KEYWORDS: *Petroglyph – Cupule – Biomechanics – Tribology – Kinetic energy metamorphism*

FORENSIC SCIENCE OF CUPULES

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Abstract. In appraising the value of the etic interpretations of cupules, this wide-ranging review of the potential applications of forensic principles in their scientific study illustrates the huge credibility gap between impulsive etic explanations and a scientific approach. The interdependence of lithology, technology, morphology and taphonomy of cupules provides insights into some of the variables all petroglyph research must address. Replication studies have provided first sound data about cupule production and offer considerable potential for biomechanical enquiries, but also provide impetus for investigations into the production of cupules. Forensic studies focus on variables such as production technique and the tool types used. For instance such studies can discern between the traces of metal and stone implements, or even bone tools. They range from the investigation of tool traces to the tribochemical effects of tool application, and the surviving products of modification processes. Tectonite formation is a remarkable outcome of such mineral conversion, and after its recognition in cupules has been found to occur widely in geology. Rock art research is heavily indebted to the geological sciences, but this may be the first time that the former discipline has contributed to the latter by explaining unknown phenomena.

1. Introduction

The underlying reason for the focus in this paper on cupules is that of all petroglyph forms, indeed of all types of rock art, cupules are the most ideal to consider by methods of quantification. This is because research has established credibly that the motivation inherent in their production was to create a hollow in the rock that is as deep as possible but by maintaining the smallest possible diameter (e.g. Bednarik and Montelle 2012; Krishna and Kumar 2015). This impetus offers the researcher a unique opportunity to know the ideal parameters of the motif type in question. Beginning from the premise that every maker of rock art has in his or her 'mind' a concept, a template, of what the finished product should be, it is obvious that many factors tend to conspire in frustrating the process of creation, including accessibility, unevenness and morphological variability of the support rock, variations in the precision of impact, individual skill, unpredictability of the hammerstones and so forth. The intended outcome can only be speculated about on the basis of what has remained on the rock, and this state is further amplified by the inevitable effects of taphonomy (Bednarik 1994a). In the case of cupules, however, it can reasonably be assumed that the intended outcome was a more or less circular pit of realistically obtainable depth (unless the cupule was a utilitarian specimen, e.g. forming part of a game board). Even taphonomy is not expected to affect the outcome of variable quantification as much as it would other forms of petroglyphs, because of the relative longevity of cupules. This rare access to intentionality offers a unique opportunity to the analyst — to be taken advantage of in this paper — because it imposes clear, repeatable parameters among which cupule depth is a principal variable.

The scientific study of cupules is essentially rooted in their forensic analysis (Bednarik 2015a): the recruitment of empirical evidence in determining the circumstances of their production and use. This paper seeks to explore the wealth of forensic evidence that can be extracted from a cupule. Since cupules are arguably the physically simplest motif type of petroglyphs it stands to reason that some of what can be learnt from them could be extrapolated to other petroglyphic markings; but by the same token it will become apparent that the scientific study of those other, more complex forms should be expected to be more intricate than that of cupules.

Although cupules are not of geometrically perfect shapes, they resemble the shape of a spherical cap or dome (rather than a hemisphere, as has been stated frequently, including by this author), and they are thought to be the most common surviving motif in rock art. They occur in massive numbers at tens of thousands of sites on many different lithologies in all continents except Antarctica, and they have been attributed to numerous rock art traditions, from the Lower Palaeolithic to the 20th century (Bednarik 2008). Many archaeologists have found their identification difficult and have confused them with a great variety of other rock markings, both natural and artificial. Although their scientific investigation was almost completely neglected until recent years, there is no shortage of mostly unfounded speculation about their purpose or meaning (see Bednarik 2010a, citing 71 proposals listed in the literature, most of which are devoid of any empirical justification). Credible ethnographic interpretations of the cultural functions of cupules are very rare, and these cannot be simplistically extrapolated to other corpora (Bednarik 2010b). This is particularly regrettable as the widely documented behaviour of cupule production in temporally and spatially very widely separated traditions is significant. It renders the phenomenon one of the most intriguing in the field of rock art research, yet the latter factor has been largely ignored in the discipline. Here it will be argued that the morphologically 'simplest' form of rock art can yield a great deal of scientific information that may eventually form the framework for formulating testable propositions about the significance of cupules.

It is proposed that the term 'cupules' be limited to cup-shaped depressions on natural rock surfaces, in most cases of between 2 cm and 10 cm diameter (although larger specimens are known), that can occur on horizontal, inclined or vertical surfaces, in or out of caves and rockshelters, and for which a purely utilitarian function (e.g. as mortars or game boards) seems unlikely. The latter qualification defines cupules, including 'incidental' versions such as lithophones or lithophagic marks, as exograms (Bednarik 2014), and therefore as 'rock art'. Their depth has been shown to be a function of rock hardness (Bednarik 2008: Fig. 40), which implies that depth is their crucial ('meaningful') dimension. Most cupules are of close to circular shape, but ovoid forms also occur commonly and sometimes a degree of angularity can be observed (Kumar and Krishna 2014). In section they range from the spherical dome-shaped ideal to conical shapes and roughly flat-bottomed versions. The latter two are the result of the use of metal tools, except on very soft rock (see below), while those made with hammerstones on hard facies always feature well-rounded floors. These direct percussion cupules are readily identified by their well-rounded perimeters and the cracked, battered crystals on their interior. Because of the sustained impact they have experienced, their floors are so smooth that archaeologists have on occasion described them as polished, abraded and even drilled. These views are easily refuted by replication experiments and field microscopy and mirror the experiences with superficial commentary about the technology of other petroglyph forms. They underline the need for field microscopy in rock art science, and for more attention to the relevant ethnography. The sparse information available from ethnographic sources is as unambiguous as is the information from replication experiments: cupules and other impact petroglyphs made with stone tools were made by direct percussion. This is borne out by the cupules the Tewa women pounded at their *kayé* sites in New Mexico (Jeançon 1923; cf. Parsons 1929; Ortiz 1969; Duwe and Anschuetz 2013), Mountford's (1976) observations in the Northern Territory, and Bednarik's (1998a) in the Pilbara of Western Australia. And the possible use of indirect percussion has been effectively excluded by the findings of, among others, Sierts (1968), Pilles (1976), Savvateyev (1977), Bruder (1983), Bednarik (1998a), Weeks (2001) and Krishna and Kumar (2015). The universal outcome of all replication work is that indirect percussion (pecking) is ineffective in creating cupules on hard rock facies (Bednarik 2008).

2. The nexus of morphology and taphonomy

Although cupules are not perfectly shaped geometric entities, broadly speaking their volume resembles that of a spherical cap or dome. To determine that volume within a small error, the following formula applies:

$$V = \pi\, d \,/\, 6\, (3r^2 + d^2) \qquad (1),$$

in which r = mean radius at rim, d = cupule depth and V = cupule volume. The mean radius is close to half the sum of maximum and minimum radii measured at right angles to each other. In the following considerations, the inaccuracy of applying this formula to cupules is not crucial, because the error is systematic and therefore has little effect on the respective outcomes. That error is attributable in part to the flaring out of cupule section towards the rim and the shape of the nadir region, elements that are similarly biased in most specimens. This leaves the variability of the diameter to depth ratio as the only major factor capable of significantly distorting the volume estimation by this formula. This factor is fundamentally affected by the rock's 'composite hardness index' (see below). There is no effect at all when the rock is hard — say, hardness 5 or above on Mohs scale — but on softer rock cupule depths tend to be decidedly greater: the ability to increase depth while maintaining diameter is markedly enhanced.

Although adequate statistical data have not yet been assembled, it has thus become evident that there is a trend linking harder rocks to lower diameter/depth ratios (Fig. 1). This means two things. First, the very great effort expended on the hardest rocks (Kumar 2007) renders it difficult to determine the intended objective, while it is expressed best on the softest rocks (Bednarik and Montelle in press). The objective in making cupules — and this appears to apply to most cupule-producing traditions — seems to have been to create cupules *of the smallest possible diameter*. Second, the intention was to *penetrate as deeply as technologically possible* into the rock. The investments of time expended in this quest range from a few minutes to several days of continuous work, as shown by replication experiments (see below). The quantitative or statistical information so far collected about cupules may be correct as empirical expressions, but in reality it needs to be qualified by taphonomic considerations (Bednarik 1994a). As a general rule, most cupules are deeper than most other petroglyphs, so they tend to survive longer than other forms of rock art. Taphonomic logic (Bednarik op. cit.) thus challenges the validity of all quantitative and statistical statements about cupules. For instance the populations on the more weathering-resistant rocks must be expected to be over-represented, as will be younger traditions, or those that are most protected from weathering. Numerous other factors contributing to the distortion will become progressively apparent in this paper, but it is certain that the surviving record of rock art can never be a realistic representation of what was created — of the 'living' system. Therefore, without accounting for taphonomic truncations (of several types), all forms of interpreting rock art must be qualified. This applies to cupules just as much as it applies to all forms of archaeological evidence. For instance the observation that the world's earliest known occurrences of rock art are notoriously dominated by deep cupules on some of the most weathering-resistant rocks (dense quartzite) in some of the best protected locations (caves) may merely be a demonstration of selective survival.

