Journal of Archaeological Science (2002) **29,** 000–000
doi:10.1006/jasc.2001.0711, available online at http://www.idealibrary.com on IDEAL®

The Dating of Rock Art: a Critique

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Received 17 October 2000, revised manuscript accepted 16 March 2001

The methods for estimating the antiquity of rock art are reviewed critically, dividing them into traditional and scientific approaches. The reliability of both is examined critically. It seems that the most promising options have attracted only limited interest, while those methods that have been afforded the most sustained research efforts have been discredited or provide only tenuous results. Thus the continuing difficulties in this field are to some extent attributable to opportunistic use of sophisticated but not always appropriate technology, combined with a systematic neglect of more modest but dependable methods.

Traditional Methods of Rock Art Dating

Without at least some idea of the age of rock art, this class of evidence is of no help to the archaeologist, because except in rare cases, it can be linked to archaeological constructs only by one factor: its age. Therefore the question of antiquity has been foremost in the mind of researchers for as long as rock art has been studied. The methods that have been employed to this end until recent times can broadly be described as falling into the categories of iconographic determination, stylistic claims, presumed technique of execution, association with archaeological finds by excavation, topographic proximity, weathering and patination study, superimposition of motifs, and a combination of two or more of these approaches.

Iconography

In this approach the observer attempts to relate the objects or activities supposedly depicted to archaeological or other time-related information. Common applications are attempts to identify depicted animal species, weapons or other objects, or to identify ways of life depicted in the art. Animal species may then be correlated with palaeozoological or ecological dating information, other objects (boats, ploughs, daggers, swords, halberds, rifles and so forth) with dated archaeological finds or historical documentation, supposed scenes of hunting with a hunting-foraging way of life, and supposed ceremonial depictions with archaeologically inferred practices.

This approach can produce useful supplementary information to scientific (testable) data where the iconography in question is particularly detailed, but it has been widely over-used and misused. Most rock art of the world is not adequately detailed, and many interpreters of rock art seem to be unaware that there is no a priori reason to assume that the producers of the rock art shared the observer's cognitive strategies of locating iconicity in graphic production. We know from the only blind test ever undertaken that a highly trained Western observer was incapable of correctly identifying animal species in a non-Western rock art corpus (Macintosh, 1977).

To complicate matters, our knowledge of the past distribution and appearance of animal species (did male cave lions have a mane?) is inadequate. Spatial and temporal distribution patterns available to us are not of animal species, but of their remains. The past distribution pattern of a live species may differ very significantly from that of its palaeontological remains, as a result of taphonomic processes (consider the cave bear). The depiction of an extinct animal may have been prompted by its remains, such as a frozen carcass. Animal imagery may be based on iconic hallucinations (narcotics such as harmaline and ibogane induce visions of large cats or snakes even in humans who have no concept of such real animals). Entirely fantastic creatures may be, and commonly are, depicted in rock art, so it would be hasty to assume that all rock art imagery is necessarily a reliable reflection of the artist's physical environment. Most contemporary or ethnographic religious art does not typically depict domestic scenes, it features unusual or mythological events or allegoric iconographies far too complex to be understood by an alien.

The literature on rock art is littered with the pronouncements of scholars telling us which species are depicted in the alien iconography and what it means. The case of the Chinese scholar who ''identified'' giraffes in the petroglyphs of the Helan Shan and therefore attributed them to the Tertiary may be extreme, but all similarly based dating claims are just

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as unsubstantiated, be they plausible or not. After all, hundreds of Australian Aboriginal rock art motifs seem to depict sailing ships and steamers in great detail, but it does not follow that such vessels were used by the societies concerned.

In all humans, including archaeologists, visual perception is subjective—determined by the cultural, cognitive, religious, ontogenic and academic conditioning of the individual. This is illustrated by the "identifications" of anthropomorphs with raised arms as "orants" (adorants, worshippers, supplicants) in much of Europe's rock art. We have no idea in which posture the people of the Neolithic worshipped, if indeed they did so. Modern observers have imposed their own values and mores on the mute evidence. This is not to say that such "identifications" are necessarily false, it simply means that they are not refutable, as they refer entirely to what happens within the neural and cortical systems of subjective intelligent organisms.

Few if any historically understood art traditions focus on domestically representative iconographies, yet it is assumed that in pre-Historic times this applied invariably. For instance, if animals or hunting scenes are said to be depicted, it is claimed that the culture in question was one of hunters-foragers-fishers. Yet the extensive and iconographically complex Gwion art traditions of the Kimberley, Australia, is entirely devoid of hunting depictions and has almost no animal figures, nor is there a single known female anthropomorph. We have no evidence that these rich traditions relate to an agricultural people, or to a population that lacked females. In many cases it has been proposed, based on perceived hunting arts, that these traditions must be pre-Neolithic, e.g. in the Spanish Levant, the Sahara and central India. These pronouncements are not accepted today (e.g. Beltrán, 1992; Hernández Pérez *et al.*, 1988; Muzzolini, 1990).

Style

This dating approach seems to be borrowed from art history, where historically documented art styles can assist in dating artworks. Nevertheless, the validity of extending this practice to traditions that are beyond ethnographic or historical access has not been demonstrated, nor can this procedure be said to be universally valid in art history itself. Individual artists may use different styles at different times (of their lives, or for different purposes), and reliable ethnographic work with contemporary producers of rock art provides no evidence that the artists of a specific group (clan, language group, even family) necessarily share a common distinctive style (see Mulvaney, 1995; Novellino, 1999, for pertinent ethnographic examples). Two closely related Aboriginal artists from the same family group and generation, living in the same locality, may depict the same object quite differently. While cultures do exhibit certain preferences in the genres of art they produce, intra-cultural variability is almost never of a more narrow range than inter-cultural stylistic variability.

Claims of stylistic dating seem to be based on the beliefs of their advocates to possess some special powers of detecting which variables shared by two or more pictures express ideological Gestalts that are specific and unique to a particular culture (Anati, 1976, 1994). The reluctance of practitioners to present the basis of their pronouncements in a repeatable and testable format is of concern, and where such tests have been conducted they yielded distinctly negative results (Bednarik, 1995*a*). Science has a clear preference for experiments that are repeatable, and processes of discrimination that are transparent. Attempts to render stylistic pronouncements transparent seem to founder on the intractable problem of translating subjective processes of perception into quantifiable, repeatable and thus testable entities.

Technique

Although numerous techniques have been used in producing rock art, most of them are repeated in various regions or periods. The possible techniques of making rock art, both as pictograms and petroglyphs, are necessarily limited—particularly those readily available to the peoples of early periods. The risks in using technique as a criterion of age or cultural provenience are therefore obvious. Variables of technique are susceptible to taphonomic selection and technique is frequently misidentified, especially in the case of petroglyphs.

Excavation

Where rock art has become covered by sediment, concealing strata may be considered to postdate the art. They may contain evidence that permits the estimation of the time of deposition. Sediments used in this way must not have been disturbed subsequently, or be the result of deflation or colluvial processes (Abreu & Bednarik, 2000).

The minimum dating of rock art by excavation has not been possible in more than a few instances. Cases of pictograms that have been discovered under archaeological deposits are particularly rare, while the prospects are considerably better for petroglyphs. There have been attempts in most continents to relate pictograms to pigment traces found within a nearby sediment (Combier, 1984; Linares, 1988; Macintosh, 1965; Wakankar, 1983), but such links were not satisfactorily demonstrated: the relative chemical taphonomies of the two pigments were not considered.

Dating via excavation is an indirect form of dating rock art, i.e. we have to accept inductive pronouncements on trust, such as the validity of the chronological association of charcoal and sediment, the claim that there was no recent contamination in the charcoal sample, and we must accept the archaeologist's pronouncements concerning sedimentological issues. Furthermore, dating of rock art by excavation provides never more than minimum ages.

Logically there are two different types of processes that may cover rock art with sediment strata. Rock art on either vertical or horizontal panels may be covered in situ (Crivelli & Fernández, 1996; Rosenfeld, Horton & Winter, 1981; Steinbring, Danziger & Callaghan, 1987), or a fragment of decorated rock may have exfoliated and fallen to the ground, where it eventually became covered by sediments (Fullagar, Price & Head, 1996, but cf. Roberts *et al.*, 1998; Hale & Tindale, 1930; Mulvaney, 1969: 176; Thackeray *et al.*, 1981). In the second case, dating attempts may well provide a fairly precise timing for the event of exfoliation, but not for the rock art.

Proximity

Archaeologists have often deduced the age of rock art from evidence found nearby. This idea is based on the intuitive perception that different activity traces of the same period are more likely to occur together than at diverse locations. The concept of activity foci in an "archaeological space" is thus ignored: the probability that two types of occupation traces found at one site are contemporaneous is millions of times greater at some random site in a featureless plain or desert, than it is at a site that was an occupation focus, such as a rockshelter, a cave, a spring or other favoured locality. Logic tells us that the probability that two activity traces at a site are of similar age is inversely related to its popularity as an activity focus: correlating rock art and other evidence of human presence in places that were likely to be much frequented is a practice based on false premises (Bednarik, 1989).

