

AGE DETERMINATION OF PETROGLYPHS IN SOUTHEAST COLORADO

by

RONALD I. DORN
Department of Geography
Arizona State University

WILLIAM R. MCGLONE
Albuquerque, NM

PHILLIP M. LEONARD
Kamas, UT

INTRODUCTION

Although they are not very well known or documented, many interesting petroglyphs on sandstone in southeast Colorado were made over an extended period of time. The area of interest is bounded by the Arkansas River on the north, the Cimarron River to the south, the Apishipa River to the west, and the Kansas state line to the east. Several tributary streams, notably the Purgatoire River and Rule Creek, have incised canyons in the sandstone of the Purgatoire formation.

The area is rich in petroglyph panels along these canyons, but few records have been made of them prior to Loendorf (1989). Warren Moorehead (1931) illustrated some in his archaeological survey of the Arkansas River valley. Renaud (1936) recorded more. Specific topical concerns of the petroglyphs and petroglyph sites have been evaluated by Tatum (1944), Campbell (1969), Eddy (1982), Buckles (1974, 1989), and Quinn (1989). Recently McGlone and Leonard (1986) and McGlone et al. (1989) investigated the possibility of an association with Old World scripts. Loendorf (1989) conducted a classic investigation of petroglyphs in the upper Purgatoire River Canyon.

Petroglyphs in arid and semiarid regions start to accumulate a coating of rock varnish soon after they are engraved (e.g., Figure 1). Rock varnish is a dark, thin accretion of manganese- and iron-oxides, clay minerals, and over 30 minor and trace elements. Its formation is catalyzed by manganese-oxidizing bacteria (Dorn & Oberlander 1982; Krumbein & Jens 1981; Palmer et al. 1985). The manganese- and iron-oxides cement the clays to the rock surface (Potter & Rossman 1979). It has long been hoped that a dating method for the varnish would be developed (cf. Basedow 1914; Heizer and Baumhauf 1962), as dating the onset of rock varnish formation would place a minimum age for the underlying petroglyph.

Two methods have been developed and tested over the past several years that permit the dating of rock varnishes on petroglyphs: radiocarbon dating (Dorn et al. 1986, 1987b, 1989) and cation-ratio dating (Dorn 1983, 1989; Dorn et al. 1987a). Cation-ratio dating of rock varnish, calibrated by accelerator mass spectrometry radiocarbon dating, was used to assign minimum ages to petroglyphs in eastern California (Dorn & Whitley 1984; Whitley & Dorn 1987), arid South Australia (Dorn et al. 1988), and southeastern Colorado (Loendorf 1989).

The purpose of this investigation is to present new cation-ratio (CR) dates

on rock varnishes formed on petroglyphs engraved into sandstone in southeastern Colorado. Loendorf (1989) also presents new CR dates of varnish on petroglyphs on basalt and sandstone in southeastern Colorado. The major distinction of this report is that it presents ages for a different style of petroglyphs in the region. This work concentrates on styles that have been hypothesized to relate to Old World scripts (McGlone and Leonard 1986; McGlone et al. 1989). The ages of sandstone petroglyphs in the region from six sites were determined by assigning cation-ratio ages to the rock varnish that has formed on the engravings. It is beyond the scope of this study to present cultural interpretations of these measurements.

CATION-RATIO DATING OF PETROGLYPHS IN THE SOUTHEAST COLORADO REGION

Methods

Both radiocarbon and cation-ratio dating are typically used together in the age determination of petroglyphs. Radiocarbon dating provides numerical dates to calibrate the chemistry of the rock varnish on the petroglyphs. Radiocarbon dating of the varnish on the petroglyphs itself would be preferred, but carbon 14 measurements of organic matter in the bottom (first formed layer) of rock varnish typically require the sampling of from $\frac{1}{4}$ to 1 sq meter of rock surface. Few petroglyphs are large enough for this. It is possible, however, to obtain precise and accurate measurements of the chemistry of the varnish on petroglyphs.