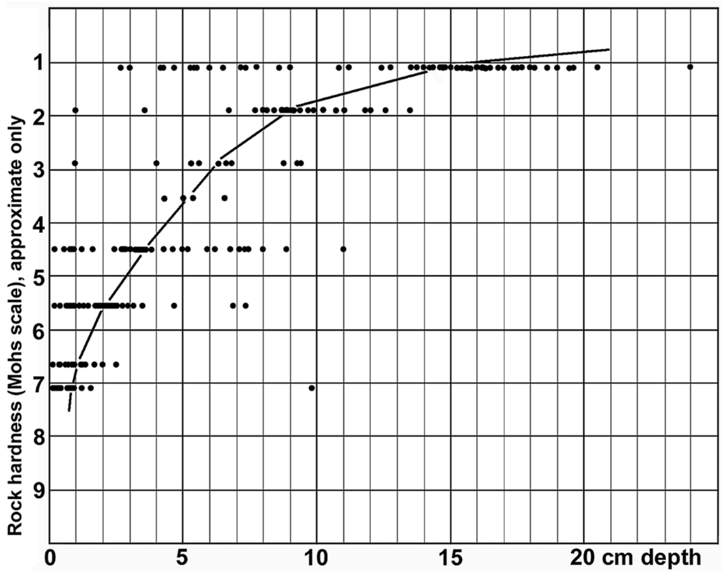

Figure 1. *Depths of a random sample of cupules shown as a function of rock hardness (updated from Bednarik 2008: Fig. 40).*

Cupules survive on all major rock types, being most common on sedimentary rocks, but there is a distinctive bias in favour of recent traditions being preferably found on the most erodible rocks, while the oldest are exclusively limited to the least erodible. Clearly, then, such variables as cupule depth, rock type and antiquity are interrelated in some complex fashion that needs to be understood to be credibly interpreted. Typically, cupules were made by direct percussion, i.e. using hand-held hammerstones, although it has been suggested that in rare cases less effective methods may have been employed to produce odd-shaped specimens (Krishna and Kumar 2015). Although rocks of every relative hardness from 1 to 7 on Mohs scale have given rise to cupules, there are distinctive quantitative trends in the depths and antiquities of the cupules made on this large range of rock 'hardness' (Fig. 1). In that context it needs to be remembered that hardness is only one of many variables of a rock resisting kinetic impact, as will be discussed below. What will emerge is that the interrelations determining the status of cupule data are in fact much more complex than has so far been considered. However, the theoretical considerations concerning cupule production need to be buttressed by sound empirical evidence, and here forensic science needs replicative experimentation.

3. Cupule replication

The term 'replicative archaeology' refers to research that seeks to explore archaeological issues through experiments of replication. A vast range of possibilities of this exists, and there is no sharp division between this field and the experimental study of taphonomic (related to survival of objects) processes, or indeed the practical application of taphonomic logic (Bednarik 1994a). Generically such experiments may involve technical processes used in the past, such as in metallurgy or the production of ceramics, to determine how the products known from archaeology were made. Such propositions are falsifiable, and therefore scientific. Broadly speaking, there are two forms of replication in archaeology, *product-targeted* and *result-targeted*. The easier and more reliable procedure is the former, in which one endeavours to copy an archaeologically demonstrated physical result, generally an artefact, such as a cupule. In order to arrive at precisely the same result, one identifies all its quantifiable variables, such as material type, form, surface striations, wear traces, damage and so forth; and then determines experimentally how they can most readily be duplicated, using appropriate means. One has then not only determined how the artefact was probably made and how long it took to make it, one can go on to establish how it may have been used to acquire the microscopic wear traces or damage the original specimen exhibits. Result-targeted replication, on the other hand, is less straightforward and may involve considerably greater efforts. Here, the artefacts or strategies involved are unknown, as no physical trace of them has survived (Bednarik 2015).

The first controlled replication work with cupules was conducted on well-weathered sandstone in Bolivia (Bednarik 1998a: 30, Fig. 5) and found that it takes two minutes to fashion a cupule of 12 mm depth on that kind of surface. Kumar has since conducted several detailed replication experiments under controlled conditions on unweathered, highly metamorphosed quartzite in central India, establishing that it requires 21 730 strokes with hammerstones 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 is reduced considerably, possibly

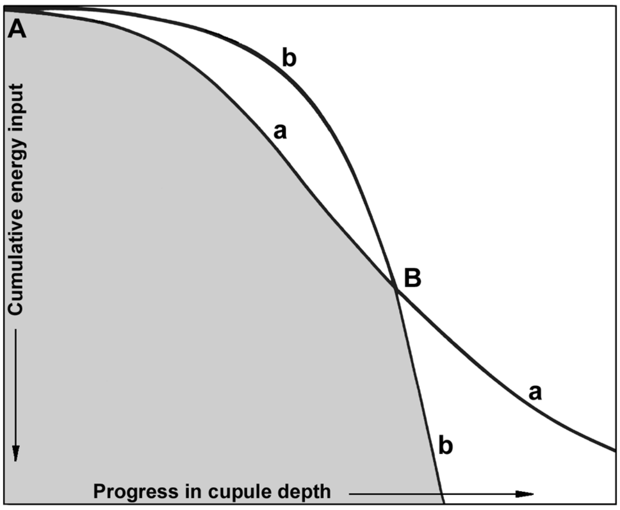

Figure 2. Progress in cupule depth versus required input of energy. Schematic curve a *defines depth gained per amount of energy applied, based on cupule geometry alone: initial gain slows as depth increases, but then improves with greater depth. Curve* b *defines the presumed effect of tectonite formation: initially negligible, it then increases strongly and at point* B *overtakes curve* a *in determining progress in cupule depth. Thus the shaded area indicates real progress in depth, which remains low after point B due to being retarded by KEM (see below) (all images by author).*

exponentially. This slowdown is caused by several factors. Firstly, the subsurface layer of most rocks is weathered and considerably less resistant to crushing by percussion than the unweathered interior. However, the geometry of the emerging cupule also contributes significantly to this trend, because the deeper the spherical dome transects the rock mass, the more contained the diffusion of the shockwaves becomes within the rock mass, rendering the dissipation through fracture of crystals more difficult. Also, the volume required to be removed per unit of depth increases exponentially until the trend reverses (Fig. 2).

The geometry of cupules prescribes an initial deceleration in progress: the deeper it becomes, the more strokes per depth unit are required. As the roughly spherical cap-shaped indentation gains depth, each depth unit demands the removal of a greater volume of rock than the previous. Initially the volume increases steeply, but later, as the final diameter is approached, this gain slows down considerably, leading to the development indicated by the curve *a* in the graph (Fig. 2). Finally, there is another factor retarding progress, perhaps just as potent: the development of products of kinetic energy metamorphosis (curve *b*; see below, and Bednarik 2015c), which are more resistant to any form of deterioration but which are also much more resistant to crushing.

Based on Kumar's diligent replication work it is reasonable to estimate that it would take between 45 000 and 60 000 strokes to create a 12 mm deep cupule on the same quartzite rock, involving perhaps in the order of 12 to 16 hours 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. These figures, pointing to a roughly 400 times greater effort than for weathered sandstone, are not surprising when it is considered that hardness 7 rock is roughly 26 times more resistant to abrasion than hardness 3 rock (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 relative longevity of a given petroglyph is also predictable. This principle is of fundamental importance in roughly estimating the age of petroglyphs: one can appraise how long it takes to create it by replication, and if it takes 400 times as long as another petroglyph, it will also take in the order of 400 times as long to naturally erase it as it will to expunge that other image in otherwise identical conditions. This reasoning, now called 'Robert's Rule' (Bednarik op. cit.), is fundamental to appreciating not only the greatly varying propensity of petroglyphs to survive, depending on the weathering resistance and hardness of the rock and on such factors as its groove depth and exposure. It also provides a means of estimating the realistically possible age range of any petroglyph. For instance if it takes minutes to produce a given petroglyph on schist, but hours to create the same design on granite, then the schist petroglyph will also weather away significantly faster than the granite motif. We may know that an equine petroglyph on granite must be under 2000 years old, because the wall on which it was engraved is Roman or post-Roman (as is the case at the major petroglyph site Castro, near Yecla de Yeltes, western Spain; Fig. 3). It is then entirely unreasonable to claim that a very similar horse-like figure on schist is of a period archaeologists have chosen to call the Upper Palaeolithic. Such a claim is absurd, and defending it is irresponsible, yet there are many horse and bull petroglyphs at open schist sites in Europe that have been claimed to be in excess of 20 000 or 30 000 years old and these contentions are tenaciously defended (e.g. Gondershausen, Siega Verde, Domingo García, Mazouco, Piedras Blancas, Carbonero Mayor, Bernardos, Ortigosa, Ocreza, and many of the Côa sites; for refutations see Bednarik 2015d, in press a). These errors are always attributable to the same factor: protagonists lack the most basic comprehension of geology, rock weathering processes and taphonomic effects.

