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Rock Metamorphosis by Kinetic Energy

Robert G. Bednarik [a, b*]

[a] *International Center for Rock Art Dating, Hebei Normal University, Shijiazhuang, China*

[b] *International Federation of Rock Art Organizations, Melbourne, Australia*

Abstract

The objective of this work was to test the hypothesis that weathering-resistant surface layers found in intensively hammered petroglyphs at many sites worldwide and on other heavily battered metamorphosed rocks are the result of kinetic energy-induced tribological reactions. The methods of material testing included extensive fieldwork and in-situ studies at an Indian site that had been subjected to fluvial battery in the distant geological past; the removal of numerous surface and subsurface samples; and their analysis by several laboratory methods. These included binocular light microscopy, scanning electron microscopy, thin sectioning and elemental composition determination of crucial sites. It was confirmed that samples show evidence of crystallization by ductility of formerly amorphous silica cement in quartzite, yielding a tectonite of fully crystalline quartz. This finding confirms that the surficial application of very high levels of kinetic energy to certain rock types that are susceptible to metamorphosis can yield exceptionally weathering-resistant surface layers. This phenomenon has not been described before. Although it was first observed in rock art it is now thought to occur much more widely in numerous geological contexts, such as at fault mirrors, in the form of what has been regarded as glacial polish and on ventifacts.

Keywords:

Kinetic Energy Metamorphosis;
Petroglyph;
Quartzite;
Fluvial Battery;
Tribology;
Tectonite;
Paleo-channel;
India.

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1- Introduction

Introduced half a century ago [1], tribology is the science of interacting surfaces in relative motion [2]. It has applications in numerous fields, including in geology where it has, nevertheless, been largely ignored thus far. Similarly, tribochemistry is the science dealing with the chemical and physico-chemical changes of solids due to the influence of mechanical energy [3]. Mechano-chemical reactions can result in compounds or microstructures that differ from the products of ‘ordinary’ reactions. The crucial factor of mechano-chemical reactions is the highly localized impact of energy, well above kT (product of Boltzmann constant and temperature). Reactions that cannot occur thermally become possible—in rather the same way as the reactions the energy of photons induces in photochemistry. The relevance of tribology to tectonic phenomena is self-evident, but indications of tribological reactions occur also on small scales in geology. They are the subject of this paper, introducing the phenomenon of kinetic energy metamorphosis (KEM).

KEM has been identified only recently, and initially not as a geological phenomenon. Rather, it was recognized as a by-product of an anthropogenic process: the production of petroglyphs on particular hard rock types. More specifically, the creation of cupules—spherical cap or dome-shaped depressions created by percussion [4]—involves the localized application of considerable energy. Cupules are the most numerous rock art motifs, usually between 2 cm and 10 cm in diameter but most are in the range of 3–6 cm. Replication studies have shown that when they occur on very hard rocks (specifically quartzite), many tens of thousands of blows with hammerstones were required to produce one of them (e.g. [5]. This massive cumulative deployment of energy applied to a small area has resulted in metamorphosis of some specific rock types, developing a surface lamina of tectonite. Such layers, while chemically similar to the supporting

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* **CONTACT**: Robertbednarik@hotmail.com

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protolith, are significantly more resistant to weathering, being the result of crystal re-orientation and foliation processes [6–9]. The kinetic energy applied in the creation of cupules, i.e. the ability of the mass of the hammerstone in motion to have a physical effect, derives from:

$$E_k = M.v^2 \tag{1}$$

Where M = quantity of mass in motion, v = velocity in straight line, and E_k = kinetic energy. The most intensively worked cupules currently known in the world, those on heavily metamorphosed quartzite in Daraki-Chattan Cave in India [10], appear to have required more than 100,000 percussion strokes to produce, based on replication studies. Assuming that each stroke delivered 0.4 N, the total force applied would be in excess of 40 kN, focused on an area of less than 15 cm^2. Some of this force of 40,000 $kg{\cdot}m/s^2$ (cf. Newton's second law) would have been dissipated as heat and fracturing force, but a significant portion of it resulted in the tribological effect of further metamorphosing the protolith and converting it to tectonite.

