KEYWORDS: *Cupule – KEM lamina – Taphonomy – Daraki-Chattan Cave – Central India*

SCIENTIFIC STUDY OF THE CUPULES IN DARAKI-CHATTAN CAVE, INDIA

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Abstract. Daraki-Chattan Cave, a Lower Palaeolithic cupule site in the Chambal basin in India, is one of the oldest known rock art sites in the world. Containing more than 500 cupules, it has been studied by the EIP Project since 2000 and the sediment deposits at the cave's entrance have been excavated. This paper presents an analysis of the cupules in the cave as well as those of another, nearby site at Chanchala Mata Hill. The formation of the erosion-resistant surfaces in the cupules is explained and how it facilitates their enhanced preservation. However, the taphonomy of these extremely resistant tectonite layers not only protects the cupules from weathering, but it has also significant retarding effects in the production of such features. Future work needs to focus on the relationship between cupules, KEM phenomena and the quantification of weathering processes.

1. Introduction

The quartzite cave of Daraki-Chattan at Indragarh Hill near Bhanpura, central India — one of the oldest known rock art sites in the world — features more than 530 cupules on its walls, floor and on exfoliated rock fragments that were recovered from the sediment (Fig. 1). These are of particular importance because they have been excavated from most of the site's sediment layers, almost down to bedrock. These sediments comprised, from the top, Middle Palaeolithic, Acheulian and handaxe-free Lower Palaeolithic stone tools (Kumar 1996; Bednarik et al. 2005). Moreover, some of the hammerstones used in the production of cupules were also found in the lowest layers with their Oldowan-like lithic industry. Therefore, at least some of the cupules were made at the same time as the early Lower Palaeolithic stone tools, which places them at the time of the very beginning of rock art production. Only one other rock art corpus of apparently similar antiquity is known, in Auditorium Cave at Bhimbetka, also in central India (Bednarik 1993). It features a very similar sequence of sediments of human occupations, except that in the Bhimbetka site, the lowest occupation layers are separated from the overlying Acheulian by a sterile horizon containing pisoliths. The latter indicate a significant environmental shift, which at Daraki-Chattan is marked by the deposition of ferruginous accretions on the lower lithic material, both on stone implements and natural clasts.

Figure 1. The location of Daraki-Chattan Cave in India.

One of the issues to be clarified is how it was possible that the cupules in Daraki-Chattan could have survived such enormous periods. The longevity of petroglyphs is a function of the rock's resistance to erosion and other environmental factors. The relative susceptibility of any petroglyph to erasure or erosion by natural means (be it aeolian, fluvial, marine, solution or any other agent) is roughly proportional to the time it takes to create it (Bednarik 2012: 79). This tribological axiom is of fundamental importance to the science of rock art (Bednarik 2019). The time required to fashion a petroglyph is a known variable (in the sense that it can be determined by replication); therefore, the relative longevity of a given petroglyph is predictable. In the case of the cupules of Daraki-Chattan, replication experiments on the same rock near the cave have established that a 9.0 mm deep cupule involved 17 300 strokes in 138 minutes spread over two days; another, made by focusing on the centre of the pit, also ended up 9.0 mm deep and required 28 327 strokes in 372 minutes. It was also attempted to create a slightly triangular cupule, matching one of these found in the cave. This involved a total of 111 261 strokes over 812 minutes but included experimentation with indirect percussion which proved completely ineffective. Essentially, to make the deeper ancient cupules each required between 50 000 and 100 000 strokes with a hammerstone and some even more than that (Kumar and Krishna 2014). That would be more than 1000 times the time needed to create similar cupules on un-metamorphosed but weathered sandstone (Bednarik 1998). On that basis, it is reasonable to assume that the quartzite cupule would survive in the order of 1000 times longer than an identical cupule on weathered sandstone, in the same environment. However, the protected location within a cave would accentuate the difference even more.

There are effectively three factors that contributed to the extremely long survival of the Daraki-Chattan petroglyphs. Firstly, the rock is a fully metamorphosed quartzite, one of the two most resistant rock types that have ever been decorated with petroglyphs (the other being crystalline white quartz). Secondly, the cave is subjected only to limited water runoff during heavy rains, and most of it experiences no solar radiation. Therefore, degradation by weathering processes is limited relative to an open site. Significantly, despite these factors, many of the wall cupules provide clear indications that the rock surface around them has retreated considerably since the cupules were made. Finally, there is one more factor that facilitated the survival of this rock art over immense periods, and it is the primary topic of this paper. A survey of the several hundred wall cupules suggests that many specimens feature what appear to be hardened surface laminae in their interior, although in some it may be concealed by accretions or by thin black lichen.