Possibly most rock art occurs at localities that can be assumed to have been activity foci for as long as the region has seen human occupation. Rock art usually marks "special places" in the landscape, and ethnography has often shown why that is so. Similarly, occupation sites are not randomly distributed, their locations are highly predictable, and they often coincide with the types of localities favoured in rock art production. Therefore any attempt to extrapolate the dating of any such occupation evidence to the same site's rock art is unacceptable if it is not corroborated by alternative and credible methods.

Flood (1987) has shown that 64% of the rock art sites of the Koolburra Plateau in north Queensland have no or very minimal sediment deposits and she observed stone tools at only 4% of these sites. The majority of them offers no evidence of human presence other than the rock art. If we insisted that rock art must be accompanied by occupation evidence, it would logically follow that most Koolburra rock art should not even exist. Indeed, the opposite may be more likely, particularly in cultures segregating rock art production from domestic activities. In one claim to have dated rock art by proximity, Lorblanchet (1992) constructed an entire 18,500-year petroglyph sequence at Gum Tree Valley near Dampier, Australia, after securing a single radiocarbon date from a shell, a surface find from near the petroglyphs, which is over twice as old as all other dates from the area.

Patination and weathering

The study of rock surface alterations in the service of dating rock art was the forerunner of scientific methods to address this issue. It was through the analytical and microscopic study of time-related changes to rock surfaces that "direct dating" was developed in the 1970s (Bednarik, 1979). Such changes may be reductive (resulting in loss of mass, e.g. erosion), additive (resulting in addition of mass, e.g. accretion) or transformational (resulting in chemical or physical changes). The aging process of rock surfaces has been considered relevant to estimating the ages of petroglyphs for at least 180 years: Belzoni (1820: 360–1) examined the numerous petroglyphs on Egyptian granite and noted the different stages of re-patination, compared to the evenly dark-brown accretion on the unworked rock surface. Among the researchers using this approach were Basedow (1914), Rhotert (1938, 1952), Mori (1965), Goodwin (1960) and Anati (1960, 1961, 1963, 1968), but statements about patination colour were often imprecise and sometimes misunderstood. For instance, Anati's key observation was misrepresented by two Australian writers. Anati's careful formulation,

> [I]n this region we know of no engraved surface from [Iron Age to recent] with a patination identical to that of the original rock surface. This seems to mean that in this area it took a minimum of 2500 years to reach . . . the natural colour of patina (Anati, 1963: 189)

was rephrased thus:

> . . . no engravings have re-weathered to match the natural dark rock surface. As some of them are associated with the Iron Age, Anati believes it takes a minimum of 2500 years for a thin, initial surface patination to form in that region (Edwards, 1971: 361).

An almost identical error had earlier occurred in Mori (1965: 63), who corrected himself (Mori, 1974: 89–90), substituting "*quasi scura quanto*" for "*tanto scura quanto*".

There are other significant difficulties with using patination and weathering states in estimating ages of petroglyphs. Both weathering and patination processes are highly variable, depending on petrography, climate, topography, surface geometry, chemical environment and other factors. There is no simplistic method of quantifying such changes, and attempts to do so (e.g. by measuring reflective properties of accretionary deposits such as rock varnish) have only resulted in unconvincing results. Moreover, the role of engraved groove depth on re-patination remains poorly understood, as does the influence of cation-scavenging micro-organisms and other processes of re-cycling accretionary matter. The use of patinae to estimate rock surface ages, including those within petroglyphs, requires an intimate understanding of the processes active in re-patination, and an ability to discriminate between those that are endogenous and the exogenous. Most literature relating to rock art dating elicits no confidence in the conclusions drawn from such observations.

Weathering rinds are zones of oxidation, hydration, hydrolysis or solution forming parallel to clast surfaces and their thickness is a function of time (Carroll, 1974; Colman, 1981; Colman & 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 it would only yield imprecise results (Knuepfer, 1994). Černohouz & Solč (1966) developed a method for determining the ages of macro-wanes on sandstones, claiming an accuracy of ± 10–20%. Although their hypothesis was subsequently refuted (Bednarik, 1992), they correctly recognized that weathering rind thickness is a function of surface geometry, and that this aspect is the cause of wane formation (see below).

Surface rinds often suffer from mass loss due to abrasion, erosion, frost action, *Salzsprengung* or exfoliation, which introduces a major error source. It may be preferable to measure subsurface rinds on submerged rock, as Colman & Pierce (1981) did, examining a large sample of clasts from B horizons of deposits. They proposed a logarithmic function involving two constants *a* and *b*, the rind thickness and time. However, this is of limited use in estimating the age of petroglyphs. Destructive sampling is usually out of the question, and non-intrusive methods, such as the use of the Schmidt hammer (Birkeland *et al.*, 1979; Burke & Birkeland, 1979; Day & Goudie, 1977; McCarroll, 1991), have attracted no interest.

Superimposition

Similarly, there is considerable scope in the use of superimposition of motifs which has hardly been explored so far. Some researchers have admitted that they find it difficult to decide which of two overlapping motifs precedes the other, especially in petroglyphs. Microscopic study of superimpositions offers many means of distinguishing between peck marks of different ages, or between paint residues applied over or under others. In the case of pictograms, microscopic examination of the edges of areas of paint residue should permit a clear definition of superimposition sequence. The only exceptions would be cases where significant mixing of paints has occurred, because the application of the superimposing paint layer has mobilized the earlier paint; or in cases of severe degradation of paintings or drawings. However, nanostratigraphic studies of paint layers have been used very profitably in Australia, by A. Watchman, J. Clarke and others, and have shown well-defined stratigraphies of up to about forty layers of paint and mineral accretions (Watchman, 2000; Watchman & Campbell, 1996).

Superimpositions of petroglyphs may seem more difficult to determine, especially if the time span between the two events is very short and differential weathering cannot be detected. However, even these cases yield their sequence if individual impact scars along the edge of the superimposition are examined under magnification. There are always diagnostic features, such as truncated scars, and in the case of abrasion petroglyphs, methods similar to those developed for portable art objects, called "internal analysis" by Marshack (1972, 1975, 1985, 1989, 1992), are usually most helpful. They involve the examination of features such as crossing grooves under a binocular microscope, and they fail only in the case of heavily weathered engravings.

Superimposition as such provides no age information, but it does permit us to distinguish the older from the more recent motif. Naturally they may be separated by only a very brief time, even minutes, so traditional forms of studying superimpositions are of very limited use. However, in combination with field microscopy, more reliable data are attainable, e.g. through comparative studies of relative erosion (Bednarik, 1995*b*). Indeed, when used together with methods of direct dating, the analysis of superimpositions can be a very potent tool of rock art science.

Estimating the Age of Rock Art Directly

"Direct dating" of rock art is contingent on two prerequisites: first, the physical relationship of the art and the dating criterion must be direct and indisputable; second, the propositions made concerning the chronological relationship of the rock art and the dating criterion (e.g. a paint binder, or the fracture surfaces caused by the impact used to make a petroglyph) should be scientifically testable (i.e. they should be refutable) (Bednarik, 1981, 1996). The second requirement excludes, for instance, the subjects supposedly depicted in the art as a form of direct dating. As noted above, iconographic "identifications" depend upon an untestable relationship between a form perceived by a subjective organism and the iconography of an alien culture.

The criteria of direct rock art dating are clear, precise and rigorous. Direct dating does not produce actual ages of rock art, it generates testable propositions about the relevance of specific physical or chemical data to the true age of rock art. The interpretation of the relation demands a considerable understanding of the dating technique used; of the circumstances of sample collection, processing and distorting factors; and of the limitations and quite specific qualifications applying to the stated results. *None* of the methods used in direct dating of rock art produces results that can be fully conveyed by some simple numerical expression, which is how they are often quoted in the archaeological literature, and archaeologically published results of direct dating are often presented in a misleading form. Such results should always be understood within the context they were acquired and within which the archaeometrists expect them to be seen.

Radiocarbon analysis of mineral accretions

The first technique to yield tangible "direct" dates for rock art was the determination of ^{14}C in a secondary calcite skin reprecipitated over petroglyphs in Malangine Cave, South Australia (Bednarik, 1981, 1984). Radiocarbon occurs in such deposits because about one half of its carbon derives from atmospheric carbon dioxide (Bögli, 1960; Franke, 1951, 1967; Franke & Geyh, 1970; Franke, Münnich & Vogel, 1958; Geyh, 1970; Hendy, 1969).