The formation of such laminae within cupules has so far been observed on three types of metamorphic rock [6, 11]:

1. On *quartzite* at Indragarh Hill, including in Daraki-Chattan Cave, near Bhanpura, India; at Nchwaneng, Korannaberg site complex, South Africa; and at Inca Huasi, Mizque, central Bolivia.
2. On *sandstone* at Jabal al-Raat, Shuwaymis site complex, northern Saudi Arabia; at Umm Singid and Jebel as-Suqur, Sudan; at Tabrakat, Acacus site complex, Libya; and at Inca Huasi, Mizque, central Bolivia.
3. On silica-rich *schist* at Condor Mayu 2, Santivañez site complex, Cochabamba, Bolivia.
4. On granite at Wushigou 1, Henan Province, China.

Typically, the converted layer is whitish or pale in color and thickest where most impact has evidently occurred, i.e. in the cupule's deepest part. Plotting of the tectonite layer's thickness against cupule diameter or depth yields a distinctive pattern of distribution [12], emphasizing that layer thickness is a function of impact intensity. Tectonites are characterized by minerals that have been affected by natural forces of the earth, which prompted their orientations to change. This foliation involves an anisotropic recrystallization of a component, in the case of sandstone or quartzite its cement. The silica cement binds the grains and reduces porosity and permeability as it fills the voids between the detrital clasts [13]. 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 [14], therefore the voids between the detrital quartz grains are not fully occupied by cement. This provides the potential for re-metamorphosis.

Since the results of this development have been first identified in a limited number of cupules worldwide, it has been discovered that what is a rare outcome of an anthropogenic practice is also a fairly common product of geomorphological processes. Several similar phenomena are considered to be tectonite formations, deriving (a) from fluvial battery; (b) from glacial tribological action [15–18]; (c) from aeolian bombardment by small particles (creating ventifacts); and (d) small-scale tectonic stresses forming fault mirrors. Because cupules are cultural relics protected by law, intrusive research into the phenomenon of KEM (kinetic energy metamorphosis) has been limited to geological expressions of the conversion process. Numerous of the more than 530 cupules in Daraki-Chattan exhibit significant KEM deposits, but these have only been examined optically, by binocular light microscopy. In this paper, particular emphasis is placed on the KEM products attributable to severe fluvial percussion, and the intensive study of a site featuring hundreds of square meters of surface tectonite caused by KEM. This is because there are no restrictions on sampling such sites of 'geological' KEM laminae.

2- The Indragarh Paleo-channel Site

To the immediate north of the small town Bhanpura in Madhya Pradesh, central India, lies the Chanchala Mata quartzite plateau, surrounded by steep escarpments. Its western extension, Indragarh Hill, is occupied by the extensive ruins of an 8th-century CE fort, and is separated from the main plateau by the residue of a paleo-channel (Figure 1). This ancient but still very distinctive feature runs in a roughly north-south direction, draining north and preserved over a distance of 240 m. At both ends it is truncated by the steep ramparts of the plateau, so in effect this tiny fragment of a geologically ancient river course is now at an elevation about 90 m above the course of the nearby river Rewa. The age of the channel is unknown. Following its formation millions of years ago it became submerged under at least eight strata of very coarse-grained siliceous conglomerate, which in turn were extensively eroded long ago.

Figure 1. **Satellite view of Indragarh Hill, showing the locations of Daraki-Chattan Cave (A) and the KEM sampling site (B). The 240 m long paleo-channel is shown by a dotted line. Most of the hill's plateau is covered by the ruins of a fort.**

In the northernmost part of the paleo-channel, the original bedrock has been fully exposed by this erosion process, revealing a site of former rapids leading to a small waterfall at a location where the main-channel is joined by a tributary from the east. The usually cream-colored quartzite bedrock at this location has been subjected to intensive battering by the fully rounded cobbles and small boulders swept through the paleo-channel. This bedload of purple-colored quartzite debris remains preserved in the lowest conglomerate layer. At the paleo-rapids, the channel's thalweg forms a chute allowing maximum acceleration and release of kinetic energy as the bedload became suspended. All surfaces affected by this prolonged bombardment have developed KEM laminae. However, not all of these panels have survived, because where the protective tectonite has been breached, weathering eroded the substrate and caused widespread exfoliation of the intact hardened surface. Some of the laminae are still concealed by the superimposed coarse conglomerate. The KEM lamina can even be detected on hundreds of cobbles and small boulders exposed in this lowest-most conglomerate (Figure 2).

