archaeometry

Archaeometry 58, 6 (2016), pp. 899-911 doi: 10.1111/arcm.12216

THE SCIENCE OF CUPULES*

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As the apparently simplest of all petroglyphs, cupules are shown to be scientifically and culturally very complex phenomena. Despite being the most common motif in rock art, their meaning or purpose remains largely unknown. This paper explores their physical and production properties, including their technology, taphonomy, morphology, biomechanics and energy investment involved, leading to the formulation of the production coefficient. The various quantifiable factors involved in cupule production are examined, including the phenomenon of kinetic energy metamorphosis (KEM). The tribological products, tectonite laminae, a new geological phenomenon first identified in cupules, offer the possibilities of developing a direct dating method as well explaining several related geological features.

KEYWORDS: PETROGLYPH, CUPULE, TAPHONOMY, LITHOLOGY, REPLICATION, BIOMECHANICS, TRIBOLOGY

INTRODUCTION

This paper seeks to illustrate the complexity of the scientific study of rock art by focusing on the physically most simple motif type in world rock art, cupules. The obvious corollary of the intricacies encountered is that the scientific parameters of other, visually more complex, forms of rock art are likely to involve even more complicating variables that need to be accounted for. Hopefully this can deter simplistic assessments of all types of rock art more intricate than cupules.

Cupules are most frequently described as hemispherical indentations of anthropogenic origin on rock, which is, however, not a valid definition. They resemble more closely, although not accurately, the shape of a spherical cap or dome, rather than a hemisphere. The name cupule derives from the Late Latin *cūpula*, ‘little cask’. These features are usually between 1.5 and 10 cm in diameter, although larger specimens are occasionally seen. They occur commonly in groupings that may on occasion number several hundred; they may be arranged in geometric formations, such as aligned sets, or they occur in unstructured, random groups; and they can be found on horizontal rock pavements and on inclined surfaces, as well as on vertical panels. Groups of cupules have been created in limestone and quartzite caves, in sandstone rock shelters, and on tens of thousands of open sites on numerous lithologies in all continents except Antarctica. They are thought to have been produced by many rock art traditions, transcending all major divisions of human history, from the Lower Palaeolithic to recent centuries (Bednarik 2008). Indeed, cupules are the world’s most common rock art motif, and one of the most neglected. At least in Australia and Bolivia, their production only ceased in the 20th century (Mountford 1976, 213; Querejazu Lewis *et al.* 2015), but the earliest known cupules date from Lower Palaeolithic contexts. Some specimens in the southern Kalahari Desert are suggested to

*Received 27 April 2015; accepted 29 July 2015

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be in the order of 410 000 years old (Beaumont and Bednarik 2015) (Fig. 1), and those of two sites in central India should be even earlier (Bednarik *et al.* 2005). In Middle Palaeolithic or Middle Stone Age contexts, cupules occur in Africa and Australia, and are also attributable to that era in Europe (Peyrony 1934). They seem to become less common in the course of the European Upper Palaeolithic, but still occur occasionally (Capitan and Bouyssonie 1924; de Beaune 1992, 2000; Clottes *et al.* 2005). Cupules are extremely common in the Neolithic and the Metal Ages, in Europe and Asia, as well as in Africa, and more recently in medieval Europe.

In spite of these factors, surprisingly little is known about their purpose or significance, and their scientific study was begun only in recent years. Many meanings or purposes of cupules have been suggested in the literature (Bednarik 2010a lists 71), and in a number of cases cupules were demonstrated to mark specific rocks used as lithophones (Bednarik 2008, 74–6). In just a few instances worldwide, credible ethnographic interpretations of their former cultural functions have been secured (Bednarik 2010b), but these cannot necessarily be extrapolated to other corpora, which are widely separated temporally as well as spatially. Even their identification remains tenuous: archaeologists have encountered problems in distinguishing cupules from other features, such as potholes, mortars, querns, metates, *tacitas* and small solution pans; and in one unusual instance even the negative impressions of a tabular pebble layer in conglomerate were considered to be cupules (Bednarik 2008, 65–6). In these circumstances it may be useful to summarize the reliable information available, and to outline some of the scientific work so far attempted in relation to cupules.

