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Archaeotribology: The interaction of surfaces in relative motion in archaeology

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ABSTRACT

It has long been appreciated that there are many applications of tribology in the geological sciences. These range in scale from microscopic levels to those of intercontinental tectonic processes. Some of the key aspects of geotribology are briefly discussed to illustrate the advantages of such an interdisciplinary approach, before exploring the even greater benefits of applying tribological methods to many aspects of archaeology. That discipline comprises a vast array of physical evidence that derives from tribological processes and cannot be credibly explained by traditional archaeology. Many of these processes are briefly described, and the methodology required to define and elucidate them is discussed. The paper concludes that, for the further development of archaeology and the study of rock art, it is essential to establish a sub-discipline of archaeotribology.

1. Introduction

Except for relatively limited forays into such fields as geotribology or tribochemistry, the discipline of tribology has since its inception in the 1960s [75] focused almost entirely upon technological or engineering applications. This is not surprising; even Jost was already sensitive to the need to justify the discipline's being in economic terms. His seminal publication explored the failures of plant and machinery and the associated economic costs of friction, wear and corrosion to the British economy. After an initial focus of the discipline on the operation and lifecycle of machinery, its principles were applied much more widely elsewhere, in biomedicine, nanotechnology and the technology of alternative energy sources. For instance, nanotribology involves the commercialization of microelectromechanical and nanoelectromechanical systems, such as disk drives or magnetic storage systems. Scanning probe technologies have given rise to the investigation of processes at the microscopic, molecular, and even atomic levels. These have led to the development of chemical and bio-detectors, drug delivery systems, molecular sieves, chip systems, nanoparticle-reinforced materials and a new generation of lasers.

Most tribological research has been in these economically important spheres, while applications of the discipline to "natural systems" or in the form of basic research into the relevant universals have been less commonplace. It is argued here that this emphasis on economic relevance might, in some ways constrain the potential of the discipline. It favors directions perceived as advantageous to human society, a criterion not relevant to a science. It also tends to deter the participation of research fields that would greatly benefit from becoming involved with tribology, which in turn would be likely to broaden that field's horizons through feedback from such client disciplines. Another limitation is imposed by the preoccupation of traditional tribology with friction, which is not the only form of interaction of surfaces in relative motion. Tribology is a distinctly interdisciplinary field and to appreciate its full importance it can only benefit from a universalist approach that explores all of its possible aspects. In an epistemologically balanced scientific approach, all forms of interactions of surfaces in relative motion need to be considered comprehensively.

The validity of this view is well illustrated by geotribology, a sub-discipline that offers many applications of tribological principles to phenomena of the uppermost lithosphere and enriches both geoscience and tribology. For instance, the mechanical, thermodynamic, and physicochemical interactions occurring at tectonic stress faults yield distinctively tribological effects [135]; cf [40,106,110,119,129,132,133]. However, there are several other forms of surface interactions in

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geology, not all of which are frictional; some are by percussion or impact, and as we shall see, there are even effects caused by compression that need to be considered. Impact is not only as pertinent as friction; it is also apparent that the two cannot be properly separated: they form the ends of a continuum. For instance, it is impossible to separate, in the behavior of a suspended load of a river, the effects that derive from impact from those occasioned by abrasion. Much the same applies to any fluvial or aeolian load, irrespective of granular fraction size. As a river cobble being transported in a bed load is worn round, it is difficult to say which part of the wear derives from friction, which from percussive impact. The same applies to the wear experienced by bedrock affected by fluvial sediment, and many other examples of such combined effects are evident.

Similarly, the tribological role of lubrication is not limited to applications in mechanical engineering but extends to geological systems, among others [32,52]. For instance, Boneh and Reches [39] derive a theoretical model for the rate of wear at faults based on the observation that the dynamic strength of brittle materials is proportional to the product of load stress and loading period. The concept of lubrication, which in geology includes the role of meltwater under glaciers, also incorporates non-traditional forms of friction minimization, e.g. by tribofilms [70,105]. Examples are the transformation of minerals and rocks in the zones of friction arising from seismic-tectonic reactions through kinetic energy. These can range from transcontinental megazones to nanozones inside the crystal lattice [85]. Such tribometamorphic products include eclogites, lherzolites, and phengite-bearing schists, and we will encounter one more that can form at the surface, not only at faults.

An important conclusion of Boneh and Reches [39] is that they "found that utilization of tribological tools in fault slip analyses leads to effective and insightful results." Geology and other disciplines can benefit greatly from sharing the insights gained by tribology, just as that field can advance further from client-disciplines' feedback, and from expanding its scope to all aspects of the discipline.

2. Geotribology notes

Geotribology is well suited for preparing the groundwork in this quest. Besides the mentioned tectonic stress fault reactions, all aeolian, fluvial, and glacial erosion processes of rock mass are tribological. Three forms of particle movement are distinguished: in suspension, through saltation, or by creep (reptation). Each of these involves various complexities, for instance, saltation is accompanied by electrostatic effects, in any fluid, be it water, air, or any other substance subject to the laws of rheology. There is also the possible development of tribofilms or the formation of any cutaneous metamorphosis products. Typical examples of suspension are sand storms in deserts or suspended loads of rivers, in which fluid flow is of adequate velocity, and the mass of the particles is small enough to allow the grains to remain in suspension for some time [114]. In reptation, the grains are lifted only weakly and do not rebound, as fluid flow removes the embedding smaller particles. In saltation, as fluid velocity reaches a critical value [3,4] called the entrainment velocity, the drag and lift forces exerted on the grain can lift it and move it in a roughly ballistic trajectory with the flow [83]. All effects of these movements are governed by tribological laws, in terms of friction, asperities of contact zones, stick-slip phenomena, deformation by percussive collision and so forth. To appreciate the full complexity of these processes, consider the variables of velocity, eddying effects and their causes, or the static electric fields (saltating particles acquire a negative charge relative to the ground, which affects the stability of the grains on the ground). Or consider the tribological effects of a collision between rock particles and the stress waves it causes, which can be rendered visible by photoelasticity [33]. This level of complexity is beyond the means of standard geological practice; it is rightly in the domain of geotribology.

So are many other phenomena of geoscience. Just as the floor deepening of a pothole is attributable primarily to friction while its walls are more susceptible to impact [24], in most geological effects it seems impossible to separate one result from the other; there is no hard line of division. Impact is as much part of the reductive process (wear) as is friction. In this process of reduction of mass, the primary determinant of the amount of material removed from the less resistant of the two elements is the aggregate hardness of one of its components relative to the other. The sand tends to be harder than the bedrock because the smaller fraction has survived the greater duration of weathering, hence the sand is more resistant to it. Indeed, most sand grains are of quartz, whereas most common rock types are of lower aggregate hardness. On some rock types, even factors such as brittleness or cleavability can play significant roles in determining tribological outcomes.

A geological process similar to fluvial transport of rock particles of all fractions applies to littoral zones, where these are worn by a combination of friction and impact at lake and ocean shores. They, in turn, wear the bedrock where it is exposed to them. The effects include potholes similar to those in fluvial contexts [24,76,123].

The best-known factors of aeolian erosion are perhaps sandblasting and the ventifacts it can yield. Windborne particles are subject to tribological laws similar to those affecting a fluvial load, a combination of abrasive and kinetic impact damage. Angular particles are more effective than rounded, having more asperities helping to incise the softer ductile material. In this, an impact angle of about 30° is the most efficient. The cause of the glazing-like sheen found on the ventifacts produced by the bombardment of high-velocity aerial loads is self-evident, but the precise derivation has not been established and is likely to involve kinetic energy metamorphosis on certain rock types (see below; [27]). Surfaces struck by prevailing winds at angles of well below 90° tend to display fluted surface sculpting, while direct right-angle impact yields typical pitting.

