

Weathering of petroglyphs: direct assessment and implications for dating methods

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Petroglyphs weather at varying rates, compared to the unengraved host rock into which they are carved. Most petroglyphs are significantly harder or significantly softer than surrounding rock, depending on the nature of weathering. Variability and intensity of weathering probably introduces error into radiocarbon, rock varnish and microerosion dating methods.

Key-words: petroglyphs, dating methods, weathering

Introduction

Few records of ancient human cultures evoke the sense of wonder and concern over their precarious survival than the remains of their 'art', applied with pigments or etched into the rock of canyon cliffs and cave walls. But for all its potential value toward interpreting the past, rock art remains difficult to date. This is particularly the case with petroglyphs, or rock engravings, with little else but gouged clefts in the rock to provide information. Traditional dating methods using stylistic correlations are widely used, but only arriving at relative ages. More recently developed methods applying isotope decay, erosion rates and trace element chemistry have the potential to provide more accurate chronologies (reviewed in Bednarik 1996 and Dorn 2000), though debate over their application is still active. One such debate concerns the open-air engravings found in the Vale do Côa of Portugal (Rosenfeld & Smith 1997). The debate deepened with the discovery late in 1999 of new rock art buried under fluvial sediments at nearby Fariseu (J. Zilhão pers. comm.). Radiocarbon (Watchman 1995) and microerosion (Bednarik 1995a; 1995b) methods suggest that the petroglyphs are of recent (perhaps even historical!) vintage. The reliability of the ^{14}C dates has been questioned (Zilhão 1995; Dorn 1997; Welsh & Dorn 1997), and Watchman (1999) now recasts his original findings with more caution. Stylistic methods suggest that the petroglyphs are much older, perhaps

Upper Palaeolithic in age (Zilhão 1995), establishing their prominence in the great collections of rock art from this time period. Phillips *et al.* (1997), using cosmogenic isotope analysis, determined that the engraved panels are of sufficient age to have been used by Palaeolithic artists. Stratigraphic ^{14}C correlations with the new petroglyphs at Fariseu (Zilhão 1999) and tool markings (d'Errico *et al.* in press) may corroborate a Palaeolithic age.

Clearly, several unresolved issues inhibit reliable dating of petroglyphs. One core issue of background research relevant to petroglyph dating concerns rock weathering. There is a limited understanding of how weathering of the host rock impacts petroglyphs. Weathering affects not only the rock and petroglyph (Walderhaug & Walderhaug 1998), but many of the dating methods employed as well. Several studies (Walston & Dolanski 1976; Steinbring & Callaghan 1985; Campbell 1991; Sjöburg 1994; Laver & Wainwright 1995; Young & Wainwright 1995; Wang & Hua 1997; Walderhaug 1998; Waulderhaug & Walderhaug 1998; Russ *et al.* 1999) discuss the weathering of rock panels on which petroglyphs are engraved. Only Bednarik (1992; 1995a, 1995b) has made descriptions of 'microerosion' of petroglyphs for the purposes of dating (erosion being an end product of weathering). The purpose of this paper is to expand upon these previous studies and specifically address the weathering of the petroglyph engraving itself.