The approximate age of reprecipitated calcite is therefore measurable by determination of its remnant content of radiocarbon, at least in theory (Wendt *et al.*, 1967). But there are, as with most dating methods, certain reservations. Carbonate speleothems (Moore, 1952) may experience "radiocarbon rejuvenation", for example where porosity is available for the deposition of younger carbonate, as well as through isotope exchange in the presence of moisture. An indication of the extent of such rejuvenation are the bulk carbon ratios from Malangine Cave, where an accretionary ceiling deposit over petroglyphs yielded 5550 ± 55 carbon-years BP, while a thorium-uranium analysis provided an age of $28{,}000 \pm 2000$ years BP (Bednarik, 1999). This may provide an inkling of the massive distortion possible through the deposition of much younger solute in highly porous travertines.

The most reliable dates of this type are from densely crystalline deposits, especially those of stalagmites (Bednarik, 1981, 1998*a*; Geyh & Franke, 1970), but we know of no instances in the world where stalagmites conceal rock art. Rock art does occur frequently on their surface, so they might provide a means of securing maximum ages for it. Stalactites sometimes do conceal rock art but their crystal structure is less dense, so they are less suitable. Recent research has also illustrated the great time span a travertine skin may take to form: the outer lamina of such a deposit in Prung-kart Cave, also in South Australia, has provided a result of 1150 ± 80 BP, while the inner (and older) part of the same thin cutaneous deposit yielded 2660 ± 70 BP.

Carbonates are not the only mineral accretions datable by radiocarbon. Oxalates, by virtue of being salts of oxalic acid derived from the atmosphere or organic sources, also contain ^{14}C. Their frequent occurrence at some rock art sites has prompted their use in estimating the ages of rock paintings (Campbell, 2000; Watchman, 1990, 1991, 2000; Watchman & Campbell, 1996), but the problem of rejuvenation, which also applies to them, needs to be addressed. Ideally, the radiocarbon isotope concentration in the accretionary strata sandwiching the rock art refer to the time the organisms in question absorbed or assimilated atmospheric carbon, but there is an obvious time lag between that event and the precipitation of an accretion. Once deposited, these mineral layers are not necessarily closed carbon systems, they may remain open to several potential processes of distortion: rejuvenation through deposition of younger solute, deposition of organic matter of various sources, and isotopic exchange or fractionation. A. Watchman (pers. comm. Sept. 1994) has observed interstices in crystallized whewellite, one of the oxalates, which permit the precipitation of younger minerals subsequent to the initial deposition of the accretion. However, this potential is probably lower for oxalates than for the often much more porous carbonates.

Radiocarbon analysis of inclusions in accretions

Besides carbonates and oxalates there are many other forms of mineral accretionary deposits on rock surfaces that may conceal or underlie rock art, and while their essential components contain no radiocarbon, a variety of inclusions may be present in them. Among these residues are organic particles, such as pollen and spores, dead algal matter, micro-organisms and so forth. The most widely researched type of such mineral deposits are rock varnishes, dark-brown to almost black ferromanganous coatings found in many environments, but best preserved in arid regions due to their high-pH and low precipitation regimes. The involvement of micro-organisms in the formation of some forms of rock varnish was demonstrated by Scheffer, Mayer & Kalk (1963), although earlier observations had pointed in that direction (e.g. Francis, 1920). Analyses in the late 19th century and of the first half of the 20th century have frequently assumed non-organic sources (e.g. Loew, 1876; Merrill, 1898; Walther, 1924), while Blake (1905) recognized that the accretions must be at least partially of exogeneous origin. White (1924) suspected pollen to be a varnish-forming factor, mistakenly believing them to be rich in iron and manganese. The comprehensive analytical work of Engel & Sharp (1958) ushered in modern studies of rock varnishes (Allen, 1978; Krumbein, 1969; Krumbein & Jens, 1981; Perry & Adams, 1978; Potter & Rossman, 1977, 1979).

The cation re-cycling of such deposits by microbes accounts probably for at least some of the stratigraphical complexities of the varnishes, and it may also effect the incorporation of introduced matter, including carbonaceous matter. Its other common components are essentially clay minerals, commonly accounting for two-thirds of the deposit's bulk. It needs to be emphasized that the terms rock varnish and desert varnish probably refer to the stable products of a number of quite heterogeneous processes and sources, which merely lead to similar end effects. Indeed, the term has often been misused to describe a variety of *dunkle Rinden* and other accretionary deposits that are not rock varnish. Even weathering rinds with some iron patination have been so misidentified at times (e.g. Pineda, Jacobson & Peisach, 1988).

Since the early 1980s, Ronald I. Dorn sought to secure radiocarbon dates from supposedly organic substances extracted from rock varnishes from control sites near petroglyphs he sampled for his cation-ratio method (i.e. to calibrate CR ratios; see below). When the CR method (Dorn, 1983, 1986, 1990, 1992; Dorn & Whitley, 1984; Dorn *et al.*, 1992; Nobbs & Dorn, 1988) was widely rejected, Dorn resorted to applying AMS analysis directly to samples taken from petroglyphs. By that time Alan Watchman, who had played a pivotal role in refuting the CR method (Watchman, 1992), was developing the FLECS method for the same purpose (Watchman, 1993). Whereas Dorn continued to work almost exclusively with rock varnishes, Watchman diversified his technique and, having earlier experimented with oxalates, included analyses of other accretionary deposits, notably silica skins.

Under identical controlled conditions of a "blind test", Dorn (1997) and Watchman (1995, 1996) sampled accretionary deposits in the Côa valley, Portugal. Watchman analysed silica skins both over and under petroglyphs, and he took control samples from a surface of known age, a railway quarry, thus realizing that all the samples were contaminated. After locating the source of this distortion in graphite inclusions and correcting for it he provided minimum and maximum age estimates for a few petroglyphs. Dorn published his uncorrected but very similar results from different motifs at the same sites but then rejected them, saying that he had lost confidence in the entire method of analysing carbonaceous inclusions in mineral accretions (Dorn, 1996*a*, *b*, 1997). In his "change of perception" as he called it he admitted that he had noticed many "anomalies" over the years, but this had apparently not prevented him from confidently publishing and defending his results. He admitted in 1996 that for over 15 years he had made critical mistakes which had "blinded" him: he had falsely assumed homogeneity in his bulk samples even though it was clear that the organic matter was heterogeneous and of different ages; and he had assumed that the carbon was sealed into a closed system, until discovering that it was in fact an open system (cf. Beck *et al.*, 1998; Dalton, 1998; Dayton, 1997; Malakoff, 1998). The latter point, the susceptibility of the system to carbon rejuvenation and the widespread presence of organics in all mineral accretions and substrates, had been demonstrated previously (Bednarik, 1979), so these mistakes were unnecessary and Dorn's "conversion" should not affect the development of rock art dating.

Moreover, many of Dorn's arguments remain erroneous: his own carbon dates must be false, he said, because the cosmogenic radiation nuclide results from the same panels demonstrate that they "should be infinite" (Dorn, 1997: 106). Yet the ^{36}Cl data from these panels are random numbers reflecting migratory chlorides in a surface that is realistically not even datable by these means (because pre-exposure effects cannot be quantified, see below), so there are no such credible exposure age estimates from the sites concerned (Bednarik, 1998*b*). Even if there were they would be of no consequence to the dating of the art. Dorn (1997: 110) assumes graphite is organic matter (an allotropic phase of carbon, graphite is a mineral), and his description of the "flooding of weathering-rinds" with then modern carbon at the time of petroglyph manufacture (1997: 109) is incorrect. However, some of his other concerns are realistic and need to be taken aboard. In particular, as he emphasizes, organic matter can be deposited in joints long before they are exposed to the atmosphere, for instance in ferromanganous deposits ("inherited weathering" products of Dorn). It should be of concern that in most cases so far published we have in effect obtained bulk samples from what were described as rock varnish deposits, without any indication of what the target substances were, or from what precisely the carbon dates were secured.

Does radiocarbon analysis of carbonaceous inclusions in accretions have a future? Contrary to the tenor of Dorn's *mea culpa*, careful analysis of such deposits remains a valid method of direct rock art dating, particularly in dense and stable accretions such as silica skins. It does not provide numerical ages of rock art, but it does provide falsifiable data concerning the age of an entity that is physically related to the rock art in question.

Lichenometry

The term lichenometry refers to a calibrated-age dating technique attempting to provide minimum dating of rock surfaces using measurements of lichen thallus size or other indices of lichen growth. The use of lichens in the dating of archaeological remains was initially proposed by Renaud (1939) in Spain. Developed by Roland E. Beschel half a century ago, and first applied in the Austrian Alps (Beschel, 1950, 1957), this dating technique has been widely used in estimating the ages of recent geomorphic exposures, particularly glacial moraines (Worsley, 1990). Its use in archaeology has rarely been explored (Benedict, 1975, 1985; Bettinger & Oglesby, 1985; Broadbent, 1987; Broadbent & Bergqvist, 1986; Follmann, 1961; Laundon, 1980;

Winchester, 1988), and besides myself, no rock art researcher has ever sought to apply lichenometry to rock art. I investigated its use in the age estimation of relatively recent Austrian Alpine petroglyphs in 1965, but neglected to develop my experience further.

