Archaeological and Anthropological Sciences _####################_
https://doi.org/10.1007/s12520-020-01266-0

ORIGINAL PAPER

Rock art dating by $^{230}Th/^{234}U$ analysis: an appraisal of Chinese case studies

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Received: 3 July 2020 / Accepted: 17 December 2020
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Abstract
A reconsideration of the application of $^{230}Th/^{234}U$ analysis to thin accretionary skins of re-precipitated carbonate to secure minimum or maximum ages for physically related rock art suggests that the controversy it has created can be resolved. A program to test the method's results indicates that such calcite skins tend to yield age estimates that are too high, particularly from Pleistocene samples. Although the controversy about such results has escalated in recent years, it had initially become apparent several decades ago. Here, two case studies of Chinese rock art, in Heilongjiang and Yunnan Provinces, are presented. Potential error sources accounting for the discrepancies are proposed. Some cautionary measures are presented to prevent the promotion of sensational but ultimately erroneous rock art age estimates deriving from this method.

Keywords $^{230}Th/^{234}U$ dating · ^{14}C dating · Rock art · Cross-checking · Blind testing

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Introduction

The rock art of Heilongjiang Province, the northernmost state of China, was recently introduced (Tang et al. 2020). The primary significance of this paper was not, however, that it was the first international report of Heilongjiang's rock art but that it discussed rock art dating methodology and, in particular, its examination of $^{230}Th/^{234}U$ analysis. In recent years, rock art dating by that method has caused a significantly acrimonious but likely unnecessary debate. The present paper discusses the debate and hopefully provides the impetus to resolve the unwarranted controversy by showing how to constructively settle it.

Tang et al. (2020) reported the rock paintings at nine sites and site complexes across northern Heilongjiang Province. In most sites, these assemblages have relatively small numbers of motifs, generally < 100. Located on cliffs, they have limited or no protection from the weather. Thus, they have been assumed to have been painted relatively recently. The limited literature available on the longevity for rock paintings exposed to the elements (e.g. Trezise and Wright 1966; Donaldson 2012: 23–29) suggests that preservation is severely reduced relative to well-sheltered situations, especially deep caves. Rock paintings exposed to precipitation are thought to survive for only a few centuries in most cases. The absence so far of petroglyphs in Heilongjiang is puzzling, because they are quite common in neighbouring Inner Mongolia and on the Siberian side of the Amur River, which forms the border with Russia.

At two sites, Tayuan Rock Art Site, Xinlin District, and Tiantaishan Rock Art Site, Jagedaqi Forest, microerosion data provided maximum age estimates for rock paintings. In both cases, the painting pigments were applied to small panels that had formed when slabs exfoliated from granite tors in geologically recent times. The time for such an unloading event can be estimated from the amount of microscopic rounding (micro-wane formation) at fracture edges on quartz or feldspar crystals that fractured along the edge of the new surface formed. The paintings on such new panels must be more recent than the time the slabs detached. The findings were particularly important at Tayuan, because one of its two schematic zoomorphs had been suggested by local archaeologists to depict a rhinoceros. If that were correct, it would imply that it portrays a woolly rhinoceros, an extinct Pleistocene species.

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Two instances of very recent damage at the 'head' of the image, however, cause the pareidolic effect creating that impression. One flake scar truncates the lower end of the vertically arranged motif, while the other modification comprises four or five small impact scars by a metal tool. Together, they create the impression that the remaining pigment might depict a horn (Fig. 1). The panel's maximum age, 2000 years, however, contradicts this interpretation squarely, as does the exposed nature of the pictograms.

At two other Heilongjiang sites, samples of calcium carbonate re-precipitated over rock painting pigment layers were dated by ^{230}Th/^{234}U to estimate when these accretions had been deposited. At Yilin 2, in the Amur Forest northeast of Mohe, China, a vertical cliff of strongly metamorphosed schist is partly exposed to rainwater. A few paintings occur several metres above the ground, accessible by a relatively easy climb. An exfoliating rock fragment bearing both pigment traces and carbonate accretion was removed, YILIN-1, and a 6-mm core, YILIN-2, was drilled a few centimetres from the first sample.

At Mohe Station Rock Art Site, a small cliff lies on a steep hillside near Mohe. Carbonate precipitated from solution seeping through the poorly foliated schist partly covers the undecipherable red pigment traces. One sample (MOHE 1 + 2) consisted of two 6-mm cores removed from adjacent locations, while the other (MOHE 3) was a loose chip of bedrock bearing both pigment and accretion. John Hellstrom, Geology Department, University of Melbourne, Australia, analysed all the samples with ^{230}Th/^{234}U.