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engraving	location*	ID	N	mean R	std. dev.	probability [†]
<i>Hieroglyph Canyon, Pinal County, Arizona. Pre-Columbian engravings into varnished rhyolite</i>						
'sheep 1'	inside	HGC-1a, 1b	26	57.5	5.06	0.005
	outside	HGC-1c, 1d	26	61.3	4.33	
'sheep 2'	inside	HGC-2a	12	43.6	6.95	0.002
	outside	HGC-2b	12	52.7	5.78	
'zig-zag'	inside	HGC-3a, 3d	24	56.4	5.79	0.000
	outside	HGC-3b, 3c, 3e	36	48.4	7.74	
'lion'	inside	HGC-4a	15	51.1	8.11	0.019
	outside	HGC-4b	15	57.8	6.31	
<i>Cromeleque Almendres, near Evora, Portugal. Neolithic megalith engravings into granitic stones</i>						
'stone 3'	inside	CDA-3a	10	45.8	6.52	0.070
	outside	CDA-3b	6	35.2	11.11	
menhir 56	inside	CDA-56a	6	34.9	6.88	0.295
	outside	CDA-56b	13	31.0	7.68	
menhir 64	inside	CDA-64a	12	26.5	3.89	1.000
	outside	CDA-64b	12	26.5	2.35	
<i>Cromeleque Portela de Mogos, near Evora, Portugal. Neolithic megalith engravings into granitic stones</i>						
menhir 25	inside	PDM-25a	6	35.6	3.35	0.303
	outside	PDM-25b	10	37.4	3.04	
<i>Outiero Menhir, near Monsaraz, Portugal. Neolithic megalith engravings into granitic stones</i>						
Outiero menhir	inside	MSZ-1a	5	37.0	8.42	0.477
	outside	MSZ-1b	5	40.2	4.19	
<i>Bethesda Terrace, Central Park, New York. Recent graffiti engraved into calcareous sandstone</i>						
'heart'	inside	CPB-1a	10	50.6	2.14	0.000
	outside	CPB-1b	10	47.1	1.53	

* 'Inside' refers to data from within the petroglyph, 'outside' from areas adjacent to but not within the petroglyph.
[†] Probability based on a two-sample separate variance student's t test. Statistically significant differences in *italics*.

TABLE 1. Rock hardness (R) data for Hieroglyph Canyon, Arizona; Évora and Monsaraz, Portugal; and Central Park, New York.

Study sites and methods

This study surveyed four separate rock engraving locations, each with different lithology and age (TABLE 1). The Hieroglyph Canyon (FIGURE 1a) and Vale do Côa sites are 'classic' petroglyphs engraved into dark coatings and surface weathering on exposed rock. The Alto Alentejo sites consist of symbolic engravings made on megalithic menhirs. The Central Park example is recent graffiti, a typical 'heart with initials', carved into the Bethesda Terrace tunnel bridge (FIGURE 1b).

Weathering impacts were assessed by visual inspection and Schmidt hammer rock hardness tests in the field; a few samples taken from the rock panels (not from the petroglyphs themselves) were inspected with a scanning electron microscope (SEM). Visual and SEM inspection helped to describe and verify weathering processes, while the Schmidt hammer provided the quantitative data for this paper.

The Schmidt hammer (seen in FIGURE 1a) is used to quantify weathering in a variety of environments and rock types, including petroglyph sites (Campbell 1991; Sjöberg 1994); details of its use are given in Day & Goudie (1977). The spring-loaded device measures rock hardness, giving an R (rebound) value ranging from <10 (very soft) to 100 (very hard). Weathering processes may soften the rock by disintegration, or they may superficially harden the rock with weathering-derived cements such as silica, iron oxide and calcium carbonate.

To overcome inherent variability in rock, several readings (at least 5, preferably 10 or more) are used for each test. A mean R can be calculated with the set of readings. For petroglyphs, tests were made within the engraved areas wide enough to accept the entire width of the plunger (15 mm). Unengraved areas immediately surrounding the petroglyph were tested for comparison.



FIGURE 1. Petroglyph examples. a Typical petroglyph, Hieroglyph Canyon, Pinal County, Arizona. Schmidt hammer at base of engraving for scale. b Graffiti engraving (about 129 mm across) now in positive relief, Bethesda Terrace, Central Park, New York City.

It should be noted that while the type-L Schmidt hammer is considered a 'low-impact' device suitable for easily damaged surfaces, damage or marking is possible on fragile surfaces such as highly weathered and/or softer rock, rock coatings and petroglyphs. Thus, not all petroglyphs are suitable for Schmidt hammer tests. Because of their value (both aesthetic and scientific) and fragility, none of the Vale do Côa petroglyphs were tested directly with the Schmidt hammer. In all other cases, an initial inconspicuous strike was assessed for potential damage, with further testing abandoned if a visible impact was made. Fortunately, destructive impact was not a problem with the sites tested, and the rock and engravings suffered no damage.

