Palaeoart and Materiality

The Scientific Study of Rock Art

edited by

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Cover image: Part of the Huashan site in Guangxi Province, southern China, the largest rock painting site in the world. Photograph by R. G. Bednarik.

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The Tribology of Petroglyphs

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This paper presents the first applications of tribology in rock art research. Tribology is the science and technology of interacting surfaces in relative motion and of related subjects and practices. It has several important applications in the study of rock art as well as in the geology of metamorphic rocks, including the solid-state localised metamorphosis of silica sandstones. The examples presented include the formation of tectonites in sandstone, quartzite and schist cupules, by a process named kinetic energy metamorphosis (KEM). Neither this process nor its products have been described before. Other examples presented of tribological features are those found on portable palaeoart objects, on rock engravings and on finger flutings. The paper explains also the tribology and forensics of several classes of natural rock markings that have been mis-identified as petroglyphs, and illustrates the role of these two disciplines in the correct identification of such markings.

La tribología de los petroglifos

Este trabajo presenta la primera aplicación de la tribología a la investigación del arte rupestre. Tribología es la ciencia y la tecnología de las superficies que interactúan en movimiento relativo y de los temas y prácticas relacionados. Posee varias aplicaciones importantes en el estudio del arte rupestre, así como en la geología de las rocas metamórficas, incluyendo la solidificación mediante la metamorfosis localizada de areniscas de sílice o cuarcitas. El ejemplo presentado se refiere a la formación de tectonitas en las cazoletas sobre cuarcita y pizarra, mediante un proceso denominado metamorfosis por energía cinética (KEM). Ni este proceso ni sus resultados se han descrito con anterioridad. Se conocen ejemplos de muchos lugares en varios continentes, lo que demuestra que parte de la energía cinética empleada en la creación de las cazoletas en cuarcitas muy duras o en esquistos ricos en sílice puede dar lugar a la metamorfosis de la cobertura de cuarzo sintaxial definida como cemento. Se puede propiciar la formación de láminas que son significativamente más resistentes a la meteorización que el protolito. Estas tectonitas se asemejan a las que se encuentran como placas de foliación laminar en zonas erosionadas de facies de areniscas.

1. Introduction

Tribology is the science of interacting surfaces in relative motion, and the technology of related subjects and practices. This discipline was formally introduced half a century ago (Jost 1966) and was named by combining the classic Greek verb *tribo* (which means 'I rub') with the suffix *-logy* ('study of'). However, this followed various precursor insights, ranging from Leonardo da Vinci's determination of the first known laws of friction, to work conducted in the 18th and 19th centuries (Dowson 1998). Tribology considers the principles of friction and wear; therefore its primary applications are in materials science and mechanical engineering. 'Wear' is a process leading to the loss of material, a key factor shared with another science, forensics, as enunciated in Locard's Exchange Principle (Miller 2003: 172). Thus tribology deals with such diverse matters as ball bearings, lubrication, the transference characteristics of lipstick, or the tribochemical changes caused by mechanical energy (Kajdas 2013). The discipline provides an excellent illustration of the differences of viewing or organising knowledge as they exist between the anthropocentric humanities and social 'sciences' on one hand, and the proper sciences on the other. Tribology has applications in geology, but even here has not been integrated effectively, despite such obvious applications as in seismology.

Nor has tribology ever been applied to rock art, or consulted by rock art researchers, until raised by this author recently (Bednarik 2015a, 2015b, 2015c). This was as much a significant omission as is the inadequate involvement of forensic science in rock art research (Bednarik 2001, 2015c; Montelle 2009). Nevertheless, tribology has important applications in rock art science, especially in the study of petroglyphs. They will be explored in the present paper. But before this is attempted such evaluation will greatly benefit from an investigation of the tribology of natural rock markings. Those that need to be considered are taphonomic kinds, such as clastic movement marks and glacial striae; kinetic plant markings, especially those made by tree roots; and rock markings made by animals. From this basis of forming an understanding of the tribological profiles of non-human rock markings it will be expedient to move on to the two basic types on humanly made rock markings: incidental anthropogenic marks (e.g. drag marks, mining marks, marks made by core drills and other machinery) and rock art. In the latter case, tribology is generally only relevant to rock art created by a reductive process, collectively defined as petroglyphs. These are divided into two main groups on the basis of tribology: petroglyphs made by abrasive processes, such as engravings and abraded grooves; and petroglyphs made by impact. Tribology is of importance to both of these groups, although in different ways.

2. Tribology of natural rock markings

While it is correct that indigenous producers of rock art, such as the Aborigines of Australia, may not discriminate between natural and artificial rock markings, regarding both as having been made 'when the rocks were still soft', and often incorporating natural markings in their lore or responding to them by adding petroglyphs to them, from a scientific perspective the discrimination between the two forms of rock markings is required (Bednarik 1994a). The concept of the formerly soft rocks derives from the ethno-scientific observation of such empirical evidence as lava flows and fossil casts, which is one of various examples showing that Aboriginal comprehension of reality was superior to that of Europeans until very recent history. Until little more than one and a half centuries ago, Europeans lacked any comprehension that they descended from other animals; in fact they regarded themselves as distinctly different from animals. Yet Aborigines had assumed this connection since time immemorial. Similarly, if a few centuries ago in Europe one would have promoted the notion that rocks were once soft, one would have risked being burnt at a stake, or at the very least one would have been excommunicated.

The ability of effectively discriminating between natural and artificial rock markings is a very recent development in science. Archaeologists and others have misidentified one or the other on thousands of occasions and the specialist literature abounds with examples (Bednarik 2001: 15–36; 1992a, 2013). Xenoliths and other petrographic markings, solution marks, kinetic plant marks, taphonomic marks and animal scratch marks have all been defined as petroglyphs, as has a variety of humanly made rock marks that are not petroglyphs. Indeed, there are instances of researchers perceiving petroglyphs on rock surfaces that bear no markings at all, and of a whole group of them recording hundreds of elaborate motifs on rocks that bear no grooves, all because of mass-pareidolia (Bednarik in press). From the perspective of tribology, the following types of non-rock art rock markings are of relevance.

2.a. Taphonomic rock markings

This group, defined as GK1 marks in the first publication addressing the topic comprehensively (Bednarik 1994a), derives its description from the science of taphonomy, i.e. the modifications experienced by materials since they became part of what is called the 'archaeological record', among others. It includes markings acquired by clasts through movement relative to their sediment matrix, by such processes as cryoturbation, solifluction, animal activity, trampling, gravity or even unintentionally by human agency. The production of such markings falls under tribology, which as noted is the science of interacting surfaces in relative motion. The most common manifestations are the grooves produced as coarse sand grains, usually of quartz, move relative to a clast of softer rock while in contact with its surface and under pressure. The pressure is likely to derive from the weight of overburden, but can be from another source, especially in the case of trampling. When the kinetic energy exceeds the shear strength, i.e. the resistance to the forces that cause the two adjacent parts to slide relative to each other, the asperities of the harder material will remove material from the softer (Bhushan 2013). The asperities are likely to have particular, distinctive shapes, resulting in a similarly characteristic shapes and striations in the grooves they occasion. They may be so distinguishing that repeated application by the same grain can be deduced in different grooves. These grooves also present other idiosyncratic details, especially concerning their points of commencement and any sudden changes in direction (Bednarik 1994a).

