Rock Art Research **2020** - *Volume 37, Number 2, pp. 217-227. R. G. BEDNARIK*

KEYWORDS: ***Rock art – Archaeotribology – Friction – Percussion – Contact mechanics***

THE ROLES OF TRIBOLOGY IN PALAEOART STUDY

Robert G. Bednarik

Abstract. Tribology, the science of interacting surfaces in relative motion, is at the basis of interpreting rock art and portable palaeoart by scientific means, and yet it has remained almost entirely ignored in that application. Tribological work conducted with palaeoart, but without involving its discipline, is briefly summarised, and examples are cited to illustrate the value of a scientific approach. In particular, the focus is on the contact mechanics of petroglyphs and the compressive-tensile principles involved. The tribology of rock art has also been invoked in the discrimination of anthropogenic from other rock markings.

1. Introduction

The systematic and analytical study of physical traces of engraving or wear on the surfaces of ancient objects reminiscent of art is certainly not a new topic, but it has not been formalised as a sub-discipline of tribology. Various explorations have been made into this specialised subject — some of no more than anecdotic merit, others being quite sustained and productive efforts (e.g. Marshack 1964, 1970, 1972a, 1972b, 1985, 1989a, 1991; Bednarik 1986, 1987/88, 1991a; d'Errico 1987, 1988; 1989a, 1989b, 1989c; d'Errico and Cacho 1994). Most of these projects have dealt exclusively with portable objects, especially with engraved plaques of stone, bone and ivory, while the application of relevant techniques to rock art has been almost entirely neglected. This is explained by one simple factor: the utilisation of microscopy, the principal technique in this research, has remained woefully inadequate in rock art research. The application of scanning electron microscopy is inherently limited to portable specimens, as such equipment is not portable. Even binocular field microscopy seems to present challenges to almost all practitioners, and its use in the study of immovable palaeoart remains limited to few exceptions. Suitably modified equipment is not widely available, and the technique is logistically demanding in such places as caves or remote locations. However, with the recent availability of digital microscopes, these traditional difficulties have been somewhat reduced, although for specific applications the binocular light microscope remains essential.

This paper presents an attempt to demonstrate the advantages of tribology to palaeoart research, and it will also offer a formalised methodology for procedures that are much in need of standardisation if research results are to be compatible. Although d'Errico's work was in a sense modelled on that of Marshack (which he was trying to test), it seems fair to say that the endeavours we have so far seen in this field were individual pioneering efforts, conducted essentially in isolation. Future research in this field would decidedly benefit from establishing standard procedures, which would also facilitate a better scientific footing of palaeoart research generally.

Tribology, for its part, has been preoccupied with friction, machinery, wear and lubrication since its inception in the 1960s (Jost 1966). As the science of the interaction of surfaces in relative motion, it has branched out into many further, economically rewarding fields. These include microelectromechanical and nanoelectromechanical systems, biomedicine and alternative energy sources. Investigation of processes at the molecular or atomic levels by scanning probe technology has led to the development of drug delivery systems, molecular sieves, chemical and bio-detectors, chip systems, nanoparticle-reinforced materials and a new generation of lasers. By comparison, less marketable domains such as geotribology have been neglected, while archaeotribology as a research subject was introduced only most recently (Bednarik 2019a, 2020). This is even though all archaeological artefacts of the Pleistocene derive from tribological processes, as do many of the Holocene. Similarly, rock art and palaeoart generally are entirely attributable to tribology.

Palaeoart tribology, as a sub-discipline of tribology, can trace its lineage to forensic science, where techniques such as the attribution of a fired projectile to the particular firearm, for instance, has been the stock-in-trade for most of the 20th century. However, forensic investigation methods, which are of such obvious relevance to rock art research (Bednarik 2001, 2016a; Montelle 2009; Bednarik and Montelle 2016), have also been exceptionally under-utilised in that pursuit. However, just as some characteristics of a gun barrel can be detectable in the markings on a bullet, those of the tools used in incised or engraved rock markings may have also left tell-tale traces. Their scientific study is the task of tribology.

2. Engraved plaques

The methodology summarised here has its precedents in the important pioneer work of Semenov (1957, 1964, 1968, 1970, 1974), who introduced systematic artefact and microwear analysis. However, Soviet work tended to be poorly received in the West and even after its 1964 English publication in the form of a substantial and well-illustrated book, Semenov's work, begun in the 1930s, remained ignored. One complication was that the book contained only scant details of the technology he had used, and Western researchers used magnifications that were much too high (Tringham et al. 1974). This mirrors the experience of the present author when he introduced micreoerosion analysis (Bednarik 1992a): commentators tried to replicate it by using scanning electron microscopy and reported that they could not see micro-wanes. The important field of taphonomy provides another Soviet example: introduced by Efremov (1940) in palaeontology, it took the West almost four decades to apply, and it was then promptly misinterpreted as actuo-palaeontology, which is precisely what Efremov had tried to replace (Solomon 1990). It also took half a century to discover that the theory of taphonomy has many applications beyond palaeontology (Hiscock 1990; Bednarik 1990–91) and the full implications of taphonomic logic (Bednarik 1994a) remain widely misunderstood even today.

Semenov relied heavily on microscopy of specimens (Semenov 1964: 22–23). All the phenomena he described are tribological, and he was a tribologist many years before that discipline had been founded. His use of a Linnik-type interferometer, still utilised in tribology, helps illustrate this. The concept of archaeological applications of tribology was first mentioned at a meeting held in Burnaby, British Columbia, in 1977 (Hayden 1979) but remained undeveloped for many years. Alexander Marshack employed what amounts to tribological methods to engraved plaques, especially those of the Final Pleistocene of Europe. He was prompted in this by specific research questions he posed, such as the possible use of notation by Upper Palaeolithic people in their symbolic systems. For instance, Marshack was interested in the possibility that the passing of moon phases might have been recorded in engraved objects. Irrespective of the answers to the issues he sought to clarify, the principal importance of his work is that he realised the significance of and introduced microscopy. He did this to establish how precisely the engraved marks on some plaques seem to have been made, e.g. in what sequence, in which direction, reconstructing the engraving procedure. He emphasised repeatedly the futility of relying on interpretations derived from 'simple eye-balling' (e.g. Marshack 1985). In working with bone, stone and ivory palaeoart plaques and other objects, Marshack contended that the direction of tool application, repeated reaming of a groove, superimposition sequence of a set of intersecting grooves and other details can all be determined by binocular microscopy.

D'Errico tested some of Marshack's propositions, such as his pronouncements concerning the anthropogenic nature of tribological traces on the Berekhat Ram stone object (Goren-Inbar 1986; Marshack 1997; d'Errico and Nowell 2000) and Marshack's claims concerning the notational character of certain Upper Palaeolithic objects (e.g. Marshack 1972c, 1989b; d'Errico 1989b, 1989c; d'Errico and Cacho 1994). D'Errico's work marks the formalisation of the methodology Marshack had outlined, especially in standardising the graphic documentation of observations (d'Errico 1991). Although he eventually agreed with Marshack concerning the notational quality of series of engraved markings on plaques, both authors are mistaken on this issue (Bednarik 1991a). The question hinges on notational tool marks having been made with different stone tool points, presumably at different times. Contrary to the views of both writers, this is not possible, because one stone point will yield different sets of striations and groove cross-sections depending on its precise manner and direction of application. If the tool is slightly rotated on its main axis, the resulting characteristics, including groove width, can differ so significantly that apparently different tools were involved. This is so even if the applied pressure, angle of tool and other variables were identical. Stone tool points are rarely equi-symmetrical or of a uniform profile from all sides.