Although in favourable cases the method has been suggested to be effective to 9000 years BP and possibly even beyond (Miller & Andrews, 1972), it is commonly only precise up to 500 or so years (Innes, 1985). In geomorphological terms this makes it particularly useful for recent glacial deposits. However, most rock art of the world presumably falls within the effective range of the method, and some of it does occur together with lichen. Therefore the complete lack of interest rock art researchers have shown in lichenometry is astounding, bearing in mind its reliability, simplicity and obvious economy, together with its non-intrusive nature. This applies also to its potential to be used in tandem with other dating methods, such as amino acid racemization or radiocarbon analysis of thalli (Bednarik, 1996), provided their carbon is derived from the atmosphere. Instead there has been a worldwide campaign to destroy lichen at petroglyph sites, resulting not only in the denuding of thousands of sites, but also in the destruction or chemical contamination of accretionary deposits (Childers, 1994), removal of mineral mass (Jaffe, 1996), and acceleration of deterioration, while the claimed degradation remains unproven (Bahn, Bednerik & Stenbring, 1995; Tratebas & Chapman, 1996; Walderhaug & Walderhaug, 1998).

Two different approaches can be distinguished in lichenometry. In the direct approach, growth rates are determined by monitoring individual thalli over several years, typically of yellow-green specimens (subgenus *Rhizocarpon geographicum* agg.) which have provided the best results and are often abundant. The growth curves predict the thallus size through time. In the indirect approach, surfaces of known ages are used to calibrate growth rates empirically. Under ideal conditions, the lichenometric dating curves produced by both methods permit the age estimation of a thallus of unknown antiquity, but there are a number of qualifications. Ecesis (the establishment of a thallus) may not occur for a long time after the surface has become available, or it may occur almost immediately. This was countered by Beschel by focusing on the largest thalli present at a site. While the direct approach is more readily available, because it requires no chronological reference points in the construction of its curve, the indirect approach makes no assumption about ecesis lag and is less susceptible to environmentally determined growth fluctuations. Therefore the latter has been used in the majority of studies and would be the more relevant in rock art dating.

Different metrical and statistical devices have been used to collect lichenometric data, including the determination of the longest axis present (Anderson & Sollid, 1971; Bickerton & Matthews, 1992; Bornfeldt & Österborg, 1958), the mean of the longest and shortest axes (Erikstad & Sollid, 1986; Hole & Sollid, 1979), the shortest axis (Locke, Andrews & Weber, 1979) and the largest thallus surface area. Lichenometric dating curves are slightly parabolic, with a decreasing growth rate as the thallus ages. They can be related to rock art in one of two different ways:

(1) Where an engraved line has been made through an existing thallus, it must postdate it, and the lichen's growth will be impeded. The thallus provides a *terminus post quem* dating.
(2) Where a thallus has formed over a petroglyph, or encroached on a petroglyph surface, it provides a *terminus ante quem* reference, although one involving certain qualifications.

Microerosion analysis

The rationale of microerosion analysis is that, after a new rock surface has been created, by either natural or anthropic agents, it is subjected to chemical weather ing processes. This applies especially in unsheltered locations, and it results in cumulative effects that are a function of time, among other factors. While this is a fairly self-evident principle, the difficulty in using the results of such processes to estimate the age of a rock surface is that our understanding of them, of their effectiveness on different rock types, and of their susceptibility to environmental factors remains limited (Acker & Bricker, 1992; Busenberg & Clemency, 1976; Lin & Clemency, 1981; Oxburgh, Drever & Sun, 1994; Rimstidt & Barnes, 1980; Williamson & Rimstidt, 1994).

The term "*microerosion*" (one word, unhyphenated) refers to solution processes, the effects of which can be seen only at the microscopic level. Hence, for the time-spans we are concerned with in dating petroglyphs, only comparatively erosion-resistant rock types are of interest. In most cases this excludes especially sedimentary rocks. It must also be emphasized that microerosion analysis is not one specific method, but a cluster of possible methods around a basic concept. Two have so far been applied practically: the measurement of micro-wanes on fractured crystals (Bednarik, 1992, 1993), and the selective, often alveolar retreat in certain rock types of components that weather at vastly different rates (Bednarik, 1995*b*). Alternative indices of microerosion may also prove to be useful, but so far their potential remains unexplored.

Macro-wanes on rock are the results of progressive rounding of freshly broken rock edges. Černohouz & Solč (1966) claimed to be able to estimate the ages of such wanes to within 10–20% accuracy on two rock types. After observing similar rounding at the microscopic scale, on individual mineral crystals that had been fractured, it occurred to me that these phenomena were likely to obey the same physical laws. I explained these fundamental laws geometrically and mathematically (Bednarik, 1992, 1993), which made it possible to attempt dating by measuring wane sizes. These formulae explain how, under ideal conditions, wane development is related to time. (They explain also many other things in nature, for instance the geometry determining the course of temperature transfer within a solid object, or the geometry explaining how a solid body melts.)

In microerosion studies, the analyst scans the rock surface microscopically to locate crystals that have been truncated (either fractured by impact or truncated by abrasion) by the event to be dated (e.g. the petroglyph production). A statistically significant sample of micro-wane widths along the edges of such truncation surfaces is recorded under certain conditions and placed within an already available calibration curve for the region and mineral in question. Age estimates are prefixed with a capital E, indicating that the result is erosion derived.

Until we know much more about solution rates of common and suitable component minerals, we need to establish these rates regionally with calibration curves. The use of two (or more) curves for two (or more) different component minerals is recommended. Since it is unlikely that different minerals would all react similarly to past environmental changes, one would expect to detect irregularities because the corresponding values of a sample would appear displaced in the calibration graph's ordinate. No other dating method currently used in archaeology offers such a self-checking mechanism.

The accuracy of the method is probably poor at this early stage, because it depends entirely on the number and precision of calibration points. The principal potential variables in microerosion are temperature, pH and moisture availability. The first two are regarded as unimportant: variations in mean temperatures would not have affected solution rates appreciably; variations in pH would certainly apply back through time, but in the case of both amorphous silica and quartz, there is almost no change in solubility below pH 9. For alumina it is negligible in the central region of the pH scale, which coincides with most natural conditions. Quartz, then, can serve as a control against which to check the effects of pH changes on other minerals (Rimstidt & Barnes, 1980). It is expected that significant changes in precipitation would affect component minerals differently, and should thus be detectable by multiple calibration.

The microerosion method by micro-wane measurement has been used on petroglyphs in six blind tests now, in Russia, Italy and Bolivia (Bednarik, 1992, 1993, 1995*b*, 1997, 2000*a*). Archaeological expectations were matched in all cases except one, where, however, results matched those of other scientific analyses (Bednarik, 1995*c*; Watchman, 1995). Calibration curves are now available from Lake Onega (Russia), Vila Real (Portugal), Grosio (Italy), Qinghai (China) and eastern Pilbara (Australia), and the technique has also been applied in India and South Africa. The method has a practical time range from 0 to perhaps 50,000 years BP, which renders it particularly suitable for rock art. Results ranging from a few centuries to almost thirty millennia have so far been obtained.

While microerosion analysis is not thought to provide great accuracy, it is probably more reliable than most alternative methods of dating petroglyphs, and it is certainly cheaper and simpler than most. It does not attempt to determine the age of some accretion or other feature somehow relatable to the rock art, it focuses on the age of the actual petroglyph, the "target event" of Dunnell & Redhead (1988). No other method currently available does this. Finally, microerosion analysis involves no removal of samples, or even contact with the rock art, being a purely optical method. The valid arguments *against* microerosion analysis are that we have inadequate calibration curves for it, that its accuracy is inherently limited, that it can only be applied to certain rock types, and that it is unsuitable where the rock surface may not have been continuously exposed to precipitation (i.e. where it may have been concealed in the past by sediment, mineral accretion etc.).

Luminescence dating

Although the use of thermoluminescence (TL) for archaeological purposes was first mentioned as early as 1953 (by F. Daniels; cf. Michels, 1973: 189), the initial practical uses of TL were in the detection of nuclear and radiation hazards (Fleming, 1979). The term TL refers to the release of energy by crystalline solids when heated or exposed to light. Ionizing environmental alpha, beta and gamma radiation results in the release of electrons and other charge carriers ("holes") in these materials which become trapped in defects of their crystal lattice, such as impurities or chemical substitutions. These metastable charge carriers accumulate over time at a known and largely constant rate determined by the dose of the radiation. They can be ejected from their "traps" by an input of additional energy, causing them to recombine, which releases their excess energy as light, measurable in photons. This energy (TL) is therefore, with some qualifications, a function of the time since the material was last heated (e.g. ceramics or heating stones) or exposed to light (e.g. crystalline mineral grains in a stratified sediment).