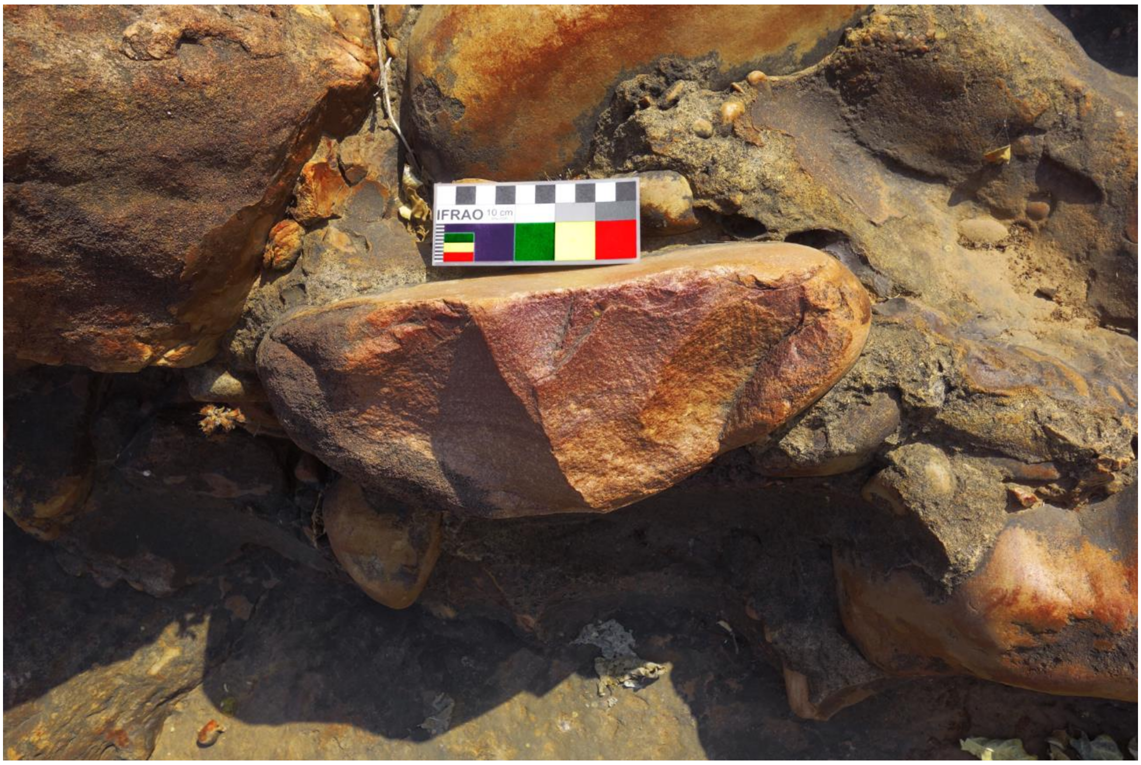

Figure 2. **Large cobbles of the conglomerate immediately overlying bedrock, bearing KEM veneers. Eastern sector of the paleo-channel site at Indragarh Hill near Bhanpura.**

3- Methods

The main focus of this study is an area within 20 m of the former waterfall in the northern sector of the described paleo-channel, located at N24° 32.095’ E75° 44.036’and at an elevation of about 467 m a.s.l. The KEM sampling site (locality B in Fig. 1) was mapped in full. Three specific sites were selected for sampling: sites 1 and 2 are on either side of the waterfall, and site 3 is in the eastern tributary channel that was formed after the erosion of much of the conglomerate to the north. A total of sixteen samples of the tribological tectonite, the weathered substrate and in some cases the unweathered protolith were collected. Each sampling location was recorded by multiple photographs, both before and after sample extraction; and in each case the sample was thoroughly examined by binocular light microscope before its removal, using a custom-modified Motic SMZ143 stereo-zoom microscope equipped with an internal ocular scale.

In the laboratory, samples were examined and photographed under a Nikon SMZ1000 binocular light microscope. This process resulted in the selection of samples of particular qualities capable of clarifying specific research questions concerning the formation of KEM laminae. These samples were placed in a vacuum, coated with either graphite or gold, and examined by scanning electron microscope Jeol JSM-35. Numerous photographs were taken, both by backscattered electron analysis and secondary electron analysis. Selected samples providing a complete sequence from the surface tectonite through to the unweathered quartzite were sectioned perpendicular to the surface and thin sections were produced. These were then examined and photographed by a Zeiss Axiotron microscope with a MCU26 3 axis controller and 10 MP Moticam camera as well as by the above SEM equipment.

