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ADVANCES IN MICROEROSION ANALYSIS

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Abstract. This paper reviews current developments in microerosion analysis, including the testing of a universal calibration curve based on regional precipitation. This enables the use of the method in regions that are unlikely to provide suitable calibration surfaces. The paper also considers the creation of the archive of the International Centre of Rock Art Dating, and the need for it to facilitate the testing of rock art age estimates.

Introduction

Microerosion analysis was deliberately designed to provide a relatively simple method for the direct dating of petroglyphs with a high degree of reliability, even if its precision was always regarded as relatively low. Bearing in mind that 'indirect' (archaeological) methods of age estimation (e.g. by excavation, stylistic reasoning) of rock art created by reductive processes (petroglyphs) have proved to be quite unreliable, and have led to estimates that have been wrong by as much as 250 times (e.g at Siega Verde, Spain; Bednarik 2009), the preference for 'direct' methods is justified. The concept of direct rock art dating refers to the direct physical relationship between the rock art and the actual dating criterion, and the falsifiability of the propositions concerning this relationship (*IFRAO Rock Art Glossary*).

About thirty years ago we developed the methodology of microerosion analysis and in 1990 first applied it at Lake Onega in Russia (Bednarik 1992, 1993). This microscopic approach to estimating the age of petroglyphs comprises not a single method, but a cluster of methods focused on the idea that a variety of erosional variables affecting rocks after they were engraved should be quantifiable, and would express approximate ages of the rock art motifs they pertain to. These chemical weathering processes apply especially in unsheltered locations and they result in cumulative results that are a function of time. So far, only two such methods have been applied: the measurement of micro-wanes on crystals that were fractured during the production of petroglyphs; and the selective, alveolar retreat of certain rock types of component minerals that weather much faster than others.

The first of these two methods has been used extensively since the early 1990s and now forms a core approach of the International Centre for Rock Art Dating at Hebei Normal University, China. It has been applied in all continents except Antarctica, and in some of them with considerable success. The crucial variable utilised in this method derives from the primarily chemical weathering of a surface feature created when a petroglyph was produced. In fracturing mineral crystals, edges are formed that are perfectly sharp at that time. Solution removes surficial mass from the new surface as a function of time, but it does so selectively. Retreat occurs significantly faster from the edge than from a flat or concave aspect of the fractured crystal face. Therefore, the edge becomes progressively more rounded, a process following a fundamental law of nature. The same law applies to the geometry of heat dissemination in a solid object; the way coffee penetrates a cube of sugar; or the way macro-wanes develop on rock, such as basalts, sandstones or granites. Macro-wanes in geology have long been recognised as a measure of surface age, and Černohouz and Solč (1966) claim credibly to estimate the ages of such wanes to within 10–20% accuracy on two rock types (cf. Trendall 1964). The geometry determining this fundamental law is, however, more complex than they envisaged, because the rock surface retreats not only at the edge (as they assumed), but also on the surfaces forming it. The governing geometry (Bednarik 1992, 1993a, 2007) was eventually explained, which opened the way to quantifying the process variables.

The second microerosion method so far applied to rock art utilises a process of differential solution, typically of two minerals co-occurring in a rock. For instance, the syntaxial quartz overgrowth that forms the cement of sandstone is of colloid silica and dissolves much more rapidly than the quartz grains it envelopes. In this method the retreat of the cement is determined microscopically, and if the rate of retreat can be established from a surface of known age nearby, such calibration can lead to securing age estimates of petroglyph surfaces of unknown antiquities. Despite its evident validity and procedural simplicity, this method has only been applied very rarely so far (Bednarik 1995).

