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PALEOENVIRONMENTAL SIGNALS IN ROCK VARNISH ON PETROGLYPHS

Ronald I. Dorn
Arizona State University

Recipient of the Kenneth Castleton Award for excellence in Rock Art Research

ABSTRACT

The objective of this paper is to assess whether paleoenvironmental research methods, previously used in the analysis of rock varnish on landforms, can yield useful information to aid in the interpretation of rock art. My findings of the feasibility of reconstructing the paleoenvironment of petroglyph sites using rock varnish on engravings are: (1) The rock varnish that coats petroglyphs in drylands records at least four types of environmental fluctuations at a rock engraving site—the abundance of manganese, the micromorphology of varnish, silica skins, and stable carbon isotope values of organic matter; (2) Cross-correlation of sequences of paleoenvironmental fluctuations can indicate relative ages of petroglyphs at a site, and also provide an independent check on the sequence of petroglyph age-determinations, whether by rock varnish or another dating approach; (3) Varnish paleoenvironmental techniques cost much less than accelerator radiocarbon measurements; (4) In conjunction with new methods of providing ages on rock art, rock varnish can add unique information on past environments that might be missed by just correlating the archaeological record with regional paleoclimatic records; (5) Understanding a sequence of environmental changes at a rock art site provides the interpreter a local and independent source of data on interrelationships between environment and archaeology; and (6) Paleoenvironmental fluctuations, recorded in varnish on petroglyphs in the Coso Range of eastern California and petroglyphs in South Australia, reveal that the same sites were reused during different environmental conditions.

INTRODUCTION

Art is valued highly by our civilization, and the study of art is an important component of how western culture is perceived (Glacken 1967). It is paradoxical, therefore, that the study of rock art frequently takes a back seat to other types of cultural records obtained from archaeological excavations. There are notable exceptions to this generalization, but they are relatively few. One likely explanation is the inability to place the rock art record chronologically into cultural reconstructions that have been established by radiocarbon-dated stratigraphic sequences.

Several methods now exist for the dating of rock art. Excavation of sediments at the base of petroglyph panels has revealed charcoal for radiocarbon dating that constrains the ages of petroglyphs that extend under the excavated and dated material (e.g., Buckles 1980; Loendorf 1989). Turner and Reynolds (1975) and Dragovich (1986) radiocarbon dated calcium carbonate coatings over rock art. Along with collaborators, I developed cation-ratio dating (Dorn 1983, 1989; Dorn and Krinsley 1991) and accelerator radiocarbon dating (Dorn et al. 1989, 1992) of rock varnish that coats petroglyphs (Whitley and Dorn 1987, 1988; Dorn et al. 1988; Loendorf 1991). Loy et al. (1990) accelerator radiocarbon dated

human blood in pictograph pigments, and Russ et al. (1990) present a general method for extracting organic matter in rock pigments for accelerator radiocarbon dating. Watchman (1985, 1990) is investigating the dating of organics incorporated into silica skins formed over rock art and the direct radiocarbon dating of oxalate coatings on rock art. These and other efforts aimed at developing new dating techniques for rock art should be viewed as experimental, and there is a need to cross-check these different methods. However, there is an overwhelming trend toward the development of new ways to date rock art. The precision, accuracy, general applicability, and availability of rock art dating can only improve over time.

The datable material that covers rock art, thus far charcoal in soils, calcium carbonate, silica skins, oxalate coatings, and rock varnish, may also reveal information on the nature of environmental changes at rock art sites. For example, considerable potential exists to extract paleoenvironmental information from stable isotopes in carbonate coatings (e.g., Amundson et al. 1988; Cerling et al. 1989). Paleoenvironmental information has also been extracted from rock varnish on landforms (Table 1). None of these methods, however, has been applied to coatings on rock art.

The objective of this paper is to present results on the feasibility of obtaining paleoenvironmental data from coatings on rock engravings; in this case the coating is rock varnish. Similar studies could be conducted on other types of rock art coatings. However, this is the first study of its kind on interpreting the environmental history of an engraving site by the study of coatings on the engravings themselves.

METHODS

The rock varnish that coats petroglyphs is dark, often reddish-brown to black. It is composed of mostly clay minerals that are cemented to the engraving by oxides of manganese (Mn) and iron (Fe) (Potter and Rossman 1977, 1979). Bacteria play a key role in the enhancement and oxidation of manganese and probably iron (Dorn and Oberlander 1981, 1982; Palmer et al. 1985; Jones 1991). Over 30 other minor and trace elements are trapped or adsorbed as varnish constituents accrete (Bard 1979; Dorn et al. 1990).

Rock varnish can be used to reconstruct paleoenvironmental fluctuations only where the process of varnish accretion produces continuous layers with no episodes of intervening varnish erosion. However, chemical and mechanical erosion can occur. For example, acidity dissolves the manganese and iron oxides that bind

the varnish, and mechanical erosion by wind readily abrades varnish. Fortunately, it is possible to select only the varnishes with continuous layers, illustrated in Figure 1. In contrast, Figure 2 exemplifies eroded varnishes with discontinuous layers that are not appropriate for paleoenvironmental interpretation.

It is a time consuming task to prepare samples to assess whether varnish erosion has taken place on a petroglyph. Small chips (<1/4 cm diameter) are flaked with a tungsten-carbide needle from a rock engraving in the field. (This process does not significantly alter the appearance of the petroglyph, but only removes a tiny bit of rock varnish. In order to be noticed by observers of the process, the spot must be pointed out.) The chips are then mounted on a glass slide with epoxy so that a cross section of the varnish can be polished. Sections are viewed with a light microscope and by scanning electron microscopy with a backscatter detector (Krinley and Manley 1989). Although backscatter displays greater detail, as seen in Figures 1 and 2, light microscopy is a less expensive means of conducting an initial investigation of varnish layering.

If varnish on a petroglyph has discontinuous layering, it cannot be used for the analysis of a sequence of paleoenvironmental fluctuations. However, the very nature of unconformities within rock varnish layers can still reveal valuable information. If the erosion truncates the varnish along an even plane, the source of the erosion is typically aeolian abrasion. I have not observed this type of erosion in petroglyph varnishes, but Figure 2a presents examples from a geoglyph context. In contrast, erosional hollows drilled into the varnish (Figure 2b) result from the activity of acid producing cyanobacteria, microcolonial fungi, or lichens. The rock art interpreter, however, must keep in mind that each erosional record reveals only the history in one place. It is only by the analysis of multiple cross-sections that consistent records of events can be reconstructed for a petroglyph site.

Table 1 displays the variety of paleoenvironmental signals that have been extracted from continuous layers of rock varnish formed on landforms. Of these signals, only the first four were evaluated for this study of varnish on petroglyphs.