Rock grains travelling on aeolian turbidity currents can travel great distances, including intercontinental journeys crossing the Atlantic or the Mediterranean [84,92]. It is also responsible for the vast deposits of loess, aeolian sediment especially found in the Northern Hemisphere. Loess is an entirely tribological product, deriving from glacial action grinding down rocks to silt-sized mineral dust. Its transport by wind results in a narrow range of size fractions and composition, and it is deposited without internal stratification in parcels representing glacial or stadial periods [134]. These are important in archaeology as they have long been used, especially in Eurasia, in attributing Pleistocene sediments to specific periods [45,46,56,58]. In particular, there is a consistent increase in the content of dolomite relative to calcite with decreasing age of stratigraphic units (cf [57]). This had been assumed to be a function of preferential weathering until Hädrich's [65] pedogenetic enrichment hypothesis was proposed, which has since been tested and confirmed to be valid [25]. My results showed that enrichment by dolomite accounts for the stepped profile of its compositional depth functions in cave sediment, where external weathering does not apply.

Glacial erosion tends to be just as effective as fluvial, aeolian, or marine erosion, and again consists entirely of tribological processes. It counteracts to a significant extent the tectonic uplift of major mountain chains brought about by the tribological interaction of continental plates. Glacial erosion operates through the action of moving fragments of rock relative to the bedrock, in combination with the effects of freeze and thaw cycles. It is only possible through the agency of meltwater acting as a lubricant [131] because a glacier frozen to the bedrock does not move. Glacial ice behaves like a Newtonian viscous fluid subjected to gravity flow [93,96]. The load of rock fragments it carries, along the base and sides of the ice flow, grinds against the bedrock as well as each other, gradually pulverizing the rock of all surfaces affected. The rock particles derive from freezing-regelation cycles and, to a lesser extent, from plucking; i.e. lifting blocks of bedrock from their socket. Both friction and impact occasion the wear experienced by them. The striations caused by the asperities of blocks dragged over bedrock pavements are the most common rock markings and can be preserved for hundreds of millions of years [7]. Glacial striae have been studied by glaciologists [36,49,53,72,73] but not by tribologists. They are occasioned through rotational movement of the abrading clast (the "tool"), whereby the asperities of the propelled particles are continuously renewed. Altered tool orientation results in different striae morphology [37] and has been used to infer preceding ice extent and basal thermal conditions [54, 115].

There are essentially two models attempting to explain the dynamics of glaciers, those of Boulton [42,43] and Hallet [67,68,69]. Boulton perceives the pressure of overlying ice and basal water pressure affecting the rate of glacial wear, whereas Hallet considers that the contact pressure between the basal particulate matter and the bed it overlies is related to the rate at which ice flows toward its bed, thereby forcing the particle into contact with the bed [59]. Both models emphasize the role of the basal thermal regime, whereby increased basal temperatures result in enhanced potential for abrasion [66,122]. As the basal debris is subjected to gradual comminution until silt grade is reached, clasts lose asperities and renewal is required [60,74].

Both the uplift of mountains by plate tectonics and their wearing down by fluvial, glacial, or aeolian erosion are thus essentially attributable to tribological forces. This indicates the great importance of investigating the precise processes of geology by methods of tribology. The finer details of most of these processes remain unaccounted for, and there are still other geophysical effects in need of tribological attention. Numerous further phenomena exist in nature that were caused by the interaction of surfaces in relative motion, at least one of which is a rock. For instance, one of the greatest difficulties in archaeology concerns the discrimination between stone artifacts and natural products closely resembling them, for which that discipline still lacks reliable diagnostics (see next section). Many forms of rock markings may resemble rock art, especially petroglyphs, so closely that they are often misinterpreted by archaeologists [17]. The correct identification of animal markings, especially in limestone caves and most commonly made with claws, has often presented difficulties to researchers [11,30]. They range from the scratches made by megafauna such as cave bear in Europe [15] or Thylacoleo in Australia to the tiniest claw marks made by small rodents or chiroptera. Animals such as proboscideans, bison and cave bear have also created rock polishes with their bodies, while others produced rock markings with their teeth, horns, antlers, or tusks. Rhinoceroses use rock surfaces to sharpen their horns, which over long periods can lead to the formation of sets of deep linear grooves. In Brazil, numerous caves have been formed by an unknown extinct megafaunal species with its teeth [127]. Caves are libraries of billions of such events because even rock markings on soft surfaces can survive for long periods in speleo-environments. They have often been described as the deliberate work of humans, i.e. as rock art. In one case, even linear marks made by quartz grains embedded in the shaggy fur of cave bears rubbing against cave walls had been identified as Paleolithic engravings [22]. This shows how difficult it can be to discriminate between rock art and natural markings resembling it. Once again, it is worth remembering that all kinetic rock marks are tribological effects.

Still, other patterns on rock have been misconstrued as anthropogenic by archaeologists. Regolith movement marks in such places as rock shelters and caves can be attributable to gravity, tectonic events, changes in aquifer level, or eustatic fluctuations, as talus clasts adjust their locations and their asperities create grooves. Rocks in such sites may, as a result of trampling by humans or other animals, become heavily marked by sedimentary quartz grains in the process, and if this occurred in a human occupation context, the thousands of grooves have on occasion been interpreted as engravings [10]. Analogous natural markings can also occur as the result of sediment movement by solifluction or similar processes. Even plants can cause surface markings on rock, by chemical solution of limestone through the respiratory CO_2 of mycorrhizal fungi [12] as well as by kinetic effects of two types: plant parts scraping rock in wind action ([125]: Fig. 8); or when a tree hugs rock for support with its roots [34]. Every time the tree sways in the wind there is a minute movement in its main roots just below the ground. Together with silt and sand acting as an abrasive, this is sufficient to produce quite deep grooves on the rock, which in turn improve the tree's hold on its support. After the tree and the soil disappear, the grooves may be interpreted as artificial [116].

Unintentional and utilitarian anthropogenic rock markings are caused by human agency, but without the intention of attributing meaning to them (as in the case of rock art). Examples are the gouge marks left on rocks by plow shears, which have occasionally been defined as petroglyphs, as have grooves made by steel cables or vehicular parts dragged over a rock. The same applies to rock markings caused by mining or construction equipment such as rock drills or core drills. There are even a few types of rock markings that were deliberately made by early humans but are not rock art. Examples are mining marks where flint or ochre had been mined in the distant past [13], or rainwater drainage grooves created to keep sites for the sharpening of stone axe heads dry, crystalline and hard. These channel systems of axe-grinding workshops had been interpreted as extensive "geometric" petroglyph patterns.

The perhaps most enigmatic rock markings I have examined were at three sites along the Lena River in Siberia. They comprised sets of short parallel grooves high up on vertical cliff faces, on very smooth rock. Inspection by binoculars in 1990 was inconclusive. Though they seemed human-made, the marks appeared to be attributable to mechanical force of some kind. Eventually managing to reach such markings by climbing the rock, close inspection revealed no evidence of actual impact. Rather, there was the dense crushing of grains evident, as if the marks had been pressed into the rock with considerable force. I hypothesized that perhaps there had been a rock tower leaning loosely against the cliff, and if a hard clast had become lodged between it and the cliff, it might have slowly wandered downwards with each minute movement, only to be pressed against the cliff by the weight of the tower in each successive position. This seemingly desperate explanation was found to be correct when I located an angular clast that had become stuck between a sheer cliff and a detached rampart leaning against it. It had already produced several similar pressure marks, as each time there was an adequate movement in the tower the clast had dropped a few centimeters.

