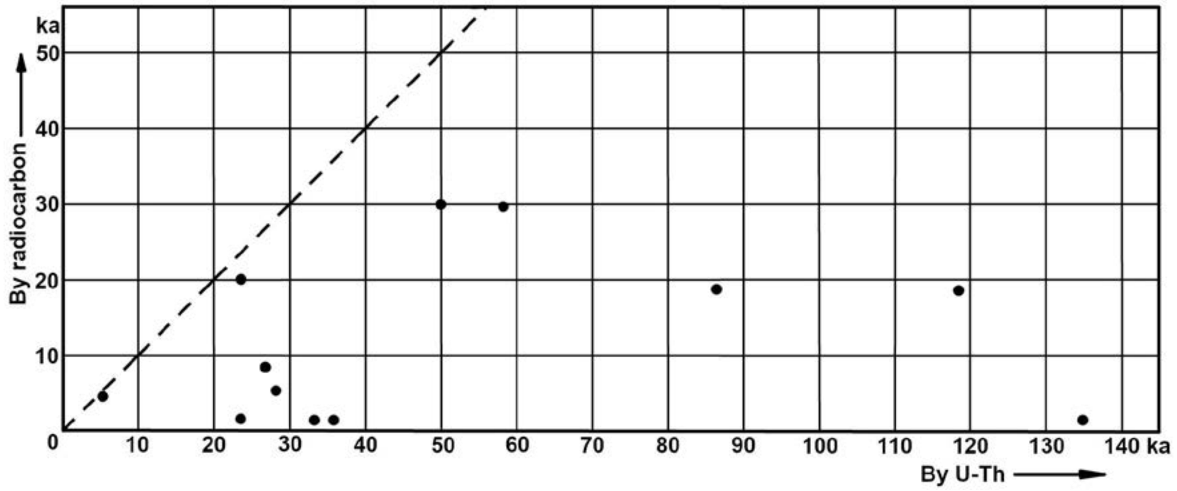

Figure 2. *U–Th age determinations of speleothems compared with archaeologically realistic or radiocarbon ages of these same deposits. The 'dates' listed have been extracted from Bednarik (1984), Bard et al. (1990), Holmgren et al. (1994), Plagnes et al. (2003), Quiles et al. (2014), Sanchidrián et al. (2017), Valladas et al. (2017); Tang et al. (2020) and Pons-Branchu et al. (2020).*

Shao et al. (2021) have provided a careful assessment of the 57 U–Th and four AMS radiocarbon results they secured from four of the Cangyuan rock paintings that were the first rock art from China published outside that country (Wang 1984). Wang had correctly placed them well before the Christian era, and several ^{14}C dates from speleothem covering rock art range from 3100 to 2960 years BP (Bednarik and Li 1991). Corroborative evidence comes from a pollen spectrum taken from paint and the site's excavation by Woo Sheh Ming (2895–2735 yr BP, from charcoal). Shao et al. (2021) have confirmed that the Cangyuan rock paintings seem to be between 3800 and 2700 years old, introducing an effective statistical method of comparing their many maximum and minimum ages. Three of their ^{14}C dates are almost twice the corresponding U–Th result, raising the possibility that it was missed to account for the nearly 50% 'dead' carbon-bearing component of any reprecipitated calcite (Franke 1951; Bednarik 1999). The fourth of Shao et al.'s radiocarbon dates is >43.5 ka BP. Their paper confirms the previous finding by several authors that U–Th results of the Holocene are often likely to be correct.

All studies applying ^{14}C and ^{230}Th/^{234}U analysis in tandem to reprecipitated calcite physically and stratigraphically related to Pleistocene rock art have reported discrepancies in the results, often of significant differences. While Holocene results from both methods tend to correspond reasonably well, the U–Th findings from putative Pleistocene samples are too high by a margin increasing exponentially with greater age (Fig. 2). However, in some studies, some of the Pleistocene U–Th results appear to be coherent (e.g. Valladas et al. 2017). In an extreme case described below, a presumed final Holocene sample even provided a U–Th date from the end of the Middle Pleistocene. Many dozens of authors have questioned the majority of Pleistocene ^{230}Th/^{234}U dates in a series of papers (e.g. Bednarik 2012; Clottes 2012; Pons-Branchu et al. 2014; Sauvet et al. 2015; Aubert et al. 2018; Tang et al. 2020; Tang and Bednarik 2021; White et al. in press; Bednarik et al. 2022). The proponents of the method (e.g. Pike et al. 2012; Hoffmann et al. 2016a; 2016b; Pike et al. 2017; Hoffmann et al. 2018a; 2018b; 2018c) have consistently refused to subject their results to any form of testing, declaring 'U–Th is the way to go' (Pike et al. 2017). Their ultimate quest seems to demonstrate that Neanderthals created rock art, yet this has been known at least since the reports of the sepulchral block over interment No. 6 in La Ferrassie, France, bearing eighteen cupules on its underside (Capitan and Peyrony 1921; Peyrony 1934). Since then,