Besides quartzite and sandstone, cupule replication has also been conducted on schist and granite (by both Kumar and Bednarik, unpublished) and on soft limestone surfaces (Bednarik and Montelle in press). Although this experimental work remains incomplete and more comprehensive procedures are being developed, fundamental trends have been adequately identified to be presented, albeit in preliminary form. For instance forensic techniques developed in the particularly conducive research environment of limestone caves have been found to be also applicable at certain open air lithologies, with the appropriate care. This approach will be developed below.

Figure 3. *Equine petroglyphs on granite blocks in the walls of the Castro fortifications, built less than 2000 years ago, which have become so weathered they are almost unrecognisable (photo 2015).*

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 1994a). All extant rock art has been subjected to taphonomic processes, as schematically illustrated in Bednarik (2008: Fig. 43). Most of the rock art ever produced can be assumed to have been lost over time; therefore the *cultural* significance of extant statistics (quantitative, distributional, formal, lithological etc.) is subordinate to their *taphonomic* significance. The lack of consideration by archaeology of the latter so far, at more than the most rudimentary level, does not bode well for 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. It is from this basis that the taphonomic study of cupules, and indeed any petroglyphs, must begin before there can be a science of rock art.

4. Cupules made with metal tools

A significant factor in the forensic study of cupules is the determination of the tool type and material used in their production. For instance if it can be established that a cupule, or any other petroglyph, was made with a metal tool, this excludes categorically the possibility that it was created before the introduction of metal tools with the Bronze Age. Such a determination is certainly possible in many cases, assisting in the maximum dating of many petroglyphs. Conversely, the demonstration that a petroglyph must have been made with a stone tool does not, of course, necessarily place it before the Metal Ages: petroglyphs were certainly still made with stone implements up to the 20th century (Mountford 1976; Bednarik 1998a; Querejazu Lewis et al. 2015).

Almost all cupules made with stone tools are the result of direct percussion, i.e. pounding with a hammerstone (see above). Such tools were surprisingly small; the average weight of hammerstones used in petroglyph creation has been estimated to be in the order of 160 g (Bednarik 2008). Although such stones were somewhat pointed at their working edge, this was generally a blunt point, stout enough to withstand the blows administered by it. Therefore it is universally impossible for cupules made with such tools to be conical in section, or to have near-'vertical' sides and relatively flat floors. Such shapes were simply unattainable with hammerstones, and this is precisely the factor accounting for the ubiquitous spherical cup shape and slightly rounded rim of most cupules. The exceptions tend to occur on rocks softer than hardness 5 on Mohs scale, such as many schists, phyllites and slates, and most especially on rocks of hardness 1 or 2 (note that schist is a composite rock, comprising minerals ranging from Mohs hardness 2 to 7, but where minerals such as chlorite dominate it can be quite soft). On these rock types, cupules can have 'vertical' walls and flat floors, and often the impressions of the points of the tools used can be found on these floors.

One of the most mysterious aspects of cupules is that they occur on both sides of the significant divide into Stone and Metal Ages: despite the spectacular change in technology, cupules continued to be made as before. When bronze and later iron and steel tools provided more effective means of creating this pervasive petroglyph form that seems to span all periods of human history, from the Lower Palaeolithic to the Middle Ages, the practice continued seamlessly. While other expressions of exograms changed regularly, the very idea of cupules (penetration of the rock) remained embedded in the human brain for hundreds of millennia, representing a human universal. This factor has not received sufficient attention.

Of relevance is that cupules made with steel tools, like those made on very soft rock types, offer by far the best insights into the technology of cupules: what was the intent of the maker? This is not a question about the purpose of cupule making; it is simply a query regarding the desired shape, which the hammerstone on hard rock simply cannot resolve adequately. There are two strands of empirical evidence answering this question. One concerns the Iron Age cupules found extensively on schistose rocks, for instance in Henan Province, China; the other involves the deep cupules found on very soft rocks, such as the hardness 1 or 2 limestones of cave walls in Australia.

The cupules dating project led by Tang Huisheng, Director of the International Rock Art Dating Centre (ICRAD), has already provided age estimates from many of the provinces of China (Tang et al. 2014, in press), but of particular interest are those from Henan Province, a recently recognised major concentration of tens of thousands of cupules (Tang 2012). This major project, involving numerous Chinese and foreign specialists (Bednarik 2015e; Taçon et al. 2016), has been spectacularly successful in providing age estimates of dozens of petroglyphs, mostly cupules. Here, those of the Metal Ages are of particular interest. They have been identified in two regions: on granite in Yémá Gōu (Wild Horse valley) near Xiaojinggou, north of Hohhot, Inner Mongolia; and in several sites of the cupule region of central Henan Province, on schists. Those on granite can safely be assumed to have been made with steel tools: creating cupules with practically vertical walls on this relatively hard rock would be virtually impossible with hammerstones, and probably not feasible with bronze punches. Bronze has a hardness of about 3 on Mohs scale, whereas the compound hardness of schists tends to be 3.5 or higher, depending on composition. Therefore indirect percussion with steel stamps is the only realistic option, and the round impressions of their points have remained preserved on the flat floors of some of these cupules (Fig. 4).

In northern Henan Province, near Xinzheng, the mountains are of schistose rocks rich in quartz veins and inclusions. This has facilitated the age estimation of cupules at several sites (Tang et al. in press). One of hundreds of cupules on a mountain ridge at Xuanluoling, c. 20 km south-west of Xinzheng, has yielded estimates from two micro-wanes: one of E1603 +280/ -490 years BP (i.e. before 2015 CE), the other of E1424 +400/ -210 years BP. The cupule is 26 mm deep and at the point where its vertical sides commence it has a diameter of 35 mm. Its floor is nearly flat but it bears the impressions of a circular tool point of 4–5 mm diameter, providing sound information about the steel punch used in its production (Fig. 5). This confirms the relatively recent antiquity of this corpus.

Such forensic details are frequently observable in the schist cupules of northern Henan. They include not only impressions of the point of the metal tool used, but also grooves on the side walls of the more or less cylindrical cupules. An example are the several distinct gouging grooves on the walls forming an undated cupule at one of the spurs of Mt Juci, a major concentration of cupule

Figure 5. *Cupule made with a steel punch on schist, Xuanluoling, Henan Province. It is approximately E1500 years old and the dints of the point of the tool are clearly visible on its flat floor (2015).*

Figure 4. *Cupule made with steel tool on granite block in Yémá Gōu, Inner Mongolia, 36 mm deep. Note the virtually vertical walls and the several impressions of the tool point on the fairly flat floor of the cupule (2015).*

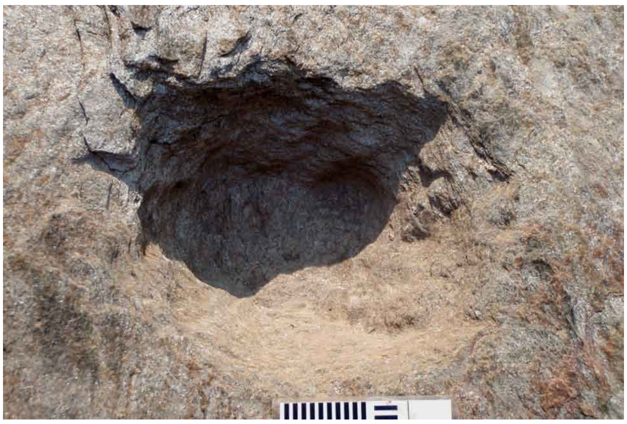

Figure 6. *Grooving by metal tools on the wall of a cupule at one of the Boshishengtailin sites, south-western spur of Mt Juci, Henan Province. At least four grooves can be discerned, as well as the impression of a rather blunt, thick metal tool point on the cupule's flat floor (2015).*

Figure 7. *Cupule of roughly conical section with typical metal implement dint in the centre, on the same block as the cupule in Figure 6, Boshishengtailin site (2015).*

sites, at the site complex Boshishengtailin (Fig. 6). Two other cupules of that corpus have been assigned ages in the order of E3200 years BP, but it appears that the practice of creating cupules at the many Mt Juci sites has been continued over a considerable time span, and many were made with stone implements. Those of conical section, however, are probably the result of metal tools, which in the case of another specimen from the Boshishengtailin site complex can be shown by the presence of the impression of a distinctive circular tool point, of rounded section and 4 mm diameter near the point (Fig. 7).