This observation shows poignantly that the interaction between two objects in relative motion can be compressive, not only abrasive or percussive. It is, however, not the only form of a tribological reaction involving compression. In 2019 I was requested to determine the cause of radially arranged grooves on granite tors at Dong Men Yu Island in Fujian, China, that were believed to be petroglyphic Sun images of great antiquity (Fig. 1). They are attributable to long-term weathering of radial cracks in the rock, so the question was what had caused these cracks. Having seen similar kinds of patterning of fractured rocks

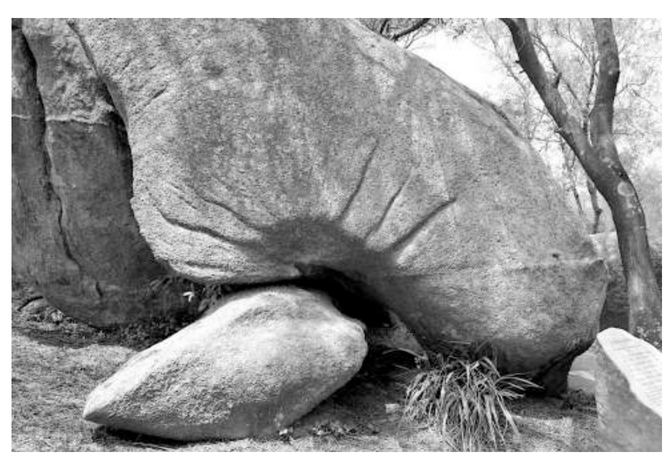

Fig. 1. Rock markings on granite at Dong Men Yu Island near Dongshan, Fujian Region, China.

previously, I hypothesized that this was attributable to high kinetic impact between large blocks in the geological past, but this did not explain the geometric arrangement. As geology lacked a rational explanation, I sought help from the field explaining the effects of rock blasting. Just as in kinetic impact, explosions in rock produce radial fracturing, but whereas in geology, no elucidation of the process had become available, ample experimental work had been conducted with the effects of blasting (because it is economically important to control the extent of effects). A shock wave of kinetic energy emanates from the point of impact, travelling through the rock in a circular pattern as it compresses the rock and crushes it. That pattern of stress by Hertzian geometry can be rendered visible by the technique of photoelasticity (Fig. 2), an important method for the tribological study of contact between objects. The surrounding rock mass then reacts by containing the energy wave in a distinctive circular area (semi-circular in the case of surface impact) and the remainder of the energy is spent as a tensile force applied to the rock mass, prizing it apart just slightly. This reaction results in radial stress fissures centered on the point of explosion (or impact). This led to the discovery of the phenomenon of compressive-tensile rock markings and its explanation [33]. The reaction upon the high impact contact between two rock masses is certainly a tribological effect, and as this example shows, it is neither friction nor actual percussion that causes that effect, but a compression of the rock. In the described example, the mechanically compromised rock in the central part of the pattern and along the radial cracks has become more susceptible to weathering processes, leading to the distinctive visual effect.

3. Tribology and archaeology

The purpose of the above brief notes about geotribology is to illustrate the productiveness of taking tribology outside the purely technological sphere by exploring its innumerable applications in natural systems. In a sense, such an inclusive and systematic approach may uncover potential applications of newfound insights in more traditional tribology. For instance, the realization that compression can be a tribological factor could easily be relevant in more conventional fields of the discipline. Here I wish to explore the tribology of a discipline that has never before been considered pertinent—a field that, in any case, lacks a universal scientific theory and traditionally has been a client of many sciences. Most archaeologists are unfamiliar with tribology or its role in their specialty, while some tribologists are likely to question the relevance of archaeology to them. And yet, large areas of archaeological concerns are actually issues of tribology.

This is fairly self-evident in such areas as the analysis of engraved markings on portable objects of many types, where the roles of asperities and stick-slip are key considerations. It may not be immediately obvious in the case of other material culture of the human past. However, most artifacts made by hominins are ultimately the results of tribological action: the reduction of materials always involves interaction between surfaces in relative motion. Just as in geology, there are countless applications of tribological principles and archaeology stands to gain a great deal from their introduction. Objects carved, abraded, knapped, chipped, drilled or otherwise manufactured from such materials as bone, ivory, stone, ostrich eggshell, amber, teeth, fossil casts and so forth should always involve tribology in the study of work traces. Moreover, the traces of their wear inevitably also amount to vestiges of interaction between surfaces. Together, manufacture and wear traces form a major part of the scientific challenges in archaeology, and it is fair to observe that their empirical study requires improvement. That would be the role of the discipline that studies such effects, tribology. Here I would like to rehearse some of the key issues requiring such attention.

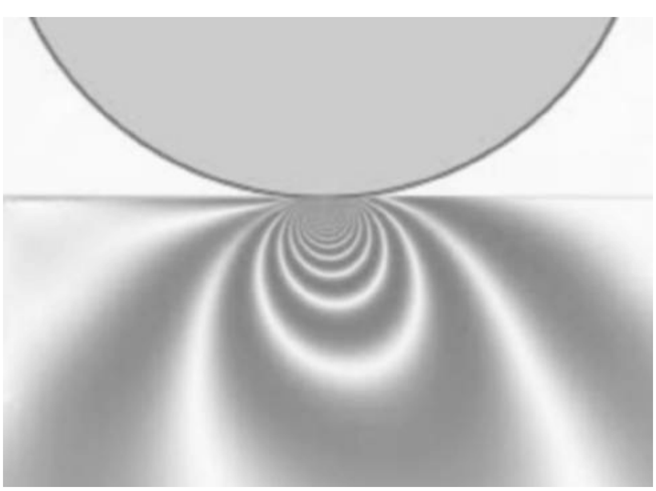

Fig. 2. Stresses in a contact area with slight tangentiality, rendered visible by photoelasticity.

One of the most glaring shortcomings of archaeology concerns its lithics, the stone artifacts that are seen as the "leitfossils" for well over 99% of the duration of human history. Their formal characteristics determine the chronological nomenclature of "cultures"—although this is a misnomer because what is meant is "technologies" rather than cultures. The problem here is that in nearly two centuries, archaeology has been unable to design effective prescriptions for discriminating between stone tools and similar natural products called "geofacts". One of its many controversies occurred in the mid-19th century when for several decades it bluntly rejected the stone tools Jacques Boucher de Crèvecœur de Perthes [41], Casimir Picard and others presented as evidence that humans coexisted with Pleistocene fauna. Although this issue was eventually resolved (by geologists and amateurs), formal diagnostics for distinguishing stone artifacts from geofacts were never established, and even the most elaborate guidelines (e.g. [88]) today remain epistemologically unsound. Determinations are internally untestable and rely greatly on practitioners' beliefs in their individual ability to manage the distinction intuitively. No doubt they are right in the majority of cases and especially when dealing with relatively recent traditions that tend to be more distinctive than older technocomplexes. It is especially in the earliest tool industries, those of the Lower Paleolithic, that the differentiation between stone artifacts and geofacts continues to present the greatest difficulties and even the foremost specialists are prone to errors. Two examples are the assemblages of the Calico site near Barstow in California [71,100], and Toca do Boqueirão do Sítio da Pedra Furada in southern Piauí, Brazil [63,64], but there are many others. Another expression of this problem is the "eolith debate" that began in England in the 1880s [55,98] and is still not fully resolved [51,62,97,107].

Since stone tools are the most important material evidence from nearly the entire history of our genus, it is rather sobering to think that archaeology is not equipped to *conclusively* determine whether a stone object was a tool or not. The discipline shows little trepidation at what seems to be a significant impediment that introduces systematic uncertainties. No concerted effort to establish sound criteria for differentiating geofacts and artifacts is apparent. It would only be feasible if the subject came under intensive scrutiny by a thoroughly scientific rather than a humanistic mode of discourse, and that would require tribological and forensic attention more than any other factor. The lack of enthusiasm in archaeology to investigate these issues is a part of a more general malaise across the discipline, in addressing a variety of issues. For instance, there is the inability of differentiating reliably between rock art and many kinds of natural rock markings resembling it. It is self-evident that a field incapable of discriminating between the two has severe limitations dealing with rock art effectively. Another controversy concerns the distinction between grooves on bone surfaces that are defleshing marks, and those that were made deliberately, having symbolic or other deliberate significance. Still, other expressions of this inability to conclusively determine the "intentionality" expressed in a phenomenon are the identification of hearths and occupation floors. In archaeology, concentrations of charcoal particles tend to be seen as hearths, but they can form naturally when such fragments are subjected to transport by trampling, wind and water, accumulating in hollows on the floor before becoming covered by sediment. Similarly, the process of deflation, in which the larger components of sediment, such as bones, shells, or stone tools, are left behind when aeolian erosion removes the smaller granular fractions (the sand, silt and clay), thus forming a layer dominated by the larger fraction that may resemble an occupation deposit.