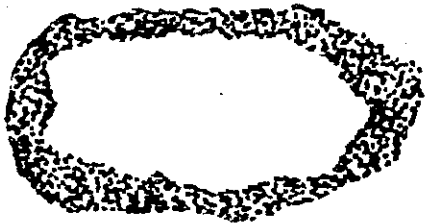
(1) *Paleoalkalinity*. Perry and Adams (1978) first observed microlaminations of Mn-rich and Mn-poor layers in rock varnish. Dorn and Oberlander (1982) hypothesized that these are created by variations in alkalinity, where high alkalinity inhibits the concentration of manganese by bacteria. Dorn (1984, 1990) supported this hypothesis, but extended it by noting alkalinity inhibits Mn-enhancement, whether the concentrating mechanism is biological or abiotic. Jones (1991) tested

Figure 1. Examples of layered varnishes, illustrated by both backscatter electron microscopy and light microscope imagery of polished cross-sections. Since most of the images presented in this report are by these methods, a more detailed explanation will be provided for the first images.

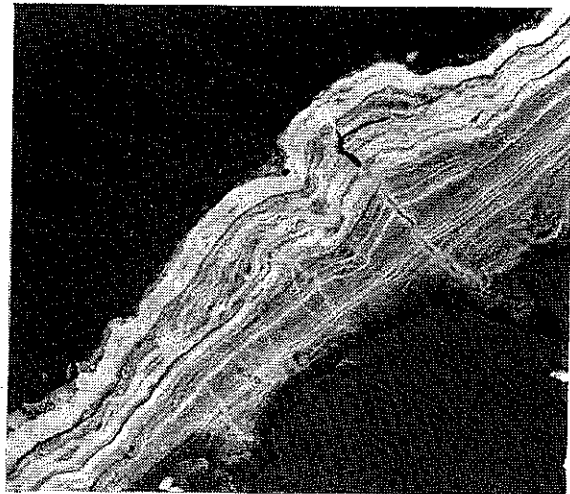
The black and white backscatter images reflect the atomic number and the texture of polished material. Varnish layers with an abundance of manganese and iron usually appear brighter than the underlying rock that typically has more alumina and silica-rich minerals. Within the varnish, variations in the abundance of manganese and iron can also produce contrast, revealing layers. A more detailed discussion of the backscatter technique is provided by Krinsley and Manley (1989).

Color optical microscope images are taken of ultra-thin sections of varnish. The black areas are greatly enriched in manganese (typical concentrations $> 10\%$ MnO), as determined by electron microprobe studies. The orange-red layers are not greatly enriched in manganese (typical concentrations $<< 1\%$ MnO).

1a. Backscatter image of layered varnish on petroglyph WH5 from the Wharton Hill site in South Australia discussed in the text. The varnish is about 80 microns thick. The fractures running through the varnish are places where water has mobilized and reprecipitated manganese and iron oxides. All motifs adjacent to the images have scale bars of 5 cm.

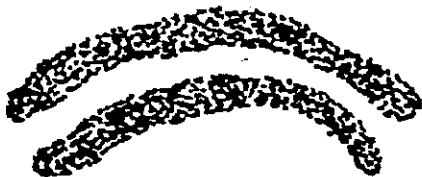


WH5



* Due to technical difficulties in reproducing the following color illustrations, the back side of the page will be blank.

1b. Light microscope image of layered varnish on a motif of curved lines, PN6 from the Panaramatee North site in South Australia discussed in the text. The varnish is about 90 microns thick.



PN6



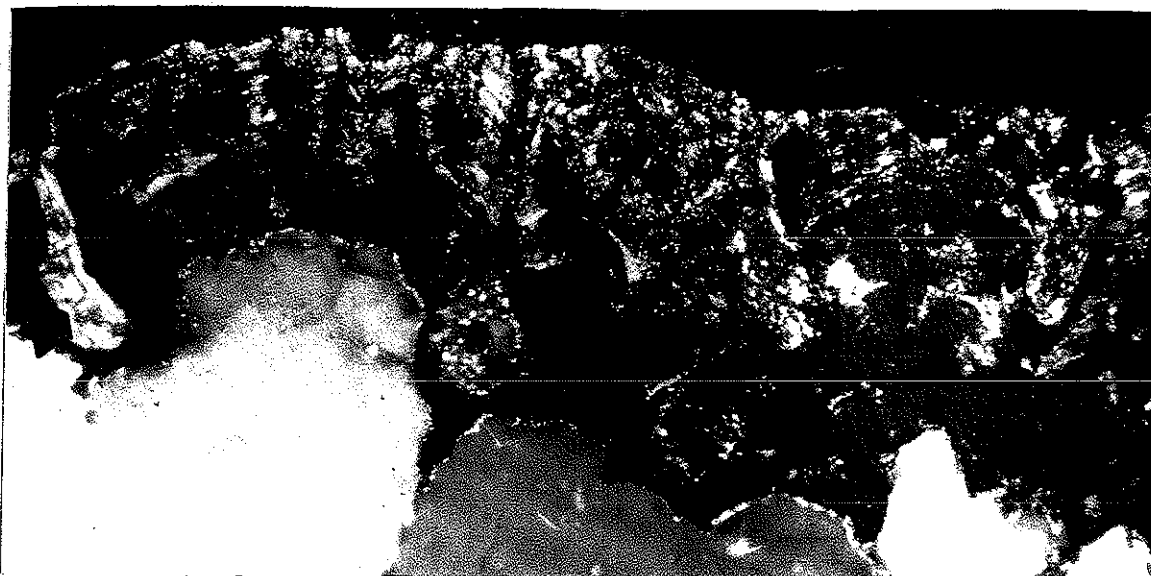
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Figure 2. Examples of eroded varnishes with discontinuous layers.

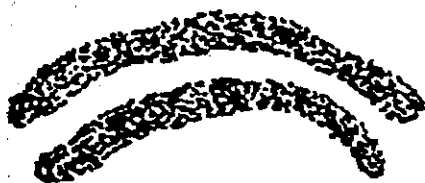
2a. Light microscope image of varnish on a desert pavement of the Nazca pampa in southern Peru. Note how the layers have been truncated on the surface. The sample came from an area with other evidence of being abraded by wind, ventifacts and abundant loose sand. This varnish was abraded by aeolian activity that was not harsh enough to completely remove the varnish. Depth of varnish ranges from ~10 microns on the right to ~120 microns in the deep depression.



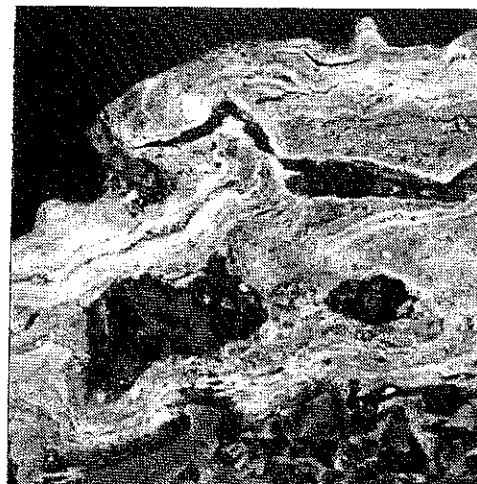
2b. Light microscope image of rock varnish from a motif of curved lines, PN6 (the same petroglyph as Figure 1b) from the Panaramatee North site in South Australia. This sample was collected from a portion of the petroglyph with abundant microcolonial fungi, known to erode varnish in Australia (Dorn and Dragovich 1990). Note the hollows that interrupt the layering (see arrows). In studies on geomorphological surfaces, these hollows are known to lower cation ratios and provide anomalous ages (Dorn 1989; Krinsley et al. 1990). Varnish about 50 microns thick.