2. Examination of the Daraki-Chattan cupules

This work was conducted from 8 to 21 November 2016. Field microscopy was performed by binocular light microscope, using a custom-modified Motic SMZ143 stereo-zoom microscope equipped with an internal ocular scale (Fig. 2), as well as by two digital microscopes. Related samples from other sites were subjected to laboratory examination by a Nikon SMZ1000 binocular light microscope; by scanning electron microscope Jeol JSM-35; by Zeiss Axiotron microscope with an MCU26 3 axis controller and 10

Figure 2. *Field microscopy of the western-most part of the north wall of Daraki-Chattan Cave (photo by RGB).*

MP Moticam camera; and by SEM combined with EDAX EDS x-ray detector using WINEDS software. Field microscopy in Daraki-Chattan commenced with cupule 36 on the cave's south wall, which contains a prominent surface layer visible on two edges, consequently found in many other specimens. Definite and clearly discernible surface laminae on the south wall were also detected in cupules 44 and 45. These are small and were truncated by subsequent exfoliation, which means that only the deeper, central part of the original cupule has survived. Further examples on the south wall are cupules 36, 35, 34, 33, 6, 8, 4, 5 and 16A (Fig. 3-S). Many other hardened surface layers appear to be concealed by accretionary deposits or lichen cover. On the cave's north wall, many further cupules show clear and unmistakeable surface layers: 16A, 31, 30, 15A, 14A, 2, 3, 4, 5, 22, 24, 27, 47, 48, 50, 140, 135, 121, 115, 113, 110, 159, 158, 162, 164, 174, 173, 171, 172, 181, 144, 201, 208, 205, 206 and 219 (Fig. 3-N).

Examination of these 48 cupules suggests a tendency of finding the best-developed tectonite layer in the largest and especially the deepest specimens, including those that became truncated by wall exfoliation. Another finding is that cupules 33 to 36 inclusive, forming a small group on the south wall, all show microscopic residues of red pigment on their

