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Review

Direct Dating of Chinese Immovable Cultural Heritage

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Abstract: The most extensive corpus of ancient immovable cultural heritage is that of global rock art. Estimating its age has traditionally been challenging, rendering it difficult to integrate archaeological evidence of early cultural traditions. The dating of Chinese rock art by 'direct methods' began in the late 1990s in Qinghai Province. Since then, China has acquired the largest body of direct dating information about the rock art of any country. The establishment of the International Centre for Rock Art Dating at Hebei Normal University has been the driving force in this development, with its researchers accounting for most of the results. This centre has set the highest standards in rock art age estimation. Its principal method, microerosion analysis, secured the largest number of determinations, but it has also applied other methods. Its work with uranium-thorium analysis of carbonate precipitates in caves is of particular significance because it tested this widely used method. The implications of this work are wide-ranging. Most direct-dating of rock art has now become available from Henan, but results have also been reported from Heilongjiang, Inner Mongolia, Ningxia, Jiangsu, Hubei, Guangxi, Yunnan, Qinghai, Tibet, and Xinjiang. Intensive work by several teams is continuing and is expected to result in a significantly better understanding of China's early immovable cultural heritage.

Keywords: rock art; petroglyph; microerosion dating; radiocarbon dating; uranium–thorium dating; China

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1. Introduction

Immovable cultural heritage occurs throughout the world and in many forms, of which rock art is the most numerous of manifestations. In the case of China, the connection between rock art and other such heritage is particularly important because features such as statues, religious and secular structures or rock inscriptions of known ages have been used extensively to calibrate the direct dating of rock art. Estimating the ages of rock art is one of the most challenging tasks of archaeology and is riddled with controversies [1]. Many approaches have been tried, and it has become evident that the methodology of 'direct' dating is the most dependable of them. It is characterized by a direct physical relationship between the rock art in question and the dating criterion, and the falsifiability of the propositions concerning that relationship.

A wide range of potential 'dating criteria' has been appraised, but there are difficulties with many of them. Most importantly, the demand for falsifiability renders it is essential that the analysis should be repeatable: another researcher must be able to test the claim by repeating the experiment. Such replication is not possible with many methods proposed or already used because they involve the removal of physical samples that are sacrificed in the process of analysis. Such methods may also be challenged on ethical grounds by arguing that these interventions damage the integrity of the rock art or its relationship with contiguous features, such as mineral accretions. Examples include extracting carbon-bearing substances contained in rock art paint residues, cations present in rock varnishes covering petroglyphs, or determining the nature of uranium and thorium components of reprecipitated carbonates. Many of these applications are severely hampered by the significant variations of the concentrations of the dating criteria elements in coeval mineral skins on a millimetre-scale, which may be well above 100% [2,3]. For instance, the method of cation-ratio dating of iron and manganese-rich mineral accretions has long been discredited [4], and the uranium-series analysis of speleothem skins is currently under intensive review (see below).

The topic of rock art age estimation in China was first reviewed over three decades ago [5], and given the significant progress made in this field since then, it is worthwhile assessing how much change there has been. It is notable that the first-ever academic report about Chinese rock art in a Western language only appeared in 1984 [6]. Since 1991, when a sizeable Australian delegation attended a rock art conference in Yinchuan, Ningxia Province, the collaboration between Chinese and Australian rock art researchers developed and eventually flourished. The status of rock art dating in China in 1991 was that such practices were then limited almost wholly to archaeological or indirect means, such as "presumed association with a dated sediment deposit, perceived stylistic connection, spatial association and similar" [5]. Much rock art 'dating' derived from the pareidolic 'identification' of presumed animal species depicted or from correlation with ancient documents, such as the *jia gu wen* (writing on tortoise shells or bones). Other indirect approaches were the perceived degree of weathering, presumably depicted activity themes, and alleged styles [7]. Only two examples of direct rock art dating were then known in China: radiocarbon dating of stalactitic deposit physically related to a rock painting at the massive Huashan site in Guangxi Zhuang Autonomous Region [8]; and the ^{14}C content of flowstone laminae and pollen in the underlying paint layer were determined at one of the rock painting sites at Cangyuan, Yunnan Province [6]. The Huashan motif appears to date from between 2370 and 2115 BP, but more recent analytical work at the site has suggested a somewhat younger age. The Cangyuan image seems to be approximately 3000 years old, an estimate that has recently been confirmed [9]. A careful assessment of the 57 U–Th and four AMS radiocarbon results secured from four Cangyuan rock paintings has suggested that the paintings seem to be between 3800 and 2700 years old. Excavation results from the sites corroborate this conclusion.

