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STRANGER THAN FICTION: DISTINGUISHING BETWEEN ANTHROPOGENIC AND NON-ANTHROPOGENIC ROCK MARKINGS

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Abstract. This paper first briefly reviews a classification of geological and biological rock markings. It then examines the nature of a previously baffling geological phenomenon in western Victoria, found so far at four sites. The clustered groups of circular rock markings have been defined as Aboriginal petroglyphs by both archaeological and geological reviewers. They are 'cannonballs' — spherical inclusions in the sandstone that became sectioned by unloading events, and they are attributable to inherent diagenic features of the rock. The circle 'petroglyphs' are, in fact, reaction fronts where carbon derived from decaying animal tissue caused the spherically expanding precipitation of $CaCO_3$ before the final lithification of the sandstone. The paper then reports several examples of misidentification of rock markings in recent years that led to the discoveries of geological processes, such as compressive-tensile rock marking, kinetic tree root marking and kinetic energy metamorphosis. In such cases, it was through their connection with rock art rather than basic geological research that understandings of these effects were secured.

1. Introduction

More than thirty years ago, after wrestling for many years with frequent misidentifications of rock markings in the rock art literature, we began developing a systematic approach to the issue. For anyone who has struggled to distinguish between anthropogenic and non-anthropogenic phenomena, the consequences of getting it wrong are obvious. This means that we go to great lengths to consider alternative explanations and refute those which are easily refutable. However, we know we can sometimes make errors, or such errors might become apparent in future as more sophisticated insights become available. This is especially important as we move further back in time, given the paucity of palaeoart from the Middle and Lower Palaeolithic. Such evidence has profound consequences for the understanding of what ancestral humans were capable of at that time in our evolution. Our efforts in the early 1990s resulted in the paper 'The discrimination of rock markings', an attempt to provide a methodical classification of all forms of rock surface markings (Bednarik 1994). In that scheme, such marks are divided into twelve classes, ten of which are natural, and the remaining two are humanly made:

G. Geological rock markings
GP. Petrographic markings
    GP1. Inclusions in igneous rocks
    GP2. Naturally enhanced inherent markings
GW. Weathering markings
    GW1. Solution marks
    GW2. Exfoliation marks
GK. Kinetic markings
    GK1. Taphonomic marks
    GK2. Clastic movement marks

B. Biological rock markings
BP. Plant markings
    BP1. Kinetic plant marks
    BP2. Chemical plant marks
BA. Animal markings
    BA1. Animal scratches
    BA2. Animal polish
BH. Humanly made markings
    BH1. Unintentional or utilitarian anthropogenic marks
    BH2. Non-utilitarian marks (rock art)

In this taxonomic system of rock markings, only the last two types, BH1 and BH2, are anthropogenic. Of these, only the second refers to rock art. So, the system provides a rationale for identifying rock art through the need to ensure that rock markings could not be any of the other eleven types. To be petroglyphs, they must not be utilitarian or unintentional marks made by humans or their tools (BH1) or one of the previous ten types. A grey area is possible between BH1 and BH2, and of course there are numerous instances where natural markings have been modified by human hand.

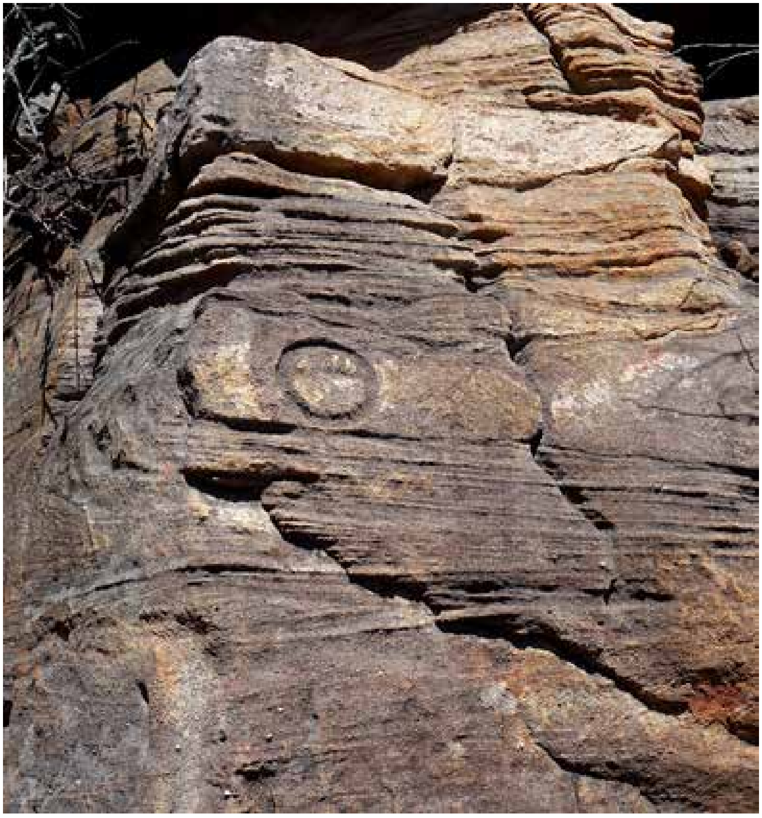

Figure 1. *The Gariwerd circular rock marking most resembling a petroglyph. Its outside diameter is 12.6 cm horizontally (photographs by author unless noted otherwise).*

Experience suggests that identifying these different types of rock markings has been difficult for many archaeologists and some geologists, with vast numbers of misidentifications on record.

Since this classification was proposed, it has been amply confirmed, but in some instances, the facts have turned out to be stranger than fiction. A few identifications are still rejected by scholars of archaeology and even of geology, reflecting some of the flaws of these fields. Such deficiencies have been noted before; some were mentioned in the 1994 attempt to secure a classification. Clegg (2007) also notes the inability of geology specialists to explain mysterious phenomena: 'These respondent experts clearly knew much less than I remembered from physical geography courses in the 1950s. … Authorities and experts, including scientists are only useful when they know the answer; their human failings of being unwilling or unable to admit they do not know may mislead' (Clegg 2007: 59). Based on our experiences, we sympathise with Clegg's comments.

Through our continuing investigations of contested rock markings, especially by applying principles of tribology (the science of interacting surfaces in relative motion; Bednarik 2019a, 2020a), several fundamental geology processes were discovered that had remained undetected or whose products had been misunderstood. They include kinetic energy metamorphosis (Bednarik 2015), compressive-tensile marking (Bednarik 2019b), kinetic tree root marking (Bednarik 1990, 2016a) and fossil (or spent) trovants (these are included and classified in this paper). Thus, investigating the differentiation between deliberately, humanly made and other rock markings has unexpectedly led to the definition of various hitherto unknown phenomena in geology. This paper endeavours to present the circumstances and effects of these discoveries, and it begins with what is perhaps the most confounding case.