THE TECHNOLOGY AND TAPHONOMY OF CUPULES

The observations concerning the distribution and frequency of cupules, while empirically correct, require immediate qualification in reference to their taphonomy. As a general rule, cupules tend to be deeper than other petroglyphs, and in extreme cases have been reported to be up to 20 cm deep. It is therefore a given that, other things being equal, they can survive longer than any other form of rock art. This application of taphonomic logic immediately questions the validity of quantitative statements about cupule distribution (by lithology or site profile), and has a direct

Figure 1 *A group of cupules, thought to be about 410 000 years old, on a glacial quartzite pavement at Nchwaneng, Kalahari Desert, South Africa.*

bearing on the observation (e.g., Bednarik 2008) that the oldest occurrences of rock art in the world are greatly dominated by deep and large cupules on some of the most weathering-resistant rocks, especially heavily metamorphosed quartzite. Taphonomic logic (Bednarik 1994) suggests that this implies the opposite of what it seems to indicate; it implies not that the earliest rock art was only of cupules, but that cupules are all that remains of it.

Cupules occur on practically all major rock types, but are most common on sedimentary rocks, including metamorphosed types. Typically they were created by direct percussion—that is, using handheld hammer stones—although on rare occasions other methods were used (Bednarik 2008; Kumar and Krishna 2014). The time required for their production has been established to vary enormously, depending on the rock type. Rocks covering the entire range of relative hardness from 1 to 7 on the Mohs scale have been used in cupule making, and it is obvious that the time required to create the same depth cupule on these rocks is related directly to their hardness and method of production. It tends to be correlated with the prevalent depths of cupules: the softer the rock, the deeper the cupules on it tend to be, on average (Bednarik 2008, 87). Figure 2 presents the matrix of a random study of cupule depths as a function of rock hardness, showing a distinctive trend in a first investigation of this kind, a type of survey that could be refined by plotting hardness against diameter to depth ratios. However, in all this it needs to be remembered that hardness is only one of the variables contributing to the resistance of a rock to kinetic impact, others being toughness and strength (see below).

This is not the only distinctive trend in the dimensions of cupules. Although adequate statistical data have not yet been assembled, it has become evident that there is a trend linking harder rocks to lower diameter/depth ratios. This means two things. First, the very great effort expended on the hardest rocks renders it difficult to determine the intended objective, while it is expressed best on the softest rocks. The objective, and this seems to apply to practically all cupule-producing traditions, seems to have been to create cupules of the smallest possible diameter. Second, as implied by the cupules on the softest rocks, the intention seems to have been to penetrate as deeply as possible into the rock (see Fig. 2). The investments of time expended in this quest range from a few minutes to several days of continuous work. The first controlled replication work with cupules was conducted on well-weathered sandstone in Bolivia (Bednarik

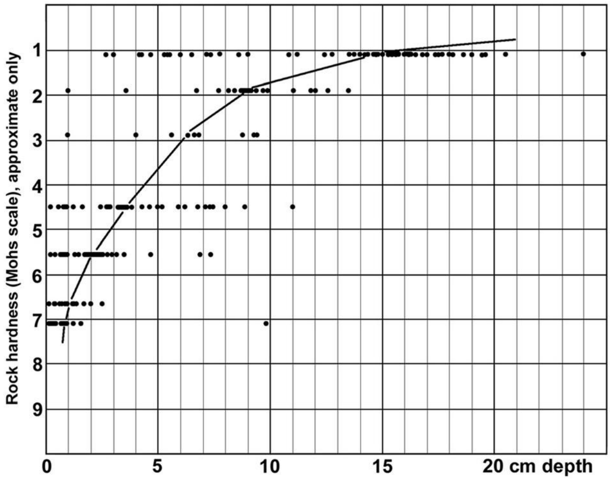

Figure 2 *The depths of a random sample of cupules, shown as a function of rock hardness.*

1998, 30, Fig. 5) and found that it takes 2 min to fashion a cupule of 12 mm depth on that surface. Kumar has since conducted several detailed replication experiments under controlled conditions on unweathered, highly metamorphosed quartzite in India, establishing that it requires 21 730 strokes with hammer stones to achieve a cupule depth of 6.7 mm (Kumar 2007; Kumar and Krishna 2014). The progress of depth relative to time or number of blows is not a linear relationship, however; as the cupule becomes deeper, increase in depth slows down. This is primarily because of the development of kinetic energy metamorphosis (see below, and Bednarik 2015). It is therefore reasonable to estimate that it would take between 45 000 and 60 000 strokes to create a 12 mm deep cupule on the same rock, or somewhere in the order of 12–16 h of continuous work, which is physically impossible to accomplish in one sitting due to the severe fatigue that sets in after a few hours of this demanding work. It is therefore likely that different individuals contributed to cupules on hard rock types.