Although Marshack and d'Errico were both applying some of the principles of tribology, they professed no knowledge of that discipline and were probably not even aware of its existence. Instead, a field of 'traceology' was proposed, a term that refers rather loosely to use-wear, i.e. the wear traces found on implements that are linked to their utilisation (Odell 2004; Thomas et al. 2011). Extending that term to deliberate markings on mobiliary palaeoart objects obscures the issue because tribology, the scientific discipline concerned with these phenomena, already defines traceology as something specific.

The most fundamental issue in the study of engraved plaques is illustrated by the example of the six flat aeolian calcarenite cobbles from Devil's Lair in south-western Australia (Dortch 1976, 1979a, 1979b, 1984; Dortch and Dortch 1996). It refers to the discrimination between anthropogenic and non-human markings, also widely relevant in the study of rock art. The markings these specimens bear, described as deliberate engravings for over twenty years, were eventually investigated by tribological methods (Bednarik 1998a). Not one of the many hundreds of grooves on these rock fragments was found to have been occasioned by a stone tool. Furthermore, there were very few that could even be considered as marks of stone asperities. The markings lacked characteristics such as longitudinal striations, *stries parasites*, *sillons rectilignes* and others (Bednarik 1992b, 1994b; d'Errico 1994). Several of the grooves were claw marks made by two different species (Bednarik 1991b), the others were taphonomic marks of various types or derived from modern damage, e.g. by toothbrushes used to clean the objects.

The generic issue of discriminating between artificial and natural markings, especially on rock but also on other materials, is frequently encountered in archaeology (Bednarik 1998b) and can be resolved by tribology in most circumstances. The vast majority of surface markings created by reductive processes are tribological features. The notable exceptions are those caused by chemical reactions, e.g. of carbonic acid formed by respired carbon dioxide deriving from mycorrhizal microorganisms.

3. Beads and pendants

Several tribological aspects are also involved in the study of archaeological, especially Pleistocene, beads and pendants. Those whose manufacture entailed abrasion include especially disc beads, e.g. of ostrich eggshell, mollusc shell or similar materials. The perforations of most of the early beads and pendants were made by drilling, reaming or puncture, clearly the result of interacting surfaces in relative motion. Specific patterns of wear, another purely tribological effect, can be found on items worn on the skin and rubbing against apparel. More specifically, beads arranged on a string have been shown to feature distinctive wear marks (Bednarik 2005). In the case of disc beads, their flat sides rubbed against the neighbouring bead (Goren-Inbar et al. 1991), while spherical beads may feature extensive concave wear around their perforations (Fig. 1).

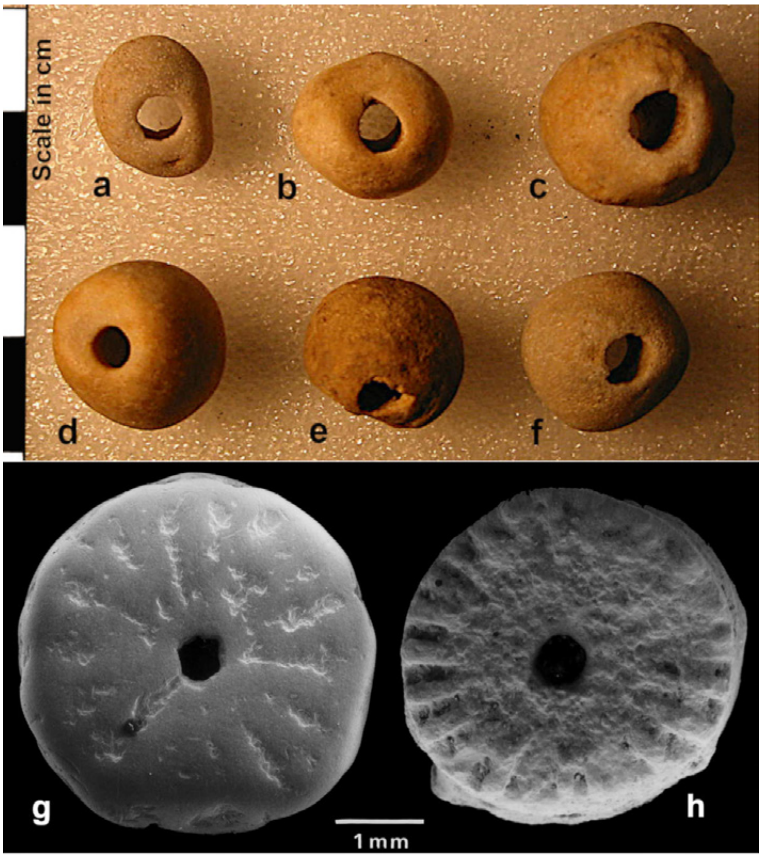

Figure 1. *Six Acheulian* Porosphaera globularis *beads showing different degrees of wear at tunnel opening, including major asymmetrical concave wear facets (b, d); and two crinoid fossils of the Acheulian (g, h, note heavy wear on g; g and h courtesy N. Goren-Inbar).*

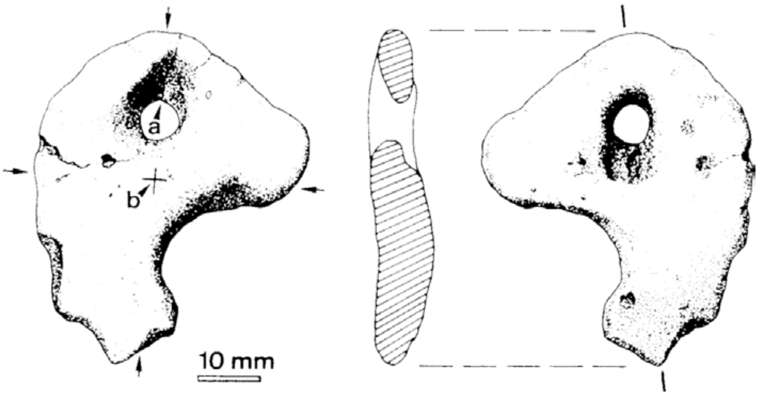

Figure 2. *Marl pendant of the Final Pleistocene, Devil's Lair, Western Australia. (a) Four grooves; (b) centre of gravity.*

Beads or, especially, pendants featuring evidence of wear by a string are relatively common, particularly on specimens of excellent condition of preservation. They may have been worn for prolonged periods. If the centre of gravity does not coincide with the perforation, i.e. when they are pendants rather than beads, the most prominent wear traces of strings occur on the side of the hole furthest from the centre of gravity. Sometimes there are distinctive grooves at that location, occurring singly or even in groups of up to four where the string settled into specific positions (Fig. 2). In the case of a small marl object from Devil's Lair, it had long been suspected to have served as a pendant, and this hunch was decisively confirmed when a tribological study of the stone revealed a series of four grooves undeniably caused by suspending strings (Bednarik 1997a). Most of them are very shallow and vary widely in width, but one groove is well-rounded in a section of 225 μm diameter. This seems to indicate the approximate diameter of the suspending string, which is surprisingly thin. With an age of roughly 15 000 years, the object is the oldest known stone pendant of Australia.