2. The 'circle petroglyphs' in Gariwerd, Australia

In a presentation of the known petroglyphs of the Australian state of Victoria, we have recently introduced circular rock markings occurring in three discrete groups in the central Gariwerd (Grampians) mountain ranges and one at Mt Arapiles in western Victoria (Bednarik 2016b: 71, 2020b). Discovered by (former) National Parks rangers David Handscombe and Ryan Duffy, the first three groups were thought to be petroglyphs (rock art created by a reductive process) by specialists from both archaeology and geology. We detected no microscopic evidence of percussion or abrasion in their grooves but noted that their rock fabric, colour and composition differ distinctly from the protolith matrix, having undergone a conversion. Moreover, the groove walls are perpendicular to the rock face rather than the U-shaped section of petroglyphs, and no indentation marks are visible. We found that these rings were formed by differential weathering and erosion rates between the grooves and the sandstone parent rock, but we could not offer a causal explanation for the enigmatic features (Fig. 1). Finding a realistic clarification proved difficult due to various factors:

1. Circular markings of this type have been commonly described from plutonic rocks (xenoliths or autoliths; Bednarik 1994) but seemed much harder to explain in sandstones.
2. At one of the three sites, the sandstone was much more weathered than at the others, and the material forming the grooves had weathered so deeply that it became evident that these circles were all formed by the dissection of *spherical* inclusions or concretions. In some cases, it was possible to insert a hand around these 'cannonball' formations (Fig. 2).
3. Many of these spheres seemed spatially associated with kinetic energy metamorphosis products along fault mirrors (polished and glossy fault-slip surfaces; Bednarik 2015), which might be coincidental or connected to the spheres' formation.
4. The most perplexing characteristic of the spheres was that any structural features in the sandstone, such as faint traces of stratification, continue right

through the core of the 'cannonballs'.

Figure 2. *Heavily weathered concretion sphere, of which only about one quarter remains in situ, Gariwerd, Victoria.*

The last-mentioned aspect seemed to indicate that, somehow, these features 'transcend' the rock fabric, rather as if they were 'bubbles' 'floating' within it. This seems impossible in a well-stabilised arenite with marked development of syntaxial quartz overgrowths on grains. Several hypotheses were considered to account for these mysterious phenomena until geologists Alan Watchman and Charles R. Twidale suggested they might be related to trovants. These 'growing stones' are best known in Valcea County in Romania but can also be found in several other regions. They grow in size and are also said to 'multiply'. They range from a few millimetres to 10 m in diameter and were first described by Gheorghe Munteanu-Murgoci (1907; Ticleanu et al. 2012). The Gariwerd spheres could not grow or multiply, but trovants share some aspects of epigenic (alteration of rocks after the surrounding rock has formed) histories with phenomena variously known as cannonball concretions, hiatus concretions, mega-spherulites, Moqui marbles, Kansas pop rocks and septarian concretions.

The process accounting for trovants is based on Berner's (1968a, 1968b) observation that bacterial decomposition of butterfish and smelts in sealed jars containing seawater and other solutions yields significant amounts of dissolved bicarbonate, ammonia and volatile amines. Taking several months, this conversion process is accompanied by a rise in pH. The precipitation of Ca^{++} ion from the solution occurs as a mixture of calcium fatty acid salts or soaps with from 14 to 18 C atoms, rather than as $CaCO_3$. The thermodynamic instability of $CaCO_3$ can explain this, relative to calcium soaps or adipocere (a wax-like organic substance formed by the anaerobic bacterial hydrolysis of fat in tissue) in the presence of excess free fatty acid. It is this process that accounts for trovant-like phenomena. Authigenic mineralisation and permineralisation of the organic remains capture organic carbon within carbonate matrices at various stages of alteration, creating a fossil in the sediments accumulating below the sea floor and often ensuring its survival through the geologic record (Grice et al. 2019). Anaerobic microbial decay of the carbon source results in localised supersaturation of HCO_{3-} ions generating an alkalinity gradient proportional to the rate of decay and diffusion. It leads to decreased solubility and consequent precipitation of carbonate (Raiswell 1976), but it remains unknown whether the concretions grow concentric in-to-out (Raiswell and Fischer 2000) or out-to-in (Coleman 1993).

In this environment, the decay products expand equally in all directions from the decaying organic matter, i.e. they expand spherically as they diffuse in the consolidated but not yet lithified sand sediments below the sea floor. At the reaction front, Ca is precipitated as $CaCO_3$, and other cations present respond in similar patterns. Fe is also markedly elevated in the reaction front (the hollow spherical shape forming the surviving concretion), whereas Mn concentrations vary inversely to Fe and Ca (Yoshida et al. 2018). Those of Ca range from several times to twenty times higher than in the surrounding matrices (concretion CaO: 30~60 wt%, background CaO: 1~12 wt%). The thickness of the reaction front (*L*) increases almost linearly with increasing growth times and hence cumulative concretion diameter (*R*) (Yoshida et al. 2018: Fig. 4; a= 0.0807± 0.0105 and b = 0.992 ± 0.017):

$$L = aR^b \qquad (1)$$

The HCO_{3-} deriving from R-COOH (fatty acid) with its low $\delta^{13}C$ value reacts with the Ca_{2+} in the reaction front. With decreased HCO_{3-} and Ca_{2+} in the pore water within the reaction front, concentration gradients furnish Ca cations until the HCO_{3-} concentration matches $CaCO_3$ equilibrium, and the organically derived carbon is exhausted. This explains why specific phenomena of this type, such as the trovants, can continue to grow when exposed to water until all organic matter within them is consumed. This carbon, usually from tissues

Figure 3. Small specimens of the concretion spheres, truncated by an unloading event at a cliff face in Gariwerd. The lack of mass loss in the reaction front relative to the rock matrix implies that they were exposed relatively recently.

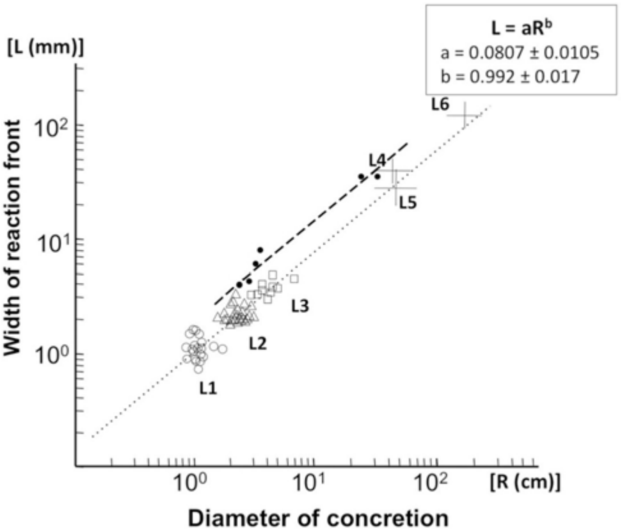

Figure 4. Relationship between concretion diameters (R) and widths of reaction fronts (L) at six sites illustrated by Yoshida et al. (2018) compared with that determined in six of the Gariwerd specimens (broken line).

of decaying organisms, drives the system. In most environments, the concretion arises quite rapidly, within several months, and it is thought to form some tens of metres below the seabed. As the sediment is consolidated into argillaceous rock or sandstone or even metamorphosed further, it can preserve the initial concretion's form as perfectly as a fossil. The weakly cemented material is removed preferentially if it becomes exposed at the lithosphere's surface and subjected to weathering processes.