In these and other cases, the problem arises that the archaeologist perceives human intent in the evidence, when in reality there may be merely natural phenomena: geofacts, natural surface markings, or natural aggregations of specific materials. It is also related to the discipline's indebtedness to apophenia, the detection of patterning in the way evidence presents itself. All of archaeology's pronouncements are essentially based on apophenic observations of mute phenomena; they are also what Searle [111] defines as "institutional facts". Or to be more specific: they are unreliable propositions and are not falsifiable within archaeology. To test them, they need to be subjected to the attention of science rather than humanities. In the case of the artifacts vs geofacts quandary, a review of the prescriptions of any number of lithic tool authorities will show the extensive differences and mutual contradictions between them (Fig. 3). For instance, Barnes [5], Patterson [99], Luedtke [89], Peacock [101], Nash [94], and Bradbury [44] together review thirteen supposedly diagnostic attributes, disagreeing among themselves and in several cases squarely contradicting some of their colleagues. This lack of consensus of how to recognize stone tools or discriminating between them and geofacts [1] illustrates the precarious state of much of archaeology and its reliance on authority.

Tribology could go a long way in introducing falsifiability to the discipline's propositions, and the described example shows how this could be approached. Removal of mass by percussive impact, which is the cause in both stone tools and geofacts, is a tribological process like any other that can be subjected to analytical procedures. Although the outcomes are quite similar, there is a systematic difference between the two processes of creation. Geofacts (Fig. 3) are formed by impact or

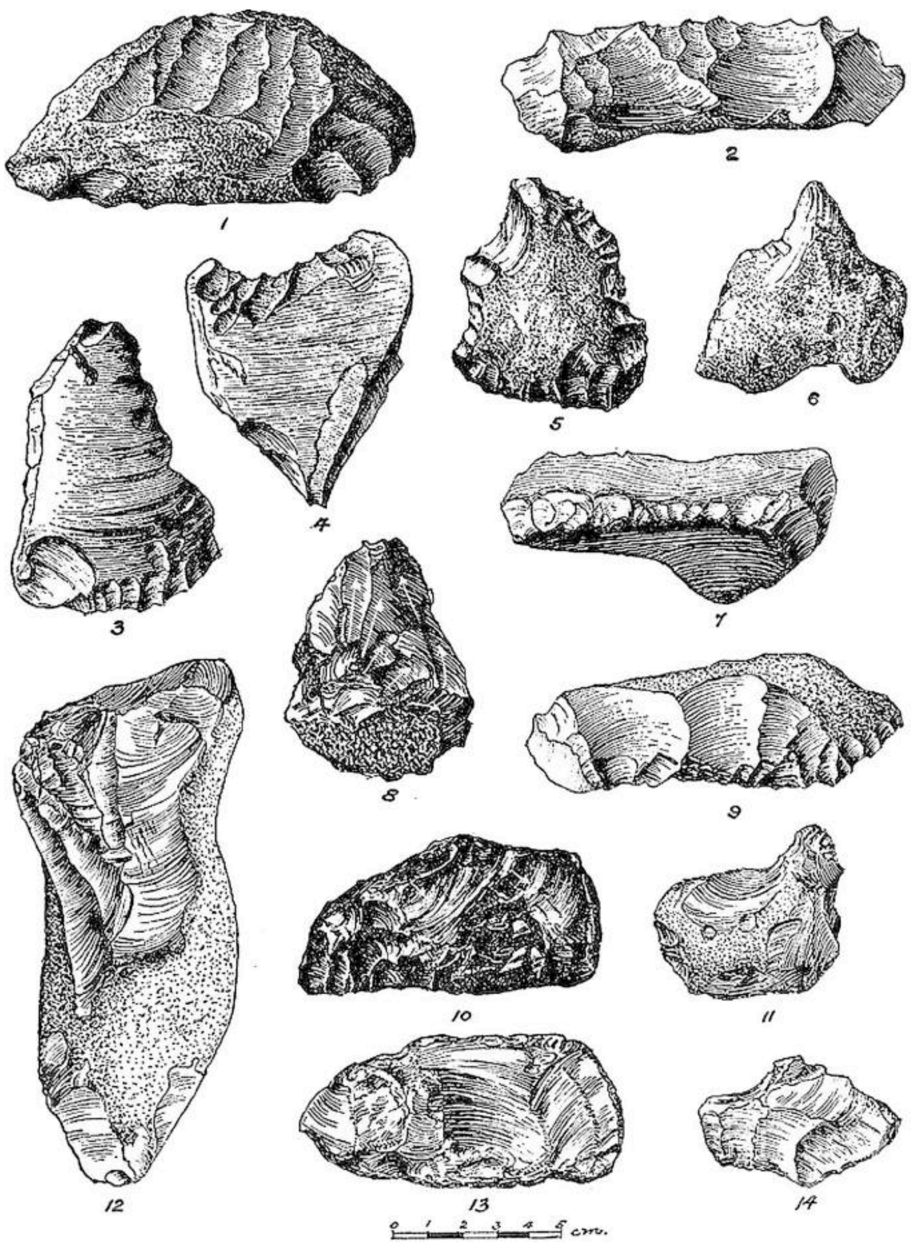

Fig. 3. A selection of geofacts, naturally flaked flint pieces.

pressure flaking that is subject to physical laws deriving from in certain ways random applications of stress. In artifacts, by contrast, these stresses are moderated by variables of intentionality. Therefore, the differences between the two products, geofacts and artifacts, are not determined by factors such as the presence of cortex on a flake's striking platform; bulb of percussion; shape of the bulb of percussion; presence of eraillure scars; exterior platform angle of $<90^\circ$; presence of ripple lines; degree of relative weathering on flake dorsal scars; absence of dorsal flake scars; flake scar orientation being parallel to medial axis; absence of dorsal cortex; presence of platform faceting; radial ventral fissures; or by the ventral and dorsal surfaces being identifiable. To consider, as an example, just the last mentioned: in assuming that the ventral/dorsal surfaces can be identified we fall victim to circular reasoning; we assume so because we believe that we can make this identification. Therefore it must be valid, but we cannot test the proposition. A discipline that aspires to become a science needs to exercise considerably more discipline.

Microwear study is one method to assist in the identification of stone tools. It is the examination of microscopic wear traces found on stone tools, a method pioneered by Semenov [112,113]. This is a typical tribological approach, the object of which are the effects of two surfaces in relative motion. Indeed, Semenov conducted tribological work just before the concept of tribology as a scientific discipline became apparent. He tried to establish what artifacts were used for and how they were used. However, due to the political tensions during Soviet times, his systematic lithic functional analysis remained ignored in the West for some decades [77–81]. His work, begun in the 1930s, involved not just archaeology, but also ethnology, anthropology, economics, paleontology, sedimentology, petrology, physics; and it relied most especially on the microscopy of specimens [113]: 22–23. He distinguished five types of microwear:

1. *Edge chipping:* the removal of tiny conchoidal scales from the working edge of silica stone tools.
2. *Striations:* tribological grooves caused by asperities of the material being worked or of sand grains, parallel to the direction of relative motion.
3. *Polish:* the dispersion of minute particles and micro-plastic alterations of the surface.
4. *Grinding:* the application of higher pressure with the dispersion of more substantial particles.
5. *Rasping:* macroscopic destruction of a surface.