The elemental composition of various specific features of samples, particularly of the uncontaminated and unweathered protolith underlying modified surface zones, was determined by Jeol JSM-35 SEM combined with EDAX EDS x-ray detector using WINEDS software. In particular, the attention of all analytical efforts was focused on three aspects of thin sections that held promise of providing information about the process of KEM: deposits at the boundaries between quartz grains and former amorphous silica cement; residual sediments entrapped in cement; and inclusions embedded in detrital quartz grains.

4- Results

4-1- Surficial Kinetic Shattering

Before examining the characteristics of the KEM layers, the kinetic effects of the bedload on the bedrock surfaces affected by fluvial bombardment were thoroughly studied at the KEM sampling site in the paleo-channel of Indragarh Hill. In Figure 3A, a quartz grain on the surface of sample PAL-2a is embedded in several bodies of formerly amorphous silica, which had been partially metamorphosed in the quartzite state but have now taken on the fracturing patterns of fully crystalline quartz. A few smaller, similarly worn quartz grains are visible in the lower part of the image, but the intervening former ‘cement’ has experienced much more distinctive battering. Further magnification reveals numerous impact traces (Fig. 3B), including even concentric wave patterns as they occur on the ventral surfaces of anthropogenic stone flakes. But what is most evident is that the patterning of the kinetic damage is identical in the ‘cement’ (in Fig. 3B appearing as the horizontal middle third in the area shown) and the upper part of the alpha quartz grain visible below it. The formerly colloid silica has lost its physical characteristics and has become indistinguishable from the crystalline quartz.

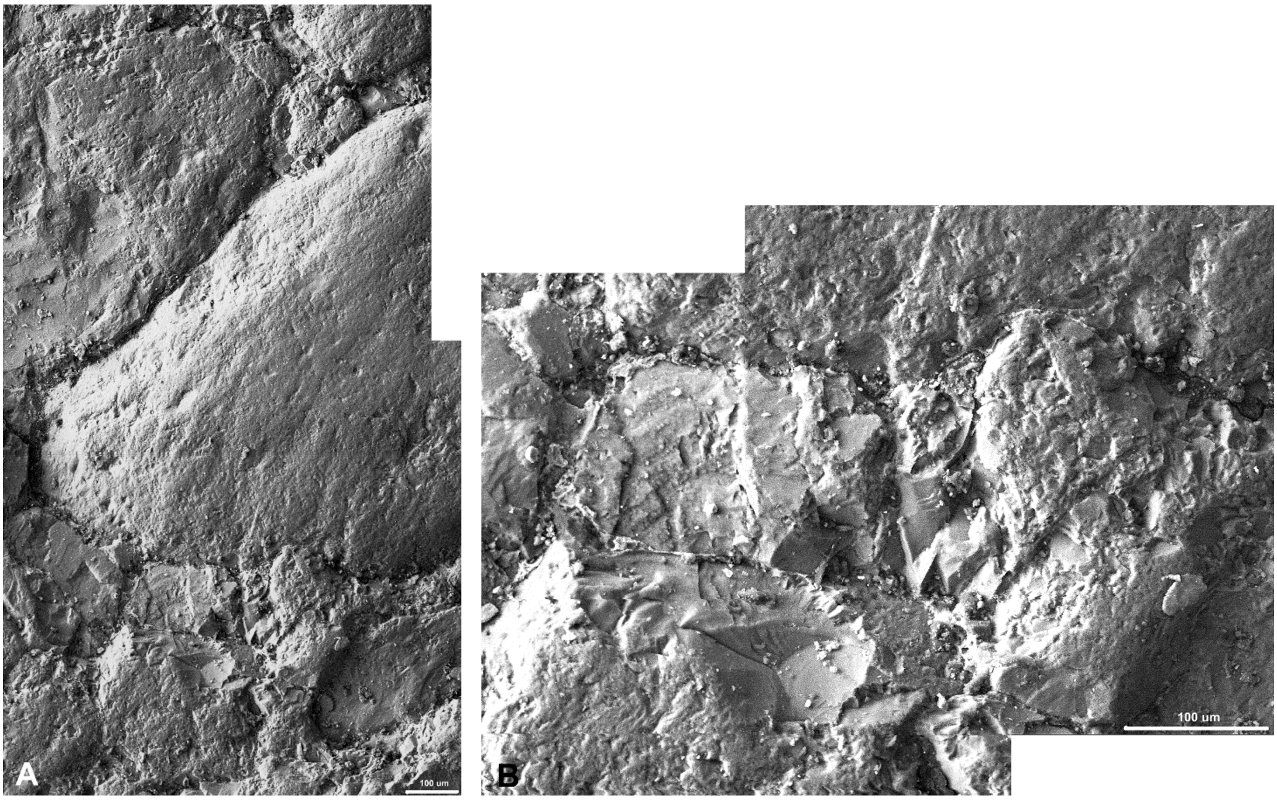

Figure 3. (A) Battering fracture patterns on quartz grains and former zones of colloid silica; (B) Close-up of two such zones, showing the complete conversion to crystalline quartz.