The observed two dozen or so (several specimens were not fully accessible) Gariwerd examples measure from 1.5 to 13 cm in diameter. Their outer modification zone's thickness seems to be a function of the spheres' sizes: the greater their diameter, the thicker the modified zone (Fig. 3). That zone is manifestly richer in Ca and Fe than the matrix in which the spheres occur, accounting for its darker colour and higher susceptibility to weathering.

The Gariwerd concretions so far found in three clusters all occur in Wartook Sandstone, a late Silurian facies of the Mount Difficult sub-group. This sandstone is pale, fine to coarse-grained quartz to quartzo-feldspathic, laminated, cross-laminated and rarely trough cross-laminated (Cayley and Taylor 1997). The proximity of all three localities to the Granicus Fault meandering through central Gariwerd is possibly reflected in the nearby fault mirrors at two of the sites. The spherical concretions' most perplexing attribute, the continuity of any structural textures observed in the rock matrix through its core, suggests that authigenic mineralisation caused by organic carbon is the sole explanation possible for the formation of the spheres. This process can only have occurred before the diagenesis of the sand to sandstone when the spheres were already formed, but syntaxial quartz overgrowths on the quartz grains had not yet closed the pores between them (Bednarik 2019a). Therefore, these spheres are perhaps best defined as 'fossil trovants' or 'spent trovants', i.e. as trovants that have depleted the carbon available to them in the distant geological past. Concerning the above taxonomic system of rock markings, the Gariwerd 'circle petroglyphs' are of the type GP2, naturally enhanced inherent markings. They are attributable to the accelerated weathering of the reaction front of sectioned cannonball formations, which has created a relief prompting them to resemble petroglyphs.

Much more recent unloading events, in some cases along faults transecting the spheres (as in Fig. 1), have sectioned the former trovants and exposed the rings formed by their reaction fronts. As these freshly exposed circular features were subjected to weathering, they retreated faster than the matrix or interior rock because of their high carbonate content established during early diagenesis. Therefore, the depth of each circular groove provides a measure of the relative age of the unloading event that exposed the reaction front. The reaction front widths of those specimens that could be reliably measured were inserted in Yoshida et al.'s (2018) graph depicting the relationship between concretion diameters (*R*) and widths of reaction fronts

(*L*) (Fig. 4). This implies that the Gariwerd specimens form a distribution pattern close to and parallel to those reported by Yoshida et al. from six localities (dotted line) and slightly above them (broken line).

Since the origin of the 'circle petroglyphs' of the Gariwerd mountains has been established, several other sandstone exposures featuring similar clustered groups of 'cannonballs' have been observed along the southern coast of New South Wales (e.g. at Warden's Head, Ulladulla, Wheeler's Point, Huskisson and Crookhaven) and Artillery Rocks near Wye River on the Great Ocean Road of Victoria (Gill 1977). It is suggested that these features are quite common in some sandstone facies (Fig. 5).

Two circular rock markings like those in Gariwerd have also been observed on Mt Arapiles, located about 80 km to the north-west and of similar sandstone. However, it needs to be mentioned that circle markings that have been misidentified as petroglyphs are not limited to the type described here, and they are frequently found on granites and basalts. Some of the more spectacular examples are sites or site complexes reported in the United States, where such markings can occur in their hundreds. Examples are Pinnacle Mountain in South Carolina (Charles 2012; Cerveny 2022; attributed by some to the Hopewell culture) or DuPont State Recreational Forest in North Carolina (Loubser 2011). They tend to be relatively small, usually about 10 cm in diameter, whereas the deep circle depressions at a Victorian granite site are mostly more than 1 m in diameter. These autolithic features occur near the peak of Mt Korong at Wedderburn (Bednarik 2007: Fig. 3). Many other circular rock markings have been thought to be petroglyphs, including the numerous small, weathered autoliths on basalt at the very peak of Mt Loch (Bednarik 1994: Fig. 3); the vaguely circular markings of type GP2 on the dolerite of Mersey Bluff, Tasmania (Murray 1980); and the circles on a small sandstone slab at the Sutherland Creek site at Maude near Geelong (Bolger 1979; Bednarik 1994: Fig. 17). The latter were created with two rotating steel tools, so they are not defined as petroglyphs even though they are anthropogenic features.

Like the described cannonball features, another type of circular rock marking was also created before the lithification of sand. Under favourable conditions, aeolianites have the capacity to preserve a record of events that transpired on them when they were composed of unconsolidated sand. Such markings were caused either by plant parts moving in the wind (Fig. 6) or, as a very rare phenomenon, created by hominins (Helm et al. 2020: Fig. 1) before the arenite's stabilisation. The latter phenomenon, now named ammoglyph, was discovered only recently by Charles W. Helm and his colleagues and is of considerable importance to appreciating the cognitive status of Middle Stone Age humans. It falls into the category BH2 and is thus a new form of rock art.

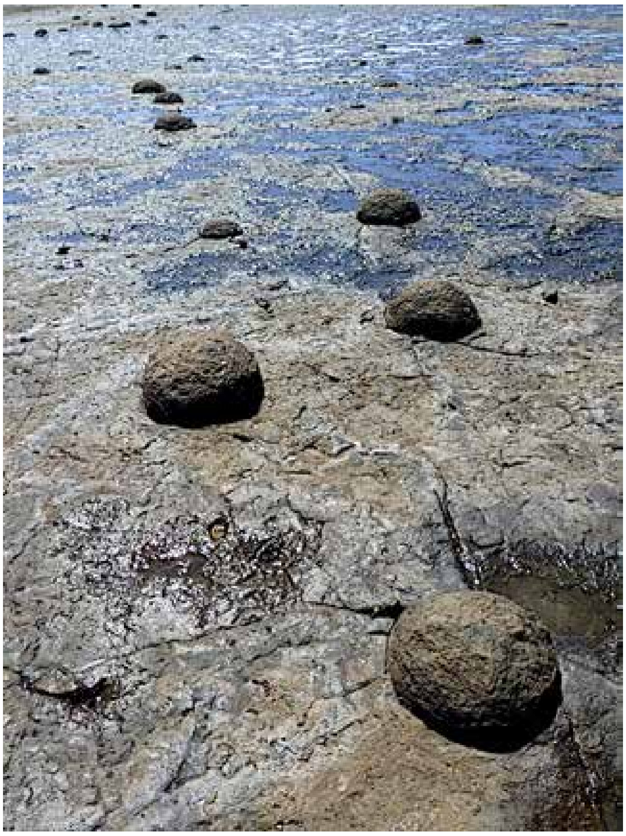

Figure 5. *Cannonball features at Ulladulla, New South Wales south coast (photograph by Robert Bednarik jun.).*

Figure 6. *Circular markings on sand at Langebaan Lagoon in the West Coast National Park, South Africa (photograph by Charles W. Helm).*

3. The 'vulva petroglyphs' of central India

In early 2022, Nileshkumar Kshirsagar reported to us the discovery of hundreds of petroglyphs on sandstone in the central Indian mountain ranges. In some cases, their identification as cannonball formations is unmistakable (see Fig. 7d). Others deviate from these standard forms and show various features, notably elongate shapes. Their distinctive, sharply delineated clefts exclude the possibility that these are petroglyphs as they could not have been produced with tools.