Significantly older are the ostrich eggshell beads of the Lower Palaeolithic at El Greifa site E in Libya, about 200 000 years old (Bednarik 1997b), or at Kathu Pan in

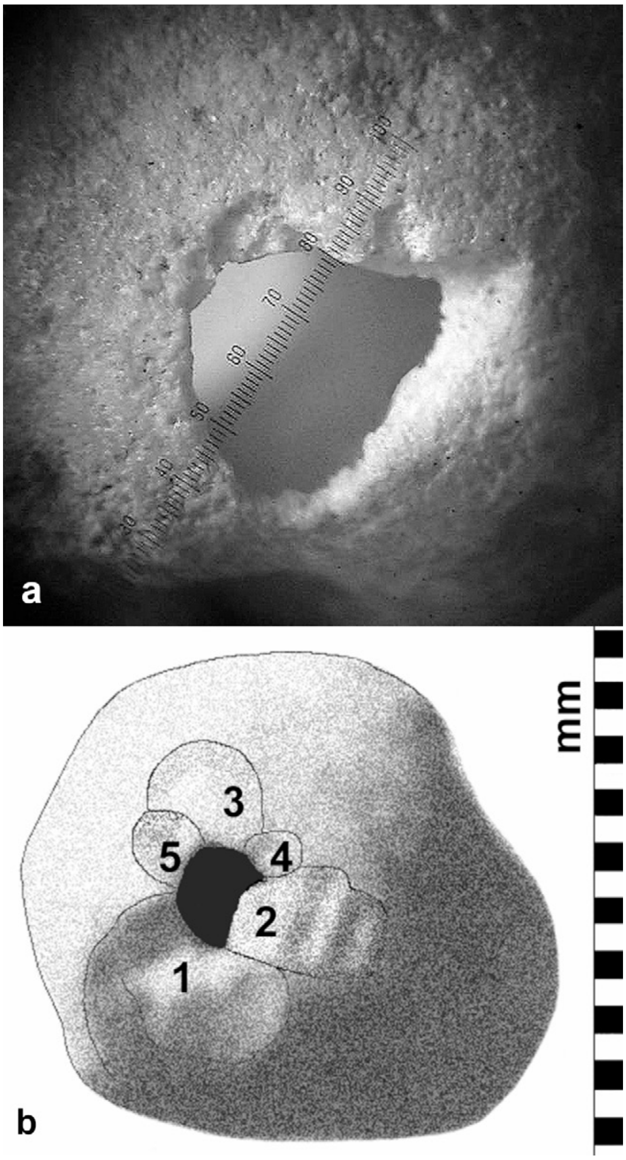

Figure 3. (a) Microphotograph of the artificially enlarged orifice of a Bedford Acheulian bead. (b) Flake scars at the previously closed end of the tunnel of one of the Bedford Acheulian beads. Note the rippling typical of impact fractures in No. 2 scar.

South Africa, dated to c. 290 000 years ago (Beaumont 1990; Porat et al. 2010). Disc beads made from ostrich eggshell are the most numerous ancient beads archaeology has provided. They occur not only at several sites of the Middle Stone Age but also very many sites of the Later Stone age or the Upper Palaeolithic, from Africa to Siberia (Bednarik 2017). Their study is very much the concern of tribology, as demonstrated by our extensive replication experiments (Bednarik 1997b). Indeed, replicative experimentation is a significant component of all archaeotribology (Bednarik 2020). We conducted numerous experiments from 1990 to 1996 to determine the technological dimensions involved in the production of ostrich eggshell beads with stone tools, particularly of the reduction and drilling processes, their traces and waste products. This work led to the discovery that the Lower Palaeolithic ostrich eggshell beads were of the smallest size realistically possible. Because the diameter of the central hole can be no smaller than 1.4 to 2.0 mm, using stone drills, the bead's fragility increases exponentially as the outside diameter of 6 mm is approached. That the Acheulian beads from Libya are about 6 mm in size and have perfectly central perforations implies a strong sense of perfection in the makers. Replication with Acheulian stone tools and the absence of the *heishi* technique (Dunn 1931; Clark 1959) demonstrates this, and it provides vital evidence for the cognitive state of the hominins concerned (Bednarik 1997b). This, once again, reveals the significance of tribology to archaeological interpretation.

The next example demonstrates this importance perhaps even better. The principal significance of beads is that they imply the level of cognitive development in the hominins that made and used them. Therefore, the earliest examples we have of them are of particular value to interpreting the human past. Beads and pendants demand several cognitive prerequisites, such as a state of self-awareness and Theory of Mind. They cannot exist in isolation, their roles had to be culturally constructed, and their use demands shared meanings. Even if it was assumed that they were simply considered 'attractive', a concept of attractiveness can only arise by cultural consensus. The probably earliest beads we know of are the spherical stone beads of a series of Acheulian sites in northern France and England, first reported by Boucher de Perthes (1846) and three others in the 19th century. These beads consist of fossil casts of the Cretaceous sponge *Porosphaera globularis* Phillips 1829. A parasite had partially perforated them, and Acheulian hominins collected specific sizes that presented fully spherical forms. Only about 0.1% of a natural sample falls within that range (Bednarik 2005); therefore, it is impossible to find natural accumulations of the fossils of the specific size range, globularity and penetration. Moreover, the beads show two types of tribological effects. First, the second openings of their natural tunnels had to be created before they could be used as beads (Fig. 3). Whatever that process was, it was tribological.

Second, once these beads were threaded onto strings and worn, they rubbed against the two neighbouring beads and over a long period, concave wear facets began to form around the tunnel entrances. In extreme cases, these could be so profoundly worn that the bead had lost around half its volume. Such specimens can be assumed to have been handed down and reused virtually for generations. At this point, the full importance of tribological analysis comes sharply into focus, because such seemingly minor details can tell us a great deal about the hominins concerned. If beads were indeed worn long enough to develop such deep hollows it infers not only that they were highly valued; it also implies that the society in question possessed social structures of a complexity unimaginable to traditional archaeology. So this example illustrates how rigorous science can test preconceptions in a humanity.

The beads rubbing against one another are of the same hardness, so they cannot effect any wear as such. For this to occur, there has to be a harder abrasive medium present, which presumably would have been airborne quartz dust. It needs to be appreciated that the beads are of chalcedony, with a hardness of 6.5–7.0 on Mohs scale. Quartz, of hardness 7.0, is barely able to abrade the stone beads. This is testable by subjecting two of these fossil casts to mechanical wear in the laboratory to see how long it would take to obtain the described damage in the presence of small quantities of quartz dust. Here it is proposed that some of these beads were passed on from generation to generation (Fig. 4).

Social and other signifiers, including beads and pendants, were not only made from eggshell and fossil sponges, but also gastropod or mollusc shell, limestone or marl, schist, talcum-schist, steatite, teeth, bone, antler, pyrite, haematite, lignite, jet, fossil belemnite, fossil coral, contemporary and fossil specimens of marine and freshwater shells, and ivory. An observation providing an inkling of the record's taphonomic distortion is that one single site of the Russian Streletskian, an Early Upper Palaeolithic tradition with distinctive Middle Palaeolithic roots, has yielded more beads from just three burials than the remaining Pleistocene of the entire world. The three interments at Sungir, perhaps in the order of 28 ka old (but quite possibly older), yielded 13 113 tiny, laboriously made ivory beads and more than 250 perforated fox teeth (Bader 1978). Ivory beads of the Aurignacian have also been reported from France (Abris Blanchard, Castanet, Souquette, Isturitz, Saint-Jean-de-Verges), Germany (e.g. Geißenklösterle), Belgium (Spy, Goyet) and Bulgaria (Hublin et al. 2020); while Russia has provided similar evidence from other traditions of the transition from Middle to Upper Palaeolithic modes of production (Sungir, Kostenki 17). White (1992) described many of these beads and their production sequences. Shell beads are among the earliest 'ornaments' found in many regions, including India (Francis 1981: 140), China (Cheng 1959: 31), Australia (Morse 1993), South Africa (Henshilwood et al. 2004), Morocco (Bouzouggar et al. 2007) and Algeria (McBrearty and Brooks 2000). One of the earliest pendants of Europe, from the Châtelperronian of the Neanderthals, is even made of a fossil cast of a shell (Bednarik 1995: Fig. 6). Stone beads of the Pleistocene have been reported from Russia (e.g. Kostenki 17), China and Japan (Bednarik 1994c). Tribological processes produced all of these many thousands of beads of the Ice Age, and their effective scientific study is therefore by the discipline of tribology.