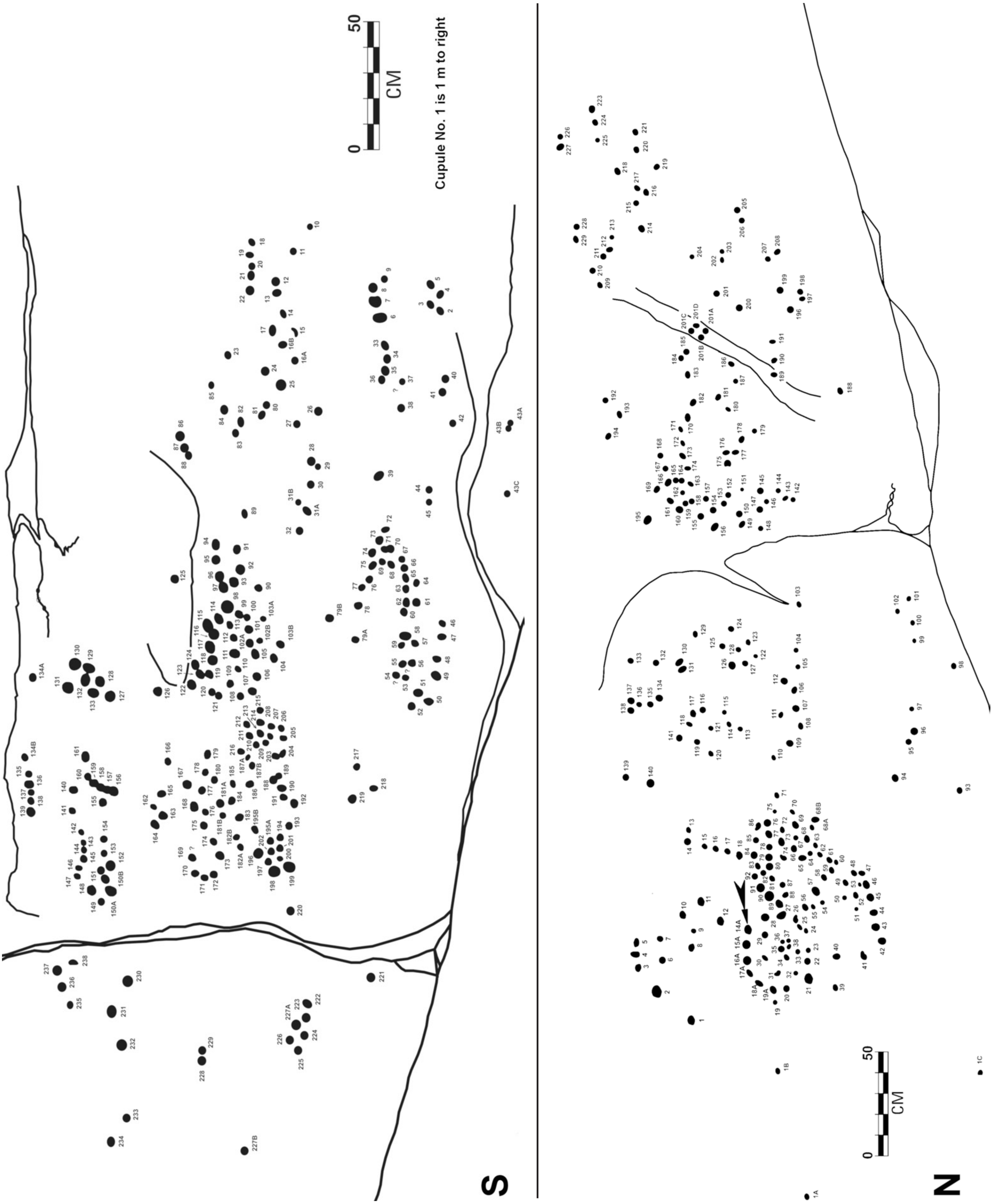

***Figure 3.** The distribution of cupules on the south wall (S) and north wall (N) of Daraki-Chattan as originally determined in 1996. More cupules have since been detected (image by GK).*

floors (Fig. 4). Although these remains occur as very isolated, discontinuous remnants found only in tiny recesses, they seem to have once formed a continuous coating of the cupule interiors. This red pigment occurs as very tiny haematite flakes adhering to recesses, but elsewhere on the cupule floors, reddish discolouration of the quartz is evident, resembling typical painting pigment 'shadows' as they are often found on sandstone. Therefore, it can be assumed that these cupules were once coated by red paint, assumed to be ferruginous. This was not detected in any of the site's many other cupules.

Figure 4. *Cupules 36 to 33 (from left to right), south wall, with significant KEM development and evidence of having been covered in red pigment. Only the deepest parts of the cupules have survived laminar exfoliation of the surrounding rock substrate (photo by RGB).*

In the course of these studies, cupule 14A on the north wall emerged as the main object of investigations, because it is not only the largest of the cupules but also the deepest and one of the best-preserved. It is one of many if not most cupules in the cave that are now shallower than at the time they were created because the rock surface surrounding them has retreated. The magnitude of that retreat is unknown, but we estimate it to be between 5 mm and 20 mm in cupule 14A. Today the cupule is 46 mm wide and high and 18.0 mm deep, therefore it may have been 23–38 mm deep at the time it was created. All other cupules in the cave, including those that appear fully preserved, are under 15 mm deep today. The most common depths in the larger-diameter category are between 12 mm and 14 mm. Careful consideration of several laminar exfoliation scars around cupule 14A that have reduced its depth (and to a small degree its diameter) yields the most realistic former depth estimate of c. 25 mm, which based on replication work can be safely assumed to have involved well over 100 000 hammerstone blows. Not surprisingly, it features also the most pronounced tectonite development seen in any cupule. This feature is particularly well sectioned and visible along the left margin of the cupule (Fig. 5).