Not having had the opportunity to examine these

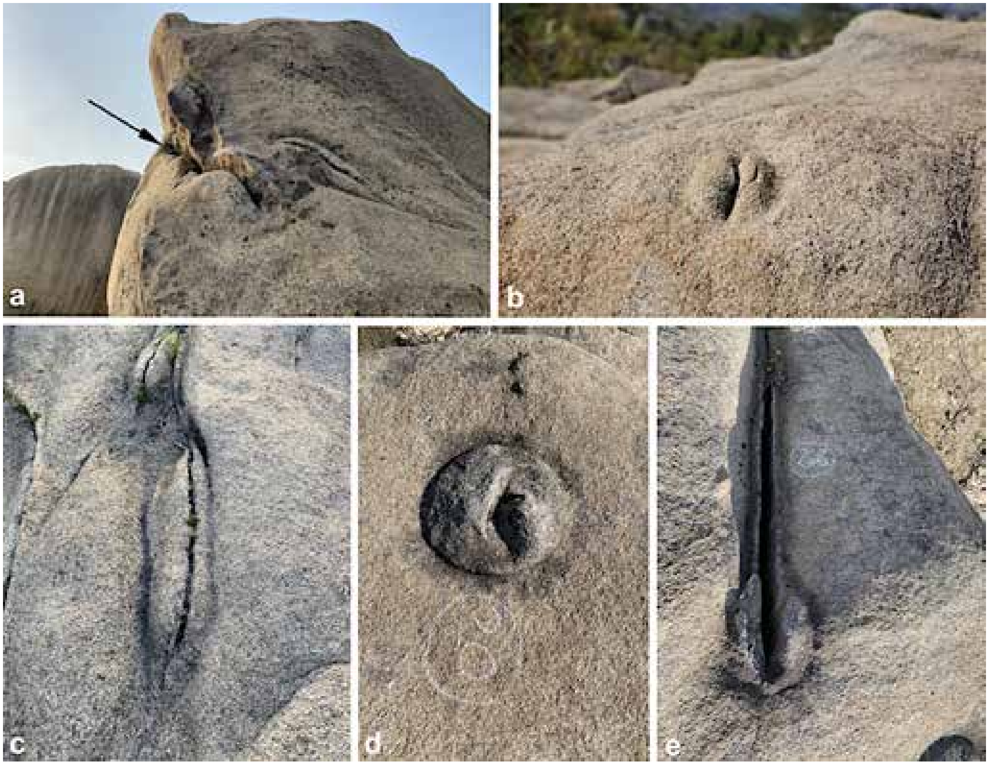

Figure 7. *A sample of the 'vulva petroglyphs' found in central India; all are natural features. Photographs by Nileshkumar Kshirsagar.*

phenomena, we suggest that the most likely explanation for them is that they are cannonball features subjected to various degrees of compression in one direction. The apparent continuum from Figure 7d supports this explanation, clearly a cannonball-type feature with central erosion prompted by the carbonate-rich middle, to 7b to 7c and 7e, with the left feature in Figure 7a (see arrow) being the most extreme form. The central Indian arenites tend to be well metamorphosed and are often defined as quartzites (Bednarik 2019a; Polymeris et al. in press) and may have been subjected to conversion stresses. A detailed study of these features is required.

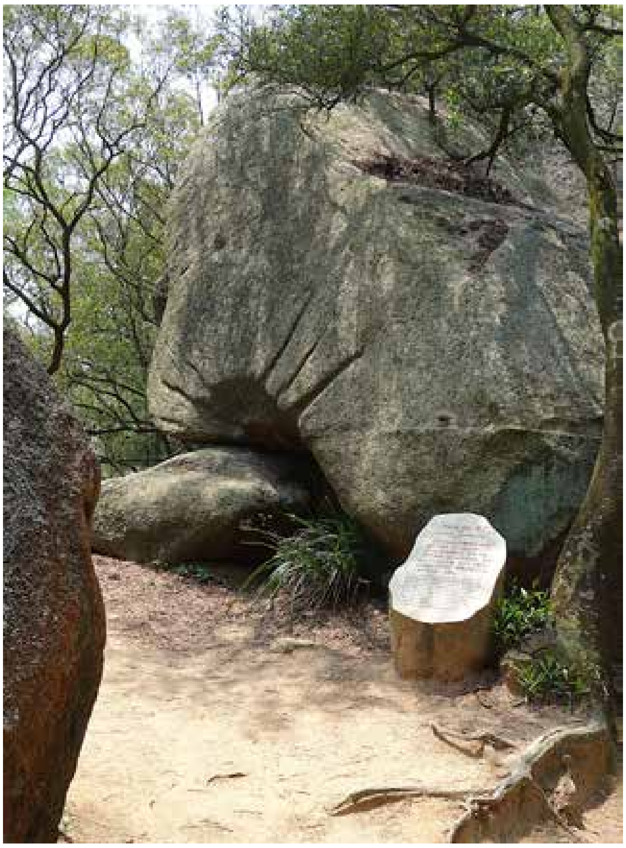

Figure 8. *A radial rock markings set, Dong Men Yu Island, Fujian Region, China. Promoted as a petroglyph, it prompted the discovery of compressive-tensile rock markings.*

4. Compressive-tensile rock markings

The class of compressive-tensile rock markings was established after we were requested to determine whether a large rock marking on a small island in the Fujian Province of China is a petroglyph of a rising sun or a natural marking (Bednarik 2019b, 2019c). Upon examination, it was evident that the 'rays' of the 'sun symbol' are weathered-out grooves triggered by very deep and narrow tensile fissures that are arranged in a relatively evenly spaced radial pattern (Fig. 8). As there were several other, similar features on the granite island, the defining factors were readily established and it was considered that the markings derive from massive collisions between huge granite tors in the distant geological past. However, as the process had not been explained before, we resorted to the well-understood effects of explosives on rock to define the relevant mechanics (Bednarik 2019c). In both cases, a shock wave travels from the point of impact or explosive discharge in a radial pattern, deforming and damaging the rock's fabric by compression until it is arrested by the inertia of the surrounding rock mass. The rest of the energy is spent applying tension to this surrounding mass, yielding evenly spaced radiating cracks aligned to the point of impact. These fissures are only around 1 mm wide, but the contiguous rock has also been structurally deformed to a depth of several centimetres. It then weathers progressively, as does the similarly impacted core area. The only difference between the effects of an explosion and natural impact is that in the former case, the affected area forms a full circle, whereas, in the impact scenario, it can only be part of a circle, generally semi-circular. This is because impact occurs at the surface, whereas an explosion occurs in the rock's interior. The several expressions of the phenomenon are substantially different from the effects of lightning strikes on rocks which have been defined (Bednarik 2007: 89). The impact area of lightning is often marked by surface glazing where minerals became fused or new ones formed instantaneously by the extreme conditions. Iron minerals may turn to bluish or greenish colours. Large blocks may be broken in half, or chunks were flaked off conchoidally, but signs of compressive-tensile impact are observed only faintly. Most importantly, lightning impact lacks the distinctive circular central zone of deformation.