4. Other portable objects

Besides engraved plaques, beads and pendants, mobiliary palaeoart includes many other classes, some of which tend to be misinterpreted without tribological analysis. For instance, ostrich eggshells were used as containers by many African and Asian societies and were often decorated with engravings. However, line markings on eggshell can also be occasioned by several other agencies. One of these is the effect of carbonic acid deriving from carbon dioxide exhaled by mycorrhizal microorganisms along the fine rootlets of plants that were in contact with the eggshell specimens while in the sediment (Bednarik 1993). These grooves have been mistaken for engravings. For example, of the 46 ostrich eggshell fragments archaeologists defined as bearing engraved marks in India, only one is, in fact, engraved, the Patne specimen. Mycorrhizal line markings can also be found on buried objects of ivory, bone, teeth, antler and limestone (Bednarik 1992c). Their identification is the task of tribology, which has focused on the effects of the engraving tool's asperities on the outermost layer of the three-layered eggshell (Bednarik 2001: Fig. 70).

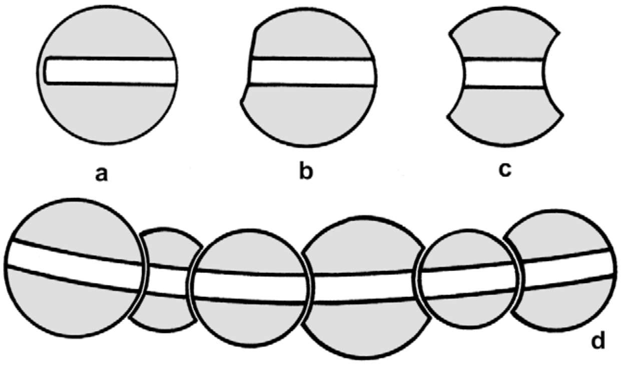

Figure 4. *(a) Section of initial fossil before anthropogenic action; (b) flaking to open the second tunnel entrance (c); heavy wear from rubbing against other, fresher beads for many years; and (d) beads of different ages on a string, some having been worn for very long periods.*

Many materials bear what may appear to be deliberately engraved markings or regularly spaced edge notches, including also bone, ivory, amber, teeth and mollusc shells. Tribological analysis tends to secure their identification and involves the rigorous assessment of their characteristics. The need for a scientific approach is illustrated, for instance, by the controversies of incisions on bones. They may have meanings (i.e. constitute exograms), they may be de-fleshing marks, or they may simply be attributable to one of several natural causes (taphonomic, gnaw marks, gastric acids). The issue of their correct determination is, as in the cases mentioned above, rendered more difficult by the preservation state of much archaeological material, which contributes significantly to the potential for misidentifications.

Another class of portable palaeoart, figurines, were also created by tribological processes, the traces of which can inform us about the circumstances of the manufacture of these items. In the few instances we have of very early 'proto-figurines', this becomes particularly acute because they can only be identified by clarifying the nature of their modifications. Acheulian proto-figurines such as the Berekhat Ram (Goren-Inbar 1986) or Tan-Tan (Bednarik 2003) finds are naturally shaped stones that bear tribological markings, including in the second case traces of a former haematite coating. Their analysis and identification is again the task of tribology.

Some forms of evidence usually included under the umbrella of 'palaeoart' involve no tribological study. They include unmarked manuports, such as crystals, objects naturally shaped to visually resemble other things (e.g. the 'head' from Makapansgat or the 'penis' from Erfoud; Bednarik 2017: Figs. 2 and 4), even stones of unusual attributes of colour or shape, and mineral pigments (although the latter may feature marks of human work, which are of tribological relevance). To qualify as manuports, such objects must be of materials that cannot occur naturally in the occupation deposits in which they were found; they must have been carried for some distance.

5. Petroglyphs

The discrimination between animal scratches in caves, anthropogenic linear engravings and parietal finger flutings has long confounded researchers, particularly in Europe and Australia (Walsh 1964; Hallam 1971; Sharpe and Sharpe 1976; Gunn 1986; see Bednarik 1991b, 1994b, 1998a). Finger flutings (*sillons digitales*, *Fingerrillen*, *estriado por dedos*, макароны) have now been reported from five regions (south-western Europe, Austria, Australia, New Guinea and Hispaniola) but no doubt occur elsewhere as well. They are endemic to limestone caves where extremely soft calcite precipitates called moonmilk have been marked with sets of outstretched fingers sweeping across these surfaces (Bednarik 1984, 1985, 1986). Under specific preservation conditions, these multiple groove markings harden by calcification and desiccation and their most delicate details may be preserved in the stable speleoclimate of caves (Bednarik 1998c, 1999). Most sets of finger flutings are usually of three or four fingers, although sets of two or single finger grooves can on occasion be found also. They occur as single sets and up to extensive accumulations measuring many dozens of square metres. Finger flutings are well suited to tribological analysis, particularly those that are best preserved. This is of considerable significance to the study of early human cognition and behaviour because finger flutings are among the earliest forms of rock art known. They permit biokinetic observations of their production procedures and the study of stick-slip phenomena and transverse tear marks, as well as longitudinal striations reflecting asperities of grains caught, and moonmilk squeezed to the margins of the grooves forming 'curls'. These and other tribological phenomena permit many observations concerning the direction, pressure and momentum of movement of the fingers, as well as their sizes.

The study of finger flutings, linear engravings and animal scratches in limestone caves must involve a very detailed understanding of the natural modifications to which their media can be subjected. The soft deposits of re-precipitated carbonate speleothems are frequently exposed to morphological changes of several types:

- Corrosion can remove some of the surface, resulting in progressive coarsening;
- or a speleothem skin covers the markings but has preserved their outlines well;
- or a thick speleothem skin conceals finger flutings, causing them to appear as narrow grooves;
- or the medium is gradually dissolved exposing the primary rock;
- or coralline speleothems form selectively on the ridges between grooves.

These are not tribological issues, but they need to be thoroughly appreciated in the appraisal of these phenomena. Tribology is particularly relevant to abrasive stone tool markings on cave walls. The diagnostic characteristics of these engravings tend to be more clearly expressed than in the finger flutings often found in the same caves. In attempts to identify multiple applications of the same tool, however, the qualification explained above needs to be reiterated. The asperities of the tool's point can only create identical striation patterns if it is applied in the same orientation relative to the direction of the tool's motion (Bednarik 1991a). Pressure can detach micro-spalls from the point, modifying the micro-topography of its asperities. Therefore, tribology is capable of identifying multiple engravings made with the same tool, but cannot determine that different patterning is due to the application of different tools.

The first tribological analyses of rock art were conducted on tool marks in several Australian caves in the 1980s, especially in Nung-kol and Mandurah Caves (Bednarik 1987/88, 1992b). Figure 5 illustrates an attempt to identify the repeated application of specific tools, determine the cross-section of their tool points as applied tangentially, and ascertain the relative sequence of all the marks in one panel. Replication of the striation patterns recorded demonstrated that the markings were made with clasts of the local aeolian limestone, whereas another, nearby panel was created with local chert.