Figure 3. Speleo-weathering indicates that these finger flutings are about four times as old as the zoomorphic engraving which is believed to be of the Upper Palaeolithic. Baume Latrone, Gard, France.

instances of Neanderthal rock art have been reported from Baume Latrone, France (Bednarik 1986) (Fig. 3); Gorham's Cave, Gibraltar (Rodríguez-Vidal et al. 2014); and possibly Zarzamora Cave, Spain (Collado et al. 2016). The irony is that according to Pike, Hoffman et al., radiocarbon dating yields results that are much too young, yet the method has primarily provided the chronology of the Upper Palaeolithic we have. Therefore, if datings of that era were roughly doubled, it would only indicate that Neanderthals faded out much earlier than we had assumed based on ^{14}C data. That would merely defeat the U–Th advocates' quest of proving that these hominins created rock art, which has in any case long been demonstrated by much more credible means.

The most recent sensational claim based on U–Th analyses places the world's earliest known rock art in the central Tibetan Plateau at an elevation of 4269 m a.s.l. (Zhang D. D. et al. 2021). A panel of hand and footprints pressed into formerly soft travertine is proposed to be between 169 and 226 ka old, in a region where no hominin presence prior to ~40–30 ka BP has been demonstrated (Zhang X. L. et al. 2018). This is an open site fully exposed to severe weathering, where its porous travertine would rapidly shed uranium under moist conditions, which would substantially increase its apparent U-series age. The extraordinary claims involving this site are currently being investigated (Bednarik et al. 2022).

The difficulties with U–Th analyses of travertines have been known for as long as those with calcite skins. Indeed, the first relevant controversy was the prominent case of the dating of a human skull from Petralona Cave in northern Greece (Liritzis 1980a, 1983, 1984; Schwarcz et al. 1980; Liritzis and Galloway 1982). The skull appeared to be intermediate between *Homo erectus* and robust *Homo sapiens*, and U–Th results from the travertine encasing it ranged from 70 to 700 ka. Alternative dating methods were also applied: TL (burnt soil), ESR and magnetostratigraphy.

Due to the U–Th advocates' refusal to test their results in any way, this controversy has remained unresolved. The hallmark of science is falsifiability and testability of propositions, and the negation of these principles by Pike, Hoffman et al. demands that others test their notions. Before doing so, it is helpful to review other aspects and applications of the U–Th method. For instance, it has frequently been used to estimate the ages of fossil bones and teeth.

Bones of contention

Uranium-series dating of fossil bones has been conducted for over half a century, but early work soon showed that U-migration patterns in buried faunal remains rendered the method unreliable (Cherdyntsev et al. 1963). Similarly, Hennig and Gruhn (1983), who reviewed many radiometric dates from bone, emphasised that a closed system does not appear to apply. Rae and Ivanovich (1986) assumed that surface layers of bone reached U saturation within a short time and that subsequent deposition of U would pass through this saturated zone. However, their subsequent work showed that this model was oversimplistic (Rae et al. 1989). Similarly, van der Plicht et al. (1989) found that the U concentration at the surface is in some bones lower than in the middle of the bone, which contradicts the view that it should be higher near the surface. This implies leaching of U from the surface, indicating that the chemical system is an open one and rendering credible dating impossible. The migration of U into the bone occurs during phases of ambient moisture, i.e. it is contingent upon environmental factors that vary significantly between and even within sites. An intensive study of bone and tooth enamel samples from Tournal Cave in France (Bischoff et al. 1988) showed that the results from both materials were incompatible with their stratigraphical ages as well as radiocarbon controls; i.e. all aspects mirrored the issues with thin calcite skins listed above. This even applied to samples of supposedly closed systems (as suggested by similar ^{230}Th/^{234}U and ^{231}Pa/^{235}U ages).

