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THE KINETIC ENERGY METAMORPHOSIS OF PETROGLYPHS

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Abstract: *This paper examines a phenomenon in nature that has never before attracted any attention. Petroglyphs that had been created by particularly intensive anthropogenic application of kinetic energy were found to bear thin surface laminae of metamorphosed rock that had become more resistant to erosion than the parent substrate. The phenomenon is most prominent on sandstone and quartzite, but has also been noted on another metamorphic rock, a schistose facies. To establish the relevant empirical variables the phenomenon is examined and described in several continents and then considered in the context of products of other localized, small-scale metamorphosis. Kinetic energy metamorphosis (KEM) is introduced as a new phenomenon and an elucidation of its diagenetic basis and recrystallization process is attempted. The chapter also considers related phenomena in geological metamorphosis, and the potential wider implications of the findings are presented.*

Introduction

There are essentially two forms of rock art: motifs made by a reductive process are called *petroglyphs*; rock material has been removed in their production. Motifs created by an additive process are *pictograms*, which include paintings, drawings, stencils and beeswax figures. The study of rock art is usually dominated by archaeology, even though that discipline has much less to contribute than such fields as geomorphology, geochemistry, neuroscience, cognitive science, semiotics, ethnography and others. This paper is concerned with a specific nexus between scientific (rather than humanistic) study of rock art and the geological sciences, with special attention to the sciences of tribology and tribochemistry.

Cupules represent the most common form of petroglyphs in the world. They are found in all continents except Antarctica, often in groups of large numbers. They are mostly circular features that have been found pounded into horizontal, somewhat inclined, or vertical rock surfaces and they have the shape of a spherical cap or dome (Bednarik 2008). In size they tend to range from 2 cm to about 10 cm diameter, but larger specimens do occur. They can resemble several other phenomena, and small potholes especially have often been misidentified as cupules. The purpose of cupules is essentially unknown, despite a few ethnographic glimpses of their significance (Bednarik 2010). But one of their most astonishing characteristics is that cupules have been produced by a majority of human societies all the way back hundreds of millennia, yet they were still produced by cultures of the 20th century. They are in fact the oldest surviving rock art known, with examples in southern Africa thought to be about 410,000 years old (Beaumont and Bednarik 2015) and others in central India suspected of being even older than that (Bednarik et al. 2005). Cupules can occur on many different lithologies, and replication has shown that the production of a standard-sized cupule can range from one minute on soft limestone, to several days (30,000 to 40,000 blows with a number of hammerstones) on well-metamorphosed, unweathered quartzite (Bednarik 2008). Clearly then, an almost incredible amount of energy has been expended in their creation on particularly hard rock (Bednarik et al. 2005; Kumar and Krishna 2014). This factor suggests that at least some of these cupules, or the act of their creation, had great significance to the makers, and perhaps also that it involved a level of obsessive behaviour. Typically, cupules are deliberately kept to the smallest possible diameter, and it is clear from those found on relatively soft rocks that the intent was to render them as deep as possible, but maintaining the smallest possible diameter (Bednarik 2008). This suggests that an element of deliberate perfection was often involved in their making, a factor that first becomes evident on the record of early artefacts during the Lower Palaeolithic (Bednarik 2011). That sense of perfection is expressed in non-utilitarian elements such as cupules, beads and pendants, as well as in utilitarian ones like hand-axes, several hundred millennia ago. It is also of relevance that the oldest surviving cupules are always found on the most deterioration-resistant rock facies, which is no doubt a taphonomic phenomenon, i.e. it is determined by selective survival of the rock types involved.

The earliest currently known rock art are Lower Paleolithic petroglyphs in two quartzite caves of central India, Auditorium Cave at Bhimbetka (Bednarik 1993) and Daraki-Chattan Cave (Kumar 1996). They consist mostly of cupules in both cases and are hundreds of thousands of years old, as demonstrated by stone tools deposited with stratified rock art. Their actual age remains unknown, but work is currently proceeding to establish it securely. Daraki-Chattan is located in a Proterozoic quartzite hill named Indragarh, and there are just over 500 cupules on its two walls, and another twenty-eight have been excavated in the floor sediments. Those found in the stratified floor deposit of the cave occur together with Lower Paleolithic stone tools of Mode 1 technology, comparable to the African Oldowan industry. Also stratified with the lowest cupules in the floor deposit were found a number of the hammerstones that were used in making cupules. On the plateau above the cave, only a few hundred metres from it, are more recently made cupules at an open site, on horizontal surfaces. It was here that the unexplained phenomenon that is the primary subject of this paper was first observed a decade ago:

> At one of the cupule panels we have examined a light-coloured crust-like feature, about one millimetre thick, now exfoliating, which comprises the same grain sizes as the rock but presents the visual appearance of an accretionary deposit. We could not determine its nature, but, having observed a similar phenomenon on some of the ancient river polish just mentioned, consider the possibility that the energy applied in the making of the cupule created a cutaneous zone that was more resistant to the weathering processes (Bednarik et al. 2005: 186).