Rock markings caused by such processes have on occasion been mistaken for anthropogenic engravings. For instance dozens of very fine-grained sandstone blocks from Toca do Sitio do Meio in southern Piauí, Brazil, bear tens of thousands of incised grooves up to 4 mm wide, which archaeologists had interpreted as anthropic engravings. They are taphonomic markings deriving from trampling and the movement of clasts (Bednarik 1989). Another example is a series of six soft aeolian limestone (calcarenite) slabs from Trench 9 in Devil's Lair Cave in Western Australia, which were several times published as 'engraved plaques' (e.g. Dortch 1976). A detailed study showed the markings to be a variety of taphonomic marks as well as two types of animal scratch marks (Bednarik 1998a). In another example, cave divers had discovered a panel of incised wall markings in a limestone cave near Mt Gambier, Australia, 7 m below the water level. Because this location has been flooded since the beginning of the Holocene, it was suggested that the presumed engravings must be of the Pleistocene. Their forensic study by the author suggested that the marks were made by an ancient tree trunk that had become caught in the location and scratched the soft cave walls as it was buffeted by water flow.

2.b. Clastic movement markings

Among the most common rock markings on this planet are GK2 marks (Bednarik 1994a), particularly in the form of glacial striae. These were made by rocky detritus dragged or pushed by glaciers over stationary rocks, which had typically been smoothed in the process already

Figure 1. Petroglyphs superimposed on glacial striation marks, Bedolina near Capo di Ponte, Valcamonica, northern Italy (photo 2015, all images by the author).

(Fig. 1). The striae presently surviving are normally from the final phase of the very last glaciation, because if they were older they would have been obliterated by subsequent glacial action. The direction of the striations is usually very uniform as it is aligned with the flow of the glacier. Their sizes range from barely discernible incisions of sub-millimetre widths, to massive gauges of about one metre width. Tribologically, the same laws apply as to the taphonomic markings just described. As a by-product of stick-slip (Bowden and Leben 1939), as friction force builds up to a certain value and once a large enough force has been applied to overcome the static friction force (Bhushan 2013), transverse tear marks can be observed. They are distinctly curved, the convex side facing in the direction of the ice flow. Other typical features are serrated edges along the margins of wide grooves, and distinctive morphologies at the point of commencement: comet-like impact pits where the clast made initial contact with the bedrock.

Although the most common group of clastic movement marks, glacial striae are not the only form. Where a floor subsides, especially in caves with fluctuating aquifer levels of a sub-floor phreatic reservoir, clasts in contact with vertical walls may gradually scrape down a wall and if walls are soft enough, distinctive grooves may be formed. Similar kinetic effects have been observed attending tectonic subsidences. One of the most unusual phenomena of this kind reported were several occurrences of parallel grooves high up on vertical cliffs facing the river Lena in central Siberia. They were clearly attributable to great mechanical force or impact, they appeared to be anthropogenic, but this seemed to be contradicted by their locations high on the cliffs. Microscopy revealed dense crushing rather than typical percussion marks, as if something had been pressed into the rock with great force (Bednarik 1994a: Fig. 12). The author proposed the hypothesis that there had been rock towers leaning loosely against the cliffs, that hard clasts became lodged between the two surfaces, slowly wandering downwards with each minute movement of the towers. At the time this seemed a desperate attempt to explain the mysterious rock markings, but intensive searching yielded one example where such a rock tower was still in place, and an angular clast was still wedged in position and had already produced similar markings.

2.c. Kinetic plant markings

The BP1 marks of Bednarik (1994a) include two groups. Both are subjects of tribology, but the mechanism of the application of kinetic energy is quite different. The first group concerns the action of vegetation matter, such as large tufts, stalks or branches, as they sway in the wind and rub against a rock face. In most cases the relief of the markings they produce is imperceptible, because the plant matter is not hard enough and there is very little material capable of acting as an abrasive. However, there have been cases reported of removal of rock matter where the rock was soft enough. Nevertheless, there are no known misidentifications of such markings as petroglyphs on record.

That does not apply to the second form of kinetic plant markings. For instance Shepherd and Jolley (2016) describe in excellent detail a series of thirty sandstone locations in the Pennines region of Yorkshire, United Kingdom, that feature groups of linear, rounded grooves, some of them branching antler-like or dendritic. Having consulted numerous eminent British geologists, archaeologists, rock art specialists and others, they report that the geologists could not match the grooves with any of the many rock marking phenomena they were familiar with, so they tended to favour an anthropogenic cause. At least one archaeologist also viewed the grooves at one site as representational, while rock art researchers preferred a geological interpretation. The explanations as plissoirs, plough marks, small-arms fire or mortar round marks were discounted, as was the involvement of weak acidic acids emitted by plant roots. The latter effects are well known only from carbonates, which are particularly susceptible to the respiratory CO_2 of mycorrhizal microbiota, forming weak carbonic acid in the presence of moisture. This process would not, however, affect siliceous sandstones, nor have chemically induced marks by plant roots, such as those found on ivory (dentine) and other carbonates (Bednarik 1992, 1993), been reported from sandstones. The correct explanation of this phenomenon has long been known: it is attributable to tree roots that in the distant past hugged the rock for support. Every time the trees swayed in the wind, there was a minute movement in their main roots just below the ground, and this, ‘together with soil and fine sand acting as abrasive, is sufficient to produce quite deep grooves on the rock, which in turn improve the tree’s hold on its support. Over a tree’s life time, such grooves can become up to 10 cm deep. After the tree disappears and the soil erodes, the grooves remain’ (Bednarik 1994a: 35; 2016).

The same phenomenon can be found on granitic rocks, as demonstrated by a similar controversy in Tasmania (Luckman 1957; Ellis 1958; Bednarik et al. 2007). Here, too, the issue was resolved by examining the tribology of the phenomenon.