Fig. 1 Zoomorph recently modified to resemble a rhinoceros (centre). Tayuan Rock Art Site, Heilongjiang, China

Tang et al. (2020) reported that the red pictograms from Yilin and Mohe had been exposed to precipitation and had experienced degradation (partial mobilization) by both meteoric and interstitial vadose water. As they would not survive these conditions for more than a very few centuries at the most, they were thought to be relatively recent. The sampled thin carbonate accretions, mostly < 1-mm thick, occurred over the pigment layers and, therefore, must be even more recent. For the two Mohe samples, the carbonates, however, yielded 'raw' estimates of 32.9 ka and 35.3 ka, respectively, and the 'corrected' ages are 0–28 ka and 0–30.6 ka (corrected as per Hellstrom 2006). Yilin 1 and 2, both from the same lamina, produced ^{230}Th/^{234}U estimates of 23.1 ka and 134.6 ka, respectively, 'corrected' to 7.6–20 ka and 0–113 ka. Not only does the significant incongruity exist between the two Yilin results for the same calcite skin; the primary inconsistency is between their apparent Pleistocene provenance and their realistic attribution to most recent centuries (Table 1, from Tang et al. 2020).

The U/Th controversy

The difficulties with securing credible ^{230}Th/^{234}U age estimates from carbonate accretions related to rock art are not a new phenomenon. In 1981, the first ^{230}Th/^{234}U ages for deposits associated with rock art were presented (Bednarik 1984, 1985, 1986a, 1997, 1998, 1999, 2001, 2012). A substantial carbonate deposit on the ceiling of Malangine Cave, South Australia, ~15-mm thick, that concealed, as well as bore, petroglyphs, had exfoliated naturally, providing an unusually large quantity of sample (Fig. 2). It yielded a ^{230}Th/^{234}U estimate of 28.0 ± 2.0 ka, which would represent a very conservative minimum age for the petroglyphs under the speleothem, and a similarly conservative *terminus post quem* date for the petroglyphs added on the surface of the carbonate accretion. A bulk carbon ratio from the same sample, however, however, yielded 5550 ± 55 years BP (Hv-10241) (Bednarik 1984). The two methods were used in tandem specifically to test one against the other. The ^{230}Th/^{234}U result, impossible to reconcile with the corresponding ^{14}C result, remained unreported for several years, while an explanation was sought for the apparent mismatch. A sample from a stratigraphically *earlier* coralline speleothem yielded a *lower* ^{14}C date of 4425 ± 75 years BP (Hv-10240) which matched perfectly with a corresponding ^{230}Th/^{234}U age of 4.3 ± 0.5 ka.

Similar disparities were subsequently reported by all other researchers who also analysed such samples by both methods. Bard et al. (1990) recorded a considerably smaller discrepancy than had emerged at Malangine Cave. In their experience with corals from Barbados, until about 9.0 ka, ^{14}C and ^{230}Th/^{234}U dates matched reasonably well, but beyond that range, the ^{230}Th/^{234}U ages become increasingly higher, reaching a

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Table 1 Series of four $^{230}Th/^{234}U$ dating attempts of re-precipitated calcite samples from rock art sites in northern Heilongjiang, determined by John Hellstrom (from Tang et al. 2020)

Sample →	YILIN-1	YILIN-2	MOHE 1/2	MOHE 3
Lab number	UMD190211-409	UMD190211-414	UMD190211-418	UMD190211-433
U(ngg^{-1})	1227	1454	1821	3456
[$^{230}Th/^{238}U$]^{a}	0.258 (11)	0.749 (11)	0.405 (12)	0.4446 (24)
[$^{234}U/^{238}U$]^{a}	1.3383 (127)	1.0479 (37)	1.5306 (71)	1.5780 (19)
[$^{232}Th/^{238}U$]	0.2605 (34)	1.296 (14)	0.4771 (60)	0.4616 (64)
[$^{230}Th/^{232}Th$]	0.99	0.58	0.85	0.96
Age (ka)^{b}	7.6–20	0–113	0–28	0–30.6
Raw age (ka)^{c}	23.1 (1.1)	134.6 (4.1)	32.9 (1.1)	35.34 (0.23)

[a] Activity ratios determined after Hellstrom (2003) and Drysdale et al. (2012)

[b] Corrected age range at the 95% confidence level in ka using Eq. 1 in Hellstrom (2006), the decay constants of Cheng et al. (2013) and a [$^{230}Th/^{232}Th$]$_i$ range of 0.15–0.69 (Yilin) or 0.15–1.02 (Mohe)

[c] Uncorrected $^{230}Th/^{234}U$ age in ka calculated using the decay constants of Cheng et al. (2013)

maximum difference of ~ 3.5 ka at ~ 20 ka. Next, Holmgren et al. (1994) conducted the same experiment with a late Pleistocene stalagmite from Botswana. They also reported that 'at least one of the dating series does not reflect the true growth ages'. The deviation increases rapidly with age, they noted, 'resulting in a discrepancy of 20,000 years at the $^{230}Th/^{234}U$ age of 50,000 years'. Unlike the previous studies, these authors believed that the $^{230}Th/^{234}U$ ages were more reliable.