A cation ratio of potassium plus calcium, divided by titanium (K + Ca)/Ti

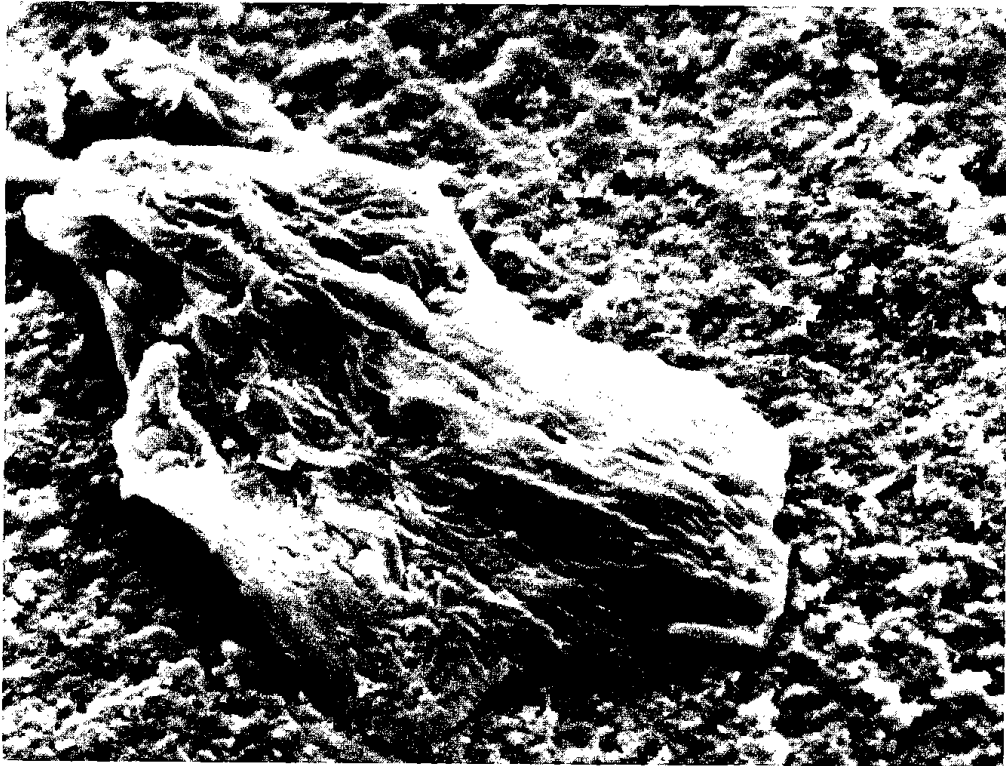


FIGURE 1. Scanning electron microscope image of varnish formed on a 1905 historical petroglyph in southeast Colorado, near Springfield, Colorado. Length of dots in lower right corner is 14 microns.

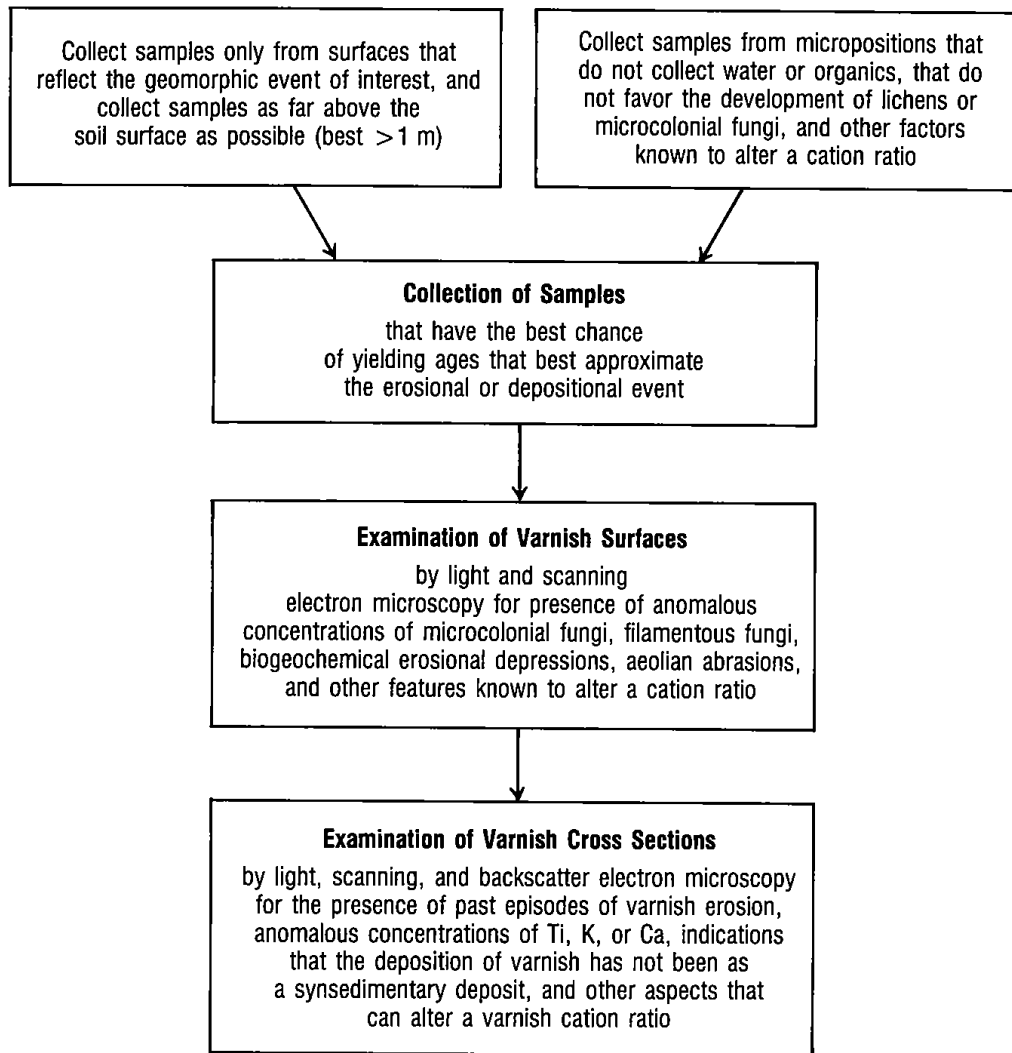


FIGURE 2. Generalized steps in the collection and evaluation of samples for cation-ratio dating and radiocarbon dating of rock varnish for calibration sites.

provides an age when calibrated by numerical dates (Dorn 1983). (See Colman et al. 1987 for dating terminology.) The numerical dates can come from established ages, such as potassium-argon (K-Ar) dated lava flows or radiocarbon-dated features. Few petroglyph sites, however, are in areas where a set of numerical ages are available for calibrating varnish cation ratios. The numerical dates, therefore, are often derived from carbon 14 dating of the varnish. These radiocarbon dates, in turn, provide a calibration for the cation ratios (CR) in the varnishes. Because only a few milligrams of material are required for a CR analysis by particle-induced X-ray emission (PIXE) (Cahill 1980; Cahill et al. 1984), there is usually enough varnish on petroglyphs for several PIXE determinations of CRs, and the visual effect on the petroglyph of taking the sample is often nearly indiscernible. The CRs are ultimately calibrated by the radiocarbon dates. The accuracy of these radiocarbon dates has been the subject of a study completed only recently. The results indicate varnish radiocarbon dating closely reflects the conventional radiocarbon dates of landforms on which the varnish has formed (Dorn et al. 1989).