Weathering impacts

Visual description

The host rock and petroglyph continue to weathering after engraving. To the naked eye, differential weathering of petroglyphs is difficult to

discern except when the engraving becomes more resistant to weathering when compared to the host rock. In several instances, formerly engraved petroglyphs now stand in positive relief with respect to the surrounding rock. The surrounding rock weathers and erodes to a greater degree, and the engraving eventually stands with positive relief. This phenomenon was not seen at Vale do Côa or at Hieroglyph Canyon. Two of five megalith engravings surveyed are now raised, although it is possible that they may have been carved that way. The most obvious example of positive relief weathering is the heart graffiti at Bethesda Terrace (FIGURE 1b). It is unlikely that a vandal would take the time to abrade the soft rock into a *bas relief* feature, so I assume that weathering resistance accounts for the positive relief. Uneven erosion on the sandstone column illustrates a state of aggressive deterioration, yet the modern 'petroglyph' persists. The heart now stands 5 mm above the surrounding rock, while deeper erosion (up to 10 cm) is evident on the rest of the column.

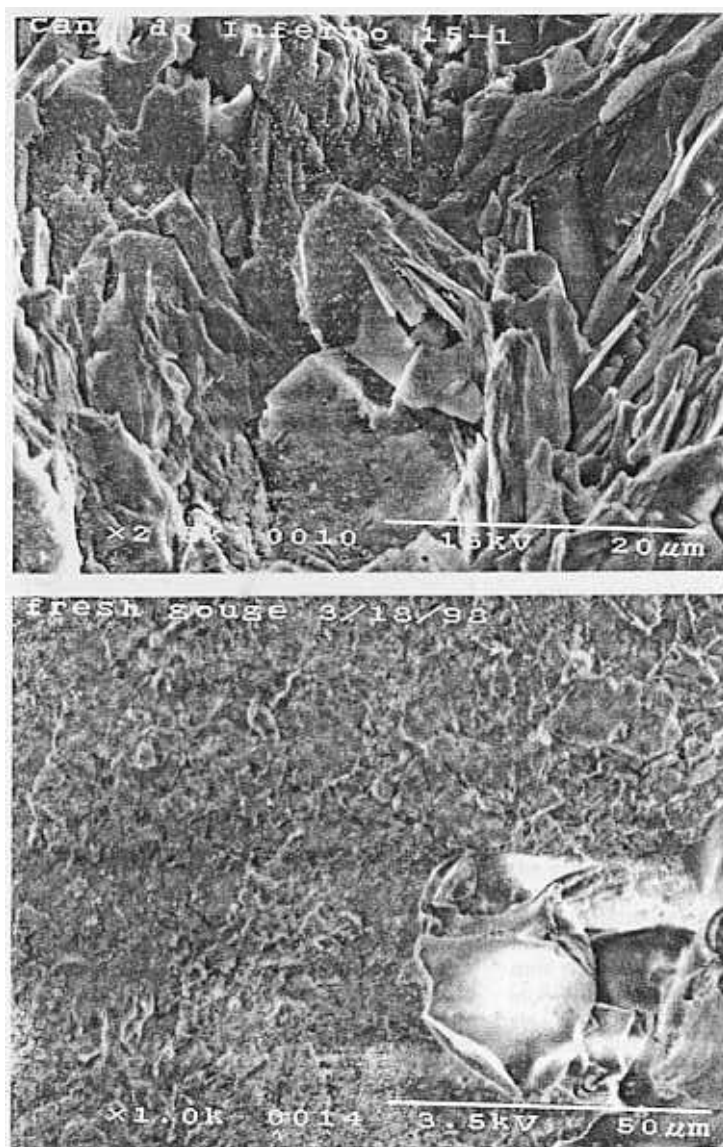


FIGURE 2. High-resolution scanning electron micrographs of rock panel samples from Vale do Côa, Portugal.

a From Panel 15, Canada do Inferno, given an exposure age of $73,500 \pm 21,200$ years by Phillips et al. (1997). High magnification (2500x) reveals the sharp-edged mineral plates typical of schist, which do not appear to be rounded with age. Scale bar 20 μ m.

b High magnification (1000x) of the fresh engraving made in Côa schist sample. The engraved surface appears flakey, but edges are subdued. In contrast, the bright quartz grain in the lower right (a fragment from the engraving 'tool'), exhibits sharp edges typical of freshly fractured quartz. Scale bar 50 μ m.