The texture of these fractures looks rather fresh and relatively angular, but when subjected to greater magnification the effects of rounding by microerosion [19] become amply evident (Figure 4). However, the level of general micro-wane development implies that these surfaces have been exposed to the atmosphere for only a few millennia; until then they were concealed under vast deposits of conglomerate strata. We can therefore confidently assume that for most of the time this tectonite sample, No. PAL-4a, has existed, it has been concealed by younger sedimentary deposits.

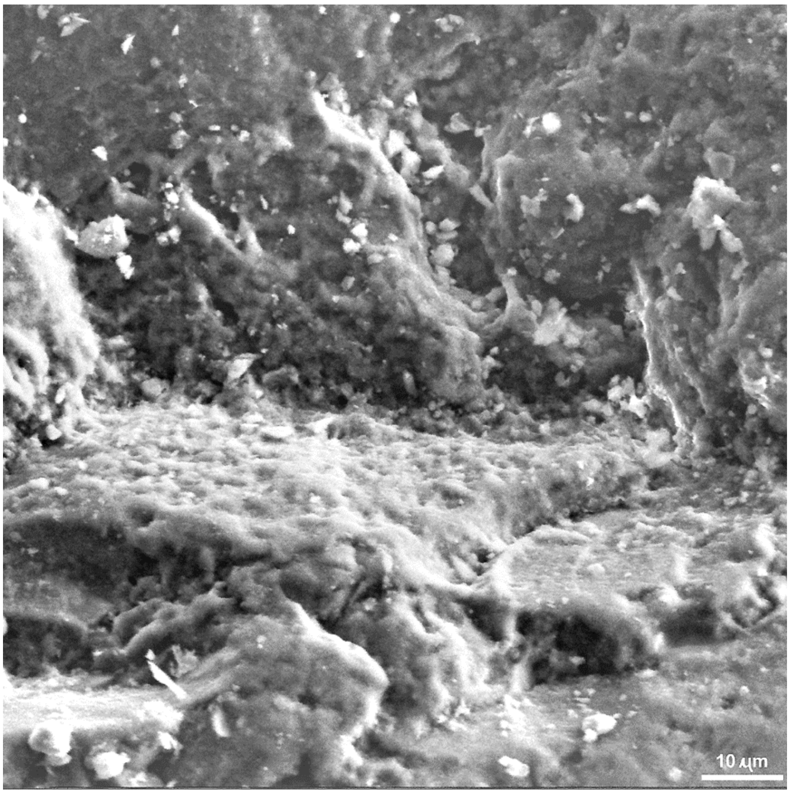

Figure 4. Texture of the crystalline quartz at high magnification.

In section, the consequences of the kinetic energy shattering of quartz grains forming most of the present surface of the tectonite is just as distinctive. In the thin section of the single quartz grain shown in Figure 5, the crushing effects are clearly evident on the exposed truncation plane, as are several semi-detached fragments still adhering. Also visible are internal shock fractures in the surface-nearest sector of the grain, and a distinctive hairline rupture across the entire grain and roughly parallel to the present surface. All of these features are attributable to the bombardment of the hardened bedrock exterior before the first deposition of coarse conglomerate commenced.