Again, the results of these work processes must be distinguished from surface changes due to natural causes. That discrimination is reminiscent of the previously detailed difficulties of distinguishing between natural and artificial features in various contexts. Seen from the perspective of tribology, three different types of relationships are evident. In the first, an artifact modifies surface aspects of other material; for instance, a tool produces a groove with its asperities. Alternatively, the material being worked impacts on the surface of the tool, becoming in the tribological sense the "tool". In the third alternative, a sand grain may become caught between the two interacting surfaces in relative motion and thus becomes the "tool", affecting one or the other surface, or both. Effectively one element becomes the active, another the passive surface, and generally the active surface is of the material of the higher degree of hardness. Often material such as sand grains, dust, or grit acts as the active element, in the same way as the tools being moved by a glacier do. At this point, the need to subject these complex processes to tribological analysis becomes again apparent.

Archaeotribology, however, involves numerous other fields, questions, and issues that need to be resolved by the methods of science. Many of these issues are of great importance to archaeological interpretation. For instance, if archaeology cannot decide credibly and reliably whether some grooves on a bone surface were made deliberately to create a pattern, or are incidental to such work processes as defleshing or cutting, then it is in no position to make any statement of significance about such a find. Linear surface markings provide a case study well-suited to illustrate the relevance of tribology often found on fragments of ostrich eggshell. They can be one of two basic types, which archaeologists tend to misinterpret. Natural grooves derive from the solution of the calcium carbonate through carbon dioxide respired by mycorrhizal microorganisms along plant rootlets combining with moisture as carbonic acid. Many plant species have symbiotic associations of the mycelium of a fungus with their roots. Artificial grooves, by contrast, were deliberately made with stone tools to create decorative patterns on the eggs as they were used to store liquids. The differentiation between these two kinds of surface markings is important archaeologically, but is not the preserve of archaeologists; it is an issue of tribology. The mycorrhizal grooves, which can also be found on ivory and gastropod shells, are rounded in section and free of longitudinal striations. On ostrich eggshell, the anthropogenic grooves are recognized by striations of asperities and the jagged margins along the grooves where the thin surface veneer (<0.1 mm; [108] splintered from the application of kinetic energy (Fig. 4)). Where the striae are well enough preserved they can function as a "signature" of the tool point when it is applied in a given orientation [16].

Rootlet-caused surface markings are not limited to ostrich eggshell; they are found on many materials frequently recovered by archaeologists. Limestone, marl, travertine, and marble all consist primarily of calcium carbonate and can be affected the same way. Ivory is a dense form of dentine, which consists mainly of hydroxylapatite, $Ca_5(PO_4)_3(OH)$, and some non-crystalline amorphous calcium phosphate. The outer layer of teeth is of dentine, which is largely crystalline calcium phosphate. Antler is mostly of calcium phosphate, and calcium and phosphorus account for more than one-third of its composition. The principal components of the mineral part of bone (i.e. besides collagen, an elastic protein) are again calcium hydroxylapatite and calcium carbonate, although there are considerable variations in composition among species and body parts. All of these materials can be subjected to solution by mycorrhizal acidity along plant rootlets, and all of them have been marked deliberately by the stone tools of hominins. Again, the distinction between such markings, collectively known as "mobiliary art", and others that are not cultural, is the business of tribology. Many natural processes can cause non-cultural markings on portable objects, and the largest group of them are summarized as "taphonomic marks".

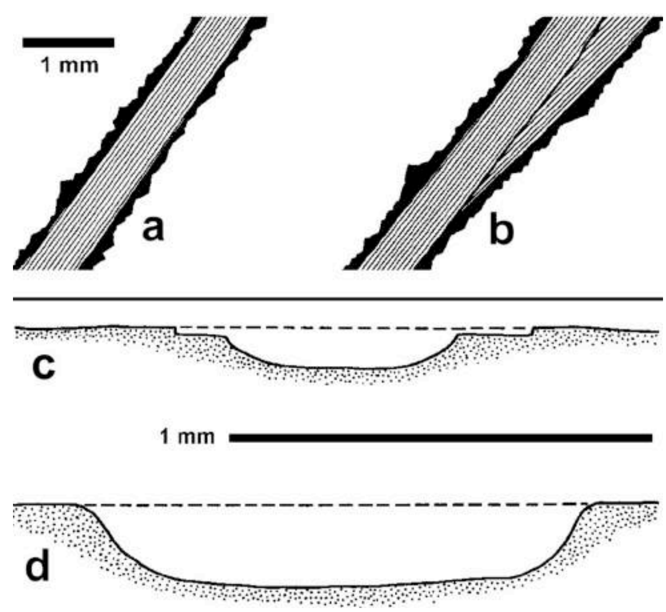

Fig. 4. Engraved grooves on ostrich eggshell in plan-view, showing the jagged margins caused by the splintering of the outermost layer of the shell (a, b) and in section (c), compared to the section of a natural solution groove (d).

They are the result of relative movement of sedimentary detritus with adequate asperities under pressure [19] but have sometimes been interpreted as paleoart. Similarly, exfoliated wall fragments in caves bearing entirely natural markings have been presented as engravings or portions of rock paintings [22]. Animal claw marks have also been described as mobiliary art, and they too are a subject of tribology.

A key element in archaeological studies are beads, especially very early forms of them because they are secure indicators of cognitive abilities and potentials of the hominins making and using them. Beads have complex, culturally transferred meanings that can only exist in the context of social consensus and communication. Beads and pendants can ward off evil spirits or spells, they can be good luck charms, signify status, and they convey complex social, economic, emblematic, ethnic, or ideological meanings. These meanings can be public or private, and although they cannot be known archaeologically, certainly, they can only exist if beads are commonly used. Moreover, the identification of beads is secure: small drilled objects that are too brittle or too small to serve as pulling handles or quangings (as used by the Inuit; [38]: Figs 15, 17, 121d; [95]: Pl. 17; [86]: Fig. 8) can only have been beads or pendants. Various types have been in use during the Pleistocene, including shell beads, disc beads and spherical forms. Their production processes were all tribological, including abrasion, polishing, boring, and, rarely, impact. Materials used in creating these ornamental objects during the Ice Ages included limestone, schist, talcum-schist, steatite, teeth, bone, antler, pyrite, hematite, lignite, jet, fossil belemnite, fossil coral, contemporary and fossil specimens of marine and freshwater shells, ivory, and fossil sponges.

The last-mentioned are the oldest on record and it is instructive to remember that the founder of Pleistocene archaeology, Boucher de Perthes, who was rejected by archaeologists for decades for proposing that humans coexisted with Pleistocene fauna, not only recognized stone tools. He was also the first to report stone beads from a period later named the Acheulian, which is famous for its hand-axes. This tradition existed hundreds of millennia ago and has been found in western Europe, most of Africa, and large parts of Asia. But whereas archaeology eventually accepted the hand-axes as authentic tools, the stone beads of the Acheulian were forgotten and when I proposed that they are just as genuine [23] and that Boucher de Perthes [41] had been right all along, archaeologists rejected my evidence just as they did his one and a half centuries previously. However, the determination of authenticity, be it of beads, of rock art, mobiliary art and various other classes, such as stone tools, is not the business of archaeology, a non-science. It is the business of tribology, using the techniques and approaches of that science.

Conversely, the rejection of Acheulian beads made from perforated sponge fossils (*Porosphaera globularis*) is irrational because, apart from the French and English spherical beads (Fig. 5), we also have ostrich eggshell disc beads of roughly the same time from El Greifa site E in Libya [18,136] and Kathu Pan in South Africa [6,104], as well as crinoid fossils from the Acheulian of Gesher Ya'aqov in Israel [61]. Therefore, hominins of the second half of the Lower Paleolithic period were not the primitive, mute creatures most archaeologists see them as. That is amply evident from various other strands of evidence, such as the indications that maritime colonization occurred certainly in Wallacea, and possibly also at Socotra and in the Mediterranean (Crete, Gavros, and perhaps Sardinia) many hundreds of thousands of years ago [28]. This implies that complex language and forward planning were available to humans up to a million years ago.