The analysis of micro-wanes, by contrast, has become a standardised and much used method. That employment over many years and by several analysts has resulted in various collaborative improvements, in the establishment of routine procedures and in the identification of specific difficulties. Of particular significance concerning the latter are the challenges posed by the microerosion coefficients used in calibration. Essentially, there are two complications. First, in many parts of the world it has been very difficult, if not impossible, to secure calibration surfaces. These are rock surfaces of known antiquities that contain the minerals used in the method (so far only quartz and feldspar have been utilised). They include rock inscriptions, monuments, ancient bridges and other structures, glacial striations; such features of known ages are simply lacking in many regions of the world. Second, it became increasingly evident that the variations in the microerosion process across countries, especially large countries, mean that any calibration curves obtained were likely to apply only on regional scales. Such climatically uniform regions tended to be small and, obviously, independent of national borders. This paper endeavours to address these issues and also to clarify procedural matters of the microerosion method as it has developed over the years.

Calibrating microerosion coefficients

While applying microerosion analysis in the southern Kalahari Desert in 2009 we failed to find any suitable calibration site for this arid region. Up to that time, the practice in such cases was to substitute a microerosion coefficient previously secured from another, apparently similar climatic region. In the Kalahari experiment we considered the use of the Spear Hill calibration from north-western Australia (Beaumont and Bednarik 2015: 170). The climate seemed broadly similar to the target region, although apparently more arid, but in trying to test the assumption made we decided to compare the precipitation rates of Spear Hill and southern Kalahari. In the process we happened to *experimentally* place the five most reliable coefficients so far obtained worldwide into a graph plotting precipitation against coefficients. To our considerable surprise they formed an almost perfect alignment (op. cit.: Fig. 14). The five coefficients were those of Jubbah in Saudi Arabia (Bednarik and Khan 2005), Spear Hill in Australia (Bednarik 2002), Deyunshan in China (Tang et al. 2017), Grosio in Italy (Bednarik 2001) and Vila Real in Portugal (Bednarik 2003).

The first direct dating analysis of Brazilian petroglyphs, attempted in 2016, was the first concerted effort to rely on the universal calibration curve. The only available local calibration surface, a 160-year-old engraved date, was considered inadequate because of its low age. This was despite the close match between the two: the engraved date suggested a coefficient of 6.25 μm/millennium, while the universal curve coefficient was 6.35 μm. In that case, a regional calibration coefficient of 6.3 μm was adopted as a compromise (Santos Junior et al. 2018: 88–89).

In another important development, microerosion analyst Jin Anni (pers. comm. Nov. 2018) reported that she has discovered a rock inscription on schist at Lianyungang in Jiangsu Province, China. It reads '*Yan shi hou san shi li*' ('The stone is thirty miles far from the town') and is written in the distinctive Kay Shu style, a calligraphic style established during the Tang Dynasty, 618–907 CE). A fractured quartz grain in one of the characters yielded an average micro-wane width of 11.5 μm (spectrum 9–15 μm), which would correspond to an age of E1742 years bp by reference to the Deyunshan calibration curve. However, if the local precipitation of 860 mm is applied instead, the UCC implies a microerosion coefficient of 9.8 μm. Whereas the first estimate is not compatible with the demonstrated attribution to the Tang Dynasty, the UCC-derived coefficient indicates an age of E1173 (845 CE), i.e. late Tang period. Once again, the UCC is suggested to be superior.

The question now arising is, which way should microerosion methodology be developed further? Should we focus on collecting more calibration values or simply rely on the universal curve?

Our answer is that there needs to be a combination of both approaches. The universal calibration curve is not yet as well developed as we would like it to be before we can rely on it exclusively. The acquisition of more calibration references must continue where this is possible, but it needs to be recognised that in many parts of the world it is unlikely to succeed. There are simply no weathered fracture surfaces of known ages available. The strategy therefore needs to be two-pronged: to secure more calibrations wherever

Site	Age	Coefficient	Precipitation
a. Jubbah, Saudi Arabia	1150–1200	2.83 μm/ka	95.8 mm
b. Spear Hill, Australia	Average 7 values	4.62 μm/ka	392.8 mm
c. Deyunshan, China	1016	6.6 μm/ka	636 mm
d. Lianyungang, China	1400–1111	9.8 μm/ka	860 mm
e. Grosio, Italy	12 000	10.67 (7.5–12.5) μm/ka	920 mm
f. Vila Real, Portugal	1900	12.0 μm/ka	1074 mm