There is a geometric arrangement of about twenty cupules (some are very faint), forming a double row and thought to be of the Holocene, on the basis of their preservation. Many of these cupules bear a remarkable surface feature, resembling an accretionary deposit of some kind. However, examination by binocular microscopy revealed that this lamina, which varies in thickness between one and two millimetres and is visually quite distinctive, is of the same quartzite as the rock matrix, but apparently more stable (Fig. 1). This very light-coloured, almost white lamina is not a remnant of some mineral accretion, as it seems at first sight; it is clearly the original floor of the cupule. The layer is limited to the cupules' interior and it is evidently much more resistant to weathering than the protolith (parent) rock. It tends to have become exfoliated from the rim of each cupule inwards, but remains intact and evidently protects the less resistant rock beneath it in the central areas of each cupule.

Figure 1. Non-accretionary surface layer of re-metamorphosed quartzite in a Holocene cupule on Indragarh Hill, near Bhanpura, India.

This poses a considerable problem to interpreting these laminae. Sandstones and quartzites may contain laminar zones of more metamorphosed, denser fabric as described below, but it seems statistically impossible that the floor of a cupule would follow such a zone through sheer coincidence. That is particularly obvious where several instances of this phenomenon co-occur at a site. The structurally different lamina cannot be related to any inherent structural feature of the rock; rather, it must somehow be connected with the production of the cupule. We know that cupules were made by direct percussion with hammerstones, which progressively fractured and removed quartz grains as well as silica cement. This process of pounding the hard rock many thousands of times with very carefully targeted blows resulted in the semi-hemispherical depression in the rock's substrate we call a cupule. The surface-near rock was in some cases converted by some process to assume a more erosion-resistant condition. The primary purpose of this paper is to examine the nature of this conversion process. While the surrounding rock has been subjected to extensive granular exfoliation and is gradually receding, the floor of each cupule remains intact. The possibility has been suggested that 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).

The modified laminae

This impression was reinforced by the discovery nearby, on top of the plateau of Indragarh Hill, of a palaeo-riverbed that millions of years ago would have consisted of highly dynamic rapids. Here, the bedrock and boulders were heavily polished by intensive fluvial action on the oncoming surfaces, i.e. the side bombarded by the bedload (and possibly also the suspended load). These impacted aspects exhibiting the same surface lamina that is more resistant than the quartzite rock as was observed in the nearby cupules. In this case it appears to derive from intense battering by clasts in turbulent water.

Subsequent to these observations, similar occurrences emerged in various parts of the world. At Jabal al-Raat at the Shuwaymis petroglyph complex in northern Saudi Arabia, a sandstone panel of cupules and other petroglyphs has been denuded by granular exfoliation of surficial rock mass, of several millimetres thickness, but in some of the cupules the original surface has remained intact within them (Bednarik and Khan 2005: Fig. 14) (Fig. 2). It also has somehow become consolidated as a result of the production process. Similarly, cupules on sandstone at Umm Singid in Sudan, and particularly from Jebel as-Suqur, seem to illustrate the very same phenomenon (Francaviglia 2005: Figs 2, 7, and especially the close-up in Fig. 5). A classic example of this phenomenon was then observed at one of the oldest known rock art sites in Africa, Nchwaneng in the southern Kalahari Desert (Beaumont and Bednarik 2013: 41–42). The earliest petroglyphs at this major site on a glacial quartzite pavement are all cupules, occurring next to the largest of several waterholes that were created by glacial plucking some 300 million years ago. The cupules are thought to be either of the Middle Stone Age or the Middle Fauresmith tradition, i.e. somewhere between 50 and 500 ka (thousand years) old and their most likely age is in the order of 410 ka (Beaumont and Bednarik 2015). The lamina formed in them and even on some adjacent surfaces is 2–3 mm thick and has very effectively retarded erosion of the rock beneath it (Fig. 3).