2.d. Animal scratches

Another group of rock markings that have presented discrimination difficulties for archaeologists are BA1 marks (Bednarik 1994a), subsumed under the heading of 'animal scratches'. They also are among the most common rock markings, and they are, among other things, tribological phenomena. Those occurring in limestone caves are perhaps the most frequently observed, essentially because the weathering regime in protected locations permits much longer survival, despite the relatively soft nature of moist limestone walls (Bednarik 1991a). Many animal scratches in caves have survived since the Pleistocene, the most common being those of the cave bear (*Ursus spelaeus*; Bednarik 1994b) (Fig. 2). Animals have produced rock markings with various parts of their bodies, such as antlers, tusks, mandibles (birds), but the most numerous are those made with claws. In contrast to scratches with stone tools, claw marks bear usually no striations, are rounded and comparatively symmetrical, and tend to be U-shaped in cross-section (Bednarik 1998b). Morphologically, one end tends to be deeper and abrupt, the other shallow and fading. At the deeper end a fairly good impression of the shape of the claw point is sometimes preserved. Nevertheless, reliable discriminating between animal scratch marks and anthropogenic engravings is not possible without extensive experience in the variability of both types. Another factor complicating such work are the modifications cave walls tend to be subjected to, which may obscure the marks in a variety of ways relating to the re-precipitation processes active on such surfaces. Again, specialist knowledge is essential.

The possibly most numerous animal scratches are those of chiroptera, mostly caused by the wings of airborne bats. However, these are so faint that they have not been mistaken for artificial phenomena. Apart from scratches, another class of animal marking found on rocks are polishes by the bodies, especially of large species. At open sites, in North America and Africa, such polishes have been attributed to proboscideans, bisons and other species, while in European caves the *Bärenschliffe* (wall polishes by generations of cave bears using the same routes in the dark) are a prominent example (Bednarik 1994b). Of particular relevance is the case of the exfoliated bear polishes from Hohle Fels in Germany, bearing linear incised grooves that were widely interpreted as rock engravings (Hahn 1991, 1994; Scheer 1994; Conard and Uerpmann 2000; Holdermann et al. 2001). Detailed microscopy demonstrated the fully natural origin of these tribological phenomena (Bednarik

Figure 2. Pleistocene engraving, finger flutings and claw marks of the cave bear; the latter are limited to the lower half of the image, which implies that the cave floor was much lower when they were made; Rouffignac, France (1981).

2002). They were caused by quartz grains embedded in the shaggy fur of the cave bears, as they rubbed their bodies against the polished surfaces of the cave walls. Such random cave markings are well known from many other European caves that served as hibernation lairs of these powerful ursine visitors (Bednarik 1994b). However, these markings are not animal scratches, but more correctly belong under the above heading of taphonomic markings.

2.e. Unintentional or utilitarian anthropogenic markings

In Bednarik's (1994a) taxonomy of rock markings, BH1 marks are those occasioned by humans, but lacking any symbolic or exogrammatic (Bednarik 2014) content. They include mining marks made by pre-Historic people, such as those in Gran Gran Cave, South Australia (Bednarik 1992c), and marks left by rock drills, core drills, steel tracks of track-mounted vehicles, gouge marks where a vehicle brushed against a rock face, drag marks on rock pavements, or grooves cut by steel cables being pulled over rock. These are just some examples, chosen because each one has been misidentified as petroglyphic by an archaeologist on at least one occasion. All of these, and others, can be studied by tribology, as they always involve interacting surfaces in relative motion, in which one material is harder than the other. As noted with the previous class, weathering can significantly affect the characteristics of such markings. To illustrate the tribological aspect, an example from Russia is cited. A large group of archaeologists identified a groove on granite, above a lake and below of lighthouse, as a petroglyph, but the author's close examination suggested that the 1 m long groove had been made in a single uphill abrasive motion. It seemed to be aligned with the lighthouse, and the author suggested that it was caused when some heavy piece of equipment was dragged up the hill, perhaps with the help of a tugboat. It was subsequently confirmed that, during World War 2, artillery pieces were brought to the hill, which has never had road access, so cannons would have been transported by boat and had to be moved to the top of the hill.

Another interesting group in this category are rock grooves that were produced by pre-Historic people but had no symbolic meaning. Rather, they were purely utilitarian. The obvious example is the numerous axe/hatchet grinding grooves that can be found in significant number in many parts of the world. Less known, and easier to mistake for petroglyphs, are long linear grooves on sandstone pavements whose role was to drain water away from specific areas of a pavement that were preferred for abrading stone tools. This was done to keep the locations dry, crystalline and hard. Such grooves can be several metres long and resemble uncompleted petroglyph motifs, having been made by the same process.

3. Tribology of portable palaeoart objects

Now that the great diversity of rock markings and their respective tribologies have been briefly explored, relevant aspects of portable palaeoart objects are considered next. There is a range of such objects, including tablets and plaques, figurines and proto-figurines, beads and notations on small articles of various materials, ranging from stone to bone and teeth to ivory, amber, jade, steatite, serpentine, limestone and ostrich eggshell. Microscopy is an essential component of a scientific study of their tribology. This is because the most important aspect in the investigation of portable palaeoart objects are the effects of asperities of harder material, such as chert, used in modifying these pieces. In abrasive contact, as in the production of engravings, abraded grooves or incisions, the relevance of both forensic and tribological perspectives is self-evident. They have been productively explored, especially through the phenomena of tool striations and other tell-tale signatures in portable engravings on many materials (e.g. Semenov 1964; Marshack 1984, 1985, 1986; Bednarik 1988, 1992d; d'Errico 1988, 1991). By comparison such techniques have been inadequately applied in abraded/engraved rock art, simply because several decades after the introduction of binocular field microscopy in palaeoart studies (Bednarik 1979) most practitioners in the discipline have still not availed themselves of this method.

Essentially, the microscopy of portable engravings and other markings evolved from work determining technological processes in pre-History, including the identification of micro-wear on stone implements. One initial principal goal of what Marshack termed 'internal analysis' was to determine the notational function of sequences of notches. Another was to, more broadly, evaluate from the physical characteristics of engraved marks on portable items the direction in which they were made, the order of their sequence, and information about the tools involved in their making. Although the debates between Marshack and d'Errico led to agreement about notations, this author argued that notational intent cannot be conclusively resolved. Notations may be made in a single sitting, or they can be cumulative in the course of a period of time. The number of different tools used in one set of marks cannot decide the issue, nor is it even possible to decisively identify specific tools from the striations and groove profiles they produce (Bednarik 1991b). As a rule, the points of burins or other tools used in the production of engravings are irregularly and non-symmetrically shaped, leaving behind grooves and striations that depend entirely on the way the tool is held. What can be decisively determined is that two or more marks were made with the same tools if their morphologies are identical; but if they are different it does not necessarily mean that two different tools were applied. Nor does the use of different tools demonstrate notation. If micro-spalls are detached from a tool point during application, the next mark produced, even if the implement is held the same way, may differ in its section or striation pattern.