However, the primary importance of the phenomenon of compressive-tensile rock marking is not its role in explaining the nature of unusual patterns resembling rock art. It is a widespread occurrence in nature and even in archaeology. Rocks are fractured by various types of kinetic impact and tensile stress markings arranged in sub-parallel to radial patterns are frequently seen in geology. We use as an example a dense quartzite clast we observed on the Tibetan Plateau, near the Gengzhuo site complex of petroglyphs, west of Zhengwen Township, Yushu Tibetan Autonomous Prefecture (Li et al. 2022). The block has been transported by the Tongtian River (the primary source of the Yangtze) and, on a cleavage face, features a radial pattern delimited by an arcuate flat area (Fig. 9). We have observed numerous such patterns in many lithologies. In cases where the fractured rock was of relatively narrow depth in the direction of fracture, the tensile stress markings are preferentially shaped as if the kinetic force 'anticipated' the contour of the opposing surface. In Figure 10, the well-delineated arcuate marking defines the point of impact, at the top of the image. The tensile markings on the left are curved towards the opposite surface below. Their stepped appearance derives from the foliate structure of the schist. The described aspect of 'anticipation' appears to be of particularly promising future research potential as it seems related to the shock waves' Hertzian cone response to the topography of the rock mass.

Figure 9. *Compressive-tensile rock markings on quartzite block on Tibetan Plateau.*

Figure 10. *Compressive-tensile rock markings on schist fracture surface, Indian Valley, Gengzhuo site complex, Tibetan Plateau.*

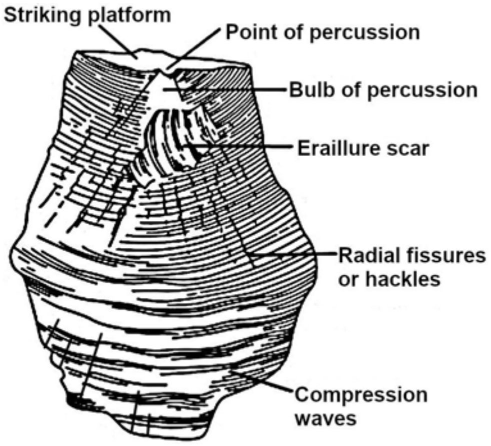

Figure 11. *The features typically seen on the ventral surfaces of stone tool flakes.*

Another phenomenon attributable to compressive-tensile reactions of rock has long been appreciated in archaeology. The typical features found on the ventral surfaces of flake stone tools (other than those made by the bipolar technique) include the point of percussion on the edge of the striking platform, and the bulb of percussion extending from it for part of the ventral face, which expresses a Hertzian cone. Beyond it frequently occurs a series of vague concentric rings, continuing up to the flake's distal end, indicating the effects of the shock wave travelling through the stone. Two features can often be observed on the bulbar area: an eraillure scar and several linear fissures or hackles arranged in a radial configuration centred on the point of percussion. Occasionally these reappear towards the lateral margins or the distal end of the flake, still roughly aligned to the point of percussion (Fig. 11). The mechanics of stone tool knapping causes the Hert-

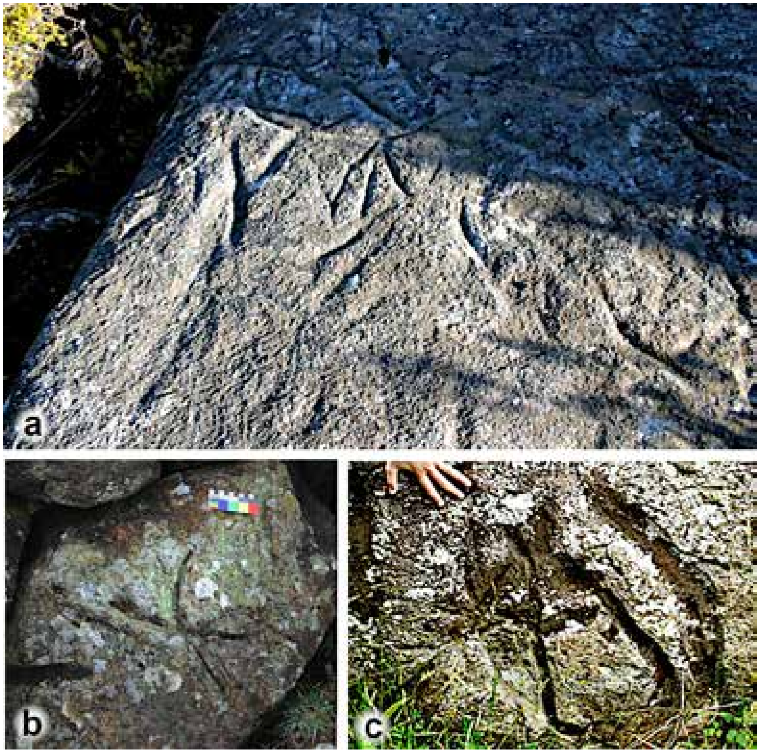

Figure 12. *Kinetic tree root marks from (a) Tasmania, (b) Terceira Island (Azores, photograph by M. T. M. Azevêdo) and (c) Pennines (U.K., photograph by D. Shepherd and F. Jolley).*

zian cone when a flake is removed by a combination of 'opening force' (operating at a right angle to the cleavage face) and 'shearing force' (in the direction of cleavage), demanding an angle of direction of about 165° to the intended cleavage direction. Therefore, the bulbous shape of the ventral surface's proximal part reflects a *partial* Hertzian cone. The radial fissures are as much expressions of a compressive-tensile reaction as the large-scale radial rock markings on the Fujian island where they were first identified.

Compressive-tensile rock markings are obviously of kinetic origin, i.e. of class GK in the 1994 classification of rock markings. More specifically, they belong to GK2 marks, 'clastic movement marks'. However, in the case of the Dong Men Yu arrangements, they have been extensively modified by weathering over the duration of geological periods. So, there is also an element of GP2 markings involved, 'naturally enhanced inherent markings', in which the 'inherent markings' refer to rock deformation at the time of impact.

5. Kinetic tree root markings

The quest of David Shepherd and Frank Jolley (2016) to determine the origins of 'strange' rock grooves found on thirty rock panels in the Pennine mountains of Yorkshire, U.K., has been reported in this journal. It took them several years (Shepherd and Jolley 2011, 2014) and involved the collaboration of numerous geologists, archaeologists and learned societies (historical, archaeological and geological). Their search was of impressive sophistication, indicated by their ability to discriminate between cupules and natural erosion hollows at one of the sites, Withens Clough; most investigators would have failed in this. Ultimately, all their intensive endeavours to establish the status of the Pennines grooves led to no solution. Both anthropogenic (e.g. petroglyphs, polissoirs, various types of incidental human markings) and non-anthropogenic (e.g. chemical solution marks, fossils, glacial scarring, current bedding, erosion phenomena) explanations were offered, but none of them was found credible.