2. Introduction of Direct Rock Art Dating in China

These first two direct dating attempts of Chinese rock art refer to endeavors that were not testable by replicating the experiments on which they were based. The subsequent results were derived from Tang Huisheng, who, in 1997–1998, introduced the use of microerosion analysis in Qinghai Province [10]. He collected microerosion calibration data from three petroglyph sites: Shuixia, Lebogou and Kexiaotu. These were then used to place petroglyphs from three more sites chronologically: Lushan, Lumanggou and Yeniugou. These were found to be approximately E2000, E2300 and E3200 years old, respectively (the 'E' prefix indicates that the age estimate was derived from erosion data). Since these measurements are repeatable, they fully comply with the requirements of direct rock art dating (Figure 1). Tang then secured age estimates from three cupules at the Jiangjunya site at Lianyungang City, Jiangsu Province, ranging from E4300 to c. E11,000 years BP, using calibration obtained from a Buddhist inscription at nearby Kongwang Hill, dating from April 61 CE [11].

All methods currently used to estimate the ages of rock art are experimental, and that includes microerosion analysis [1]. However, that method offers significant advantages, such as full replicability and lack of physical intervention. Microerosion-derived age estimates of petroglyphs can only be approximate because precipitation can vary as a function of time. Therefore, in the present report, only approximate estimates are given (for proposed tolerances, see individual publications cited). Nevertheless, the results of seven 'blind tests' conducted in Russia, Portugal, Italy, Bolivia, Australia (2) and China matched archaeological expectations very well [12–18]. In terms of their magnitude, results from this method are fully reliable. Radiocarbon analysis, by contrast, can provide very precise results, but when obtained from rock art these may be entirely false. Those obtained from paint residues can only be accepted if the substance analyzed has been identified and separated, be it at the molecular or at the object level [19].

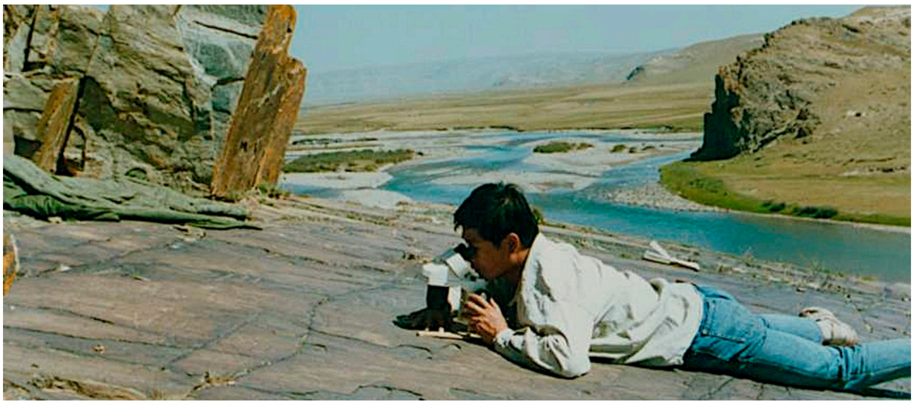

Figure 1. Tang Huisheng conducting the first replicable direct dating of rock art in China in 1997 at the Lushan petroglyph site in Qinghai Province (photograph by Gao Zhiwei, with permission).

The discovery of a major rock art concentration in Henan Province [20] prompted a very successful rock art dating expedition in that region and Ningxia and Jiangsu Provinces during June and July 2014 [21]. It utilized China's wealth of rock surfaces suitable for microerosion calibration, especially soundly dated rock inscriptions. Several calibration curves, as well as twenty-seven age estimates from petroglyphs, were secured. This work included testing previous archaeological age predictions for some of the best-known Chinese petroglyph complexes, such as those of Helanshan and Jiangjunya. For instance, there had been numerous age estimates for the famous Helanshan petroglyphs near Yinchuan, ranging from the Pleistocene to recent centuries, and based on various methods. The 2014 campaign furnished reliable estimates of E2000 to E2330 years BP.

