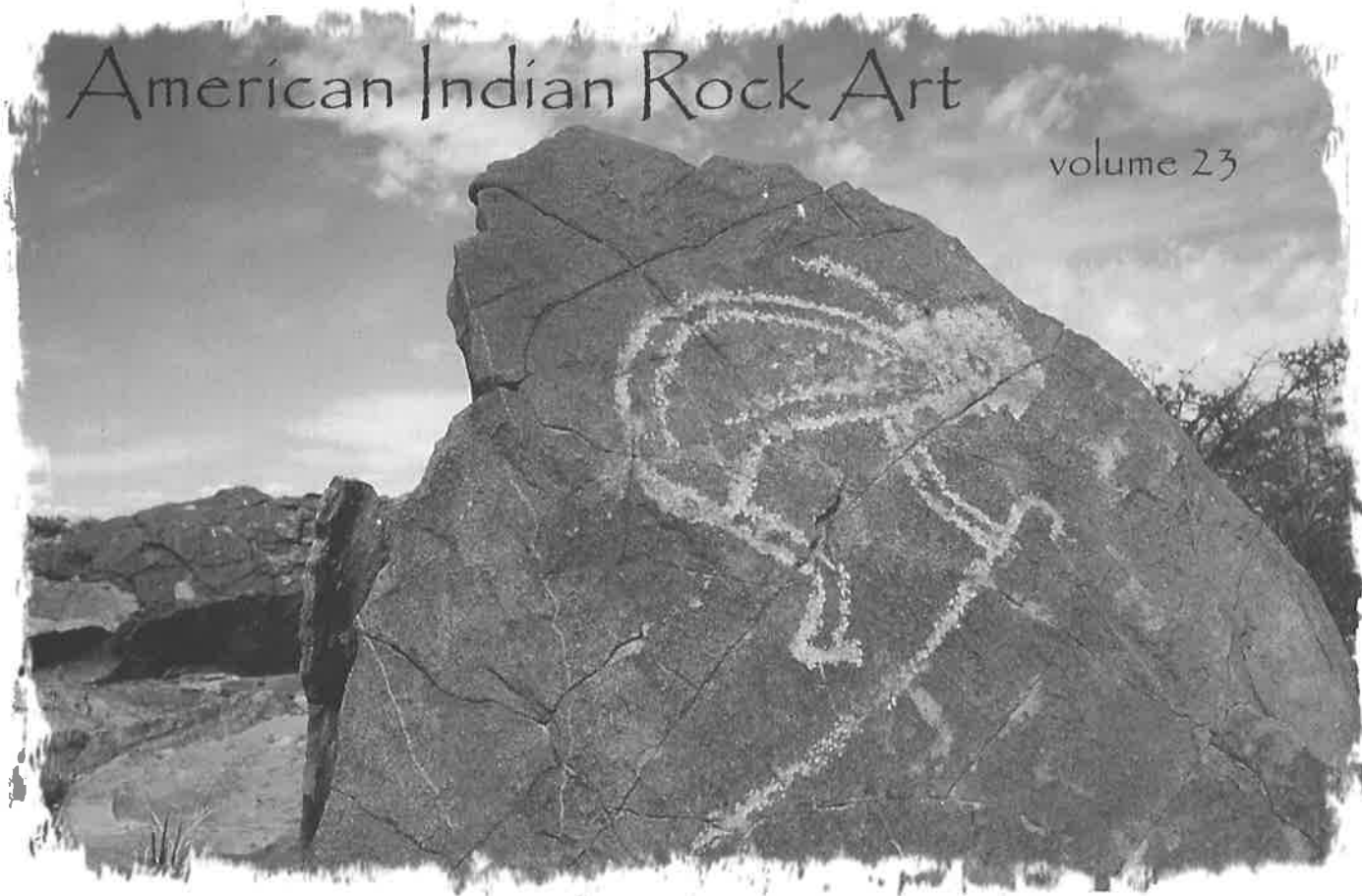


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Critical Analysis of Petroglyph Radiocarbon Ages from Côa, Portugal and Deer Valley, Arizona



Peter H. Welsh and Ronald I. Dorn

The ability to obtain ^{14}C ages on small amounts of organic material through accelerator mass spectrometry (AMS) has created a situation in rock art research where new chronometric information is generated in a virtual vacuum of independent control. A major exception is the work of the rock painting group at Texas A&M, where rigorous testing has allowed the oxygen plasma approach of dating paint to move forward steadily (Chaffee et al. 1993; Chaffee et al. 1994; Ilger et al. 1995; Reese et al. 1995; Russ et al. 1990).

In petroglyph research, comparative independent ages have only come from excavation-based research (Loendorf 1991). For sites that have not experienced panel burial (or partial burial), a different approach is possible. By measuring the radiocarbon ages of organics within the panel face—adjacent to the petroglyphs, but at the same depth as the carving—it is possible to obtain a different sort of temporal reference point. The material adjacent to the petroglyph should provide an independent frame of reference on the organic material that existed before a petroglyph was made.

The objective of this paper is to present data on the possible influence of organics “inherited” from the original panel face, and then to analyze the implications of these data for petroglyph dating in general. We first explain the site contexts. Second, we turn to the methods employed. Third, we present our results and focus the discussion on a critical analysis of the uncertainties. Lastly, we turn towards future directions in the radiocarbon dating of petroglyphs.

Study Sites

Rationale for Comparing Portugal and Arizona Data

In this study, we present and compare radiocarbon data from petroglyph sites in Portugal and Arizona. In particular, we explore in greater detail some of implications of ^{14}C ages on control (panel) faces. The

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Portugal dataset is the largest accumulation of radiocarbon data on host rock faces, and the Deer Valley dataset provides the first insight from a western USA site on relationships between panel and petroglyph organics.