Nevertheless, these controversies helped develop the relevant technology, as protagonists needed to refine their respective methods and epistemologies. These illustrate the close connection of the issues with those subjected

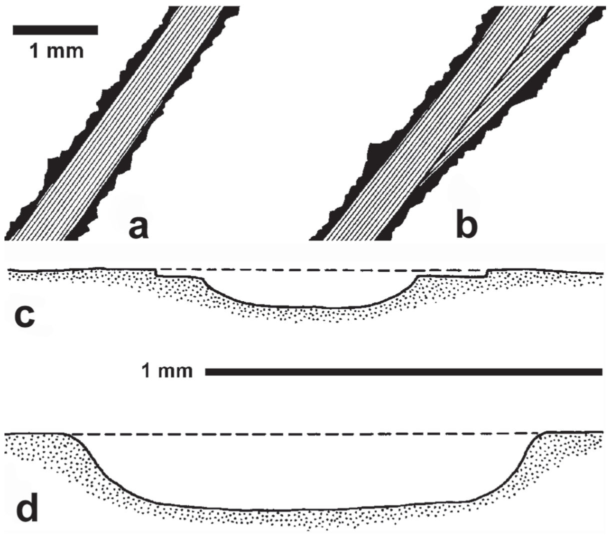

Figure 3. Engraved grooves on ostrich eggshell: (a) plan view with tribological striae; (b) superimposition, the jagged margins are the result of the splintering of the outermost layer; (c) typical section of the engraved lines, note splintering of the outer layer of the eggshell along margins; (d) section of a natural solution groove on ostrich eggshell.

to other branches of forensic science. For instance the detection and 'fingerprinting' of striations found on fired bullets derives from precisely the same principles. And in both cases the effects are the subject of tribology.

An example of such an analytical method is provided by the need to discriminate between natural and artificial markings on ostrich eggshell, a material widely used and engraved by pre-Historic peoples in Africa and Asia, as far back as the Pleistocene. It consists of three layers, the outermost of which is less than 0.1 mm thick (Sahni et al. 1990). Natural grooving of eggshell occurs in response to solution by carbonic acid along the roots of vegetation, deriving from carbon dioxide respired by mycorrhizal microbes. These grooves are of various widths and possess rounded rims. By contrast, the grooves made by stone tools are of a distinctive morphology attributable to the tribology of the hard tool point ploughing through the softer calcium carbonate of the eggshell. In response to the kinetic energy and the stick-slip as static friction force is overcome once the friction force exceeds the shear strength, the thin outer layer of the eggshell splinters in a jagged, angular pattern fringing the groove on both sides (Fig. 3).

4. Tribology of rock engravings

Whereas the methods of analytical study of portable objects have been fostered by specific interests, such as the recognition of notational signs, and facilitated by the ability of examining them in a laboratory, rock art is generally immovable (except fragments that have exfoliated from it naturally) and its forensic and tribological study involves quite different strategies. Particularly well suited to analysis are engravings in limestone caves, because they are generally better preserved and provide far more technological detail than most open air petroglyphs. However, research work in caves involves additional difficulties. Not only does it frequently require field microscopy in difficult terrain, it demands appropriate lighting conditions and also tends to involve elevated difficulties of access. Field microscopy in the service of rock art study has so far been used by only very few specialists globally, hence the amount of tribological work conducted with rock art remains minute. It commenced with research undertaken in a series of newly discovered caves along the southern coast of Australia, especially Mandurah Cave (Bednarik 1987/88) (Fig. 4) and Nung-kol Cave (Bednarik 1992e). Speleo-environments, with their stable relative air humidity and temperature as well as the absence of precipitation, have in many cases preserved engravings impeccably. Exceptional preservation applies when markings had been made on soft surfaces that had subsequently hardened by stabilisation or by filling of voids in microscopic carbonate lattices; or by desiccation close to entrances. Such changes can cover the range from hardness 1 on Moh's scale to hardness 4, and

Figure 4. Detail of tool marks in Mandurah Cave, Western Australia, showing tribological features (1987).

when details are well preserved they allow tribological observations matching those possible on portable objects.

Interrogation of such empirical data provides many explanatory insights helping to reconstruct the production of these rock engravings, including the sequence in which they were made ('internal analysis' of Marshack), the direction the tool points moved in, the material the tools consisted of, the cross-sectional shape of the tool points, the handedness of the mark producers, and other idiosyncratic details in the way the marks were made. Many of these forensic minutiae require the observation of tribological specifics, some involve field microscopy. Figure 5a provides an example of a panel of tool markings made on a vertical cave wall that at the time was very moist and bore a cutaneous surface deposit of reprecipitated calcium carbonate of a type called moonmilk (*Mondmilch*, *montmilch*), a white and very soft material as long as it remains moist. It ranges from a consistency similar to freshly fallen snow to clayey or pasty texture. After it was marked with a series of notches with tools bearing blunt points, the moonmilk desiccated or stabilised to a state of considerable hardness, but the surface detail of the markings remained well preserved (Bednarik 1999). The asperities of the tool points left their characteristic striations in the grooves, allowing two determinations: the 'signature' of the striae to identify repeated use of the same implement in the same orientation; and in some cases the cross-section of the tool point perpendicular to the direction of its movement (Fig. 5c). The sequence in which the markings were made was established from the superimpositions, while the direction of tool movement over the surface was demonstrated by a tribological phenomenon, the transverse tear marks resulting as the force applied overcame the static friction force in a stick-slip reaction. The material of the tools was determined by replication, testing dry wood, green wood, bone, chert and local limestone clasts on a material as soft and