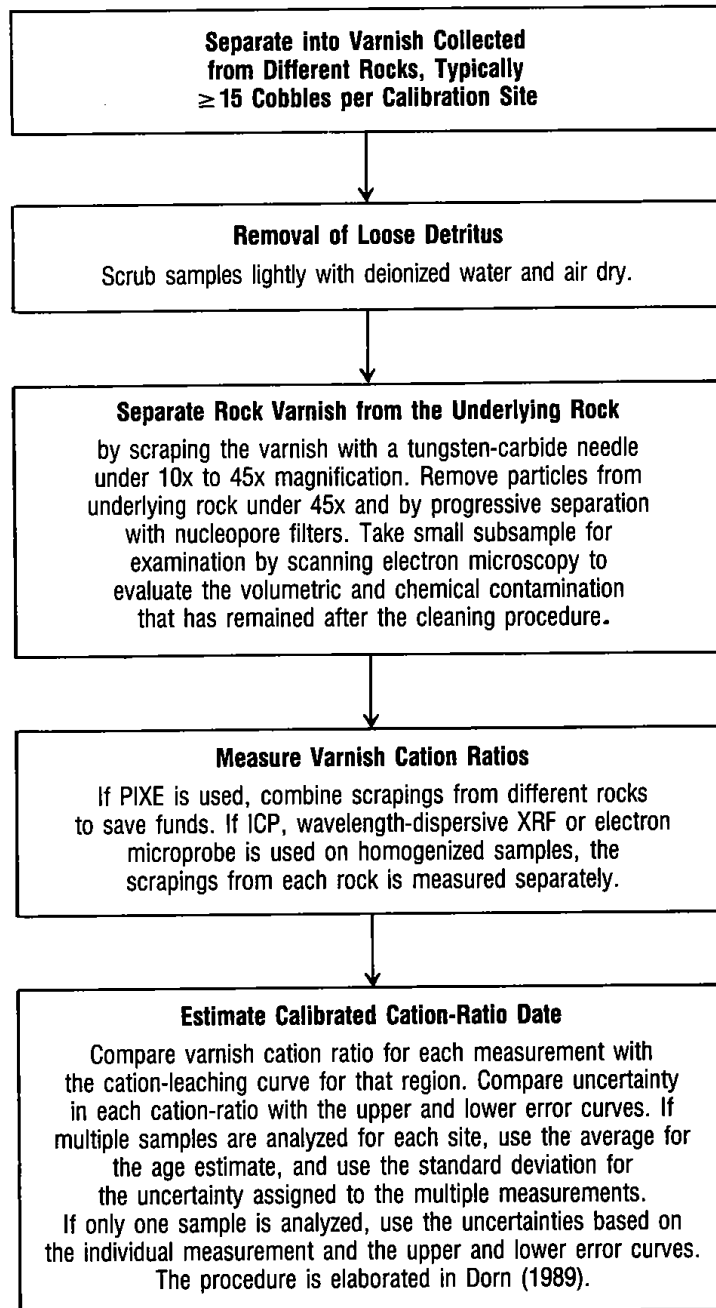


FIGURE 3. Generalized steps in the cation-ratio dating of rock varnish, after the samples have been collected in the field and evaluated in the laboratory.

CR dating of petroglyphs (Figures 2 and 3), is summarized in the discussion below. A calibration with numerical ages is first established for varnish CRs. Then, varnish CRs of petroglyphs are compared to this calibration. In establishing a calibration, numerical ages are first obtained for the exposure of geomorphic surfaces. The assumption is that the numerical age represents the time when the varnish started to form. This is a reasonable assumption in southeast Colorado, because varnish starts to form on subaerial rock surfaces in arid regions before about 100 years (Figure 1). The numerical age may

be obtained by such means as K-Ar dating of volcanic flows, but this method is often beyond the period of archaeological interest, at least in the New World. A more useful time scale is radiocarbon, and AMS (accelerator mass spectrometry) radiocarbon dating of varnish provides an estimate of when the varnish started to form.

CRs are calibrated by the numerical ages by measuring both the radiocarbon and (K + Ca)/Ti ratio from the same varnish. Great care is used in sampling to reduce the likelihood of biochemical erosion by acid-producing agencies or problems of mechanical abrasion from wind erosion. It is also important in the sampling process to select microenvironments for the calibration sites that are similar to the sites where petroglyphs are to be dated. The idea is to have the same leaching environment for the calibration samples as for the petroglyphs. A full list of environments avoided in the field are presented in Dorn (1989:Table 2). Once collected in the field, and mechanically removed from the underlying rock in the lab, the varnish is analyzed by particle-induced X-ray emission (PIXE) at Crocker Nuclear Laboratory at the University of California at Davis (Cahill 1980; Cahill et al. 1984). These calibrations are in Table 1.

An initial cation ratio for the varnish is established by proxy, since the cation ratio of newly formed varnish cannot be measured accurately by PIXE or scanning electron microscope methods. Dust is collected from natural dust traps, in this case crevices in rock joints, and a CR is established for the less than 2 micron fraction of dust collected from each of the calibration and petroglyph sites. This is to estimate the "initial ratio" and to make sure that no anomalies of K (potassium), Ca (calcium), or Ti (titanium) are present at the calibration sites or petroglyph sites. If a local aeolian anomaly were found, for example, the site might not be datable. None of the local environments sampled in this study have high levels of ambient calcium, potassium, or titanium. The initial ratio is used in the calibration in Table 1.

