KEYWORDS: *Weathering – Geometry – Patination – Taphonomy – Petroglyph – Stone tool*

THE USE OF WEATHERING INDICES IN ROCK ART SCIENCE AND ARCHAEOLOGY

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Abstract. Research into the types and processes of rock weathering plays a key role in two areas in the field of rock art studies. First, it is crucial to issues of conservation and preservation. This paper focuses on the second area of interest in weathering phenomena, in providing evidence supporting the efforts of estimating the age of rock art, most especially that of petroglyphs. In this area, weathering is arguably the most promising variable in the 'direct dating' methodology that has been developed in recent decades. The reasons for the failures of alternative dating methods are explored, leading to the proposition that weathering and related features offer the most reliable basis for future work in this field. Some of this new methodology is discussed within the overall context of the considerable difficulties generally experienced in rock art dating. Particular attention is given to the geometry of weathering, which is often most amenable to quantification, including that of the taphonomy of stone tools and rockshelters.

Introduction

Rocks form through many different processes, but once exposed at the earth's surface they deteriorate through the universal process of weathering. While the rate of rock formation differs enormously, from the rapid crystallisation of volcanic rocks to metamorphic modification that can extend over geological epochs of many million years, the courses weathering takes are of a more limited spectrum of time. Nevertheless, there are considerable differences in the duration a given amount of weathering will take, depending on the rock type and the ambient conditions of moisture, climate, pH and so forth. The lithosphere's principal agent of rock weathering is water, most especially derived from precipitation. Water occurs within pores or cracks within rocks in gravitational, capillary, or hygroscopic form (as thin films on grains); or it is held in chemical combination in some rock-forming minerals. Apart from oxygen, the two most abundant chemical elements in the lithosphere are silicon and aluminium, and the most abundant minerals are quartz and aluminosilicates of various kinds. As quartz is almost immune to weathering in most surficial conditions, chemical weathering is principally concerned with aluminosilicate chemistry, and the principal products of rock weathering are the minerals aluminosilicates decay to, clays and various oxides. In general, the processes are essentially solution, hydration, hydrolysis, ion exchange (including chelation), oxidation, reduction, and carbonation.

Chemical weathering is almost invariably conditional upon the presence of water; even oxidation of minerals by gaseous oxygen appears to require water as an intermediary agent (Keller 1957). Such weathering is usually by means of very complex processes that are frequently rendered more intricate by the ability of many of their own products to accelerate them. For instance, a by-product of the oxidation of pyrite is sulphuric acid, which readily reacts with numerous minerals; or clays, themselves the result of weathering, will induce hydrolysis with their hydrogen ions. Atmospheric water travels within the surficial weathered and porous zones of the lithosphere by means of gravity, capillarity or heat-induced circulation. Although atmospheric precipitation can range from pH 3 to pH 9, most weathering reactions occur in the acidic range.

This paper focuses on the quantification of the products of these processes as they are of relevance to the scientific study of rock art and archaeology, and of anthropic rock surfaces generally. The morphological effects that are perhaps of the greatest significance to the rock art researcher are surface retreat, saprolithisation (the initial decay phase of rock) and the development of weathering rinds.

It is well known that rock surfaces retreat with time, be it by solution (Acker and Bricker 1992; Busenberg and Clemency 1976; Lin and Clemency 1981; Oxburgh et al. 1994; Rimstidt and Barnes 1980; Williamson and

Rimstidt 1994), physical wear, or a combination of both. But to render weathering processes useful for rock art age estimation ('dating'), ways need to be found to quantify them: at what rates, relative to rock type and ambient environment, do they occur, and how can they be measured and calibrated? Much the same applies to the potential ability of countering rock weathering in the quest to preserve rock art or other immovable cultural heritage made of rock: the processes of deterioration need to be understood thoroughly before intervention to arrest them can be considered.

Susceptibility to chemical weathering varies greatly among common minerals (Chou et al. 1989; Rimstidt and Barnes 1980; Bednarik 2001: 61). The rates of surface retreat of common rock types have been determined from monumental masonry of known ages in Europe. They vary greatly according to rock composition and climate. In the ambient conditions of central Europe these empirically determined ranges are, in millimetres per one thousand years:

Sandstone	5 – 50
Limestone	2 – 20
Schist	1 – 10
Marble	0.4 – 5
Dolomite	0.3 – 2.5
Serpentine	0.25 – 2.5
Dolerite, porphyry	0.2 – 2
Gabbro	0.1 – 1.5
Diorite	0.1 – 1
Quartzite	0.1 – 0.5
Granite	0.05 – 0.2

It is therefore unrealistic, for example, to expect to find Pleistocene petroglyphs on a schist panel that was always fully exposed to precipitation, schist also being up to two orders of magnitude more erodible than quartzite (Attal and Lavé 2005: 156, 159). The abrasion coefficient of schist is 16, that of quartzite is 0.15. Preservation would be significantly better in an arid or Arctic climate, where the four last-listed rock types might show minimal surface deterioration over ten millennia. Indeed, petroglyphs on granite surfaces in northern Karelia are relatively well preserved after 4000 years (Bednarik 1992), while historical, dated inscriptions on schist in the Côa valley of Portugal (Bednarik 1995) or Siega Verde in western Spain (Bednarik 2009a) are barely decipherable after a few centuries. In the arid Pilbara of north-western Australia, petroglyphs have survived for many millennia on gabbro, and for several tens of thousands of years on granite (Bednarik 2002a). These kinds of observations assist the rock art student greatly in gaining an initial understanding of the potential antiquity of petroglyphs.

This raises one of the most fundamental issues in estimating the age of petroglyphs of unknown antiquity. The longevity of a petroglyph is roughly proportional to the time it took to produce it. Depending primarily on the rock type and its weathering state, it can take from about one minute to several days or a week to create one cupule, for instance (Bednarik 1998a; Kumar 2010). Similarly, it can take several hundred times as long to efface a petroglyph on an extremely resistant rock, than it would take nature to erase an identical motif on a highly susceptible rock type (see concluding paragraph of this paper).

The second type of weathering effect, the formation of saprolite, is of less interest to rock art science than surface retreat, but still important. Decay of rock begins with the formation of a carious zone around individual grains or crystals where reaction with water occurs, and progressively leads to breakdown into detrital material (Keller 1957). Feldspars weather to clay minerals, typically kaolinite, and in some situations even to the aluminium hydroxide mineral gibbsite. Quartz is largely unaltered in the weathering environment, while ferromagnesian minerals such as pyroxene and amphibole weather to iron oxides and montmorillonite clays. Of particular interest is the saprolithisation of sandstone as interstitial amorphous silica is leached out (it can be ten to twenty times as soluble as quartz; Krauskopf 1956, 1967; Greenberg 1957; Lovering 1959) and the detrital material disintegrates into quartz sand. This is important in appreciating the difficulties of applying thermoluminescence dating to the resulting sediments (cf. Fullagar et al. 1996; Roberts et al. 1998).

Of particular relevance to rock art science is the formation of weathering rinds, which are typically distinct zones of alteration with their thickness a function of exposure time (Bednarik 2001a). If the process could be calibrated against time it would probably yield rough estimates of geomorphic exposure ages. Černohouz and Solč (1966) attempted this with basalts, claiming to obtain reliability to within 10%–20%, but there has been no adequate attempt to pursue this possibility further (Colman and Pierce 1981). Although the hypothesis of Černohouz and Solč was subsequently refuted (in the sense that they assumed uniformity in the thickness of the weathering zone, which in fact does not apply; Bednarik 1992), they correctly recognised that weathering rind thickness is a function of surface geometry, and that this aspect is the cause of wane formation.

Weathering rinds are zones of oxidation, hydration or solution that form parallel to rock surfaces and their thickness is a function of time (Carroll 1974; Colman 1981; Colman and Pierce 1981; Crook 1986; Gellatly 1984). The growth rate of weathering rinds can be quantified for a given rock type under given climatic conditions if it can be calibrated by another dating method, but surface rinds often suffer from mass loss due to abrasion, erosion, frost action, *Salzsprengung* ('saltdamp') or exfoliation, which introduces a major error source for age determination. In addition, surface shape and aspect as well as petrological variations within the rock also affect the process. It may be preferable to measure subsurface rinds on submerged rock, as Colman and Pierce (1981) did, examining a large sample of clasts from B-horizons of deposits. They propose a logarithmic function in the form of

$$d = \log(a + bt), \quad (1)$$

where a and b are constants, d is the rind thickness and time t can be determined. Although this is of limited use in estimating the age of petroglyphs, it does imply that approximate quantification for dating purposes should be possible.

One of the principal difficulties in studying rinds is that the need for destructive sampling normally excludes such methods from consideration in the case of rock art. The Schmidt hammer may be a suitable non-destructive technique for measuring the degree of rock surface weathering (Birkeland et al. 1979; Burke and Birkeland 1979; McCarroll 1991). This instrument was originally designed to measure the surface hardness of concrete, but it has also been widely used on natural rock (Day and Goudie 1977). The Schmidt hammer has had limited use in rock art research (Campbell 1991; Sjöberg 1994; for a preliminary but unsubstantiated and inconclusive attempt, see Pope 2000), nor have there been any serious attempts so far to employ weathering rinds in estimating rock art ages in any more than the most cursory fashion. Clearly there is more research required in this area.

A relevant potential analytical method that can be useful in combination with both weathering rind and patination analyses derives from the spalling of boulders bearing rock art, be it by *Kernsprung*, insolation, kinetic impact, lightning strike or through grass, brush or forest fires. (The term 'boulder' throughout this paper refers to the granulometric definition, and is not intended to relate to its history.) Vast numbers of petroglyphs throughout the world occur on various types of rock that have been subjected to gradual size reduction by spalling. The various types of fracture can be recognised readily. Lightning generally strikes at the highest point of a rock outcrop or hill, and the impact area is typically discoloured or glazed where superficial vitrification occurred. Lightning-induced fractures resemble impact fractures, commonly with a bulb of percussion or featuring radial stress lines. Spalling caused by brush fire is extremely common in some regions (Blackwelder 1927; Emery 1944; Rosenfeld 1985: 33; Selkirk and Adamson 1981; Gunn and Whear 2009; Gunn 2011) and results in thin flakes up to 30 cm diameter, with a thickness of one or two centimetres, tapering towards the sharp edges due to the typically convex shape. Both insolation and fire spalling gradually remove protruding aspects and acute edges, essentially reducing clasts of any shape to a sub-spherical form (Fig. 1).

The progressive reduction of a rock through fracture, by whatever spalling process, results in many convex scars, often truncated by other scars. The chronological sequence of the spalling events can be reconstructed, as schematically depicted in Bednarik (2011a: Fig. 1). Each relevant spalling scar needs to be identified and its chronological position relative

Figure 1. *Typical spalling scars caused by brushfire, destroying petroglyphs, eastern Pilbara, Australia.*

to all other types of surface phenomena, including intentional anthropic marks (i.e. rock art), needs to be recorded.

Clarifying patination

One of the key factors in chronologically sequencing the various surface facets of a boulder is that faces of different ages commonly bear different degrees of patination. The word patina, in rock art science, defines a visually obvious surface feature that differs from the unaltered rock in colour or chemical composition. It is a collective, almost colloquial term for a variety of phenomena, all acquired gradually over time. Hence they are an indication of antiquity, as researchers have appreciated for centuries (e.g. Belzoni 1820). However, the use of patinae in age estimation has so far remained difficult and controversial, at least partly because of misunderstandings. For instance, there is a well-known polemic concerning the 'repatination' (this is a misnomer: freshly exposed rock does not 'repatinate'; it has never been patinated before) of petroglyphs: if a groove has been cut into the weathering rind beneath a ferromanganese accretion, will its 'repatination' occur at an accelerated rate relative to unaltered rock? Also, the applicability of the term to quite disparate phenomena has been responsible for erroneous views. Although most forms of patination are not, strictly speaking, weathering phenomena, some are, and others relate closely to them. Therefore these issues need to be considered here.

Unless the type of surface alteration defined as patina is identified, archaeological controversies concerning such phenomena are predictable. If the principal component of the patina were rock varnish, patination would proceed independent of the substrate, but if the process relied largely on the oxidation of bedrock iron cations, then it would be affected by the state of the exposed substrate. To make this judgment it is essential to analyse the patination products responsible for the macroscopic appearance of the surface.