Microscopic description

Microscopic analysis achieves detailed descriptions of weathering morphologies. Bednarik (1992; 1996), for example, uses a microscope for field studies of petroglyph weathering. Unfortunately, the simplicity of the field mi-

croscope precludes obtaining reproducible and publishable images, and we are reliant on his verbal description for details. He does describe a process of rounding of sharp edges or 'microwanes', created by the forceful fracture of minerals during engraving. This is analogous

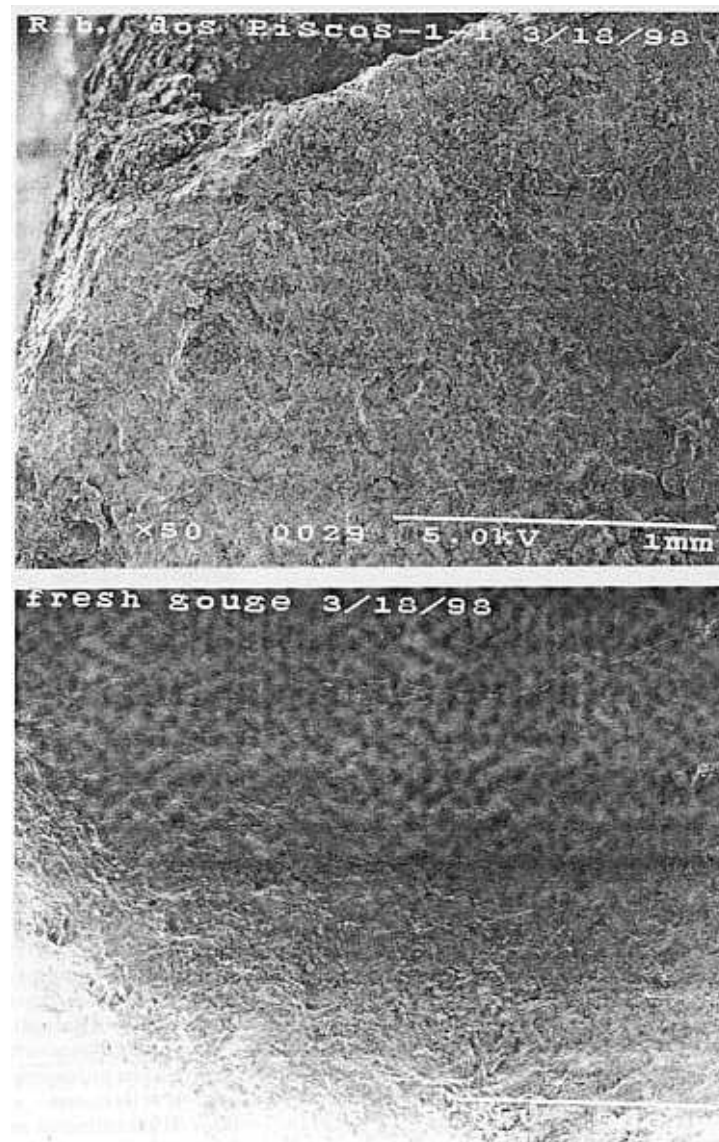


FIGURE 3. Low-resolution micrographs from Vale do Côa, Portugal.

a From Panel 2, Ribeira dos Piscos with exposure ages 91,000–170,000 for several en echelon joint faces (Phillips et al. 1997). The surface of this joint face appears relatively featureless at 50x magnification, except for some superficial flaking. Scale bar 1 mm.

b A wider view (80x magnification) of the engraved gouge 1 made in the Côa schist. The image darkens in the upper part as the sample recedes from the SEM electron beam, but the gouged 'valley' is clearly visible. The gouge is generally smooth, except for the small-scale flaky texture. The tiny quartz fragment seen in FIGURE 2b appears in the upper right of this image. Scale bar 500 μ m.

to the rounding of sharp-edged rocks (Ollier 1984) or engraved inscriptions on monuments (Meierding 1993) during weathering.