On the other hand, the seven dates secured from the Jiangjunya site, 14 km west of Lianyungang, ranged widely, from about E369 to E5380 years BP, demonstrating the use of the site from Neolithic to recent historical times. Some of the site's many petroglyphs have been demonstrated to have been retouched after their initial creation. For example, Petroglyph 1 was made about E2210 years ago but was retouched some E360 years ago. Such reworking of a petroglyph cannot be readily identified by any other dating method. All age estimates of this campaign were again obtained by microerosion analysis and are thus repeatable. Now or centuries into the future, any researcher can locate the dated motif and even the specific micro-wane and re-measure it. This adds the benefit that future erosion rates can be determined.

The microerosion method endeavors to ascertain when crystals in the grooves of percussion grooves were fractured by impact during petroglyph production. At that time, the edges of these fractures were totally sharp, but erosion gradually rounds them at the microscopic level in a quantifiable process that is a function of time. The resulting micro-wanes reflect the time since the fractures occurred [12,13]. In contrast to most other known direct dating methods, it refers to criteria that are functions of actual age rather than minimum or maximum ages. It is also non-invasive and involves no contact with the rock art and there are no contaminating factors. The method even allows age determinations in the field. However, it also entails several disadvantages: it has so far only been applied to two minerals (quartz and feldspar); it requires minimum grain sizes of about 1.5 mm with fractures of about 90° between the cleavage surfaces, orientated so that the micro-wane faces the microscope; and the rock surface must have been exposed to precipitation ever since the petroglyph was created. Microerosion analysis provides very reliable but imprecise age estimates, with tolerances often in the order of 20–25%. The significant differences in rainfall in different environments can be accounted for by calibration against the microerosion of surfaces of known ages. In recent years a universal calibration has been created that is based on relative regional precipitation and can be applied where local calibration is not possible [22,23]. The only minerals calibrated so far are quartz and feldspar and the former is thought to have a range of up to maximal 50 ka.

In June and October 2015, rock art dating missions were undertaken in the Xinjiang, Inner Mongolia, Ningxia, Guangxi, and Henan provinces [18]. Although new age estimates were only secured from two of these regions, the expeditions provided an essential overview of the scale of Chinese rock art and the logistics of developing comprehensive approaches to its dating, as well as several other scientific data. More than any such work previously undertaken in China, these journeys impressed the need to develop flexible approaches utilizing multiple methods, with geomorphological procedures forming the most reliable core. Nevertheless, a series of five other microerosion estimates were secured from the Henan sites Xuanluoling, Taibailing and Paomaling, all forming part of the extensive Mt Juci complex. Of particular interest was determining the age of a mask/face petroglyph at Xiao Fengshan site in Inner Mongolia. This motif on rhyolite turned out to be late Neolithic at about E4730 +1400/−810 years of age. This was subsequently found to confirm the archaeological expectation that the area's face/mask images are of that period. However, there is no proof that this age estimate can be applied to all face/mask motifs of the region.

Another microerosion-based rock art dating program was undertaken in 2016 [24]. Five sites were investigated in Xianju County of eastern Zhejiang Province. They yielded fifteen microerosion results, including calibration from three surfaces of the Wufubei site complex. Several motifs at the Xiaofangyan and Songlongshan sites provided seven quite consistent dates ranging from E1200 to E1360 at the second site and slightly earlier results from the first.

The effects of the 2014 rock art dating campaign have led to developments beyond the provision of more credible rock art dates than any previous project. Most importantly, it persuaded Tang to establish the International Centre of Rock Art Dating and Conservation at the College of History and Culture, Hebei Normal University, Shijiazhuang.

3. The International Centre of Rock Art Dating (ICRAD)

This agency of Hebei Normal University was formally established on 16 June 2016 [25]. That university was chosen because it already possessed facilities for AMS radiocarbon, uranium–thorium and OSL analyses, three of the methods used in rock art dating work. The Centre will establish a comprehensive archive for global information on all direct rock art dating projects and results in the world since the early 1980s, and it will conduct its own research in age estimation of rock art in China. The ICRAD established a simple ground rule to ascertain the scientific integrity of records: they must be presented so that another researcher can try to duplicate (or refute) the reported results, be it by the same or another method. Therefore, the dating criterion must be described so that the second researcher can re-locate the criterion reliably. ICRAD also emphasizes the need to establish protocols that would stand the test of time and will not need to be significantly modified in the future.