The name *patina* was initially intended to refer to copper carbonate or copper sulphate, the corrosion

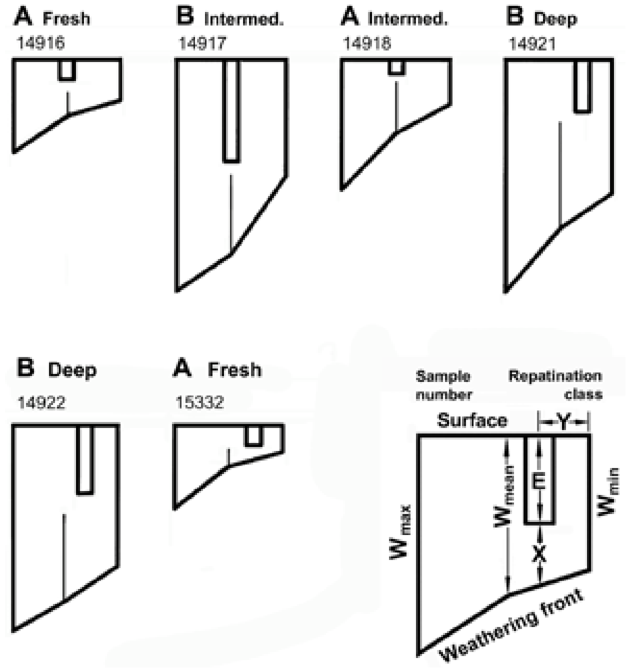

***Figure 2.** Schematic comparison of six core samples from variously weathered petroglyphs on Depuch Island, Western Australia (after Bednarik 1979).*

skin that develops on copper and its alloys (*verdigris*), deriving originally from the Latin word for a 'shallow dish' (*OED*). It came to include the sheen or wear polish on antique surfaces, and was extended to cutaneous alteration of rocks or stone tools that seemed to indicate great age. Thus the surface skins defined as patination could be the result of bleaching or leaching (e.g. of sedimentary silica; Bednarik 1980), limonite staining (Goodwin 1960), mineral accretion (e.g. by rock varnish; Engel and Sharp 1958), chemical alteration of substrate components (most rock weathering processes are candidates), and abrasion or polish (e.g. by sediment grains or biological agents, such as cave bears). All these processes are slow and gradual, resulting in cumulative products that represent lengthy time spans. Patinae have long been recognised as potential means of estimating the age of petroglyphs (e.g. by Belzoni in 1820, observing the varying degrees of patination of petroglyphs on the Nile in Upper Egypt), but until recently the difficulties of quantifying and calibrating the processes involved have fostered the view that these are too intractable for quantification (but see Bednarik 2009b). Such scientific utilisation of the phenomena is renderd particularly difficult by the co-occurrence of different patination processes. Therefore what is simplistically called 'patination' is in fact the macroscopically visible outcome of several factors and their interplay.

Changes in rock surface composition can either involve deposition of extraneous matter (e.g. airborne material) or they can be attributable to endogenous alteration products. In some cases local and introduced matter may have contributed, e.g. the oxalate patina on marble statues (Del Monte and Sabbioni 1987; Lazzarini and Salvadori 1989). The most commonly encountered form of patination is a dark-brown coating of rock surfaces, particularly in arid and semi-arid regions, which derives its appearance primarily from iron compounds. It is always the product of multiple processes and frequently combines exogenous and endogenous components. It is often incorrectly defined either as a rock varnish (formerly desert varnish) or as an oxidation product.

The term rock varnish should be limited to a very thin (<0.5 mm), often reflective ferromanganese skin that covers even rocks entirely free of its contributing cations, sich as iron and manganese (Engel and Sharp 1958). It can be found, for instance, on pure quartz, which indicates its extraneous origin. Cation-consuming micro-organisms have long been implicated in its formation (Francis 1920; Scheffer et al. 1963; Bednarik 1979). Other deposits of similar composition and appearance occur commonly on rock surfaces and should be described as *dunkle Rinden* (Walther 1891) if their more precise nature has not been established by analysis or microscopy. This term defines all dark rinds on rocks, irrespective of their nature.

The graphic convention shown in Figure 2 is useful in defining issues concerning the relationships of weathering depths, petroglyph depths and patination (for another example, see Bednarik 2007: Fig. 18). This image depicts these relationships for six core samples collected from petroglyphs at Depuch Island, Western Australia (Trendall 1964). Crawford (1964: 50) classified two petroglyphs each as being of 'fresh', 'intermediate' and 'deep' patination, and misinterpreted Trendall's data as indicating that these groups corresponded to age groups. However, the graphic convention introduced in the 1970s facilitates a better understanding of the issues. It compares the mean weathering depth with maximum and minimum weathering depth of each petroglyph, with the groove depth (*E*), the weathering zone thickness left beneath the petroglyph (*X*), and the position of the groove depth relative to weathering depth (*Y*). The shape of the line representing the weathering front reflects the relationship of median and mean weathering depth, and these diagrams demonstrate the lack of correlation between 'repatination' intensity. Although the three samples of heavy patination coincide with those of deeply weathered rock they also correspond with the most deeply engraved. Figure 2 demonstrates the concurrence of deep patination and greater distance between groove bottom and weathering front. That dimension increases as a function of time (because the weathering front advances), while aeolian and other erosion reduce groove depth progressively. Therefore of the oldest petroglyphs only the most deeply engraved tend to remain discernible, while those of shallow depth have become unintelligible, as demanded by taphonomic logic (Bednarik 1994a).

Crusts of the *dunkle Rinden* type (iron-rich accretions) are the most common kind of patination encoun-

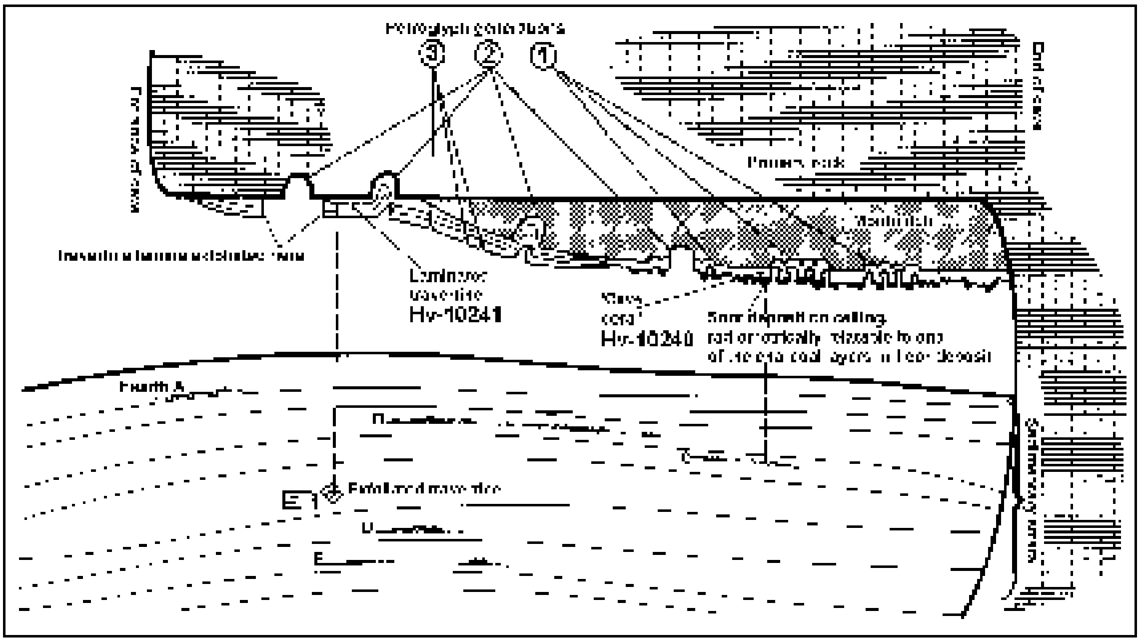

Figure 3. *Schematic depiction of dating framework for Malangine Cave, South Australia (after Bednarik 1984).*

tered with petroglyphs. Their colour is determined primarily by several iron compounds that are subject to progressive and continuous modification. For instance magnetite is metastable with respect to maghemite, which in turn can be altered to haematite in ambient conditions at the earth's surface, e.g. by solar radiation. Haematite can also be derived through dehydration of lepidocrocite (γ-FeO[OH]), and heat can dehydrate even the much more stable goethite to haematite, effecting the characteristic colour changes. As the most stable form of Fe_2O_3 at surficial conditions, haematite content tends to proportionally increase with time, as it also does in iron-rich paint residues, even though it can be reduced to magnetite by high temperature.

The colour of iron compounds can also be determined by degree of agglomeration or particle size. While it is thus a function of the combination and state primarily of iron salts, especially through the taphonomy favouring haematite, other cations are also present, such as manganese oxides.

These crusts comprise significant amounts of clay and aeolian detritus, demonstrating that few if any of their components derive from conversion (e.g. oxidation) of host rock components. Quartz, tourmaline and other crystal grains, plant matter and even charcoal fragments have been observed in these accretions (Bednarik 2007), caked together by iron compounds and amorphous silica. Where they are subjected to modification by rainwater, the formation of distinctively 'laced' or 'terraced' morphologies is favoured (Bednarik 2007: Fig. 21). Although quite patchy at the microscopic level, in the macroscopic sense these deposits form fairly consistently as a function of time. Engraved dates in the Australian Pilbara have shown that an incipient film becomes evident after a fresh surface has been exposed for 30–40 years, and after about 100 years, the deposit reaches a thickness locally of 30–50 μm, or 100–150 μm after 230 years (Bednarik 2002a).

Just as rock varnish and other *dunkle Rinden* need to be recorded where they are related to petroglyphs, the same applies to a range of further accretionary mineral deposits. Thin ferromanganese patinae grade into thicker deposits of similar composition, and mineral skins and crusts consisting principally of silicas, oxalates and carbonates occur commonly under or over rock art. Where such mineral deposits are layered, nano-stratigraphical excavation has been successfully applied to separate strata under binocular microscopes for analysis (e.g. in ferromanganese accretions; Bednarik 1979). Rock art may be sandwiched between such layers which may contain datable matter.

The stratification of datable mineral accretions over and under petroglyphs was first used over thirty years ago, analysing layers of reprecipitated carbonates in Malangine Cave, South Australia (Bednarik 1981, 1984, 1985), in the first 'direct dating' of rock art. Calcite, aragonite and dolomite are readily converted to bicarbonates in an aqueous solution of carbon dioxide, and then mobilised and reprecipitated in a great variety of forms. Cutaneous travertine deposits up to several centimetres thick occur commonly in limestone caves (Fig. 3). These formations may be faintly layered, and occasionally they contain petroglyphs (e.g. in several caves near Mount Gambier), the outlines of which remain visible on the surface. The rock art as such is then sandwiched between two of the strata, having at some stage been engraved into the developing accretionary deposit. These carbonate speleothems are datable (but cf. Bednarik 1999 for qualifications) by several methods, especially carbon isotope and uranium series analysis. Reprecipitated calcite crusts are not limited to caves, they occur commonly in semi-arid regions in pedogenetic form as a light-coloured skin at the uppermost level of calcareous sediment. Deposited over other weathering and patination phenomena, sometimes over petroglyphs (Bednarik 1987), they might also be datable.

Silica skin forms through the precipitation of amorphous silica from aqueous solution of silicic acid ($Si[OH]_4$). Like rock varnish it tends to be very thin (mostly <0.4 mm) and is usually of light colour or translucent, sometimes brown or grey, and of vermiform surface texture. Like rock varnish it can contain a great variety of inclusions, such as bacteria, pollen, fungi and algae, which may yield AMS (accelerator mass spectrometry) dates, and also numerous mineral substances occurring as clays and silts. In a classical stratigraphic study of siliceous accretions, Watchman (1996) documented the occurrence of two layers at Penascosa Panel 7 in the lower Côa valley of northern Portugal. The older is of whitish colour, the younger is of a silty brown appearance, consisting largely of weathered schist detritus and platy mica fragments. An animal figure abraded into Panel 7 cuts through the white layer, whereas the superimposed brown deposit also covers the engraved groove. Consequently the petroglyph postdates the older and predates the younger crust, and its age should lie between carbon dates Watchman derived from the two. Recently organics in a thoroughly silicified wasp nest underlying rock art in Cape York Peninsula have been dated to the Pleistocene by AMS (Bednarik in prep.).