The scanning electron microscope (SEM) is widely used for microscale weathering studies, and it may be used to clarify this issue. I

obtained rock samples from Vale do Côa, not of petroglyphs themselves but from rock panels adjacent to petroglyphs. All of the samples were taken from panels previously studied by Phillips et al. (1997), Bednarik (1995a; 1995b), Watchman (1995) and Dorn (1997). The sam-

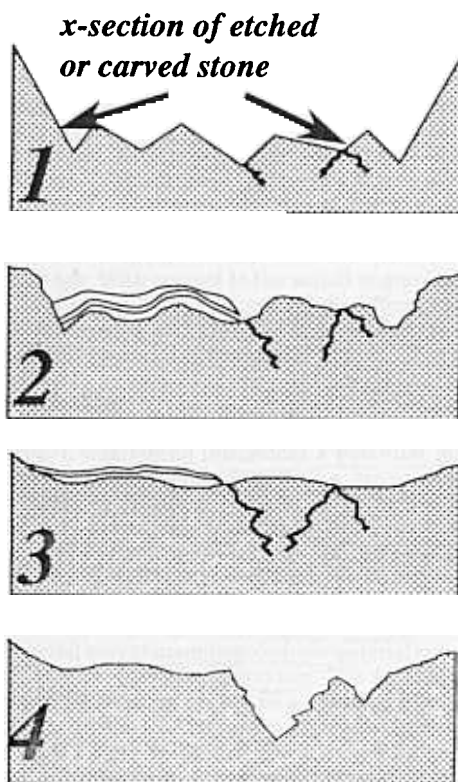


FIGURE 4. Schematic representation of micromorphology evolution. Sharp edges soften progressively as they erode over time (1–2). Accumulated layers also modify the surface (2–3). Fractures also grow over time (3), and eventually create new sharp surfaces by spalling (4).

ples therefore represent naturally weathered, unengraved rock (schist, in this case). For a proxy of what a fresh petroglyph might look like under SEM, I engraved one of the rock samples using a quartz rock fragment 'tool'. (While I wanted to create some base reference for an unweathered engraving, I cannot presume that this method was used by the original artists.)

Higher magnification (FIGURES 2a–b) revealed sharp-edged phyllosilicate mineral plates common in schist, apparent in samples of prolonged weathering exposure. The freshly engraved sample presented a smoother surface, counter to what might be expected according to Bednarik (1992;

1995a; 1995b). At lower resolution (FIGURES 3a–b), rock surfaces exposed recently or over long periods exhibited a similar smooth appearance with a flaky texture. Spalling of surface crusts was evident in some cases and confirmed in cross-sectional SEM images (not shown here).

If one accepts that the ages published by Phillips *et al.* (1997) are at least relative, there is no obvious rounding of sharp edges over time. This may be due to the combined processes of rounding and spalling (as illustrated in FIGURE 4). Alternately, schist may not be particularly exemplary of rounding or spalling over time (thereby bringing in to question the appropriateness of microerosion as a dating tool for this locality).

Rock hardness (Schmidt hammer) data

Rock hardness data indicate that petroglyphs respond differently to weathering. At Hieroglyph Canyon, all petroglyphs tested showed statistically significant differences in rock hardness (FIGURE 5A). Three of the four petroglyphs tested were softer than the surrounding rock, while one (the 'zig-zag') was harder than the surrounding rock. Slight differences in rock structure and composition may account for this variation, although this was not apparent with visual observations. Further conclusions would depend on detailed petrographic studies.

Results from the megalithic stones of Évora and Monsaraz were more ambiguous (FIGURE 5B). The anisotropy and heterogeneity of coarse-grained plutonic rocks tend to create large variations in the degree of weathering, even on the same rock outcrop or stone. One menhir ('stone 3') tested at Cromleque dos Almendres had a marginally significant difference in rock hardness. On this stone, the engraved circles now stand in positive relief. Other engravings at Almendres were slightly harder than host rock, but not significantly so. In contrast, engravings at Portela de Mogos and at Outiero tended to be softer than surrounding rock, but again, not significantly softer.