TL dating made its debut in archaeology primarily to help in estimating the ages of pottery remains (Aitken *et al.*, 1968, 1971; Fagg & Fleming, 1970; Fleming, 1968, 1971, 1979; Kennedy & Knopf, 1960; Mejdahl, 1969; Sampson, Fleming & Bray, 1972; Zimmermann, 1967, 1971). The use of its principles to determine when sand grains had last been exposed to sunlight is a more recent development (Aitken, 1990, 1994; Huntley, Godfrey-Smith & Thewalt, 1985; Murray, Roberts & Wintle, 1997; Roberts & Jones, 1994; Smith *et al.*, 1990). It has been enthusiastically applied in Australia where archaeological dates exceeding 40,000 years were derived from two of the three luminescence methods now in use (Roberts & Jones, 1994; Roberts *et al.*, 1994, 1996). These are, besides standard TL analysis, optically stimulated luminescence (OSL) and infrared-stimulated luminescence (IRSL) analyses. The latter use either a green laser beam (OSL) or infrared light to free the trapped electrons.

Several technical difficulties apply to luminescence methods. An inherent problem concerns the annual environmental dose rate, which can be measured in the field or laboratory and which introduces the largest uncertainties into the method. For instance, substantial variability has been observed in K, Th and U, the principal sources of the environmental dose rate (Dunnell & Feathers, 1994). Indeed, variations in sedimentary K may be directly related to former human occupation. For a field measurement the dosimeter would have to be placed virtually in the same location as the sample for a year, which is physically not feasible. Another difficulty concerns the moisture content, an important factor that cannot effectively be determined for the duration of the time in question.

Then there are specific problems relating to dating that relies on measurements taken from saprolithic or regolithic sediments, i.e. sediments that comprise grains from rock that decomposed *in situ* within the sediment. This is particularly crucial in sandstone shelters being formed by mass exfoliation, one of the most common types of rock art sites. Rock fragments are prized from the walls and ceilings by *Salzsprengung* and other processes attributable to capillary moisture, they fall to the ground, become covered by sediment and then slowly decay due to ground moisture, becoming sand again. Only the surface grains of the rock fragments could have been exposed to daylight, while in the remainder of the material the "TL-clock" has not been "reset" (i.e. the traps have not been emptied of electrons and holes). Therefore most of the sand formed by this process would show a TL age of millions of years, and an attempt to date such a sediment would combine essentially two groups of age readings. Significant errors through the misinterpretation attributable to this effect have already occurred in rock art dating, notably at the Australian site Jinmium. Here, archaeologists using TL analysis claimed an age of 58,000 to 75,000 years for petroglyphs that were clearly and obviously of the Holocene (Fullagar *et al.*, 1996; cf. Roberts *et al.*, 1998). Such cases can readily be clarified by using OSL analysis instead, measuring each quartz grain separately and then discarding those results that are distinctly greater than the target cluster of data.

However, OSL dating too is not without significant qualifications. In TL dating it is customary to remove the outermost 2 mm of samples in the darkroom, to eliminate the need to account for dose rate alpha and beta radiation. This only penetrates to a depth in the order of microns, whereas gamma rays penetrate very much deeper. In the case of single-grain OSL analysis, this is obviously not possible, the grains are as a rule well under 1 mm in size. Their outermost rind may be removed by etching with hydrofluoric acid, but since the environmental radiation regime of the distant past cannot be known to us, absence of alpha-particle dose effects is not necessarily secured. Alpha and beta particles are far more ionizing in their effects than gamma radiation. Consequently such results remain provisional, even in their order of magnitude, until they can be tested or the concerns can be dismissed. This applies especially to results secured from deposits on rock surfaces, such as mud-wasp nests. Disequilibrium in the uranium and thorium decay chains might occur more readily at such locations (Aitken, 1985), and radon may be present in the sandstones concerned. These and other factors (changes in the hydrology due to past climatic changes) could have significant effects on past dose rates, which would yield correspondingly distorted age estimates.

An example of such experimental work are the OSL analyses currently being conducted of quartz grains from mud-wasp nests in northern Australia, some of which are physically related to rock paintings (Roberts *et al.*, 1997, 2000). Their study involves the added difficulties of having to assume that the mud-nests were built in adequate daylight to bleach all grains, or that the inner parts of the droplets of mud transported by the wasps were always sufficiently exposed to the sun. The first set of results reported consists of 15 OSL dates ranging up to 1800 years BP, plus three dates of about 10 times that age. It is hard to believe that such fragile structures should survive for up to 24,000 years, particularly as the authors mention no evidence of mineralization. I have observed totally mineralized mud-wasp nests at Toro Muerto, a rock art site in central Bolivia, which are only of the late Holocene. Moreover, the claim that one anthropomorphous painting at a Kimberley site is more than 17,000 years old is difficult to reconcile with Watchman's radiocarbon dates of the late Holocene, for similar figures in the same region (Watchman *et al.*, 1997). Finally, it is rendered less credible by the taphonomic factor that nowhere else in the world is there a Pleistocene painting tradition that has survived in such large numbers of motifs out of caves.

It is to be hoped that these exciting claims from the Kimberley in Australia will withstand falsification attempts successfully, but for the time being the results need to be considered carefully. They refer to the first attempt to introduce luminescence dating into rock art science and deserve every encouragement, but as with any pioneering endeavour of this type it is important that archaeologists exercise the requisite restraint in interpreting such preliminary and experimental results. Certainly this methodology is among the most promising in the age estimation of rock art, it applies not only to nests of mud-wasps, but also to similar structures by ants, termites and birds, all of which occur widely together with rock art.

Other possibilities

A group of radiometric or isotopic methods, *uranium-series dating*, is based on the decay series of the uranium isotopes to lead. Uranium-238 is by far the most abundant radioactive element in the Earth's crust, consequently its decay products are widely dispersed in the lithosphere. Precipitated in surface minerals it produces daughter isotopes, and where this process occurs in a closed system, it provides a good measure of the length of time since the formation of the mineral. Several specific decay processes have been used for dating, whose relevance and applicability depends upon their effective time range (determined by the half-life of the decaying isotope) and sample availability. In rock art dating we deal usually with Late Pleistocene and Holocene ages, and in this range only $^{230}Th/^{234}U$, $^{231}Pa/^{235}U$, ^{226}Ra, $^{231}Pa/^{230}Th$ and $^{230}Th/^{232}Th$ may be relevant. The preferred materials for analysis are carbonates (particularly reprecipitated carbonates, such as travertines, speleothems, corals and marl, also mollusc shells, bone and teeth) but other materials may be suitable. One of these methods, thorium-uranium dating, has been used to estimate the minimum ages of two petroglyph traditions in Malangine Cave, South Australia, which were both concealed by subsequent secondary calcite skins (speleothems). Among the results is one of the oldest credible rock art dates currently available, the conservative minimum age of $28{,}000 \pm 2000$ years BP for Karake-type petroglyphs on the ceiling of the cave (Bednarik, 1999).

No other attempts have been made to use any of these methods in estimating the age of rock art. Indeed, the number of dating techniques that have potential applications in rock art dating but have apparently never been used is considerably greater than the number of those that have been applied. Even in the case of rock varnish, whose significance to direct rock art dating is beyond dispute, several dating methods appear to be more reliable than the much-used but now discredited CR technique. For instance, it is self-evident that this ferromanganous accretion would be well suited to palaeomagnetic dating, and yet none of the projects favouring CR dating has included a comparative study using this method (Clayton, Verosub & Harrington, 1990). Uranium was known to precipitate with the Mn-oxides of rock varnish even before the CR method was conceived (Knauss & Ku, 1980) and uranium-series dating would provide more reliable information than the supposed leaching indices derived from the ratio of three cations. Rock varnishes contain clays that may be susceptible to potassium-argon dating where their ages are great enough, and if they conceal any quartz grains these may be datable by luminescence analysis. The latter would also offer far more reliable estimates of minimum age than the CR method is likely to provide, and yet again no comparative study has been attempted by the protagonists of CR dating.