In contrast to silicas, oxalates are not only datable through the organic inclusions they may contain, but the oxalate itself is datable by virtue of being a salt of oxalic acid ($H_2C_2O_4$), a crystalline organic acid containing ultimately atmospheric carbon and therefore ^{14}C (Watchman 1990). Oxalates can be found as whewellite ($CaC_2O_4 \cdot H_2O$) and weddellite ($CaC_2O_4 \cdot 2H_2O$), and are generally darker than silica skins (dusty-brown to black) as well as thicker (>1 mm). Their dating potential has already provided useful results (Watchman 1992a, 2000). The most spectacular example of a dated sequence of oxalate strata is from a 2.11-mm-thick nano-stratigraphy in Walkunder Arch Cave, northern Queensland, that yielded ten AMS carbon isotope determinations ranging sequentially from c. 29 700 to 3300 years BP (Campbell 2000; Watchman 2000).

The dating of rock art

None of the geomorphological or geochemical methods of estimating the age of rock art has much precision and some may seem like rather desperate measures (Table 1). This raises the question: are there better, more precise methods?

The answer is that all of the many approaches that have been tried have problems. The most popular method has been determination of the carbon isotope ratios of paint residues, thought to be derived either from organic components (binders, brush fibres, incidental inclusions) or from charcoal pigment. However, all rock surfaces, including accretionary materials applied as paint, contain organic material of some types. Micro-organisms occur in rock kilometres below the earth's surface, but the greatest concentrations are near the surface, and the carbon system has long been demonstrated as being open (Bednarik 1979; cf. Nelson 1993; Ridges et al. 2000). Therefore *any* sample from a rock surface is likely to yield a ^{14}C age, but this may be a random number that does not reflect the age of any rock art that happens to be present. If the paint traces were concealed by a natural mineral skin, of silica or oxalate, soon after the painting was executed, the chances of securing reasonably precise radiocarbon results increase significantly, as Watchman has demonstrated. But isolated ^{14}C dates from unprotected paint residues provide no credible age estimates, unless the paint was made with charcoal. Such black paintings, stencils or drawings are still just as contaminated by other organic matter present on any rock panel, but because the charcoal is such a dominant component in such samples the error margin is not expected to be as great. By far the most reliable ^{14}C dates from rock art are those derived from beeswax pictograms, because there is always adequate datable substance available, and the physical properties of the beeswax render it unlikely that it would have been used in any but nearly fresh condition. Therefore the time of the production of the wax, which approximates its radiocarbon age, is unlikely to differ significantly from the time the art was created (Nelson et al. 1995; Taçon and Garde 2000; Bednarik 2001b). Nelson (2000) reports radiocarbon ages from 137 figures at sixteen sites in the Northern Territory. However, beeswax rock art is limited to very few regions, having been reported only from western Arnhem Land (Brandl 1968; Chaloupka 1993), Kimberley (Welch 1995), Reynolds River, Keep River and Groote Eylandt, i.e. only from northern Australia.

Nevertheless, concerning the credibility of radiocarbon assays there are still other issues to be considered. Firstly, the carbon isotopes of charcoal can at best reflect the conditions at the time of assimilation, i.e. when the tree in question was alive and absorbed CO_2 from the atmosphere (Bednarik 1994b, 1996, 2000a). This must have preceded the paint application by perhaps as much as several centuries (Table 2). Secondly, the charcoal may not have been fresh at the time it was used. Charcoal often occurs in profusion on the floor of shelters and caves, some of it thousands of years old, and cases have been reported where one motif yielded two dramatically different carbon results, separated by up to tens of millennia (e.g. McDonald et al. 1990; David et al. 1999). Thirdly, it has been suggested that 'fossil wood' may have been burnt (Schiffer 1986; Fetterman 1996). Although this may seem unlikely in most cases, the wood used may certainly have been several centuries old, especially in arid regions.

These major impediments are in addition to the numerous qualifications inherent in the radiocarbon method itself (Fig. 4). The atmospheric concentrations

'Dating' method	Attributes						
	Access	Ease	Interv.	Target	Contam.	Precisn	Reliab.
Iconography	3	3	3	0	-	0	1
Style	3	3	3	0	-	0	1
Excavation	2	3	3	0	0	1	2
^{14}C of carbonate	2	2	2	0	0	3	1
U-series of carbonate	2	1	2	0	0	2	1
U-series, ferromanganese	2	1	1	0	0	2	?
^{14}C, ferromanganese	2	1	1	0	0	3	0
^{14}C of oxalate	2	1	1	0	1	2	2
^{14}C of non-carbon paint	2	2	1	0	0	3	0
^{14}C of charcoal paint	2	2	1	2	1	3	2
^{14}C of identified matter	2	1	1	2	1	3	3
^{14}C of beeswax	2	2	2	3	2	3	3
X-ray fluorescence	2	2	3	0	0	2	?
Racemisation	1	1	1	1	1	?	?
Cosmogenic radiation	1	1	1	0	0	2	0
OSL analysis insect nests	1	2	2	0	0	2	1
Lichenometry	3	3	3	0	-	1	3
Surface retreat	3	3	3	1	-	1	3
Microerosion analysis	3	3	3	3	3	1	3
Cation ratio of accretion	1	2	2	0	0	0	0
Fluvial erosion wear	3	3	3	1	-	1	3
Paint drips/grains in soil*	2	3	3	1	1	2	1
Colorimetry of patina	3	3	3	3	3	2	3

* Refers to paint drips from pictograms; or grains, dust or rock chips from petroglyphs.

Access. = Accessibility of the method to most researchers
Ease = Ease of application of method
Interv. = Degree of physical intervention in rock art
Target = Closeness of dating criterion to target event
Contam. = Possibility of contamination of samples
Precisn = Anticipated precision of the result
Reliab. = Anticipated reliability of the result

Table 1. *Schedule of tentative ratings of methods used to estimate the ages of rock art, highest numbers for attributes representing the most favourable conditions.*

<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Sequential events</td><td>Assimilation of carbon</td><td rowspan="2">Death of tree or separation of limb</td><td>Carbonisation of wood</td><td>Painting</td><td>'Dating'</td><td>'Archaeological date'</td></tr>
<tr><td>Effect</td><td>^{14}C 'date'</td><td>Wood burnt</td><td>Charcoal used</td><td>Charcoal analysed</td><td>Interpretation of result</td></tr>
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Table 2. *The sequential events relating to the dating of charcoal pigment of a rock painting. The purported 'date' relates to event 1, not to event 4; in fact, the two events may be separated by millennia.*

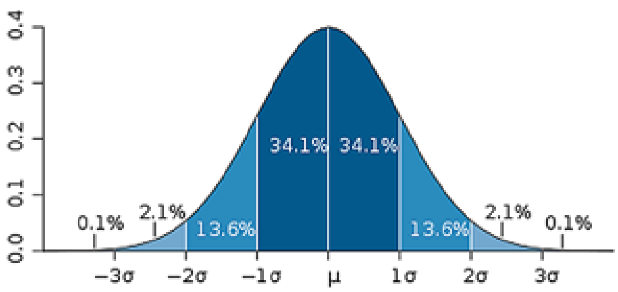

Figure 4. *The probability curve for carbon isotope data being true. Dark blue is less than one standard deviation from the mean. For the normal distribution, this accounts for about 68% of the set, while two standard deviations from the mean (medium and dark blue) account for about 95%, and three standard deviations (light, medium, and dark blue) account for about 99.7%.*

of carbon isotopes in the distant past are unknown to us, because they are the result of cosmogenic radiation, which fluctuates over time. The ^{14}C decay rate to nitrogen we use in all calculations, Libby's original half-life estimate of 5568 years, is incorrect; we think the true figure is 5733 years. But in any case, carbon isotope analysis yields radiocarbon years, not absolute or calendar years. To 'calibrate' them is not realistically feasible (Muzzolini 1999), yet it is often attempted in archaeology. Despite these and many other limitations (e.g. Watchman 1998; Hedges et al. 1998; Armitage et al. 1999) of the radiocarbon method, archaeology relies heavily on it, as does rock art dating. And yet it provides no certainty, no reliability, and often produces completely false results. Other supposedly reliable methods used in rock art 'dating' are probably far less credible than those derived from carbon isotope analysis. The determination of cosmogenic radiation nuclides (Davis and Schaeffer 1955), for instance, has been used (Williams-Thorpe et al. 1995; Phillips et al. 1997), providing ages that are probably random numbers. This is particularly so if the highly mobile ^{36}Cl nuclide is used and self-contradictory assumptions are made (Bednarik 1998b). Similarly, cation leaching of rock varnish (Dorn 1983, 1986; Nobbs and Dorn 1988; Francis et al. 1993) is based on several logical errors and has been falsified (Watchman 1992b). Besides the inappropriate method of calibration, the use of carbon analysis of ferromanganese accretions (which always yields false dates because of the open carbon system; Bednarik 1979), it has many procedural or logical flaws. For instance, the varnishes are highly variable, spatially (at the microscopic scale) and temporally, because they are dynamic features subject to frequent changes, e.g. through the involvement of micro-organisms. The proximity of soil, oxalate, amorphous silica, or organic matter all affect cation ratios, as do lichens, fungi, ambient pH, water run-off, and surface aspect-derived relative exposure to leaching or weathering. Cation scavenging by micro-organisms has been demonstrated by SEM photographs of varnish micro-sections, even by Dorn himself. Moreover, the individual solubility of the targeted cations, Ti, Ca and K, is not relevant, because they occur in minerals, sometimes within the same compounds (e.g. titanite), and it is the solubility of these minerals that is relevant. Consequently Dorn's spectral-analytical results from his samples are irrelevant random data.

Luminescence dating has been applied to rock art in a few instances, leading to a refutation in the case of the Jinmium cupules in northern Australia (Fullagar et al. 1996; cf. Roberts et al. 1998 for correction). A single optically stimulated luminescence result from a wasp nest superimposed over paint residues at a Kimberley site remains controversial (Roberts et al. 1997, 2000). It is contradicted by other age estimations (Watchman et al. 1997) and its magnitude of about 17000 years seems to be wrong on logical grounds: it would be the world's only case of a figurative Pleistocene rock painting above ground. It is also to be questioned why the method was not combined with radiocarbon analysis, because as recently demonstrated, silicified ancient wasp nests can contain adequate organic matter to check an OSL result (Bednarik in prep.) by the more reliable method. Similarly, the only attempt to use amino acid racemisation (Denninger 1971) has been refuted, although it has been found that amino acid residues can be preserved in rock paints (McCarthy et al. 1994), and the method may warrant further testing.

When we consider alternative methods that have often been applied by archaeologists, the credibility of rock art age estimation work becomes even bleaker. Identification of iconography is the most frequently used approach, and yet it is largely without justification. It is non-scientific in almost every context, because identification of meaning is an unfalsifiable variable based essentially on autosuggestion. There is no evidence that past people or societies shared our subjective construct of reality, our perception or our cognition. Very few rock art motifs are reasonably naturalistic depictions, and even then the emic meaning remains inaccessible to the alien interpreter. Similarly, the stylistic constructs of rock art 'interpreters' are entirely etic, or are 'institutional facts' (Searle 1995), or archaeofacts or 'egofacts' (Consens 2000). Individual artists may use different styles at different times or for different purposes, and the artists of a specific group do not necessarily share a common distinctive style (Mulvaney 1995; Novellino 1999). Two closely related traditional artists of the same generation might depict the same object quite differently. Imagery relating to totemic ancestors, sorcery figures, and secular meanings, produced by members sharing a cultural tradition, can be of very different styles (Layton 1991, 2001: 315). Styles as identified by non-participants of a culture are, like all archaeological taxonomies, entirely unscientific and subjective constructs of specialists (Bednarik 2011b).