Such forensic details can be found in many cupules on schistose rocks or mudstone (Bednarik 2008: Fig. 38), but they are even clearer in those on less resistant rock types. Ngrang Cave is located in far-western Victoria, Australia, and among its rich cave art inventory is a panel bearing forty-five very deep cupules (up to 20 cm deep). The Miocene limestone of the cave wall is of hardness 1–2 on Mohs scale. The rock art has been subjected to detailed analysis to establish whether the deep cupules were made with tools of stone, bone or wood (Bednarik and Montelle in press). Importantly, they present the most extreme expression of the principle observed in many cupules on rocks ranging from hardness 3 to 5, in the sense that their rim diameters were kept relatively small, and many are much deeper than wide. The occasional occurrence of walls slightly converging towards the opening demand the use of a relatively thin but sturdy, elongated tool, and this applies particularly to the ensemble of deeper pits (≥75 mm, n=16, or 35%). These cases strongly imply a motivation to drive the holes as deeply as possible, yet maintaining the smallest possible opening diameter. They also virtually exclude the use of stone implements, as shown by both replication and point impressions. Moreover, many of the deep cupules feature tool grooves on their walls and wedging marks at their rims, providing information about the morphology of the tools used (Fig. 8). Finally, the floors of several of them show well preserved impressions of the tool points, just as the schist cupules made with metal tools have provided. These imply tools of circular cross-section of

Figure 8. *Deep cupules in Ngrang Cave, Australia. Note the longitudinal gauge grooves in the central specimen, pointing towards the floor of the hole (2011).*

Figure 9. *View of the floor of a deep cupule in Ngrang Cave, showing the circular impression of the end of the tool that was used in its creation (2011).*

18 mm to 22 mm diameter (Fig. 9).

In the absence of knowledgeable owners or custodians among the relevant Indigenous community, credible understanding of the circumstances of the rock art's production can only be derived through forensic procedures, and in combination with an understanding of taphonomic effects on the results and the relative or absolute chronology of relevant events. The research target of the work conducted in Ngrang Cave (Bednarik and Montelle in press) was to formulate testable propositions, based on the forensics of the site, of how these up to 20 cm deep cupules were made. Although a definitive answer remains elusive after three weeks of fieldwork, the cupules are certainly the product of indirect percussion. The use of stone implements can be safely excluded, except for the shallowest specimens; the use of wooden chisels remains possible, but the most likely tools used were fractured long-bones of macropods. These are hollow and act as receptacles for the limestone debris removed in the process, which can be cleared at intervals to remain highly effective. Very little wear was observed in the experiments, and the work traces these bone tools leave match those found in the cupules in every detail.

5. The biomechanics of cupule making

One of the advantages of replication studies is their ability to inform researchers about aspects of the biomechanics involved in the process, including the energy invested in creating cupules. Every aspect of their production can be measured, assessed, quantified and recorded, be it the kinetic energy applied, the characteristics of the rock or hammerstones, the effects of impact on these, the forensic and tribological processes occurring at the contact surfaces, or the consequences on the body of the cupule maker. In the embryonic stage of cupule research so far undertaken this approach has hardly been initiated, or indeed in rock art research generally. Given the physical similarity of hominins at least since the final Pleistocene, biomechanical observations in cupule replication can inform about the production of ancient specimens. It has become evident from such work that cupules tend to be larger and more symmetrical on horizontal surfaces than on vertical. Those on vertical panels can be slightly ovoid, their greater width being oriented vertically. The production of vertical cupules is physically more demanding, and their deepest point is often below the geometrical centre of the rim of such cupules. Biomechanically this confirms that the strokes are not applied horizontally, but from above the central axis of the cupule. As the blows tend to land marginally below the centre, a vertical section develops as shown schematically in Figure 10. This observation can lead to archaeologically significant insights; for instance a group of such uniform characteristics, i.e. the nadir 'sagging' in the same direction, may imply that cupules now seen on an upper surface may have been on a vertical surface at the time of their production.

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; the operator experiences fatigue and pain, especially in the hand and the joints of the arm. This is in part due to physical exertion, in part due to the rebound transferred from the hammerstone via muscles, bones and sinews, deriving from one hard object battering another. Replication shows that this effect is greater for cupules on vertical panels than for 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 hammerstone, to minimise both fatigue and physical pain, and this appears to be kinetically more effective when applying strokes downwards, i.e. on horizontal panels.

Another dimension of cupules that can have archaeological significance is the amount of physical energy invested in their creation: it permits speculation about motivation and determination of the producers. Clearly the required energy investment is determined directly to two factors: the 'composite hardness' of the rock (i.e. its resistance to being crushed) and the amount of mass removed in the process. Again, this correlation is quantifiable.

The factor to be correlated with the cupule volume V is the rock hardness, and this predictive relationship can be expressed by the production coefficient ρ:

$$\rho = V\,\theta^2 \qquad (2),$$

in which θ is an expression of 'composite hardness index'. Rock hardness is not a single material attribute, but is a rather complex articulation of several factors, essentially a measure of how resistant rock is to various kinds of permanent shape change when a compressive

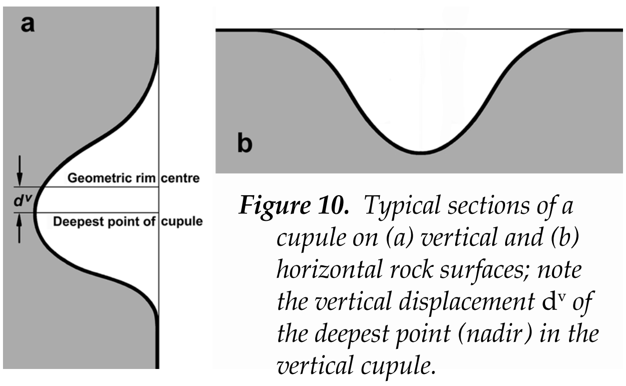

Figure 10. Typical sections of a cupule on (a) vertical and (b) horizontal rock surfaces; note the vertical displacement d^v *of the deepest point (nadir) in the vertical cupule.*

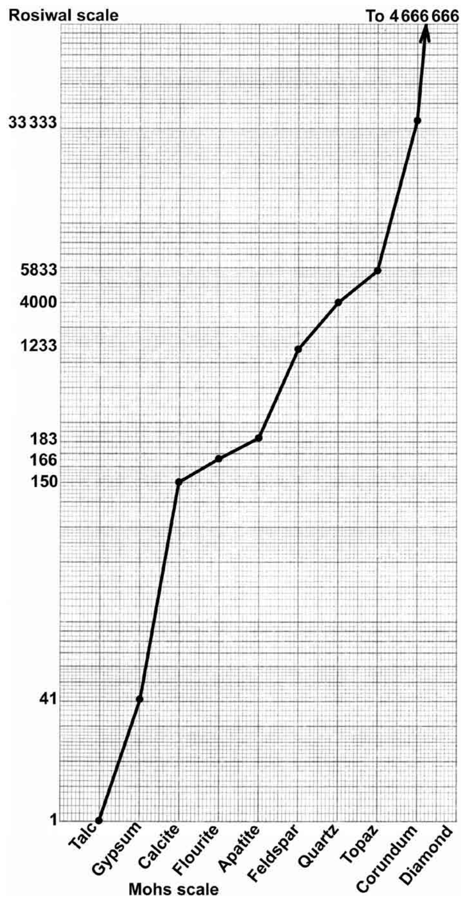

Figure 11. A comparison of Mohs scale and the Rosiwal scale, showing the irregular spacing of the former's referents and the exponential increase in abrasion resistance; note the logarithmic scale of the graph.

force is applied to it. These factors include toughness, strength, ductility, scratch or abrasion resistance (as measured by the Rosiwal scale), indentation hardness (measured by the Brinell scale and expressed in BHN, or measured by the Vickers test and expressed in kg/mm^2) and brittleness factor (Iyengar and Raviraj 2001). The simple standard test of rock hardness, Mohs scale, reflects the range quite inadequately, as a comparison with the 'absolute abrasion hardness' of Rosiwal (1898) readily demonstrates (Fig. 11). The Rosiwal scale is accurate to within 1–2%. For instance Mohs hardness 7 (e.g. quartz) is 4000 times harder than Mohs hardness 1 (talc), and quartz is 3.24 times as hard as feldspar (Mohs hardness 6). The increases of rock hardness in Mohs scale are exponential but irregular, and production times increase correspondingly as one works with harder rocks. There is of course no reason why abrasion hardness alone should determine resistance to compressive force; indentation hardness and brittleness factor (*Kp*) must also play major roles, the latter being the ratio of the uniaxial compressive strength and the uniaxial tensile strength. The combined effects of all factors cannot be measured; it can be expressed as the composite hardness index θ, which can only be estimated experimentally. The matter is complicated by the characteristics especially of coarse-grained rocks, which are not well mixed on the scale represented by a sampled thin section.

Another aspect of cupule replication is that the energy applied in their production can be estimated. Kinetic energy is the ability of a given mass in motion to have a physical effect:

$$E_k = M\ v^2 \qquad (3),$$

in which M = quantity of mass in motion, v = velocity in straight line, and E_k = kinetic energy. This aspect of petroglyph research has so far remained unexplored, including in the work referred to here. However, to underline the importance of replication, and in preparation for subsequent argument, a theoretical consideration may be useful here. If it is assumed that each stroke in the making of a cupule delivered, as a reasonable estimate, 0.4 N, the total force to bear on an average cupule of 12 mm depth on unweathered quartzite would have been in the order of 20 kN, focused on a small area of perhaps 15 cm^2. As per Newton's second law of motion this corresponds to 20000 kg·m/s^2 — a rather great force applied to a rather small surface area. This leads to the tribological effects of focusing this massive impact of kinetic energy on a small area of rock surface.