The tribological study of most forms of petroglyphs has not yet begun (Bednarik 2016b), but one class of them has been subjected to such attention (Bednarik 2015). Cupules are the most numerous rock art motifs in the world, deriving from countless cultures that span from the Lower Palaeolithic to the very present. One of the reasons why they need to be subjected to tribological analysis is because they are often confused with natural phenomena, such as potholes (a phenomenon of geotribology) or solution effects. Cupules are typically the shape of a spherical cap or dome, and most were created by percussion (Bednarik 2008). The hammerstones used have been recovered at some sites and were also subjected to tribological study. Exceptions

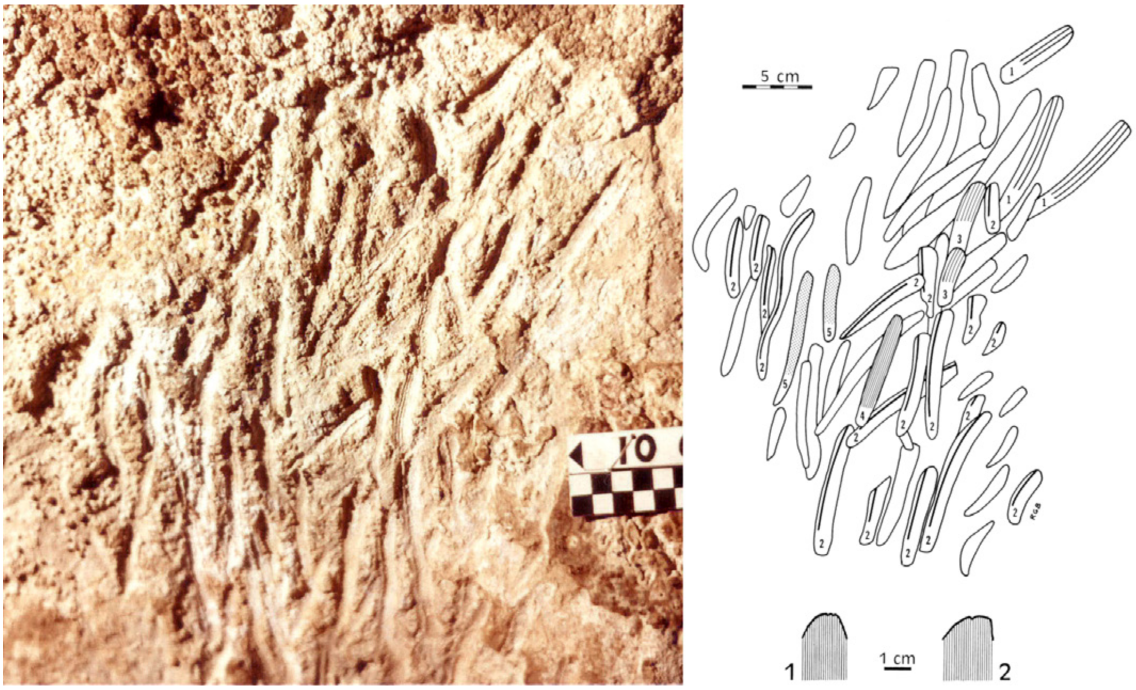

Figure 5. *Tribological reconstruction of the production sequence of a small panel of tool markings on formerly soft wall deposit in Nung-kol Cave, South Australia. Where striation patterns are preserved, five tool points have been identified, numbered 1–5. The cross-sections of the tips of two tools were determined, and are shown below (tools No. 1 and 2).*

are cupules made with metal tools or produced on relatively soft rock. When a cupule is pounded into very hard rock, the amount of rock dust removed gradually diminishes as the cupule deepens. This is, first, because the subsurface tends to be weathered and thus softer; second, because the diameter is enlarged as the depth and thus the volume to be removed per depth unit increase; third, because of the rock's progressively higher capacity of absorbing the kinetic energy at the base of the deepening cupule (as per Hertzian geometry); and fourth, the increasing tendency, in some rock types, to form kinetic energy metamorphosis (KEM; Bednarik 2015) products through ductilisation of specific components. These become considerably more resistant to deformation and thus impede further impact. Two factors determine progress in cupule depth per amount of energy applied in the cupule's creation: the depth gained according to the cupule's geometry, and the diminishing depth gain as KEM products form. Initially, progress is governed by the first factor, but there is a point when the second factor decisively overtakes the first and limits further advance (Bednarik 2020: Fig. 5).

A significant aspect of tribological work with cupules is their replication under controlled conditions to secure reliable data on their production. After early experiments (Bednarik 1998b: 30), Kumar and Krishna (2014) conducted detailed investigations near one of the earliest rock art sites known, Daraki-Chattan in central India. According to their findings, it takes in the order of 1000 times as long to create a cupule on unweathered dense quartzite than it takes to produce a similar one on well-weathered quartz sandstone. By applying the tribological axiom that *the relative susceptibility of any petroglyph to natural wear or erasure is roughly proportional to the time it takes to create* (Bednarik 2012: 79), we can roughly estimate the age of a petroglyph because the latter variable can be determined credibly. This should end the spate of specious dating claims that have so much prevented progress in the scientific study of petroglyphs.

Percussion petroglyphs range widely, from the ubiquitous cupules to large compositions measuring tens of metres. The ethnographic and replicative evidence suggests that they were all made by direct percussion (Sierts 1968; Savvateyev 1977; Bruder 1983; Bednarik 1998b, 2008; Weeks 2001; Kumar and Krishna 2014). Abrasion petroglyphs or engravings are the second primary class. Tribologically, all petroglyphs are the result of compression, the difference being that friction is compression by extreme tangentiality, while percussion is compression by an extreme applied force. Although percussion and friction petroglyphs appear to be technologically disparate, in a tribological perspective, they both derive from compressive/tensile forces. In both methods, the objective is to remove rock mass under well-controlled conditions to create the intended motifs. In percussion, the kinetic energy is applied at an angle approaching 90° to the rock surface and with a relatively high degree of velocity. In friction, the degree of tangentiality, usually below 30°, and the low velocity of the tool's motion allow the tool to remove rock mass by exploiting the compressive/tensile differential created in front and behind its point, relative to the direction of movement. These two tribological processes are the basis of all petroglyph production, except finger flutings, the tribology of

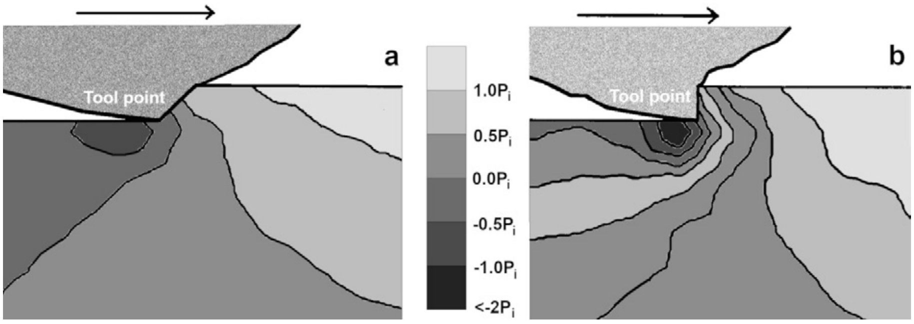

Figure 6. (a) The development of stresses by the application of a striator or tool point 'leading-edge' of 35°, compared with (b) the application of a 'leading-edge' perpendicular to the direction of application.

which is a little more complicated.