2c. Backscatter image of the eroded portion of the PN6 petroglyph, showing at higher magnification discontinuous layers. Varnish about 40-50 microns thick.



PN6



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Table 1. Methods obtaining paleoenvironmental information from layers in rock varnish.

METHOD	THEORY	INDICATOR	REFERENCES
Microchemical laminations	Exposure of varnish to abundant alkalinity inhibits the concentration of Mn. Less alkaline fall-out allows more enhancement of Mn.	Mn:Fe Ratios	Dorn 1990 Jones 1991
Silica skins	Silica skins are deposited over Australian rock art during more moist periods (Watchman 1985).	Superposition of silica skins and rock varnish	First presented in this paper
Micromorphology	Abundant dust fallout promotes lamellate micromorphologies. Less dust allows nucleation centers to grow together and form botryoidal micromorphologies	Superposition of dissimilar micromorphologies	Dorn 1986
Paleovegetation	Adjacent vegetation sheds organic matter that is incorporated into varnish. $\delta^{13}\text{C}$ values in varnish reflect $\delta^{13}\text{C}$ values of adjacent plants.	$\delta^{13}\text{C}$ values	Dorn and DeNiro 1985
Paleolead	Abundance of lead in Antarctic rock varnishes may be correlated with lead variations found in ice cores.	Lead concentration	Dorn (in press)
Paleoaeolian	Aeolian abrasion erodes varnish. If erosion is incomplete, subsequent deposition leaves an unconformity that records a past episode of eolian abrasion.	Planar unconformities seen in cross-section	Krinsley et al. 1990 Dorn (in press)

the assumptions of this model with experiments and by an examination of rock varnish from Peru; he concurred that Mn-poor layers (with low Mn:Fe ratios) form under more alkaline conditions and that bacteria best explain the enhancement of manganese in rock varnish. White (1990) also explains Mn-poor varnish in Tunisia from high alkalinity.

(2) *Paleosilica skins*. Watchman (1985) found that skins of amorphous silica sometimes coat petroglyphs and rock paintings in Australia. Amorphous coatings of silica also interfinger with rock varnishes in South Africa (Butzer et al. 1979) and on petroglyphs in semiarid Australia. According to Watchman's model, the deposi-

tion of silica skins between varnish layers should represent a time of more moisture availability.

(3) *Paleodust*. The micromorphology of rock varnish is controlled, to a large part, by the abundance of dust settling on rock surfaces. With minimal dust fallout, nucleation of Mn-Fe oxides occurs at discrete points that develop into a botryoidal form (similar to melted marbles). With abundant dust deposition, a more lamellate (or layered) varnish is deposited (Dorn and Oberlander 1982). Superposition of dissimilar micro-morphologies records a change in the nature of aeolian fallout (Dorn 1986).

(4) *Paleovegetation*. The stable carbon isotope composition of rock varnishes has been found to relate to

Figure 3. Cross-sections of varnishes formed on petroglyphs from the Conejo Mine site in the Coso Range, eastern California (Whitley and Dorn 1988).

3a. One of five ultra-thin sections displaying only a Mn-poor layer of varnish on CM7, a bighorn sheep petroglyph. The reddish varnish is about 10-20 microns thick and has been assigned a cation-ratio date of $11,500 \pm 3,800$ B.P. (2 sigma) in Whitley and Dorn (1988). Note that the center of the depression has an area slightly darker due to more manganese (Mn:Fe ratio about 0.4, determined by the electron microprobe). These depressions are more favorable micro-environments for manganese-oxidizing bacteria, because they collect dew and rain water. However, the overall varnish is not greatly enriched in manganese.



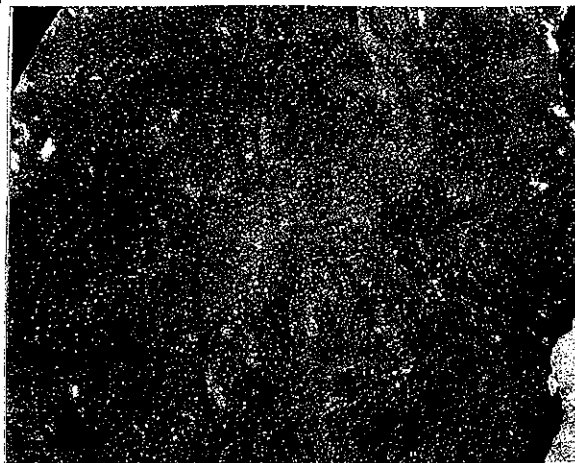
CM7



3b. One of five ultra-thin sections of varnish on CM12, a bighorn sheep petroglyph (Figure 3c). In all sections, a layer depleted in manganese (red-orange) covers a layer enriched in manganese. The varnish is about 40 microns thick.



3c. Photograph of petroglyph CM12; the length is about 60 cm in the longest dimension.



^{13}C ?? values of adjacent vegetation (Dorn and DeNiro 1985). ^{13}C values of organic matter sandwiched between the petroglyph and varnish can, therefore, also provide insight into past vegetation at an engraving site.

RESULTS AND DISCUSSION

This is the first study of its kind, exploring the feasibility of extracting paleoenvironmental information from coatings on rock art. The reader is, therefore, cautioned from treating specific results reported below as definitive. However, I hope to illustrate how this type of analysis can provide data that may assist in the interpretation of rock art.

Paleoalkalinity

Almost all of the varnish on petroglyphs I have examined in western North America have low ratios of Mn:Fe, indicative of formation during the Holocene period of greater aridity (Figure 3a). Exceptions occur where Mn-rich varnish occurs locally in microdepressions that collect dew and rain water. These are the more favorable microsites for Mn-oxidizing bacteria.

Varnish was collected from six petroglyphs from the Conejo Mine (abbreviated 'CM') site in the Coso Range (Figure 4). Cross sections were examined for a paleoalkalinity signal. Although dating is not the focus of this paper, I will present previously obtained data to provide a context to interpret these new data. All six petroglyphs were those analyzed by cation-ratio dating (Whitley and Dorn 1988), and the cation-ratio dates are reported with a 2 sigma error. The four petroglyphs cation-ratio dated to be Holocene in age display only orange-red, manganese-poor varnish, including: bighorn sheep CM7 (Figure 3a); bighorn sheep CM6 (7100 ± 2600 B.P.); abstract motif CM16 (4000 ± 1200 B.P.); and an anthropomorph petroglyph CM11 (750 ± 100 B.P.).