6. The tribology of cupules

The science of tribology deals with interacting surfaces in relative motion, and with the technology of related subjects and practices (Bhushan 2013). As would be expected, its primary applications are in mechanical engineering and materials science, and it includes the study and application of the principles of friction, lubrication and wear. The discipline was introduced half a century ago (Jost 1966) and has applications in many fields, for instance in geomorphology (in the study of earthquakes, for example). Its name derives from the classic Greek verb *tribo* (I rub) and the suffix *-logy* (study of). The sub-discipline tribochemistry considers the chemical and physico-chemical changes of solids caused by mechanical energy (Kajdas 2013). In the study of rock art, tribology has so far only been applied by one author (Bednarik 2015a, 2015c, 2015f, in press b), and should be included in the training of rock art scientists. However, the state of other disciplines is not much better, for instance many applications of tribology in geology (and various other sciences) remain thoroughly neglected.

In the case of petroglyph production, the study of interacting solid surfaces in relative motion is of fundamental importance. Irrespective of the direction of the motion, there is contact between the rock and the tool used, be it in an abrasive, drilling or percussion motion. According to the underpinning principle of forensic science (another discipline crucial to rock art study that remains neglected; but see Montelle 2009 for a thorough review), whenever two objects come into contact with one another, a transfer of material will occur (Locard's Exchange Principle; Miller 2003: 172). In the case of an abrasive contact, as in the production of engravings, abraded grooves or incisions, the relevance of both forensic and tribological perspectives is self-evident. It has been productively explored, especially through the phenomena of tool striations and other tell-tale signatures in portable engravings on stone, bone, ivory, eggshell and amber (e.g. d'Errico 1991, 1992; Bednarik 1992a). By comparison such techniques have been inadequately explored in abraded/engraved rock art, simply because several decades after the introduction of binocular field microscopy (Bednarik 1979) most practitioners in the discipline have still not availed themselves of this method. Tribology is crucial to the study of rock engravings (made by abrasive action), particularly those that have remained well preserved in deep caves (Bednarik 1987/88, 1992b), and it has been employed most profitably in the analysis of finger flutings (Bednarik 1984, 1985, 1986a, 1986b). It has also been crucial in discriminating between natural and anthropogenic rock markings (Bednarik 1993, 1994b, 1998b).

The application of tribology to impact-caused petroglyphs may seem somewhat less obvious, but is just as advantageous. It was prompted by the discovery of an unexplained phenomenon found in a small number of cupules in several continents. In all cases the cup marks were located on rock panels that had been subjected to both granular and mass-exfoliation since the time the cupules had been made (Fig 12). Indeed, some of them were of very great ages (c. 410 ka in the Kalahari desert; Beaumont and Bednarik 2015). But despite the retreat of the rock surface by several millimetres, the interior of the cupules had

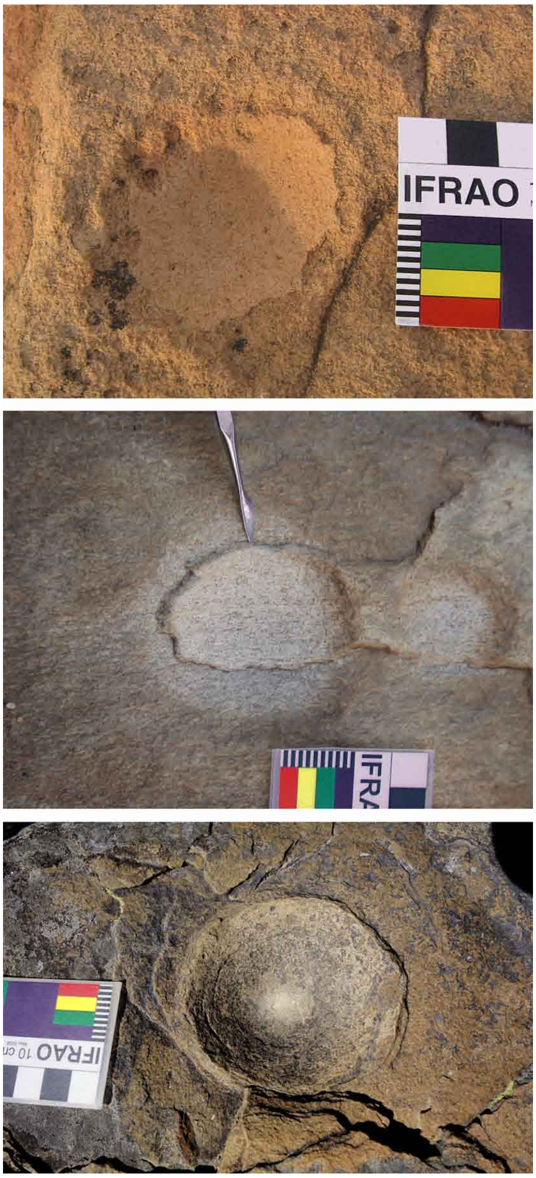

Figure 12. *Examples of the modified laminae found in cupules on quartzite at, from the top, Indragarh Hill (Madhya Pradesh, India), Nchwaneng (Kalahari desert, South Africa) and Inca Huasi (central Bolivia) (photos 2004, 2009, 2014).*

Figure 13. *Large cupules on granitic rocks at Morajhari, Rajasthan, India.*

remained perfectly preserved. Microscopy of their floors revealed many cracked or battered crystals, caused by the percussion during cupule production, and even microscopic conchoidal impact scars were detected on individual quartz grains. This damage can only be the result of well-targeted heavy percussion. The presence of densely packed grains of crystalline quartz, identical to that shown by the protolith, demonstrates that this cannot be a deposit of amorphous silica but must be the original floor of the cupules. Their interior surfaces had become modified to a lamina of this rock that was lighter coloured than the background rock (the protolith) and had somehow acquired significantly more resistance to weathering processes. Sandstones may contain within their fabric zones of dense fabric of similar properties, but the potential explanation of the cupule floor phenomena as fortuitously coinciding with such inherent features can be safely disregarded as being statistically unviable, seen in context. Moreover, such laminar features are lacking in both quartzites and schists, which have given rise to the same phenomenon in cupules.

This lamina has only been observed in cupules on sedimentary rocks comprising amorphous silica (Fig. 12), so far at the following sites:

1. On *quartzite* at Indragarh hill, Bhanpura, India; Nchwaneng, Korannaberg site complex, South Africa; and Inca Huasi, Mizque, central Bolivia.
2. On *sandstone* at Jabal al-Raat, Shuwaymis site complex, northern Saudi Arabia; Umm Singid and Jebel as-Suqur, Sudan; Tabrakat, Acacus site complex, Libya; and Inca Huasi, Mizque, central Bolivia.
3. On *schist* at Condor Mayu 2, Santivañez site complex, Cochabamba, Bolivia.

The significance of this phenomenon is underlined by its complete absence on cupules occurring on massive crystalline alpha quartz, even on specimens of unusually large dimensions, i.e. where the estimated production coefficient ρ may be one order of magnitude greater (e.g. at Moda Bhata, India; Bednarik et al. 2005: 181–182) than of the largest sandstone or quartzite cupule possessing the conversion product. Similarly, no formation of a hardened lamina has so far been observed in extensively worked cupules on granitic facies such as those at Papagaio II, Município de Santana do Matos, Rio Grande do Norte, Brazil; or Morajhari site, Rajasthan, India (Fig. 13), despite the presence of crystalline quartz.

The thickness of the laminae formed in cupules expresses the cumulative nature of the conversion process involved: the larger and deeper the cupule is, the thicker the lamina that formed in it (Fig. 14). The statistical distribution of lamina thickness relative to cupule diameter or cupule depth expresses this, although a strong trend is not evident from the very small sample currently available (n = 11) (Table 1). The patterning, especially in the distribution of cupule depth versus metamorphosed lamina thickness, does imply a correlation (Fig. 15). Greater size and depth of a cupule, which under otherwise identical conditions would correlate directly with applied total cumulative impact energy, are apparently correlated with greater thickness of the modified lamina. Moreover, the hardened lamina is thickest in the deepest part of the cupule, the portion of any cupule that experienced the greatest application of kinetic energy. Therefore the thickness of the laminar formations found in cupules can be considered a function of the production coefficient ρ. As the conversion process gradually advances it increases the resistance of the rock to the pounding activity and progress in increasing the depth of the cupule slows down considerably.

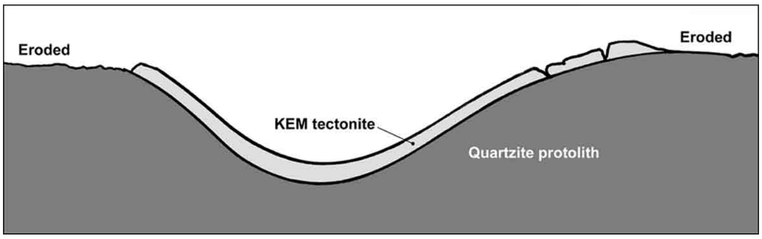

Figure 14. Section drawing of a cupule at Inca Huasi, central Bolivia, of about 70 mm diameter.