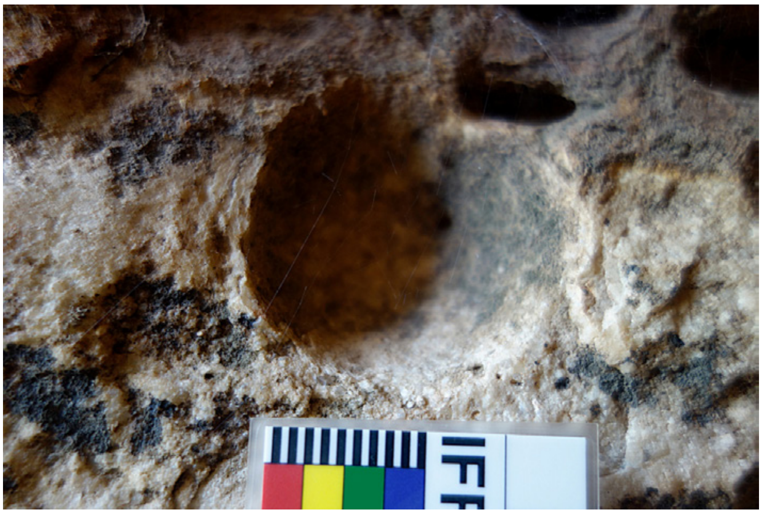

Figure 5. *Cupule 14A, north wall of Daraki-Chattan, which features the most extensive KEM conversion evidence ever observed (photo by RGB).*

The thick surface layer of 14A consists of fully crystalline quartz that has shattered into reticulate patterns, such as rectangular fragments. It ranges in thickness from 2.0 mm to 2.4 mm and is separated from its immediate substrate by a somewhat irregular fissure parallel to the cupule's interior. The fissure is in places only 40 μm wide and appears to result from material stress. The surficial tectonite appears to be fully converted and microscopically there is no granularity detectable in the structure; all traces of the former quartz grains have become obliterated. The grains and the amorphous silica have coalesced into a single mass, rather as if fused or molten. There is also no trace of crystal structures; therefore, any re-crystallisation process can also be excluded. The fully developed tectonite includes areas of shingle-like arrangements of plate-like (foliate) fragments and reticulate arrangements reminiscent of Voronoi cells, all of which appear 'reorientated' or fused. Most importantly, a thorough search reveals no presence of partial hexagonal structures, so the modification process is not

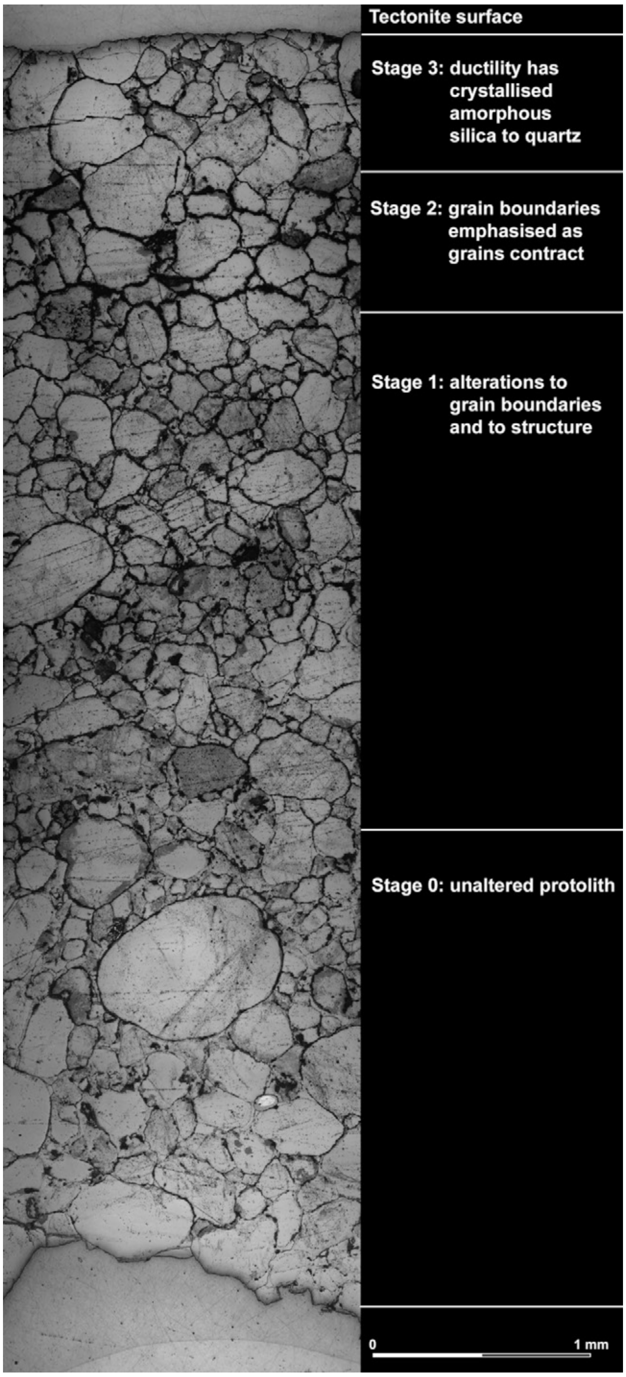

Figure 6. Composite SEM microphotograph of a thin section through the zones of modification of a geological KEM sample (image by RGB).