This example shows the importance of resolving by scientific means such issues as bead production and use. There is nothing extraordinary about this demand: archaeology is heavily indebted to numerous sciences, such as geology, sedimentology, chemistry and physics, without which it could not operate meaningfully. For instance, the all-important work of dating sediments and physical remains falls inevitably to some of the sciences. In the context of tribology, it also needs to be considered that the scientific analysis of all replicative experiments in archaeology

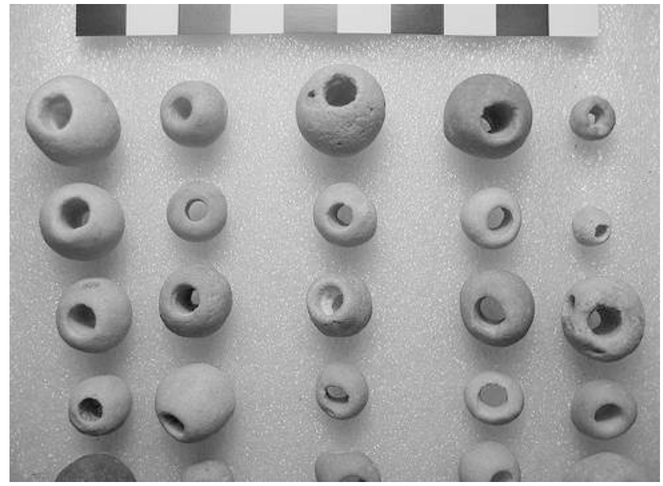

Fig. 5. Some of the hundreds of stone beads found of the Acheulian.

ultimately concerns the results of tribological processes: friction, impact, and, in rare cases, compression. Replication of production practices in early human history is one of archaeology's most expedient methods to explore ancient technologies, but it needs to be combined with a deep understanding of the interactions between surfaces in relative motion. I have conducted experimentation at scales ranging from the creation of ostrich eggshell beads [18] to making bone harpoons, to the construction, with primitive stone tool replicas, of simple rafts and testing them to determine the minimum technological capacity of crossing sea narrows known to have been crossed in the Pleistocene. All of these experiments involved work processes that applied tribological procedures, and I consider that without their examination, such research is not worthwhile. Indeed, archaeotribology should be an essential sub-discipline of either archaeology or tribology; I recommend the latter.

4. Tribology and rock art

The portable component of paleoart mentioned in the previous section accounts for only a very small part of "pre-Historic art"; nearly all of the known paleoart—the art-like productions of pre-History—consists of what is defined as rock art. All of it is the result of tribological processes. Rock art comprises essentially two kinds: rock markings made by a reductive process (petroglyphs) and those made by an additive process (pictograms). In the first type, material was removed from the rock surface to create a symbol, producing engravings, percussion petroglyphs, and finger flutings. Pictograms include paintings, pigment stencils, pigment prints, dry pigment rock drawings, and applications of other materials, such as beeswax. This basic nomenclature reflects not just the technology of creation, but also the nature of the analytical methods applied, the dating methodology and the respective approaches to conservation. The tribology of petroglyphs considers the processes of removal or re-shaping of rock surface material by friction or percussion through their traces or other empirical evidence [27,31]. Pictograms can also involve various tribological procedures, such as the grinding of pigment and the application of paint to rock surfaces. Irrespective of which technique was used or which substance was applied to the rock surface, the process was also one of forensics: it involved a transfer of material, as per Locard's principle. Another application of tribology is the study of finger paintings which may present details such as stick-slip evidence. Although some work processes have been investigated, especially by chemistry, their precise details have not been explained satisfactorily.

The tribological implications are particularly interesting in petroglyphs. Engravings, abrading, polishing, and scratchings record the effects of asperities of engraving tools applied under pressure as these are moved over rock surfaces under controlled conditions. Standard phenomena include stick-slip and striae in some cases. It is of particular importance to archaeology whether these grooves were created with stone or metal tools. If the latter can be identified credibly, it limits the maximum possible antiquity of the rock art to the time metal was introduced in the region in question, and most often the advent of steel (bronze is only effective on relatively soft rock types). Such information would be of great help to archaeology, and a preliminary tribological study suggests that discrimination between marks made with stone and metal should be feasible.

Impact petroglyphs were made with percussion by pounding (direct impact by a hand-held stone tool), bruising, and chiseling. The latter method seems to be limited to the application of metal, especially steel chisels, applied by indirect percussion. Often pecking is mentioned, a term defined as indirect percussion, but it is widely held that this method was not used with stone tools. Indeed, all efforts to replicate it found that it is unsuitable for the production of petroglyphs [20,24,47,87,102,109,117,130]. In creating petroglyphs, it is impossible to separate the processes of friction and percussion, however different they are in theory. This resembles the experience in geotribology, where that separation is also delicate.

The tribology of petroglyphs has only been considered preliminarily so far [31]. This has shown the importance of the relationships between the "aggregate hardness" of the rock, production times of petroglyphs, total volume of grooves, kinetic energy expended, and perhaps even the formation of tectonite layers, which may extend to all rock art created by a kinetic impact. Toughness, strength, ductility, scratch or abrasion resistance, indentation hardness, and brittleness factor of the rock medium all play a role in such studies. Indeed, this complex aggregate of variables defines scientific access to the interpretation of rock art. No understanding of these variables can be expected from archaeology, but the relevant methodology is available from geological material testing and structural engineering fields, and tribology. For instance, the determination of the volume of petroglyph grooves has been available for some time (e.g. Refs. [82,126], using such indices as the symmetry index, sharpness index, V-shape index, and flatness index). Digital photogrammetry [50], 3D laser scanning [103,124], or residual morphological modeling [48] can all be applied. To improve precision, the software for these applications would be able to yield volumetric data by making reasonable predictions of the former rock surface microtopography (before the petroglyph was made) and computing the volume of grooves from its 3D matrixes. Greater precision can be achieved by applying laser microscopy, which also quantifies groove topography [121]. The method has been developed for metallurgical analysis, and in paleoart studies, it provides a means of determining intentionality (op. cit.). It provides reference profiles at any intervals as well as 3D modelling matrixes of individual sectors to an accuracy of one-tenth of a micron.

All variables of the scientific properties of petroglyphs are accessible by conventional, already available methodology, deriving especially from the practices of material testing, as is also often the case in traditional tribology. Many petroglyphs are initially made by percussion, and as the grooves form, abrasion is added to connect the puncture marks. The two techniques are very different tribologically: in percussion, kinetic force fractures crystals by compression, also creating small amounts of heat and releasing mineral dust and small debris. Typical diagnostic features of impact petroglyphs are cracked mineral grains and, in quartz grains, conchoidal fractures. In abrasion, the tool must be harder than the rock medium, and since tools of hardness in excess of 7 on Mohs scale are very rare in nature, abrasion petroglyphs are not possible on such hard rock. Abrasion petroglyphs are caused by asperities on the tools' working surface as they score into the medium and remove a mass in the process. Damage also occurs at the surface of the abrading tool and is especially focused on the effective asperities and projections, which may shatter or be subjected to distinctive patterns of wear.

In particularly soft rock types and where preservation conditions have allowed this, striations are often visible in abrasion petroglyphs. They can be studied, quantified, and defined in much the same way as other tribological marks, be they glacial striae or abrasion marks on steel machinery. Their topography tends to display far more continuity than the grooves of percussion petroglyphs. Digital photogrammetry, 3D laser scanning, residual morphological modeling, and laser microscopy are all well suited for analyzing them. The same applies to digital fluting in deep limestone caves, a form of rock art occurring on formerly soft calcite deposits that are usually re-precipitated carbonate (called moonmilk). Consisting of a microscopic, often fiber-like lattice of calcite crystals, this speleothem is initially as soft as snow but tends to harden through desiccation or carbonatization [8,21]. Finger flutings were made by dragging human fingers across very soft cave surfaces. They have been reported from 74 sites worldwide, of which 37 occur in Australia. Their often excellent state of preservation renders it possible to isolate such features as striations and stick-slip phenomena in them. As in glacial striae, the latter features permit the determination of the direction the fingers were moved. Their tribology thus facilitates the analysis of sequences and strategies, i.e. reconstructing *chaînes opératoires*.