Cupule	Diameter in mm	Depth in mm	Lamina thickness in 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

Table 1. Dimensions of cupules with KEM laminae, at four sites in India, South Africa, Bolivia and Saudi Arabia.

Tectonites in cupules

It was noted above that, as a cupule becomes deeper during its production, increase in depth slows down. Initially this may be attributable to the less resistant weathering rind of the rock, the subsurface zone of a given thickness that has experienced a variety of physico-chemical changes weakening the rock fabric (e.g. hydration, oxidation, removal of cement). In addition, the geometry of the cupule demands the removal of a greater volume of material per unit of depth as its production proceeds and the diameter increases (Fig. 2). However, there is a third factor involved: at some point the floor of the cupule commences to increase its resistance to impact because a layer that is more resistance to being crushed (cf. 'composite hardness') begins to be formed gradually. It is essentially attributable to tribochemical conversion prompting the formation of tectonite. Tectonites are rocks containing minerals that have been affected by natural forces of the earth, which caused their orientations to change. The foliation formation involves an anisotropic recrystallisation of one of the components, which in the case of sandstone or quartzite is its binding cement. The cement of silica sandstones not only binds the grains; it reduces porosity and permeability as it fills the voids between the detrital clasts (Macaulay 2003). The source of the syntaxial quartz overgrowths on quartz grains can be biogenic (δ^{30}Si ~ -1–2‰) or detrital silica (δ^{30}Si ~ 0‰) but disagreement about it remains unresolved. The silica is thought to derive largely from overlying shale and sandstone beds. Sandstones can be vertically separated from potential silica sources by more than a kilometer, requiring silica transport over long vertical distances to form the cement. Mineral coatings on detrital quartz grains, such as clays, and entrapment of hydrocarbons in pores retard or prevent cementation by quartz, whereas highly permeable sands tend to sequester the greatest amounts of quartz cement (McBride 1989). The voids between the small

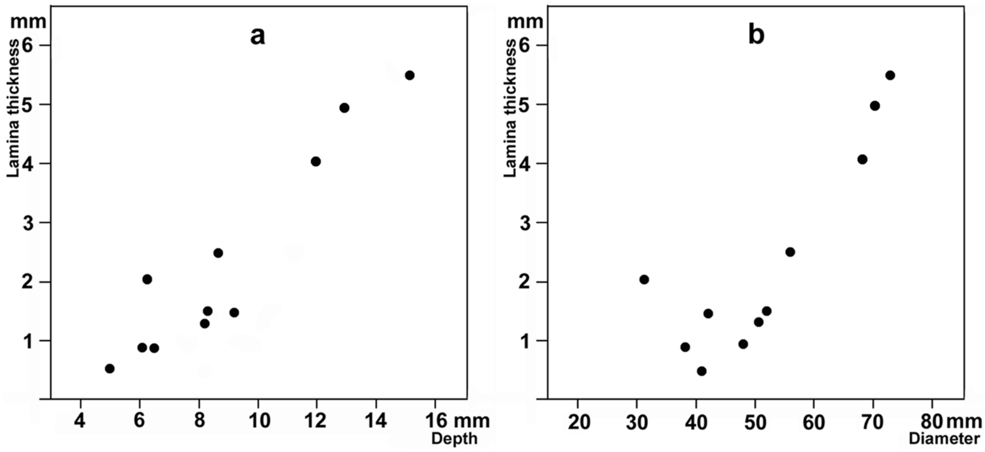

Figure 15. Metamorphosed lamina thickness plotted against (a) cupule depth and (b) cupule diameter, for a sample n = 11 cupules containing laminae formed by kinetic energy metamorphosis.

quartz clasts (the sand grains) are usually not fully occupied by cement; in fact sandstones with more than 10% imported silica cement pose the problems of fluid flux and restricted silica transport. If the silica forming the cement is transported entirely as H_4SiO_4, convective recycling of formation water has been suggested to explain the volume of cement present in most sandstones. Most cementation by quartz takes place when sandstone beds were in the silica mobility window specific to a particular sedimentary basin.

Therefore the cement in silica sandstones is usually discontinuous, containing remaining pores that provide the opportunity, under adequate temperature, pressure and tensile stresses, for ductile deformation, compressive stress and consolidation, in the form of highly localised metamorphosis. The resulting laminae retain the chemical properties of the sandstone, as does sandstone undergoing metamorphosis to quartzite, but they are significantly more resistant to erosion, becoming more dense, whitish and free of granulate texture before weathering alters them and renders the texture visible. The phenomenon of the tribochemical conversion to KEM laminae has been provisionally attributed to 'the sustained application of kinetic energy during cupule production ... has somehow created a cutaneous zone that was more resistant to weathering than the unmodified surface' (Bednarik 2008: 88). Since then it has been named 'kinetic energy metamorphosis' (KEM) and explained as a process in which the cumulative kinetic energy of tens of thousands of impact blows with hammerstones metamorphoses the cement of the rock through recrystallisation (Bednarik 2015c).

The cement of silica sandstone and quartzite comprises syntaxial quartz overgrowths on the detrital quartz grains plus the voids sealed off by this deposition. In the case of schists, the KEM lamina is probably a hornfelsed version of the protolith, i.e. the schist has been re-metamorphosed. Both the quartz grains and the overgrowths cannot be compressed, in contrast to the voids formed by the latter. The highly localised impact of energy, well above kT (product of Boltzmann constant and temperature), facilitates mechano-chemical reactions that can result in compounds or microstructures which differ from the products of 'ordinary' reactions. Reactions that cannot occur thermally become possible, rather as in photochemistry the energy of photons induces chemical conversion. The direction of the mechanical stress relative to the orientation of crystallographic axes in solids can create KEM laminae, their foliate formation deriving from an anisotropic recrystallisation of some of the components. The KEM laminae are thus chemically similar to the protolith, but very different structurally, and significantly more weathering resistant.

Three alternative potential explanations have been considered as the cause of the conversion process, but were refuted. The first was the piezoelectric hypothesis: quartz is one of the most piezoelectric substances. A 1 cm^3 cube of quartz with 2 kN (500 lbf) of correctly applied force can produce a voltage of 12.5 kV (Repas 2009). Although the actual process is not defined, it seems plausible that the very considerable kinetic force applied to a cupule made on very hard quartzite could have yielded an electric charge adequate to modify the crystal structure of the quartz grains. It needs to be appreciated and bears repeating that replication experiments have shown that to create an average-size cupule on well metamorphosed, unweathered quartzite involves several tens of thousands of blows with a hand-held hammerstone. As proposed above, a cupule of 12 mm depth on unweathered quartzite might have been subjected to a total of 20 kN of force, focused on a very small area. Some of that energy caused the fracture of rock grains and cement, and a minor component was dissipated as heat. A significant portion came to bear directly on the fabric of the rock. However, the proposition is refuted by the complete absence of modification in cupules of much greater production coefficients occurring on pure crystalline quartz (such as the Moda Bhata cases mentioned above). It suggests that the syntaxial silica cement rather than the quartz grains is being modified.

A second interpretation proposed and refuted is that the impact of the hammerstone will result in microfracture of the silica rock and therefore the formation of nanoparticles with a very high surface to volume ratios. These particles might react faster than the cupule surface, i.e. they will dissolve easily, forming reactive fluids with atmospheric CO_2 and other chemical species, thus developing a coating, a film that may be more resistant to further dissolution (pers. comm. Juan Manuel Garcia Ruiz, 5 Sept. 2013). However, this is negated by the observation that the laminar formation is not a precipitate; it is the original cupule surface and often bears evidence from the process of its manufacture (such as fractured or bruised grains, including conchoidal scars).

A third alternative has been suggested by Alan Watchman, who considers the possibility that the layer could be of amorphous silica derived from chemical weathering of the adjacent rock. This possibility is negated by the presence of densely packed grains of alpha quartz, often fractured by impact, of a morphology and granulometry identical to the protolith. Although amorphous silica (silica gel) may form 'coagulate' structures, due to its inherent short-range orderliness these differ significantly from crystalline sand grains, for instance in the way they weather and fracture. Silica is 3–4 times more soluble in water than the ordered state (Fournier and Rowe 1977) and does not normally survive superficially where exposed to precipitation. There are also significant differences in the amount and rate of contaminants absorption and desorption.

Therefore the KEM hypothesis remains the only potential explanation that accounts for the relevant empirical observations.