The diffusion-adsorption (DA) model (Millard and Hedges 1996; Pike et al. 2002) and the diffusion–adsorption–decay (DAD) model (Sambridge et al. 2012) both try to compensate for the inherent uncertainties. However, the U migration is entirely contingent upon

the embedding sediment's hydrology, and a cave's sediment may be entirely dry or exposed to heavy water flow; or any intermediate or intermittent conditions. A bone may be subjected to mineralisation (e.g. by U-bearing calcite) and other fossilisation processes that cannot be accounted for quantitatively. The accumulation of U may have commenced a considerable time after the burial of the bone, if indeed at all, and under moist sediment conditions, U leaching occurs very commonly because U is soluble in natural waters. Added to this are the complications arising from the incorrect use of the method, for instance, by opting for measurement of the bone's interior because the subsurface has been contaminated by preservation agents (Fladerer et al. 2006), or by making unwarranted assumptions about the reliability of results (see below). An example is the comparison of results from the different approaches: a bone from Jingnuishan, China, provided a mean DA age of 240 ka (Pike et al. 2002), but the same data set results in a mean DAD date of about 400 ka (Grün et al. 2014). As these latter authors state, '[a]ny researcher who wants to engage in this field needs to be aware of the limitations and complexities of this dating approach'.

Unfortunately, this precept has not been applied to most of the U–Th dates of faunal remains published. An example is the frequent use of U–Th results in the age determination of fossil bone in caves of the European Alps, particularly of the cave bear. Although Hercman (2012: Fig. 1; cf. also 2014) believes that testing U–Th results against those of ^{14}C has shown good correspondence, a review of U–Th dates from cave bear remains inspires less confidence. Those from five Austrian Alpine caves (Repolusthöhle, Ramesch-Knochenhöhle, Bärenhöhle in Hartelsgraben, Herdengelhöhle, Schwabenreith-Höhle) were provided without a scientific context or they are archaeologically incongruous (Fig. 4).

Repolusthöhle in Styria is a key Palaeolithic site in the eastern Alps, almost fully excavated in the mid-20th century (Mottl 1950, 1951, 1964; Murban and Mottl 1955) and yielding around 2000 lithics, more than any other Alpine Palaeolithic site (for a summary see Bednarik in press). The number of human occupation events is unknown, but two Palaeolithic inhabitations have been suggested. They have been described as being of Lower, Middle and Upper Palaeolithic typologies but may well be of the Olschewian tradition and a late Middle Palaeolithic, respectively. Although much charcoal was present, only one radiocarbon date was secured from it, 13 370±150 yr bp (GrN-2036) (Mottl 1964). The cave's 35 m long tunnel ends in a 9.5 m deep shaft that has been subjected to heavy water flow and 'sagging' of the sediments, yet its contents were interpreted as the lower continuation of the tunnel's contents. Although the sole ^{14}C date from the shaft deposit is 32 000+400/-410 yr bp, from a reindeer bone (Pacher 2014), the six U-series results from cave bear bones range from about 50 ka to 223 ka (Fuchs et al. 1997, 1998). Confirmation of such a long

Figure 4. The locations of (1) Repolusthöhle, (2) Ramesch-Knochenhöhle, (3) Bärenhöhle and (4) Herdengelhöhle and Schwabenreith-Höhle in Austria.

chronology was sought through the putative *Ursus deningeri* features of bear remains from the shaft's basal deposit, but these atavistic characteristics are just as conspicuous in the most recent cave bear finds from the site. Based on the Middle Pleistocene U–Th date, it was even suggested that the site had produced an Acheulean industry (Kusch 1998), although there is not a single Acheulean type among the lithics and the sediments are exclusively of the late Würm glacial. These issues were eventually resolved by the meticulous work of Modl (2013; Modl et al. 2014) and Brandl et al. (2011), who sought to establish the site's stratigraphy through the analysis of small pockets of remaining sediment. The cave's shaft deposit has all been washed in, and this has most probably resulted in the removal of U and the consequent early U–Th dates from that sediment.