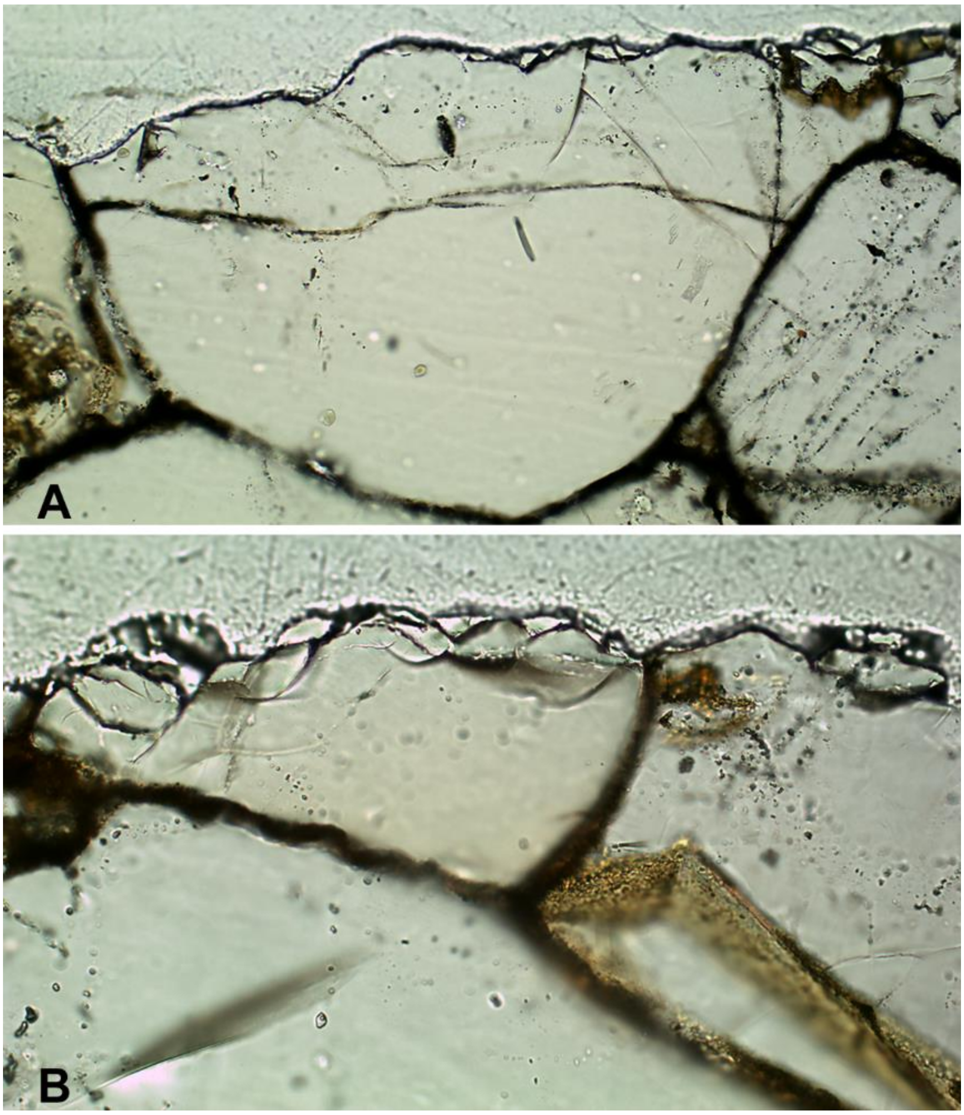

Figure 5. (A) This section of quartz grain truncated by the fluvial bombardment of the bedrock surface. (B) Another example of the battering evident at the tectonite surface.

4-2- Effects of the KEM Process

As noted above, in assessing the specific effects of the process causing kinetic energy metamorphosis of the quartzite's non-crystalline silica components we focused on three criteria: the deposits forming the grain boundaries of the formerly amorphous silica zones, any residual sediments associated with this cement, and inclusions entrapped within quartz grains. The first two elements were expected to inform us most about the progression of the final metamorphosis, because if this process is one of consolidation as hypothesized [6–8] it would involve specific effects. First, the physical properties of the 'cement' would change as the remaining voids left by the syntaxial quartz overgrowths are purged by the release of energy brought to bear on the silica, ductility aligning it into a crystalline structure. This should also involve a very tiny compression of volume, presumably resulting initially in a minute widening of the boundaries between grains. As the annealing ductilization progresses further, these gaps would gradually close. This predicted behavior is fully borne out by the evidence.

First, the initial field observations derived from the most heavily developed KEM formations in the cupules of Daraki-Chattan Cave are considered. The following stages of KEM conversion were tentatively identified by binocular field microscopy, from the subsurface to the surface:

0 – No alteration of the protolith.

1 – Grains remain clearly visible and no concentric 'halos' or 'fused' are appearance evident.

2 – Few grains remain and they may have concentric 'halos' indicating that the tribological modification from amorphous to crystalline silica is well developed.

3 – Bodies of completely metamorphosed, foliate crystalline quartz.

These stages were identified in several cupules, most especially in Cupule 14A on the cave's north wall, the most heavily converted specimen known in the world (Figure 6).