Similarly, there is no justification for using technique of rock art production as a credible variable to estimate age. Firstly, identifying technique reliably is not as easy as it might seem (Bednarik 1994c); secondly, identical treatment or technique is no indication of cultural coherence, nor do differences in technique imply different cultures. Another variable often cited is proximity: if the rock art occurs together with occupation evidence, it might be of the same age. This argument has no logical basis, in fact the opposite could be argued more persuasively: rock art sites are often ceremonial places, which are unlikely to coincide with domestic sites. But more relevantly, rock art sites are invariably places of cultural focus, they as well as occupation sites are not randomly distributed across the landscape. Therefore the probability that two types of use traces, such as rock art and domestic refuse, found at one site are contemporaneous is millions of times greater at some randomly selected place in a featureless plain or desert, than it is at a site that was a focus of interest, such as a spring, cave or rockshelter

(Bednarik 1989a). This rule is habitually ignored, which leads to innately improbable contentions appealing to proximity.

Superimposition in rock art, obviously, can only provide a relative sequence, but is not always readily determined without specialist analysis. Excavation of sediment can certainly lead to credible minimum dates for rock art by one of two methods: either by determining the age of a stratum that covers in-situ rock art, or by excavating exfoliated fragments of rock art from a datable sediment layer. However, the number of published instances where this has been attempted is small. The ages of in-situ petroglyphs have been estimated, at least in terms of order of magnitude, on the basis of excavation in just one dozen cases (Daleau 1896; Lalanne and Breuil 1911; Lemozi 1920; David 1934; Passemard 1944; Ampoulange and Pintaud 1955; de Saint Mathurin 1975; Anati 1976: 34, 41; Rosenfeld et al. 1981; Cannon and Ricks 1986; Steinbring et al. 1987; Crivelli et al. 1996). Pictograms are very rarely preserved below ground, but they were convincingly minimum-dated through a concealing sediment at Perna 1, Brazil (Bednarik 1989b; Pessis 1999). Exfoliated fragments of petroglyphs have been located in datable strata in six cases (Capitan et al. 1912; Hale and Tindale 1930; Mulvaney 1969: 176; Thackeray et al. 1981; Roberts et al. 1998; Bednarik et al. 2005), whereas similar claims for exfoliated fragments of pictograms are less persuasive (e.g. O'Connor 1995). Dating attempts of excavated petroglyph fragments may well provide a fairly precise timing for the event of exfoliation, but it must be appreciated that this occurred probably much later than the production of the rock art. Finally, patination studies, if conducted in a scientific framework, can provide very useful age information for petroglyphs, as indicated above.

What follows from these considerations is that estimating rock art ages, particularly those of petroglyphs, through geoscientific means is more reliable than nearly any alternative. This is where we arrive at the core subject of this paper, the use of weathering and weathering-related phenomena in rock art dating.

Petroglyphs, weathering, accretions

As noted in the introduction, most minerals are dissolved in aqueous solutions, but at very different rates. Rocks are generally composed of two or more minerals, which dissolve at different rates. Under ideal conditions, the determination of the time passed since the surface in question came into existence could be calculated as follows: if mineral A dissolved at $t = x$, and mineral B at $t = 10x$ then a difference in retreat of $9x$ indicates $t = 1$. This kind of approach offers more substantial possibilities for rock art age estimation than most other techniques so far employed. Similarly, weathering rinds are only suitable for order-of-magnitude age estimates, but in contrast to the mirages often conjured up by more 'sophisticated' methods, these might be nevertheless acceptable. In contrast to the often-reversible indices on which other methods rely, the processes of weathering or erosion are simply not reversible: dissolved mineral mass does not 'grow back', whereas the indices utilised in most alternative methods are either reversible, or are susceptible to variables the analyst cannot factor in. Even the use of some forms of patination very commonly associated with petroglyphs is, as recent research suggests, far more reliable than some alternative approaches used or currently contemplated. It is therefore fully justified to review geoscientific possibilities.

Figure 5. *Inscription in calcarenite rockshelter at shipwreck site, almost completely obliterated by weathering in 300 years.*

Surface retreat

Also called 'erosion retreat' or 'micro erosion', some archaeologists have confused this with a very different phenomenon, microerosion (see below). Erosion retreat refers to the measurement of the rate of retreat of rapidly eroding rock surfaces (High and Hanna 1970; Atkinson and Smith 1976), especially those on certain sedimentary rocks, such as poorly consolidated sandstones (Fig. 5). This retreat may be attributable to solution or granular exfoliation, and is often a combination of the two processes. The method involves the use of an engineering precision dial gauge mounted on a frame supported by three legs, and the placement on the rock of a permanent reference stud of a corrosion-free metal (Smith 1978). With this instrument, the gradual retreat of a rock surface can be monitored over a period of many years by measuring it against the reference device. The data so gathered could provide good information concerning petroglyphs at the site that have been subjected to similar surface retreat. Obviously this method would only be applicable to relatively recent rock art on such rocks as limestone and carbonate-cemented sandstone. Effectively this excludes petroglyphs that are more than a few centuries old, because on such rock types it cannot be expected that petroglyphs survive over an extended period. A good measure of the rate of retreat found in such rock

Figure 6. *Weathering of iron-containing minerals in the weathering zone of gabbro.*

types is apparent from a rock inscription the author found at a Dutch shipwreck site on the West Australian coast, occurring in a partially protected location within a rockshelter (Fig. 5). The inscription is practically unreadable, except possibly a few letters, and the shipwreck occurred in 1712 (Bednarik et al. in prep.). A fake inscription at the same site has been identified through the relative retreat of the carbonate cement.

This method is therefore of limited relevance to rock art dating, and has not been used for this purpose so far. That it is likely to be of only limited applicability should not, however, discourage its further exploration. At the very least it is of considerable pertinence to issues of art conservation research.

Weathering rind

The term 'weathering front' can have two different meanings. In the sense used by Mabbutt (1961) it denotes the contour of the deepest penetration of weathering processes into the general lithosphere. Typically this proceeds along faults and fissures and extends some hundreds of metres deep into the earth's crust. In the sense used here, the term refers to the deepest perceptible penetration of modifications of the rock's constituent minerals within an individual clast or rock mass (Bednarik 1979). In some rock types this 'weathering zone' or 'weathering rind' is not readily detectable in the field; in others it is very clearly delineated and easily measured, being separated from the apparently unaltered core. In most of the latter cases, the weathering rind measures in the order of millimetres or centimetres in thickness, and it differs from the unaltered rock in colour, texture and other physical properties.

The weathering rind of dark chert, often called flint (cf. Tarr 1938; Oakley 1939: 277; Zeuner 1960: 319; Milner 1962: 256 for corrections), is of whitish or buff colour and differs from the unaltered stone in its bulk specific gravity (Bednarik 1980). The dramatic change in colour manifests an etching of the microcrystalline grains' surfaces that alters the stone's reflective properties (Hurst and Kelly 1966). The character of the alteration zones of chert nodules in their natural lithological context tends to vary somewhat, which reflects the reversible nature of the replacement process that marks the diagenesis of most cherts (Walker 1962). Therefore here the light colour reflects the presence of carbonates rather than the micro-pores of the weathering rind developed on individual clasts or artefacts exposed to precipitation and atmospheric buffering of pH (Bednarik 1980).

The pronounced weathering rind found on clasts or rock masses of basalts, dolerites and other rocks has been mentioned above. Trendall (1964) perceives an extremely slow development of such weathering rinds, suggesting that a veneer of 0.2 inches (5 mm) may be well in excess of one million years old. Studies of fractured stone and stone tools in the same region of coastal north-western Australia render this figure quite reasonable (Bednarik 2007), and it also agrees with the findings of Černohouz and Solč (1966), on whose scale a weathering rind (or zone) thickness of 5 mm on basalt corresponds to 1.1 Ma in central Europe. The distinctive weathering rind on mafic rocks is formed by alterations of the component minerals when exposed to oxygen and water. In mafic rocks, olivine, where present, is typically the most weathered mineral, with pyroxene less susceptible, and plagioclase still less readily altered, be it sodium or calcium based. Quartz, where present, remains almost unaffected. Thus the decay of the rock's fabric proceeds from the surface inwards and affects the iron-containing minerals first, forming distinctive patterns that are visible in cross-section as rust-brown features under the microscope (Fig. 6). Rainwater carries atmospheric CO_2 and other acidic anions, which are progressively neutralised as the solution percolates into the rock. The rock minerals are converted to hydrous states along grain boundaries, and microscopic carious zones develop around individual crystals or laths. Once the process continues towards its end products, the feldspars can change to mica or montmorillonite, and eventually to kaolinite and gibbsite as the rock fabric finally breaks down. The existence of weathering rinds demonstrates, however, that the final removal of degraded rock mass proceeds at a significantly slower rate than the weathering front; otherwise there would simply be no rind.

The most instructive aspect of weathering rinds concerns their relationship to surface geometries: progress of the weathering front is a function of shape, as discussed below.

Accretions

Most petroglyphs have a thin cover of ferromanganese, silica, oxalate or carbonate accretionary deposits. There are, however, great differences between the different types of accretions. Carbonates occur almost exclusively as calcite, aragonite or dolomite, may be some centimetres thick, and in some conditions may form quite rapidly. Typically they form in cavities of karst systems, precipitating from supersaturated bicarbonate solutions percolating through the rock, and include flowstone speleothems and laminar sheet deposits. In some cases, rock art has been created on such surfaces; in others it has been concealed under or even within such a series of laminae. These accretionary deposits have been subjected to age estimation by three methods, carbon isotope analysis (because ~50% of their carbon derives from the atmosphere), uranium-series analysis (such formations tend to contain small quantities of uranium), and thermoluminescence analysis (thought to detect the time the crystallisation of such deposits occurred). Obviously such verifiable results are from substances that are physically and indisputably related to rock art, being either older or younger than it; they offer direct dating evidence (Bednarik 1980, 1984, 1999).

Silica and oxalate skins (discussed above) can contain bacteria, pollen, fungi, algae or other organics, which have already yielded a radiocarbon date from a silicified wasp nest of the Pleistocene (Bednarik in prep.) (Fig. 7). Ferro-manganese deposits may comprise both accretionary and endogenous components, the latter deriving from weathered primary minerals in the host rock. However, it is suggested that the exogenous component is significantly greater, and that the portion defined as inherited weathering products (the product of ancient deep weathering) is minimal (*contra* Donaldson 2011) and has in any case been recycled. Iron and manganese play an important role in the metabolism of lithotropic bacteria (e.g. *Ferrobacillus, Leptothrix, Spirophyllum, Thyobacillus, Gallionella*), deriving energy from the oxidation of bivalent iron and manganese (Bazylinski and Frankel 2003; Kappler et al. 1997; Konhauser 1997; Perez-Gonzalez et al. 2010). These and anoxygenic photoautotrophic bacteria have catalysed the principal cations of the ubiquitous ferromanganese deposits almost since life first appeared on the planet and their recycling has continued ever since. Therefore most components of such an accretion today are not of an age corresponding to its antiquity, nor can a bulk sample of its carbon component be expected to yield an age resembling the time of its deposition. Yet the method of bulk-sampling such accretions for radiocarbon analysis (and even for calibrating another short-sighted dating method, cation-ratio determination) has been the most-used so far in attempts to determine the ages of petroglyphs. This has been the case despite this author's warnings for over thirty years that the carbon system of these features is open, and that this method can therefore only produce false datings.

On the other hand, this does not absolve ferromanganese accretions from becoming involved in the estimation of petroglyph ages. But the methods to be engaged in this quest will need to be quite different from those applied to them in the late 20th century, and one, via colorimetry, has been tried and has yielded surprisingly consistent and credible results (Bednarik 2009b). Although these mineral accretions can only survive at neutral to alkaline conditions at the atmosphere-lithosphere interface, and are being depleted by the widespread atmospheric acidification experienced by the earth, they still remain very common and occur together with the majority of surviving petroglyphs. They are found in different forms, ranging from the dense rock varnishes predominantly of arid regions, to less distinctive forms of essentially *dunkle Rinden*.

Figure 7. *Fossil stump of mud-wasp nest, silicified, with superimposed white paint, both of which were sampled for ^{14}C analysis. Cape York Peninsula, NE Australia.*

Nevertheless, colorimetry and analyses of accretions occurring with rock art — whilst providing securely relatable empirical evidence in rock art age estimation — provide only experimental results. Those likely to be secured from actual weathering phenomena may lack precision, but provided their significance and limitations are fully appreciated, they are certainly the most reliable. But before developing a specialised methodology it would be useful to explore some of the inherent principles of the processes that lead to the reduction of rock to sediment. Here, a quite specific aspect of rock weathering will be considered in an attempt to derive some 'first principles' of rock weathering as it might pertain to rock art study and to archaeology.