Ramesch-Knochenhöhle in Upper Austria is another cave bear hibernation lair that provided hominin occupation evidence of the late Würm (Rabeder 1985; Draxler et al. 1986). The five stone implements and the faunal remains are heavily worn from transport within the main sediment unit that accounts for 70% of the deposit. Two radiocarbon dates are in the order of 35 and 37 ka, respectively, contrasting with the nine U–Th results from the same stratum that range up to 64 ka and include two inversions. If the datings and the stratigraphy seem incongruent, the site's interpretation by the excavator, palaeontologist G. Rabeder, is even more improbable. He attributes the few lithics to the Mousterian, based on one Levallois point, but emphasises the very warm flora indicated by pollen. It would seem to place the occupation deposit in the Eem Interglacial (115–130 ka), but Rabeder consigns it in the Paudorf or Stillfried B interval (c. 25–26 ka bp). Not only does this coincide with the cave bear's extinction in the region (roughly 27.8 to 24 ka ago; Fladerer 1995; Pacher and Stuart 2009; Bocherens et al. 2014; Baca et al. 2016), it also renders the attribution to the Mousterian impracticable. A series of nine more recently secured ^{14}C AMS dates from cave bear bones ranges from 31.1 ka to >49.9 ka (Rabeder et al. 2005). They suggest that the most realistic interpretation of the data is that the human occupation of the cave occurred during the main Würm interstadial (Göttweig), and the stratigraphy is dislocated beyond reliable interpretability.

The cave bear lair Herdengelhöhle in Lower Austria

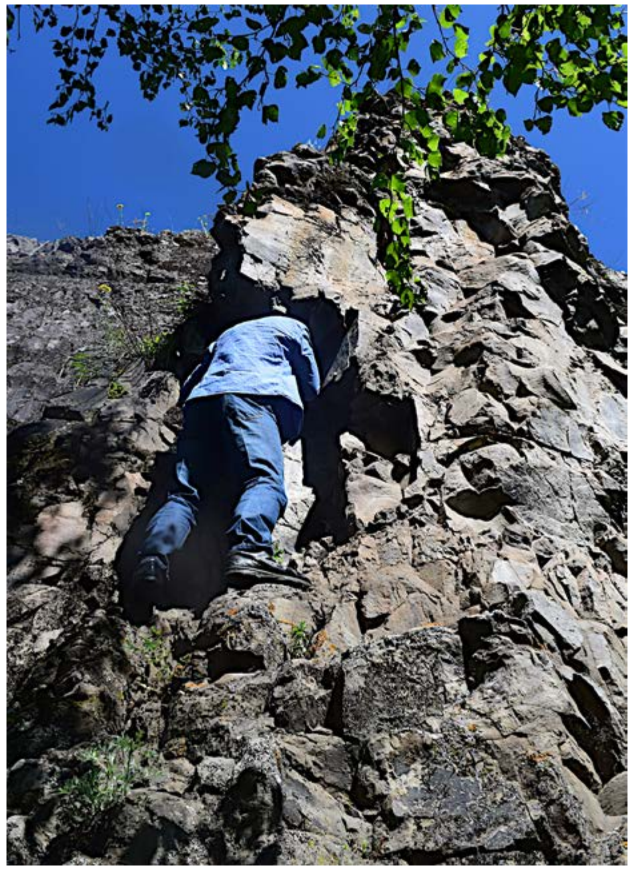

Figure 5. *Sampling carbonate precipitate high on the cliff of Yilin Site 2, Heilongjiang, China.*

(Rabeder and Mais 1985; Rabeder 1987; Frank and Rabeder 1997) has provided U–Th dates of 112.8+13.1/-11.6 ka bp (speleothem fragment) and 135+11/-10 ka to 127±7 ka bp (cave bear bone), but the site is episodically so wet that excavation is difficult, rendering U depletion very likely. Similarly, the nearby Schwabenreith-Höhle (number 4 in Fig. 4) has yielded U–Th ages of 116±5 ka and 78+30/-23 ka bp, respectively (Frank and Rabeder 1997), from two separate speleothem floor deposits. U leaching likely accounts for the high ages of presumed Würmian samples in both sites. On the other hand, the U–Th date obtained from a cave bear bone from the Hieflauer Bärenhöhle in Styria (number 3 in Fig. 4) may be realistic (Döppes and Rabeder 1997: 178). At 35.8+8.4/-7.7 ka bp, it agrees well with the attribution of the cave's hominin occupation evidence to the Olschewian or Alpine Palaeolithic.