7. Generic KEM phenomena

The phenomenon of KEM was first recognised in cupules, and it has been reported from them only in rare cases so far. That does not, however, render it an unusual or exotic peculiarity. It is a much more common occurrence in geology, where the energy causing it derives from various non-anthropogenic sources. More specifically, the conversion processes arising in shear zones of sandstone that has been subjected to great ductile stresses at high temperatures and pressures, at great depths in the earth's crust, have yielded similar products. When the shear strength, i.e. the resistance to the forces that cause two adjacent parts of a body to slide relative to each other, is exceeded, the kinetic energy involved can metamorphose sandstone to tectonite. Energy is dissipated through the deformation between the two sliding masses of rock. The asperities of one of the surfaces may plough into the other, especially if one of them is harder, and produce grooves if shear strength is exceeded (Bhushan 2013). The tear marks clearly visible in Figure 16 are the result of stick-slip (Bowden and Leben 1939), as friction force builds up to a certain value until a large enough force has been applied to overcome the static friction force, and the grooving attributable to asperities is also evident. The resulting shear-zone laminae may be tabular to sheet-like, planar or curvi-planar, randomly orientated zones of whitish, very weathering-resistant schistose tectonite (Fig. 17).

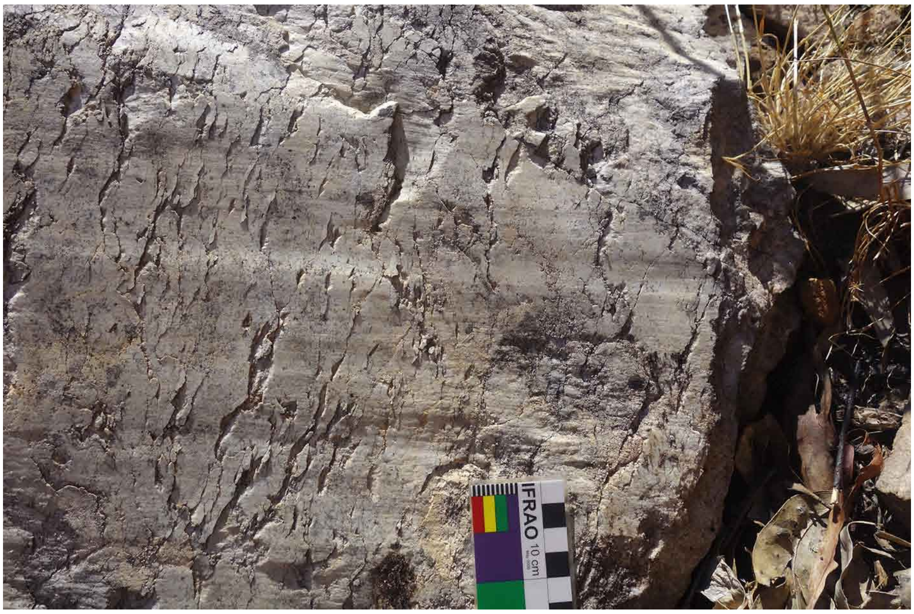

***Figure 16.** Plan view of a flat metamorphosed lamina formed in a ductile shear zone in sandstone, showing distinctive horizontal foliation grooves and tear marks; northern Gariwerd mountains, Victoria, Australia (2014).*

***Figure 17.** Randomly orientated, planar and curvi-planar ductile shear zones showing local metamorphosis, in sandstone; central Gariwerd mountains, Victoria, Australia (2014).*

KEM is also implicated in the formation of hard cutaneous surfaces on blocks or bedrock exposed to heavy barrage by fluvial battering, involving clasts accelerated by river torrents of particularly high kinetic energy. The result is similar to what has been described from cupules. Sheets of KEM laminae covering bedrock and block surfaces in palaeo-river beds so affected can be quite extensive. Such ancient rivers may have been dry for millions of years, yet the tectonite skins have survived without significant weathering for geological time spans. Another possibility is that the power of glacially induced abrasion has effected tribological conversion of a thin surface veneer on some glacial pavements, rendering them outstandingly impervious to weathering processes. An example is the c. 300 million-year-old quartzite exposures in the Korannaberg region of South Africa (Beaumont and Bednarik 2015). Their pristinely preserved polish may be the result of tribological action, although no work has so far been conducted to test this hypothesis.

Therefore KEM, although first identified in cupules, is perhaps a more widespread feature of geological processes, found wherever susceptible facies have been subjected to tribological conversion by a massive release of kinetic 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 significant levels of energy impact upon rocks susceptible to metamorphism or re-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 in future work, by methods not yet available. KEM has caused a profound change in the crystallographic fabric of the rock, and its product is probably subject to some form of decay in the course of time. The methodology for this might resemble that of thermoluminescence analysis, or it might involve radiometry of trace components trapped in the voids formed by the syntaxial quartz overgrowths on the detrital quartz grains. The prospects of securing such a dating method seem encouraging and this is certainly one of the most promising future directions of cupule research.

Future research

This paper has presented no more than an initial footing for a science of cupules, sketching out possibilities for exploring this ubiquitous feature in rock art by forensic approaches. Nevertheless, a number of obvious options for future research and its standardisation have become apparent:

1. Determining the diameter to depth ratio of cupules as well as other empirical factors, such as their volumes, need to become accepted practice to provide a standard methodology in cupule research. For the components of a recommended universal method see Bednarik (2008: 90–91).
2. The exploration of depth as a function of rock hardness as depicted in Figure 2 is of importance for several reasons, and expanding the data is a priority, perhaps to be improved by plotting hardness against diameter to depth ratios instead of considering just depth.
3. The production coefficient ρ is the crucial variable in developing research further forwards for an archaeological understanding of cupules. Its effective comprehension necessitates quantification of the 'composite hardness index' θ, therefore this is a key variable and its determination needs to be standardised.
4. A particularly interesting and no doubt rewarding direction would be to pursue the quantification of kinetic energy applied in the production of cupules, or other petroglyphs. This could be conducted as an essentially self-containing research project.
5. Obviously the phenomenon of KEM is in need of further definition and exploration, particularly its occurrence across various areas of geology.
6. Finally, the investigation of the potential to use KEM laminae in dating work is of significant potential.

Items 3 and 4 apply not only to cupules, but affect the study of all forms of petroglyphs, and are thus absolutely fundamental to a scientific inquiry of rock art.

7. Conclusion

This paper seeks to illustrate the complexity of the scientific study of rock art by focusing on just *some* of the scientific facets of a very simple motif type in rock art, the cupule. In doing so it illustrates how multifaceted a proper science of *other* rock art, which is inevitably more complex, needs to be. Impulsive etic 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 merits (Bednarik 2010a), and there is a distinct shortage of credible ethnographic explanations of cupules (Bednarik 2010b). Much the same applies to all other forms of rock art, if not more so, which should be of great concern to rock art researchers.

Here it has been shown that a forensic 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 to the makers, but may even have wider implications in other areas of science, such as in geology. The relatively rare phenomenon of KEM laminae formation in cupules observed at a series of sites in various continents has been noted most often on well-metamorphosed quartzite, but from one site it has been reported from silica-rich schist. The KEM (kinetic energy metamorphosis) lamina resembles an accretionary deposit, but the impact damage on its exterior shows that it is in fact the floor of the original cupule that has become more resistant to erosion than the support rock. It is interpreted as the result of re-crystallisation of the silica cement in the already metamorphosed protolith. KEM laminae were thus formed by re-metamorphosis, attributable to the aggregate application of kinetic energy that attends the tens of thousands of hammerstone 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 lithology, technology and taphonomy of cupules, providing a benchmark in their scientific study and a precondition to any credible 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 physical effort, kinetic energy applied and the production coefficient. Here it has been attempted 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 etic 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 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.

Acknowledgments

The author thanks the referees of this paper, Dr Mike Donaldson, Dr Yann-Pierre Montelle, Dr Amy Roberts and Dr Alan Watchman. Special thanks are due to Professor Giriraj Kumar, for his collaboration in cupule replication work, and to Professor Tang Huisheng, for organising several expeditions in China in recent years that have greatly expanded understanding of cupules; and to the Gunditj-mirring, Gunditj-mara and Pangula Mannamurna Inc. Aboriginal communities. Others who have contributed to the work reported here are Dr Liu Wuyi, Dr Wu Jiacai, Dr Peter Beaumont, Dr Juan Manuel Garcia Ruiz, Professor Majeed Khan and Professor Roy Querejazu Lewis. The remaining shortcomings of this paper are the author's responsibility.

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REFERENCES

Beaumont, P. B. and R. G. Bednarik 2015. Concerning a cupule sequence on the edge of the Kalahari Desert in South Africa. *Rock Art Research* 32(2): 163–177.

Bednarik, R. G. 1979. The potential of rock patination analysis in Australian archaeology — part 1. *The Artefact* 4: 14–38.

Bednarik, R. G. 1984. Die Bedeutung der paläolithischen Fingerlinientradition. *Anthropologie* 22(1): 73–79.

Bednarik, R. G. 1985. Parietal finger markings in Australia. *Bollettino del Centro Camuno di Studi Preistorici* 22: 83–88.

Bednarik, R. G. 1986a. Cave use by Australian Pleistocene man. *Proceedings, University of Bristol Spelaeological Society* 17(3): 227–245.

Bednarik, R. G. 1986b. Parietal finger markings in Europe and Australia. *Rock Art Research* 3(1, 2): 30–61, 162–170.

Bednarik, R. G. 1987/88. The cave art of Western Australia. *The Artefact* 12: 1–16.

Bednarik, R. G. 1992a. Natural line markings of Palaeolithic objects. *Anthropologie* 29: 233–240.