The endeavours by Labonne et al. (2002) helped to define the difficulties in dating dirty speleothem calcite of Holocene or latest Pleistocene age. Their investigation of the flowstone deposit sealing the Magdalenian occupation layer in Altamira Cave, Spain, found that, contrary to their expectations, ^{14}C ages yielded the most precise estimates for its deposition time. Their comparison between ^{14}C and $^{230}Th/^{234}U$ ages (Labonne et al. 2002: Table 2) suggests that those dating at 10 or 12 ka are still reasonably similar, but there is a distinct divergence in older materials, just as Holmgren et al. (1994) had found.

Plagnes et al. (2003) reported results closely resembling those obtained in Malangine Cave. Sample Bor2 from a deposit concealing a hand stencil in the cave Gua Saleh in Borneo yielded a $^{230}Th/^{234}U$ age of 27.32 ± 0.21 ka, whereas its ^{14}C age fell between 9.90 and 7.84 ka BP (with a dead carbon correction of 5% and 20%, respectively). As in the Australian case over two decades earlier, when the age discrepancy was attributed to the rejuvenation of a porous deposit by the deposition of younger solute as well as the unreliability of the $^{230}Th/^{234}U$ ratio, Plagnes et al. (2003: 172) also ascribed it to 'disturbance of Th/U and/or ^{14}C geochemical systems, showing the limits of the geochronological approach applied to this kind of material'. They ascribed the U concentration and $^{234}U/^{238}U$ activity ratios to 'open system conditions'. Just as in Malangine Cave, one of their several samples showed concordant ages for the two methods.

Taçon et al. (2012) also employed both methods in their work in the Baiyunwan Rock Art Site in Yunnan Province, China. They managed to analyse subsamples from both above

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Fig. 2 Petroglyphs on the ceiling of Malangine Cave, South Australia, emerging after natural exfoliation of speleothem skin. The accretionary carbonate bears much younger engravings on its surface. Scale intervals 10 cm, photograph 1981

Table 2 The results of the four Yunnan samples by the Xi'an laboratory

Sample →	MR-1	HY-1	YDG-1	YDG-2
$^{238}U_{(ppb)}$	1359.2 ± 5.9	1199.0 ± 6.7	159.8 ± 0.5	156.0 ± 0.4
$^{232}Th_{(ppt)}$	17,716 ± 363	147,830 ± 3067	33,257 ± 669	16,311 ± 328
$^{230}Th_{(atomic)}$	29 ± 1	7 ± 0	7 ± 0	27 ± 1
$\delta^{234}U_{(measured)}$*	514.6 ± 5.8	3.6 ± 5.5	− 130.7 ± 2.9	− 129.9 ± 3.3
$^{230}Th/^{238}U_{act}$	0.0231	0.0543	0.0901	0.1693
^{230}Th $_{age(uncorrected)}$	1675 ± 26	6063 ± 79	11,966 ± 279	23,733 ± 1075
^{230}Th age$_{(corrected)}$	1425 ± 179	2428	4740	20,143
$\delta^{234}U_{initial(corrected)}$	517 ± 6	4 ± 6	− 132 ± 3	− 138 ± 4
^{230}Th age$_{(corrected)}$, in years	*1359 ± 179*	*2362 ± 2573*	*4674 ± 5118*	*20,077 ± 2742*

and below a paint layer, subjecting eight of them to $^{230}Th/^{234}U$ analysis and five to ^{14}C AMS tests. The subsamples analysed by $^{230}Th/^{234}U$ all had low $^{230}Th/^{232}Th$ ratios, indicating contamination by detrital ^{230}Th. Those from above the paint ranged in age from ~ 7.17 to ~ 13.96 ka and those from below it yielded 11.33 to 11.98 ka. The corresponding ^{14}C results were more consistent. Three collected above the paint were clustered around 4.5 BP; the two below it produced dates of ~ 10.3 and ~ 10.6 ka BP. After correction for detrital Th, the painting was reported to be anywhere between 15.4 and 3.4 ka BP old. Taçon et al. (2012) attributed the uncertainties to U depletion, detrital ^{230}Th occurrence and the presence of 'dead' carbon. Next, Fontugne et al. (2013) also combined $^{230}Th/^{234}U$ and ^{14}C analyses in their work in Capivara National Park, Brazil, and detected distorting geological material.