In most of these projects, the U–Th data were obtained from bone, but occasionally carbonate speleothems were utilised. U-series analysis can be applied to various materials, including teeth, shells, corals and eggshells (Miller et al. 1999). However, most biogenic carbonates and phosphates, i.e. faunal remains, provide no 'closed systems' (Pike et al. 2002; Hedges and Millard 1995). Speleothems also occur in many forms, of which stalagmites are the most amenable to both ^{14}C and U–Th analysis. Here we are only concerned with the least suitable, among which two have been consistently used in attempts to extract archaeologically meaningful dates: fossil bones and thin calcite skins. In both cases, we have noted instances where U-series dates appear to be valid age estimates, but in most examples considered, they seem to be too high, particularly for Pleistocene samples (see Fig. 2). There have also been instances in which the differences between reasonably expected results and actual results secured were truly substantial. When conducting analyses of samples from far-northern China, it was decided that the many uncertainties surrounding the applications of the method and the need to resolve the antagonistic conversation that had developed demanded testing the method and its efficacy. Two opposing factions have formed over the past decade: one advocating that U–Th analysis should be used exclusively and without testing by other methods (such as ^{14}C, Pa, Ra isotope analysis, thermoluminescence or optically stimulated luminescence; cf. Liritzis 1980b), the other insisting that the sensational results it has furnished are incompatible with all archaeological contexts. Both factions have been unable to sway the other, and the ensuing deadlock must be resolved.

Testing ^{230}Th/^{234}U analysis of speleothem skins

Pike et al.'s (2017) title statement that 'U–Th is the way to go' goes further than just advocating that method; it implies no need to develop alternative rock art dating methods. Their refusal to subject their results to checking by another method contradicts science's most fundamental tenet, testability and falsification of propositions. It also negates the need to develop the still very rudimentary science of rock art age estimation.

The ongoing program of dating Chinese rock art conducted by ICRAD (International Centre of Rock Art Dating, Hebei Normal University) has included the use of U-series analysis at various sites in four provinces. The first analytical study of rock art sites in northern Heilongjiang Province, adjacent to Siberia, included U–Th dating of thin reprecipitated carbonate crusts formed over rock art pigment at two sites, Mohe Station Rock Art Site and Yilin Site 2, Amur Forest (Tang et al. 2020). Both sites are episodically exposed to meteoric and interstitial vadose water flow, and the paint remains are thought to be very recent, at most a few centuries old. Two deposits sampled at the Mohe site, covering paint, produced 'raw age' estimates of 32.9 and 35.34 ka, respectively. The two coeval samples from Yilin Site 2 were taken from the same lamina concealing paint residues and within a few centimetres, providing U–Th estimates of 23.1 ka and 134.6 ka, respectively (Fig. 5). These enormous discrepancies illustrate the extreme effects of diagenetic alteration by U migration and the high Th variability within the same deposit, the isotopic ratios of which are entirely determined by taphonomic processes. Carbonate crusts are generally precipitated from interstitial bicarbonate solutions that must shed some solutes upon emerging from the rock and reverting to atmospheric pressure. Pressure within the rock can be vastly greater, and solubility is a function of it and turbulence and temperature. The sites of the formation of these authigenic laminar deposits may be revisited by aqueous solutions frequently, each time potentially adding or removing U. Th, too, can be added or removed, despite being insoluble in water, travelling as a detrital component (especially as clay minerals) of the carbonate. Therefore, isotopic ratios in such laminae tend to be transient, and there is no expectation that they reflect the isotopic decay of a closed system. This is even more evident in carbonate speleothems than in fossil faunal remains. We are not aware of a case in which a bone yielded a U–Th age estimate hundreds of times its actual age, as in the Yilin Site 2 sample.

In the spirit of testing the method, we provided four split samples from a Jinsha River cave in Yunnan Province, southwestern China, to two different ^{230}Th/^{234}U laboratories: the Isotope Laboratory of the Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an, Shaanxi Province, China (also involved in dating the Tibetan travertine mentioned above); and the ^{230}Th/^{234}U Laboratory at the Geology Department of the University of Melbourne, Australia. Reproducibility is such an important test in science that we cannot rely on any results without it. This introduces another problem with U–Th dating: the U concentrations in coeval calcite skins can vary by >100% on a millimetre-scale (e.g. Hoffmann et al. 2009; Pons-Branchu et al. 2020; as well as the present study), where every sub-millimetric crystal produces ^{230}Th according to the ^{238}U present. Reproducibility of the method when applied to speleothem skins and travertines may be severely limited, and the scientific relevance of such results is similarly constrained.