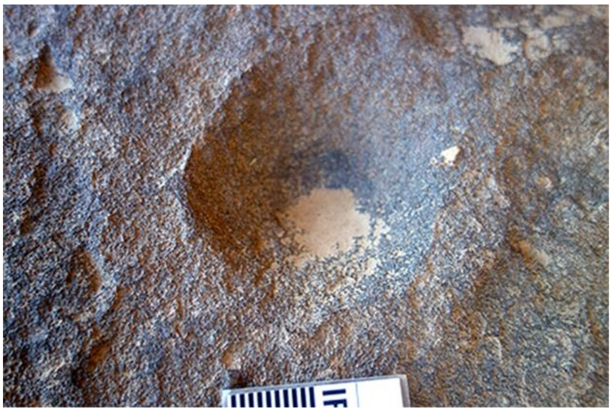

Figure 2. The cupule floor is preserved on this eroded sandstone panel at Jabal al-Raat, Shuwaymis, Saudi Arabia. Microerosion analysis of the white quartz pebble in the right of the cupule shows that it was fractured about 9000 years ago.

Figure 3. Re-metamorphosed quartzite lamina on two Pleistocene cupules at Nchwaneng, southern Kalahari Desert, South Africa.

All of these examples refer to sandstone, quartzite or intermediate forms, but the very same effect has recently, in 2014, also been observed on a metamorphosed mudstone facies, i.e. on schistose rock. Most of the sites of the Santivañez site complex near Cochabamba in central Bolivia are of schist or phyllite, and a few of the cupules at Condor Mayu 2 show the same kind of hardening on their floors. Schists retreat relatively rapidly, up to 10 mm per millennium (Bednarik 2007: 61), but here cupules have retained their floors while the rock around them has retreated several millimeters (Fig. 4).

Figure 4. Re-metamorphosed schist lamina in Holocene cupule at Condor Mayu 2, Santivañez, Bolivia.

One of the most closely examined cupules with this kind of surface lamina is also in Bolivia, on the quartzite of Inca Huasi, near Mizque (Bednarik 2000). This petroglyph site comprises a sandstone mass preserved by a short section of a several kilometres-long quartzite dyke from the eroding power of the Uyuchama River. Of the two different petroglyph traditions present, the earlier, featuring only randomly distributed cupules, seems limited to the quartzite surfaces, while the more recent rock art occurs on the sandstone slope below it. The latter features cupules often arranged linearly, as well as circles, circles with central pit, a wave line and linear grooves. Some of these elements seem to form more complex geometric groupings. Just above the site, to its west, occurs a sloping sandstone pavement featuring numerous horizontal polished grinding dishes, each around 50 or 60 cm long. These are better preserved than the recent petroglyphs on the same type of rock, and are spatially separate from them. One of them has yielded a microerosion date of E1028 ± 300 years (Bednarik 2000), by reference to the Grosio calibration value from Italy (Bednarik 1997). On the basis that the cement retreat of the recent petroglyphs is more than three times that in the polished surfaces, it has been suggested that they may be in the order of two to three times as old (the solution of the cement is thought to increase with progressing recession) and should be between 1500 and 4000 years old. The old cupules on the quartzite dyke are assumed to be of the early Holocene (Bednarik 2000).

Figure 5. Small horizontal panel of eroding cupules atop the quartzite dike of Inca Huasi, near Mizque, Bolivia. Note laminar exfoliation on the right.