Let no one enter who does not know geometry
(inscription on Plato's door, probably
at the academy at Athens).

THE GEOMETRY OF ROCK WEATHERING

The geometry of stone tool taphonomy

While stone artefacts are not rock art, they are often used in archaeological arguments about rock art, and the geometry of their weathering is a convenient starting point for the generic subject of the geometry

Figure 8. *Sectioned flint-like chert nodule from Mount Gambier, South Australia, with white cortex.*

of rock weathering. Most stone tools are made from sedimentary silicas, usually cherts, including flint (Tarr 1938; Oakley 1939: 277). Cherts are fine-grained silica rocks comprising mostly silica (SiO_2) and calcium carbonate ($CaCO_3$) and occurring most frequently in limestone facies. The practice of defining nodular microcrystalline and chalcedonic quartzes as flint may reflect their mode of occurrence but is geologically invalid (Zeuner 1960: 319; Milner 1962: 256) unless they are indistinguishable from flint in every important physical aspect. Since Judd's (1887) attempt to explain the 'patina' of flint and other cherts there has been much speculation about this form of weathering rind (Tarr 1926; Correns and Nagelschmidt 1933; Gehrke 1935; Donnay 1936; Bosazza 1937). As the correct hints by Washburn and Navias (1922a, 1922b) remained unheeded until 1951, archaeological writers of the time (e.g. Curwen 1940; Mitchell 1947) had no choice but to subscribe to the opaline content theory. However, since the work of Midgley (1951) and Weymouth and Williamson (1951), and the overwhelming evidence provided by Folk and Weaver (1952), there remained no justification for repeating earlier fallacies.

Diagenetically, cherts are the result of selective replacement of calcium carbonate by silica at normal ambient temperature, forming as nodular deposits that may coalesce into tabular formations following the limestone host rock's strata. As each crystal is gradually replaced, the chert's fabric copies that of the former limestone faithfully in every detail, so that fossil casts in it are precisely replicated. The nodules of chert are surrounded by zones of partial replacement, often called their 'cortex' (Fig. 8), and since the process of replacement is reversible (Walker 1962), subject to environmental fluctuations, there may be concentric formations present that indicate variations in silica content (Bednarik 1980). The darkest zones are those richest in silica, culminating in black flint. The colour is simply a function of light reflection: a fully silicified stone absorbs all light and is therefore black.

The light-coloured weathering rind of chert, by contrast, is the result of mobilisation of silica in the form of monosilicic acid (Mosebach 1955). Schmalz' (1960) view on flint patination contrasted with that of Oakley (1939), who considered carbonic acid in the ionised state to be the chief patinating agent. Schmalz, however, misunderstood the crucial passage in Weymouth and Williamson (1951) and since he was apparently unaware of both Midgley (1951) and Folk and Weaver (1952), he believed to be the first to demonstrate the absence of opal in flint. Clark (1979) later noted the diverging concepts of some writers on the role of calcareous sand. Mitchell suggested repeatedly (e.g. 1947: 299) that carbonate waters leached silica from the surface of cherts, but his assumption that the specific gravity of flint is higher than that of the cortex contradicts his espousal of the interstitial opal theory (removal of colloid silica would increase, not decrease, the S.G., but would decrease the bulk density G_S). In that he followed Moore and Maynard (1929: 276) who had defined carbonate water as the most effective solvent of silica from norite and diabase. Curwen's (1940) experiments indicate the involvement of both organic and calcareous matter, bringing to mind an early comment (Murray and Irvine 1891) that siliceous remains are appreciably soluble in cold seawater in the presence of $CaCO_3$ and decaying matter (cf. Fairbridge 1964: 444–7). The tenability of the implied process is, however, challenged by the tendency of many organic compounds to interact with carbonate mineral surfaces, forming mono- or multi-molecular layers isolating the carbonate from water and inhibiting even inorganic equilibrium (Suess 1970).

All early commentators believed colloid silica to be the only form present in natural waters. Because it was proposed only in the year of their own publication, Kahlenberg and Lincoln (1898) lacked the benefit of the colorimetric silica determination method, but the several later writers repeating their view (e.g. Tarr 1917: 433, 1926: 25; Twenhofel 1932: 44, 510; Van Tuyl 1918: 456) did not. Diénert and Wandenbulcke (1923), enlarging upon Jolles and Neurath's (1898) method, were unable to detect any colloid silica in their samples of river water and in the following year confirmed its absence by their failure to raise the molecular silicate content of water by increasing its pH, which should convert any colloid fraction present (Diénert and Wandenbulcke 1924). Harman (1926) scrutinised Kahlenberg and Lincoln's (1898) propositions and concluded that they are untenable in the light of his meticulous and varied experiments. After pursuing established concepts of another discipline, Roy (1945) asserted that silica of natural waters is molecularly and not colloidally dispersed. Aoki (1951) suggested molecular dissolving of silica in water up to a certain concentration, claiming that surplus silica (which would be produced by a lowering of temperature or pH) will polymerise to the colloid state (cf. Tsai et al. 2006). Whilst solubility in the range of pH 0–9 differs little (Krauskopf 1956) and may in fact be slightly greater in acid than in weakly alkaline conditions (White et al. 1956) — at least at low temperatures (Okamoto et al. 1957: Fig. 2) — it increases

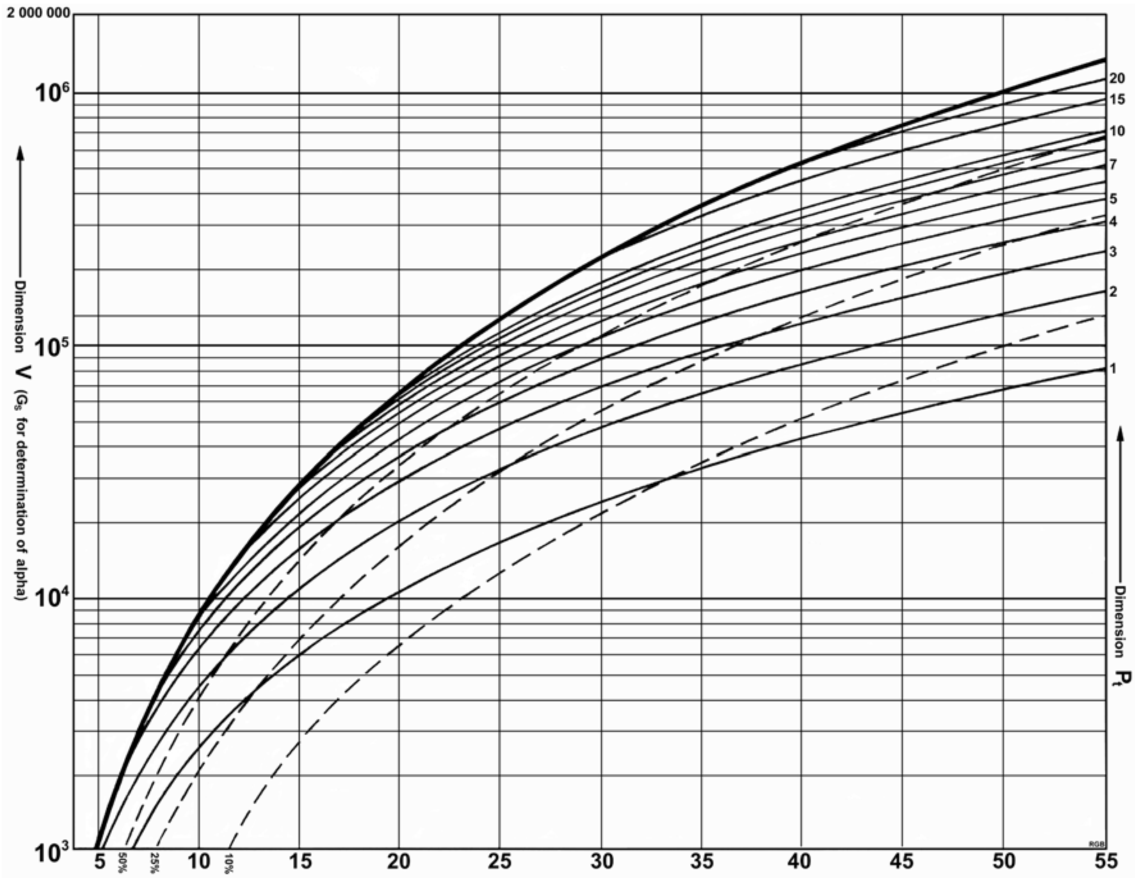

Figure 9. *Relationship of G_S, P, α and P_t, for cuboid of π = 25 (being a function of A_i = 3).*

dramatically above pH 9, where silicic acid only polymerises in high concentrations (ibid.: 126). Silicic acid will of course dissolve in water to the concentration of equilibrium solubility, which also rises rapidly above pH 9. Iler (1955: 25) reported that in highly alkaline environments the ion $H_3SiO_4^-$ becomes important to the point of dominating over H_4SiO_4 above pH 10, and it is generally acknowledged that ionic forms are present in appreciable amounts only at >pH 9. Thus formation of a weathering rind on microcrystalline sedimentary silica is attributable to the etching of the microcrystalline grains' surfaces, which alters the reflective properties of the stone (Hurst and Kelly 1966).

Since the process can occur on the surface of soil and in the absence of limestone, but is almost ineffective in sheltered and dry conditions even after burial for hundreds of millennia, frequent exposure to moisture under ambient conditions of high pH is the principal cause. Both the cortex and the weathering rind ('patina') of cherts can absorb iron salts into its pores and acquire a brownish colour (Bednarik 1980). The weathering zone tends to be better delineated than the cortex, and the fact that it exists demonstrates that the progress of solution at the weathering front must be significantly faster than the total reduction of the surface crystals (the surface retreat rate). This is despite the immensely (fractally) increased surface area within the altered zone and the outer zone's higher penetrability to alkali replenishment, which would not be so readily attainable at the weathering front, where the silicic diluents would be both nearer equilibrium and less readily transferable. For instance, if a 1-mm-thick weathering zone is immersed in sodium hydroxide solution (saturated at its boiling point), exposure for one hour will result in its almost complete removal, without corrosion of the structurally unmodified core (Bednarik 1980). Therefore the main factor in the progress of the weathering is the frequent flushing of the interstitial spaces of the weathering zone. This is confirmed by the observation that the upper surface of specimens exposed to precipitation exhibits a thicker weathering zone than the underside.