After the numerical ages are obtained and the varnish CRs are determined, three cation-leaching curves (CLC) are constructed (Figure 4). A central curve is a least-squares regression of the mean CRs and mean numerical ages for the different geomorphic surfaces and the initial ratio (ratio estimated by CR of <2 micron fraction of dust fallout). The age assigned by the initial ratio is 100 years, the age of the youngest historic surface where varnish has been detected (Figure 1).

Upper and lower error curves are determined by using the plus-2 standard

TABLE 1. Calibration Data Used to Construct the Cation-Leaching Curve in Figure 4

Calibration Site	Corrected C-14 Date	(K+Ca)/Ti Cation Ratio	Uncorrected C-14 Date	Lab No. (Beta; ETH)
Initial Ratio (IR)	Historical 100 yr	9.91±0.86		
near 5LA5602	1810±150	7.30±0.12	1730±75	26690;4294
5LA2224A	1450±250	7.48±0.13	1420±110	24366;3672
5BN10	4675±300	6.55±0.14	3840±135	24367;3673
near 5LA5602	8975±110	5.80±0.16	8160±110	26692;4292
5BA108	13,900±300	5.40±0.08	12,650±300	24365;3671
34Ci-37	17,950±350	5.19±0.15	16,320±350	22209;3195
5LA2224B	20,350±220	4.99±0.09	18,500±220	22207;3193

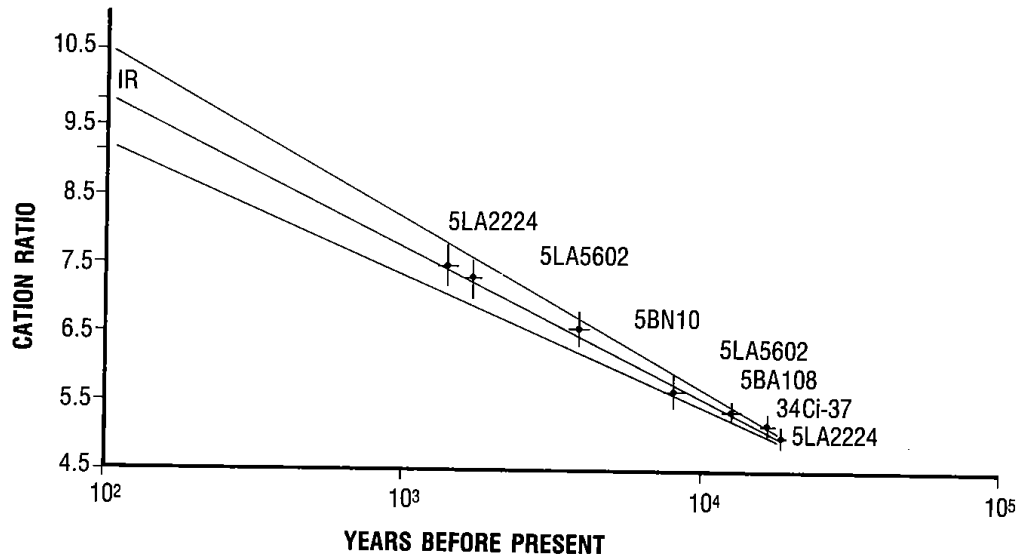


FIGURE 4. Cation-leaching curve in southeast Colorado represents changes in the $(K + Ca)/Ti$ ratio over time. The numerical age calibration is by corrected radiocarbon dates (Table 1) on varnish. The IR (initial ratio) represents the cation ratio of varnish when it first starts to form. The central curve represents the semilog least-squares regression of the mean CR and the mean age. Error bars are two sigma.

errors and minus-2 standard errors of the varnish CRs and the numerical age estimates. An empirical approach is used for constructing the upper and lower error curves, rather than a theoretical diffusion approach, because the variables that affect how varnish CRs change are not completely understood. Further, it seems inconsistent to use an empirical approach to determine a central calibration and a theoretical approach to determine the error CLCs.

Calibrated ages for petroglyphs are obtained here by using three CR measurements by PIXE. Varnish is removed mechanically from the petroglyph in the field from three different spots on the petroglyph. The scrapings are cleaned of rock contamination using a 45x microscope and using a nucleopore filter system. Petroglyph ages are obtained by comparing the varnish CRs with the CLC. A cation-ratio date is assigned to each separate PIXE analysis (by the central CLC). The average of the three CR dates gives the mean age, and the standard error provides the uncertainty.

The field procedures used for collecting varnishes for a calibration require the collection of enough varnish for both an AMS radiocarbon analysis and a series of CR analyses from the same site. Only black (manganese-rich) subaerial varnish is collected. Microenvironments with lichens, microcolonial fungi, abundant organic detritus, and other variables (see Dorn 1989: Table 2) that can alter a CR are avoided. The idea is to standardize the environment so that time is the only important variable affecting a cation ratio.