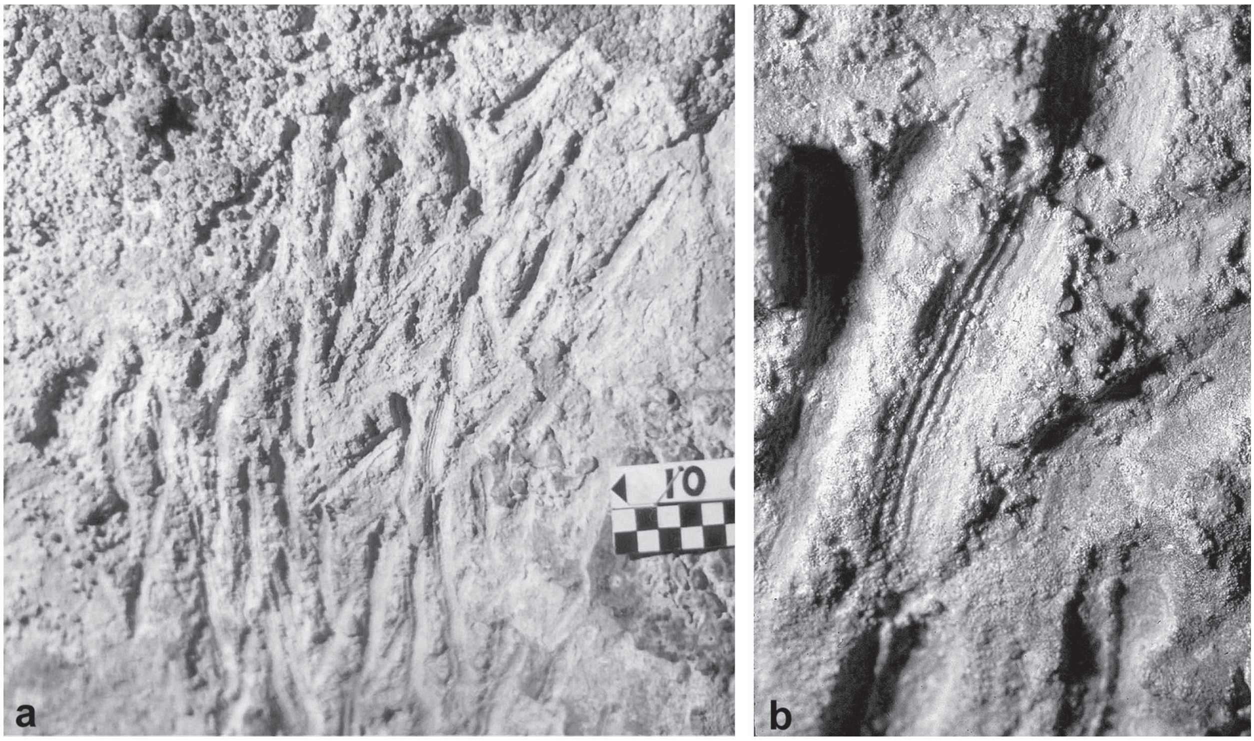

Figure 5. (a) Tool markings on wall in Nung-kol Cave, South Australia; (b) close-up view of the central part of the same panel, showing tribological markings; (c) internal analysis of the panel, identifying multiple use of five specific tools from their characteristics, and defining the cross-sections of two of them (1 and 2) (1986).

pliable as the rock surface was at the time the markings were created.

5. Tribology of finger flutings

Finger flutings (*sillons digitaux parallèles*) are a form of rock art resulting from dragging human fingers over a soft surface in a limestone cave, usually a deposit of moonmilk (Bednarik 1999). They thus consist of subparallel grooves that are rounded in section, forming streams that sometimes, but quite rarely, form iconic motifs, but in most cases seem aniconic. Finger flutings have been reported from some ninety caves in south-western Europe, southern Australia, New Guinea and Hispaniola. Most of their known occurrences date from the Pleistocene, although cases of Holocene antiquity have also been demonstrated (Bednarik 1998). The forensic analysis of digital flutings began with the re-discovery of two sites of their occurrence in South Australia in 1980 (Bednarik 1984, 1985, 1986, 1987/88). The significant attributes of finger flutings are that finger sizes and other data provide information about the age of the makers; and that the superimposition sequence informs about their succession. Another factor of relevance is that in some sites finger flutings have been found sandwiched between layers of re-precipitated calcite; and that such speleothems are under favourable conditions datable by both radiocarbon and uranium series analyses. Indeed, the first applications of direct dating in rock art research were by these methods, on carbonate speleothems in Malangine Cave (Bednarik 1984).

The tribology of finger flutings is similar to that of engravings on soft rocks as described above, but may be very complex due to the wide range of morphologies the moonmilk can assume. The medium ranges from a downy-soft lattice of fibrous crystals that under a microscope can resemble textile fibres, to a dough-like mass of high moisture content, frequently comprising in excess of 50% of mass (or about 75% of volume). It can occur in massive deposits over one metre thick, down to very thin, powdery efflorescences, and it even forms stalactitic growths (Bednarik 1999). Moreover, it is highly susceptible to various modification processes, and these have great effects on the appearance of the digital flutings. The impact of the finger marking is that the minute crystal lattice is compressed and demolished by the fingers, and subsequent growth focuses on the ridges between the finger grooves (Fig. 6), effecting deformation of the flutings that have prompted misidentifications as animal scratches. At other locations, there has been no subsequent speleothem growth, and the flutings are well preserved and may even have become stabilised by hardening of the moonmilk medium. To add to the complexity of the issue, many of the different states of both moonmilk and finger flutings may be found in the same cave and in close proximity. Instances have been recorded where a clear set of finger flutings enters a zone of heavy subsequent growths of the kind illustrated in Figure 7, which obscures the markings almost completely.

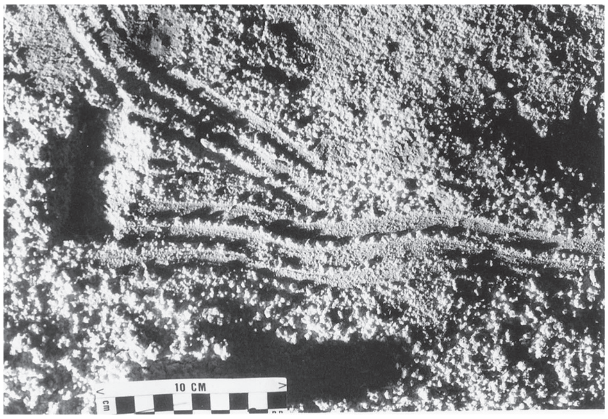

Figure 6. Finger flutings and more recent speleothem growth, Karlie-ngoinpool Cave, South Australia (1985).

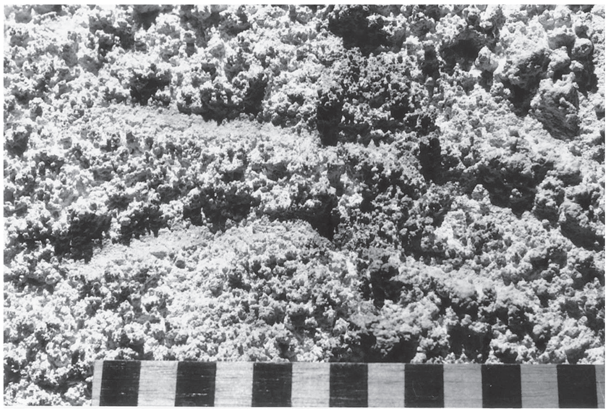

Figure 7. Finger grooves disappearing under subsequent speleothem efflorescence on the right, Malangine Cave, South Australia (1981).