The geometry of the weathering process is here of particular interest because it introduces the subject of the way weathering generally proceeds. Attempts to gain some insight into the factors influencing patination rates of clasts or stone tools by quantifying their effects identify weathering progress either by patina thickness (P_t, cf. Fig. 9), or by total weight loss through weathering (see Legend of Symbols):

$$W_L \text{ (in \%)} = \frac{(2.55\,V - W)\,100}{2.55\,V} \qquad (2)$$

Alternatively, percentage of weathering by volume can be calculated:

$$P = \frac{255 - 100\,G_S}{\alpha} \qquad (3)$$

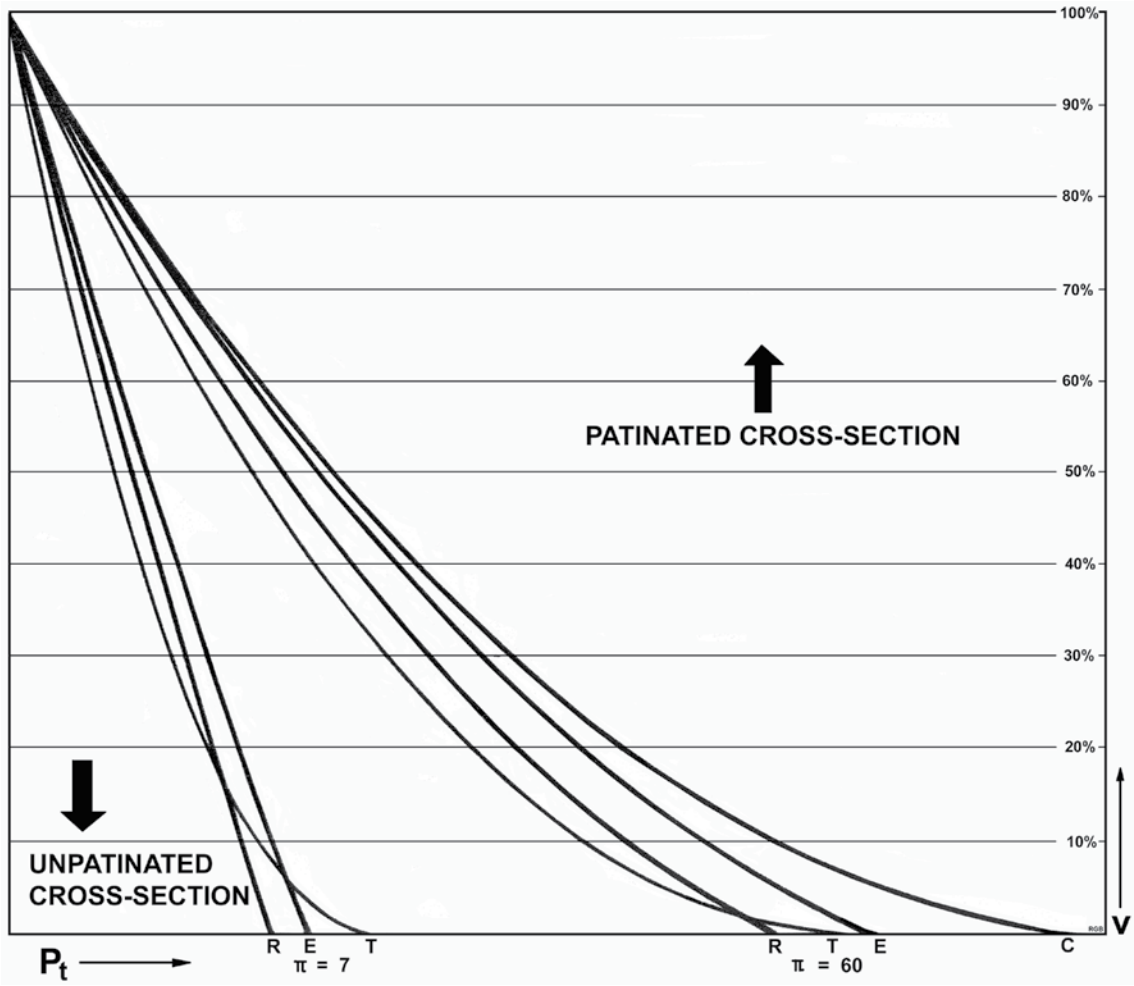

Figure 10. *Influence of cross-section shape and Index of Flatness π on patination progress: C = circular, E = elliptical, R = rectangular, T = triangular. Two Indexes of Flatness (7 and 60) are considered.*

Legend of Symbols

V = Bulk volume
G_S = Total bulk *S.G.*, or *W/V*
L = Maximum length
E = *Grösste Dicke*, after Cailleux (1951), or π_L × L/100
P = Percentage of patina (by volume)
π_L = *Abplattungswert*, after Lüttig (1956)
A_i = *Abplattungsindex*, after Cailleux (1951)
P_t = Patina thickness
α = Patination index; or $S.G._{silicate} - G_{S\,(patina)}$
β = Porosity index, % water accepted after 90 seconds (by volume)
S.G. = Specific gravity
W = Weight, after drying at 105°C until no further loss
W_S = Weight, immersed in water at 20°C, waterproof coating discounted and specimen fully dried
W_{90} = Weight of dried specimen in water at 20°C, after immersion for 90 seconds
W_L = Total weight loss through patination

To eliminate the need of physically measuring P_t (which usually involves damaging the specimen), α can be estimated by an experienced observer (it can only vary from 0.5 to 0.9) and theoretical P_t can be determined by translating the principles established in Figure 9 into seven co-ordinates. In practice, a difficulty to be taken into account is that posed by the possible presence of 'grey zones', which can introduce an unknown variable. They are patches of grey within the weathering zone, presumably where silica crystallisation had resisted weathering locally. Such 'grey zones' are present in early specimens possessing a G_S >2.2, except those of *W* >100 g. In one sample analysed the *S.G.* of 'grey zones' ranged from 1.95 to 2.20 (Bednarik 1980).

As readily demonstrated by Figure 10, the Index of Flatness (depending on application, either that of Cailleux [1951] or of Lüttig [1956] was employed) is of far more consequence than implement shape, as expressed by nominal cross-section (which was divided arbitrarily into circular, elliptical, segmentary, rectangular or triangular, to show the great difference in rate of weathering relative to shape), when relating P_t to cross-section. To assist with the estimation of α, the porosity index β was established. Porosity or void

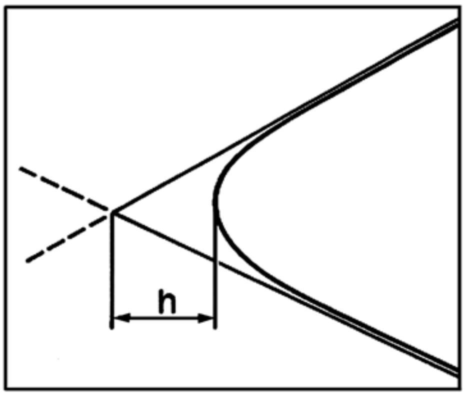

Figure 11. *Development of sandstone wanes as assumed by Černohouz and Solč (1966).*

content can be ascertained either with the McLeod porosimeter or with the wax-coating method.

$$\beta = \frac{(W_{90} - W_S)\ 100}{V} \qquad (4)$$

For a sample of early Holocene and late Pleistocene chert tools (free of cortex, W = <80 g) from 39 coastal sites along Discovery Bay, southern Australia, β ranges from 1.92 to 20.31 (mean 7.36). In general, a porosity index exceeding 10, for flakes of the sizes surveyed, indicates not only weathering, but also the presence of extensive leaching and an early stage of granular disintegration. The latter always commences from the artefact's thin margins, but where cortex is present this, too, accelerates the process of weathering significantly. This is probably because leaching proceeds more readily from the porous contact zone (larger area of exposure) than from the initially smooth surface of a fresh fracture. Contrary to popular archaeological belief, cherts can totally disintegrate within a few tens of millennia in environments found commonly in nature, such as exposure to precipitation in the presence of an alkaline buffer, e.g. at sea coasts.

The quantification of patina thickness and proportion of a specimen's volume is thus possible without sectioning. Their relationships with total and specific gravities, flatness index and implement cross-section, albeit complex, are fully quantifiable and are illustrated in Figures 9 and 10.

The geometry of erosion weathering

Having thus opened an investigation into the geometry of rock weathering, the possibility of determining the age of rock surfaces has been considered by archaeological investigators for at least two centuries (e.g. Belzoni 1820: 360–361). As already noted, two Czech geologists, J. Černohouz and I. Solč (1966), tried to solve part of the problem and described a method of determining the ages of blunted edges on sandstone and basalt. They used the angle of the edge, the distance of retreat at the edge, and two 'experimentally found' constants (a, b). The age of the edge t can then be determined from the distance of its retreat h and angle φ:

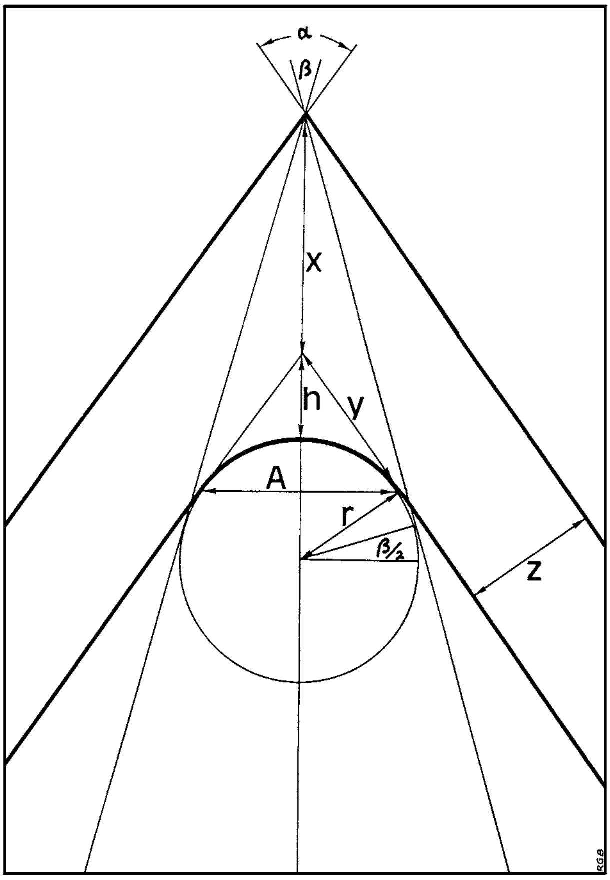

Figure 12. *Diagram depicting the universal laws of wane formation in simplified fashion.*

$$h = \frac{a\ t\ \sqrt{(2)}}{1 + b\ \sqrt{(t)}}\ cot\ \frac{\varphi}{2} \qquad (5)$$

The age was reportedly determined with an accuracy of ~10–20%. However, the distance of retreat from the originally sharp edge cannot be measured (Fig. 11), because the rock surface recedes not only from the edge but also from the two surfaces forming it (Bednarik 1979). Therefore the original dimension h, at the time erosion commenced, remains unknown (see Fig. 12, which shows that the actual edge retreat is not h, but the sum of $h + x$, x being a function of z and α). Although the theory has thus been refuted, the underlying principle is sound, and such rounded edges do relate to their ages. However, the solution to the quantification of the process was not available until a quarter of a century after Černohouz and Solč's proposal (Bednarik 1992).

The 'radius' of rock wanes (in geological usage, 'wane' refers to the progressive rounding of a rock edge) clearly does increase as a function of age. It should be noted, however, that the retreat at the edge 'does not occur as the simple curvature shown by Ollier (1969: Fig. 149); it consists of a hyperbola in section' (Bednarik 1979: 28). Although wanes are thus not equicircular in section, to simplify the following explanation it shall be pretended that wanes have a radius; the resultant error is not significant to the overall issue. It is of greater consequence to appreciate that the process must be seen as an attempt

Figure 13. *Section through weathered dolerite clast, showing deeper penetration at corners and shallow penetration under concave surfaces.*

of an eroding mass to attain a state approximating equilibrium (i.e. where erosion coefficients would affect the surface uniformly). Inevitably, this leads to a spherical form in the case of shape. The process thus conforms to geometrical axioms, in precisely the same way as heat is transferred proportionally within a solid body; or, for that matter, the pattern of penetration of a cube of sugar dropped into coffee is that it occurs faster from the corners than on the flat sides; and the same applies to a melting solid. This pattern follows a universal law, according to which the unaffected core increasingly resembles a sphere. Or, geometrically speaking, the unaffected zone trends towards the smallest surface area relative to mass, achieving that 'perfect shape' at its vanishing point. Another way of expressing this principle is to regard the sharp unmodified edge as a parabolic curve with the coefficient of zero, and the process as seeking to replace it with one of infinite (i.e. a straight line), at which point the object disappears.

This means that heat transfer in a solid object, or weathering of a clast, or melting of a piece of ice, must proceed faster from convex or protruding surface aspects, and relatively slower from concave aspects. The process has been defined in algebraic fashion, confirming that it is quantifiable and that wane formation, be it on rock, or on dissolving or melting objects, is a function of time (Bednarik 1992). These principles of wane formation are universal; they apply microscopically as well as macroscopically, to individual crystals or to rock masses, and throughout the physical world generally (e.g. relative rate of heat transfer). This fundamental law of physics quantified in 1992 offers a variety of practical applications in geomorphological and archaeological dating. At the macroscopic level it can be used to estimate the age of rock edges, where these are affected by progressive weathering rather than by episodic events, such as thermal spalling. The microscopic edges of crystals fractured, or truncated by abrasion when a rock surface was freshly exposed, are subjected to microwane formation, and when these microscopic wanes are clear enough for quantitative assessment they provide a reliable measure of the age of the rock surface in question (see next chapter).