One of the types of cave art in Australia is tool marks on the formerly soft wall and ceiling surfaces [2]. They occur as apparently unstructured assemblages of sub-parallel lines, but occasionally form patterns such as lattices. Again, their tribological study has been most profitable in learning about their production details, including superimposition, the direction of application (Fig. 6), and even the determination of the tool material used in their production as determined from the traces of asperities [9,14].

The tribology of another form of very simple rock art is of particular interest because its investigation led to the discovery of a hitherto unreported geotribological process. Cupules are cup-shaped depressions on natural rock surfaces, in most cases of between 2 cm and 10 cm diameter, that resemble most closely the shape of a spherical cap or dome. Because the oldest known rock art consists mostly of cupules, their tribology has been considered in some detail [27]. Before the Metal Ages, all cupules were apparently made by direct percussion or pounding with a hand-held hammer-stone. The world's oldest, in India and the Kalahari Desert [7,35], have been executed on very hard quartzite rock. Replication work has established that each of them required tens of thousands of blows with hammer-stones to create [87]. As a cupule is deepened, its progress in depth, when plotted against the cumulative input in kinetic energy, shows an interesting pattern (Fig. 7).

As the depth increases, progress is determined by four factors: the often weathered subsurface; the volume to depth ratio; the progressively greater capacity of the rock mass of absorbing the kinetic energy with increasing depth; and the formation of a hardened layer on the floor of the cupule. The last-mentioned is due to the development of a stratum that is more resistant to being crushed than the protolith, attributable to conversion to tectonite—rock containing minerals that have been affected by forces that caused their crystal orientation to change. Until recently, this process of kinetic energy metamorphosis (KEM) remained unknown, and after it was first explained [27], it was found to occur widely in geology. It is manifested whenever the surfaces of specific rock types experience sustained exposure to massive kinetic energy. This includes the bombardment of bedrock by fluvially propelled clasts; the effects of glacially transported rocks on bedrock [36,73,120]; the formation of ventifact surfaces by aeolian action; and the development of seismogenic fault friction mirrors in the lithosphere [32,118,128]. KEM, despite having first been discovered as a product of cupule creation, is, therefore, a rather common geotribological phenomenon that until recently had not been understood or correctly identified. KEM phenomena can be defined as the reaction of rock surfaces to the application of intensive kinetic energy and the tribological alteration of the rock fabric rendering it more resistant to deformation, compression, and

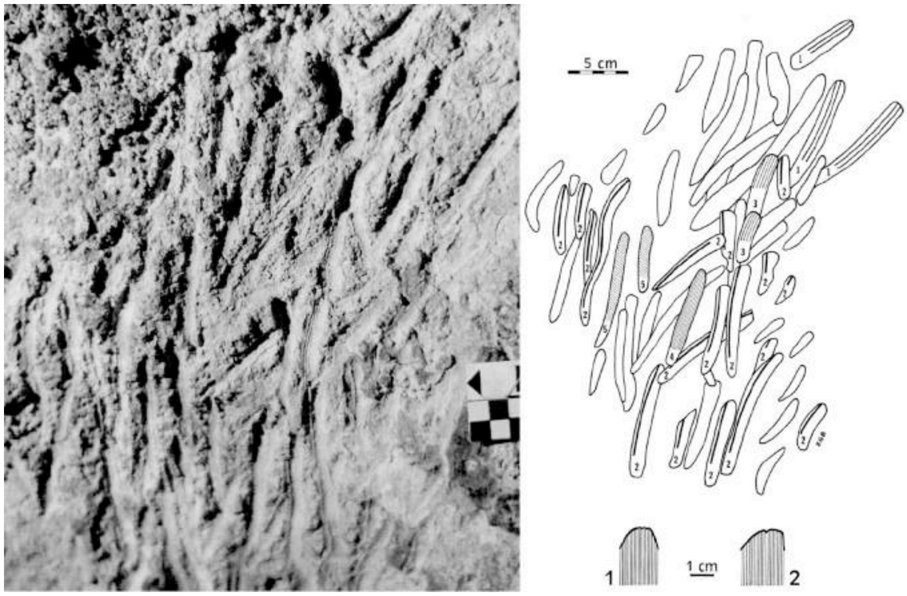

Fig. 6. Analysis of a small panel of tool markings on formerly soft but now hardened wall deposit in Nung-kol Cave, South Australia. These markings were made with aeolian limestone clasts, and the cross-sections of two of the five tool points identified have been reconstructed (1 & 2).

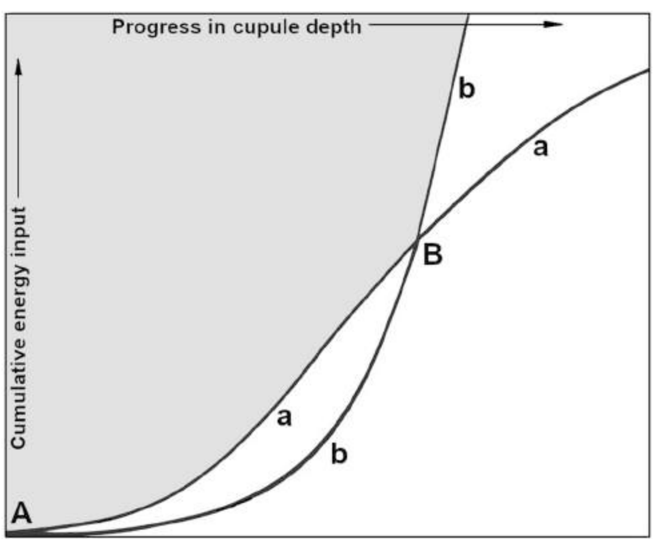

Fig. 7. *Progress in cupule depth versus required input of energy. The shaded area indicates real progress in depth, which remains very low beyond point* B *when further progress is impeded by tectonite formation. Curve* a *defines the progress made without factor* b*, the influence of KEM.*

erosion. In addition to the listed expressions, it is thought to be responsible also for other phenomena, such as the tribochemical changes to bone surfaces subjected to intensive abrasion ([113]: 12). It is, in all the listed cases, a purely tribological effect, caused entirely by the interaction of surfaces in relative motion under conditions of very high kinetic energy regimes. These reactions may be instantaneous, or they may derive from cumulative effects over considerable periods.

Due to cultural heritage protection laws, KEM-derived tectonite layers in rock art may not be subjected to destructive sampling. Such research has therefore been limited to just one of the geological forms, fluvial KEM formations. This work has focused on a site in central India, the Indragarh Paleochannel site near Bhanpura [32]. Although many millions of years old, the extensive tectonite surfaces of this ancient river channel are very well preserved and have been subjected to intensive sampling and analysis. The site formed at river rapids and a waterfall in the distant geological past and features more than 50 m^2 of surviving tectonite skin. The fluvial barrage modified the surface of the Proterozoic quartzite to a depth of a few millimeters, which has protected the rock covered by this layer from weathering. The converted lamina is of pale color and minerals have changed their orientation by foliation involving an anisotropic re-crystallization of a component. In the case of quartzite, this is its silica cement. It binds the quartz grains and reduces porosity and permeability as it fills the voids between the detrital clasts [90]. 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‰). Mineral coatings (e.g. of clays) and entrapment (e.g. of hydrocarbons, clay minerals) retard the syntaxial deposition [91], and the voids between the detrital quartz grains are not fully occupied by cement [29]. This provides the potential for re-metamorphosis of the quartzite protolith (Fig. 8).