To facilitate the implementation of these protocols, ICRAD has established a system of numbering each rock art age determination attempt with a unique code, much in the way radiocarbon dating results are identified. Without such a system, the growing mass of uncollated and incompatible data would eventually become unmanageable. ICRAD's direct dating register will eventually be made available publicly to facilitate its use globally.

Since the establishment of ICRAD, the efforts of direct-dating Chinese have continued unabated—in fact, they appear to be accelerating. In 2017, a large team conducted the first rock art dating program undertaken in Hubei Province, focusing on a mountainous area east of Tongbai [26]. Huai River rock art corpus includes numerous sites that generally resemble the Henan rock art to the north. Eight of them yielded age estimates, which in all cases derive from cupules. They all fall under 1270 years, ranging down to about 650 years, indicating that the extensive rock art complex is relatively young. The results of this work were interpreted according to the recently established universal calibration curve (UCC) [22,23].

A second team revisited petroglyph sites in the granite region of Fangcheng in Henan Province and secured a series of nine age estimates from the sites Fangshan 2 and 4, Zhangzhuang, Wushigou 2 and 4 [27]. The first site produced the earliest results from two zoomorphs that are between 4000 and 5000 years old. This was soon followed by the team's assessment of several sites at Lianyungang in Jiangsu Province during two field seasons [28]. The authors provided 14 microerosion age estimates from eight sites, including three results from two of the Jiangjunya sites. They ranged from E710 to E2020 years BP, broadly confirming that the area's petroglyphs cover a considerable period, but the majority is 1000 to 2000 years old. Calibration was secured from a rock inscription at Xioaxishan 1 site, which was also confirmed by the UCC recently established. This paper also introduced a local phenomenon, standing stones bearing petroglyphs that are very common in northern Chinese regions but rare further south. In Lianyungang, they are called *shiganma* (stone mother) and bear anthropomorphous petroglyphs. Jin and Chao studied eleven of them, managing to secure age estimates from four. These corresponded well with ancient literature and inscriptions.

Jin and Chao then presented the first rock art dating results from Liaoning Province in north-eastern China [29]. They investigated three site complexes featuring eight sites near Anshan City. The authors provided age estimates of three cupules from the site Bafen'gou and one each from cupules at Wangjiayu 1 and 2, ranging from E1140 to E2030 years. Of interest is their detection of KEM (kinetic energy metamorphosis [30]), which they had also reported previously from the granite of Wushigou 1 at Fangsheng [27]. KEM was only discovered in recent years but has since been investigated intensively [31]. It has been recognized as an essential tribological variable in the study of petroglyphs.

Most recently, the focus of rock art dating has turned to the Tibetan Plateau, specifically to Garze Tibet Autonomous Prefecture in Sichuan Province and Yushu Tibetan Autonomous Prefecture in Qinghai Province [32]. Twelve petroglyph sites were investigated in that area, featuring vast numbers of zoomorphs and more recent Buddhist rock inscriptions. Despite strenuous endeavors, only one dating could be extracted from the petroglyphs. It is from a geometric design at the Kewa site that was E2089 +218/−295 years old, i.e., most probably of the Han Dynasty.

Although most direct rock art dates from China were secured by microerosion analysis, it would be wrong to assume that no other methods were used or at least tried. For example, a project investigating cave art in Guangxi Region that found a tradition rich in feline depictions used ^{14}C analysis to estimate the ages of two types of material: charcoal applied in rock painting and the wax of a small beehive superimposed over paint residues [33]. The charcoal flakes in the white paint of a feline provided a date of 250 ± 30 years BP, and the beehive yielded 80 ± 30 years BP. This relatively recent tradition has been explained in terms of available ethnographic information provided by the Zhuang people of the region.

Another analytical method much used for rock art age estimation in China is one of the uranium-series techniques, determining the ^{230}Th/^{234}U ratio. It has been used predominantly in two regions, Yunnan, and Heilongjiang Provinces, but was recently also applied in Tibet. The method demands that the initial ratio of ^{230}Th/^{234}U at the sample formation must be known or determined. Thorium is not soluble in water under naturally occurring conditions, whereas uranium is, and the optimistic assumption is made that freshly formed carbonate precipitates are free of Th. The method was first introduced in rock art age estimation in 1981 [34] when it was found sometimes to provide significantly misleading results. In China, the method was first used at the Baiyunwan rock art site in Yunnan, yielding only inconsistent results, and the uncertainties were attributed to U depletion, detrital ^{230}Th occurrence and the presence of 'dead' carbon [35]. Tang collected samples from Jinshajiang sites in Yunnan, some of which were subjected to analysis by two different laboratories. Significant were the ^{230}Th/^{234}U results of the June 2017 ICRAD expedition to Heilongjiang Province, conducting the first scientific rock art research in

China's northernmost region [2]. Its results led to a fundamental reassessment of a method that had been the subject of scientific controversy for many years.