Finally, the graffiti heart at Central Park was significantly harder than the surrounding stone (FIGURE 5A). Though exposed for only a fraction of the time of the other sites, this 'petroglyph' was the least ambiguous in terms of weathering. The engraving's distinct resistance to the aggressive weathering evident on the stone column was readily apparent with Schmidt hammer data.

FIGURE 5. Box plots (statistical distribution) of Schmidt hammer rock hardness data. Ends of the box enclose 50% of the data. A Hieroglyph Canyon petroglyphs (lion, sheep 1, sheep 2, zigzag) and Bethesda Terrace graffiti (heart). 'In' refers to readings within the engraving, 'out' refers to readings surrounding the engraving. B Alentejo megaliths at Cromleque dos Almendres (EV-CDA), Portela de Mogos (EV-PDM) and Outiero (MS-OUT). Readings from within engravings are designated 'a', readings surrounding engravings are designated 'b'.

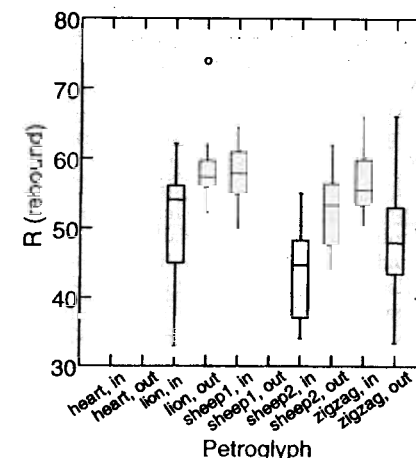
Discussion

Based on these results, five possible scenarios exist for the weathering of petroglyphs, established on whether the engravings are harder, softer or the same hardness as the host rock:

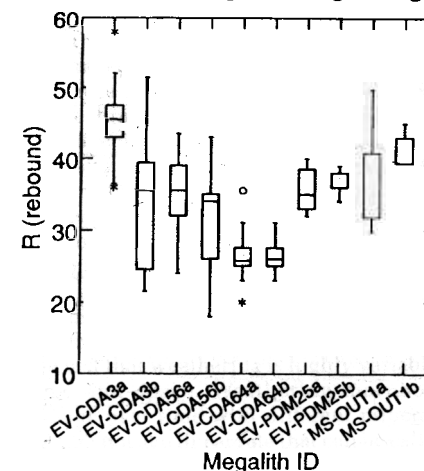
- 1 Engraving removes a surface softened by weathering of the host rock, and the petroglyph appears harder.
- 2 Engraving alters the microstructure of the rock by compacting it, or by armouring it with a polished layer, and the petroglyph appears harder.
- 3 Engraving removes indurated weathering crusts (for instance, cemented by secondary silica, iron or calcium carbonate) or rock coatings that can harden the rock surface, thus the engraving appears softer.
- 4 Engraving weakens the rock, and contributes to weathering that makes the petroglyph softer.
- 5 In cases where engravings show no discernible difference in hardness, any of the four scenarios mentioned above may be valid, but without enough influence to render statistically significant differences in rock hardness. Alternately, engraving may not entirely remove weathered rock or coatings, and the petroglyph and host rock retain similar weathering histories.

It is possible that all five scenarios are valid. Because of intrinsic rock properties and extrinsic environmental factors, especially at the microscale, more than one scenario may be valid at a given site or even within a single engraved rock panel. Given this variability (and the apparent uncertainty) in how weathering processes act on petroglyphs, dating methods influenced by weathering, particularly those reliant on discerning weathering, are subject to error.

A) Rock Hardness, Hieroglyph Canyon & Central Park



B) Rock hardness, Alentejo megalith engravings



Weathering impacts on dating methods

Cosmogenic isotopes (CI) Cosmic rays penetrate a metre or more into the rock, beyond the normal depth of surface weathering (Granger *et al.* 1996). Assuming that the erosion rate (controlled in part by weathering)

does not exceed the rate of accumulation of isotopes, weathering would have little impact on CI dating. On rock exposures subject to more rapid weathering, CI dating would not be appropriate. Watchman (1998) questioned the erosion rates assumed *a priori* by Phillips *et al.* (1997). However, short of wholesale mass wasting, even a doubling of erosion rates would produce only minor corrections to the exposure age. With respect to the actual engraving, CI dating would not discern subtle differences in weathering and erosion rates between the petroglyph and the host rock.