In Nerja Cave, Spain, secondary calcite skin covering a dot of red pigment yielded a $^{230}Th/^{234}U$ age of between 60 and 56 ka and ^{14}C age between 33 and 27 ka cal BP (Quiles et al. 2014; Sanchidrián et al. 2017; Valladas et al. 2017). This resembles the discovery by Holmgren et al. (1994) noted above of a $^{230}Th/^{234}U$ age of 50 ka but a corresponding ^{14}C age of ~ 30 ka. Bednarik (1984, 1997), Bard et al. (1990) and Plagnes et al. (2003) all reported similar situations. Particularly striking were the samples GN13-15 and GN13-17 from Nerja Cave, collected from above and below a charcoal mark previously dated by ^{14}C to ~ 20–18 ka (Sanchidrián et al. 2017). Not only were they much too high for late Upper Palaeolithic rock art but they were also stratigraphically inconsistent. The older sample produced a $^{230}Th/^{234}U$ date of 86.9 ka; the sample younger than the charcoal layer yielded 118.9 ka (Pons-Branchu et al. 2020). Of even more concern is that the observed inverse relationship between U concentration and the age (or the $^{230}Th/^{234}U$ ratios) these authors report for their samples also applies to some results secured by the Pike-Hoffmann team. It could be due to the transformation of aragonite to calcite or U remobilization by water.

The studies employing both $^{230}Th/^{234}U$ and ^{14}C have, therefore, provided consistently similar findings since the early 1980s. Holocene age estimates secured by the two methods tend to be comparable, but for sites older than the very early Holocene, the $^{230}Th/^{234}U$ ages become progressively higher, until, at ^{14}C age of about 30 ka, the $^{230}Th/^{234}U$ results can be as much as ~ 60 ka. Thus, numerous authors have commented on the need to explain the discrepancies (e.g. Bednarik 2012; Clottes 2012; Pons-Branchu et al. 2014; Sauvet et al. 2015; Aubert et al. 2018; White et al. 2020). This is not, as claimed by some, a competition between the two dating methods. If the very early $^{230}Th/^{234}U$ results were right, it would negate the archaeological chronology of much of the Late Pleistocene, which is largely based on thousands of ^{14}C dates. This would defeat the quest of those who cite $^{230}Th/^{234}U$ ages to show that Neanderthals created rock art: if the ^{14}C dates were too young, as they claim, it would only prove that Neanderthals disappeared much earlier than widely thought.

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Placing the controversy into context

A controversy has developed since the early years of the twenty-first Century, beginning with the claims to have found Pleistocene cave art in some of the Creswell Crags caves in England, especially in Church Hole (Bahn et al. 2003). To reinforce these claims, $^{230}Th/^{234}U$ analysis was applied to a thin calcite deposit near one of the images attributed to the Pleistocene, motif No. CH19. The speleothem however, covers no part of that motif and is, therefore, irrelevant to the issue (Wilson 2018). At over 13 ka, that result is probably also too old, as Pleistocene results of the method appear to be.

From this project emerged the practice of exclusive use, i.e. without testing it by another method, of $^{230}Th/^{234}U$ of dating cave art (e.g. Pike et al. 2017). Concomitantly, some of the proponents also developed a predilection of rejecting competing claims of very early cave art elsewhere, especially that of Chauvet Cave, France (Pettitt and Bahn 2003; Pettitt et al. 2009). Possibly the most extreme proposal was that a rectangular painted motif in La Pasiega, hand stencils in Maltravieso and red pigment traces in Ardales, all in Spain, are at least 65-ka old (Hoffmann et al. 2018a). However, the tripartite rectangular motif at La Pasiega, considered widely to be of the

Magdalenian tool industry, has yielded three minimum ages by ^{230}Th/^{234}U analysis: 3.07, 12.60 and 64.86 ka (Hoffmann et al. 2018a). Here and elsewhere, these authors selected the oldest of a series of results they secured, discounting the others. Similarly, the minimum raw age of the Yilin 2 motif, of ~134 ka, could have been promoted as the earliest known for painted rock art.