These figures, pointing to a 400 times greater effort than for the weathered sandstone facies, are not surprising when it is considered that hardness 7 rock is roughly 26 times more resistant to abrasion than hardness 3 rock (on the Mohs scale). Moreover, this line of reasoning lends itself to further development. The relative susceptibility of any petroglyph to erasure by natural means (be it aeolian, fluvial, marine or any other agent) is roughly proportional to the time it takes to create it (Bednarik 2012, 79). Since the time required to fashion a petroglyph is a known variable, or can become so through replication, the longevity of a given petroglyph is also predictable. This principle is of fundamental importance in roughly estimating the age of petroglyphs: estimate how long it takes to create it, and if it takes 400 times as long as another petroglyph of known age, it will also take about 400 times as long to naturally erase it, as it will to expunge that other image of otherwise identical properties. This reasoning helps appreciate the greatly varying propensity of petroglyphs to survive, depending on the resistance to weathering and the hardness of the rock, and on such factors as its groove depth and exposure.

The taphonomy of rock art determines not only its prospects of survival; it also governs the quantifiable expressions of the distribution and preservation condition of the surviving sample (Bednarik 1994). All extant rock art has been subjected to taphonomic processes, as schematically illustrated in Figure 3. Most of the rock art ever produced can be assumed to have been lost over time; therefore the *interpretational* significance of extant statistics (quantitative,

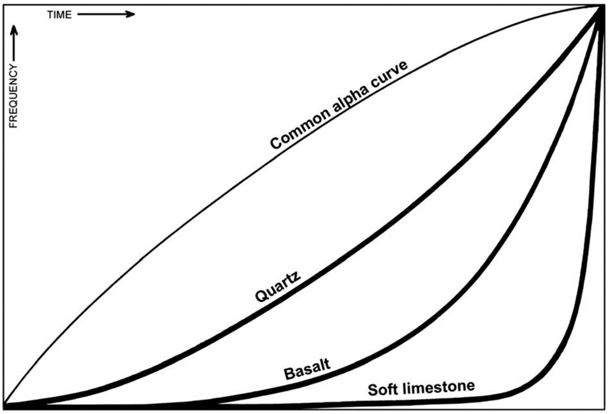

Figure 3 *Predictions on the basis of taphonomic logic of beta curves for cupules on three very different lithologies.*

distributional, formal, lithological etc.) is subordinate to their *taphonomic* significance. The lack of consideration of the latter so far, at more than the most rudimentary level, does not bode well for archaeological speculations based on statistics of rock art. In practical terms, we cannot know which quantifiable characteristics of the surviving remnant sample are culturally determined, and which are determined by such factors as locality, type of support, exposure to weathering processes—indeed, any environmental circumstances.

BIOMECHANICS AND ENERGY INVESTED

Replication studies of cupules can also inform about aspects of biomechanics that can be extrapolated to ancient specimens (Bednarik 1998; Kumar and Krishna 2014). Generally, cupules on horizontal surfaces tend to be, on average, larger than those on vertical rock panels on similar lithologies. This can reasonably be assumed to be attributable to the relatively greater physical effort in pounding a wall, compared to a pavement. Moreover, exceptionally large examples (over 10 cm in diameter) seem entirely limited to horizontal supports. The rims of cupules on vertical surfaces are frequently ovoid, with the greater width orientated vertically. A biomechanically significant observation is that in such cupules on walls, their deepest point tends to be below the geometrical centre of the cupule's rim (Fig. 4). The absence of this trend in specimens on horizontal surfaces suggests that the 'sagging' of the nadir is attributable to the gradual displacement of the centre of kinetic effort by the arcuate movement of the striking instrument: the strokes are not applied horizontally, but from above the central axis of the cupule. Therefore the blows tend to land slightly below its centre, and the vertical section tends to become 'drooping' with time. Indeed, this effect can be so pronounced that it can be cited as evidence that the cupules on a portable slab were created when it was orientated differently. This can be an archaeologically important observation.