Radiocarbon

According to Dorn (2000) and Welsh & Dorn (1997), weathering introduces a potential for error in petroglyph carbon dating. Microscale weathering produces porosity in the rock surface. As a result, the rock is not sealed into the 'closed system' necessary for encapsulating carbon (Zilhão 1995; Dorn 2000; Welsh & Dorn 1997). Older organic material (associated with older weathering) and more recent organic material may contaminate organic material contemporary with the engraving. The fact that much weathering occurs as a result of biotic agents (lichens, bacteria, algae, etc.; Krumbein & Dyer 1985) ensures that newer organic material is available and transported deep into the rock. Watchman (1998) argues that post-engraving silica glazes are sufficient to trap datable carbon and protect from weathering. In my observation, even silica glazes are not impervious: cracks develop in the glaze as the rock substrate decomposes (Pope 1995). The weathering system is anything but closed.

The possibility that the act of engraving indurates the petroglyph, somewhat protecting it from weathering (scenario 2 above), suggests that encapsulated carbon may be more protected from contamination. Further tests would be necessary to determine the nature of this indurated layer. Still, a minority of petroglyphs fall into this category. In all other cases, the petroglyph is already weathered and/or has the potential for further weathering.

Varnish and other rock coatings

Caution advised for radiocarbon applies to rock varnish geochronometry. Contamination of trace elements in the sequential laminations of rock coatings may occur for similar reasons. For

example, Dorn (1998) and Fleisher *et al.* (1999) observe that lead from automobile pollution and radioactive fallout can enter into the surficial layers of rock varnish. Another source of error stems from erosion of rock coatings over time. Zilhão (1995) presented a viable scenario of rock coating erosion that contradicts the assumptions of sequential layering used by Watchman (1995; 1998). This scenario becomes more complicated as sections of coating (and layers of rock substrate) exfoliate at different rates due to differential weathering. Variability in Schmidt hammer readings within the same petroglyph seem to corroborate this.

Microerosion

While my methods did not duplicate those of Bednarik (1992; 1995a; 1995b), none of my cursory microscopic investigations of the Vale do Côa schist (FIGURES 2–3) indicate that weathering (and erosion) modifies rock micromorphology in a time-dependent fashion. Very sharp edges were apparent at higher magnifications in weathered rocks with a wide range of exposure ages (but similar microenvironments). In contrast, smooth, rounded morphologies were seen at lower magnifications (such as might be seen with Bednarik's field microscope, ~100x), even on a sample with fresh engraving. Bednarik (1995a: 93; 1995b: 879) cautions that schist is less than optimum for the microerosion technique, as the phyllosilicate minerals do not fracture in a way to produce suitable sharp edges. However, the foundations of the technique are flawed for any lithology, based on uncertainties pertaining to weathering (Dorn 2000). Bednarik's first assumption is that 'no chemicals have accelerated or retarded the development of erosion [sic: weathering] phenomena' (1992: 281). Further (1992: 282), he assumes that 'fluctuations [in environmental factors] are probably minor'. Both cases are highly unlikely, as changes in climate, vegetation, and human impact invariably change the extrinsic weathering environment over geologic as well as human time-spans (Pope *et al.* 1995). Numerous authors cite changes in environments to explain differences in weathering damage at archaeological sites (Danin 1985; Steinbring & Callaghan 1985; Meierding 1993; Sjöberg 1994; Young & Wainwright 1995; Wang & Hua 1997). Bednarik's second assumption is that sharp edges, corners, scallops and fractures are solely

the product of human action, and that weathering acts to round the sharp edges. This is an oversimplification of actual weathering processes. First, what may appear as 'rounding' may in fact be accretion of weathering-derived secondary deposits (Krinsley & Doornkamp 1973). Bednarik (1992) notes that microerosion analysis should avoid such accretions (1992: 281), and that 'frosting' warrants further investigation (1992: 285). However, data here suggest that spalling does occur on petroglyphs. Weathering resistant coatings may have been present in the past, but are now gone due to spalling (Dorn 2000). The biggest pitfall lies in the fact that a combination of chemical and mechanical weathering readily produces ragged and sharp edges (Pope 1995), particularly under older, more advanced weathering (see schematic in FIGURE 4). Possible differences between human-created and weathering-created micro-roughness have not been discussed so far, but probably warrant further study.