4. The Trouble with U–Th Dating of Rock Art

The first application of U–Th analysis to estimate the age of rock art relates to petroglyphs on the ceiling of Malangine Cave in South Australia [34]. A speleothem lamina covers one generation of them that in turn bears another tradition of petroglyphs, thus providing a minimum date for one and maximum date for the other. Its radiocarbon age was 5550 ± 55 years bp, but the sample's U–Th date was five times greater, 28.0 ± 2.0 ka. All subsequently dated similar carbonate speleothems subjected to both tests showed a similar pattern: the U–Th results were always older and, in most cases, significantly older than ^{14}C or archaeological estimates (Figure 2) [36–42]. Indeed, in two cases, both from China, the U–Th dates were more than one hundred times as old. A reprecipitated carbonate film at Yilin in Heilongjiang that can only be a few centuries old at most has provided a U–Th raw age of 134.6 ka, i.e., hundreds of times its realistic age [2]. An international team recently discovered a few hand and foot impressions of juveniles in a hardened travertine deposit at the Quesang Hot Spring site in Tibet. They correctly proposed that the age of these prints should approximate the rock's age, which must have been soft and still forming at the time they were produced. They secured U–Th 'dates' from the travertine that would place the age of the formation between 169 ka and 226 ka. On that basis, they claimed to have found the oldest known rock art globally, probably made by Denisovans [43].

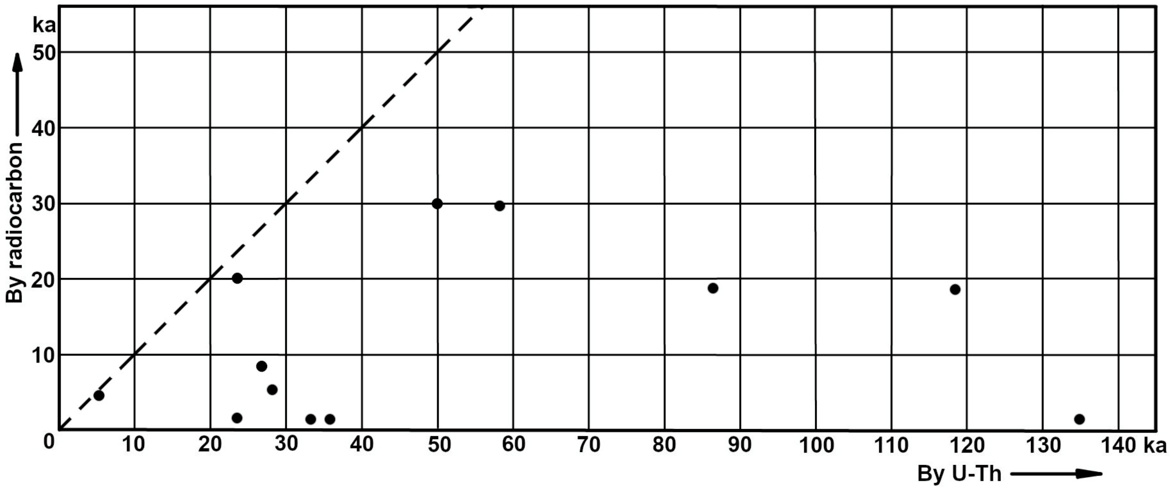

Figure 2. U–Th age determinations of speleothems compared with archaeologically realistic or radiocarbon ages of these same deposits.

This follows similarly spectacular claims from several cave sites in Spain, also based on U–Th data, that paintings thought to be of the late Upper Paleolithic were much older and were made by Neanderthals [44–46]. Due to these many concerns about the credibility of U–Th dates from non-crystalline reprecipitated carbonates, an intensive debate of the method when applied to thin or porous carbonates has developed over the last decade [47–56]. The primary cause of the excessive ages attributed to reprecipitated carbonate deposits is the depletion of U by moisture. Solution may also remove detrital Th, there may be a transformation of aragonite to calcite, or samples may be contaminated by components of the support rock [57–59].