Moreover, since U–Th samples are in any event sacrificed in the analysis, their results cannot be reproduced. Our 'blind test' resulted in totally different data sets, showing no correspondence whatsoever (Tang and Bednarik 2021: Tables 2 and 3). This introduces one more fatal impediment: if different laboratories can provide vastly different results, there is no reproducibility of any kind assured. The first laboratory provided three late Holocene dates for which the second facility supplied negative ages. The fourth sample, YDG-2, returned an age of 20.077±2.742 ka from the first laboratory, 0.4±7.7 ka from the second. The negative ages derive from a literal interpretation of the data, but they are archaeologically futile.

Summary

The principal obstacle to relying on U-series analyses of Pleistocene fossil bones and speleothem skins is the mobility of U. Uranium is deposited by moisture, but by the same token, moisture can mobilise it by leaching. Therefore, the ^{230}Th/^{234}U ratio of the sample at its collection is a random figure reflecting a moment in time of a transient variable. A much younger or older result might have been secured if the sample had been obtained a century earlier or later. Moreover, in the cases when the result happens to compare reasonably well with an archaeologically realistic age range, there are two potential reasons for such concurrence: either the process has indeed not distorted the ratio significantly; or the distortions of deposition and leaching have roughly cancelled out each other. We cannot know which of these alternatives applies; all we have are free-standing results, and if a set of such results clashes severely with established chronology — as with the sensational dates reported from several Spanish caves — their uncritical publication is premature. Moreover, U-leaching is not the only taphonomic process likely to distort U-series dating. Others include the presence of detrital Th, the inclusion of geological material in the samples and transformation of aragonite to calcite (Lachniet et al. 2012; Fontugne et al. 2013; Bajo et al. 2016). Therefore, the taphonomic processes affecting the fossil bone or speleothem U–Th ratios render a credible interpretation of the results elusive.

In theory, the event that disturbed the equilibrium state of the uranium-series isotopes, such as the formation of a speleothem, can be dated by determining the extent isotopes have re-established equilibrium. This applies to ideal conditions where no subsequent moisture presence has affected the deposit. However, in practice, the sediments embedding faunal remains often experience alternatively dry and wet conditions, as dictated by climatic and hydrological variations. The effects of such environmental variations on thin speleothem veneers are even more spectacular, in some cases suggesting that they are hundreds of times their actual age. Thus, the ^{230}Th/^{234}U ratios of both fossil faunal remains and carbonate speleothem skins are often distorted by the effects of episodic moisture presence. In bones, U is deposited or mobilised by water, depending on the chemistry of the aqueous interaction (e.g. the potential of H), so some surface-near samples seem younger than corresponding interior samples, whereas, in other objects, the inverse condition applies. A common effect appears to be that the apparent ages of Late Pleistocene samples increase exponentially with age until they seem a few times their actual ages. However, in the speleothem skins, these differences can be much more pronounced, to the point that a final Holocene deposit at Yilin Site 2 shows an apparent U–Th age of the final Middle Pleistocene.

The interventional nature of U-series dating of speleothems related to rock art is another concern about the method. The destruction of samples in the analytical process renders the results non-reproducible, and the notion that this is a good approach to rock art dating is misguided. Methods that involve no destructive intrusion in either the paint or the speleothem are preferred as they preserve both elements in pristine condition. Destroying rock art or the layers it is contained in diminishes cultural monuments, particularly if it only provides dubious results that might be discredited in the future. Compared to the methods we are likely to apply in some centuries from now, our current arsenal of approaches is primitive and crude.

The second fundamental objection to physical sampling is that it excludes reproducibility. Microerosion analysis provides an example to illustrate this. The dating criterion of that method, the micro-wane width, is determined without intervention and can be re-located by a future researcher for re-measurement, testing and falsification. This is what is required of a sustainable approach to rock art age estimation. No such method indeed exists for rock paintings currently, but the concept that U–Th 'is the way to go' can only discourage the development of new methods. It is incumbent upon scientific rock art dating to develop methods that do not prejudice the application of future approaches and offer reproducibility.

It follows that faunal remains and speleothem skins (or travertine) are two materials not credibly datable by U–Th ratios. The method is better suited for very dense speleothems, notably stalagmites. Most specifically, results derived from it should not be used to sustain extraordinary claims that conflict with established archaeological acceptance. Most certainly, all archaeological contentions are open to challenge but not by methods that are themselves challenged.

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