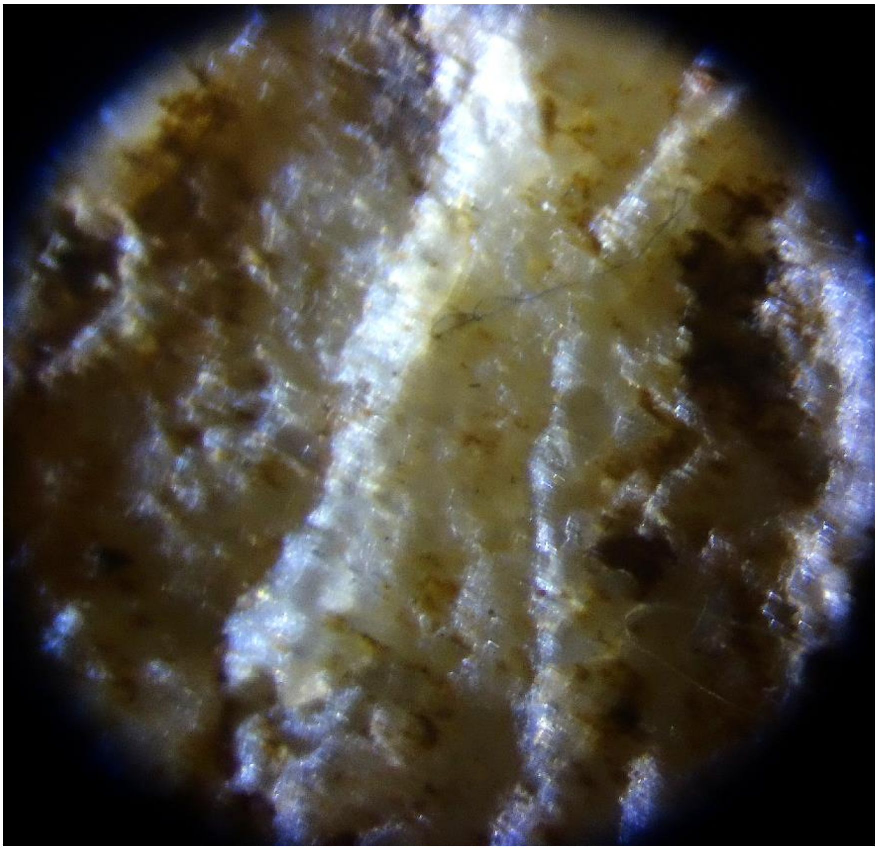

Figure 6. Field microscopic image of the left margin of cupule 14A, north wall of Daraki-Chattan Cave, showing stage 2 alteration of the quartzite protolith.

These same stages can be observed in the KEM samples from the paleo-channel near Daraki-Chattan. Figure 7 presents a typical thin section through a fully developed KEM column of several millimeters. At the top is the severely battered tectonite surface, followed by the most extensively modified layer in which all silica has been crystallized to quartz. Below that thin surface zone is a layer showing gaps between grains and former cement of 10 to 20 microns, where the latter has been subjected to ductilization and crystallization. The stage 1 zone below that illustrates the initial modifications to the grains, their perimeters and non-siliceous inclusions. The lower part of the column is of unaltered quartzite; it ends where the sample was detached from the rock during sampling.