It was only because of their submission of a paper to *RAR* that they discovered that the conundrum had long been solved in Australia (Shepherd and Jolley 2016; Bednarik 2016a). We had encountered sets of deeply cut irregular grooves on sandstone in Quinkan country of the Cape York Peninsula in the 1980s. These wrapped around the edge of a rock platform at the Amphitheatre petroglyph site, some 2 m above the nearest sediment. Although they superficially resembled aniconic petroglyphs, we realised that they would be impossible to create with stone tools. We then undertook a literature review and consulted numerous rock art researchers (including Andrée Rosenfeld, Percy Trezise and members of the Parietal Markings Project), which yielded no solution, just like the work of Shepherd and Jolley some 30 years later. We developed the hypothesis that these grooves resulted from tribological action between the rock and the uppermost roots of trees swaying in strong wind, with resultant abrasion assisted by sediment. That hypothesis was tested and found to be correct on 12 November 1989, when several sets of similar markings were first observed in Ku-ring-gai Chase National Park in Sydney, and then identical markings next to the roots of a recently uprooted eucalypt tree, matching the morphology of the tree's roots:

> As [trees] swayed in the wind the minute movement in some roots, with sand and soil acting as an abrasive, was adequate to produce grooves of [in extreme cases] up to 10 cm depth over a tree's lifetime. Clearly, rock art researchers need to be familiar with many phenomena and maintain a very sceptical approach in all their work (Bednarik 1990: 4).

In both examples known at that time, the kinetic tree root markings were found on sandstone, but the lithology is not a defining factor and in subsequent decades, we found them also on other rock types, including granitic rocks (Bednarik 1994: 35, 2007: 26; Bednarik et al. 2007: 166) (Fig. 12). One common factor emerging in new observations was that this kind of rock marking always coincided with locations highly exposed to wind, on rocky mountain ridges or spurs and at windswept coastal rises with minimal sediment cover. Shepherd and Jolley had also reported two occurrences beyond the Pennines, one at Orkney and one on a sandstone ridge in the Chuckanut Mountains in Washington State, U.S.A.

Much more recently, a professor of geology faced the same need to explain rock markings previously assumed to be petroglyphs but which to her seemed to be natural (Azevêdo 2021). Terceira Island is part of the Azores in the mid-Atlantic, located at the Azores Microplate, where the African, Eurasian and North American continental plates meet. The islands are therefore subjected to a highly active tectonic regime, with very frequent micro-earthquakes that are more effective in shaking trees than the wind (Azevêdo 2021: 127). Moreover, the slopes above the calderas are very rocky and of limited sediment cover, yet forests of very large trees densely covered them before Portuguese colonisation. These included beech (*Myrica faya*), over 40 m high, and cedar (*Juniperus brevifolia*), 50 m high with roots that typically envelop and hug the rock for support. Azevêdo initially found that geological processes such as erosion could not possibly account for the grooves in the trachytic or trachyandesitic rock, so she considered that they must have been made by human action. However, she found it difficult to reconcile this explanation with the vast numbers of such markings. 'It would take thousands of carvers to produce such an immense number of engraved stones over time', she notes, 'and what could be the purpose of such exhaustive work?' She considered that an ancient written script might be represented, but 'the immeasurable number of markings' 'did not appear to match any known form of writing'. Only when she discovered our explanation as tree root markings, she realised that they are extensive evidence of biotribology. Their great number is undoubtedly attributable to the windswept and highly earthquake-prone nature of the Azores Islands.

Azevêdo and Shepherd and Jolley quite correctly rejected the possibility, supported by some geologists, that the grooves in, respectively, trachyte and siliceous sandstone might be caused by organic acids exuded by tree roots. However, it needs to be emphasised that chemical plant marks do occur on carbonate rocks, e.g. in caves, listed in the classification of rock markings as class BP2. We have described these on several occasions (e.g. Bednarik 1994: 35–36) as the result of CO_2 respiration of mycorrhiza living on the tree's roots. By contrast, the kinetic tree root marks described here are included in class BP1, 'kinetic plant marks', which also include other forms. Their most characteristic attributes are that they usually fade out or are tapered at their ends, they may wrap around curved surfaces, and they may branch. The grooves are smooth and free of impact evidence, most frequently measure between 20 and 40 mm in width and may feature undercut margins. In short, they may reflect all the characteristics potentially attributable to tree roots.

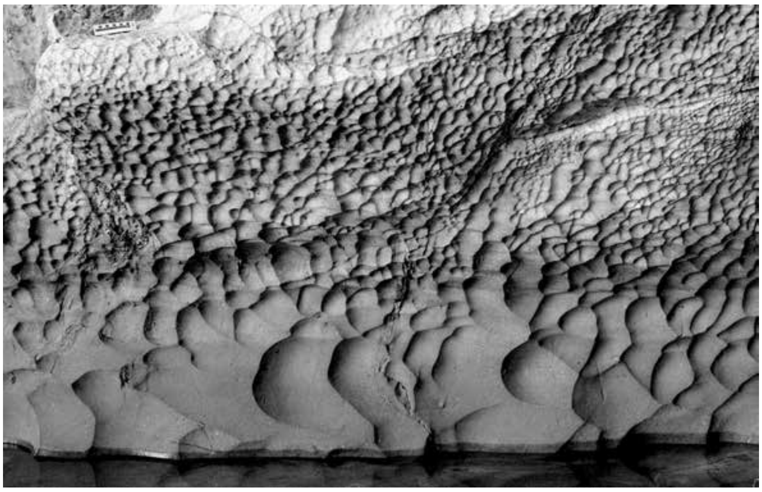

Figure 13. *Solution scallops of varying sizes representing differing flow conditions, Grand Arch, Abercrombie, N.S.W., Australia (photograph by K. Grimes).*

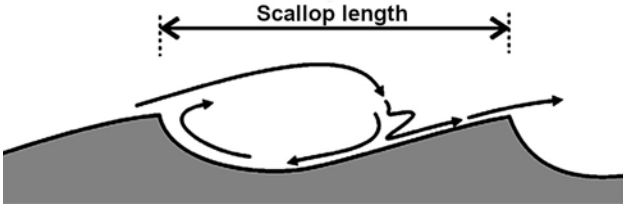

Figure 14. *Typical section through solution scallop in the direction of water flow, showing the eddy current.*

6. Solution scalloping

One of the rock surface markings not considered in the seminal paper on the topic is solution scalloping in carbonate rock caves affected by water flow (Fig. 13). However, they were first described nearly two centuries ago (De Serres 1835: 24; cf. Monroe 1970). Solution scallops (*cannelure* or *vague d'érosion* in French, *Fließfacette* in German, *huelle de corriente* in Spanish) are shallow concavities formed through erosion by eddies in flowing water, particularly in caves. They occur in groups, are separated by sharp ridges and are of a great range in sizes. Their asymmetry in horizontal section allows flow direction to be established because the upstream end is always steeper inclined (Fig. 14). Also, their size indicates flow velocity: the faster the water flow, the smaller the scallops. There is no instance on record in which solution scalloping was misidentified as petroglyphs, but Campbell et al. (2007) described them as 'natural cupules', which is a non sequitur because all cupules are humanly made; natural features are not.

In the class GW1, solution scallops join other solution markings such as *Karren*, which are also primarily a cave phenomenon, and others are tentatively attributed to aqueous solution processes (Bednarik 1994: 29–30).