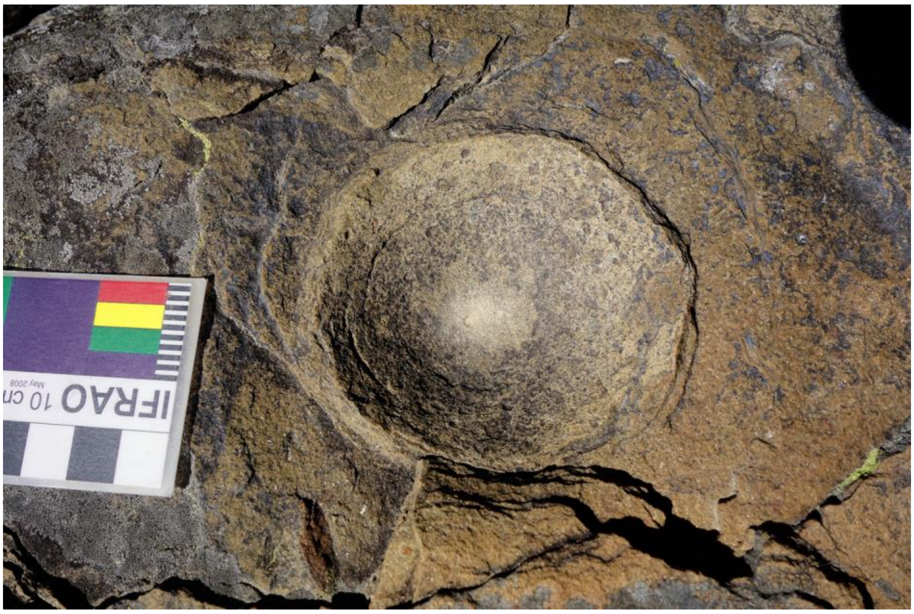

Figure 6. Well-developed re-metamorphosed surface lamina in cupule at Inca Huasi.

One of the highest-situated of these early cupules could be regarded as the best manifestation of the phenomenon considered here. Occurring almost 10 m above the river, on a small horizontal surface as the largest in a group of five cupules (Fig. 5), it measures 70 × 75 mm across and 15 mm depth. It exhibits the most extensive surface consolidation of this kind so far reported. The panel has experienced extensive laminar exfoliation around the cupule and on its margins (Fig. 6). Therefore the cupule must have been larger and deeper in the past. As far as can be established without sectioning it, the re-metamorphosed zone ranges in thickness between 4.5 and 6.5 mm, exceeding that seen anywhere else thus far. Visually the stabilised material differs from the background, in that it is much lighter than the brown-coloured rock matrix and of a different, denser morphology. Most importantly, it exhibits a vague internal lamination that follows the curvature of the cupule. The modified lamina has survived best in the cupule's interior, suggesting that the effectiveness of the metamorphosis was related to the depth of the petroglyph (i.e. to the cumulative amount of energy that impacted on the rock). Consequently the peripheral parts of the lamina have exfoliated, except on the northern side where a 30-mm-wide remnant of the otherwise eroded surface material remains. It is here up to 12 mm thick, which provides an idea of the amount of retreat of the rock since the cupule was made (Fig. 7). Effectively, the cupule may have been in the order of 25 mm deep originally, and only its central 60–70% has been preserved. Detailed microscopic examination of the lamina confirms that its surface represents the cupule's original floor, in which cracked quartz grains can still be seen. Most of the surface is quite smooth, with very little retreat of the cement evident and remaining mechanically stable. There are patches of recesses that seem to indicate where damaged grains or cement eroded. The largest grain measured is 212 microns long, but the average size of the detrital grains is in the order of 70 microns. On the sides of the cupule and near its margin, the grains are significantly more exposed, i.e. the cement has retreated greatly. Other than that, there is no microscopically detectable morphological difference between the lamina and the adjacent protolith rock.

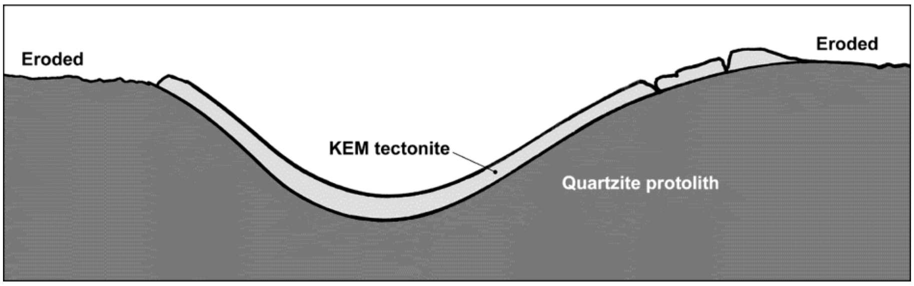

Figure 7. Section drawing of the Inca Huasi cupule.

The quartzite block on which this cupule occurs features extensive further evidence of laminar exfoliation parallel to the surface, most particularly on its western end, which is where the Uyuchama River has in the distant past, when it was at a level almost 10 m higher than now, bombarded this resistant vertical dyke with the clasts rafting past. The laminar layering is so distinctive here, and on other blocks exposed to the river's onslaught, that it seems to have been caused by the same factor, kinetic energy (Fig. 8). This phenomenon seems to be similar to the lamina observed on the palaeochannel on top of Indragarh Hill described above. The effects of the river on the uppermost blocks of the quartzite are evident all along the exposure at this level. Other evidence of the effects of the river when it was at a higher level are a few minor potholes that have developed downslope on the softer sandstone.