some form of crystallisation. The platelets convey the visual impression that the conversion process is more akin to a ductile re-formation resembling foliate mica plates because some of the rectangular fragments bear perfectly flat surfaces. The reticulation patterns appear to dominate at the depth of 0.5–1.0 mm.

Beneath this tectonite lamina, which manifests itself as a single translucent mass of quartz, is a substrate that grades into the protolith, beginning at c. 2.4 mm depth. In this substrate of partial conversion, the quartz grains are readily recognisable. They are generally of diameters in the vicinity of 250 μm, but the amorphous silica has been modified and in some cases has formed concentric 'halos' around grains. At the left margin of cupule 14A, some degree of modification seems apparent up to about 10 mm from the surface, which is far more than what is seen elsewhere.

3. Defining the KEM conversion

The phenomenon observed as an apparently hardened surface layer in many of the cupules in Daraki-Chattan had been identified before at sites in several continents (Bednarik 2015a, 2015b, 2016a, 2016b, 2016c) before the work described here. In fact, it had been observed since 1987, having first been detected at Inca Huasi in Bolivia (Bednarik 2000), later at sites in Saudi Arabia, the Sahara and South Africa as well, and finally in China. In most cases, it had been found in sandstone and metamorphosed sandstone (quartzite). The kinetic energy metamorphosis (henceforth KEM) hypothesis explains the formation of these erosion-resistant surface layers on a rock as the result of the localised application of very high levels of kinetic energy. As noted above, the production of cupules on very hard rock surfaces involved massive cumulative deployment of energy to a very small surface area. It needs to be appreciated that the total force applied could be up to some dozens of kN, focused on a very small area. This modified the physical properties of the surface-nearest layer of rock. Such layers, while chemically similar to the supporting protolith, are significantly more resistant to weathering, being the result of crystal re-orientation and/or foliation processes. Some of the great force applied would have been dissipated as heat, sound and fracturing force, but a significant portion of it resulted in the tribological effect of further metamorphosing the already previously metamorphosed protolith and converting it to what is best defined as tectonite.

The following stages of KEM conversion have been tentatively identified by field microscopy, from the substrate to the surface (Fig. 6):

- Stage 0 – No alteration of the protolith, always >10 mm.
- Stage 1 – Grains remain clearly visible and no concentric 'halos' or 'fused' appearance are evident, 5–10 mm from the surface in the most extreme case.
- Stage 2 – Few grains remain recognisable and they may have concentric 'halos' indicating that the tribological modification from amorphous to crystalline silica is well developed, 2.4–5 mm from the surface in the case of cupule 14A.
- Stage 3 – Body of completely metamorphosed, crystalline quartz of foliate texture, surface to <2.4 mm depth.

Typically, the converted layer is laminar, whitish or pale in colour and thickest where the most impact has evidently occurred, i.e. in the cupule's deepest part. In tectonites, minerals have changed their orientations and this foliation involved an anisotropic re-crystallisation of a component. In the case of sandstone or quartzite, this is its silica cement. It binds the quartz grains and 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 ($\delta^{30}Si$ ~ -1–2‰) or detrital silica ($\delta^{30}Si$ ~ 0‰). Mineral coatings (e.g. of clays) and entrapment (e.g. of hydrocarbons, clay minerals) retard the syntaxial deposition (McBride 1989) and the voids between the detrital quartz grains are not fully occupied by cement (Bednarik 2015c). This provides the potential for re-metamorphosis of the quartzite protolith, and metamorphosis of the sandstone or schist.