The theoretical principle of quantification is depicted in Figure 12. In wane formation, the ratio $h : r$ is constant for any given angle α, irrespective of distance of retreat of the faces and the edge. Dimensions h, y and A can be measured, and r can be either determined physically (but only approximately, being a hypothetical value) or it can be determined from α and y:

$$r = y \tan \frac{\alpha}{2} \qquad (6)$$

Ratio $x : z$ is a function of α, and at $\alpha = 60°$, $x = 2z$. Dimension x can be expressed in algebraic fashion:

$$x = \sqrt{\left[\left(\frac{z}{\tan 0.5\alpha}\right)^2 + z^2\right]} \qquad (7)$$

This leads to the prediction of β, the angle expressing the rate of wane development relative to surface retreat:

$$\beta = 2 \sin^{-1}\left(\frac{r}{x + h + r}\right) \qquad (8)$$

The relationship wane width A with age, irrespective of actual retreat, is ultimately determined by the ratio $\alpha : \beta$, which must be established empirically. It follows that the dimensions A, r, z, and angles α and β are all related geometrically and algebraically, and that the variables A, r, x, z and h are all proportionally equivalent, and increase linearly with age. Of these, A is most easily measured physically. It is therefore the variable used in wane measurement. It can be measured with a gauge bearing a full selection of semicircular openings of calibrated sizes held to the rock wane. Despite both the ease of the method and its obvious potential, it remains little used. Of particular relevance is the observation that the development of weathering rinds on rock surfaces follows the same geometrical laws: on any rock surface of equal exposure it will be markedly thicker on any prominent aspects than on a flat surface, and conversely it will be thinner beneath concave surface aspects (Fig. 13). Therefore it can be assumed that here, too, the unaltered core would approach spherical shape before its disappearance.

The geometry of microerosion

Instead of developing the measurement of rock wanes as a tool of estimating weathering duration, the geometric principles of wane development have been more often applied at the microscopic level. As a purely optical technique, microerosion analysis was the first direct dating method for petroglyphs that involves no destructive removal of samples, is of very little cost, and provides statistically meaningful data; under favourable conditions, hundreds of measurements can be taken from a single sample. It is also expected to be more accurate than other methods of dating petroglyphs, especially once it has been tested in different geological and climatic environments (Bednarik 1993a). Obviously it has a variety of potential applications in archaeology, such as the determination of approximate age of stone structures, quarries, monuments, statues, and even some stone tools. However, its intended main use is in petroglyph dating, and it was conceived primarily to provide a relatively simple method of reliable age estimation of geomorphic exposures (Bednarik 1992, 1993b, 1995, 1997, 2000b, 2001a: 129ff, 2002a, 2010; Tang Huisheng and Gao Zhiwei 2004; Tang Huisheng in prep.). The method was initially based on the very same geometrical principles defined in the previous chapter, and applied to the microscopic wanes forming on fracture edges of particularly erosion-resistant minerals, especially quartz.

This method has now been applied in several blind tests, having been used to estimate the ages of petroglyphs in all continents, in numerous countries. In all blind tests it has met prior archaeological predictions that were unknown to the analyst. Where surfaces of known ages (such as those of glacial striae, graffiti, gravestones, monuments, dated inscriptions, stone bridges, stone sculptures etc.) are present at a site, a calibration curve can sometimes be derived from their micro-wanes, leading to the dating of a surface of unknown age (e.g. a petroglyph) in the vicinity. To limit the possible effects of past climatic fluctuations, the microerosion coefficients of two or more component minerals of composite rocks are compared from the same surface, such as those of quartz and feldspar on a granite surface. The method is not eligible for rock surfaces that were covered for any great length of time, be it by soil, rock varnish, water or whatever else; nor can microerosion dating be used where a rock surface has been subjected to the application of certain chemicals or has been physically worn, for instance by the activities of graffiti removers.

In considering microerosion dating we have to distinguish between two types of rock: those on which the individual grains or crystals that were fractured, exposed or truncated during the manufacture of a petroglyph are capable of remaining in situ for periods exceeding the age of the petroglyph tradition in question; and those sedimentary rocks that are subjected to relatively swift granular exfoliation or chemical corrosion, such as carbonate-cemented sandstones, calcite, dolomite etc. (cf. Emery 1960). Only the former are of interest here, because for microerosion analysis to be possible, the presence of crystals or grains truncated (through impact fracture or abrasion) by the rock artist is absolutely essential. Moreover, certain rock types are inherently much better suited than others, and at least initially, composite rocks which include quartz (or another comparatively stable component), such as granite, quartz porphyry, gneiss, diorite, granophyre and the like, are more likely to produce valid results. As reliable quantitative information becomes available, other rock types will become susceptible to the method.

The rates of micro-wane development may vary somewhat through time; they are likely to be susceptible to environmental factors, but such fluctuations may cancel each other out over long time spans. However, of the three main variables, two have no effect on the relatively coarse results: ambient pH and temperature have hardly any impact within the range of natural conditions, and moisture availability can be accounted for by checking the response against a second mineral that is differently affected. Obviously there are also variations to be expected according to relative location of an edge (i.e. relative to prevailing climatic factors, exposure to anomalous influences such as abrasive wear, and other factors), but these have no bearing on the regularity of the underlying theoretical principles of the wane-forming processes as described. These factors are the method's only potential major error source, but while they can influence its accuracy they can certainly not affect its intrinsic validity. The only critical comments made so far (Pope 2000) raised irrelevant objections, e.g. that crystalline quartz occurs in two different forms. That is correct, but beta quartz is only stable at temperatures above 1063° F (573° C). Thus, all quartz in nature is alpha quartz, because once a sample of beta quartz is below the mentioned temperature, it automatically transforms into alpha quartz. A second critique of microerosion analysis has been offered by Field and McIntosh (2009), but can be ignored as being hopelessly misinformed (Bednarik et al. 2010).

To limit the possible effects of past climatic fluctuations on the results of microerosion analysis it is useful to compare the microerosion coefficients of two or more component minerals of composite rocks. In the example from Lake Onega, Russia, where the method was first applied (Bednarik 1992, 1993b), those of quartz and feldspar were compared. It is reasoned that, whatever the past climatic fluctuations were, and however they affected the minerals, it is likely that two different minerals would have been differently affected, and this would be reflected in variations in the two calibration curves. If the related values on the two calibration curves correspond on the ordinates it suggests that erosion rates have not been sufficiently affected to distort age estimates significantly, and the reliability of the result is considerably enhanced.

While this method was conceived initially for estimating the age of petroglyphs, it is of course valid for any geomorphic surface. It can be applied to any rock surface where edges of crystals were freshly exposed to weathering, provided there are at least remnants of the crystals' surfaces still present for examination. However, on present indications it would appear that the susceptibility of quartz to the method would be limited to a maximum of a few tens of thousands of years, perhaps 50 000 years at most, because beyond such age the effects of microerosion would not permit reliable measurement.

The immediate, tangible advantages of the micro-

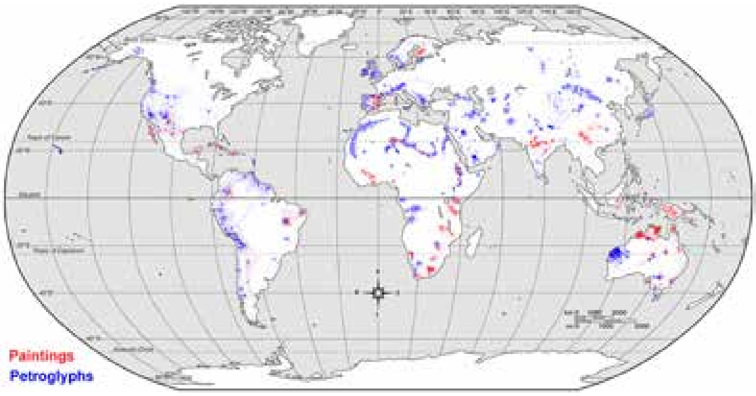

Figure 14. *Tentative map of the global distribution of rock art.*

erosion dating method are its most impressive aspects (see Table 1):

- It is cheap and reliable, and requires little training apart from field microscopy.
- It offers very considerable scope for development, being in fact a variety of methods, most of which have hardly been explored.
- It is one of very few currently available petroglyph dating methods that seeks to date the event of petroglyph manufacture itself (the 'target event' of Dunnell and Redhead 1988) rather than a physically related feature that merely provides minimum or maximum age.
- It is one of very few rock art dating techniques currently available that involve no sample removal.
- It involves no possibility of sample contamination, as practically all other dating methods do.
- It offers a mechanism of internal crosschecking when two or more component minerals are considered.
- It is the only currently available rock art dating method that has the capacity of satisfying statistical sampling requirements, because it can furnish vast numbers of age-related values from a single motif.

Perhaps most importantly, microerosion dating will induce researchers to scan petroglyphs very carefully in the field, prompting the finding of much forensic evidence concerning the history of the motif and its support surface that would otherwise be overlooked: later modifications to the motif, use traces, traces of aeolian wear, fire damage, glacial or sediment scouring, frost or regelation damage, deposits of precipitates and their alterations through time, patination and weathering, effects of vandalistic recording practices etc. Indeed, where microerosion dating differs most from other methods of rock art age estimation is that the latter are rather like hunting expeditions, from which researchers bring their samples to the 'safety' of the laboratory. Microerosion analysis involves lengthy field studies, but no laboratory work at all (the results can be determined in the field). Finally, it reverses the underlying strategy of previous attempts to date petroglyphs directly: instead of using non-archaeological data to produce minimum or maximum dates of the art, it utilises surfaces of known ages to calibrate a non-archaeological process (erosion), which is then used to provide a time frame in which to place petroglyphs of unknown age.

Finally, alternative methods of microerosion analysis are possible, one of which has already been applied occasionally. This is the examination and measurement of alveolar development on the floor of petroglyph grooves, where more erosion-resistant minerals project above the more soluble components (Bednarik 1995: Fig. 10). The relative relief differences are a function of time, becoming greater with increasing age, but no attempt has been made so far to quantify the process.

The geometry of sandstone shelters

When we look at the world's quantified distribution of surviving rock art, it is immediately obvious that most of the major rock painting occurrences are found in four regions: southern Africa, India, northern Australia, and the Noreste of Brazil. Petroglyphs dominate numerically in the rest of the world (Fig. 14). A logical explanation for this observation is that during the Mesozoic these areas were joined as the supercontinent Gondwana, and they have similar extensive sandstone sequences. This is fairly obvious to the traveller, through similar landforms, hill shapes, erosion patterns, hydrologies and even vegetation regimes. Most relevantly in the present context, these sandstones are more susceptible to rockshelter formation than practically any other rock type. Rock paintings, wherever they may have been made, can only survive in sheltered locations for any prolonged period of time. A small number worldwide has been preserved in deep limestone caves; the vast majority of pictograms occur in sandstone shelters. In addition, weathered sandstone surfaces tend to be pervious to some degree, allowing mineral pigments to penetrate slightly, which adds to their ability to survive, or provides the potential of traces to persist after the paint residues have largely eroded.

But how do these rockshelters form in sandstone, especially in specific types of this rock? There are essentially two processes at work: granular and laminar mass-exfoliation (Maranca 1983–84). Both are largely (but certainly not entirely) caused by the same factor, capillary moisture in the rock, which rises from the base and is buffered by the contiguous sediment deposit. Every time the moisture rises, it weakens the rock's fabric by mobilising solubles, leading to the fretting of small particles or individual grains. But the process also leads to the formation of subcutaneous salt deposits (subflorescence), usually in a zone 10–20 mm from the surface and parallel to it. In due course *Salzsprengung* (fracture through expansion of salts, such as gypsum, anhydrite, or a chloride or nitrate) causes the exfoliation of a laminar rock flake. Since this process is more effective near the floor (i.e. within the zone of greatest effectiveness of rising capillary moisture) and tends to be ineffective above a certain height from the floor (as a function of duration and severity of the moisture regime), it logically has to result in the formation of a concavely shaped rear shelter wall. Over the course of centuries and millennia the succession of countless rises of interstitial moisture, which are most effective just above the floor, results in a more or less curved profile, with the greatest shelter depth typically at floor level.