In all of this, it needs to be considered that the making of a cupule on very hard rock involves not only great cumulative expenditure of energy, but the operator experiences fatigue and pain, especially in the hand and the joints of the arm. This applies more so to cupules on vertical panels than to those orientated horizontally. An experienced operator will time the frequency of contact and the energy and velocity applied according to the natural rebound of the hammer stone, to minimize both fatigue and physical pain, and this is kinetically far more effective when applying strokes downwards; that is, on horizontal panels (hammer stones have been examined from excavations and surface contexts of cupule sites; cf., Bednarik *et al.* 2005; Kumar and Krishna 2014; Querejazu Lewis *et al.* 2015).

Another dimension of cupules that can have archaeological significance is the amount of physical energy invested in their creation. Clearly, this is related directly to two factors: the hardness of the rock (its resistance to being crushed) and the amount of mass removed in the process. Again, this correlation is quantifiable. Geometrically, cupules are not perfectly shaped, but broadly speaking their volume resembles that of a spherical cap or dome. To determine that volume approximately, the following formula applies:

$$V = \frac{\pi d}{6}\left(3r^2 + d^2\right), \tag{1}$$

in which r is the mean radius at the rim, d is the cupule depth and V is the cupule volume. The mean radius is close to half the sum of two radii measured at right angles to each other. In the following considerations, the inaccuracy of applying this formula to cupules is not crucial,

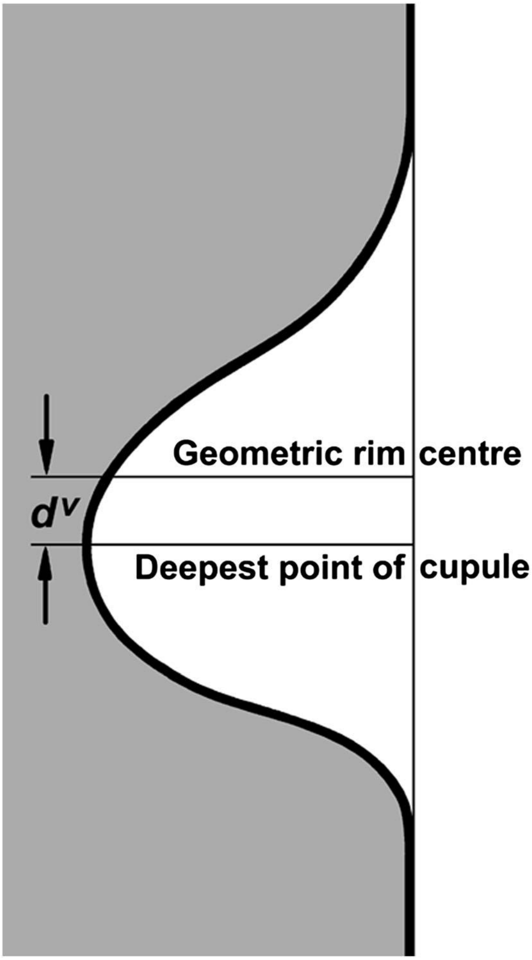

Figure 4 *A typical section of the majority of cupules on vertical support panels, showing the vertical displacement* d^v *below the geometrical centre of the cupule.*

because the error is systematic and therefore has little effect on the outcome. That error is attributable to the flaring out of the cupule section towards the rim and the shape of the nadir region, which is similar in most specimens. The factor to be correlated with the cupule volume is the rock hardness, and this predictive relationship can be expressed by the production coefficient ρ:

$$\rho = V\theta^2, \tag{2}$$

in which θ is an expression of the 'composite hardness index'. Hardness, in this context, is a complex articulation of several factors, essentially a measure of how resistant rock is to various kinds of permanent shape change when a compressive force is applied to it. These factors include scratch or abrasion resistance (on the Rosiwal scale), toughness, strength, ductility, indentation hardness (measured by the Brinell scale and expressed in BHN, or measured by the Vickers test and expressed in kg mm^{-2}) and the brittleness factor (Iyengar and Raviraj 2001). According to the ‘absolute abrasion hardness’ of Rosiwal (1898)—which is accurate to within 1–2%—Mohs hardness 7 (quartz) is 4000 times harder than Mohs hardness 1 (talc), and quartz is 3.24 times as hard as feldspar (Mohs hardness 6). This confirms the empirical observation through replication that the spectrum of production duration of cupules on various lithologies is much greater than might be speculated intuitively. It also shows clearly that abrasion hardness alone cannot account for the observed differences; some or all of the other measures of resistance to compressive force, especially indentation hardness and brittleness factor, must also play major roles. The brittleness factor (*Kp*) is defined as the ratio of the uniaxial compressive strength and the uniaxial tensile strength. There is, however, no simple expression of the combined effects of all factors, and the composite hardness index θ can only be estimated experimentally. Typically, many rocks, particularly coarse-grained rocks, are not well mixed on the scale represented by a sampled thin section. The grains of a specific mineral are often segregated into clusters or glomeroporphyritic aggregates (Thomson 1930).