Laboratory processing of the samples for radiocarbon dating is reviewed (Dorn 1989; Dorn et al. 1987b, 1988). The approach is to date carbon in organic matter incorporated when the varnish first started to form. Organics from the manganese and iron oxides in varnish and pieces of detritus are removed from the bottom layer. The sample is then analyzed by accelerator mass spectrometry (AMS). A detailed description of sample preparation for AMS radio-

carbon dating is presented in Suter et al. (1984) and Jull et al. (1986). Although the bottom layer did form over a period of time, and hence is younger than the true onset of varnishing, radiocarbon dating of this bottom layer is about 10 percent younger than onset of varnishing in semiarid regions like south-eastern Colorado (Dorn et al. 1987b, 1989).

A cation-leaching curve (CLC) is a semilog, least-squares regression where the CR of (K + Ca)/Ti in varnish is calibrated by numerical dating methods. The central CLC in Figure 4 is constructed by correlating mean calibration age with mean CR for the same site. The initial ratio is based on historic time. All other calibrations are based on radiocarbon measurements of organic matter in the basal layer of varnish. Research recently completed by Dorn and the University of Arizona Accelerator Research Group has found that the varnish AMS radiocarbon age is about 10 percent younger than the conventional date at semiarid sites like in southeast Colorado and about 5 percent younger at desert sites (Dorn et al. 1989). Therefore, the laboratory measurements in radiocarbon years are first corrected, where possible, by the tree-ring calibration of Stuiver et al. (1986) and Stuiver and Reimer (1986). What is of interest in petroglyph dating is when the varnishes started to form on the petroglyph. This provides a minimum-limiting age for the actual manufacturing of the motifs. Therefore, 10 percent is then added to these AMS radiocarbon dates to correct for the net lag between the exposure of the rock and the development of the bottom layer of the varnish. This gives the corrected carbon 14 dates in Table 2. A semilog least squares regression between this corrected radiocarbon date and the cation ratio of the varnish from this same site yields the central CLC in Figure 2, represented by equation 1:

$$\text{Varnish CR} = 14.17 - 2.11 \log_{10} (\text{age}) \quad (1) \text{ Central Curve}$$

The upper CLC in Figure 2 represents an empirical semilog regression of the upper 2 S.E. errors of the calibration dates and the calibration CRs (and lower 2 S.E. errors for lower CLC). These CLCs are represented by equations 2 and 3.

$$\text{Varnish CR} = 15.50 - 2.41 \log_{10} (\text{age}) \quad (2) \text{ Upper Curve}$$

$$\text{Varnish CR} = 12.87 - 1.82 \log_{10} (\text{age}) \quad (3) \text{ Lower Curve}$$

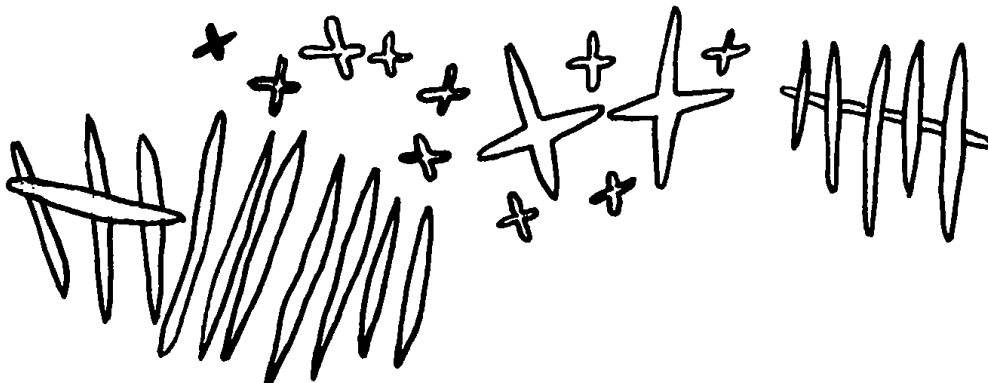


FIGURE 5. SEC-1 from site 5LA2224. Panel is 18 inches wide.

**TABLE 2. Cation-Ratio Dating Results on Petroglyphs
(numbers correspond to other figures and tables)**

Petroglyph SEC	Site Number	Mean Date	Standard Error	Cation Ratio	Standard Error
1	5LA2224	2975	200	6.83	0.07
2	5LA2224	750	100	8.08	0.08
3	5LA2224	750	100	8.09	0.12
4	5LA2224	2950	225	6.85	0.07
5	5BA108	2225	250	7.10	0.10
6	5BA108	2950	225	6.84	0.07
7	5BA108	<300		9.56	0.11
9	5BN65	2275	300	7.08	0.12
10	5BN65	2000	175	7.20	0.08
11	5BN65	1950	150	7.22	0.07
12	5BN65	<300		9.68	0.10
13A	5BN65	1350	100	7.57	0.07
13B	5BN65	1425	100	7.51	0.05
14	5BN65	1850	200	7.26	0.10
15	5BN10	1975	200	7.21	0.09
16	5BN10	<300		9.63	0.09
17	5BN10	2300	175	7.07	0.07
18	34Ci-37	1975	200	7.21	0.09
19	34Ci-37	2000	300	7.20	0.13
21	34Ci-37	1150	125	7.71	0.09
23	34Ci-37	1250	100	7.64	0.07
24	34Ci-37	1200	100	7.66	0.06

Petroglyphs Tested

Twenty-one petroglyphs were tested at six sites, three along the Purgatoire River, two sites on Rule Creek and one of its tributaries, and one site in the Oklahoma Panhandle. All sites are designated by official site numbers. Individual petroglyphs sampled for cation-ratio dating were numbered from SEC-1 to SEC-23 (Table 3). Selected motifs are illustrated in Figures 5 through 11.