The use of *potassium-argon analysis* may seem a desperate measure in this context, because it is widely seen as a method specifically for analysing lava flows of the "middle time range" (Miocene to Middle Pleistocene), but the method has been used even for Holocene materials (Evernden & Curtis, 1965: 349; Miller, 1970) and the half-life of ^{40}K (1·3 billion years) provides an effective range covering much of our planet's history. Also, the technique can be applied to a wide variety of materials, including muscovite, biotite, orthoclase, microline, leucite, sanidine, obsidian, glauconite, illite, carnallite and others (Gentner & Lippolt, 1970). Recent lava flows, tuffs and sedimentary rocks containing such minerals are often directly related to petroglyphs, and in such cases $^{40}Ar/^{40}K$ dating might be relevant. An alternative version of the method, intended to overcome the often non-homogenous distribution of the ^{40}K, is to irradiate the sample in a nuclear reactor to convert the ^{39}K into ^{39}Ar. The sample is then heated progressively to record the ratios of $^{39}Ar/^{40}Ar$ or $^{36}Ar/^{40}Ar$, and $^{39}Ar/^{36}Ar$. The slope of the curve of plotting the ratio $^{40}Ar/^{36}Ar$ against that of $^{39}Ar/^{36}Ar$ will be related to the age of the specimen (Miller, 1970).

But besides these and other technologically complex potential methods for rock art age estimation, there are various readily available approaches available which attract no interest. For instance, the formation of *macro-wanes* on rock is clearly time-related, and the processes involved seem reasonably straightforward. Just as the penetration rates of weathering processes are greatly influenced by surface contour (rocks weather faster on convex aspects), erosion affects protruding aspects more than flat surfaces. Černohouz & Solč (1966) have described a method for determining the ages of blunted edges on sandstone that uses two constants, the angle of the edge and the distance of retreat at the edge. While the intent of Černohouz & Solč is admirable, their theoretical model is false, because the distance of retreat at the edge cannot be measured; the rock also retreats on the two surfaces forming the edge (Bednarik, 1979). However, the underlying geometric principles of wane formation were subsequently explained (Bednarik, 1992), and they apply to macro-wanes as much as to micro-wanes. No further research has been undertaken into using macro-wanes in geomorphic or rock art age estimation work.

Belzoni's (1820) idea of quantifying *patination variations* in petroglyphs has certainly been shared by many rock art researchers since, but there are no credible attempts to test it. The majority of descriptive or "analytical" publications about petroglyphs contains comments on states of re-patination and their relevance to antiquity, but hardly any of them even attempt to define the type of patination. The term "patina" describes merely a visually obvious skin on rock surfaces which differs in colour or chemical composition from the unaltered rock and whose development is a function of time. It can be accretionary, it can be reductive (result of solution, e.g. in sedimentary silicas), or it can have involved not a change in bulk, but one in the composition or surface characteristics. In other words, stating that there is a change in colour with time without saying what caused it, or without quantifying that change and calibrating it with reference to time, is of no consequence to the matter at hand. Some 180 years after Belzoni presented his idea, I have made an attempt to address his question. Having discovered a series of dozens of dates hammered into a few granite boulders, which show distinctive scaling of colour relative to their ages, I have recently conducted an analysis of them. Using the IFRAO Standard Scale and appropriate computer software to re-constitute true colours with very high precision, I plotted the measured colour changes against time (in prep.). This experiment was conducted on rock almost identical to that referred to by Belzoni (coarse granite), in a region of very similar climate, the Australian Pilbara (very dry, sub-tropical), so it does provide a valid answer to him. It does not, however, provide the means for dating all re-patinated petroglyphs.

Issues relating to the dating of pictograms

While the availability of datable substances relating to the making of pictograms may foster an expectation that more reliable results can be secured from this form of rock art, this is not necessarily reflected in the results tendered so far. They range from the very reliable to unconvincing and probably false claims, so it is important to consider each result on its own merits. This applies especially to startling or sensational claims that differ significantly from expectations, as has been the case in several projects of recent years.

Beeswax figures are a local but widespread feature in northern Australian rock art, where they have been reported from western Arnhem Land (Brandl, 1968; Chaloupka, 1993), Kimberley (Welch, 1995), Reynolds River, Keep River and Groote Eylandt. Of all the rock art types in the world, these figures are perhaps the most amenable for dating. Not only is there always adequate datable substance available, the physical properties of the beeswax render it unlikely that it would have been used in any but nearly fresh condition, so the time of the production of the wax, which presumably approximates its radiocarbon age, is unlikely to differ significantly from the time the art was created. Numerous such dates have already been secured from beeswax figures (Nelson *et al.*, 1995). Nelson (2000) report radiocarbon age determinations from 137 figures from 16 sites in the Northern Territory. These range from the present time to about 4000 BP, but the overwhelming majority of the ages falls within the last 500 years, and all except four are under 1500 years. The apparent rarity of the few significantly older samples as well as the dates' chronological distribution suggest that this result reflects taphonomic dynamics (Bednarik, 1994*a*). The large number of dates available renders it possible to detect a typical temporal distribution curve implying a taphonomic threshold of about 800 years BP for beeswax figures.

Residues of rock paintings, stencils or drawings have often been concealed by *accretionary deposits*, such as carbonate, silica and oxalate skins or crusts. These and the inclusions they frequently contain have been used to secure data intended to assist in estimating pictogram ages. In interpreting such data it is important to appreciate the many qualifications that apply to them (see also comments elsewhere in this paper). The most spectacular results of such work are from Australia, where at several sites series of superimposed painting events, separated by deposition of accretions, have been analysed, and Watchman (2000) has even detected paint residues in substrates that lack any surface indication of the presence of rock art. At Walkunder Arch Cave, Queensland, a series of 10 radiocarbon dates has been obtained from finely stratified accretions totalling only 2.11 mm thickness (Campbell, 2000). These dates are in sequence and range from 29,700 to 3340 carbon-years, spanning a history of about 26,000 years. The sequence includes three painting events, at $28,100 \pm 400$, $16,100 \pm 130$ and $10,400 \pm 90$ carbon-years BP. The extraordinary precision of these nanostratigraphic techniques and the availability of sequences rather than individual "dates" certainly enhances the credibility of such results, but they are still subject to a variety of qualifications. Most important of all, until radiocarbon sampling can be focused on specific substances or compounds, i.e. at the object or molecular level (Bednarik, 1996), we cannot know what it is we are dating, and the ubiquitous presence of datable carbon in rock substrates, together with the openness of the carbon system limits reliability of this approach.

The issue is well illustrated by another Australian project. Loy *et al.* (1990) claim to have identified blood residues at two Australian rock art sites. Underlying sub-modern paintings, "fragmentary panels of weathered dark red pigment" were reported at Laurie Creek (Northern Territory) from which Loy secured a proteinaceous substance he identified as human blood. An accelerator mass spectrometry radiocarbon date of $20{,}320 + 3100/-2300$ years BP was obtained from this substance. His co-author Erle Nelson, however, had "second thoughts" about the results and re-sampled the surface deposit (Nelson, 1993). He found that the reported pigment layer was of naturally re-precipitated iron oxides of a type common on sandstone surfaces, and he detected organic matter at various surface locations that bore no paint. When he re-analysed the deposit from which the original data had been obtained, he found only very low concentrations of protein. He reports that "the material dated was not proteinaceous, and therefore not a remnant of human blood. . . . It is not a date with any archaeological meaning". Loy (1994) maintains that there was mammalian IgG present at the sampling site, saying that Nelson's new data confirm the presence of organic carbon in the samples. Indeed they do, but organic carbon is also present in the supposedly undecorated rock surface, and occurs as I have maintained since the 1970s on all rocks. Moreover, Loy's views have been soundly refuted by Gillespie's subsequent research (1997) who has also questioned similarly derived results from another site. Conversely, identification of a natural deposit as a rock painting had also occurred in an American rock art dating attempt (Loendorf, 1986; cf. Bednarik, 1987).

Endeavours to secure "direct" *radiocarbon dates from paint residues* are based on the assumption that their organic content reflects binders or incidental vegetable inclusions that are of essentially the same age as the rock art. Binders were frequently used in paint preparations, and presumed brush fibres and other material relating to paint preparation have been detected in rock paintings (Cole & Watchman, 1992; Watchman & Cole, 1993). However, unless the substances are isolated and identified before processing for carbon analysis, there is no certainty that such radiocarbon dates refer to the age of the paintings concerned. The most commonly used rock art pigments are ochres, i.e. oxides or hydroxides of iron, and Ridges, Davidson & Tucker (2000) have confirmed that samples of such minerals from rock art regions comprise substantial amounts of organic matter, such as lichen and bacteria. Ridges *et al.* detected phototropic microbes which could have radiocarbon ages that are unrelated to their actual antiquity, through recycling old organic carbon. Of particular concern should be their detection in one sample of approximately 5000-year-old unidentified organic matter. Had this sample been used in a rock painting, it would have provided a severely misleading carbon age. On the other hand, applied paints can be the target of bacteria and algal growths, as we know only too well from some decorated Palaeolithic caves in south-western Europe. Moreover, the ubiquitous presence of organic matter in probably most lithospheric surface zones (Bednarik, 1979; Nelson, 1993) questions the reliability of such dates in any case. Whether the paint residues concerned are on the surface now or are sandwiched between layers of mineral accretion is in principle irrelevant. Even the presence of a sequence of dates is no absolute guarantee, because if there were continuous contamination of a cumulative stratigraphic sequence the dates might well be in sequence, but they would still be invalid.