6. Pictograms

The second form of rock art, pictograms, are the results of an additive rather than reductive process and include rock paintings, pigment stencils, pigment prints, dry pigment rock drawings, and designs created with other substances, such as beeswax or clay. Pictograms, too, are the products of interaction of surfaces in relative motion. However, in contrast to petroglyphs, interpretation of their empirical properties is not as deeply embedded in tribological theory. They are also always subject to forensic science, following Locard's exchange principle.

In most circumstances, the rock acts as the 'tool' in the production of pictograms, be it by leaving diagnostic grooves on crayons through its asperities, or pigment deposition in minute recesses on mortars and pestles used in the reduction process, while not being involved in stick-slip phenomena or striae deriving from the application of pigment paste. As a hand-held piece of pigment (such as a stick bearing charcoal at its end or a crayon of haematite) is drawn over the rock panel, the asperities of the rock remove small amounts of material from the pigment which remains attached to recesses of the rock. This is a less effective procedure of pigment application than painting, spraying or printing. Therefore, such drawings are more susceptible to deterioration than liquid paint application penetrating the rock fabric.

The tribology of pictograms remains essentially unexplored at this stage. This is perhaps because it is perceived to offer more limited opportunities for developing analytical methodologies relative to petroglyphs.

7. Conclusions

Before the early 1980s, rock art research was mostly a field of imaginative interpretation and invented meanings, styles and antiquities, providing only limited empirical and testable information about the corpora of rock art surveyed and of their taphonomy. The few subsequent decades have seen the establishment of rudimentary scientific (testable or falsifiable) approaches, but the discipline of rock art science still needs to overcome various significant constraints to develop. In this, the support of tribology is undoubtedly needed, but so far not even its relevance to the study of palaeoart has been widely recognised. Instead, we have seen half-measures such as the introduction of 'traceology' to 'decipher' markings on plaques. To study palaeoart scientifically, it is essential to first address and understand the empirical variables defining it. This level of analysis, eschewing the traditionally favoured rationalisations about simplistic 'meanings', remains in its infancy. The lack of its development does no doubt account for the dormant state of the discipline, drowning in endeavours to provide meanings (Bednarik 2013).

Whenever two surfaces meet there are effects, whose magnitude is a function of kinetic energy, the direction of its application, as well as various properties of the two interacting surfaces, such as aggregate hardness, brittleness, toughness, strength, ductility, indentation hardness and scratch or abrasion resistance. Stress waves emanate concentrically from the point of contact and travel through the impacted matter. These mechanical deformation patterns of Hertzian geometry can be rendered visible by the technique of photoelasticity (Frocht 1965). The pattern can be observed in specific geological phenomena, such as the recently discovered phenomenon of compressive-tensile rock markings (Bednarik 2019b). It is also found in the deformation occurring when explosives are used to blast rock (McHugh 1983; Donzé et al. 1997; Esen et al. 2003; Banadaki and Mohanty 2012; Guerra et al. 2013; Torbica and Lapčević 2014, 2018).

In the production of petroglyphs, the process needs to be understood as one of compressive tribology. In friction petroglyphs, the variables determining the quantity of material displacement include the effective angle of the active asperity (the 'leading-edge'), the size of the kinetic force applied, and numerous physical characteristics of the materials of the two objects in relative motion. Figure 6a depicts the distribution of compressive and tensile forces in the mass being impacted when a 'tool' leading-edge angled at 35° to the direction of application is employed. The tensile zone of P_i=-0.5 to -1.0 'behind' the point is a response to the elevated compression 'ahead' of it. In Figure 6b, the active asperity of the tool point is perpendicular to the direction of application, yielding a distinctly different distribution pattern of stresses. Now the tensile zone 'behind' the point reaches P_i=-2.0, while the wave pattern we have previously encountered determines first the reduction of tension to P_i=0.5 to 1.00, then increase to P_i=0.0, and finally compression 'ahead' of this wave, to P_i=>1.0. These differences also explain why tools with steep leading edges tend to plough deeper into the bed with sliding progressively, whereas those with inclined edges will progressively climb out of their grooves (Bednarik 2019b). It follows that what we perceive as friction is, upon analysis, another example of compressive-tensile reaction: compression of material is balanced by the development of tensile stresses which ultimately lead to rupture and removal of a mass.

These observations confirm the empirical evidence that it is practically impossible to separate the effects that derive from percussive impact from those occasioned by abrasion. Examples of this truism abound in geotribology and archaeotribology, e.g. in the behaviour of a suspended load of a river, or any fluvial or aeolian load. As a river cobble being transported in a bed load is worn round, it is difficult to say which part of the abrasion derives from frictional wear, which from percussive impact. Similarly, it would not be feasible to achieve that separation in the processes of creating petroglyphs or in their properties (Bednarik 2020). Since both ends of the continuum between these two forms derive from the same compressive-tensile phenomena, the emphasis of traditional tribology on friction needs to be reconsidered.

In summary, it can be said that in percussion petroglyphs, high angle and velocity removes rock mass by shattering as the Hertzian mechanical deformation waves travel in the rock and apply compressive/tensile forces (Bednarik 2019a). In friction petroglyphs, the differential between compressive and tensile stresses generated by the low-angle, tangential movement of the tool point as per Hertzian geometry causes the rupture and removal of a mass. Tribologically, *petroglyphs are, therefore, results of anthropogenic, targeted endeavours to remove rock mass applying compressive/tensile forces*.

All forms of rock art need to be understood in such scientific terms, i.e. from the bottom up, before any of their variables are ready for interpretation in humanistic terms.

Prof. Robert G. Bednarik
International Centre of Rock Art Dating (ICRAD)
Hebei Normal University, and
International Federation of Rock Art Organisations
P.O. Box 216
Caulfield South, Melbourne, VIC 3162
Australia
robertbednarik@hotmail.com

REFERENCES

Bader, O. N. 1978. *Sungir: Verhnepalaeolitičeskaja stojanka*. Nauka, Moscow.

Banadaki, M. D. and B. Mohanty 2012. Numerical simulation of stress wave induced fractures in rock. *International Journal of Impact Engineering* 40–41: 16–25.

Beaumont, P. B. 1990. Kathu Pan. In P. Beaumont and D. Morris (eds), Guide to archaeological sites in the Northern Cape, pp. 75–100. McGregor Museum, Kimberley.

Bednarik, R. G. 1984. Die Bedeutung der paläolithischen Fingerlinientradition. *Anthropologie* 23: 73–79.

Bednarik, R. G. 1985. Parietal finger markings in Australia. *Bollettino del Centro Camuno di Studi Preistorici* 22: 83–88.

Bednarik, R. G. 1986. Parietal finger markings in Europe and Australia. *Rock Art Research* 3: 30–61, 162–170.

Bednarik, R. G. 1987/88. The cave art of Western Australia. *The Artefact* 12: 1–16.

Bednarik, R. G. 1990–91. Epistemology in palaeoart studies. *Origini* 15: 57–78.

Bednarik, R. G. 1991a. Comment on d'Errico (1991). *Rock Art Research* 8(2): 89–91.

Bednarik, R. G. 1991b. On natural cave markings. *Helictite* 29: 27–41.

Bednarik, R. G. 1992a. A new method to date petroglyphs. *Archaeometry* 34(2): 279–291.

Bednarik, R. G. 1992b. Base pour des études de pointe des débuts de l'art. *L'Anthropologie* 96(2–3): 369–374.

Bednarik, R. G. 1992c. Natural line markings on Palaeolithic objects. *Anthropologie* (Brno) 30(1): 1–8.