Also of relevance here is the kinetic energy applied in the production of cupules. Kinetic energy is the ability of a mass in motion to have a physical effect:

$$E_k = Mv^2, \tag{3}$$

in which M is the quantity of mass in motion, v is the velocity in a straight line and E_k is the kinetic energy. No measurements have so far been made of this aspect in petroglyph research, but if it is assumed that each stroke delivered, as a reasonable estimate, amounts to 0.4 N, the total force to bear on an average cupule of 12 mm depth on quartzite would have been in the order of 20 kN, focused on an area of perhaps 15 cm^2. In accordance with Newton’s second law of motion, this corresponds to 20 000 kg m s^{-2}—a rather great force applied to a rather small surface area.

TECTONITE FORMATION IN CUPULES

It has been observed above that, during the production of a cupule, as it becomes deeper, the increase in depth slows down as the cupule creation progresses. In the initial stages of its formation, this is easily explained by the often present weathering rind, a zone of a certain thickness that has been affected by a variety of physico-chemical changes weakening the rock fabric (Bednarik 1979, 2012). However, there is another, more important factor involved here. Indeed, there may be a point beyond which the floor of a cupule becomes almost inert to further impact. This phenomenon is explained by a process called kinetic energy metamorphosis (KEM). It is essentially attributable to tribochemical changes that prompt the formation of tectonites.

Tribology is the science and technology of interacting surfaces in relative motion, and of related subjects and practices (Bhushan 2013). First introduced half a century ago (Jost 1966), the concept of tribology has specific applications in the geology of metamorphic rocks that have hitherto remained neglected. Tribochemistry deals with the chemical and physico-chemical changes of solids due to the influence of mechanical energy (Kajdas 2013). KEM is a tribological phenomenon that was discovered only recently through research on cupules. Bednarik (2015) observed phenomena on a small number of cupules in several continents that defied explanation in traditional terms. These cupules, some of extremely great ages, occurred on retreating rock panels that had been subjected to granular and mass exfoliation, but the cupule floors had remained preserved in such good condition that microscopy revealed cracked or battered grains, and even conchoidal impact scars deriving from the original percussion that produced the cupules

(Fig. 5). The preservation of these cupule floors is due to the conversion of a surface layer of one to several millimetres thickness that rendered it significantly more resistant to weathering than the protolith (parent rock) and gave it a whitish colour, as well as a dense laminar structure. It has so far only been observed in cupules on a few sedimentary rocks: schist, sandstone and especially quartzite. Most importantly, no trace of such conversion is evident in cupules on massive crystalline alpha quartz, even where the estimated production coefficient ρ may be one order of magnitude greater (e.g., at Moda Bhata, India; Bednarik *et al.* 2005, 181–2). This observation excludes the possibility of explaining the phenomenon by a piezo-electric process (Repas 2009; Bednarik 2015).

The laminar KEM conversion product found in some cupules (Fig. 6) is attributable to a process in which the cumulative kinetic energy of tens of thousands of impact blows with hammer stones metamorphoses the cement of the rock through recrystallization (Bednarik 2015). In sandstone and quartzite, that cement comprises syntaxial quartz overgrowths on the detrital quartz grains plus the voids sealed off by this deposition. Tectonites are rocks containing minerals that have been affected by natural forces of the earth, which has caused their orientations to change. Their foliate formation derives from an anisotropic recrystallization of one of the components, which in the case of sandstone/quartzite is its binding cement. The tectonite is thus chemically similar to the protolith, but very different structurally, and significantly more resistant to weathering. The process of its metamorphosis can be likened to the reactions that the energy of photons induces in photochemistry.