There are two key assumptions in radiocarbon dating of petroglyphs that can be questioned, based on analyses of data from these sites. First, it had been assumed that rock coatings behave as a closed system, sealing off the organic matter that has been entombed within and under the coatings. This is not necessarily so; younger material can be added to the rock surface progressively over time. Second, it had been assumed that the organic matter incorporated in weathering rinds could not pre-date surface exposure. Again, this assumption can be violated; material that pre-dates the most recent surface exposure can be incorporated in rock weathering rinds and even mixed with younger material in a "bulk" sample of organics.

Deer Valley, Arizona

The Hedgpeth Hills Petroglyph Site (ASM number NA15,912) in Phoenix, Arizona, contains one of the largest concentrations of petroglyphs in central Arizona (Figure 1). Over 1500 motifs have been recorded. The Deer Valley Rock Art Center was established to preserve and provide public access to the site in the midst of urban expansion. Our dating project is only a small component of the Center's research program carried out in consultation with neighboring Native American communities.

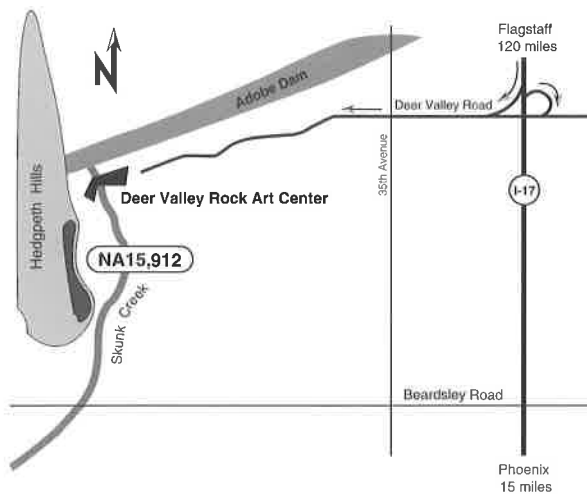


Figure 1. Location of the Deer Valley Rock Art Center.

Samples were collected from a boulder, Panel 1.69A, near the middle of the main petroglyph concentration at Hedgpeth Hills. Petroglyphs were sampled in over 35 different micropositions in a fashion to mimic natural erosion patterns, while maximizing the possibility for obtaining reliable radiocarbon ages. Petroglyphs were sampled at locales where depths were as far beneath the surface of the adjacent rock as possible (1-2 cm). The panel faces east and has three distinct petroglyphs (Figure 2), identified here as:

- I.69A-BH-1: Quadruped
- I.69A-Cur-1: Deep Groove on Abstract Motif
- I.69A-Spiral-1: Concentric circles.

The quadruped (possibly a bighorn sheep) is distinctly lighter than the other two petroglyphs, both of which appear to be as dark as the surrounding rock.

For the first time in western USA petroglyph research, we analyzed the radiocarbon content of a control sample:

- I.69A-CC-1: Carbon Control sample

The control was collected from the same panel face, and at the same depth as the petroglyph samples. In other words, if the groove was 1 cm deep and the petroglyph sample was 1 cm in depth, the dated control sample would be 1 to 2 centimeters in from the face.

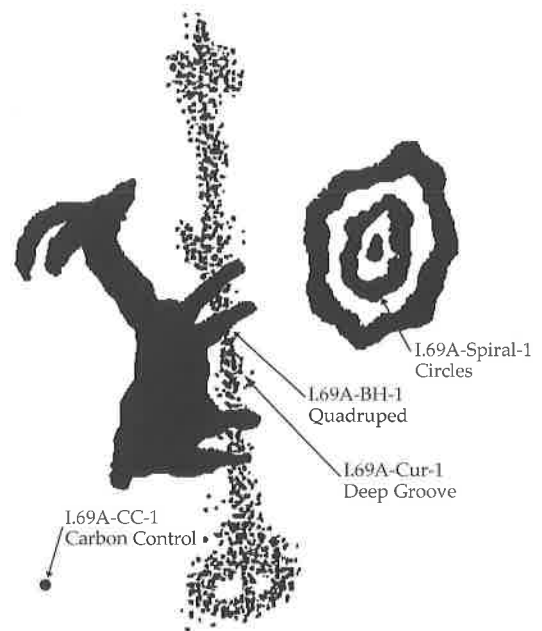


Figure 2. Panel 1.69A at the Deer Valley Rock Art Center.

Côa, Portugal

The Côa valley petroglyphs, northern Portugal (Figure 3), have galvanized archaeologists world wide (Bahn 1995b; Loendorf 1995) and have become a public controversy within Portugal (Sá and Ferreira 1995). Since their existence was made public in November of 1994, the uproar created by the possible destruction of this Upper Paleolithic-style art (Bahn 1995a; Zilhão 1995b) has stopped construction of a dam that would have flooded them.

There are claims that the petroglyphs are definitely not Paleolithic. Watchman (1995, 1996) and Bednarik (1995) argue that the engravings are younger than 1700 years and 3000 years, respectively. These claims have fueled the flames of this controversy, yielding front-page newspaper announcements in Lisbon that claims of a Paleolithic age for the rock art are a "fraud." Archaeologically, a recent age for stylistically-Paleolithic art would be revolutionary, since it would undermine the foundations for the stylistic analyses of and chronologies for rock art.