Where the flutings are very well preserved, tribological phenomena may be easily detected. These include transverse tear marks where the compacted medium has yielded to stick-slip reactions and the transfer of material adhering to the fingers. For instance the moonmilk deposits in parts of the large cave of Rouffignac, France, are coated by a red film of clays (probably aeolian), and when the fingers were dragged over the surface this inclusion was smeared along the grooves made by them. Despite being tens of thousands of years old, many panels of finger flutings are adequately preserved to enable the recording of all superimpositions (Fig. 8). It is through the sequences established by this method that the behaviour of the finger fluting producers emerges, especially in relating to the morphology of the cave walls and to accessibility of their different sections. Another

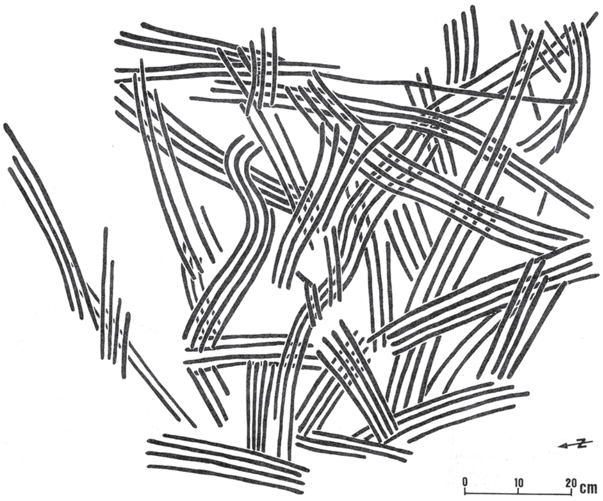

Figure 8. Sequence of finger flutings in Koongine Cave, South Australia.

factor contributing to the interpretation of this behaviour is the metrical information used to estimate the makers' ages of each set of flutings. While adult markings tend to predominate in the entrance-near portions of caves, juvenile markings are far more common in more remote locations or in those of difficult access (Bednarik 1986: 48–49). It has also been suggested that male and female sets can be distinguished by the sexually dimorphic ratio of the index to ring fingers, but this research has been focused on one racial cohort and the aetiology of the putative hormonal influence remains uncertain. Therefore it is firstly not clear that this provides a sound basis for discrimination, and secondly there is no certainty that finger length ratios can be securely determined from digital flutings.

6. Tribology of percussion petroglyphs

6.1. Overview

Other examples of applying tribology to rock engravings have involved open air rock art, for instance on relatively soft rocks such as schists and slates. Such studies can be archaeologically significant, as in the cases of petroglyphs made with steel tools that are assumed to be Palaeolithic. Among the instances where a combination of forensic science and tribological analysis demonstrated the use of metal tools in the production of percussion (impact) petroglyphs are examples from China, Germany and Portugal. In Henan and Inner Mongolia Provinces in China, numerous cupules have been identified as having been made with steel tools, on the basis of several indicators. Cupules are rounded, cup-shaped pits when made with hammerstones — as indeed most of them, from the Lower Palaeolithic to the 20th century, were made. However, the interaction with the rock is quite different when the tool is of metal, or when the rock is very soft and the use of tools of bone or wood is realistically possible. Whereas practically all cupules made with stone implements are the result of direct percussion (impact by a handheld tool), those made with metal implements can be assumed to have been made almost entirely by indirect percussion (hammer held in one hand, chisel or punch held in the other). The same applies to cupules in very soft rock (hardness 1 or 2 on Moh's scale). Using this technique permits the creation of cupules with walls that are practically perpendicular to the rock panel, and tends to create floors that are fairly flat. In other words, such cupules are in shape much closer to a cylinder than to a spherical cap or dome, although other variations also exist. Whereas the rounded section of a stone tool-made cupule is characteristic and inevitable, there is great latitude in the technically possible morphology of a cupule created with a metal tool. For instance a conical section can be achieved, possibly featuring a central impression of the actual tool point used (Fig. 9). Moreover, the flat floors of semi-cylindrical cupules may feature one or even several such tool dints, and the side walls may bear gouging grooves occasioned by the metal tool (Fig. 10). In the case of the Chinese specimens, they are on schist in all cases, which demands that the tools must have been of steel (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).

Metal tool-made cupules occur also at the schist petroglyph site of Gondershausen in Germany, but only its panel of zoomorphic petroglyphs has attracted attention (Welker 2015). The six zoomorphic percussion petroglyphs occurring with two inscriptions on a small vertical panel have been attributed to the Palaeolithic, more specifically to the Aurignacian, i.e. assigned an age of >30,000 years. However, tribological examination has established that the tool used to create the images, claimed to depict horses, was a flat steel chisel with a blunt working edge of only 8–9 mm length (Bednarik 2015d). Its rounded edge seems to have had a diameter of about 2–2.5 mm, and the marks are so well preserved that the striations caused by the chisel's friction force overcoming the shear strength are still discernible (Fig. 11). The analysis also established that the steel chisel was used by a right-handed person. The site has been extensively quarried for roof tiles in the historical period, including recent centuries.

Similar circumstances pertain to the many petroglyph sites in the Côa valley of northern Portugal and the nearby Siega Verde site in western Spain. They are also schist sites that have yielded no Pleistocene occupation evidence, yet they were widely attributed to that period. Direct dating at some of the Côa sites has established, in a blind test involving four scientists, that most of the petroglyphs are relatively recent; none could pre-

Figure 9. Cupule of conical section, with a central impression of the tool point used, Boshishengtailin site, Henan Province, China (2015).

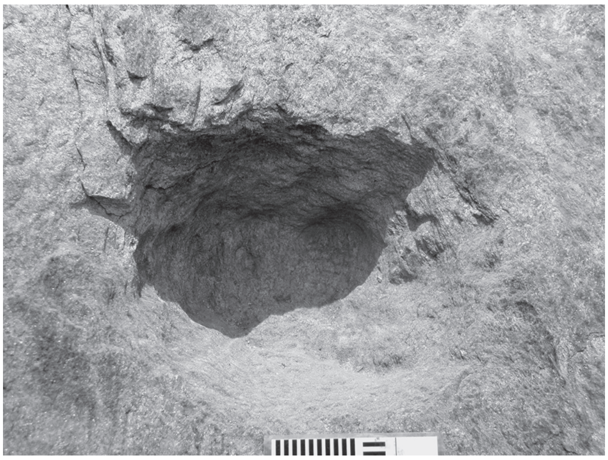

Figure 10. Grooving by metal tools on the wall of a cupule, Boshishengtailin, Henan Province, China; at least four grooves can be discerned, as well as the impression of a rather blunt, thick metal tool point on the cupule's flat floor (2015).