Panels containing petroglyphs SEC-1, 2, 4, 5, 6, and 19 (e.g. Figures 5 and 6) are groups of abraded parallel vertical lines. Various interpretations have been made for motifs of this type, some of which have accompanying solar alignments (Feyhl 1980; Halasi et al. 1981; McGlone and Leonard 1986). Petroglyphs SEC-9 to 11, SEC-13A and 13B, SEC-15, 17, and 18 are pecked. They are described as Archaic style by Buckles (1989), or as belonging to the Graneros or Aphisipa Foci by Campbell (1969). SEC-7, 12, and 16 are of a type considered to be Plains Indian rock art (Campbell 1969). Petroglyphs SEC-21, 23, and 24 are difficult to classify by previous motif groups (Table 3).

RESULTS

Table 2 presents the cation-ratio dates for varnishes formed on the petroglyphs. These represent minimum ages for the petroglyphs. However, the radio-carbon calibrations have been corrected for the stable carbon isotope ratio by the tree-ring calibration, and adjusted to correct for the net lag of surface exposure and AMS analysis. These calibrations reflect, as close as possible, the exposure of a surface to the onset of varnishing.

The mean dates in Table 2 are averages of the regression ages of the indi-



FIGURE 6. SEC-7 from site 5BA-108.



FIGURE 7. SEC-12 from site 5BB-65, panel 3.

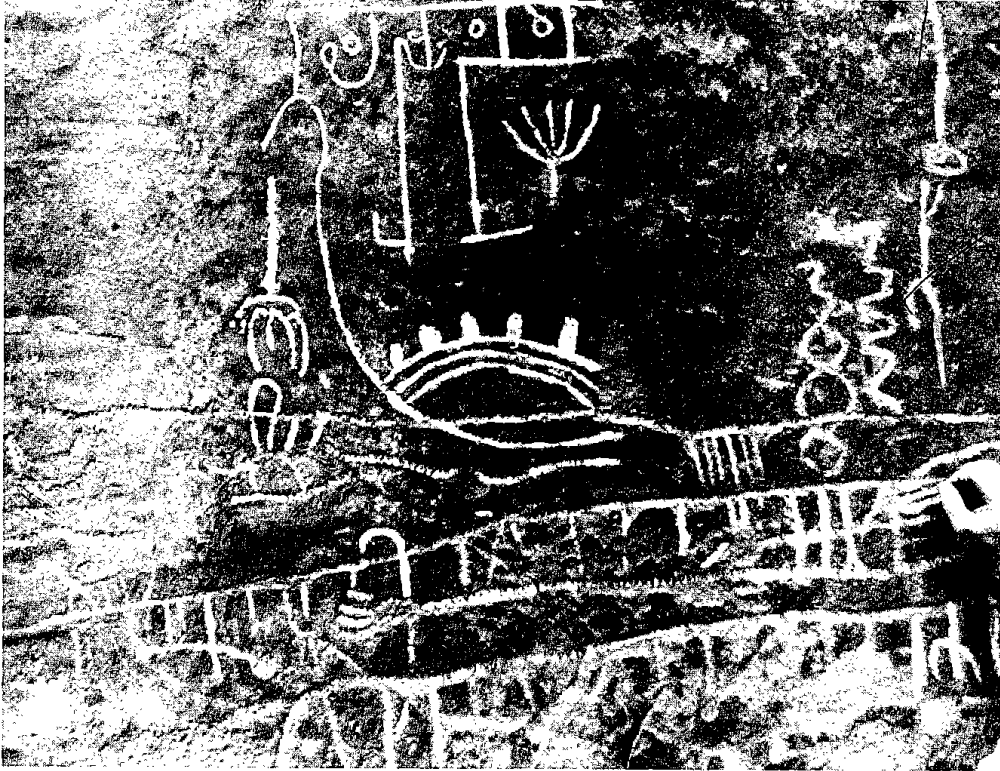


FIGURE 8. SEC-14 from site 5BN-65, panel 6.

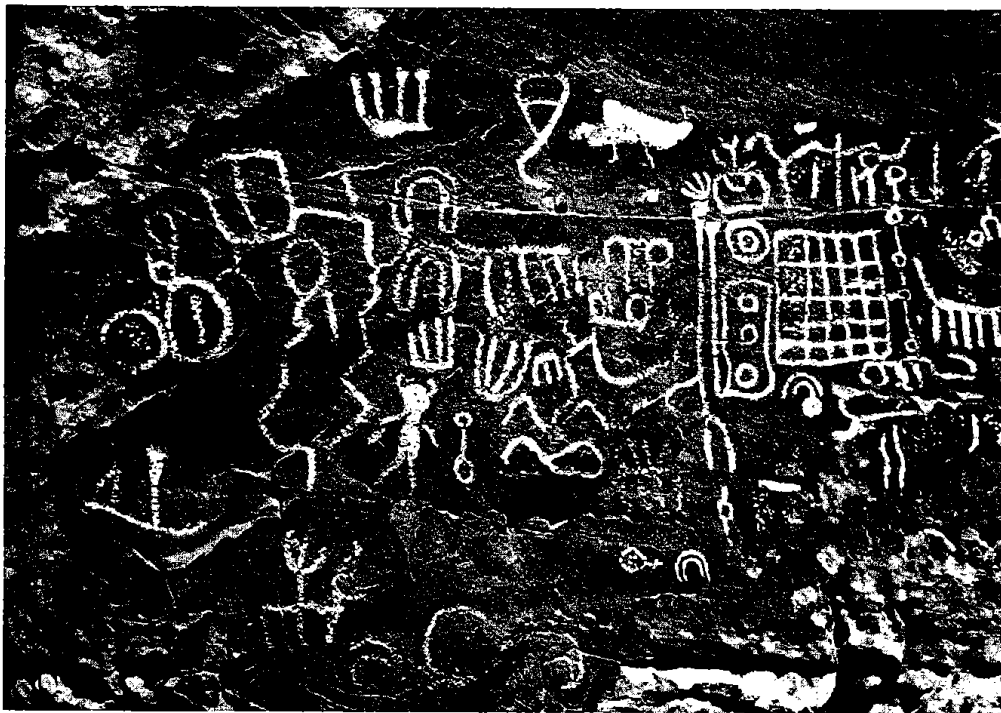


FIGURE 9. SEC-15 from site 5BN10, panel 2.