Table 1. *Calibration points, their ages, their coefficients and average annual precipitation.*

possible, but apply the UCC experimentally when it seems unlikely to secure suitable calibration surfaces and to always convey the original wane-widths data set in case age estimates need to be fine-tuned in the future. That is precisely the purpose of full publication of data sets. To show where we are at this point in time, Figure 1 presents the most detailed UCC established so far. It is based on the annual precipitation values and known ages of six sites as listed in Table 1.

Table 2 adjusts the estimates previously secured in two Chinese regions, Ningxia and Jiangsu Provinces, calibrated with the only reference then available, the Deyunshan inscription. For Ningxia, the adjustment to the microerosion coefficient is now provided by the UCC, while for Jiangsu the Lianyungang calibration value determined by Jin Anni serves that purpose. This revision takes into account the significant differences in precipitation averages across the large country. Another set of microerosion-based age estimates in need of review are the six determinations procured from quartz spalls found at petroglyphs of two of the twenty-seven sites of the Kalatrancani petroglyph complex near Cochabamba in central Bolivia.

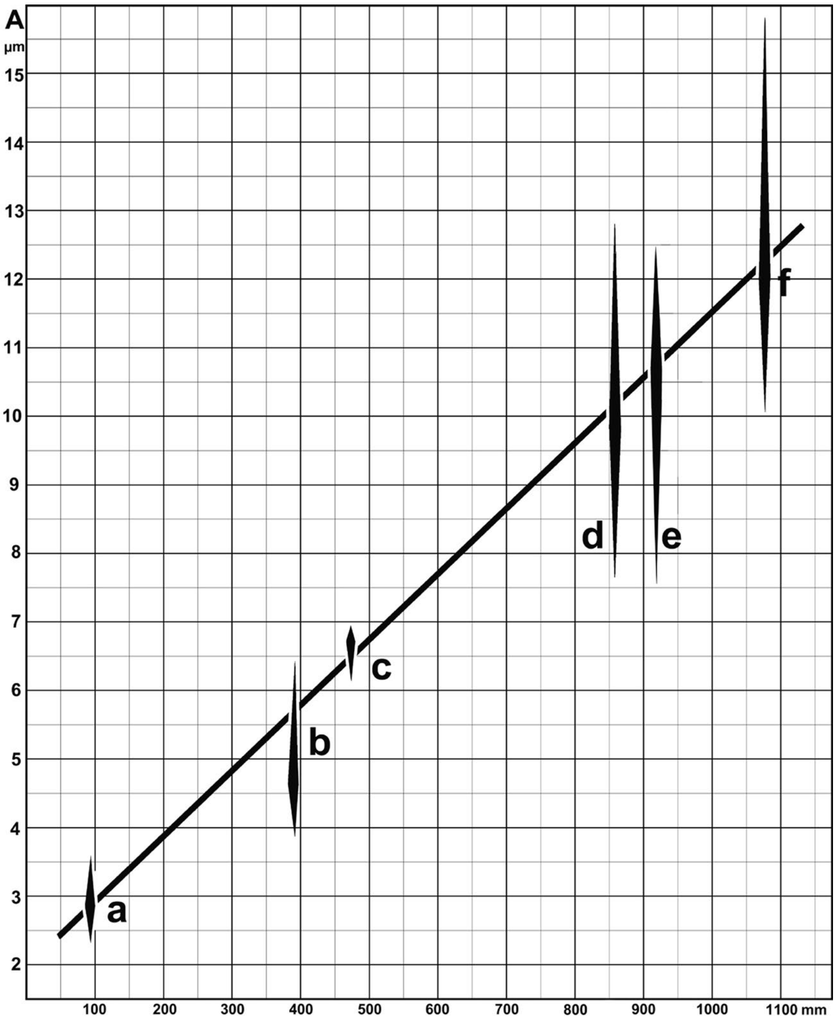

Figure 1. *Improved and updated universal calibration curve for microerosion analysis of quartz fracture micro-wanes.*