In a recent paper, cosmogenic ^{36}Cl data were used to constrain maximum ages for Côa valley rock art and ^{14}C ages for weathering rinds provided information on minimum ages (Dorn 1997c; Philips et al. 1997). The schist joint surfaces (panels)

that host engravings in the Côa valley were exposed during the Upper Palaeolithic, according to ^{36}Cl exposure ages of 16,000-136,000 years. AMS ^{14}C ages, from the same panels as ^{36}Cl samples, are significantly younger. Dorn (1997c) concluded that the only firm data are ^{36}Cl ages—indicating that the panels could have been carved during the Palaeolithic.

In this paper, we focus on the control samples—material collected from the uncarved surfaces adjacent to the engravings in Figure 3. The control samples come from three sites:

Site Canada do Inferno

FC-95-2b: control adjacent to petroglyph; sample dated from depth of rock engraving (2-4 mm)

Site Penascosa Castelo Melhor

FC-95-5a: control adjacent to petroglyph; sample dated from depth of rock engraving (2-4 mm)

FC-95-5b: control from rock crevice still overlain by schist block; sampled dated from depth of engraving (2-4 mm)

Site Riveira de Piscos

FC-95-8a: control adjacent to petroglyph; sample dated from depth of rock engraving (2-4 mm)

FC-95-8b: control from rock crevice still overlain by schist block; sampled dated from depth of engraving (2-4 mm)



Figure 3. Côa river valley, tributary of the Duoro River, and the rock art panels that were sampled for dating, modified from Zilhão (1995a).

The exposed controls (FC-95-2b; FC-95-5a; FC-95-8a) are directly comparable to ^{36}Cl ages, since the samples were collected from same face (Dorn 1997c; Philips et al. 1997). This is particularly critical information, because the ^{36}Cl age tells how long the panel face has been exposed at the surface. The Côa valley schist rock type is ideal for this comparison, because the grain of the schist foliations are oblique to the engraved joint faces. This means that if any erosion has occurred, the surface of the joint faces would have a ragged appearance. They do not; so we know that the ^{36}Cl ages can serve as controls for the radiocarbon ages.

The unexposed controls (FC-95-5b; FC-95-8b) are samples from joint faces that are still covered by an overlying block. The overlying block had begun to separate, so it was possible to pry out samples from within the still-unexposed joint crevice. These samples assess whether organic weathering—all before panel faces are exposed at the surface—can influence petroglyph ages.

Methods

Overview

Radiocarbon ages can be obtained by sampling organics within rock coatings that rest on petroglyphs (Watchman 1996), by dating the coating material itself (Dragovich 1986; Russ et al. 1996), or by analyzing organic matter that rests beneath the coating. We focus here on the last approach—dating organics trapped underneath rock coatings.

Like the A-horizon of soils, weathering rinds represent a mixing of mineral and organic matter. Pores (holes) in the rock open as minerals dissolve and mechanically separate from one another. Epilithic and cryptolithic organisms can then contribute organic matter to the pores (Friedmann and Weed 1987; Krumbein and Dyer 1985; Soleilhavoup 1992; Viles 1995). In addition, organic material including plant pieces (Watchman 1992, 1996) and even charcoal-like material (Dorn et al. 1993; Nobbs and Dorn 1993) can be trapped by rock coatings. The charcoal could potentially derive from anthropogenic additions (painted on), from natural fires (Dragovich 1994), or by the slow diagenesis of plant material *in situ*. Like the A-horizon of soils, weathering rinds are in an open system where younger carbon is added continuously while older carbon decays. A key assumption has been that the rock coating effectively "seals" the dated organics (Dorn 1994a; Watchman 1996) and that carbon then only undergoes radioactive decay.

Test for Inherited Organics

The main idea of this paper is to determine the impact of organic matter that could potentially have been "inherited" from a time before the engraving was made. This is a panel-specific issue. Different rock types, and the same rock type in different environmental settings, may have different profiles of organic matter concentration with depth in a weathering rind (Dorn 1994a; Nobbs and Dorn 1993).

Depth profiles were sampled at Deer Valley and Portugal by collecting millimeter-scale pieces from "control" surfaces adjacent to petroglyphs. Samples were chemically pretreated in the same fashion as the petroglyph samples, with HCl, NaOH, and HF. Then, the residue was combusted and the amount of organic carbon compared to the dry weight of the sample (Dean 1974). Of course, there is always the problem that the place where the petroglyph was

engraved had a different concentration of organic matter than the place where the "control" samples were collected.

Nature of the Organics

The nature of the organics was explored *in situ* with scanning electron microscopy. Rock chips were then placed in epoxy and cross sections polished for examination under a scanning electron microscope (SEM), in this case a JEOL electron microprobe. The sections were imaged with secondary electrons (SE), which provides topographic information (Kransley and Doornkamp 1973), and backscatter electron microscopy (BSE). Images formed by backscattered electrons reveal variations in sample composition, since the backscattered-electron yield is a function of the average atomic number (Z) of the sample. The various shades of gray in the image represent varying elemental compositions within the sample, with lower Z regions appearing darker and higher Z regions appearing brighter (Kransley and Manley 1989). The combination of SE and BSE allows the investigator to quickly identify the location of organic matter (Watts 1985), which has a low atomic number (appears dark in BSE) but has a topographic presence and charges (appears bright in SE). The presence of organic matter is then confirmed with wavelength dispersive spectrometry (WDS).

Nature of the Coating

Electron microscopy was used to examine the nature of the overlying rock coating—essentially to obtain a qualitative view of the layering character of the accretion. The key question asked is whether the coating is layered or has "holes" into which younger organics could have been inserted.