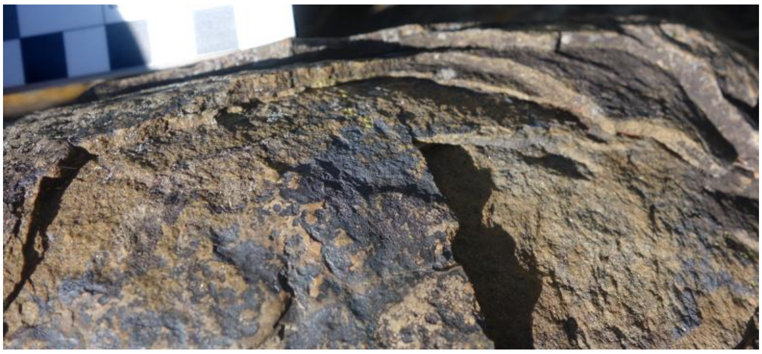

Figure 8. Exfoliating laminar surface layers attributed to fluvial kinetic energy, on the same bedrock block with the Inca Huasi cupule in Figures 4 to 6.

There is no internal lamination evident in the rock that could account for this phenomenon. The rock has vertical cleavage lines running roughly east-west and north-south, but there are no horizontal cleavage planes evident in either the quartzite or the sandstone. It could be argued that the described surface laminae are the result of weathering processes, but this does not explain why they are more resistant than the parent rock. In both cases, in the large cupule and on the rounded upper edge of the block, there is no indication that these stabilised zones express or even emphasise pre-existing features in the rock. Certainly in the case of the cupule, this is directly related to its manufacture.

Since the essential property that seems responsible for the significantly greater resistance to erosion in the lamina is the 'hardened' cement it is essential to determine what has modified that component, and by what process.

Solid-state metamorphosis of sandstone

The examples of metamorphosed sandstone described above are not the only ones to be observed of highly localized solid-state metamorphosis in such rock. To place them into the general context of such modifications it may be profitable to examine and consider other phenomena of this kind. Of particular interest are the laminae commonly seen at shear zones in sandstone which are unrelated to any inherent bedding planes. They may be tabular to sheet-like, planar or curvi-planar zones composed of rocks that have been strained more highly than the protolith. They can be randomly orientated in a single rock mass (Fig. 9), presenting conspicuous directional texture. Typically these platy laminae consist of whitish, dense sheets that may feature characteristics of schistosity, such as foliation grooves and even tear marks (Fig. 10). They reflect a considerable intensity of metamorphism, changes resulting from deformation at high temperatures and pressures occurring under kilometres of overlying rocks.

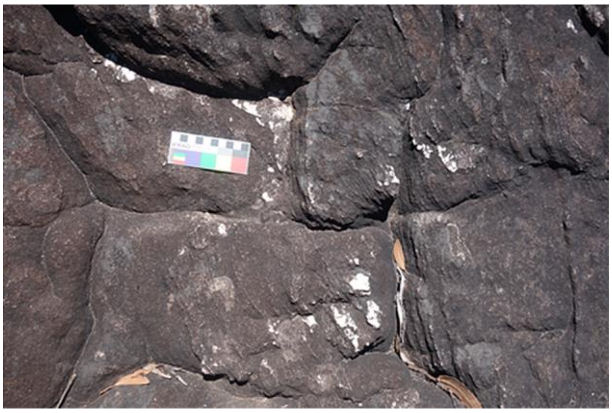

Figure 9. Randomly orientated shear zones showing local metamorphosis, in sandstone, Grampians Mountains, Victoria, Australia.