The cumulative nature of the KEM conversion process is expressed in the thickness of the laminae formed: the larger and deeper the cupule is, the thicker is the lamina that formed in it. This is reflected in the statistical distribution of lamina thickness relative to cupule diameter or cupule depth (Table 1). Although a strong trend is not evident from the very small sample currently available ($n = 11$), the patterning, especially in the distribution of cupule depth versus metamorphosed lamina thickness, does imply a correlation (Fig. 7). Thus greater size and depth of a cupule, which under otherwise identical conditions would correlate directly with applied total cumulative impact energy, are apparently related with greater thickness of the modified lamina. Moreover, the KEM lamina is thickest in the deepest part of the cupule, which is consistent with the greatest application of kinetic energy in that portion of any cupule. Therefore, the thickness of the laminar formations found in cupules is a function of the production coefficient ρ. Finally, as the KEM gradually increases the resistance of the rock to the pounding activity, progress in increasing the depth of the cupule predictably slows down considerably.

DISCUSSION

While the phenomenon of KEM was first recognized in cupules, where it has been reported only in rare cases, it is a much more common occurrence in geology, where the energy causing it derives from various non-anthropogenic sources. For instance, in the conversion processes arising in shear zones of sandstone that has been subjected to deformation at high temperatures and pressures, the kinetic energy affecting the metamorphosis to tectonites exceeds the shear strength; that is, the resistance to the forces that cause two adjacent parts of a body to slide relative to each other. Energy is dissipated through the deformation between the two sliding masses and the asperities involved. If one of them is harder than the other, the asperities of the harder surface may plough into the softer surface and produce grooves if the shear strength is exceeded (Bhushan 2013). Tear marks can be observed as a result of stick–slip (Bowden and

Figure 5 *Examples of the tectonite laminae found in cupules at, from the top, Indragarh Hill (India), Nchwaneng (South Africa) and Inca Huasi (Bolivia).*

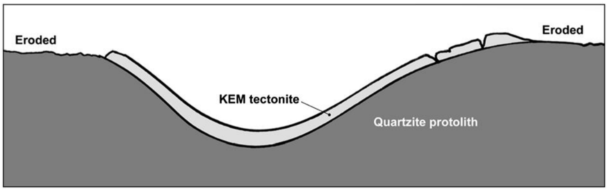

Figure 6 *A sectional drawing of a cupule of about 70 mm diameter, at Inca Huasi, central Bolivia.*

Leben 1939), as the friction force builds up to a certain value and once a large enough force has been applied to overcome the static friction force (Bhushan 2013). The resulting shear-zone laminae may be tabular to sheet-like, planar or curvi-planar, randomly orientated zones of white schistose tectonite.

Similar features sometimes form on blocks or bedrock exposed to heavy barrage by fluvial battery, involving clasts accelerated by river torrents of particularly high kinetic energy. The effect is very similar to what has been observed on cupules, and sheets of KEM tectonite covering surfaces in palaeo-river beds so affected can be quite extensive. It is even likely that the power of glacially induced abrasion has effected conversion of a thin surface veneer on some glacial pavements. An example is the ~300 million-year-old quartzite exposures in the Korannaberg region of South Africa (Beaumont and Bednarik 2015), with their pristinely preserved polish that is quite probably the result of tribological action.

Thus KEM was first identified in cupules, but is a probably widespread feature of geological processes wherever susceptible facies have been subjected to tribological conversion by the release of energy, from whatever source. The phenomenon is simply more prominent in the form it is seen in cupules, but it is a much more widely found occurrence in nature, wherever energy impacts upon rocks susceptible to metamorphism. Of particular importance appears to be the potential of KEM products in petroglyphs to secure direct dating information. These laminae are certainly of the same age as the cupules they are found in, and it is very likely that the conversion time can be determined through future work.

Table 1 *Dimensions of cupules with tectonite laminae, at sites in India, South Africa, Bolivia and Saudi Arabia*

Cupule	*Diameter (mm)*	*Depth (mm)*	*Lamina thickness (mm)*
Indragarh 1	52	9	1–2
Nchwaneng 1	56	8	2–3
Nchwaneng 2	30	6	2–3
Inca Huasi 1	73	15	4.5–6.5
Inca Huasi 2	51	8	1–2
Inca Huasi 3	38	6	1
Inca Huasi 4	42	8	1.5
Inca Huasi 5	48	6	1
Inca Huasi 6	41	5	0.5
Jabal al-Raat 1	71	13	5
Jabal al-Raat 2	68	12	3–5