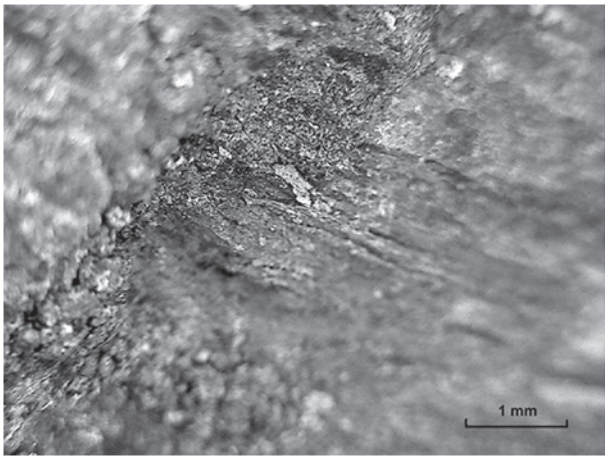

Figure 11. Microphotograph of the deepest portion of a vertical groove in 'horse II', Gondershausen, Germany; note the steep wall on left, low angle of the right slope, chisel striations and almost unweathered condition of the floor where it is not covered by lichen (2015).

date the Neolithic (Bednarik 1995a, 1995b; Watchman 1995, 1996). At the Siega Verde site, forensic evidence has shown conclusively that the rock art can only be of the last few centuries, and that most is of the early 20th century (Bednarik 2009). At some of the Côa sites the engravings were clearly made with carbon steel (Eastham 1999), and the numerous engraved dates of recent centuries tend to be far more weathered than the adjacent zoomorphs, none of which depict an extinct species. Since the supposedly Palaeolithic engraved lines dissect lichen thalli, while the largest thalli occurring over petroglyphs are only a few centimetres in size, a Pleistocene antiquity is quite out of the question.

The forensic observations to be gained from cupules are even clearer in those on less resistant rock types. The forty-five deep cupules on a wall panel in Ngrang Cave, western Victoria, Australia, are on rock of hardness 1–2 on Moh's scale. They demonstrate most clearly that the purpose of a cupule is to penetrate the rock as deeply as possible whilst keeping the opening as small as feasible. This objective appears to be almost universal in the production of this kind of rock marking. Many of the Ngrang Cave cupules are deeper than wide, and in some of the deepest specimens, the diameter even increases slightly with greater depth (Bednarik and Montelle in press). There are numerous tool markings along the side

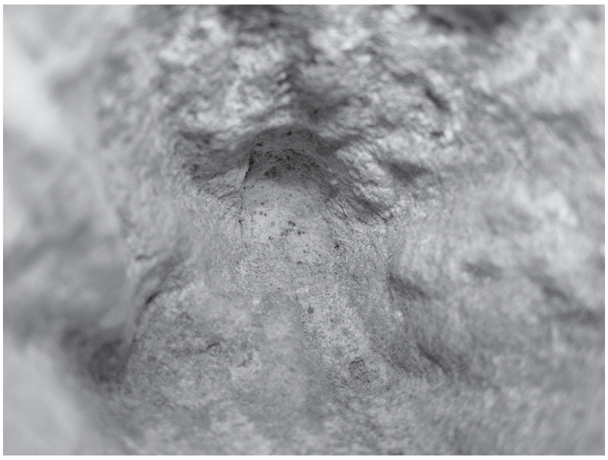

Figure 12. Floor of deep cupule in Ngrang Cave, showing the circular impression of the end of the tool that was used in its creation (2011).

walls of many, and the floors feature a number of imprints of the end of the punch that had been used to create them (Fig 12). The tools used were elongate, well over 20 cm long, and their ends were of a diameter from 18 mm to 22 mm. Extensive replication experiments managed to exclude the possibility that the indirect percussion involved stone implements, and while the use of wooden tools cannot be conclusively excluded, the most likely tools used were fractured long-bones of macropods.

6.2. Cupules

Kumar has conducted a series of detailed replication experiments 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). It is therefore reasonable to estimate that it would take between 45,000 and 60,000 strokes to create a 12 mm deep cupule on the same rock, 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. Assuming further that each stroke delivered, say, a force of 0.4N, the total force to bear on such a cupule of perhaps 15 cm^2 floor area would be in the order of 20 kN, or 20,000 $kg{\cdot}m/s^2$. Some of that energy caused the fracture of rock grains and cement, and a minor component would have been dissipated as heat. However, most of it came to bear directly on the fabric of the rock. Of particular interest are the tribological effects of focusing this massive impact of kinetic energy on a small area of rock surface. They can lead to the purely tribological conversion of the cupule floor to tectonite: containing minerals that have been affected by natural forces that caused their orientations to change (Bednarik 2015a, 2015b, 2015c).

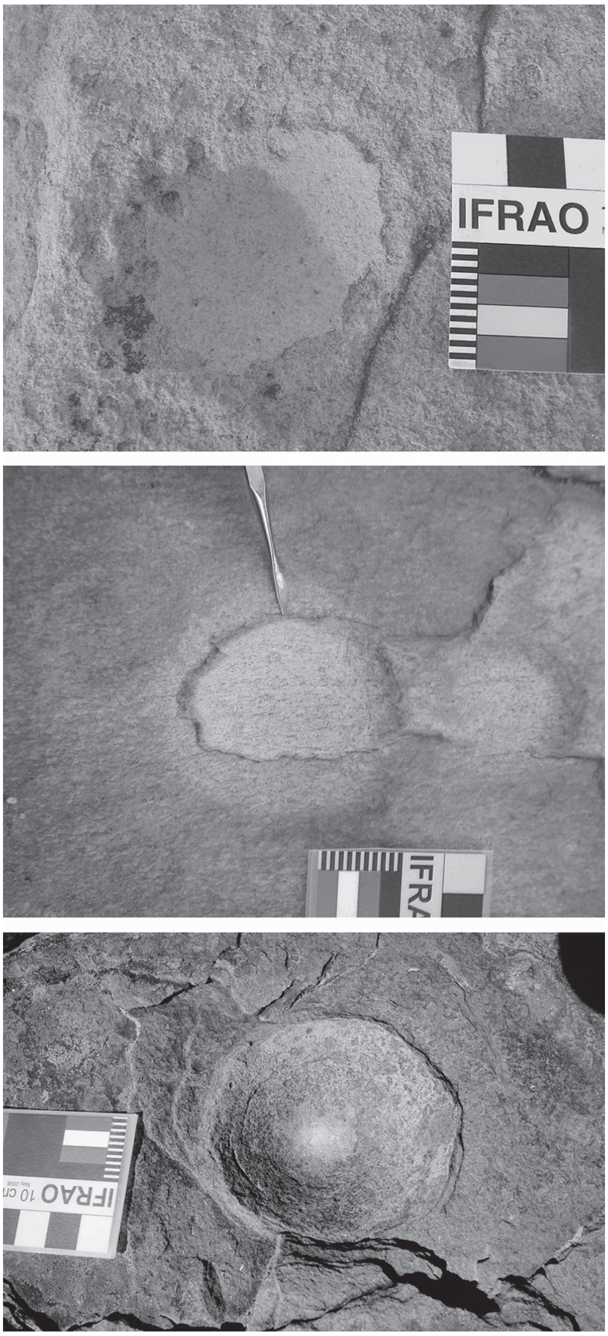

Figure 13. Modified laminae in cupules on quartzite at, from the top, Indragarh Hill (India), Nchwaneng (South Africa) and Inca Huasi (Bolivia) (photos 2004, 2009, 2014).