With carbon dates from paint residues of *charcoal pigment*, these considerations are perhaps less paramount, though still applicable. Since such samples consist primarily of charcoal, the impact of any distorting contaminations present would be somewhat lessened, but other reservations apply to such dates. The carbon isotope result of charcoal never refers to the event of rock painting, it can at best only indicate the time when the tree from whose wood the charcoal derives assimilated carbon dioxide from the atmosphere (Bednarik, 1994*b*, 1996, 2000*b*). This is followed by the death of the tree or branch, its oxidation, and finally the selection of the resulting charcoal as pigment. This chain of events may occupy only decades or centuries, but it may equally well take 10s of millennia. There is also the possibility, however remote, that fossil wood had been used (Schiffer, 1986; Fetterman, 1996). Much more reliable is the method of analysing soot deposits on a cave ceiling, but this has so far been successful only at one site (Clottes *et al.*, 1995).

Two specialized methods have been developed to process samples from pictograms for carbon nuclide analysis, and to guard against some possible contaminants. One uses a low-temperature, low-pressure oxygen plasma to oxidize the organic matter (Armitage, Hyman & Rowe, 2000; Chaffee, Hyman & Rowe, 1993; Ilger *et al.*, 1996; Russ *et al.*, 1990). The second is "focused laser extraction of carbon-bearing substances" (FLECS; Watchman, 1993): a small sample of a rock art-related substance is combusted with the help of a laser, and the resulting carbon dioxide is then reduced to a graphite target for accelerator mass spectrometry (AMS) radiocarbon dating. However, both methods cannot discriminate between different types of organic matter. They are certainly "direct dating" methods in the sense of the term's definition, but their results are not readily relatable to the actual age of the art concerned. This is because they cannot be targeted on a particular substance, but may in fact provide composite results to which any organic matter present in the sample has contributed. This can include organic pigment or binder, microscopic biota, lipids, proteins, carbohydrates, vegetable remains such as brush fibres, airborne debris and so forth. It can also include natural graphite, whose occurrence with rock art Watchman (1995) has already demonstrated and which has a significant ageing effect on samples. It is therefore likely that two dating results from different locations on the same motif, using precisely the same technique, will provide different results, depending on the proportions of the contaminating components (see McDonald *et al.*, 1990 for greatly incompatible results from charcoal of a single motif). This even renders it impossible to make precise allowance for the contaminants by determining them and their magnitudes chemically or microscopically from a control sample: their relative proportions may differ locally. Other concerns expressed about the uncritical acceptance by archaeologists of experimental data of this kind are that the petrology and morphology of the rock substrate may be inadequately accounted for; the presence of unknown contaminants; the neglect of ^{13}C measurements; effects of variations in techniques; and that indiscriminate sampling in the course of applications of this immature methodology may not be justified.

Amino acid *racemization* may have valid applications in pictogram dating, despite the severe limitations imposed on this method by the extreme susceptibility of the reaction to temperature (Murray-Wallace, 1993), and despite Denninger's (1971) refuted attempt of dating South African rock paintings. Amino acid residues can certainly be preserved in rock paints (McCarthy, Payen & Ennis, 1994).

Pitfalls in Rock Art Dating

Radiocarbon analysis

This technique produces no calendar years or absolute dates, it yields radiocarbon years, which are expressed as sets of statistical probabilities. To treat them as actual ages or to "calibrate" them as such is therefore unsatisfactory. Usually such results are expressed with tolerances stated at one standard deviation, which means that under ideal conditions the true "age" of the sample should lie between the tolerance values in 68·26% of cases. But there are many problems with this assumption, and even if they did not exist such a result is not a "date" that one can simply compare with some other data, such as another "date". In comparing two such results, the probability that the deductions we are likely to make from them are all true is only 46·59%, or 31·80% for three dates, and so on. If we compare statistical probabilities we must not treat them as finite facts or figures, and when we compare sets of probabilities derived from two different methods (e.g. ^{14}C and TL analysis) we are also bringing into correlation two sets of complex qualifications—we are comparing oranges and apples, and the logical underpinning becomes practically unmanageable.

But these simple qualifications refer to ideal conditions which in any case do not exist in reality. The radiocarbon technique relies on three false assumptions: that we know the atmospheric concentration of carbon isotopes in the distant past, that we use the isotope's true decay rate, and that the decay process has not been influenced by other factors than the decay rate. In considering just the first of these limiting factors we could examine just why the initial atmospheric concentrations of ^{14}C and $\delta^{13}C$ are not known. There is, for example, an intricate relationship between atmospheric $\delta^{13}C$, climate and vegetation: different plant communities facilitate specific carbon regimes (Cole and Monger, 1994; Robinson, 1994). This introduces yet another variable, the effect of which is an unknown factor and questions the accuracy of Pleistocene radiocarbon dates. Vulcanism would tilt the regime in favour of ^{12}C, rendering atmospheric carbon balance apparently "older", and the effects of cosmic rays cannot be known for past periods.

These systematic and other variables affecting the result (e.g. the de Vries effect, isotopic fractionation, differences in laboratory treatment, laboratory error) represent reasonable risks because they are to some extent expected. Contamination is always possible, before, during and after sample collection (e.g. oil film on supposedly sterile aluminium foil). Then there is the plethora of environmental variables that can significantly affect carbon isotopes. Among them is the hard water effect (the deposition of calcium and magnesium salts from aqueous solution in ground water), exchange with the atmosphere, humic acid, and especially the effect of the introduction of very old carbon from a variety of sources. Just as a tree growing next to a busy motorway is likely to derive much of its carbon by assimilating exhaust fumes from vehicles burning ancient hydrocarbons, an animal or plant may contain high levels of carbon derived from a limestone environment. Thus the ^{14}C level in the ivory of an elephant, related to its food source, may differ according to the geology of the live animal's environment. While the gaseous emissions of volcanic eruptions may age a sample, major forest or grass fires may make it appear younger, and past variations in cosmogenic radiation may have either effect.

Archaeologists have already introduced inductive reasoning into rock art dating in several ways. Accordingly it has been assumed that charcoal pigment found in rock paintings must be of the same age as the picture. There is clearly no connection between the two, except that the picture should be more recent than the date secured from the charcoal, but the difference may be 10s of millennia. When a motif yielded two different dates this was seen by various authors to prove that repainting had occurred, when in fact there are several alternatives possible:

The true age lies outside stated tolerances, of one or both samples.

Charcoal fragments of different ages were used at the same time.

The picture was retouched at a later time.

One or both samples are contaminated.

One or both samples provided erroneous results.

Differences in laboratory procedures.

Any combination of some of the above factors.

Thus archaeological deductions drawn from charcoal paint dates may be essentially valid, or they may quite easily be false. Bearing in mind that as a rule these data were acquired by AMS analysis from exceedingly small samples, measuring only in the order of milligrams of carbon, the kinds of interpretations of these results we have already seen proliferate in the literature are unwarranted.

Determination of cation leaching

This technique serves as a classical example of the pitfalls in rock art dating. Hailed by some as the miracle cure for petroglyph dating for about a decade, it has now been abandoned, particularly after its inventor and advocate effectively rejected its method of calibration.

Cation-ratio dating (CR) is a classical example of a method providing results that must be expected to be highly variable depending on sampling site. This method seeks to calibrate the rate of leaching of the more soluble cations of rock varnish (K and Ca) relative to the supposedly more stable Ti content (Dorn, 1983, 1986). After it was developed during the 1980s, its reliability and accuracy were seriously challenged (cf. Nobbs & Dorn, 1988 and comments; see also Bednarik, 1991; Bierman, Gillespie & Kuehner, 1991; Watchman, 1992). Dorn (1990) eventually conceded that it is an "inferior" method and that it is susceptible to an excessively high number of variables (1994).

One of the numerous flaws of this technique is the great variability of the crucial indices, the cation ratios. For instance, sedimentary rocks have great variations in Ti on a millimetre scale, e.g. due to a single layer of heavy minerals, or spotting effects of low-grade metamorphism. Such differences of cation ratios in the host rock may be reflected in those of the varnish over the motif area. Anomalies can occur not only in Ti, but also in Ca and K. In addition, numerous other factors affect the CR of rock varnishes: the proximity of soil, oxalate, amorphous silica or organic matter; lichens, fungi, pH, water run-off; and of course relative exposure to leaching or weathering. Moreover, the ratio will differ laterally, depending on how the varnish spreads out from initial colonization sites. Structurally, rock varnishes are as a rule highly variable, again on a millimetre scale, which is precisely why I abandoned the idea of using them for dating in the 1970s (Bednarik, 1979). The extent of erosion episodes or of cation scavenging by micro-organisms, which certainly invalidate CR dates, is well demonstrated by SEM photographs of varnish stratigraphies. This applies also to episodes of microcolonial fungus attack or lichen activity. Even the fundamental proposition that cations are uniformly soluble is open to question. After all, they do not occur as pure elements and it would seem to be the solubility of the minerals they occur in that determines the relative leaching rates. The solubility of diverse Ti-minerals relative to different Ca-minerals varies considerably (some minerals in fact contain both cations, such as titanite). All of the factors determining the cation ratio of a weathered rock varnish are locally variable, besides distorting that ratio, and this probably explains the significantly discordant results of Watchman's re-sampling program (1992).