Two other factors are of great concern. One issue needing more attention is the significant variation of U concentrations in coeval calcite skins demonstrated to occur on a millimetre-scale that may be greater than 100% [2,3]. The second concern stems from 'blind tests' we conducted due to the grossly incongruous U–Th results from Heilongjiang sites Mohe and Yilin 2 [2]. We split four samples from Yunnan Jinshajiang sites and submitted the two sets to two different U–Th laboratories [60]. Not only did this yield two entirely different sets of results, but the reporting protocols also differed profoundly. Moreover, three results produced negative values, probably attributable to significant leaching of U and other contaminating factors (Table 1). The stochastic distribution of the dates in Figure 2 suggests that the distortion is not systematic but seems to be a random function of taphonomic processes distorting the U–Th ratios. Most notably, the water-soluble U can be readily mobilized when the deposit is subjected to moisture. This frequently occurs with speleothems and even more so with travertine that is fully exposed to precipitation. Travertines are not dense crystalline formations like stalagmites; they have varying degrees of porosity which assists the reaction with carbonic acid to revert to their soluble (bicarbonate) phase.

Table 1. Comparison of the raw U–Th ages of four split 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

There are also a few more minor issues related to extraordinary claims of this nature about rock art. Although we have no reliable information on soft tissue dimensions of any robust humans, especially not on Denisovans, we assume that Neanderthals had thicker fingers than moderns, and we know that their feet differed from those of gracile humans [61,62]. The footprints at Quesang were made by 'modern' humans, as the authors correctly note, suggesting that they are much younger than proposed. Moreover, the earliest rock art currently known is not, as suggested, in Sulawesi: there are several earlier candidates in India, France, Spain, South Africa, even Australia [63]. Moreover, the age of the Sulawesi rock art was also determined by the unreliable U–Th method.

Considerable efforts have been made to date petroglyphs by the uranium–thorium (U-Th) disequilibrium method and optically stimulated luminescence (OSL) surface dating. For the former, the chronology of early human fossil remains overlain by precipitated calcite (stalagmites) also requires a plea for caution with regards to contamination, as described above. Associated methodological corrections are reported for Petralona Cave in Greece [64–66]. For the latter, Liritzis' surface luminescence dating of sun-exposed archaeological stone, masonry surfaces has been introduced [67] which has been extended and applied to rock art cases of exfoliated engraved fragments [68–70].

5. Summary and Outlook

It needs to be emphasized that U–Th results of the Holocene, especially the second half of that period, seem to match ^{14}C dates from the same deposits frequently. It is only as we approach the Pleistocene that the results of the two methods diverge. By the time 30,000 carbon years is reached, the corresponding U–Th ages are around 50,000 years—and this also appears to apply to fossil bone [71]. Nevertheless, the ^{230}Th/^{234}U method has been widely used to date carbonate speleothems, and when it produces extraordinary results, its advocates reject the need for checking these with another method [54]. One of the most consequential outcomes of the work by the International Centre for Rock Art Dating (ICRAD) is that it has found a path to test the results of U–Th analysis and thereby help resolve the deadlock between the opposing parties. First, it has begun to take multiple samples of coeval carbonate skins, confirming dramatic differences [2]. Second, the processing of split samples by multiple laboratories has shown no correspondence whatsoever, be it in actual dates or reporting protocols [60]. Direct rock art dating results that cannot be verified are questionable, and if different laboratories deliver wildly diverging dates of split samples, there is no basis for even the most rudimentary comparison. The refusal of the advocates of exclusive use of U–Th dating to consider applying a second method [54] also deprives the discipline of the most crucial attribute of good science—the facility of testability.

The method of microerosion analysis has become the most intensively used by ICRAD researchers, despite its lack of high precision. It offers reliability instead, simplicity of application, unlimited repeatability, the benefit of obtaining target dates rather than maximum or minimum ages, and its lack of physical intervention. In China, with so many historical sources, rock inscriptions and archaeological sources of dating information, the method has already been widely applied. Its results have, in many cases, been verified independently by archaeologically derived information of several types. By comparison, the exclusive application of U–Th analysis, especially in presumed Pleistocene contexts, has universally provided ages that are archaeologically far too great, and the reasons for this are well understood.

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