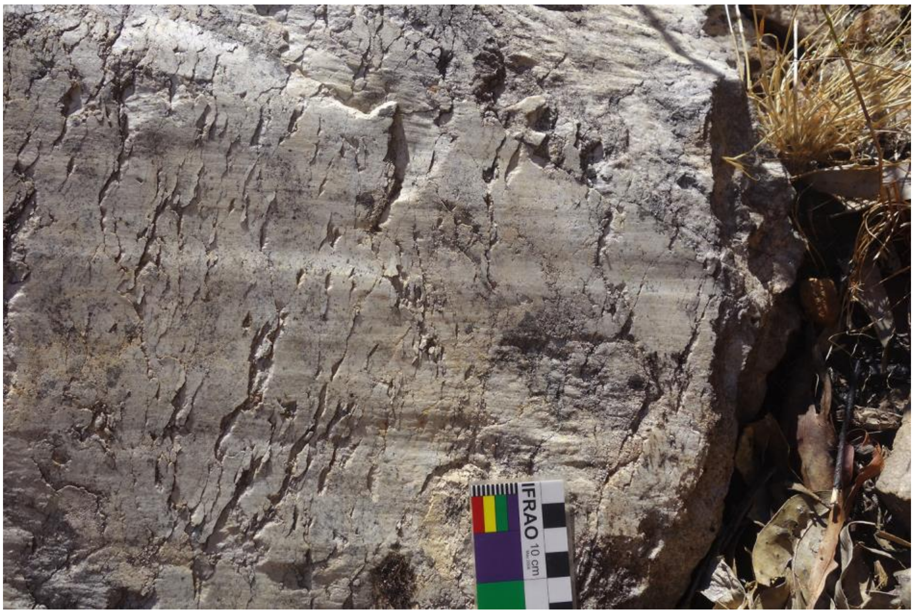

Figure 10. Schistose lamina in sandstone, showing foliation grooves and tear marks, Grampians Mountains, Victoria, Australia.

The formation of schistosity in shear zones results from the local recrystallisation of the rock along zones of ductility, where kinetic energy deriving from external stresses was released and caused the internal deformation or movement. These ductile shear zones or tectonites are chemically similar to the protolith, but differ from it structurally (Pereira and de Freitas 1993). 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 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 kilometre, 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 quartz clasts (the sand grains) are usually not fully occupied by cement; in fact sandstones with more than 10% imported quartz 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 sandstone. 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 facilitate — under adequate temperature, pressure and tensile stresses — ductile deformation, compressive stress and consolidation, in the form of highly localised metamorphosis. The tectonites of the resulting shear zones retain the chemical properties of the sandstone (as does sandstone undergoing metamorphosis to quartzite), but they are significantly more resistant to erosion, appearing dense, whitish and free of granulate texture before weathering alters them and renders the texture visible.

In short, the process of localised metamorphosis of silica sandstone by energy released in such shear zones is not limited to the phenomenon observed in some cupules; it is part of the changes that occur in rock masses under conditions involving great ductile stresses. Essentially this subject belongs to tribology, the science and technology of interacting surfaces in relative motion and of related subjects and practices (Bhushan 2013). The concept of 'tribology' was introduced by Peter Jost half a century ago (Jost 1966). As the science of interacting surfaces in relative motion, tribology certainly has specific applications in the geology of metamorphic rocks that have hitherto been neglected. Moreover, in *rock art science* the relevance of tribology has never even been considered in detail, an omission that is being corrected here. Nevertheless, the idea that the hardened laminae considered here have resulted from the application of kinetic energy to the silica cement has been fleetingly expressed before (Bednarik 2008: 88).

Here this idea is explored further. Tribochemistry is a branch of science dealing with the chemical and physico-chemical changes of solids due to the influence of mechanical energy (Kajdas 2013). Mechano-chemical reactions can result in compounds or microstructures that differ from the products of 'ordinary' reactions. It is the highly localised impact of energy, well above kT (product of Boltzmann constant and temperature), that is the key feature of mechano-chemical reactions. Thus reactions that cannot occur thermally become possible, just as the reactions the energy of photons induces in photochemistry. Of importance is the direction of the mechanical stress relative to the orientation of crystallographic axes in solids.

In the described conversion processes occurring in shear zones of sandstone, the kinetic energy effecting the metamorphosis to tectonites exceeds the shear strength, i.e. the resistance to the forces that cause two adjacent parts of a body to slide relative to each other. Energy is dissipated through the deformation between the two sliding masses and the asperities involved. If one of them is harder than the other, the asperities of the harder surface may plough into the softer surface and produce grooves if shear strength is exceeded (Bhushan 2013). Such grooves can sometimes be observed in the shear zones described above in sandstone, and the same applies to smaller grain metamorphic rocks (slates, phyllites and schists). The term stick-slip is relevant in this context, having been coined by Bowden and Leben (1939). During the stick phase the friction force builds up to a certain value and once a large enough force has been applied to overcome the static friction force, and slip then occurs at the interface (Bhushan 2013). The massive scale such phenomena can sometimes assume may be appreciated by considering the mechanics of earthquakes.