This occurrence has not been recognised before the present study, in either rock art research or geology. Its discovery was prompted by encountering an unexplained phenomenon found in a small number of cupules at seven sites in several continents (Fig. 13). The rock panels on which these cupules occurred had been subjected to both granular and mass-exfoliation since the time they had been made, some of them being of very great antiquity. Yet the interior of the cupules had remained almost perfectly preserved, despite the retreat of the surrounding rock surface by several millimetres. This was evident from many cracked or battered grains of crystalline quartz found on the modified cupule floors, and microscopic conchoidal impact scars that could only have been caused by the percussion occurring during cupule production. This lamina cannot be a deposit of amorphous silica, but can only be the original floor of the cupules. Their interior surfaces had become modified to a lamina of the support rock that was lighter coloured than the protolith (background rock) and had acquired significantly more resistance to weathering processes.

The importance of the tectonite lamina in explaining the tribology of cupules is underlined by its complete absence on cupules occurring on massive crystalline alpha quartz, even on specimens of unusually large dimensions that must have been pounded significantly longer (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, it is completely absent in large and deep cupules on rocks lacking a cement component, such as granites. So far it has only been identified on sandstones and quartzites, and in one instance on silica-rich schist. This narrows down the search for the constituent susceptible to the anisotropic recrystallisation that yields the tectonite lamina. It must be the syntaxial overgrowth that binds the quartz grains of sandstone and quartzite together and that, in the second rock type, has already undergone metamorphosis previously. The cement of silica sandstones not only binds the grains; it reduces porosity and permeability as it fills and seals the voids between the detrital clasts (Macaulay 2003). Mineral coatings on the quartz grains (such as clays) and entrapment of hydrocarbons in pores retard or prevent cementation, 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 not fully occupied by syntaxial overgrowth; they tend to be sealed off in sandstones with more than 10% imported silica cement, restricting further silica transport. In quartzites, this leaves only the pores and their trapped contents to permit further consolidation, which presumably occurs as crystallisation and foliation of the cement by ductile deformation. Reactions that cannot occur thermally become possible, and the direction of the mechanical stress relative to the orientation of crystallographic axes can create tectonites. They are thus chemically similar to the protolith, but very different structurally, and significantly more weathering resistant. The conversion process is called *kinetic energy metamorphosis* (KEM) (Bednarik 2015a, 2015b, 2015c).

6.3. Other KEM issues

Thus 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 that differ from the products of 'ordinary' reactions. In the case of the cupules mentioned, the conversion is caused by the application of highly focused kinetic energy released by the hammerstones in the form of many tens of thousands of blows. However, this is not the only KEM phenomenon now known. Similar tectonite occurs quite frequently in sandstones that have been subjected to ductile conversions under conditions of great pressure and high temperature. Conversion processes arising in shear zones of sandstone subjected to such ductile stresses 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, energy is dissipated through the deformation between the two sliding masses. The kinetic energy involved can metamorphose sandstone by KEM. The result can be manifested in thin sheets of planar or curvi-planar, randomly orientated zones of whitish, very weathering-resistant schistose tectonite. If the asperities of one of the surfaces ploughing into each other are harder, grooves will be produced if shear strength is exceeded (Bhushan 2013). These are tribological striations one can find on such sheets as that shown in Figure 14, which even shows the tear marks that are the result of stick-slip (Bowden and Leben 1939), which have been encountered in engravings and finger flutings (see above).

Similarly, KEM, first identified in cupules, is also implicated in the formation of cutaneous tectonite substrates on blocks or bedrock exposed to heavy barrage by fluvial battering (Bednarik 2015a, 2015b, 2015c). This is thought to have involved clasts accelerated by river torrents of particularly high kinetic energy and has been observed in a limited number of cases thus far. Palaeo-river beds may have been dry for millions of years, yet the tectonite skins found in them have survived

Figure 14. Flat metamorphosed lamina formed in ductile shear zone of sandstone, showing distinctive horizontal foliation grooves and tear marks; Gariwerd Mountains, Australia (2014).

without significant weathering for geological time spans. It is even possible that the power of glacially induced abrasion has effected tribological conversion of thin surface veneers on some glacial pavements, rendering them outstandingly impervious to weathering processes. In short, the KEM process was first reported from rare instances in cupules, but it may be far more common in geological conversion of those types of rock that are susceptible to it.

7. Conclusion

Although in this paper, emphasis is given to the tribology of cupules, it seems self-evident that the same analytical tools as those discussed here can be applied also to other percussion petroglyphs. There should be little doubt that most of them were made by direct impact, i.e. with a hand-held hammerstone (Sierts 1968; Pilles 1976; Savvateyev 1977; Bruder 1983; Bednarik 1998b; Weeks 2001; Krishna and Kumar 2015). Those that occur on very hard rocks of the types that are susceptible to KEM may have experienced incipient conversion to tectonite, especially where the grooves are very deep and involved the application of great kinetic energy. So far, this potential remains entirely unexplored. Similarly, the involvement of KEM in the polishing of glacial pavements still needs to be investigated.

Some practical considerations arising from the understanding of KEM so far attained derive from the insights listed above. For instance as KEM laminae must necessarily be of the same age as the cupules they are found in, and if a method can be developed that determines the time of conversion, it would provide direct dating of the cupules. KEM has caused a profound change in the crystallographic fabric of the rock it has affected, and a technique, perhaps resembling thermoluminescence analysis, might be able to quantify rates of decay as a function of time. Alternatively, radiometry of components trapped in the voids formed by the syntaxial quartz overgrowths on the detrital quartz grains may be subject to some form of decay in the course of time. The prospects of securing a new dating method based on KEM products seem encouraging, even if this is to be a development of the distant future.

The surface retreat next to a cupule with a KEM-caused tectonite lamina provides a good measure of how much protolith weathering has occurred since cupule production, because the tectonite is almost inert to weathering and therefore provides a reliable reference point. As noted above, the retreat is usually several millimetres, i.e. adequate to erase any shallow petroglyphs. This provides a telling demonstration of the rate of rock erosion at open-air sites, even on weathering-resistant rocks such as quartzite, and a timely reminder to archaeologists that *any* lithology is subject to surface retreat if exposed to the elements. Until now, researchers have had no 'inert' reference point to refer to, on surfaces lacking surviving remnants of aspects created at the time of petroglyph production. While the rate of surface retreat varies greatly between different lithologies (Bednarik 2001: 61), rocks other than the most resistant (e.g. gabbro, diorite, quartzite, granite) have no prospects of hosting surviving Pleistocene petroglyphs if they have been exposed to precipitation.

In addition to the tribology of percussion petroglyphs, this paper has also considered the discipline's contribution to abrasion petroglyphs. In the study of any rock art whose production involved interacting surfaces in relative motion, tribology and tribochemistry need to be engaged. Their contribution is perhaps not crucial in the study of pictograms (except concerning work traces on mineral pigment pieces), but in the scientific investigation of rock markings made by abrasive, percussive or drilling motion they certainly are.

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