Third, Bednarik assumes that the act of engraving removes all previously weathered material. This may or may not be true. In these cases where hardness is statistically similar, both petroglyph and host rock may be weathering at similar rates, or, alternately, a significant portion of weathered rock remains with the engraving (see scenario 5 above). Rounding assumed to be post-engraving may in fact be inherited from a much longer weathering period.

Weathering is a time-dependent phenomenon, and some weathering data is translatable to calibrated dating techniques in specific situations (*cf.* Colman & Dethier 1988). But as many researchers have admitted, weathering is complicated and highly variable. Weathering data in archaeometry should be considered experimental and used only under carefully controlled situations (Dorn 2000).

Conclusions

Along with the rock surfaces on which they are engraved, petroglyphs are subject to weathering. Expanding upon previous studies on rock-panel weathering, this paper presents data on weathering of the actual engraving. Visual observations indicate that weathering processes on the rock panels also occur on engravings. Engraving removes some of the weathered and patinated surface. In two cases, the engravings are more resistant to weathering and erosion,

and stand in higher relief against the more eroded host rock panel. This study makes no attempt to describe the microscale morphology of petroglyphs. However, with proxy samples of schist from the Vale do Côa, differences in weathering morphology are not time-dependent. At both high resolution (>1000x magnification) and low resolution (<100x magnification), micromorphology on rock panels up to 170,000 years old differed little from younger samples and from a modern artificial engraving made for this study. Spalling and disintegration were evident in all samples, regardless of age, indicating that weathering remains active through time. Finally, rock hardness tests, indicating relative degrees of weathering, demonstrated a variety of weathering states on petroglyphs and their host panels. Some engravings are similar to their surrounding host rock. In more cases, however, petroglyphs are either significantly harder or softer than surrounding rock. This variability suggests different responses to weathering based on small differences in lithology and microenvironment. Where weathered material and rock coatings are removed, fresh rock may be more susceptible to weathering. Weathering may preferentially soften the engraving, or it may preferentially indurate the engraving with secondary cements.

These results suggest that several new dating techniques now used on petroglyphs may be subject to error. The weathering-generated porosity and microfractures create an open system that allows contamination of datable radiocarbon. Trace elements contained in rock coating laminae are likewise subject to contamination, thereby creating uncertainty for rock varnish dating methods. The microerosion dating technique, dependent on measuring microscopic weathering morphologies, is compromised by the fact that weathering is highly variable over time and space. Weathering morphologies change over time with different minerals, although not at a linear rate that can be calibrated into time since engraving.

Given the scientific interest in dating rock art and the practical interests in assessing its deterioration, analytical methods used thus far pose a problem for conservation. The Schmidt hammer provides valuable information, yet it must be used judiciously in fragile settings. Micromorphological and microchemical data (employing, for instance, the backscatter electron microscope, electron microprobe and x-ray

diffractometer) provide direct information on weathering at the mineral scale, but at the expense of acquiring actual rock samples. While necessary in the cause of science, these advances are at odds with preservation. The development of 'remote' techniques would be preferable. Despite the uncertainties of the microerosion dating method, continued use of the optical field microscope (as per Bednarik) over a variety of rock types and both engraved and unengraved rock surfaces can provide useful information, particularly if a camera can be fixed to the scope. Vogt's (1999) new survey technique, using a confocal laser microscope to analyse resin casts of micron-scale 'topography', holds potential for acquiring reproducible and objective data on surface weathering morphology. While the

application of several dating methods remains unresolved, further research can establish a better understanding of the underlying factors. A combination of new methods combined with selective sample analysis (when possible) will benefit studies in archaeology and conservation.

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