Since it was discovered on cupules of several continents, KEM has been detected on a much larger scale as a process affecting various types of geological surfaces. It has been studied in the greatest detail as a result of fluvial bombardment of bedrock by clasts propelled with great energy in rivers (Fig. 7), in palaeochannels of geological ages (Bednarik 2019). The same products have also been observed in response to aeolian bombardment, as in sandstorms, and to glacial abrasive action. Glacial polish has traditionally been assumed to be the result of a process of progressive removal of material until the surface becomes optimally smooth (Iverson 1991; Benn and Evans 2010). This fails to explain the apparent hardening of the superficial lamina. A more recent explanation (Siman-Tov et al. 2017) mentioned the deformation of crystals and speculated about the involvement of a rock flour paste and silica gel. These authors are themselves puzzled as to why the surface layer exfoliates at a thickness much greater than the thickness of the modified layer they perceive. This and other aspects of glacial polish are much more compellingly explained by viewing the phenomenon as a KEM product: beneath the visually distinctive lamina are layers of various degrees of crystallisation and/or ductilisation. Similarly, the sheen seen on ventifacts, which are created by the bombardment with airborne sand and smaller grains, needs to be explained in tribological terms. Such features range in size from small stone artefacts to large bedrock exposures and are particularly common in arid environments; they are also KEM outcomes.

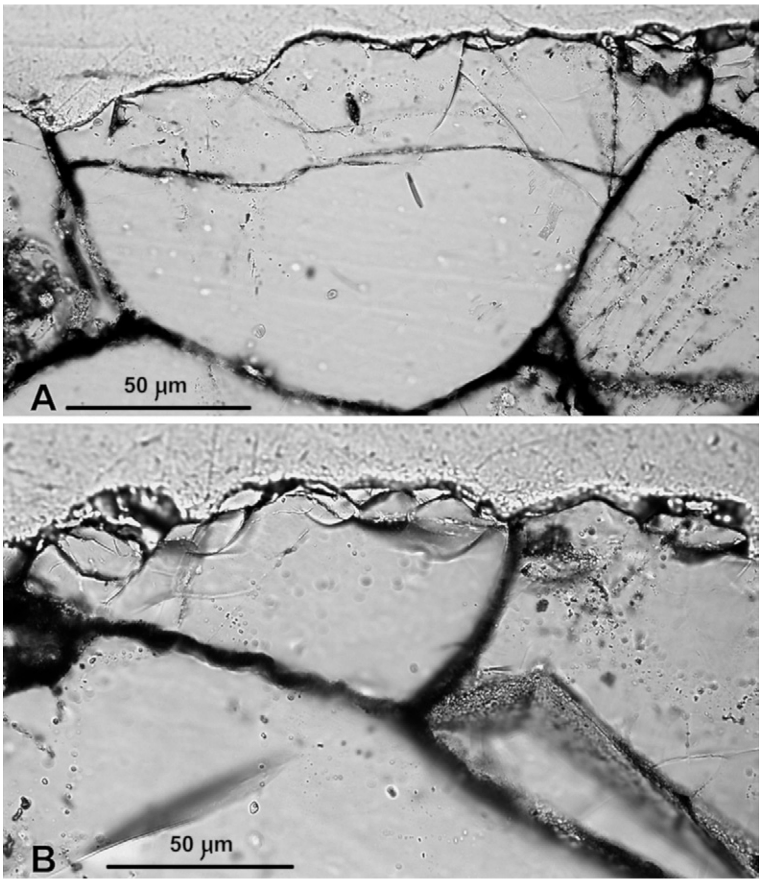

Figure 7. *Two thin sections of quartz grains that were truncated at the surface by fluvially propelled clasts, seen by scanning electron microscopy. What appears to be a very smooth surface is a surface of heavily battered grains (image by RGB).*

However, all these geological phenomena have been poorly explored because the nexus between geology and tribology has been severely neglected until now. There are still other applications of tribology in geology to be explored, and the applications of tribological science in archaeology and rock art science have remained uncharted so far. Other such discoveries are waiting in the exploration of KEM phenomena in seismogenic fault friction and the formation of fault mirrors generally. A fault is a planar fracture or discontinuity in a rock mass, formed by relative displacement of rock. At a very large scale, such faults are the result of plate tectonic forces along the boundaries between the plates. Faults occur also on much smaller scales, even at the millimetre scale. The slip in active faults can result in highly reflective or mirror-like slip surfaces formed by thin laminae of nanogranular, modified rock. Such fault rock has been reported from many different lithologies (e.g. Verberne et al. 2014; Siman-Tov et al. 2015; Bednarik 2019) and it stands to reason that their significant releases of kinetic energy are responsible for the formation of these particular tectonite formations.