While the people arguing for using only ^{230}Th/^{234}U have rejected all objections, their opponents have failed to provide conclusive evidence for the unreliability of the method. Their argument that these results contravene all of the conventional archaeological understanding of Palaeolithic cave art is not relevant to the ^{230}Th/^{234}U use advocates, who after all are dedicated to overturning that understanding. Their ultimate aim is to negate the almost universal archaeological belief that the hominins called Neanderthals produced no rock art. The flaw in this preoccupation is that its proponents seem unfamiliar with the relevant literature. Rock art and other palaeoart productions by robust *Homo sapiens* subspecies, including 'Neanderthals', have long been known. Capitan and Peyrony (1921) (Peyrony 1934) excavated a Neanderthal infant's interment (grave No. 6) in La Ferrassie, France. It was covered by a sepulchral limestone slab bearing 18 cupules (spherical cap-shaped petroglyphs), mostly arranged as pairs. Proof does not come much better than that. The single decorated chamber of Baume Latrone, France, 240 m from the cave's entrance and of difficult access, comprises widely separated traditions. The oldest are finger flutings, about four times as old as the most recent engravings, still of the Palaeolithic (Bednarik 1986b). In Gorham's Cave, Gibraltar, a deeply engraved design of eight lines was excavated below a layer dated by ^{14}C to ~39 ka BP, at which time the site was occupied by Neanderthals (Rodríguez-Vidal et al. 2014). Panels 1 and 2 in Zarzamora Cave, Spain, feature simple petroglyphs that might also be the work of robust *H. sapiens* (Collado et al. 2016).

Furthermore, the finger flutings of the 'Olschewian' (montane Aurignacian) in the Drachenhöhle, Austria, are likely to have been made by Neanderthal children, because the only human skeletal remains reported from this tradition are robust *H. sapiens* (Bednarik 2019). Moreover, if the proposition that all Early Upper Palaeolithic tool traditions are by Neanderthaloid hominins is correct (Bednarik 2007), a good deal of Eurasian rock art and portable palaeoart should be assumed to be the creation of Neanderthal-like humans. Therefore, the endeavours by the people arguing for using ^{230}Th/^{234}U only to prove what has long been established, that robust *H. sapiens* produced rock art, can only be counterproductive.

The stance expressed in Pike et al. (2017) and their refusal to test results of a method against those of another is anathema to science: testing is not only tolerated; it is favoured. It is quintessential to progress in science, and averting it negates the scientific process. In this paper, we present an effort of testing the proposition that 'U–Th is the way to go' (Pike et al. 2017). The demands to subject to testing the ^{230}Th/^{234}U results secured from a large number of sites (Pike et al. 2012; Hoffmann et al. 2016a, b; Pike et al. 2017; Hoffmann et al. 2018a, b, c) have so far not resulted in the testing of one single result. The opponents of the exclusive ^{230}Th/^{234}U use to date thin calcite skins formed by water flow have explained their objections in considerable detail (Bednarik 2012; Clottes 2012; Pons-Branchu et al. 2014; Sauvet et al. 2015; Aubert et al. 2018; White et al. 2020). They have not, however, been able to test any of the contested results, which would be virtually impossible to accomplish without the full cooperation of the ^{230}Th/^{234}U advocates. The latter seem to perceive the debate as a contest between two different methods (see, e.g. Pike et al. 2017), which it most certainly is not. All methods in rock art age estimation are experimental (Bednarik 1996, 2002). Some are no doubt more reliable than others, but that remains to be established. The universal demand for testing all scientific propositions clashes with the refusal of the exclusive ^{230}Th/^{234}U use supporters to consider such procedures, by whatever methods.

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According to the policies and practices of the International Centre for Rock Art Dating (ICRAD) at Hebei Normal University, China (Bednarik 2017), a fundamental prerequisite in direct dating of rock art is that another researcher can try to duplicate (or refute) the reported results. There are two ways such propositions can be tested, by either using the same or an alternative method. To facilitate testing in the first case, the *dating criterion* (e.g. a micro-wane) must be described in such a way that the second researcher can re-locate it reliably. In the second case, only the rock art motif needs to remain identifiable. ICRAD applies these simple principles to govern the records that must be provided for direct rock art age estimates. For ^{230}Th/^{234}U analysis, the results may not be testable, because the sample often is destroyed during the analysis. A second sample collected from the same deposit may provide a different result, because the U concentrations in coeval calcite skins can vary by >100% on a millimetre scale (e.g. Hoffmann et al. 2009). This high degree of variability, reminiscent of the failed cation-ratio dating of rock art (Bednarik 2001), remains a primary reason for difficulties in ^{230}Th/^{234}U dating of thin carbonate accretions. Thus, if the sample had been collected a few millimetres from the sampling spot chosen, the analysis might have yielded a very different age. Like Hoffmann et al.'s (2009) finding, YILIN-1 and YILIN-2 from the same deposit at Yilin 1, Heilongjiang, gave different ages. Hoffmann et al. (2018a) also secured three very different dates from the rectangular motif in La Pasiega, as noted above. These examples illustrate the fortuitous nature of such results, attributable to the taphonomic history of the analysed material and the variability of the dating criterion (the ratio of ^{230}Th/^{234}U). The ratio at the time of initial sample precipitation, which needs to be known to estimate age, is in fact unknown. Several processes can significantly affect the present ratio, among them mobilization of uranium by moisture, contamination by detrital Th, the inclusion of geological material in the samples and transformation of aragonite to calcite (Mancha Flores 2011; Lachniet et al. 2012; Bajo et al. 2016).