7. Kinetic energy metamorphosis

The phenomena so far described here define

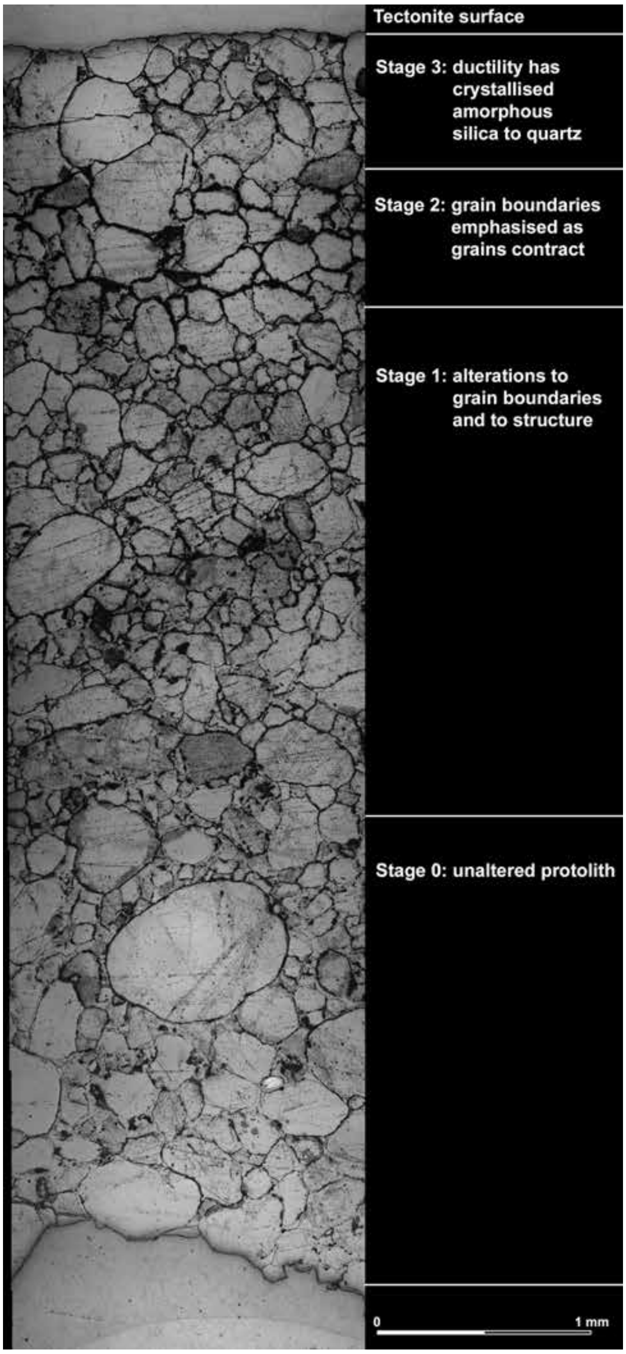

Figure 15. *Composite microphotograph of a thin section through the zones of modification of a sample of kinetic energy metamorphosed (KEM) quartzite.*

non-anthropogenic rock markings that have been reported as rock art or are likely to be mistaken for such. To illustrate the effectiveness of comprehensive interdisciplinary approaches that have accounted for all these findings and discoveries, one more phenomenon is discussed here, even though it is unlikely to be interpreted as rock art. Its relevance to the topic of this paper is that it can occur *with* petroglyphs and, in fact, was discovered in that context. However, most of its occurrences, probably over 99%, result from natural processes. This again illustrates the complexity of separating anthropogenic from non-anthropogenic rock markings.

There is a vast body of modified rock substrates and fault mirrors on this planet which geologists have attributed to a variety of processes. To cite an example: glacial polish has traditionally been assumed to be the result of progressive removal of material until the surface becomes optimally smooth (Iverson 1991; Benn and Evans 2010). This explanation is tribologically naive in that it suggests that the hardness of the glacial 'tools' suddenly decreased or that they began lacking asperities and thus allowed the establishment of a highly polished exterior. Another explanation proposes that surficial crystals have been bent in the direction of glacial slip, that the outermost 5 μm has been intensively deformed, and accretion of 'sheared wear material' has been deposited (Siman-Tov et al. 2017). How this 'rock flour paste and silica gel' could have morphed into a surface accretion harder than the supporting granodiorite remains unexplained, and the authors are themselves puzzled why the exfoliating substrate is much thicker than the very thin modified layer they perceive. Glacial polish can be preserved almost perfectly for over 300 million years (Beaumont and Bednarik 2013; Ward et al. 2014), being extremely weathering resistant.

Similar shortcomings apply to the explanations for other laminarly modified rock, such as fault mirrors, aeolian 'glazing' as found on ventifacts and identical surface modifications deriving from fluvial battery (Bednarik 2019a). Rationalisations for them tend to be vague and inadequate or refutable by empirical observations. Siman-Tov et al. (2017) quite correctly note that the similarities between glacial polish and fault mirrors seem puzzling because one forms at the rock's surface, the other deep within the Earth's crust. Therefore, a universal explanation of such phenomena seemed required. It was discovered not by geological investigation but by researching anthropogenic rock markings.

Cupules are spherical dome or spherical cap-shaped (rather than 'hemispherical'), roughly circular depressions on rock created by percussion with hammerstones (Bednarik 2008). They represent the most numerous rock art motif known and occur on many lithologies, including the hardest, such as white crystalline quartz and well-metamorphosed quartzite. Replication experiments on the latter rock type have shown that it requires tens of thousands of well-directed blows to create a single but still relatively shallow cupule on this material (Kumar and Krishna 2014). It involves a massive and very focused application of kinetic energy on an area measuring only a few square centimetres. Field microscopy revealed that the floor of some of the most intensively pounded cupules had been converted to a denser and more weathering-resistant state than the rock matrix. We first observed this phenomenon at a Bolivian site, later at sites in six other countries and on several rock types. Currently, it has been recorded in cupules on quartzite, silica sandstone, silica-rich