Cation Ratios in Deer Valley Rock Varnish

The rock coatings at C \hat{o} a in Portugal are not suitable for cation-ratio dating. However, the samples at Deer Valley were appropriate for study with this experimental dating method. Cation-ratio dating is based on empirical observations that the ratio of mobile cations (e.g. potassium-K, Calcium-Ca) to immobile cations (e.g. Titanium-Ti) decrease over time. Although this technique is controversial (Catto 1995), observations in laboratories around the world have verified that the ratio of (K+Ca)/Ti in rock varnish declines over time (Bull 1991; Clarkson 1994;

Glazovskiy 1985; Jacobson et al. 1989; Pineda et al. 1988; Pineda et al. 1990; Whitley and Annegard 1994; Whitney and Harrington 1993; Zhang et al. 1990). A full discussion of the cation-ratio methodology is presented elsewhere (Dorn et al. 1990).

Microlaminations

Layering patterns in rock coatings can serve as indicators of environmental change, and as a chronometric tool (Dorn 1994a). By using radiocarbon, cation-ratios, and layering patterns, researchers are able to compare three independent chronometric indicators of petroglyph age.

Microlamination analysis was not possible for the sampled sites. Although layering patterns did occur in the coatings in Portugal, they were not consistent enough to be used as a relative dating tool. The only microlamination pattern at Deer Valley was an orange, Mn-poor layer of varnish, diagnostic of a Holocene age elsewhere in the western USA. Thus, the microlamination patterns cannot be used to discriminate relative age.

Chemical Pretreatment and AMS ^{14}C Measurement

All samples that were measured for ^{14}C had an intact stratigraphy. In other words, there were no "holes" in the rock coatings, as seen by electron microscopy. For all dated samples, the rock coating was removed with a tungsten-carbide needle in the laboratory under 45x. The remaining material was then scraped and pretreated in such a way as to try to remove younger organic molecules that might move with capillary waters (Burchill et al. 1981; Gillespie 1991; Heron et al. 1991; Österberg et al. 1993; Warren and Zimmerman 1994). The pretreatment used here consists of HCl, NaOH, and HF in an approach outlined elsewhere (Dorn 1994a; Dorn 1994b). Pretreatment has proven to be a vital part of obtaining reliable radiocarbon ages (Taylor 1987). Although unusual, HF has been necessary to remove younger organics that can adsorb to clay minerals in rock coatings.

The insoluble residues were then sent to Beta Analytic to make the target and then to Lawrence Livermore Laboratory for the AMS ^{14}C measurement and $\delta^{13}\text{C}$ measurement. Stable carbon isotope ratio ($\delta^{13}\text{C}$) values are then used to correct the AMS ^{14}C ages that are reported here (Taylor 1987). Calendar ages were then calculated for the Deer Valley samples, because their ages are suitable for calibration (Stuiver and Reimer 1993).

Results and Discussion

Test of Inheritance of Prior Organics

The assumption that the engravings were carved beneath organics stored in the pre-existing weathering rind appears to be invalid for both Cõa, Portugal and Deer Valley, Arizona.

At the depth of engraving of the Deer Valley petroglyphs, the concentration of organics in the control weathering rind was small, but it did occur at 0.010 g/g (g of extractable carbon in the weathering rind per g of dry weight for the total sample). The appearance of this material was a combination of dense fragments <0.05 to 0.1 mm in diameter and granular, more porous organics (Figure 4). The size of the granular material was difficult to determine, because it dispersed upon physical contact. In summary, based on the control sample, the host panel could have contributed two different types of material to the petroglyph weathering rind. When these two portions were combined together for a "bulk"

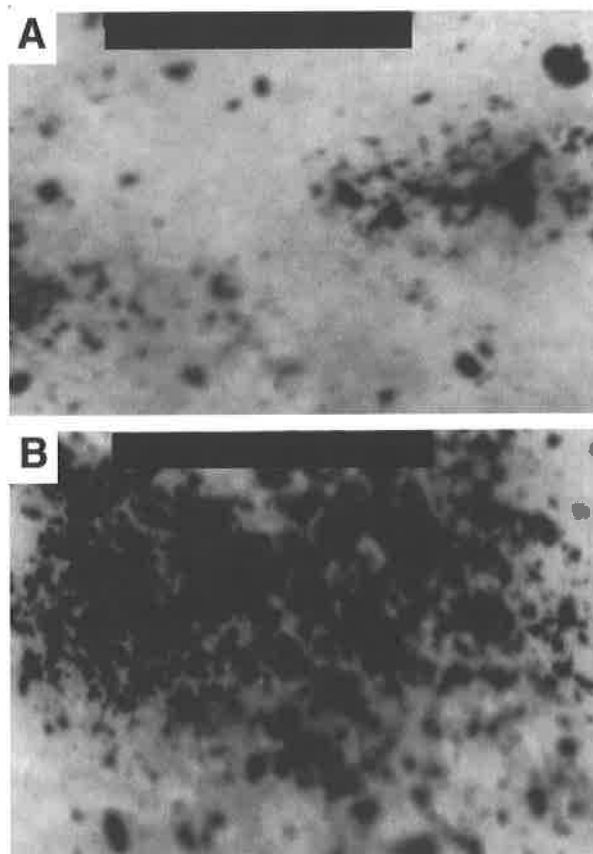


Figure 4. Optical microscope images of the granular (image A) and dense (image B) organic matter in the control sample at Deer Valley (I.69A-CC-1). The scale bar is 1 millimeter.

Table 1. Deer Valley radiocarbon results.