In my analytical work I, therefore, focused on three factors: the grain boundaries of the formerly amorphous silica zones; any residual sediments associated with this cement; and inclusions entrapped within quartz grains. The first two elements were expected to reflect the progression of the final metamorphosis because if this process is one of consolidation as was hypothesized [27,29,31], it would involve specific effects. The physical properties of the cement would change as the remaining voids left by the syntaxial quartz overgrowths are purged, ductility aligning the silica into a crystalline structure. This should also involve a very tiny compression of volume, presumably resulting initially in a minute widening of the boundaries. As the "annealing" ductilization progresses further, these gaps would eventually close. This predicted behavior was fully borne out by the empirical evidence (Fig. 9).

The discovery of KEM processes illustrates the great potential of tribological studies not only in geology but also in paleoart studies, especially of petroglyphs, in addition to the many other applications in archaeology. Another example is the involvement of tribology in the age estimation of rock art. The underlying principles are exemplified by a study of the petroglyphs at Siega Verde in western Spain [26]. This rock art was the subject of a major controversy when some scholars pronounced it to be of the Pleistocene (as the basis of its submission to the UNESCO World Heritage List) while others proposed very recent antiquity. The matter was resolved by tribology, through the effects of water-propelled angular quartz grains on the relatively soft schist. All of the petroglyphs are located in the flood zone of the Agueda River passing

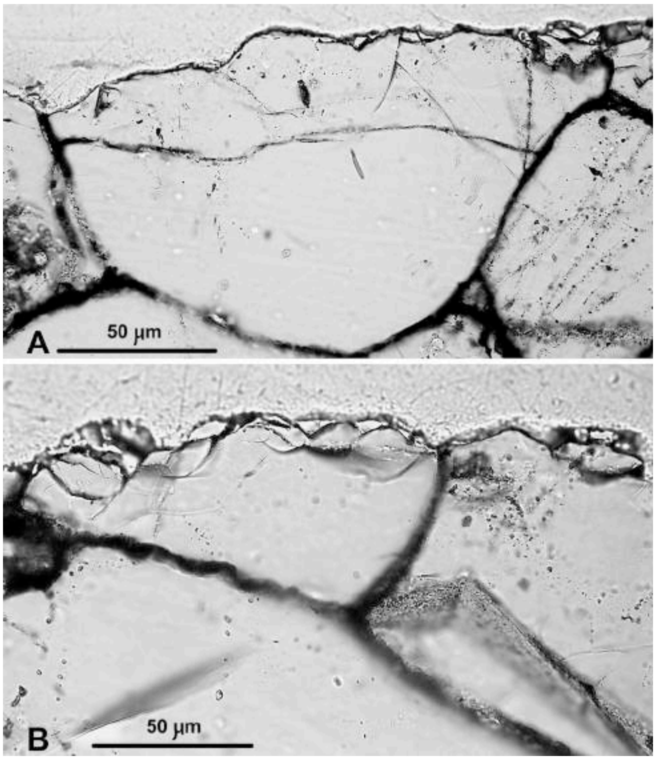

Fig. 8. SEM images of thin sections of quartz grain truncated by the fluvial bombardment of the bedrock surface, Indragarh Paleochannel, central India.

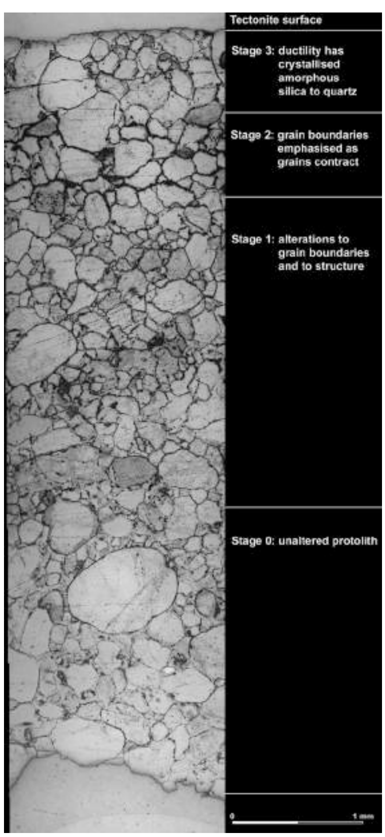

Fig. 9. Composite microphotograph of a thin section through the three modification zones of the quartzite surface at Indragarh Paleochannel.

through the site, and every time the valley is flooded the schist is bombarded by quartz grains, each of which scores the rock (Fig. 10). Besides the rock art, there are also many hundreds of rock inscriptions in the same flood zone, subjected to the same process of gradual erasure. Many of these inscriptions are dated, and it was established that after around 200 years, any groove markings on the rock would be obliterated by the tribological attrition. Based on the degree of erasure secured from the dated inscriptions, it was also determined that most of the engraved animal figures, depicting horses and Spanish fighting bulls, were made in the early 20th century. There is a huge masonry bridge right through the centre of the site which was completed in 1924, and numerous of the inscriptions date from that time, apparently created by the stonemasons working on the bridge. Most of the rock art is perhaps their work also, but what is certain is that none of it can be of the Paleolithic.

5. Discussion

This paper seeks to illustrate the need to extend the discipline of tribology to its applications in fields not traditionally associated with it, such as archaeology and rock art research. Its purpose is to assist them in resolving many issues that seem unsolvable by their methodologies. Such issues tend to be treated superficially, yet they are intrinsically multifaceted and much more intricate than is often assumed by archaeologists. For example, is the pressure flaking or retouch of stone tool edges attributable to compressive stress, or how does it differ from percussion flaking? These terms define to what degree archaeology tries to explain the inherent processes, but in a tribological sense they provide only inadequate epistemic elucidation. Contact mechanics, so relevant in traditional tribology, needs to be consulted, and again illustrates the continuum between friction, percussion, and compression. Friction is simply compression by extreme tangentiality, and percussion is compression by extreme applied forces. Understanding these connections and their implications is outside the ambit of archaeology, but it is essential in explaining countless archaeological phenomena. Some of these have been considered here, illustrating how in archaeology, just as in so much of geology, contact mechanics and frictional contact mechanics can introduce science into complex issues.

To develop archaeology beyond its present limitations, it is incumbent to establish an archaeotribology. The world's hundreds of millions of petroglyphs and portable engravings have not so far been studied in any consequential manner from a tribological or tribochemical perspective, and yet archaeology considers it has the proficiency to deduce meaning from such traces. The interpretational ambiguity of the mute archaeological record of such important witnesses of early human cognitive states needs to be subjected to testable scientific hypotheses

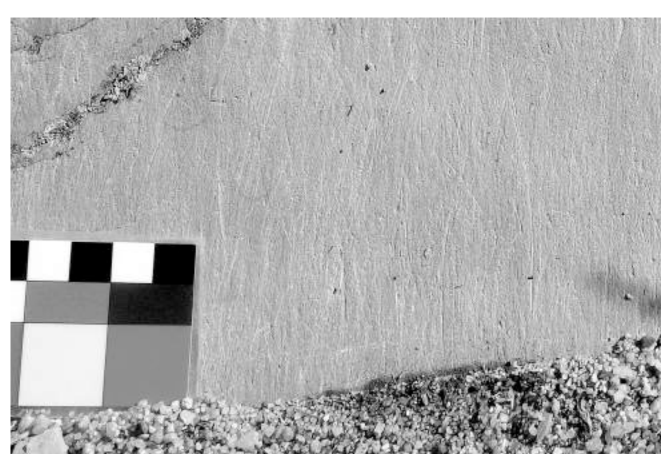

Fig. 10. Tribological effect of fluvially propelled quartz sand on the schist of Siega Verde, Spain.

derived from science. Bearing in mind that the production of all rock art involves interacting surfaces in relative motion, rock art study is a classic example of a field that needs to embrace tribology in all its scientific considerations. Just as archaeology would benefit greatly from the introduction of the methodological rigour of a science, such as tribology into many others of its practices. The striae, stress marks, and stick-slip phenomena observed in all of archaeology, as well as surface changes attributable to contact of surfaces in relative motion, are all tribological phenomena and need to be subjected to specialized analytical attention on that basis. Archaeology lacks the required proficiencies, and it is proposed that archaeotribology be a sub-discipline of tribology.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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