Two bighorn sheep petroglyphs, in contrast, display a clear superposition of Mn-poor over Mn-rich varnish. Figure 3b presents an ultra-thin section of varnish from motif CM12 (Figure 3c) with a cation-ratio date of $18,200 \pm 2400$ B.P. (Whitley and Dorn 1988). Note the orange (manganese-poor; Mn:Fe ratio < 0.1) surface layer that is superposed over the black (manganese-rich; Mn:Fe ratio > 1.0) layer. The electron micro-probe was used to determine the chemical composition of these layers. An abstract motif CM5 (cation-ratio age of $16,600 \pm 4,300$ B.P.) also displays a basal layer enriched in manganese.

I draw several tentative interpretations from these Conejo Mine petroglyphs in the Coso Range.

(1) A conservative interpretation is that the bighorn

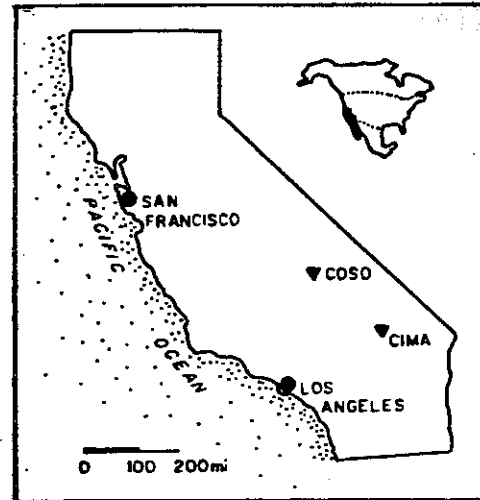


Figure 4. Sampling sites for petroglyphs in eastern California, discussed in the text.

sheep petroglyphs CM12 and CM5 at the Conejo Mine petroglyph site experienced a less alkaline (more humid) period favorable for the accretion of manganese-rich varnish. The other petroglyphs did not.

(2) Petroglyphs CM12 and CM5 appear to be older than motifs CM7, CM6, CM16, and CM11 that did not experience a less-alkaline period of manganese-enrichment.

(3) If the prior cation-ratios are accepted by the reader as a correct *relative* age sequence, petroglyph CM5 must have been manufactured during the more moist (less alkaline) period recorded in the lowest layers of the earlier CM12 petroglyph, since CM5 also has this basal Mn-rich layer. Similarly, petroglyphs CM6, CM16, and CM11 must have been engraved during the arid (more alkaline) period recorded in the stratigraphy of the earlier CM7 petroglyph. This analysis indicates that the Conejo Mine site must have been utilized during a time span that included two different types of environments: less alkaline and more alkaline.

(4) If the reader treats the cation-ratio dates as reasonably close age estimates, then the bottom layer of Mn-rich varnish recorded on the CM12 and CM5 petroglyphs could be interpreted as forming during the latest-Pleistocene period of enhanced moisture availability in the region (Benson et al. 1990; Spaulding et al. 1990), and varnish on the other petroglyphs could be interpreted as forming during the drier Holocene period.

Varnishes on South Australian petroglyphs also record fluctuations in alkalinity, as indicated by microchemical laminations. Varnish was studied on twelve petroglyphs at four sites in South Australia (Figure 5). A wide range occurs in the number of layers on

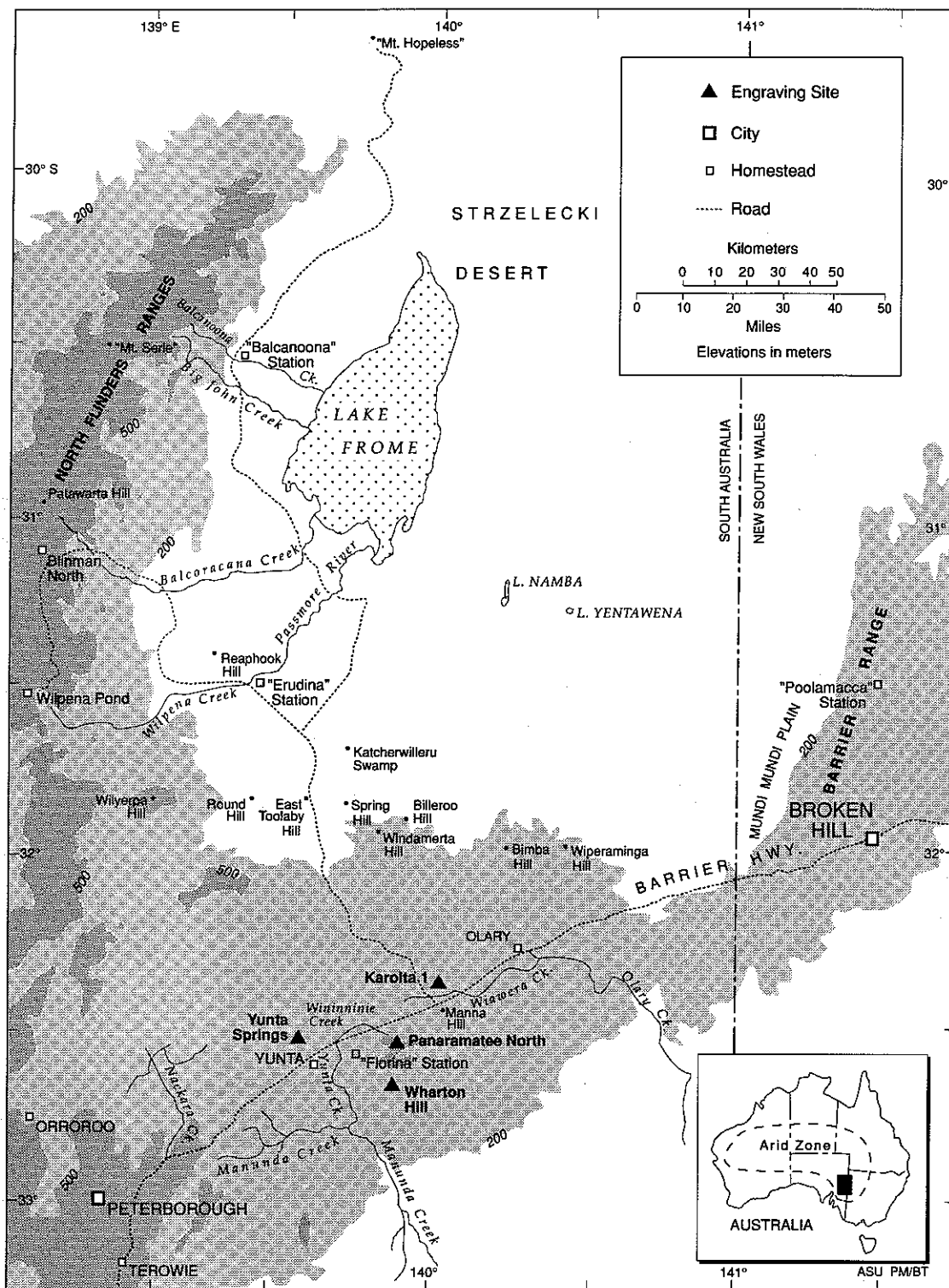


Figure 5. Sampling sites for petroglyphs in South Australia, discussed in the text. Petroglyphs in the text and in figure captions are given the abbreviations WH for Wharton Hill; PN for Panaramatee North; YS for Yunta Springs; and K for Karolita 1.

different petroglyphs. For example, varnish on engraving WH5 from Wharton Hill shows many layers (Figure 6a), whereas varnish on WH2 from Wharton Hill displays only a few layers (Figure 6b). These results suggest that the South Australian sites have been used over a period of time that has experienced many fluctuations in alkalinity. The most likely source of the alkalinity variations would be fluctuations in the ephemeral lakes, widely scattered throughout the area (Figure 5). They have seen considerable lake-level changes in the last 30,000 years (Bowler et al. 1976; Langford-Smith 1983) that could easily change the abundance of alkaline aerosols. The range in complexity in layering is consistent with prior cation-ratio ages obtained from these petroglyphs that indicate a long use of these petroglyph sites (Dorn et al. 1988).