Petroglyph	I.69A. Bighorn	I.69A. Spiral	I.69A. Deep Groove
Calibrated Age (One-Sigma) Age Range***	AD 1036-1222 AD 671-888	AD 659-883 6552-6998 B.C.	9048-9460 B.C.
OM Concentration of Dated Sample (g/g)	0.190	0.110	0.120
Measured C-14 Age	1300±50 (Beta 82033)	1570±60 (Beta 82575) 1510±60 (Beta 82576)	10,440±60 (Beta 82032) 8150±60 (Beta 82572)
Concentration of OM in control rind (g/g)*	0.010	0.010	0.010
Fraction Modern C in Control Rind**	0.0784±0.0011	0.0784±0.0011	0.0784±0.0011
Age for Organic C Added After Engraving, Assuming Control Sample Reflects Amount and Age of Rock Contamination	900±60	1280±100 1250±90	9940±80 7880±100

* At depth of petroglyph sample
**Age of control rind material at 2-4 mm for boulder I.69A 20,450±110 (Beta 83034)
*** Calibration from Stuiver and Reimer (1993)

measurement, the ^{14}C age was 20,450±110 ^{14}C years (Beta 83034; CAMS 20273) with a $\delta^{13}\text{C}$ content of -24.2 ‰ (Table 1).

At the depth of engravings of the C \hat{o} a petroglyphs, the concentration of organics ranged from 0.013 to 0.017 g/g. The appearance of this material was a combination of dense fragments, and less dense, more fibrous material (Figure 5). After processing, these pieces ranged in size from <0.01 mm to 0.1 mm in diameter; however, these sizes were likely altered by flocculation and deflocculation during chemical processing. The ages were clustered at ~9,000–11,000 ^{14}C years.

The two samples collected from the still-unexposed joint faces at C \hat{o} a yielded the oldest ^{14}C ages. The unexposed sample from Ribeira de Piscos was about 1000 radiocarbon years older than the exposed sample. The unexposed sample from the Penascosa joint was about 14,000 radiocarbon years older than the exposed sample. When the different organics from Penascosa were subdivided based upon appearance (dense, granular vs. less dense, fibrous; Figure 5), the AMS ^{14}C ages were vastly different (Table 2). The dense, shiny material contained almost no radiocarbon (~2%), at an age of 30,000 ^{14}C years; in contrast, the less dense material yielded a ^{14}C age almost half as old at ~17,500 ^{14}C years.

These results pose several difficult problems for the radiocarbon dating of petroglyphs. First, different types of material with different ages exist within "bulk" samples extracted underneath rock coatings. Second, organic matter from the rock itself (Timofeyev et al. 1980; Watchman 1995) or from a

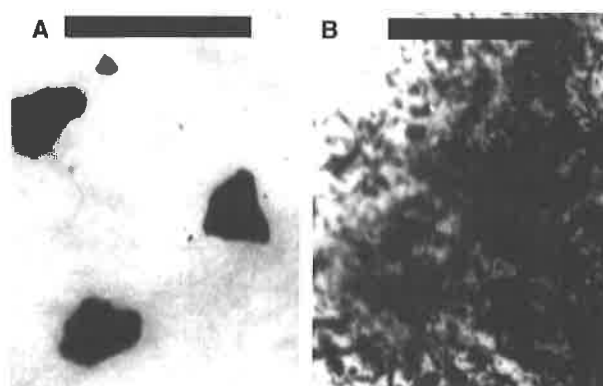


Figure 5. Optical microscope images of dense (image A) and less dense, fibrous (image B) organic matter in a control sample from the Penascosa Panel, Portugal (FC-95-5b). The scale bar is 1 millimeter.

prior history of organic weathering (Chapelle and Bradley 1996; Friedmann and Ocampo-Friedmann 1984; Fyfe 1996; Krumbein and Dyer 1985; Palmer and Friedmann 1988; Viles 1995) occurs in the panel faces that are carved. Radiocarbon (^{14}C) ages from still unexposed panel faces clearly demonstrate that organic weathering is pervasive and does not have to occur in a subaerial context. Third, considerable variability may occur in ages for this "prior" organic matter that likely contaminates petroglyph samples. Although we present a way to correct for the greater antiquity of these inherited organics, later in the paper, we note here that homogeneity does not appear probable. Without homogeneity, correcting radiocarbon ages would be difficult.

Table 2. AMS ^{14}C radiocarbon and ^{36}Cl ages on C \hat{o} a control panel surfaces. Full details on ^{36}Cl dating are presented elsewhere (Dorn 1997c).

Panel Samples	^{14}C Age	Lab. No	^{36}Cl Age
<u>Canada do Inferno Panel 14</u>			
FC-95-2b: Exposed weathering rind	9400 \pm 60	Beta-82451	16,200 \pm 1500
<u>Panel Penascosa</u>			
FC-95-5a: Exposed weathering rind	10,990 \pm 60	Beta-82456	136,000 \pm 70,000
FC-95-5b: Bulk sample of rind within unexposed joint crevice	23,550 \pm 190	Beta-82457	
FC-95-5b: Split sample of dense particles	29,990 \pm 240	Beta-86633	
FC-95-5b: Split sample of less dense particles	17,460 \pm 460	Beta-86632	
<u>Ribeira de Piscos</u>			
FC-95-8a: Exposed weathering rind	9180 \pm 60	Beta-82463	99,300 \pm 20,000
FC-95-8b Rind within unexposed joint crevice	10,350 \pm 60	Beta-82464	

Closed or Open System?

The ^{36}Cl ages (that measure how long the panel has been exposed) are much older than the corresponding ^{14}C ages for the same panels at C \hat{o} a (Table 2). As noted earlier, the texture of the host schist panels indicates that no erosion has occurred. The only reasonable explanation for the much younger ^{14}C ages at C \hat{o} a is that the carbon is in an open system of exchange (Dorn 1997c). In other words, carbon has been inserted continuously or periodically. The rock face, thus, "breathes" carbon. The radiocarbon age is a combination of the decayed and newly inserted radiocarbon. At C \hat{o} a the assumption of a closed system is, therefore, invalid. Traditional approaches to radiocarbon dating cannot work.