Bednarik, R. G. 1993. About Palaeolithic ostrich eggshell in India. *Indo-Pacific Prehistory Association Bulletin* 13: 34–43.

Bednarik, R. G. 1994a. A taphonomy of palaeoart. *Antiquity* 68(258): 68–74.

Bednarik, R. G. 1994b. The discrimination of rock markings. *Rock Art Research* 11(1): 23–44.

Bednarik, R. G. 1994c. The Pleistocene art of Asia. *Journal of World Prehistory* 8(4): 351–375.

Bednarik, R. G. 1995. Towards a better understanding of the origins of body decoration. *Anthropologie* 33(3): 201–211.

Bednarik, R. G. 1997a. Pleistocene stone pendant from Western Australia. *Australian Archaeology* 45: 32–34.

Bednarik, R. G. 1997b. The role of Pleistocene beads in documenting hominid cognition. *Rock Art Research* 14(1): 27–41.

Bednarik, R. G. 1998a. Microscopic analyses of 'engraved plaques' and other objects from Devil's Lair. *Journal of the Royal Society of Western Australia* 81: 165–175.

Bednarik, R. G. 1998b. The technology of petroglyphs. *Rock Art Research* 15(1): 23–35.

Bednarik, R. G. 1998c. Direct dating results from Australian cave petroglyphs. *Geoarchaeology* 13(4): 411-418.

Bednarik, R. G. 1999. The speleothem medium of finger flutings and its isotopic geochemistry. *The Artefact* 22: 49–64.

Bednarik, R. G. 2001. *Rock art science: the scientific study of* palaeoart, 1st edn. Brepols, Turnhout (2nd edn 2007, Aryan Books International, New Delhi).

Bednarik, R. G. 2003. A figurine from the African Acheulian. *Current Anthropology* 44(3): 405–413.

Bednarik, R. G. 2005. Middle Pleistocene beads and symbolism. *Anthropos* 100(2): 537–552.

Bednarik, R. G. 2008. Cupules. *Rock Art Research* 25(1): 61–100.

Bednarik, R. G. 2012. The use of weathering indices in rock art science and archaeology. *Rock Art Research* 29(1): 59–84.

Bednarik, R. G. 2015. The tribology of cupules. *Geological Magazine* 152(4): 758–765.

Bednarik, R. G. 2016a. Forensic science of cupules. *Rock Art Research* 33(1): 49–64.

Bednarik, R. G. 2016b. The tribology of petroglyphs. In R. G. Bednarik, D. Fiore, M. Basile, G. Kumar and Tang H. (eds), Paleoart and materiality: the scientific study of rock art, pp. 171–185. Archaeopress Publishing Ltd, Oxford.

Bednarik, R. G. 2016c. *Myths about rock art*. Archaeopress Publishing Ltd, Oxford.

Bednarik, R. G. 2017. *Palaeoart of the Ice Age*. Cambridge Scholars Publishing, Newcastle upon Tyne.

Bednarik, R. G. 2019a. *Tribology in Geology and Archaeology*. Nova Science Publishers, New York.

Bednarik, R. G. 2019b. Compressive-tensile rock markings. *Geological Magazine* 156(12): 2113–2116.

Bednarik, R. G. 2020. Archaeotribology: the interaction of surfaces in relative motion in archaeology. *Tribology International* 141; doi:10.1016/j.triboint.2020.106198.

Bednarik, R. G. and Y.-P. Montelle 2016. Forensic replication work with Australian cave art. In R. G. Bednarik, D. Fiore, M. Basile, G. Kumar and Tang H. (eds), *Paleoart and materiality: the scientific study of rock art*, pp. 99–112. Archaeopress Publishing Ltd, Oxford.

Boucher de Perthes, J. 1846. *Antiquités celtiques et antédiluviennes*. Treuttel et Würtz, Paris.

Bouzouggar, A., N. Barton, M. Vanhaeren, et al. 2007. 82,000-year-old shell beads from north Africa and implications for the origins of modern human behavior. *Proceedings of the National Academy of Science, U.S.A.* 104: 9964–9969.

Bruder, S. J. 1983. *Archaeological investigation at the Hedgpeth Hills petroglyph site*. Research Report 28, Museum of Northern Arizona, Flagstaff.

Cheng T. K. 1959. *Archaeology in China, Volume 1, Prehistory China*. Heffer, Cambridge.

Clark, J. D. 1959. *The prehistory of southern Africa*. Penguin, Harmondsworth.

d'Errico, F. 1987. Nouveaux indices et nouvelles techniques microscopiques pour la lecture de l'art gravé mobilier. *Comptes Rendus de l'Academie des Sciences de Paris* 304: 761–764.

d'Errico, F. 1988. Lecture technologique de l'art mobilier gravé. Nouvelles méthodes et premiers résultats sur les galets gravés de Rochedane. *L'Anthropologie* 92: 101–122.

d'Errico, F. 1989a. L'art gravé azilien. Analyse microscopique, reconstitution gestuelle, signification. Ph.D. thesis, Muséum National d'Histoire Naturelle, Paris.

d'Errico, F. 1989b. Palaeolithic lunar calendars: a case of wishful thinking? *Current Anthropology* 30: 117–118.

d'Errico, F. 1989c. A reply to Alexander Marshack. *Current Anthropology* 30: 495–500.

d'Errico, F. 1991. Microscopic and statistical criteria for the identification of prehistoric systems of notation. *Rock Art Research* 8(2): 83–93.

d'Errico, F. 1994. *L'art gravé azilien. De la technique à la signification*. 31e supplément à 'Gallia Préhistoire', CNRS Éditions, Paris.

d'Errico, F. and C. Cacho 1994. Notation versus decoration in the Upper Palaeolithic: a case study from Tossal de la Roca, Alicante, Spain. *Journal of Archaeological Science* 21: 185–200.

d'Errico, F. and A. Nowell 2000. A new look at the Berekhat Ram figurine: implications for the origins of symbolism. *Cambridge Archaeological Journal* 10(1): 123–167.

Donzé, F. V., J. Bouchez and S. A. Magnier 1997. Modeling fractures in rock blasting. *International Journal of Rock Mechanics and Mining Sciences* 34(8): 1153–1163.

Dortch, C. E. 1976. Two engraved stone plaques of late Pleistocene age from Devil's Lair, Western Australia. *Archaeology and Physical Anthropology in Oceania* 11: 32–44.

Dortch, C. E. 1979a. Devil's Lair, an example of prolonged cave use in south western Australia. *World Archaeology* 10: 258–279.

Dortch, C. E. 1979b. Australia's oldest ornaments. *Antiquity* 53: 39–43.

Dortch, C. E. 1984. *Devil's Lair, a study in prehistory*. Western Australian Museum, Perth.

Dortch, C. E. and J. Dortch 1996. Review of Devil's Lair artefact classification and radiocarbon chronology. *Australian Archaeology* 43: 28–32.

Dunn, E. J. 1931. *The Bushman*. Charles Griffin, London.

Efremov, I. A. 1940. Taphonomy: a new branch of paleontology. *Pan-American Geologist* 74: 81–93.

Esen, S., I. Onederra and H. A. Bilgin 2003. Modelling the size of the crushed zone around a blasthole. *International Journal of Rock Mechanics and Mining Sciences* 40: 485–495.

Francis, P. 1981. Early human adornment in India, Part 1. The Upper Palaeolithic. *Bulletin of the Deccan College Postgraduate and Research Institute* 40: 137–144.

Frocht, M. M. 1965. *Photoelasticity*. J. Wiley and Sons, London.