In short, KEM phenomena are very common in geology but have not been properly understood until now. They can be defined as the reaction of surface-near rock layers to the application of intensive kinetic energy and the tribological alteration of the rock fabric rendering it more resistant to deformation, compression and erosion. To appreciate the nature of the process of formation it can be understood as comprising three stages, reflecting the intensity and duration of energy application. The greatest change in the material occurs at the contact surface, and the effect tends to be lesser with increasing depth. At cupule 14A in Daraki-Chattan, stage 3 modification is found on

Figure 8. The sixteen cupules arranged in a double row at Chanchala Mata 1, most bearing light-coloured KEM laminae; they are numbered from right to left (photo by RGB).

its left and right margins, while the upper and lower margins are less metamorphosed, which implies that less energy was applied there. Nevertheless, this cupule features the most intensive development of KEM lamina so far found anywhere in the world. This is a very significant point because as a surface is impacted upon, it becomes increasingly resistant to further deformation or ductilisation. This means that the more its surface is hammered by the cupule maker, the less it will yield by increasing its depth. There appears to be a point at which the cupule floor will not yield further and energy is dissipated deeper into the rock. Cupule 14A may closely approximate that point of near-equilibrium: it needs to be regarded as the one point known in the world that provides the most extreme development of KEM lamina — it is a scientific reference point like absolute zero temperature or the standard metre in Paris. For that reason alone, Daraki-Chattan needs to be protected most effectively: it contains a universal scientific reference point.

In practical terms, if it were not for the KEM-caused tectonite layers, few of the cupules in Daraki-Chattan may have survived. If the interior of these cupules would have eroded at the same rate as the surrounding rock surfaces, most would have been rendered indistinguishable. In other words, the main reason for their survival is perhaps not the sheltered location, but the tectonite layer protecting them, combined with their great depths. It was noted that microscopy of the replication cupules south of the cave detected initial stages of modification in two of them: patches of flattened surface featured incipient signs of ductilisation.

4. Examination of hammerstones

Seventeen hammerstones from the excavation of Daraki-Chattan were also scanned for evidence of KEM development. Not one of them showed fully developed tectonite. On the contrary, the battered hammerstone facets feature fragmented surfaces, evidence of granular loss through percussion and fracture scars, including step-flaking. One specimen, No. 541, is a heavily rolled cobble from 47 cm depth below the surface that shows thin KEM development on several natural surfaces, which is best preserved on surface aspects of low radii. The battered facets have truncated this incipient, stage <1 lamina that derives from the fluvial transport of the cobble. The only hammerstone examined that exhibits a trace of KEM conversion on one of its impact facets is artefact No. 530. An incipient form of KEM lamina, stage <0.5, can be observed on this specimen. The effects of the granular exfoliation caused by the impact are best expressed on the following tools: 207, 220, 448, 449 and 514.

It is obvious from the vertical distribution of the stratified hammerstones in DC that the cupules in the cave must range greatly in age, as the tools used in their production were found at many depths (Kumar et al. 2016). The same is evident from relating the cupules to the multitude of exfoliation scars that have affected most of them. Not only have cupules been produced over a very long time; it needs to be questioned how many of the earliest phases of their production might have survived to the present, at least partially. This is an issue of taphonomic logic (Bednarik 1994): as a phenomenon category, the cupules have increased in number over time, as successive hominins observed earlier ones and adopted/adapted cupule-making behaviour. At the same time, the rock surfaces are receding through three processes: granular exfoliation, laminar exfoliation and rare unloading events resulting in the removal of substantial slabs (the latter by insolation near the cave's entrance). Therefore, it is reasonable to assume that much of the earliest evidence has been lost to these erosional processes, and it is perfectly possible that only a small cohort survives from the earliest cupule making activity. The issue, very simply, is that the taphonomic threshold of these extremely resistant phenomena remains unknown — but can be assumed to be very early indeed. Future work is likely to solve this problem, most likely by reference to the relationship between cupules, KEM phenomena and the quantification of weathering processes. This work, however, remains in its infancy — as does all of rock art research.

5. The Chanchala Mata 1 cupules

As part of this study, the KEM cupules at a site on the part of Chanchala Mata Hill immediately adjacent to the Indragarh Hill were examined more closely. Although not part of Daraki-Chattan and very much younger than the cupules in that cave, they are relevant to the study of the cupules and are only 300 m from the cave. The cupule site is about 120 m from the paleo-channel separating the two hills and it occurs amidst a group of other panels with cupules, none of which show any KEM lamina.