Region	Number of sample	Prev. age estimate	Precipitation & coefficient	Universal curve age estimate
Ningxia Province	China-Helanshan1-EQ-6/7/2014	E2000 + 120 / - 180	650 mm, 8.2 µm	E1610 + 100 / - 150
	China-Helanshan2-EQ-6/7/2014	E1670 ± 150		E1340 ± 120
	China-Helanshan3a-EQ-6/7/2014	E2180 + 240 / - 210		E1730 + 220 / - 140
	China-Helanshan3b-EQ-6/7/2014	E2080 + 340 / - 260		E1670 + 320 / - 210
	China-Helanshan4-EQ-6/7/2014	E2330 + 90 / - 210		E1880 + 70 / - 170
				Lianyungang calibration
Jiangsu Province	China-Jiangjunya1-EQ-13/7/2014	E1630 + 190 / - 110	860 mm, 9.8 µm	E1100 + 120 / - 80
	China-Jiangjunya2-EQ-13/7/2014	E3200 + 440 / - 170		E2150 + 300 / - 110
	China-Jiangjunya3a-EQ-13/7/2014	E2210 + 210 / - 90		E1490 + 140 / - 60
	China-Jiangjunya3b-EQ-13/7/2014	E360 + 90 / - 60		E 250 + 60 / - 50
	China-Jiangjunya4-EQ-13/7/2014	E920 + 140 / - 160		E 620 + 90 / - 110
	China-Jiangjunya5-EQ-13/7/2014	E2650 + 80 / - 230		E 1790 + 50 / - 160
	China-Jiangjunya6-EQ-13/7/2014	E5380 + 380 / - 530		E 3620 + 260 / - 350
	China-Duijiu1-EQ-14/7/2014	E850 + 210 / - 90		E 570 + 140 / - 60

Table 2. *Corrections of age estimates obtained in China before allowing for regional differences in precipitation. Corrections are derived from the universal calibration curve.*

Site	Number of sample	Prev. age estimate	Precipitation & coefficient	Universal curve age estimate
Isay Rumi South, Kalatrancani	Bolivia-Kala1-EQ-25/7/2007	E225 + 56 / - 37	518 mm, 6.85 μm	E350 + 90 / - 60
	Bolivia-Kala2-EQ-25/7/2007	E338 + 37 / - 57		E530 + 50 / - 90
	Bolivia-Kala3-EQ-25/7/2007	E297 + 78 / - 10		E460 + 120 / - 20
	Bolivia-Kala4-EQ-25/7/2007	E250 + 31 / - 62		E390 + 50 / - 100
Ph'alta Rumi, Kalatrancani	Bolivia-Kala5-EQ-2/10/2014	E198 + 83 / - 104		E310 + 130 / - 160
	Bolivia-Kala6-EQ-2/10/2014	E506 + 56 / - 131		E790 + 90 / - 210

Table 3. *Corrections of age estimates for the Kalatrancani petroglyph complex, central Bolivia, based on the Grosio calibration curve, and the corrections suggested by the universal calibration curve.*

These were *provisionally* based on the Grosio calibration curve (Querejazu Lewis et al. 2015). Their reappraisal in the light of the region's precipitation data and the alternative coefficient derived from the UCC (Fig. 1) yields the results shown in Table 3.