The interpretation of Mn:Fe microlaminations is complicated in South Australia by varnish layering being more interrupted by erosional pits in the arid region of Australia than in western North America (cf. Figure 2b and 2c). Also, layering observed in the twelve petroglyphs studied from the different sites do not match perfectly. For example, the Mn:Fe microchemical layering at the Karolta 1 site (see Figure 5) appears to differ from layering at the other sites, for a given period of time. This tentative result might imply that local microenvironments can change in a different fashion within a relatively small area in South Australia (Figure 5). With more sampling and testing, this finding might have implications for interpretation of human use at these rock art sites.

Paleosilica skins

Thin coatings of amorphous silica have been noticed on both archaeological and landform surfaces for decades; however, it was not until the work of Curtiss et al. (1985) for geological materials and Watchman (1985) for rock art that silica skins have been characterized in detail. In Hawaii, Curtiss et al. found these clear to translucent white coatings to be amorphous silica, amorphous alumina, and iron. Watchman determined that silica skins on rock art in the Kakadu area of the Northern Territory in Australia are found with the minerals whewellite and polyhalite. Organic matter encapsulated by these coatings, and the calcium oxalate skins on petroglyphs, have been analyzed by accelerator mass spectrometry for radiocarbon dating (Watchman 1990; A. Watchman, pers. comm., October 1990).

Silica skins tend to precipitate during more humid periods of time: "...during wetter intervals, solution, migration and precipitation could have reconcentrated

minerals as coatings over the rocks" (Watchman 1985:288). Following Watchman's model, in the semi-arid regions of Australia, formation would be limited to more mesic sites during more moist periods.

I have not observed silica skins on petroglyphs in North America, perhaps because the sampled petroglyph sites have been too arid. However, silica skins do interdigitate with varnishes in South Australia. In some cases, the interfingering is stratigraphically concordant, producing alternating layers, as in Figures 7a and 7c. In other cases, silica skins fill depressions in the varnish perhaps left by prior episodes of varnish erosion (Figure 7b). Believing Watchman's model to be reasonable, I would tentatively interpret these silica skins as representing more moist intervals of time.

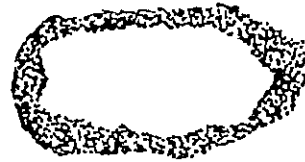
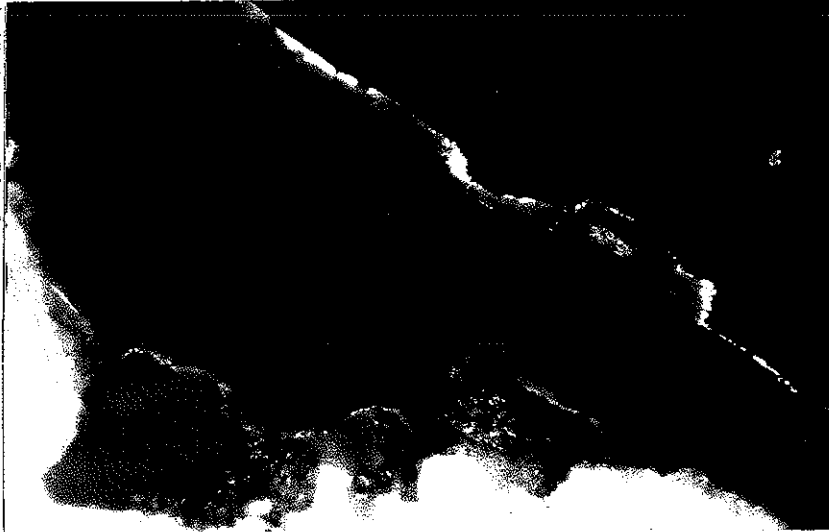
An interesting aspect of silica skins is their ability to inhibit cation leaching from rock varnish. Dorn et al. (in prep.) found that the silica skin in the South Australian petroglyph K15 from the Karolta 1 site (Figure 7a and 7b) was responsible for an anomalously high cation ratio. The cation-ratio age was 7400 ± 1400 B.P. (Dorn et al. 1988), much younger than a new varnish radiocarbon age of $12,650 \pm 150$ (Dorn et al. in prep.) for the same petroglyph. The explanation, tested by laboratory experiments, is that the silica skin seals the rock varnish and inhibits cation exchange (Dorn et al. in prep.). This would give the petroglyph too high of a cation ratio and too young of an age. In contrast, the one sigma errors of the cation-ratio and radiocarbon ages overlap for the South Australian petroglyphs without silica skins (Dorn et al. in prep.). In another example, the silica skin displayed in Figure 7c from Karolta 1 petroglyph K23 came from a section of the petroglyph that yielded an anomalously high cation-ratio.

Paleodust

All of the petroglyphs in South Australia that have thus far been examined have a lamellate micromorphology (Figure 8a), probably indicative of the dominance of dust fallout in this area (McTainsh and Pitblado 1987). Almost all of the petroglyphs thus far examined from North America also have a lamellate micromorphology (Figure 8b). However, a few petroglyphs in the Coso Range of eastern California (Figure 4) have a layer of botryoidal varnish under the lamellate varnish (Figures 8c and 8d). According to the theory presented by Dorn and Oberlander (1982) and Dorn (1986), a botryoidal layer of rock varnish forms during a period with less abundant dust fallout. This last occurred in the Coso Range in the latest-Wisconsin time, more than 12,000 B.P.

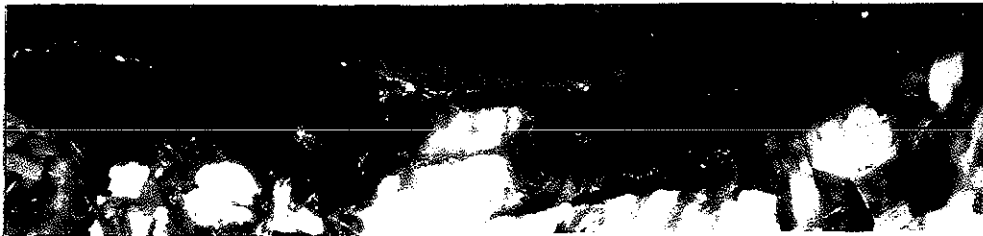
Figure 6. Microchemical laminations recorded in cross-sections from South Australian petroglyphs.