We do not have independent ^{36}Cl ages for the Deer Valley panel, but its geomorphic context is such that ^{36}Cl would not be useful. Basalt talus boulders erode by exfoliation of millimeter- to centimeter-scale spalls. This would mean that the ^{36}Cl clock would not be reset, but the radiocarbon clock might be. We cannot, therefore, independently assess whether the Deer Valley system is closed or open with respect to radiocarbon.

A qualitative way to approach this issue is to examine the nature of the rock coating. In those samples submitted for a ^{14}C AMS measurement from Deer Valley, organics were encapsulated by rock varnish that did not show evidence of prior erosion events. In other words, the layering pattern looked sound (e.g., Figure 6). Still, this is not a firm indication that the system is closed. It is always possible that the entire varnish layer eroded, allowing the

insertion of newer organics, and then a new column of varnish formed on top of the new weathering surface. Furthermore, the rock coatings at C \hat{o} a looked like a good seal (Dorn 1997c; Watchman 1995, 1996), but the radiocarbon system is clearly open. In particular, microcolonial fungi are common on Sonoran Desert rock surfaces. They can be aggressive agents of varnish erosion (Dragovich 1993).

Nature of the Petroglyph Organics

Figure 6 displays the *in situ* context of some of the organic matter associated with petroglyphs at Deer Valley. When the extracted organics are examined by light microscopy, they come in different forms (Figure 7). The deep groove had a mixture of dense-shiny organic particles, granular organics, and charcoal-like material. It is possible that the dense and granular material could have been "inherited" from the host rock, since these materials were in the control sample. Organics from the Concentric Circle and Quadruped were a mixture of fibrous material (possibly fungal or lichen remains) and charcoal-like fragments; a few fragments of the dense, shiny organics were also present—but not in abundance. The charcoal-like material associated with the petroglyphs could certainly be charcoal—added to the petroglyph after its engraving (Dorn et al. 1993), or through fire (Dragovich 1994). It is also possible that fragments of trapped plant material (Dorn and DeNiro 1985; Watchman 1992) underwent diagenesis and became carbonized, and carbonized plant material can take on the appearance of charcoal (Chitale 1986; L. Lines, personal communication 1996).

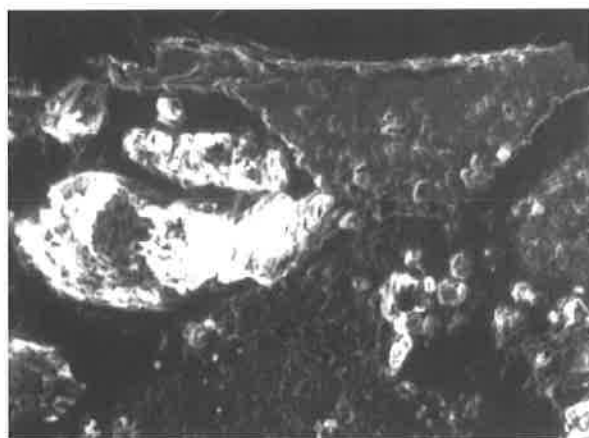
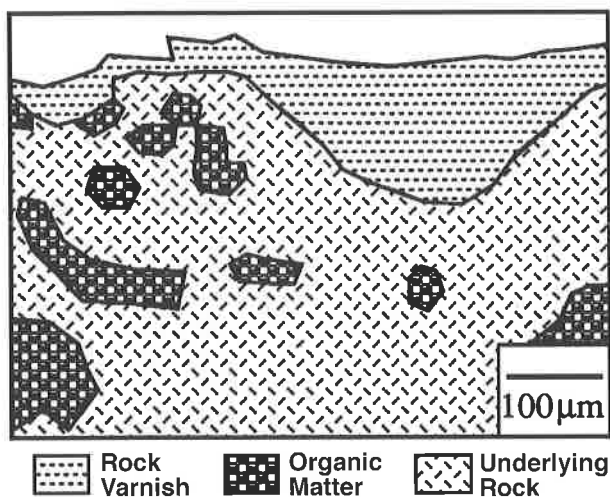


Figure 6. Electron microscopy illustrating the rock varnish and encapsulated organic matter from the Deep Groove on Boulder I.69.A. The organic matter is bright in the secondary electron microscope image, because it is charging, while it is dark in the backscatter image because it has a low atomic number. The abundance of carbon was also verified by wavelength dispersive spectrometry.

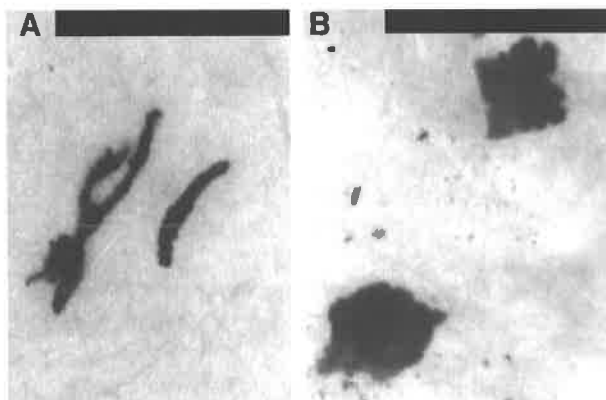


Figure 7. Optical microscope images of the charcoal (image A—still attached to the rock material from I.69A-BH-1) and fibrous (image B- I.69A-Spiral-1) organic matter. The scale bar is 1 millimeter.