Nonetheless, the exclusive ^{230}Th/^{234}U results are not scientific because, in effect, they cannot be tested currently. Their advocates reject testing categorically (Pike et al. 2017). They are right in arguing that there are significant issues also with the method many have suggested to use in tandem, ^{14}C determination of the same samples. This uncertainty does affect the integrity of this form of testing. To render the limestone soluble, an excess of carbon dioxide is necessary, causing less than 50% of the bicarbonate's carbon to be derived from the carbonate and thus practically ^{14}C free. The method of estimating the proportion of ^{14}C that should have been precipitated in a deposit was conceived by Franke (1951a, b). Subsequent research (Franke 1967; Franke et al. 1958; Geyh 1969; Hendy 1969; Franke and Geyh 1970) suggests encouraging reliability for samples from stalagmites but less so for other speleothems. ^{14}C ages have been obtained of up to 45,000 years, but they are burdened with a potential error because the initial ^{14}C concentration is not derived from the atmospheric ^{14}C/^{12}C ratio alone. A surplus of carbon from the atmosphere is necessary, and while this surplus may theoretically be up to 100% (equivalent to an error of about 5000 years), the carbon content in natural bicarbonate solutions ranges only from 70 to 80%, equivalent to an error of fewer than 1500 years. Even this can be diminished dramatically if the ^{14}C/^{12}C ratio in the modern vadose water is determined. Then there is the potential infiltration of a younger solution and the interstitial deposition of further carbonate, which is why this work with ^{14}C was focused mainly on dense, crystalline stalagmites. Rock art, unfortunately, is very rarely associated with such speleothems and occurs most frequently with porous or thin accretionary 'veils' that tend to be of complex taphonomies.

The isotopic composition of the atmospheric carbon also presents various uncertainties, considering that plant communities have a significant effect on the δ^{13}C value of the re-precipitated carbonate. Cole and Monger (1994) report values of -12 to -10‰ from respiratory carbon dioxide derived from C3 plants, while the δ^{13}C compositions of carbonate in equilibrium with carbon dioxide respired from C4 plants range from -3 to $+1$‰ (cf. Robinson 1994). However, despite the many complications with ^{14}C analysis of carbonate skins, it remains the more reliable method (Bednarik 1984; Labonne et al. 2002; Taçon et al. 2012; Pons-Branchu et al. 2020). Other methods, too, could be engaged to test ^{230}Th/^{234}U results, such as thermoluminescence and ^{235}U/^{231}Pa disequilibrium techniques—provided the initial concentrations of Th and Pa are well constrained, and the system has remained closed to a post-depositional exchange of U, Th and Pa. Sensitivity of age error to uncertainties in the initial ^{230}Th/^{232}Th ratio decreases with increasing U concentration, increasing age and decreasing detrital contamination (Dorale et al. 2007). ^{230}Th/^{234}U very probably shares the reliability of ^{14}C dates from stalagmite formations, precisely for the same reasons (Drysdale et al. 2004, 2005, 2007). The literature of the applications of the method in many different fields provides ample evidence of the method's utility, but its application to thin carbonate accretions subjected to occasional water flow should be considered very problematic. A recent example of meticulous use of ^{230}Th/^{234}U analysis is provided by Hongxia et al. (2019), who dated with it a series of stalagmites on the floor of Xinglong Cave, China.

Testing the ^{230}Th/^{234}U method

Several studies have attempted to test the efficacy of ^{230}Th^{234}U analysis in determining the age of re-precipitated authigenic carbonates, including several cases related to rock art. This was done by comparing the results with those secured by ^{14}C analysis of sample splits. The practitioners favouring the ^{230}Th/^{234}U method have contended, justifiably, that there are difficulties also with that second method, although it needs to be mentioned that these are perhaps better understood. They are, however, also ignoring the potential of alternative methods to check the ages of carbonates, such as have been explored in work on corals (e.g. Obert et al. 2018), including Pa and Ra isotope analyses. Moreover, evasion of falsifiability of results contravenes one of the most basic principles of science: that it must be possible to establish that a proposition is false. Perhaps a contradictory ^{14}C result does not necessarily falsify a ^{230}Th/^{234}U result, but how would one then test it? Three possibilities are considered:

1. Delimiting realistically possible age ranges by archaeological reasoning or potential other methods
2. Multiple sampling of the same deposits to better understand the degree and causes of local variability deriving from the complex taphonomy of thin calcite skins
3. 'Blind testing' of results by soliciting multiple analyses of samples by different laboratories

A basic comprehension of the realistic age range, either of the deposit or the rock art physically related to it, can be much help. In the case of the Heilongjiang ^{230}Th/^{234}U results, it was palpably manifested that they were all incompatible with contextual archaeological expectation (Table 1). The vast differences are very probably attributable to the occasional wet condition of the sites, as documented in Tang et al. (2020). This is likely to cause depletion of U in the repeatedly recycled carbonate. There is also the definite possibility of Th

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enrichment from a clay fraction mobilized by the solvent. Both factors would result in excessively high 'ages'. This cannot be a characteristic typical only for the Heilongjiang cliff sites, because the thin surface 'veils' commonly found in limestone caves can be just as susceptible to solution, re-precipitation and deposition of detrital fractions travelling with the bicarbonate solution. Even if these speleothem skins seem dry today, they were just as vulnerable to modifications at any time in their history. The Yilin 2 and Mohe precipitates only took a very short time to accrue enough changes to register an apparent age many hundreds of times their real antiquity. The number of such changes a speleothem many thousands or tens of thousands of years old might experience could be just as high.

Crosschecking by different methods is well established in Chinese archaeology (and elsewhere), where it is known as the 'double-evidence method'. For instance, archaeological materials and historical documents are frequently compared. Typical recent examples of this approach in rock art research are provided by Li et al. (2020), correlating ^{14}C results with historical texts, or Jin and Chao (2020), using historical sources to test microerosion data.

Using multiple sampling has shown that two samples of the same deposit at the Yilin 2 site can yield dramatically different results. Sample YILIN-2 returned a raw age about 580% greater than YILIN-1, although the two should be identical, having been collected only centimetres apart. An even more significant discrepancy has been reported by Hoffmann et al. (2018a), who found the oldest date from a superimposed accretion at La Pasiega to be about 21 times greater than the youngest (although these are not necessarily from the same deposit). Their response was to select the earliest date and discard the others as 'too young'. Multiple sampling of apparently uniform laminae is needed, if only to establish a better understanding of the taphonomy of thin carbonate speleothems.

Dating splits in two different laboratories was applied to four samples from a cave containing rock paintings in Yunnan Province, southern China. They came from a series of 20 samples collected, in most cases from above painting pigment, and were subjected to ^{230}Th/^{234}U analysis. Four samples were analysed at the Isotope Laboratory of the Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an, Shaanxi Province, China, while the second set of sample splits was analysed at the ^{230}Th/^{234}U Laboratory at the Geology Department of the University of Melbourne, Australia. The duplicate samples were all 6-mm cores taken at immediately adjacent locations, and none of the samples was crushed or mixed. If ^{230}Th/^{234}U analysis were reproducible, analyses from two (or more) laboratories processing sample splits would, using the same method, produce similar results. For instance, if differences between results were treatment-derived, it would only indicate that age estimates are random functions of treatment or protocol. Comparing the two data sets from the four Yunnan samples reveals no correspondence whatsoever (Tables 2 and 3). The results are reproduced here as provided by the laboratories, to illustrate that even reporting protocols differ significantly. They also show that three of the dates are negative ages, which are absurd but derive from the literal interpretation of the data.

Conclusions

It was tested if ^{230}Th^{234}U analyses of thin accretionary deposits of carbonate provide reliable minimum or maximum dates for rock art associated with such precipitates. It has been proposed that the dependability of such dates renders testing by any other method superfluous. Bearing in mind that this method can never actually date rock art (at best it could provide minimum or maximum dates), such reliance on one method discourages the development of alternative dating methods. The International Centre for Rock Art Dating considers that *rock art dating is only scientific if the results can be reproduced*, be it with current or future technology. Those of ^{230}Th/^{234}U analysis are not testable because the sample is sacrificed in the process and cannot be reanalysed. Moreover, the available evidence indicates great variability in isotope concentrations at a micro-level, suggesting that results are largely fortuitous, determined perhaps by the taphonomy of the authigenic carbonate deposits.