6a. Light microscope image of multiple layers of varnish on petroglyph WH5. The thickest portion of the varnish is about 60 microns. Although dating is not a part of this paper, it places the complexity of the laminations observed in perspective. The radiocarbon age of subvarnish organic matter extracted from WH5 is $36,400 \pm 1700$ B.P. (Dorn et al. in prep.).



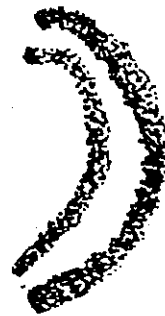
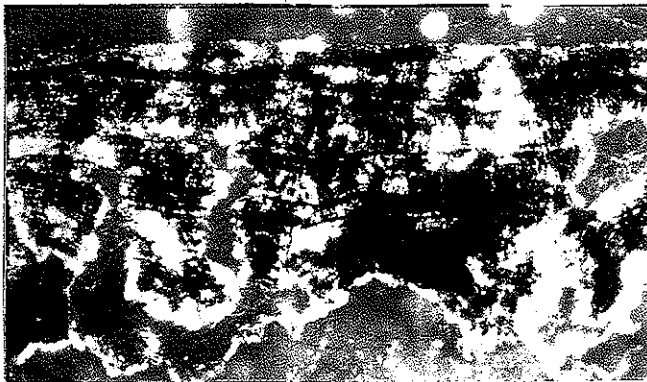
WH5

6b. A sequence of a thin surface orange layer on a thick black layer on a thick orange layer, from petroglyph WH2 from the Wharton Hill site. The thickest portion of the varnish is about 30 microns. An age is not available for this petroglyph, but it appears to be younger than WH5, based on fewer microlaminations.



WH2

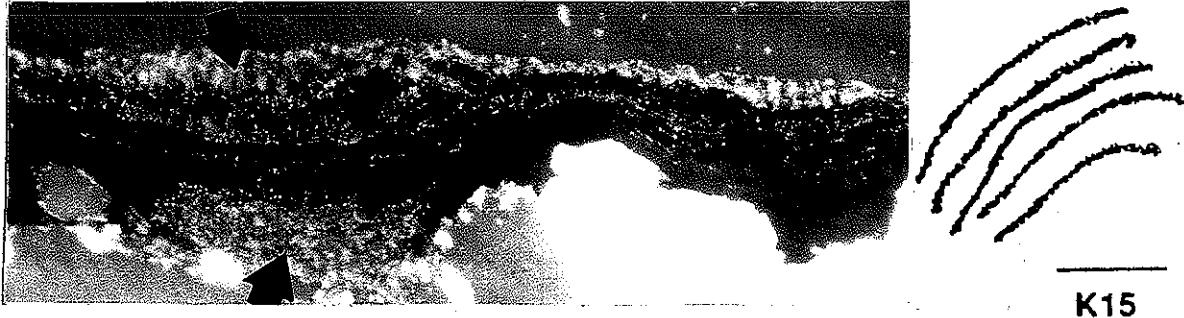
6c. Sequence of layers on petroglyph K23 from the Karolta 1 site in South Australia. The varnish radiocarbon age is $30,230 \pm 770$ B.P. (Dorn et al. in prep). Thickest portion of the varnish is about 120 microns. There are no truly black layers, as in Figures 6a and 6b, because the section was ground extremely thin and the Mn-rich layers here are represented by a darker shade of orange-red.



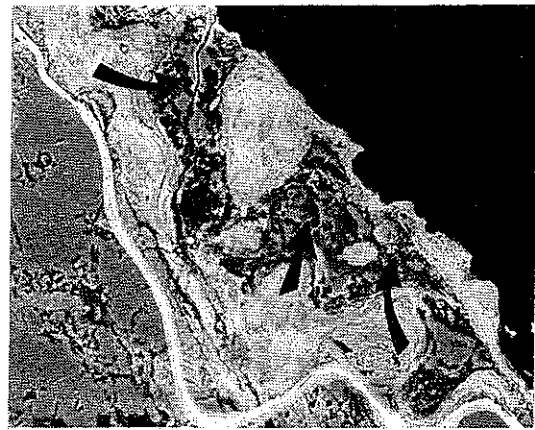
K23

Figure 7. Images of silica skins, interlayered with rock varnish.

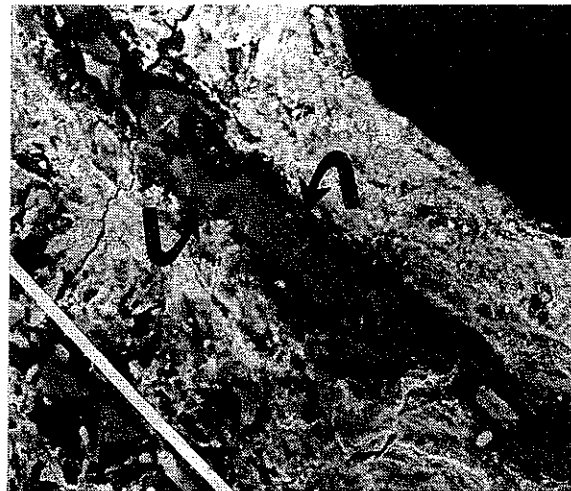
7a. Light microscope image of silica skin that interfingers with rock varnish on a petroglyph of curved lines, K15 from the Karolta site in South Australia. The coating is about 50 microns thick. The yellow-orange color at the surface and in the deepest pocket is silica skin (arrows) with a composition of about 25% SiO_2 , 22% Fe_2O_3 , 20% Al_2O_3 , 13% MgO , and trace elements.



7b. Backscatter electron micrograph of varnish and silica skin on petroglyph K15. The darker material is the silica skin (arrows), because it has a lower atomic number than the brighter colored varnish. Note the newer layer of varnish that has formed over the silica skin. The coating is about 40-50 microns thick. Line indicates the varnish-rock boundary.