A large uncertainty in the ^{14}C dating of organics associated with rock coatings comes from not understanding its organic geochemistry (Dorn 1997a, 1997b). Making this task more difficult is alteration that occurs over time or diagenesis. Diagenesis of organics associated with rock varnish could be speeded up by the manganese mineral that occurs in rock varnish (Potter and Rossman 1979), birnessite (Wang and Lin 1993). Also, the type of clay minerals (Mayer 1994) found in rock varnish (Potter and Rossman 1979) can turn plant material into a dense, organic substance when the clays are combined with high temperatures (Collins et al. 1995) found on desert rocks (Richter and Schroder 1991).

There are other processes that can influence the appearance of organic matter associated with rock coatings. The process of organic matter diagenesis could be accelerated by high temperatures on darkened rock surfaces that can reach 80°C (George 1976: 231), by the Maillard reaction (Shuichi and Ryoshi 1989) especially if the original tissue was high in sugars (Hather 1991). Iron and other heavy metals in varnish are known to alter the characteristics of terrestrial organic matter (Bird et al. 1994; Bisdorn et al. 1983; Ertel and Hedges 1984; Jones and Jarvis 1981). Chemical pretreatment can also change organic matter. For example, chemical pretreatment with HF (hydrofluoric acid) or NaOH (sodium hydroxide) yields material with a different appearance than treatment without these chemicals; different times of HF treatment can greatly alter appearance of the supporting silicates; treatment in steel centrifuge tubes yields material with a different texture than when chemical pretreatment occurs in plastic centrifuge vials.

Research on soils may provide an appropriate analogy. In the caliche in desert soils, organic matter diagenesis leads to "abundant vitrinite and inertinite [that] strongly suggests the presence of roots and possibly of fungi from the calcrete laminae" (Chitale 1986:iv). These highly evolved organic remains originally came from roots and possibly of fungi. D. Johnson (personal communication 1996) has similarly observed vitrinite-like particles in soils of Ventura County, California. In summary, a large "wild card" in the radiocarbon dating of petroglyph organics is the diagenesis of the organics that are eventually dated—and in particular, determining which fraction is appropriate for dating.

Cation Ratios in Rock Varnish at Deer Valley

The samples tested for radiocarbon had a relative sequence established by cation-ratios that are presented in Table 3. The results are presented in relative order from youngest (highest ratio) to oldest (lowest ratio).

Correcting Petroglyph ^{14}C Ages

Control samples are not homogeneous. Available morphological and radiocarbon data suggest considerable heterogeneity. Therefore, it may be quite difficult to use radiocarbon ages from "control" panels to represent the radiocarbon content of the material "inherited" in the petroglyph grooves. However, we hope that future work will allow us to isolate particular fractions appropriate for dating, which would permit such a correction to be made. Thus, we present here a procedure for "correcting" the contamination from the original panel organics.

Table 1 presents radiocarbon ages for the organics extracted from the sampled petroglyphs at Deer Valley, as well as data necessary to correct for potential contamination from the host panel. A corrected age for petroglyph organics could be calculated from FMC_{new} in equation 1:

$$^{14}\text{C}_{\text{gr}} = 8033 \cdot \text{LN}[(\text{FMC}_{\text{new}} \cdot \text{N}_{\text{con}}) + (\text{FMC}_{\text{rind}} \cdot \text{R}_{\text{con}})] \quad (1), \text{ where:}$$

$^{14}\text{C}_{\text{gr}}$ is radiocarbon age of sample entombed by rock varnish in petroglyph groove. This is measured directly;

FMC_{rind} is the fraction of modern carbon of sample entombed by varnish in the control rind. This is measured directly;

R_{con} is the concentration of extracted organic carbon in weathering rind, at an equivalent depth to the petroglyph engraving; and

N_{con} is the concentration of new extracted organic carbon, added to weathering rind since the petroglyph was engraved. This is calculated by subtracting the concentration in the petroglyph sample from R_{con} .

FMC_{new} ... is the fraction of modern carbon of organic carbon added to the petroglyph groove, after the petroglyph was engraved. This value is the unknown. The radiocarbon age of the fraction of modern carbon added to the petroglyph groove after the petroglyph was made, FMC_{new} , is then calculated from by $8033 \cdot \text{LN}(\text{FMC}_{\text{new}})$ (Taylor 1987).

In other words, the age of the carbon in the pre-existing weathering rind is measured. The age of the carbon in the petroglyph groove is measured. From these data, and the measured concentrations of organic carbon, equation 1 is used to calculate the age of the material added to weathering rind since the petroglyph was made. The error term in Table 1 includes both uncertainty in the measurement of ^{14}C and measurement of concentrations of extractable organic carbon. "Calibrated" ages are also reported in Table 1. The calibrated ages of radiocarbon are based on tests of radiocarbon production over time (Stuiver and Reimer 1993; Taylor 1987).

We stress that this procedure would be valid only if the abundance of organics in the host panel and the age of the organics in the host panel truly reflect the amount of contamination in the petroglyph samples. Unfortunately, not enough data are available to know if our single "control" sample is truly representative of the contamination in our petroglyph samples.

Interpreting Portugal and Deer Valley Petroglyph Ages

Because the Portugal "system" is open, radiocarbon ages can only be interpreted as minimum ages. Even though contamination from the organics "inherited" from the panel could have added older organics, a comparison with ^{36}Cl ages clearly demonstrates that the rate of influx of newer carbon is such that the Côa art is not datable by conventional radiocarbon approaches. It may be possible in the

future, however, to “calibrate” the rate of radiocarbon exchange in an open system of radiocarbon dating (McKay et al. 1986).

We do not know if the Deer Valley system is open or closed, with respect to the exchange of radiocarbon. We do know that contamination is likely from older carbon, inherited from the host panel. We do not have enough data to be certain that our single sample from the host panel is representative, with respect to concentration of organic carbon or with respect to radiocarbon age.