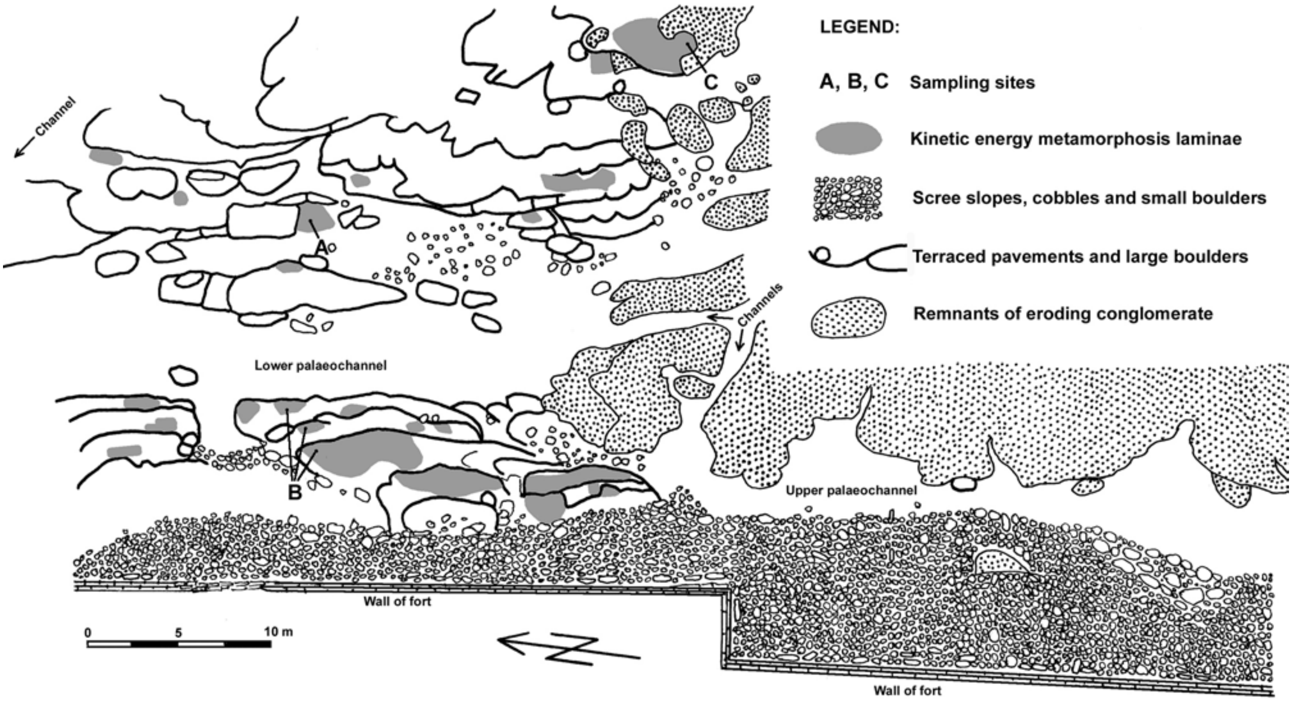

Figure 16. *The Indragarh Paleochannel KEM site near Bhanpura, Madhya Pradesh, India.*

schist and granite (Bednarik 2015, 2016c, 2019a, 2019d; Jin and Chao 2019).

Tribological study using light microscopy, scanning electron microscopy, thin-sectioning and determination of the chemical composition of minor inclusions showed that the intensive application of kinetic energy had converted the impacted surface by re-crystallisation and ductilisation (Bednarik 2019a). The conversion process occurs in three broadly defined stages that can be detected as layers beneath the most intensively modified surface layer (stage 3, in which amorphous silica cement has been converted to quartz). The presence of layers 2 and 1, which may add up to 20 mm thickness, explains what puzzled Siman-Tov et al. (2017): why the exfoliating lamina is much thicker than the fully modified surface layer. Being partially converted, it is also more resistant to weathering than the matrix rock and adheres to the surficial tectonite when that exfoliates (Fig. 15).

Once the process of kinetic energy metamorphosis (KEM) was identified, it became apparent that humans are not the only agents that may direct great cumulative energy to thin laminae of rock. There are two possible scenarios where this can occur purely naturally: on rock surfaces or within the rock, along faults. Our initial motivation to direct our attention to these alternative possibilities was purely practical. As we did not wish to physically intervene with cupules, protected cultural heritage features, it was impossible to secure samples for laboratory work. However, many years ago, we had discovered a palaeochannel near the cupule site Daraki-Chattan where fluvially induced KEM products occur in great profusion. The Indragarh Paleochannel is located on the remnants of a quartzite plateau, surviving as a hanging valley over 175 m, but now located high above the surrounding valleys. It had been covered by several substantial strata of cobble-grade, silicified conglomerate, but many millions of years ago, it was a high-kinetic energy river. Near a small former waterfall, vast quantities of quartzite cobble bedload had been rafted along a chute. They impacted bedrock exposures, converting more than 50 m^2 of surface to tectonite (Fig. 16). This site was studied intensively in 2016 with the support of Giriraj Kumar, and as it is not a cultural monument, numerous samples were secured from it (Bednarik 2019a: 217–221). Much of what we now know about KEM derives from these samples.

Glacial polish is not a consequence of accretion following distortion of a very thin surface layer but is also the result of a conversion of rock as enormous amounts of kinetic energy are brought to bear on it. Although we have conducted only preliminary investigations of aeolian surface sheen, we expect that it will similarly be shown to be attributable to KEM of the surface layer.

In the case of conversion products at faults, we have distinguished between fault mirrors and randomly oriented KEM phenomena. Fault mirrors occur along essentially planar fractures or discontinuities in a rock mass across which there has been relative displacement. The strain rate required for such movement may involve very high energy levels to release the stress, which is then discharged entirely at the fault plane. This is presumed to effect KEM conversion in a very narrow zone, resulting in a fault mirror, as illustrated previously (Bednarik 2016c: Fig 16). Identical but randomly distributed tectonite formations (see Bednarik 2016c: Fig. 17 for example) may be planar or curvi-planar. They occur in siliceous arenite that has in the geological past been subjected to intensive deformation and ductilisation some kilometres below the crust's surface. It is the result of tremendous pressure and application of kinetic energy and, therefore, also attributable to KEM. It follows that the discovery of KEM products in cupules has led to the explanation of several geological phenomena that had so far not been elucidated or clarified adequately. This is the first time rock art research has significantly contributed to geological science.

8. Discussion

This paper illustrates the benefits of interdisciplinary approaches to the study of rock markings, in which tribology, not traditionally applied to the topic, is of greater relevance than archaeology or geology (Bednarik 2019a, 2020a). Compressive-tensile rock markings, kinetic tree root markings and kinetic energy metamorphosis are entirely tribological phenomena, yet tribology as a discipline has indicated a limited interest in non-technological applications of its scientific principles. On the other hand, archaeology and geology have shown little inclination to apply tribology in their respective disciplines. This academic compartmentalisation prevents much progress in the sciences, as illustrated by the findings reported here. In all three cases cited, universally applicable laws were identified that have considerable consequences for understanding geomorphology. These changes to rock surfaces, and in some cases the rock's interior, are apparently quite common in the small-scale evolution of landforms, which happen to be particularly relevant to the science of rock art. Indeed, seen from a geomorphological perspective, petroglyphs themselves are merely a form of 'biological weathering'.

It is reassuring that the taxonomy of rock markings we introduced in 1994 has stood the test of time, having been confirmed by all the newly reported phenomena that now need to be included. We had envisaged that the system would be scrutinised by peer review (Bednarik 1994: 42), but the present paper appears to be its only review so far. One shortcoming is readily evident in this system: it deals entirely with phenomena resembling rock art produced by a reductive method, i.e. petroglyphs. However, petroglyphs account for only about one-half of the planet's rock art. Pictograms, created by an additive method, need to be addressed differently, but it is amply evident that they are rarely mistaken for natural rock markings or vice versa. The original classification (Bednarik 1994) reviewed the issue briefly and noted only two published instances when natural colour markings on rock had been mistakenly described as applied red pigment. In one example, the red colour was caused by the heat of a fire (reduction of goethite to haematite); in the other, it was a natural weathering product of iron oxides. This compares very favourably with the rampant number of petroglyph misidentification cases that apply to millions of individual features or motifs globally.

The present paper introduces several types of rock markings that were found not to be anthropogenic, and it is thought-provoking to note that the explanation of a few of them is so outlandish that some geologists remain sceptical. The ability of tree roots to create rock grooves mechanically is one example. The thought of spherical concretions formed by organic decay before the lithification of sandstone occurs is, at first glance, quite bizarre — especially their ability to expand/extend outwards within their sedimentary matrix as long as they are supplied by organic carbon from within. Such explanations are truly *stranger than fiction*, but they are, nevertheless, both rational and applicable.

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