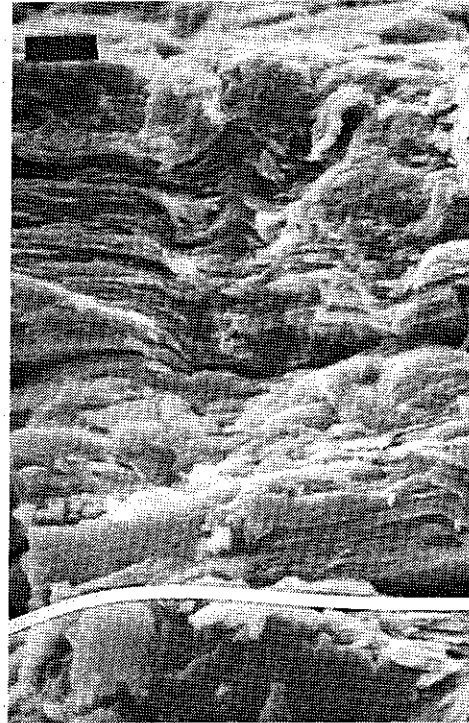
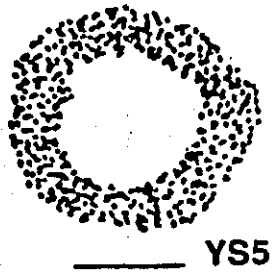
7c. Backscatter electron micro-graph of varnish and silica skin on petroglyph K23, from the Karolta 1 site in South Australia. The cation-ratio date assigned to this petroglyph was $31,700 \pm 3700$ B.P. (Dorn et al. 1988). A later radiocarbon date was $30,230 \pm 770$ B.P. (Dorn et al. in prep). Most of this petroglyph does not have any silica skin. However, in a small portion of the petroglyph, silica skins were found, as displayed here by the darker layer running from upper center to lower right (arrows). Varnish and silica skin in this section of the petroglyph gave an anomalously high cation-ratio with an anomalous age of $\sim 19,000$ B.P. This shows that silica skins can decrease the rate of cation leaching, a topic that is discussed in the text and in Dorn et al. (in prep) in greater detail. The varnish is about 80 microns thick, and the line indicates the varnish-rock boundary.



K23

Figure 8. Micromorphology of rock varnishes on selected petroglyphs, as recorded by secondary electron microscope imagery. Unlike backscatter, secondary images reveal topographic detail that cannot be seen in polished cross sections. When the varnish is mechanically broken, delicate micromorphological structures are preserved. Lines indicate the varnish-rock boundary.

8a. Only lamellate micromorphology of South Australian rock varnish on petroglyph YS5 from the Yunta Springs site in South Australia (Figure 5). Scale bar 5 microns.



8b. Lamellate rock varnish on Cima petroglyph 1-1 that has a late-Holocene cation-ratio age of 2150 ± 400 (2 sigma). The Cima results are discussed in detail by Whitley and Dorn (1987). Scale bar 2 microns. Arrow shows the varnish/rock contact.

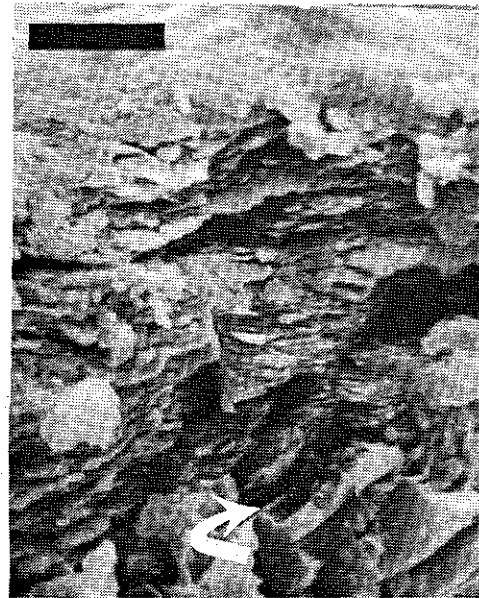
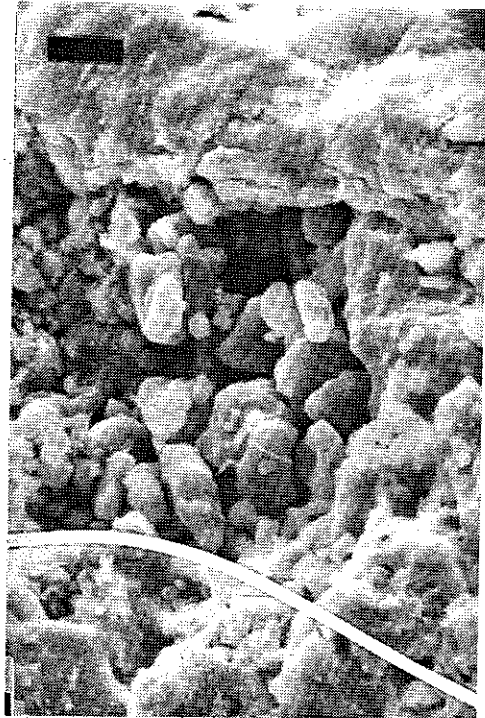


Figure 8. Micromorphology of rock varnishes on selected petroglyphs (Continued)

8c. Varnish on Coso petroglyph BSS-3, a curvilinear abstract petroglyph with a cation-ratio age of $14,200 \pm 4200$ B.P. (2 sigma error) (Whitley and Dorn 1988). Above the line (separating varnish from rock) is a layer of botryoidal varnish, with a surficial layer of lamellate varnish above. The micromorphological stratigraphy of botryoidal under lamellate varnish is characteristic of varnish on Wisconsin-age landforms in the region. Scale bar 5 microns.



BSS3



8d. Varnish on Coso petroglyph CM12, a bighorn sheep petroglyph (shown in photo below; longest dimension of petroglyph 60 cm), reveals a superposition of lamellate on botryoidal varnish. Like BSS-3 in Figure 8c, the cation-ratio age places it in the latest Wisconsin with a cation-ratio age of $18,200 \pm 2400$ B.P. (2 sigma) (Whitley and Dorn 1988). Of note, energy dispersive analysis of X-rays of these botryoidal layers give Mn:Fe ratios of about 1-1.5, indicating they probably correspond with the dark layers in the polished cross-sections displayed in Figure 3b. Scale bar 5 microns.