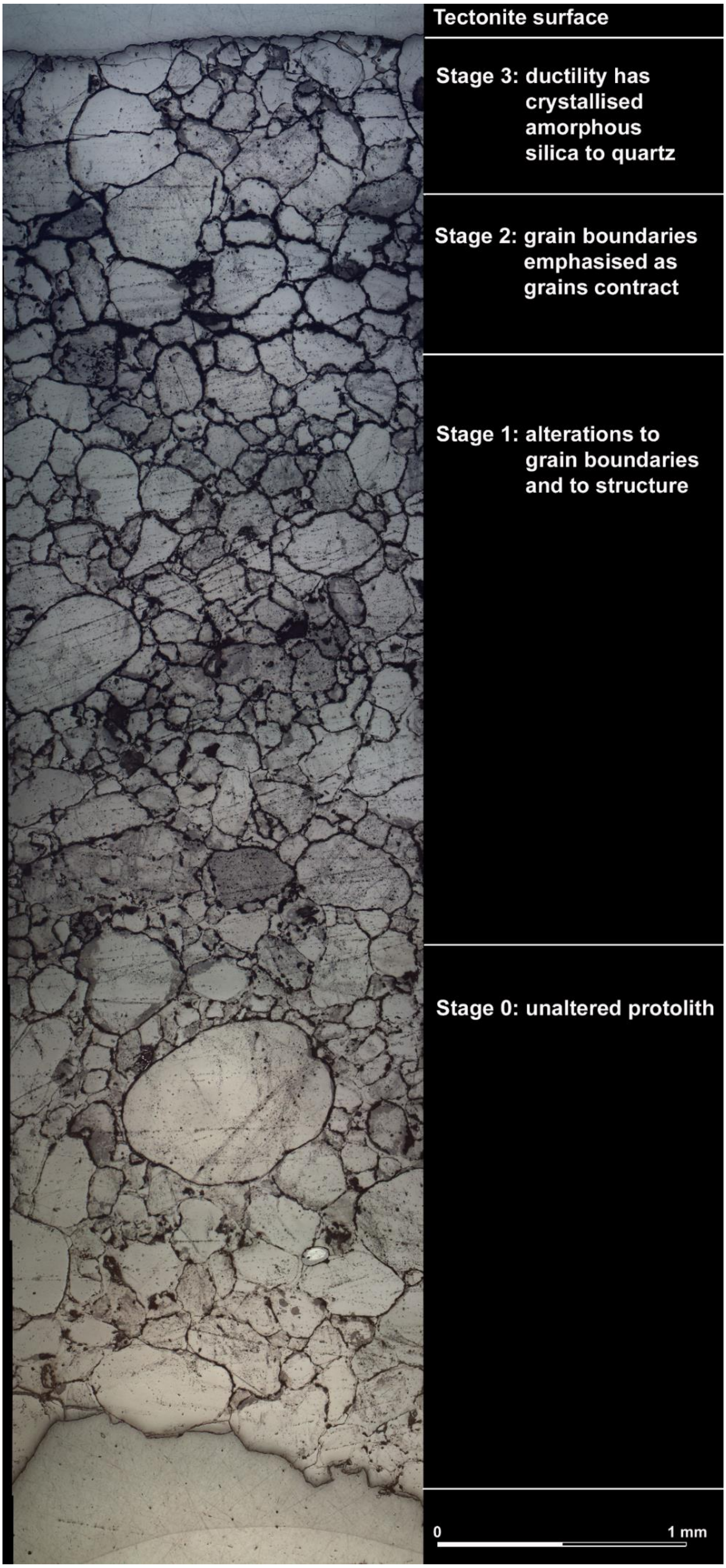

Figure 7. **Section through KEM-affected strata, the most altered layer being at the surface, seen at the top.**

5- Conclusion

The geological process of kinetic energy metamorphosis (KEM) was first identified and defined only very recently [6, 7]. It was initially observed in a form of petroglyphs called cupules, the production of which can involve very substantial application of focused kinetic energy. At the time it was hypothesized that the observed structural change within a discrete surface layer were tribological, involving crystallization of the syntaxial quartz overgrowths on quartz grains that constitute the cement component, forming a zone of tectonite. The process was considered to be attributable to the aggregate application of the kinetic force that attends the tens of thousands of hammer-stone blows that were required to produce cupules on hard rock. Similar tectonite skins observed on bedrock that had been pounded by the bedload of highly turbulent paleo-rivers was considered to have been caused by the same conversion process. To test the hypothesis, it was essential to subject removed samples to laboratory analysis, and since the destructive sampling of cultural monuments such as rock art sites is to be avoided, the extensive KEM layer found in a paleo-channel on Indragarh Hill near Bhanpura, India, was sampled instead.

Analytical work has confirmed the hypothesis and has demonstrated that the gradual conversion from the metamorphosed cement of the quartzite to tectonite is identical in the cupules and ancient river channel annealed panels. In both cases three identical stages of tribological transformation can be identified. First, subtle changes to the grain boundaries and non-siliceous inclusions become evident. As the application of kinetic energy continues, gaps begin to develop between quartz grains and former cement masses as the latter are subjected to crystallization by ductility. In the final stage, the anisotropic process is completed, resulting in the conversion of the partially metamorphosed silica to fully crystalline quartz as the molecular re-orientation is completed. Any further application of force cannot alter the material beyond this state and has limited effect in fracturing the now annealed surface layer. Instead continued impact causes the conversion to spread deeper beneath the substrate and the fully transformed tectonite can, in extreme cases, become more than 5 mm thick. Such a case is presented by Cupule 14A on Daraki-Chattan Cave’s north wall.

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7- Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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