CR analysis has not provided any accepted results, its methodology is fundamentally flawed and it does not provide a valid method of estimating the ages of rock art or of geomorphic exposures.

Cosmogenic radiation nuclides

Another analytical method strongly supported by Dorn since at least 1990 is the determination of maximum rock exposure ages supposedly attainable from measuring the presence of cosmic ray-caused radiation products in rock. This can never provide actual age estimations of rock art, and even the claims that it can offer mere exposure ages need to be carefully qualified. The nuclides available for measurement by this method are ^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, ^{36}Cl and ^{41}Ca, using accelerator mass spectrometry and noble gas mass spectrometry. Among the key qualifications are the need to be certain the sample comes from a closed system, and the production rates of the various nuclides need to be better calibrated than they are at present. There is a preference for using more than one radionuclide in tandem, and in particular the pair ^{10}Be and ^{26}Al is thought to give good results from quartz (Nishiizumi *et al.*, 1989). Their half-lives are suitable for Quaternary deposits (1·5 Ma and 725 ka respectively), contamination can be dealt with effectively (Brown *et al.*, 1991), and their production ratio of about six is not thought to be much affected by altitude and latitude. Another pair used is ^{3}He and ^{21}Ne, which is suitable for older surfaces, but helium data from radiocarbon-dated Hawaiian lava flows imply very coarse precision (Kurz *et al.*, 1990; Rubin, Gargulinski & McGeehin, 1987).

The production rates of the radionuclides in a rock surface layer that result from cosmogenic radiation are variable according to topographic exposure, altitude, latitude, oscillations in radiation, overburden and time. Even past fluctuations in the earth's magnetic field may effect variations (Kurz *et al.*, 1990). It is of concern that the method, which is almost as old as radiocarbon dating (Davis & Schaeffer, 1955; Lal, Malhotra & Peters, 1958; Lal & Peters, 1967), remains poorly calibrated, and its only two applications in archaeology, at Stonehenge (Williams-Thorpe *et al.*, 1995) and Côa valley (Phillips *et al.*, 1997), produced apparently false results (Bednarik, 1998*b*). Estimates of production rates (Lal, 1991; Yokoyama, Reyss & Guichard, 1977) remain severely hampered by the lack of appropriate reaction cross sections for neutron-induced spallation. It has been difficult securing data from polished rock surfaces of known ages (Cerling, 1990; Kurz *et al.*, 1990; Nishiizumi *et al.*, 1989; Phillips *et al.*, 1986; Zreda *et al.*, 1991), and the well-established ages of lava flows are generally very young, usually of the Holocene (Poreda & Cerling, 1992), which permits only the three nuclides with the shortest half-lives to be considered.

Cosmogenic radiation analysis has been applied at a rock art site, Penascosa in the Côa valley, northern Portugal (Phillips *et al.*, 1997). Using the less attractive ^{36}Cl nuclide, geologically and historically unacceptable results were obtained, and the analysts made several crucial errors in their interpretation of their data. Most importantly, they ignored the high solubility and mobility of chlorides, and the susceptibility of subterranean strata to the nuclide conversion process, even though both factors were demonstrated by their own data (Bednarik, 1998*b*). Moreover, their method necessitates the assumption of a rate of erosion retreat (Phillips *et al.*, 1990), while at the same time any surface retreat over tens of millennia would effectively exclude the survival of the petroglyphs they were trying to date. These several self-contradictions render the specific dating attempt of Phillips *et al.* (1997) refuted, but this does not imply that the method itself is discredited. Its use in estimating the age of geomorphic exposures is certainly valid, particularly in cases where exposure occurred on a massive scale, such as by meteor impact, major tectonic adjustment or quarrying operations. In such circumstances background radiation products would be either absent, or hopefully negligible. However, such conditions rarely apply in rock art dating, for which the determination of cosmogenic radiation nuclides therefore has no relevance.

Erosion retreat (“micro erosion”) analysis

This method is of quite limited application in rock art analysis but it must be mentioned here because some archaeologists have consistently confused it with microerosion dating (e.g. A. Rosenfeld, cited in Zilhão, 1995). “Micro erosion” is actually a misnomer, as it deals with processes that occur at the macroscopic rather than the microscopic level, and a more suitable name is *erosion retreat analysis*. It refers to the measurement of the retreat of rapidly eroding rock surfaces, especially those on sedimentary rocks (High & Hanna, 1970; Atkinson & Smith, 1976). Its primary use would be in rock art conservation research rather than dating applications. This retreat may be attributable to solution or granular exfoliation, and is often a combination of the two processes.

Essentially 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 reference stud (Smith, 1978). With this instrument, the gradual retreat of a rock surface can be monitored over a period of many years, and the data so gathered can provide good information concerning petroglyphs 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. However, it has not been used for estimating the age of any rock art so far and is likely to be of only limited applicability.

Summary

Scientific dating of rock art has been conducted for about two decades, and has resulted in significant improvements in our understanding of rock art chronologies. It has also led to some spectacular changes in perception and fundamental misinterpretations of data.

Two types of radiocarbon results have been derived from mineral accretions over or under both paint residues and petroglyphs. In one type it has been attempted to estimate the time of the accretion’s deposition from its principal component (carbonate or oxalate), while incidental inclusions were targeted in the second. Whereas the limitations of the first approach are appreciated (Bednarik, 1998*a*, 1999), there is disagreement over the second. I had long been sceptical, at least in respect of specific types of deposits (particularly ferromanganous accretions), after establishing during the 1970s that their carbon isotope system was essentially open (Bednarik, 1979), and that carbons occur widely in surfaces and substrates. Others, however, claimed for many years to obtain secure dates from such deposits. Dorn in particular argued strongly in support of radiocarbon analysis of rock varnishes, including its use in calibrating the cation-ratio method he developed (Dorn, 1983). But in the mid-1990s he recanted his results, arguing against them and those of others using similar approaches. However, it might be premature to extrapolate concerns to all forms of accretion; the prospects of finding closed systems are significantly better in silica skins and oxalates.

Carbon isotope analysis of inclusions in mineral accretions spatially related to rock art provides “direct dating” evidence, but it does not date the rock art. To succeed in this, the analytical results should be determined either at the molecular level (i.e. be from a single identified compound) or specific object level (i.e. be from an identified organic object, such as a brush fibre). Bulk sampling by FLECS or oxygen plasma treatment permits no such discrimination and probably provides no reliable dating. Similarly, carbon dates from carbonates or oxalates are certainly “direct”, but presently available data do not permit us to test the true relationship between such results and the age of the rock art effectively. In all these cases results should be regarded as relevant “preliminary dating information”.

Another crucial issue separates all dating approaches in rock art science into two groups: those expected to provide locally variable results, and those presumed to yield uniform results from any part of a specific rock art motif (Bednarik, 1996). The first type fails to meet the demand of repeatability, which science favours philosophically, and includes techniques already considered to have failed (e.g. cation-ratio, cosmogenic radiation products). The second type includes particularly "geochemical or geomorphological" approaches, using such phenomena as micro-erosion, surface retreat, weathering rinds, wanes, and possibly luminescence and others.

In relation to alternative methods, two factors stand out. First, only a minute portion of the possible options has been explored in detail, and there are numerous perfectly promising options that have not attracted any interest, have barely been attempted, or are used only rarely. Several of these alternative methods are evidently more robust and more reliable (particularly those focusing on geomorphic variables), which renders their neglect particularly perplexing. Second, most of the traditionally used, "archaeological" methods of estimating rock art age are likely to lead to errors, and the use of proximity, iconography, style and technique in particular provides only supplementary or anecdotic data. Excavation and superimpositions can yield sound supporting evidence when used in combination with scientific data, and the analysis of patination and weathering has been utilized inadequately so far.

One of the most potent general techniques in the study of rock art, including age estimation, is without doubt the use of field microscopy. As the only rock art scientist in the world who uses field microscopy regularly (I have not been to a rock art site without a microscope for more than 20 years) I posit that its wider introduction will revolutionize rock art dating work. So far, all such work (including mine) has been opportunistic, piecemeal and unsystematic, and it will remain so until field microscopy is introduced as a standard, widely used research technique. Not only can the most crucial aspects of rock art dating often only be decided by the use of a binocular microscope at the site, microscopic scanning of rock art opens a wealth of new analytical opportunities that will remain untapped without it.

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