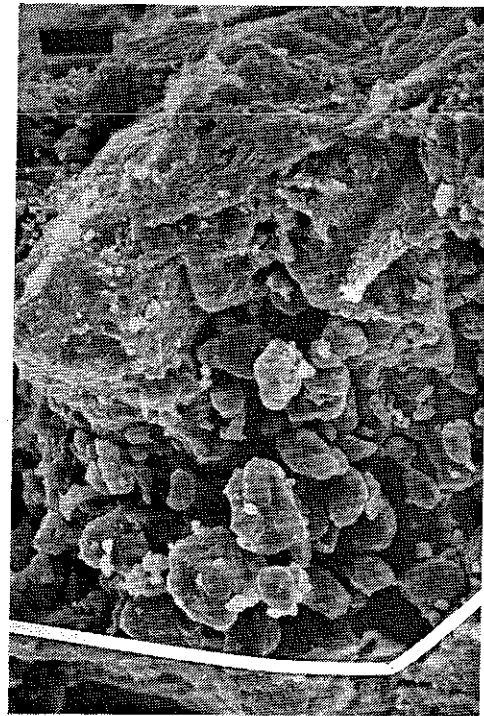
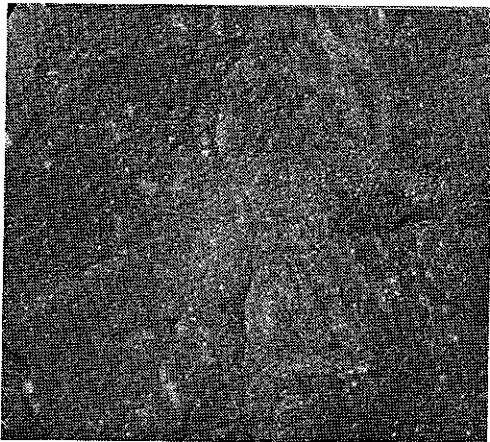
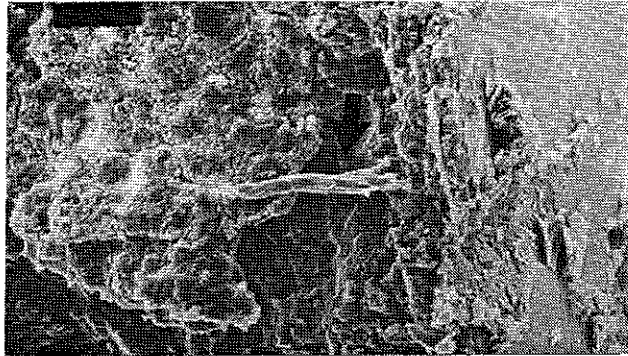
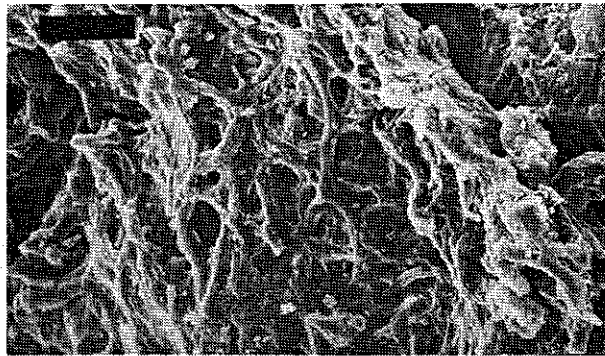
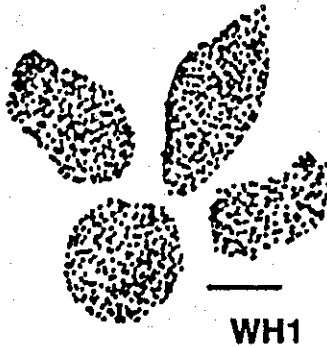


Figure 9. Subvarnish organic matter with stable carbon isotope values of about -23 per mil. Scale bars about 20 microns.

9a. Scanning electron micrograph of a patch of organic matter still attached to the underlying rock, after being scraped from underneath varnish from petroglyph K23 at Karolta (see Figure 6c). Arrow shows probably fungal hyphae.



9b. Close-up of subvarnish organic matter extracted from underneath petroglyph WH1 at the Wharton Hill site (Figure 5). The filaments are probably fungal hyphae.



Paleovegetation

It is possible to obtain stable carbon isotope (^{13}C) values for sub-varnish organic matter (Figure 9). As noted in the methods section, ^{13}C values in varnish appear to be controlled by the photosynthetic pathway of adjacent vegetation (Dorn and DeNiro 1985). Plants with C_4 and CAM photosynthetic pathways are found in more arid regions and have less negative ^{13}C values, for example -14‰. In contrast, plants with C_3 pathways tend to be found in more humid regions and have more negative ^{13}C values, for example -25‰ (DeNiro 1987).

The only experiments run on ^{13}C values of organic matter encapsulated in and under varnish on petroglyphs were conducted on South Australian engravings (Figure 5). The current vegetation at these sites is a mix of C_3 and C_4 plants (e.g., Hattersley 1983). The very surface layer of varnish on adjacent natural rock surfaces reflects this mix with ^{13}C values from -16‰ to -20‰. The subvarnish organic matter thus far examined, from only seven

petroglyphs in South Australia, has ^{13}C compositions ranging from -23‰ to -24‰. These results may be tentatively interpreted as indicating that the local area had fewer C_4 plants when the subvarnish organic matter was trapped.

Unlike the other paleoenvironmental records presented, I do not think simple ^{13}C studies of subvarnish organic matter on petroglyphs are justified at this time. Cost is not a serious problem. Commercial ^{13}C measurements are typically less than \$40. However, I would strongly recommend using the subvarnish organic matter for an accelerator radiocarbon dating (Dorn et al. 1989, in prep.) that can provide both radiocarbon and stable carbon isotope measurements on the same sample. In the near future, however, when it becomes possible to use lasers to extract this organic matter from cross-sections for ^{13}C measurements, I anticipate that ^{13}C measurements could be accomplished in tandem with the other paleoenvironmental methods on the same cross-section.

CONCLUSIONS

There are several findings of this study.

(1) Although detailed replicate sampling of dozens of cross-sections was not conducted due to cost restrictions, I believe the evidence presented here supports the view that paleoenvironmental information can be extracted from layers in rock varnish on petroglyphs.

(2) Sequences of paleoenvironmental fluctuations can be used to indicate *relative* ages at a single site. Furthermore, this relative sequence of paleoenvironmental fluctuations can provide an independent check on the sequence of ages assigned to rock art.

(3) Accelerator radiocarbon dating of rock art is quite expensive, costing about \$500 (USA) per sample for just the commercial analysis. The paleoenvironmental methods described in this paper are an order of magnitude less expensive, and can be used as a screening device to better select petroglyphs for dating. For example, if all the petroglyphs at a site had the same paleoenvironmental history, I would expect dates to turn out similar. It would be prudent to select only a few of these samples for expensive ^{14}C dating. Alternatively, if the petroglyphs at a site showed a range of paleoenvironmental histories, these analyses would provide a low-cost clue to the range of relative ages that would assist the archaeologist in deciding which petroglyphs to date.

(4) A potential danger of obtaining dates on rock art is the tendency to relate the age of the rock art to the climate of this time interval, as recorded by regional climatic signals like glacial deposits, pollen, or lake-level fluctuations. Many rock art sites are in protected rock shelters, near springs, along water courses, and at other locales with unique microclimates. These environments may not reflect a regional climatic record provided by regional records. In contrast, rock varnish records site-specific environmental changes. Along with other site-specific records, like macrofossils collected by the wood rat *Neotoma* (e.g., Spaulding 1990), rock varnish can add unique information on past environments at an engraving site that might be missed by just comparing the archaeological record with a regional climatic signal.

(5) Rock varnish paleoenvironmental analysis should not replace other methods at a site, but its advantage is in providing different types of paleoclimatic signals with different thresholds of change. For example, the environment may be moist enough to cause a shift to

manganese-rich varnish, but not cause the precipitation of silica skins or a change to botryoidal varnish.

(6) In the Coso Range and in South Australia, petroglyph sites were reused in different environmental conditions, over thousands of years. Long-term use of petroglyph sites has important implications for the cultural history of an area.

(7) Understanding a sequence of environmental changes at a rock art site provides the archaeologist a local and independent source of data by which to interpret connections between environment and archaeology.

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