We note that the replicate ages for the Deep Groove are dissimilar. One likely explanation is that the material from the host rock contaminated the Deep Groove samples differentially. There appeared to be proportionally more shiny-dense organics in the older sample—adding more older “inherited” carbon. Another equally likely explanation could be that the rock varnish itself coated the weathering rind at different times. A “time transgressive” varnishing would have meant that younger carbon was added to one sample because it was a varnished layer. Still, a third alternative is that there was more contamination from younger material in the younger sample of the Deep Groove. These hypotheses are testable with more measurements on the different fractions of the organics. However, at this point, the ages are difficult to interpret. Do we correct for the certain contamination from the host rock, as illustrated experimentally in Table 1? We cannot correct for contamination from younger material, because we do not know if it occurred, and if it did, how much?

The replicate ages for the Concentric Circles, in contrast, are quite close. The similarity in age are probably from the samples being deposited at the same time, in combination with a paucity of dense

particles (likely contaminants of older carbon). A difficult question is whether the dated organics represent contamination from younger material added long after the petroglyph was made. However, if older contaminants are truly minimal, the possibility of younger contamination would imply that the replicate radiocarbon dates would be minimum-limiting ages.

Advantage of a Multiple-Technique Approach to Dating Petroglyphs

Dorn (1994a) advocates a three-tiered approach to dating dryland petroglyphs: with chemistry (cation ratios); layering patterns; and radiocarbon. Although we do not think it is possible to make firm interpretations of the Deer Valley radiocarbon ages, we note two points of comparison with the cation ratios (Table 3). First, the cation-ratios reflect the same chronometric trends as the radiocarbon ages. Second, the control sample and the Deep Groove have considerably older radiocarbon ages than the Concentric Circles or Quadruped; similarly, the cation ratios for the control and Deep Groove samples are considerably lower (older).

At C \hat{o} a, because neither cation ratios nor layering patterns are appropriate, we do not have an independent chronometric technique to assess the accuracy of the ^{14}C ages. At Deer Valley, the cation ratios suggest that the order of ^{14}C ages is correct—even though we cannot evaluate or correct for potential contaminants at this time. At C \hat{o} a, in contrast, the ^{14}C ages can only be evaluated by stylistic means (Bahn 1995a, 1995b; Zilh \hat{o} 1995a, 1995b)—which is in direct conflict with the radiocarbon ages (Bednarik 1995).

Table 3. Cation ratios of (K+Ca)/Ti on Deer Valley petroglyphs, as measured by wavelength dispersive electron microscopy (Dorn et al. 1990). The order is from youngest (highest ratios) to oldest (lowest ratios).

Deer Valley Sample	Individual CRs	CR \pm 1 Sigma
Boulder I.69A. Bighorn	7.45, 7.58, 7.60 7.67, 7.98, 8.05	7.72 \pm 0.24
Boulder I.69A. Spiral	6.73, 6.89, 6.91 7.04, 7.22, 7.28	7.01 \pm 0.21
Boulder I.69A. Deep Groove	4.45, 4.71, 4.89 4.90, 4.95, 5.20	4.85 \pm 0.25
Boulder I.69A. Control	3.86, 3.99, 4.18 4.27, 4.40, 4.41	4.19 \pm 0.22

Conclusion

At this point in time, radiocarbon cannot be used to date Côa petroglyphs. The "open" exchange of carbon on the panel faces means that younger carbon is continuously added, and the heterogeneity of the organics implies uncertainty over which fraction is suitable for dating.

Our data for Deer Valley reveal that ^{14}C ages on petroglyph material are most consistent in the youngest range (e.g. replicate ages for Concentric Circles). Yet, we cannot rule out younger or older contaminants. Radiocarbon (^{14}C) ages are most inconsistent in the oldest range for the Deer Valley samples. A likely cause of this variability is that the two Deep Groove samples showed the greatest variability in the abundance of dense-shiny fragments; these materials appear to be from diagenesis of organic matter inherited from a prior phase of weathering. Additional work will be necessary to determine if control samples can be used to "correct" for these older contaminants. There is no method at present to correct for the possibility of younger contaminants. However, varnish cation ratios suggest that the order of the ^{14}C ages at Deer Valley is correct.

In the future, the ability to understand the significance of ^{14}C ages on organic matter associated with petroglyphs will require a more detailed understanding of the organic geochemistry of the different types of organics used in both petroglyph (Dorn 1997a) and geomorphological (Dorn 1997b) research. Our current understanding of the nature of the organics is based on optical morphology, electron microscope morphology, and $\delta^{13}\text{C}$ values. Once this characterization occurs, different organic fractions need to be tested at sites with independent age control. In the past, independent control has occurred on basalt flows (Dorn et al. 1992) that do not have problems derived from organics inherited from prior weathering. This study demonstrates that "inherited" organics from prior weathering episodes is a reality at petroglyph sites. Therefore, independent controls for petroglyphs would best occur through excavation at rock art sites. In addition, tests will have to be conducted on the influence of different particle sizes and different pretreatment procedures.

It is also imperative that comparative tests occur in a double-blind fashion, as in Portugal (cf. Bednarik 1995: 878)—where Watchman (1995, 1996) obtained a similar distribution of petroglyph ^{14}C ages to those measured by Dorn (1997c). As in the Portugal study, those individuals conducting the tests should not

be aware of previous results or independent age controls. Until the aforementioned tests are conducted and in a blind fashion, it will not be possible to do more than treat petroglyph ages as anything other than "bulk" ages on material with an uncertain history. The ^{14}C ages we obtained here and the corrections based on panel "control" samples may be valid; they may be invalid. Future tests will be needed to resolve these uncertainties.

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