Bednarik, R. G. 1992b. Base pour des études de pointe des débuts de l'art. *L'Anthropologie* 96(2–3): 369–374.

Bednarik, R. G. 1993. About Palaeolithic ostrich eggshell in India. *Indo-Pacific Prehistory Association Bulletin* 13: 34–43.

Bednarik, R. G. 1994a. A taphonomy of palaeoart. *Antiquity* 68(258): 68–74.

Bednarik, R. G. 1994b. The discrimination of rock markings. *Rock Art Research* 11(1): 23–44.

Bednarik, R. G. 1998a. The technology of petroglyphs. *Rock Art Research* 15(1): 23–35.

Bednarik, R. G. 1998b. Microscopic analysis of 'engraved plaques' and other objects from Devil's Lair. *Journal of the Royal Society of Western Australia* 81: 23–33.

Bednarik, R. G. 2008. Cupules. *Rock Art Research* 25(1): 61–100.

Bednarik, R. G. 2010a. The interpretation of cupules. In R. Querejazu Lewis and R. G. Bednarik (eds), *Mysterious cup marks: proceedings of the First International Cupule Conference*, pp. 67–73. BAR International Series 2073, Archaeopress, Oxford.

Bednarik, R. G. 2010b. A short ethnography of cupules. In R. Querejazu Lewis and R. G. Bednarik (eds), *Mysterious cup marks: proceedings of the First International Cupule Conference*, pp. 109–114. BAR International Series 2073, Archaeopress, Oxford.

Bednarik, R. G. 2012. The use of weathering indices in rock art science and archaeology. *Rock Art Research* 29(1): 59–84.

Bednarik, R. G. 2014. Exograms. *Rock Art Research* 31(1): 47–62.

Bednarik, R. G. 2015a. The science of cupules. *Archaeometry* doi: 10.1111/arcm.12216

Bednarik, R. G. 2015b. *The first mariners*. Bentham Books, Sharjah, U.A.E. (3rd edn).

Bednarik, R. G. 2015c. The tribology of cupules. *Geological Magazine* 152(4): 758–765; doi:10.1017/S001675681500-0060.

Bednarik, R. G. 2015d. The Gondershausen petroglyphs reconsidered. *International Newsletter on Rock Art*.

Bednarik, R. G. 2015e. Dating rock art in Xinjiang Province, China. *AURA Newsletter* 32(1): 6–8.

Bednarik, R. G. 2015f. Kinetic energy metamorphosis of rocks. In B. Veress and J. Szigethy (eds), *Horizons in Earth Science Research* 13: 119–134. NOVA Science Publishers, New York.

Bednarik, R. G. in press a. Horse and bull petroglyphs of Europe. *Bollettino del Centro Camuno di Studi Preistorici* 40.

Bednarik, R. G. in press b. The science of cupules. *Archaeometry* doi: 10.1111/arcm.12216

Bednarik, R. G., G. Kumar, A. Watchman and R. G. Roberts 2005. Preliminary results of the EIP Project. *Rock Art Research* 22(2): 147–197.

Bednarik, R. G. and J.-P. Montelle 2012. Forensic replication work with Australian cave art. Paper presented at the IFRAO Congress in La Paz, Bolivia, in Session 2, 'Scientific study of rock art' on 26 June.

Bhushan, B. 2013. *Principles and applications of tribology*, 2nd edn. John Wiley and Sons, New York.

Bowden, F. P. and L. Leben 1939. The nature of sliding and the analysis of friction. *Proceedings of the Royal Society London* A169: 371–391.

Bruder, S. J. 1983. *Archaeological investigation at the Hedgpeth*

Hills petroglyph site. Research Report 28, Museum of Northern Arizona, Flagstaff.
Duwe, S. and K. Anschuetz 2013. Ecological uncertainty and organizational flexibility on the prehispanic Tewa landscape: notes from the northern frontier. In B. Vierra (ed.), *Mountain and valley: understanding past land use in the northern Rio Grande valley*, pp. 95–112. University of Utah Press, Salt Lake City.
d'Errico, F. 1991. Microscopic and statistical criteria for the identification of prehistoric systems of notation. *Rock Art Research* 8(2): 83–93.
d'Errico, F. 1992. The study of engraved notches and their statistical analysis. *Rock Art Research* 9(2): 131–132.
Fournier, R. O. and J. J. Rowe 1977. The solubility of amorphous silica in water at high temperatures and high pressures. *American Mineralogist* 62: 1052–1056.
Francaviglia, V. M. 2005. Le copelle dell'area di El-Geili (Sudan). Rapporto preliminare. *Sahara* 16: 169–172.
Iyengar, K. T. and S. Raviraj 2001. Analytical study of fracture in concrete beams using blunt crack model. *Journal of Engineering Mechanics* 127: 828–834.
Jeançon, A. 1923. *Excavations in the Chama valley, New Mexico.* Bulletin 81, Bureau of American Ethnology, Washington, DC.
Jost, P. 1966. *Lubrication (tribology): a report on the present position an industry's needs*. Department of Education and Science, Her Majesty's Stationery Office, London.
Kajdas, C. 2013. General approach to mechanochemistry and its relation to tribochemistry. In H. Pihtili (ed.),*Tribology in engineering*. InTech, no page numbers.
Krishna, R. and G. Kumar 2015. Understanding the technology of very small cupules in Daraki-Chattan, India. Paper presented at the IFRAO Congress in Cacères, Spain, in Session 3, 'Scientific study of rock art' on 1 September.
Kumar, G. 2007. Understanding the creation of early cupules by replication with special reference to Daraki-Chattan in India. Paper presented to the International Cupule Conference, Cochabamba, 17–19 July.
Kumar, G. and R. Krishna 2014. Understanding the technology of the Daraki-Chattan cupules: the cupule replication project. *Rock Art Research* 31(2): 177–186.
Macaulay, C. 2003. *Low temperature quartz cementation of the Upper Cretaceous white sandstone of Lochaline, Argyll, Scotland.* University of Edinburgh Micro-analysis Unit, 4 pp.
McBride, E. F. 1989. Quartz cement in sandstones: a review. *Earth-Science Reviews* 26(1–3): 69–112.
Miller, M. T. 2003. Crime scene investigation. In S. H. James and J. J. Nordby (eds), *Forensic science — An introduction to scientific and investigative techniques*. CRC Press, New York and London.
Montelle, Y.-P. 2009. Application of forensic methods to rock art investigations — a proposal. *Rock Art Research* 26(1): 7–13.
Mountford, C. P. 1976. *Nomads of the Australian desert*. Rigby, Adelaide.
Ortiz, A. 1969. *The Tewa world: space, time, being, and become in a Pueblo society*. University of Chicago Press, Chicago.
Parsons, E. C. 1929. *The social organization of the Tewa of New Mexico*. The American Anthropological Association, Menasha, WI.
Pilles, P. J. 1976. Appendix I: Consultant's report on the petroglyphs of the ash disposal area. In D. R. Keller and D. M. Goddard (eds), *Final report for the Cholla power plant expansion: ash disposal area impact mitigation studies*, pp. 1–10. Museum of Northern Arizona, Flagstaff.
Repas, R. 2009. Sensor sense: piezoelectric force sensors. Some materials generate an electric charge when placed under mechanical stress. Machinedesign.com, *http://machinedesign.com/sensors/sensor-sense-piezoelectric-force-sensors* (retrieved on 11 Dec. 2013).
Rosiwal, A. 1898. Über geometrische Gesteinsanalysen. Ein einfacher Weg zur ziffermässigen Feststellung des Quantitätsverhältnisses der Mineralbestandtheile gemengter Gesteine. *Verhandlungen der Kaiserlich-Königlichen Geologischen Reichsanstalt Wien* 1898: 143–175.
Querejazu Lewis, R., D. Camacho and R. G. Bednarik 2015. The Kalatrancani petroglyph complex, central Bolivia. *Rock Art Research* 32(2): 219–230.
Savvateyev, J. A. 1977. *Zalavruga, cast' II. Stojanki*. Nauka, Leningradskoe otdelenie, Leningrad.
Sierts, W. 1968. How were rock engravings made? *South African Journal of Science* 64: 281–285.
Taçon, P. S. C., Tang H., M. Aubert, Wang J. and Wang B. 2016. 'Naturalistic' animals and hand stencils in the rock art of Xinjiang Uyghur Autonomous Region, north-west China. *Rock Art Research* 33(1).
Tang H. 2012. New discovery of rock art and megalithic sites in the Central Plain of China. *Rock Art Research* 29(2): 157–170.
Tang H., R. G. Bednarik and G. Kumar 2014. Preliminary report of the 2014 rock art dating expedition of China. *Purakala* 24: 13–25.
Tang H., G. Kumar, Liu W., Xiao B., Yang H., Zhang J., Lu Xiao H., Yue J., Li Y., Gao W. and R. G. Bednarik in press. The 2014 microerosion dating project in China.
Weeks, R. 2001. Indirect percussion: fact or fiction? *American Indian Rock Art* 27: 117–121.
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