FIGURE 10. Rock varnish sample being taken from SEC-18 at site 5BN124.

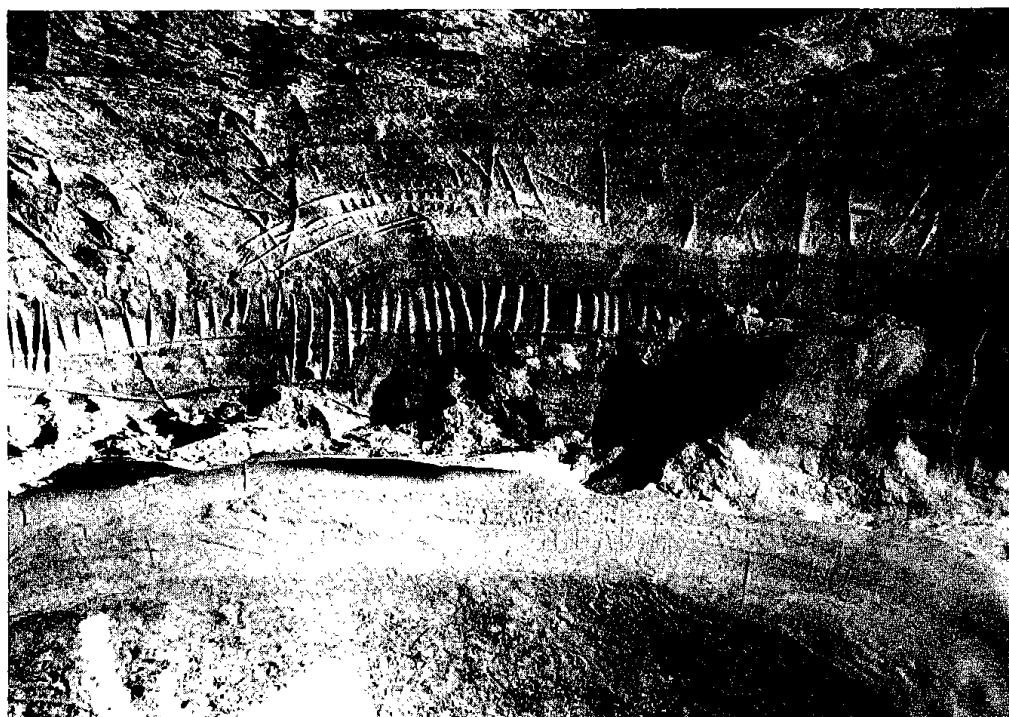


FIGURE 11. Panel containing SEC-9 at Site 34Ci37. Dating sample taken on portion of horizontal line beyond spall at black arrow right center.

TABLE 3. Individual Petroglyphs Sampled

Petroglyph Number	Site Number	Figure (this paper)	Petroglyph Element Tested
SEC-1	5LA2224	5	Vertical parallel marks
SEC-2	5LA2224		Vertical marks below and to right of SEC-1
SEC-3	5LA2224		Large ring symbol
SEC-4	5LA2224		"Tree-like" symbol
SEC-5	5BA108		Rows of vertical marks
SEC-6	5BA108		Vertical parallel marks
SEC-7	5BA108	6	Anthropomorphic figure
SEC-9	5BN65		♀ From line of symbols high on panel 3
SEC-10	5BN65		8 From panel 3
SEC-11	5BN65		♀ From panel 4
SEC-12	5BN65	7	Large abraded horse, panel 3
SEC-13A	5BN65		Left side of a U symbol, panel 3
SEC-13B	5BN65		Right side of a U symbol, panel 3
SEC-14	5BN65	8	21 m long horizontal line near "sun" symbol, panel 6
SEC-15	5BN10	9	Υ Symbol from panel 2
SEC-16	5BN10		* From group of "plus marks" on a large boulder
SEC-17	5BN10		⊕ From panel 4
SEC-18	5BN124	10	Ψ Symbol from Archaic panel
SEC-19	34Ci37	11	Horizontal line where it continues to the right of vertical parallel lines, beyond peel imprint, Cave 3
SEC-21	34Ci37		Cave 4, "hand-like" symbol
SEC-23	34Ci37		Cave 4
SEC-24	34Ci37		Cave 4, Marks in line above "Cardoba" inscription

vidual CR measurements. In other words, three PIXE measurements were taken on three separate varnish samples from each petroglyph. The mean CR of each measurement is compared to the cation-leaching curve (equation 1; Figure 4) and an age is estimated. These are averaged, and the average is reported as the mean date with one standard error. The averages of the three CRs derived from the PIXE measurement are also provided in Table 2.