This site consists of a flat horizontal panel of sixteen cupules arranged in a double row (Fig. 8). They were numbered from W to E, and the last two contain no tectonite (Table 1). Cupule No. 3 has a large clear quartz grain in its north-western quadrant, 720 μm long and 530 μm wide at its widest point. It bears a flat-battered facet that is level with the surrounding flat surface of the KEM lamina but separated from it by removed mass (colloid silica). The rounded margin of the facet could be mistaken for a micro-wane that would point to middle-Holocene antiquity, but such age would seem to be contradicted by the observation that exfoliation of the KEM has commenced on these cupule floors, progressing inward from the peripheries. Generally, the grains are dominated by the fraction between 150 μm and 300 μm. All 14 cupules with tectonite are surrounded by a significantly eroded surface that has retreated by up to several mm. Cupule No. 1 also features a large grain, but this is outside the clear KEM zone and its inclusion in the cupule area is doubtful. Of interest is also cupule No. 12, which possesses a damaged central area of the tectonite lamina, in contrast to all other KEM cupules. This may be either due to the involvement of impact or due to weaknesses in the fabric of the underlying substratum. The latter is more likely unless the impact occurred at a more recent time than cupule production.

Cupule No.	Diameter N-S, in mm	Diameter E-W, in mm	Depth in mm	KEM cover %
1	53	49	6.1	90
2	51	49	6.5	80
3	48	47	5.8	75
4	48	52	6.0	70
5	50	47	5.1	70
6	42	51	4.9	65
7	47	50	6.2	65
8	48	48	5.4	65
9	44	44	6.1	90
10	42	43	4.9	65
11	46	46	7.0	85
12	40	42	5.1	50
13	43	41	2.5	80
14	54	46	4.8	70
15	46	42	2.8	0
16	44	40	5.0	0

Table 1. *The 16 cupules of the KEM cupule site at Chanchala Mata 1 site.*

The KEM modification stage at the Chanchala Mata 1 site is determined as follows. Most converted amorphous silica cement has remained to the full height of the plateaus of the quartz grains and few of these cement bodies are missing. This would support relatively recent antiquity. In cupule No. 3, no gaps are visible between the grains and the converted cement bodies, with only limited erosion of them having occurred. The modification seen on these cupules has been defined as being of stage 1.8 to 2.0, being variable between locations and individual cupules.

As is evident from Table 1, the cupules at this site are quite uniform in size: all are between 40 and 54 mm in diameter, and except for one of the KEM-free cupules, their depths only vary from 4.8–6.2 mm. One half or more of the KEM lamina has been preserved in each one. It is not clear why No. 16 lacks tectonite.

6. Conclusion

The microscopic study of the cupules in Daraki-Chattan Cave suggests the importance of the formation of erosion-resistant KEM surface strata (the tectonite layer) in the preservation of these cupules. KEM (kinetic energy metamorphosis) is a tribological phenomenon first observed in cupules (Bednarik 2015a, 2019). Daraki-Chattan contains the most extreme development of a KEM feature currently known in the world, in the form of cupule 14A on the northern wall. Its surface layer features the complete conversion of quartzite to fully crystalline quartz.

The present study also explains that the main reason for the extremely long survival of the cupules in Daraki-Chattan is the tectonite layer protecting them, combined with their great depths. While the cupule floors remain superbly preserved, the surrounding rock panels have experienced extensive granular and laminar exfoliation that has reduced the depth of many if not most cupules with time. Thus if they were shallower, they could have been erased by exfoliation, while at the same time the thickness of their tectonite laminae is a function of their depth. Therefore, the interplay between cupule depth, tectonite thickness and weathering processes is the key to understanding these phenomena and their potential antiquity.

This study confirms that the cupules in the cave were produced over a long period of time, confirming the archaeological finding that the hammerstones used in their production derive from many different sediment layers. It is therefore likely that the cupules with the best developed KEM layers are among the oldest that have managed to survive in this site.

Finally, the study also considered the condition of some of the recovered hammerstones, and it examined a nearby open-air cupule site a few hundred metres from the cave.

Acknowledgements

We thank the Indian Council of Historical Research, New Delhi, and the Australian-India Council, Canberra, for their support of this project. ICHR Grant No. F. No. 1-18/2016-ICHR (GIA-III) RP and AIC-DFAT Grant No. 81-2016 refer.

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RAR 36-1292