Kinetic energy metamorphosis (KEM)

Of importance in understanding such phenomena as described here are a few specific observations, such as the appreciation that the metamorphosis products are not limited to sandstones; as noted above, they can also occur on schistose facies. Schists essentially derive from mud and mudstone, and weather readily if they are devoid of a significant content of non-micaceous minerals (Anderson and Hawkes 1958; Fahey 1983; Wells et al. 2006). They hydrate to their previous phases and thus ultimately revert to mud, forming again the clayey soils from which they originate (Chigira 1990). For instance the chlorite of quartz-chlorite schist weathers via vermiculite to kaolinite (Murakami et al. 1996; Wells et al. 2005). The weathering front is abrupt, and pedoplasmation follows geological structures, forming a clay-rich soil material (Zauyah and Stoops 1990). Surface retreat is relatively rapid, but it is arrested by the metamorphosis observed in cupules.

Another significant observation relates to the complete absence of such metamorphic laminae in very heavily worked and large cupules on pure white crystalline quartz at Moda Bhata, India (Bednarik et al. 2005: 181–182). The best example of this is the largest cupule of the site, with a diameter ranging from 28 cm to 35 cm, and a depth of 10 cm. Thus this cupule is exceptionally large and of a volume many times the size of the volume of an average-size cupule. The rock it occurs on would be harder to have an impact on than quartzite, although quantified replication experiments have not so far been conducted on massive crystalline quartz. As a rough estimate it should be assumed that this cupule required somewhere between half a million and one million strokes to produce with a hammerstone. Yet despite this very significantly greater kinetic energy impact, neither this cupule nor any other on pure crystalline alpha quartz shows any sign of surface conversion. Therefore it needs to be assumed that the alteration observed in the quartzite is limited to metamorphosis of the silica cement.

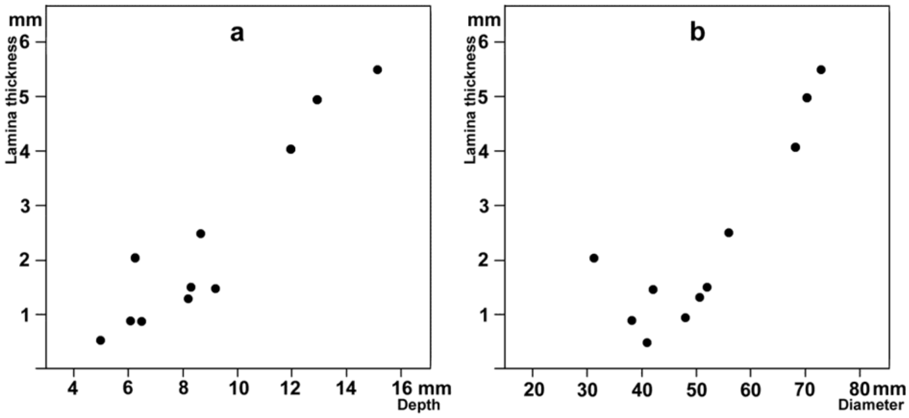

Figure 11. Metamorphosed lamina thickness plotted against (a) cupule depth and (b) cupule diameter, for a sample of eleven cupules containing laminae formed by kinetic energy metamorphosis.

Of particular relevance seems to be the statistical distribution of lamina thickness relative to cupule diameter or cupule depth (Fig. 11). This derives from the expectation that, other variables being the same, the thickness of the converted lamina increases with more impact. Of considerable relevance is the observation that the metamorphosis to tectonite increases the resistance of the rock to the pounding activity: the longer the rock is pounded, the thicker the converted lamina becomes. Although a strong trend is not evident from the very small sample (n = 11) currently available, the patterning, especially in the distribution of cupule depth versus metamorphosed lamina thickness, does imply a useful correlation. Greater size and depth of a cupule, which under otherwise identical conditions would correlate directly with applied total cumulative impact energy, are apparently related with greater thickness of the modified lamina. The volume of cupules, which are essentially spherical caps, can be estimated by

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

in which r = radius at rim, d = cupule depth and V = cupule volume. The cupule volume, in turn, is directly correlated with rock hardness, the influence of which can be determined by replication experiment. The production coefficient resulting from linking cupule volume to relative rock hardness is directly translatable into total energy applied to create the cupule. It is predicted that the thickness of the metamorphosed laminar formations found in cupules will consistently be shown to be a function of that production coefficient.