Goren-Inbar, N. 1986. A figurine from the Acheulian site of Berekhat Ram. *Mi'Tekufat Ha'Even* 19: 7–12.

Goren-Inbar, N., Z. Lewy and M. E. Kislev 1991. The taphonomy of a bead-like fossil from the Acheulian of Gesher Benot Ya'aqov, Israel. *Rock Art Research* 8(1): 83–87.

Guerra, A., V. Petr and D. V. Griffiths 2013. Radial fractures in rock under the action of explosives. Paper presented to 6th International Conference on Discrete Element Methods, 5–6 August, Golden, CO.

Gunn, R. G. 1986. Wall markings in Tantanoola Cave, Tantanoola, South Australia. Unpubl. MS, Archive of the Australian Rock Art Research Association Inc., Melbourne.

Hallam, S. J. 1971. Roof markings in the 'Orchestra Shell' Cave, Wanneroo, near Perth, Western Australia. *Mankind* 8: 90–103.

Hayden, B. (ed.) 1979. *Lithic use-wear analysis. Proceedings of the Conference on Lithic Technology, Burnaby (BC), Canada, 16–20 March 1977*. Studies in Archaeology, Academic Press, Cambridge, MA.

Henshilwood, C., F. d'Errico, M. Vanhaeren, K. van Niekerk and Z. Jacobs 2004. Middle Stone Age shell beads from South Africa. *Science* 304(5669): 404.

Hiscock, P. 1990. A study in scarlet: taphonomy of inorganic artefacts. In S. Solomon, I. Davidson and D. Watson (eds), *Problem solving in taphonomy: archaeological and palaeontological studies from Europe, Africa and Oceania*, pp. 34–49. Tempus 2, Archaeology and Material Culture Studies in Anthropology, University of Queensland, St. Lucia.

Hublin, J.-J., N. Sirakov, V. Aldeias, S. Bailey, E. Bard, V. Delvigne et al. 2020. Initial Upper Palaeolithic *Homo sapiens* from Bacho Kiro Cave, Bulgaria. *Nature*; doi:10.1038/s41586-020-2259-z.

Jost, P. 1966. *Lubrication (tribology): a report on the present position and industry's needs*. Department of Education and Science, H.M. Stationary Office, London.

Kumar, G. and R. Krishna 2014. Understanding the technology of the Daraki-Chattan cupules: the cupule replication project. *Rock Art Research* 31(2): 177–186.

Marshack, A. 1964. Lunar notation on Upper Paleolithic remains. *Sciences* 184: 28–46.

Marshack, A. 1970. *Notation dans les gravures du paléolithique superieur. Nouvelles méthodes d'analyse*. Publications de l'Institut de Préhistoire de l'Université de Bordeaux, Bordeaux.

Marshack, A. 1972a. Cognitive aspects of Upper Paleolithic engraving. *Current Anthropology* 13: 445–477.

Marshack, A. 1972b. Upper Paleolithic notation and symbol. *Science* 178: 817–828.

Marshack, A. 1972c. *The roots of civilisation*. McGraw-Hill, New York / Weidenfeld and Nicolson, London.

Marshack, A. 1985. Theoretical concepts that lead to new analytic methods, modes of enquiry and classes of data.

Rock Art Research 2(2): 95–111.

Marshack, A. 1989a. On wishful thinking and lunar 'calendars'. A reply to Francesco d'Errico. *Current Anthropology* 30: 491–495.

Marshack, A. 1989b. Methodology in the analysis and interpretation of Upper Palaeolithic image: theory versus contextual analysis. *Rock Art Research* 6(1): 17–38.

Marshack, A. 1991. A reply to Davidson on Mania and Mania. *Rock Art Research* 8(1): 47–58.

Marshack, A. 1997. The Berekhat Ram figurine: a late Acheulian carving from the Middle East. *Antiquity* 71(272): 327–337.

McBrearty, S. and A. S. Brooks 2000. The revolution that wasn't: a new interpretation of the origin of modern human behaviour. *Journal of Human Evolution* 39: 453–563.

McHugh, S. 1983. Crack extension caused by internal gas pressure compared with extension caused by tensile stress. *International Journal of Fractures* 21: 163–176.

Montelle, Y.-P. 2009. Application of forensic methods to rock art investigations — a proposal. *Rock Art Research* 26(1): 7–13.

Morse, K. 1993. Shell beads from Mandu Mandu Creek rock-shelter, Cape Range Peninsula, Western Australia, dated before 30,000 b.p. *Antiquity* 67: 877–883.

Odell, G. H. 2004. *Lithic analysis*. Springer, New York.

Porat, N., M. Chazan, R. Grün, M. Aubert, V. Eisenmann and L. K. Horwitz 2010. New radiometric ages for the Fauresmith industry from Kathu Pan, southern Africa: implications for the Earlier to Middle Stone Age transition. *Journal of Archaeological Science* 37: 269–283.

Savvateyev, J. A. 1977. *Zalavruga, cast' II. Stojanki*. Nauka, Leningradskoe otdelenie, Leningrad.

Semenov, S. 1957. *Pervobytnaja technika. Materialy i Issledovania po Archeologii SSSR 54*. Nauka, Moscow and Leningrad.

Semenov, S. A. 1964. *Prehistoric technology. An experimental study of the oldest tools and artefacts from traces of manufacture and wear* (transl. by M. W. Thompson). Cory, Adams and Mackay, London.

Semenov, S. A. 1968. *Development of technology in the Stone Age* (in Russian). Nauka, Leningrad.

Semenov, S. A. 1970. The forms and functions of the oldest tools. *Quartär* 21: 1–20.

Semenov, S. A. 1974. *The origins of farming*. Nauka, Leningrad.

Sharpe, C. E. and K. J. Sharpe 1976. A preliminary survey of the engraved boulders in the Art Sanctuary of Koonalda Cave, South Australia. *Mankind* 10(3): 125–130.

Sierts, W. 1968. How were rock engravings made? *South African Journal of Science* 64: 281–285.

Solomon, S. 1990. What is this thing taphonomy? In S. Solomon, I. Davidson and D. Watson (eds), *Problem solving in taphonomy: archaeological and palaeontological studies from Europe, Africa and Oceania*, pp. 25–33. Tempus 2, University of Queensland, St Lucia.

Thomas, T. R., B.-G. Rosén, H. Zahouani, L. Blunt and M. ElMansori 2011. Traceology, quantifying finishing machining and function: A tool and wear mark characterisation study. *Wear* 271(3–4): 553–558.

Torbica, S. and V. Lapčević 2014. Rock breakage by explosives. *European International Journal of Science and Technology* 3. 96–104.

Torbica, S. and V. Lapčević 2018. Rock fracturing mechanisms by blasting. *Underground Mining Engineering* 32: 15–31.

Tringham, R., G. Cooper, G. Odell, B. Voytek and A. Whitman 1974. Experimentation in the formation of edge damage: a new approach to lithic analysis. *Journal of Field Archaeology* 1(2): 171–196.

Walsh, W. P. 1964. Unexplained markings in Kintore and Cutta Cutta Caves, Northern Territory, Australia. *Helictite* 2(3): 83–91.

Weeks, R. 2001. Indirect percussion: fact or fiction? *American Indian Rock Art* 27: 117–121.

White, R. 1992. Technological and social dimensions of 'Aurignacian age' body ornaments across Europe. In H. Knecht, A. Pike-Tay and R. White (eds), *Before Lascaux: the complex record of the Early Upper Paleolithic*, pp. 277–299. CRC Press, Boca Raton, FL.

RAR 37-1336