Results of projects that have in the last four decades used both ^{230}Th/^{234}U analysis and ^{14}C assays reveal a distinctive trend in inconsistencies. While late and middle Holocene

Table 3 The results of the four Yunnan samples by the Melbourne laboratory

Sample →	MR-1	HY-1	YDG-1	YDG-2
$^{230}Th/^{238}U_{act}$	0.10325	0.05866	0.13817	0.06117
2σ	0.00249	0.00103	0.00190	0.00066
$^{234}U/_{238}U_{act}$	0.8722	1.0074	0.8676	0.8651
2σ	0.0037	0.0022	0.0024	0.0014
$^{232}Th/^{238}U_{act}$	1.018E−01	1.440E−01	1.493E−01	3.832E−02
2σ	2.0E−03	2.9E−03	3.0E−03	7.7E−04
$^{230}Th/^{232}Th_{act}$	1.0	0.4	0.9	1.6
$^{230}Th/^{232}Th_{act}(i)$	1.5	1.5	1.5	1.5
2σ	1.5	1.5	1.5	1.5
Age corr. ka BP	− 7.87	− 20.68	− 15.07	0.45
2σ	23.19	30.37	38.56	7.76
$^{234}U/^{238}U_{act}(i)$	0.8749	1.0070	0.8729	0.8649
2σ	0.0089	0.0022	0.0139	0.0033
Age corr. ka BP	*− 7*	*− 20*	*− 14*	*0.4*
(± 95%)	+ 21/− 26	+ 26/− 35	+ 33/− 45	7.7

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Table 4 Comparison of the raw ages of four samples provided by two laboratories; all ages in ka

Sample	MR-1	HY-1	YDG-1	YDG-2
Laboratory 1	1.359 ± 0.179	2.362 ± 2.573	4.674 ± 5.118	20.077 ± 2.742
Laboratory 2	− 7 + 21/− 26	− 20 + 26/− 35	− 14 + 33/− 45	0.4 ± 7.7

results tend to match reasonably well, early Holocene and older $^{230}Th/^{234}U$ ages are significantly higher. By about 30 ka derived from ^{14}C, corresponding $^{230}Th/^{234}U$ results in the order of twice that much. If this trend were an indication that Pleistocene radiocarbon ages are systematically too low, the chronology of the Upper Palaeolithic would need to be rewritten in its entirety.

Three ways to test the results from $^{230}Th/^{234}U$ analyses have yielded no evidence that their results are reliable. If two samples are collected from the same calcite skin, millimetres apart, the outcomes may differ radically. This could be due to laboratory error or local variations in the taphonomic history of the speleothem. Samples collected from very recent deposits have yielded Pleistocene dates, including one from the end of the Middle Pleistocene. Finally, we have demonstrated that different laboratories may provide vastly different age estimates for split samples (Table 4).

On the basis of these findings, it is suggested that, although some samples have provided what are considered to be credible $^{230}Th/^{234}U$ results, the only way to determine their credibility is by recourse to alternative approaches. These may derive from context, or there may be other dating methods. Presenting extraordinary dating results by rejecting all of the available options of testing deprives science of its most valuable asset: falsifiability. Since the experiments conducted in such work are not repeatable, they are of limited interest to science.

Invasive dating methods of rock art need to be regarded as primitive, and we should strive to phase them out. Further methods that involve no damage to the rock art or its support need to be developed, in addition to those already in use. Continuing reliance on outdated techniques contributes to neglecting the advancement of better methodology. Already some site management agencies are beginning to curtail physical sampling, or at least consider doing so.

In summary, we advocate the following precautions for future work with this method, particularly in connection with rock art age estimation:

1. $^{230}Th/^{234}U$ samples of thin accretions of calcite speleothem should be obtained from at least two adjacent locations to assess local variations in the deposit.
2. Splits of samples should be processed in blind tests at different laboratories.
3. In situ binocular microscopy of the accretions is essential, and photographs of cross sections of the calcite accretions as well as SEM/EDXA analyses would be useful.
4. As in all analytical work with rock art, destructive sampling needs to be avoided, and the development of further non-intrusive methods in addition to those now in use (e.g. microerosion analysis) is to be encouraged.
5. Experimental rock art dating results provide no support for paradigm-changing hypotheses—even if these happen to be valid.

Acknowledgements We thank the Propaganda Department of Daxinganling Prefectural Committee of Heilongjiang for initiating and supporting this project and Dr. John Hellstrom at Melbourne University for analytical work crucial to this project. This paper describes one of the research achievements of the Chinese National Social Science Foundation project 'Scientific and technological dating of rock art in the Upper Palaeolithic of the Jinsha River' (Grant No. 18BKG004).

Funding Tang Huisheng has received funding from the Chinese National Social Science Foundation project 'Scientific and technological dating of rock art in the Upper Palaeolithic of the Jinsha River' (Grant No. 18BKG004). No other funding has been received.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request. Data concerning Heilongjiang rock art are available from Tang et al. (2020).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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