There is no need to adjust other age estimates derived from microerosion analysis. Although the result from Al Usayla near Riyadh in Saudi Arabia is based on the Umm Sinman calibration (Bednarik and Khan 2005), 600 km away, the difference between average annual precipitation rates of Jubbah and Riyadh is negligible (95.8 mm vs 88.5 mm respectively). The results from Jabal al-Raat (Bednarik and Khan 2005) cannot be checked as there are no rainfall data available from Shuwaymis (we requested the installation of a weather station only recently, as part of our nomination for World Heritage listing). It is, however, likely to be very similar to Jubbah, as indeed is the rainfall at Jabal al-Mismā (Bednarik and Khan 2017). The only age estimate from the country's far south, from Ta'ar, has its own calibration from nearby ^{c}Ān Jamal. All other published microerosion estimates have either been furnished with their own local calibrations or, in the case of the most recent determinations, have already been referenced to the UCC, or at least partially so (Beaumont and Bednarik 2015; cf. Santos Junior et al. 2018; Tang et al. 2018, concerning Xiao Fengshan; Bednarik in press).

Developing microerosion analysis

These new developments show that microerosion analysis has become the most effective method of reliably estimating the approximate age of petroglyphs currently at our disposal. The method is still evolving and will continue to be fine-tuned as new data become available from around the world. However, it has already become a routine procedure whose weaknesses and strengths are well appreciated, and which is being applied successfully by various teams.

It needs to be emphasised that another essential development in microerosion analysis is the need to acquire much more data for the alternative method mentioned above. This approach utilises the differential solution rates of two minerals co-occurring in a rock, particularly crystalline grains and colloidal cement. Measuring the retreat of the more soluble component is relatively simple and is a direct reference to the amount of solution a surface has been subjected to. That measurement can be a function of time if it can be calibrated against surfaces of known ages of the same rock type in the same climate zone. This method is actually easier to apply than the more widely used measurements of micro-wanes. Its results can be significantly distorted only by the process of kinetic energy metamorphosis (Bednarik 2015a, 2015b), the results of which are readily detectable by a specialist using optical or scanning electron microscopy (Bednarik 2019).

However, more elementary developments in the practices of microerosion analysis refer to the routine procedures of collecting and archiving data. The most fundamental generic requirement for scientific status is the repeatability of experiments to render data testable. This prerequisite determines the standing of propositions as being scientific. In the case of rock art age estimates, most of the methods so far applied fail to meet this criterion, for a variety of reasons. For example, samples removed for destructive analysis obviously cannot be re-analysed. If there is adequate material sampled, sample splits may be available, but with various methods of destructive sampling the quantities of sample available are minute. There may also be variations in the composition of the substances constituting the dating criterion that are of very small-scale, leading to differences in the results of repeat analyses. For instance, the dating criterion in uranium-thorium analysis is the ratio of ^{230}Th and ^{234}U, but that relationship can be (and apparently often is) distorted in carbonate speleothems, the material most relevant in the context of cave art dating. The relevance of this ratio depends entirely on the system being a closed system, which in the case of speleothems is rarely the case. In the ^{14}C analysis of speleothems it has been known since the method's earliest applications (Franke 1951; Geyh 1969) that the most reliable type are very densely crystalline stalagmites. The same is likely to apply in uranium-series dating, yet nearly all the results so far reported derive from porous or extremely thin coatings. The solubility of U in water and the potential presence of detrital Th have to be addressed (Clottes 2012; Pons-Branchu et al. 2014; Sauvet et al. 2017), and the significant differences between the ^{14}C and U–Th age determinations of split samples need to be resolved (Bednarik 1984, 1997, 2012; Plagnes et al. 2003). It is incumbent upon the U–Th analysts to explain why in most of the cases when the method was used in tandem with ^{14}C, its results were three to five times as great. However, uranium-series analysis is no different from most other methods so far used in the direct dating of rock art: they are all burdened with significant difficulties of procedure and interpretation, and repeatability is usually impaired.