DISCUSSION

Cation-leaching curves (CLC) have been composed of different lithologies before, in the Coso Range (Dorn 1983), in the Mojave Desert (Dorn et al. 1987a), in the Owens Valley (Dorn et al. 1987b), and in southern Nevada (Harrington and Whitney 1987). Still, it should be noted that the CLC for southeast Colorado in Figure 4 was derived from varnishes on sandstone (5BN10; 5LA 2224; 5BA108; 5LA2224; 34-Ci-37) and basalt at sites in the Pinon Canon Army Maneuver area, discussed in greater detail by Loendorf (1989:Table 1).

Since less than 2 percent contamination from the underlying rock is evident in tests (cf. Dorn et al. 1987a; this study), it is not surprising that the calibration points should correspond well. One aspect of this is that varnish growth is rapid on both lithologies and is not time transgressive on either.

It is also significant to note that the calibration points are from sites tens of kilometers apart from canyons cut into the High Plains. The chemistry of the dust for the varnish appears to be similar throughout southeast Colorado. The calibration curve for southeast Colorado is also quite similar to the one for the Texas Panhandle to the south (Dorn, unpub. data). When the Texas Panhandle and southeast Colorado data are placed on the same cation-leaching curve, the correlation coefficient is still better than $r = -0.98$. When the data are plotted as a power function, both the southeast Colorado and Texas Panhandle curves are described by the equation, $\text{Varnish CR} = 18 * \text{Age}^{-0.13}$.

In the Basin and Range province of southwestern North America, calibration curves can differ dramatically from one area to the next (Dorn 1983; Dorn et al. 1986, 1987a). In contrast, the curves constructed for the High Plains from northernmost Texas to southernmost Colorado are quite similar. This could be because of the similarity of dust fallout in the region and because of similarity in the synoptic climatology. Of note, the CLC for southeast Colorado is steeper in slope than the ones published for eastern California (Dorn 1983; Dorn et al. 1987a, 1987b). This is likely from a greater influence of summer moisture at present and perhaps during the latest Quaternary.

A concern is how applicable CR dating is to different time periods. CR dating is not good at dating petroglyphs much less than 1,000 years old. CR dating for younger petroglyphs is less reliable because the varnish development is less and the measurements are based on less material. Even small contributions from anomalous sources of calcium, potassium, or titanium could strongly affect the analyses. It is encouraging that the different PIXE analyses for the different varnishes taken from a single petroglyph were so similar. These results are similar to Dorn et al. (1986) in that a given archaeological feature made at the same time (a petroglyph here; refitted sequence of artifacts in Dorn et al. 1986) has similar CRs for different subsamples of varnish.

There are two methods presently used to measure cation ratios. The one used here is to scrape the varnish and measure CRs by a high-precision method like PIXE. Another approach is to use a scanning electron microscope to generate X-rays; energy-dispersive analysis of these X-rays are then interpreted for (calcium + potassium)/(titanium) ratios (Harrington and Whitney 1987). The SEM method is not preferred here because it is destructive to artifacts and petroglyphs, whereas the PIXE method only requires that small amounts of varnish be scraped off. Other potential problems with the SEM method of dating varnish are elaborated in Dorn (1989).

Additional notes should be made regarding interpretation of some of the data. Petroglyphs SEC-5 and SEC-19 were from overhangs, protected from many of the subaerial processes that leach rock varnish cations. At sites of controlled age in the Coso Range, eastern California, such protected sites have higher cation ratios than volcanics of the same age but not protected (Dorn 1989). This is probably due to a reduction in the leaching rate. Therefore, the cation-ratio ages for SEC-5 and SEC-19 in Table 2 should be considered minimum ages. SEC-19 was from a petroglyph where a rubber peel had been applied

(Figure 11). The reported specimens were taken from where a portion of the horizontal line extended outside the peel area. A second set of specimens taken within the peel area gave anomalous results for K, Ca, Ti, P (phosphorus), and Mg (magnesium), indicating the ratio was not of natural varnish. The application of peels should, therefore, be avoided if the petroglyphs are to be cation-ratio dated accurately.

The Archaic-style petroglyphs tested ranged from 1350 to 2300 B.P. for the mean dates. The youngest, SEC-13, was tested on both the left and right sides, because the varnish had the appearance of a slightly different hue and chroma. One sigma errors of 1350 ± 100 and 1425 ± 100 overlap. The other Archaic-style petroglyphs (cf. Buckles 1989) (SEC-9, 10, 11, 14, 15, 17, and 18) ranged from 1850 to 2300 B.P. These are consistent with Buckle's (1980) stratigraphic minimum age of ca. 1850 for an Archaic motif in the region. The Plains Indian petroglyphs (SEC-7, 12, and 16) tested to < 300 B.P. at the lower limit of the method, and they were consistent with the time frame ascribed to the Plains Indian occupation of the region (Nowak and Kingsbury 1981).

SUMMARY

Petroglyphs on sandstone in southeastern Colorado have been assigned minimum-limiting ages by cation-ratio dating of the rock varnish formed on them. The cation-ratio dating technique is shown here to be applicable for use on sandstone petroglyphs. Two of the styles of petroglyphs tested range in age into the Archaic period. All the Plains Indian petroglyphs test historic (< 300 years B.P.). All petroglyphs were younger than a radiocarbon calibrated age of 3000 years before present. A cultural interpretation of these results is beyond the scope of this paper.

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ACTING BOOK REVIEW EDITOR

Dr. Payson Sheets, Book Review Editor, will be in El Salvador for about six months of fieldwork. Dr. Frederic Athearn will serve as Acting Book Review Editor between July 1990 and May 1991. You can contact Dr. Athearn at Bureau of Land Management, 2850 Youngfield, Lakewood, CO 80215-7076; (303) 236-1756.