Obviously the depth of these sandstone shelters becomes a function of their age in some fashion, as this exfoliation process gradually forms them. However, if one examines a large enough number of excavated shelters around the world a curious observation can often be made. Below the sediment floor, the wall does not recede further, as it would due to a rising sediment level. On the contrary, it tends to slope towards the shelter entrance (Fig. 15). If the deposit is deep enough one can even reach a depth at which it meets the projected drip-line, where the rock may continue vertically.

This phenomenon is explained here as follows: exfoliation, especially the laminar kind, is ineffective below floor level, because the rapid wetting and drying (or freezing and regelation) cycles are not effective within the sediment cover. Moisture and temperature levels are much less variable, and insolation is absent. If the exfoliation is most effective just above the floor, and if the floor of the sediment is gradually rising (as may be the case in most shelters), it follows that the forward-sloping rock ledge within the sediment is the result of the rising sediment. If fresh exfoliation is limited to the wall above the floor, and if the floor deposit rises, there should be a sloping rock shelf below the sediment as the depth of the shelter increases, under ideal conditions.

Moreover, this geometry also shows that the inclination of the sloping rock must be a predictable function of sedimentation rate, exfoliation rate and time: the steeper the slope, the faster sedimentation and the slower exfoliation would have proceeded. Under perfect conditions, the three variables would be proportionately related, but such conditions might be rare. Both sedimentation and exfoliation rates are usually variable through time and obviously depend on various other factors. However, as a theoretical principle determining the geometry of rockshelter sections this is a useful rough guide for the researcher. It again indicates the utility of applying geometric principles to issues of weathering.

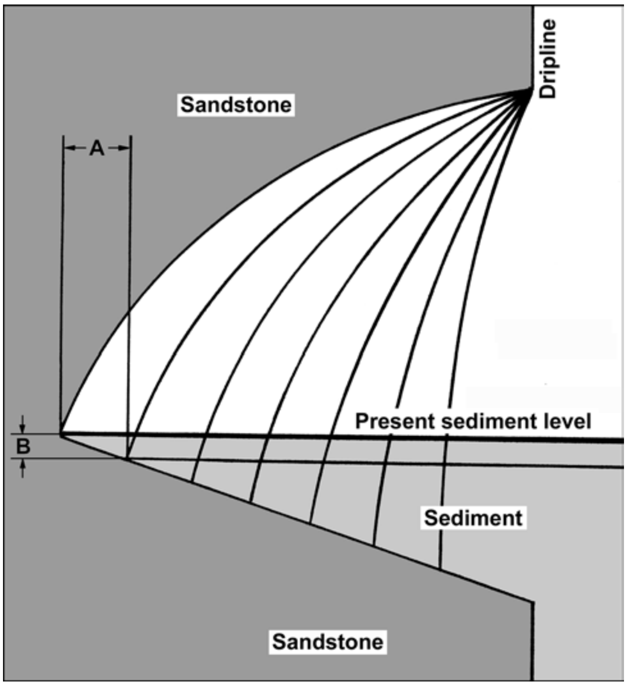

Figure 15. *Schematic depiction of the progressive morphology of a sandstone shelter, showing that the slope incline of the rock shelf below ground is a function of the ratio of dimensions A : B.*

Fluvial erosion of low-grade metamorphics

Like so many other processes in geomorphology, the fluvial erosion of valleys is also governed by geometrical laws, for instance those relating to the behaviour of suspended sediments (Alexander 1932; Foley 1980; cf. Sklar and Dietrich 1998; Snyder et al. 2000). Again, the potential of such taphonomic processes has not been adequately explored so far, with only one published example addressing the quantification of fluvial erasure of petroglyphs (Bednarik 2009a). The common rock types perhaps most amenable to such studies are the low-grade metamorphics, such as schists, phyllites, slates and mudstones. Their relative susceptibility to fluvial erosion renders quantification readily possible, particularly where transported sediments include quartz or other very hard and abrasive minerals. Hartshorn et al. (2002) have shown that small grains of diameter $d \leq 2$ mm can travel in significant numbers up to a flow depth of 4–6 m in turbulent suspension and be responsible for significant bedrock abrasion (Hartshorn et al. 2002: Fig. 3A), in particular if a soft lithology is exposed. Schist has been shown to be up to two orders of magnitude more erodible than quartzite or granite (Attal and Lavé 2005: 156, 159). The abrasion coefficient for schist (16) is significantly higher than that of granite (0.4) or quartzite (0.15). The largest grains in suspension have considerable inertia and preferentially strike obstructions on the upstream side, whereas intermediate size particles may follow gently curved streamlines upstream of obstructions, but impact on their lee side where shedding vortices produce sharply curved streamlines (Whipple et al. 2000). The smallest particles tend to follow streamlines faithfully and have negligible impact on the rock surface.

In considering the abrasive action of a single saltating quartz grain, the precise kinetic conditions of the process are relevant. The contact area of an angular

Figure 16. *Siega Verde inscription showing fluted erosion patterns; scale in cm. The water flow is from the right to the left.*

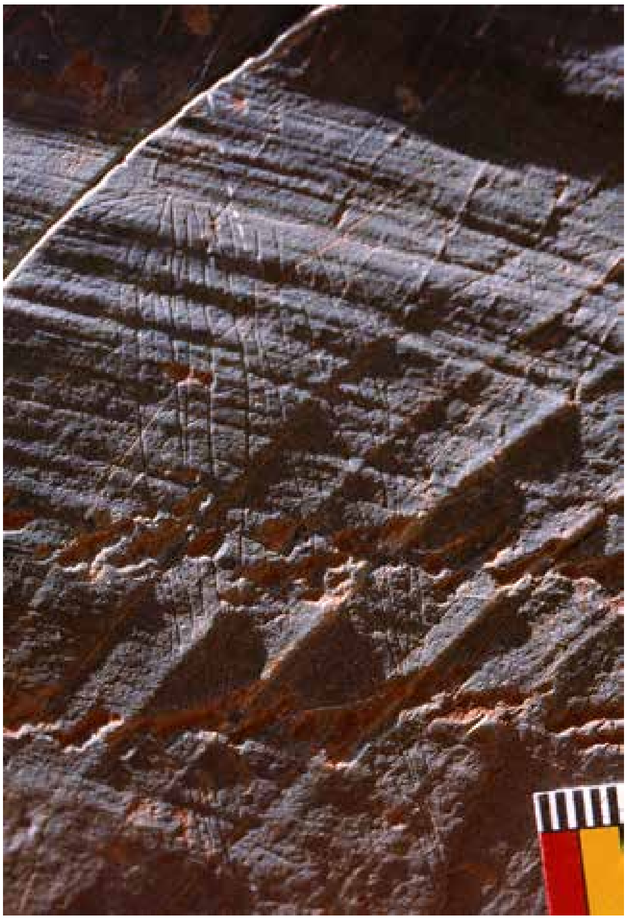

Figure 17. *Two 'neck' lines of a pounded zoomorph (equine), weakly patinated, superimposed over earlier, completely patinated single-incision markings (filiform). Many archaeologists falsely regard the zoomorph as Upper Palaeolithic. Scale in mm.*

grain with the surface that it impacts is smaller than the contact area of a similar rounded grain with a similar surface area, causing greater damage. Each quartz grain, of hardness 7 on Mohs Scale, scores the soft surface of the metamorphic rock (up to hardness 3), which is also undergoing weathering by hydration (Graf 1977; Anderson et al. 1994). Angular particles impacting softer ductile material can potentially scratch it, with a maximum material removal for impact angles of 30 degrees (Finnie 1980). The abrasive effectiveness of a coarse, angular, mostly quartzitic sand in a dynamic environment is therefore very high: the soft rock is correspondingly sculptured and cumulative wear becomes readily visible macroscopically.

There are two possible scenarios relating petroglyphs to fluvial erosion. Such rock art may be located in a narrow valley, close to the level of the river, where it is regularly (seasonally or episodically) inundated by fast-flowing river water; or it may be near the thalweg of a creek bed in an arid region, subjected to occasional flows of water and sediment. Both alternatives are considered here with examples. Typical instances of the first circumstance are the petroglyph concentrations in the Côa and Agueda valleys (eastern Portugal and western Spain, respectively; Bednarik 1995). In the latter case they occur exclusively within the river's flood zone, while in the Côa valley many of them do, and in both cases they co-occur with dated inscriptions of recent centuries. The large site Siega Verde on the Río Agueda was selected for detailed study. Its schist panels are scoured by the very coarse sand (Bednarik 2009a: Fig. 15) consisting of 86.3% quartz, and the Degree of Erasure measured on engraved dates showed that most become unreadable after 100 to 200 years of exposure to the fluvial sand blasting (Fig. 16). The site's numerous petroglyphs occur in the same flood zone and on the same rocks, and they are of the same groove depths, therefore the quantified Degree of Erasure can be applied to them to estimate their ages. They are in all cases certainly under 400 years old, and most probably under 200 years. Most seem to have been made around 1925, when the massive stone bridge spanning the site was built. This finding contrasts sharply with the pronouncements of all commenting archaeologists, that these petroglyphs are Palaeolithic (Fig. 17). There is no credible evidence whatsoever for this attribution (see Bednarik 2009a for detailed discussion), yet it was used to successfully demand World Heritage listing for the site.

The second type of petroglyph site to apply this method to is where the rock art occurs in a usually dry river bed. Examples in Australia are the Yanyarrie Creek (Fig. 18) and Stone Chimney Creek sites, both near the Flinders Ranges (Bednarik 2010: Fig. 14). Unfortunately there are no engraved inscriptions to calibrate the Degree of Erasure with, but this does not exclude the possibility of determining flow rates of the episodic streams and analysing their sediments to determine the relative effects of fluvial erosion.

Conclusion

These are a few examples of the application of geometry in assessing weathering products. Many others could be considered, such as, for instance, the laws determining the formation of solution scallops in limestone caves, with their certainly distinctive geometric properties (de Serres 1835: 24; Bretz 1942; Curl 1966, 1974; Shaw 1992; Mihevc et al. 2004: 522) — provided the term 'weathering' is extended to processes of speleomorphology. But what these examples show is that once the laws governing the weathering processes are understood and rendered quantifiable, they permit the determination of the relevant variables, most especially time. In that sense many of such phenomena can be utilised in estimating the ages of geomorphic exposures, such as petroglyphs. That potential remains under-explored and under-utilised, perhaps because a dependency has been allowed to develop, especially in rock art dating, on over-sophisticated techniques that promise more than they can deliver (Bednarik 2002b). In considering the severe limitations of these alternative techniques, the complex interdependencies, supervenience relationships and qualifications applying to them, it soon becomes evident that, at least in petroglyph dating, geomorphological methods are more reliable. While it is apparent that their degree of precision may leave much to be desired, it is perhaps the case that reliability is preferable to a promise of precision that may not be deliverable.

Figure 18. *Waterworn circle petroglyphs at thalweg of Yanyarrie Creek, South Australia; the Degree of Erasure is 30%–40%. The water flows from right to left.*

The cited example of the spectacular misattribution of the Siega Verde petroglyphs to the Pleistocene (the same considerations apply to the controversial corpus in the nearby Côa valley) raises one of the most important issues in assessing the possible antiquity of petroglyphs. History shows that most archaeologists are ill-equipped to estimate petroglyph age, and yet it is very easy to do this reliably. The many blunders made in this are largely attributable to a lack of understanding of the lithology, and its influence on the longevity of petroglyphs. No geological understanding is required to provide credible rough age estimates, if one applies the following theorem: *the susceptibility of any petroglyph to erasure by natural means (be it aeolian, fluvial, marine or by a biological agent) is proportional to the time it takes to create it* (Bednarik 2010: 110).

Since the time it takes to fashion a petroglyph is, or can become through replication, a known variable, the longevity of a petroglyph *is also predictable*. As noted above, schist (as in the cited cases) is in the order of 100 times more erodible than granite or quartzite, but in terms of percussion the difference is even greater (due to weathering rind). A 'standard cupule' (12 mm deep; Bednarik 1998a: 30) takes in the order of 40 000 hammerstone strokes to produce on sound and unweathered quartzite (as demonstrated by Giriraj Kumar; see Kumar 2010), but only two minutes on weathered sandstone, and in the order of 100 strokes on schist. Therefore, in order of magnitude and under otherwise identical conditions, a cupule on quartzite should outlast an identical cupule on schist around 400 times. This simple rule of thumb could have prevented many of archaeology's blunders over the past century and beyond.

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