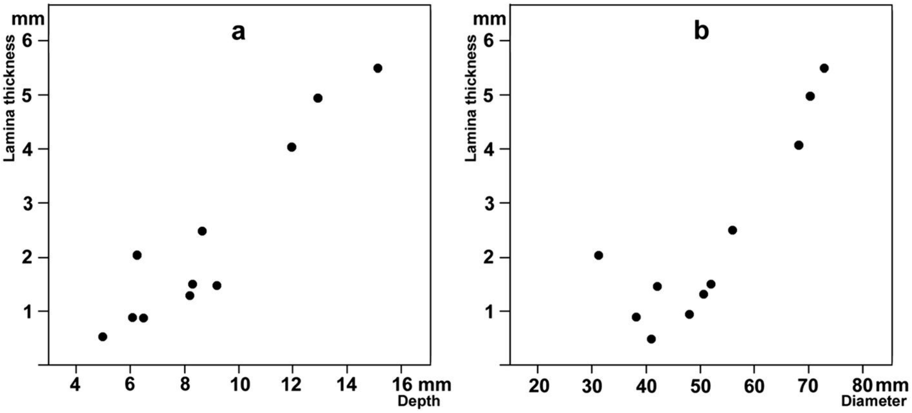

Figure 7 *The metamorphosed lamina thickness plotted against (a) cupule depth and (b) cupule diameter, for a sample of n = 11 cupules containing laminae formed by kinetic energy metamorphosis.*

CONCLUSION

More than any other aspect examined by archaeology, rock art has been subjected to a great variety of pronouncements lacking a sound scientific basis. This paper has sought to illustrate the complexity of the scientific study of rock art by focusing on just *some* of the scientific facets of the physically most simple motif type in rock art, the cupule. This illustrates how multifaceted a proper science of other rock art, which is inevitably more intricate, needs to be. Simplistic interpretation of rock art does not meet the most basic expectation of science, refutability. For instance, there have been numerous attempts to explain the meaning of cupules, nearly all of which are without merit (Bednarik 2010a), and there is a distinct shortage of credible ethnographic explanations of them (Bednarik 2010b). Much the same applies to all other rock art, if not more so, which should be of great concern to rock art researchers.

Here, it has been shown that an examination of just a few aspects of cupules provides empirical information about them that can not only provide valid data about their production or significance, but may even have implications in other areas of science, such as in geology. The relatively rare phenomenon of tectonite formation in cupules observed at a series of sites in various continents has been noted most often on well-metamorphosed quartzites, but from one site it has been reported from silica-rich schist. The KEM lamina resembles an accretionary deposit, but the impact damage on its exterior shows that it is in fact the floor of the original cupule, which has become more resistant to erosion than the support rock. It is the result of recrystallization of the syntaxial quartz overgrowths on quartz grains that constitute the cement component of the already metamorphosed protolith. Tectonite was thus formed by re-metamorphosis, attributable to the aggregate application of kinetic energy that attends the tens of thousands of hammer-stone blows required to produce such a cupule. This tribological metamorphosis resembles that involved in the formation of similar tectonite in shear zones of sandstone, where conversion also results in similarly denser, more erosion-resistant zones.

Also considered were the interdependence of the lithology, technology and taphonomy of cupules, providing a benchmark in their scientific study and a precondition to any valid attempt of etic interpretation. Cupule technology can be investigated by a combination of replicative experiments and microscopy of work traces, but both approaches remain in their infancy. Also, they possess limited viability without applying the crucial dimension of taphonomic logic, the key element in all archaeological interpretation. Replication also connects strongly with the biomechanics of cupule production, and with quantification of the physical effort, the kinetic energy applied and the production coefficient. Here, an attempt has been made to illuminate the correlations between all these properties. This implies that understanding and interpreting the properties of such a 'simple' form of petroglyph demands a level of scientific appreciation largely lacking in the existing literature on cupules. Also lacking is a standard methodology of surveying cupules empirically; therefore, credible statistical and metrical data on the morphology of cupules or their work traces are simply not available at this time. Interpretative propositions not underwritten by sound ethnographic information are therefore premature and will remain so for a long time.

This state, then, provides a measure of the primitive condition in which the scientific study of other, more complex forms of rock art finds itself in. All rhetoric about its meaning and interpretation needs to be seen in that light.

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