Whereas the adversities with microerosion analysis are well understood and appreciated, any mention of complications with other rock art dating methods tends to elicit antagonistic responses from their advocates (e.g. Pike et al. 2017), which limits constructive dialogue severely. In contrast to destructive methods, microerosion study is fully repeatable, and remains so into the distant future. That offers the opportunity of re-measuring micro-wanes in centuries from now, thereby checking the precision of microerosion coefficients in the very long term. The prospects of achieving that kind of facility with any other rock art dating method are not promising. The opposition to destructive sampling of rock art is expressed, for instance, in the recent decision of the French Commission of Historical Monuments to demand that all applications to regional authorities for permits to sample Palaeolithic cave art be referred to its central agency (Sauvet et al. 2015). In view of the recent proliferation of such activities and the sensationalist reporting of the results, such caution seems pertinent. At this stage in the development of direct dating of rock art it is certainly premature to overuse destructive sampling methods and to reject calls for checking their results against those of alternative methods (Pike et al. 2017). The rock art in question has survived for millennia and will survive for much longer, while the methodology in question will no doubt be continuously developed and improved. Rock art dating is likely to be discredited by precipitate claims that are intended to augment academic careers rather than a sound knowledge base.

This raises the question of how to develop microerosion analysis to facilitate its maximal potential. In order to be able to re-measure micro-wanes centuries from now, two prerequisites are indispensable: every measured wane must be re-locatable and the original wane width measurements must be preserved. The first requirement is satisfied by the procedures described in Bednarik (2017). Each measured wane is identified by a unique code and by its site location, the individual petroglyph, and the location of the measured micro-wane within that petroglyph. The last factor is only needed when there is a possibility that the petroglyph may have experienced renewal at some time, because if all fractures in one motif derive from one single event of production, all wane-widths in it should yield similar measurements. The second prerequisite is that the wane-widths originally determined must remain available for all future. Both these requirements can be met by the recent establishment of the International Centre of Rock Art Dating (ICRAD) which will maintain a register of all such results.

The significance of the ability to re-sample specific petroglyphs unlimited numbers of times in the future is illustrated by considering the prediction that a motif estimated to be 300 years old today should in 300 years from now yield wane widths twice as great as today. This absolute testability of predictions is the hallmark of solid science and contrasts with the opportunistic use of methods known to be subject to numerous factors of uncertainty that remain inadequately explored.

The only weakness of microerosion analysis is the issue of precipitation rates having varied in the past. Obviously rainfall does not remain the same through time, but the long-term trends over the most recent millennia, which have yielded the largest number of results, are not so dramatic that they are likely to exceed the large tolerances already attached to results. As one proceeds into the Metal Ages and beyond, variations may be greater, but firstly, they may be widely shared as global climate patterns change. Widespread reductions or increases in precipitation will be reflected in accelerated or decelerated rates of erosion for limited periods of time, but still preserve *relative* parity of results. Secondly, over very long timespans, these variations are even likely to cancel themselves out and especially then remain within the parameters of stated tolerance limits. The issues of this source of imprecision can be resolved by fine-tuning microerosion results to known past fluctuations in rainfall. This fine-calibration has not been attempted so far and should be seen as the 'final frontier' in microerosion research. At this stage in the method's development reliability of results is simply considered more important than their precision.

Conclusion

The first 35 years since we introduced 'direct dating' of rock art (and had it rejected by archaeologists who believed that rock art needs to be dated by archaeology, not by science) have been marked by lively activity in some areas, relative neglect in others; by wide variations in credibility of methods and results; and by over-enthusiastic and fervently defended notions. All age estimates of rock art are fundamentally scientific, because all are ultimately falsifiable. The way forward in this field is to create an archival system that acts as a repository of all 'direct dating' results, even those that appear to have been refuted. This rock art dating archive needs to provide, for each entry, the possibility of testing it, how it was acquired, and whether there was destructive sampling involved in its procurement. Rather than securing more new data it may be more productive at this stage to end the probationary phase of direct rock art dating, instead focusing on consolidating the data of recent decades and creating an archive designed to be fully transparent about the derivation of age estimates. In all probability new methods will be developed in the future and applied to data secured by current means. Testing of previous results needs to be encouraged and facilitated, e.g. by providing information required for re-analysis.

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