What remains to be clarified is the precise process of the localised metamorphosis of certain sedimentary rocks attributed here to the application of kinetic energy, be it by anthropogenic or natural force. Essentially three possible explanations have been considered to date. The first of them is 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 Kumar's replication experiments (Kumar 2010a, 2010b, Kumar et al. 2002; Kumar and Krishna 2014) have shown that to create an average-size cupule on well metamorphosed, unweathered quartzite involves about 30,000 to 40,000 blows with a hand-held hammerstone. With each stroke delivering, as a reasonable estimate, 0.4 N, the total force to bear on an average cupule would have been in the order of 16 kN. 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 complete absence of modification in cupules of much greater production coefficients that occur on pure crystalline quartz speaks decisively against the piezoelectric hypothesis. It demonstrates that the quartzite's component affected is the syntaxial cement rather than the quartz grains.

A second interpretation proposed is that the impact of the hammerstone will result in microfracture of the silica rock and therefore the formation of nanoparticles with very high surface to volume ratios. These particles will 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). This is negated by the observation that the laminar formation is not a precipitate; it is the original cupule surface and can bear evidence from the process of its manufacture (such as fractured or bruised grains, including conchoidal scars).

By far the most parsimonious explanation is that these features are attributable to tribochemical reactions, and that they indicate metamorphism of the silica matrix occupying much of the volume between the quartzite's grains. It is proposed that the considerable cumulative application of force releasing the kinetic energy of impact converts the cement in the same way as it is metamorphosed in the above described ductile shear zones of sandstone that has been subjected to significant tectonic stresses. Therefore the modified cement of the re-metamorphosed quartzite forming the laminar phenomena described here can be defined as a tectonite: a rock comprising minerals that have been affected by energy, which caused their orientations to change. This usually includes recrystallisation of minerals, and the formation of a foliate structure.

Conclusion

The relatively rare phenomenon described and discussed in this paper has not been explained previously, but has been observed at a series of sites in various continents. In most cases it is found on well-metamorphosed quartzite, and in one instance it has been reported from silica-rich schist. It presents itself as a thin lamina, most often 1 or 2 mm thick, that occurs on the surface of cupules. It 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, through a structural modification that needs to be explained. Here it has been proposed that this change involved crystallisation of the syntaxial quartz overgrowths on quartz grains that constitute the cement component of the already metamorphosed protolith. A tectonite was thus formed by a process of re-metamorphosis. That development is attributed to the aggregate application of kinetic energy that attends the tens of thousands of hammerstone blows that were required to produce the cupule. This tribological metamorphosis resembles that involved in the formation of similar tectonite in shear zones of sandstone, where tribochemical conversion takes place and also results in similarly denser, more erosion-resistant zones. In the case of cupules these zones facilitate the preservation of the original pounded cupule surface. It is noted that the process is most effective in the central part of the cupule. Indeed, thickness of the resultant tectonite lamina is a function of the amount of energy that has been brought to bear on the rock surface. It is proposed that the process of conversion of the rock cement be defined as 'kinetic energy metamorphosis' or KEM.

However, KEM is not limited to the rare phenomenon found in some cupules on certain metamorphic rocks. It is also responsible for the far more common highly localized solid-state metamorphosis to tectonites found in sandstones that have been subjected to internal deformation or movement along ductile shear zones. Moreover, surface hardening of metamorphic rocks can be attributed to still other causes. It has been observed as the result of fluvial battering on rocks exposed to high-kinetic energy rivers, and this is another topic in need of much more thorough investigation. Another promising line of enquiry would be the examination of glacial pavements planed by detrital rocks, which is very likely to have resulted in KEM. For instance the glacial pavements at such Kalahari cupule sites as Potholes Hoek and Nchwaneng (Beaumont and Bednarik 2013, 2015) were formed by a southward glacial movement during Permo-Carboniferous times, 320–270 million years ago, when southern Africa, as part of Gondwana, was situated near the South Pole (MacRae 1999). Freshly smoothed localised rock surfaces were at that time covered by tillites and shales that have since been eroded away, and the surface of the glacial quartzite pavements is so well preserved that it seems to have been hardened by KEM some 300 million years ago. It would be surprising if intensive glacial planning would not have resulted in surficial metamorphosis by KEM.

Therefore a tribological phenomenon first identified in a particular form of petroglyphs may in fact be a widespread occurrence in nature that has so far simply remained unrecognised. This is the first time that rock art science has identified a newly discovered universal phenomenon in nature by studying rock art.

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