Chronometric and Relative Age Determination of Petroglyphs in the Western United States

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Abstract. This paper presents chronometric age determinations of petroglyphs from the Coso Range and Cima volcanic field and relative dating from other locations in the western United States using the new rock varnish technique of cation-ratio dating. Our results verify the proposed Great Basin relative stylistic chronology, which indicates that curvilinear abstract was followed by rectilinear abstract and representational. However, these styles have greater antiquity than previously proposed, suggesting new interpretations for the significance of the Coso Range rock art.

Key Words: rock varnish, desert varnish, petroglyphs, rock engravings, dating, Coso Range, Mojave Desert, Grimes Point, Hedgepeth Hills, archaeology, arid lands.

PETROGLYPHS or rock engravings are designs that have been pecked, incised and/or scratched into rock outcrops. Although relatively common, they are perhaps the least understood archaeological remains in the western United States. Steward (1929) and Bard (1979) noted that most research on petroglyphs has been little more than speculation by amateurs. The hesitancy of North American archaeologists to undertake serious rock art studies has been largely due to the difficulty of correlating rock art with specific cultures, and the lack of an accurate dating method (Whitley 1982a). However, using the technique of cation-ratio dating recently developed by Dorn (1983), we have obtained chronometric ages for rock varnishes within the engraved surfaces of six petroglyphs from the Coso Range and Cima volcanic field, eastern California, and relative ages for rock engravings in Nevada and Arizona.

Although absolute ages for buried rock art have been obtained through stratigraphic associations by a number of authors (e.g., Deetz 1964; Randolph and Dahlstrom 1977; Thackeray et al. 1981; Brian D. Dillon, pers. comm., October 1982), our dates are the first direct chronometric age determinations from the western United States. A presentation of these dates and conclusions is therefore warranted, even though some of these cation-ratio dates have substantial uncertainties. The age determinations obtained in this study revise the previously proposed absolute chronology for Great Basin rock art, enable a more accurate determination of the cultural affiliations of the producers of the rock art, and allow us to make some interpretations of the prehistoric cultural significance of the Coso petroglyph assemblage.

Petroglyphs in the western United States are typically engraved into a natural coating called rock varnish (Dorn and Oberlander 1981, 1982). The underlying rock or weathering rind is usually lighter in color than the surficial varnish; hence the carvings are given an excellent contrast. Rock varnish is composed of clay minerals, oxides and hydroxides of manganese and iron, and minor and trace elements that accrete on rock surfaces mostly from desert dust (Potter and Rossman

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1977; Elvidge and Collet 1981; Dorn and Oberlander 1982).

Many petroglyphs have been revarnished to some degree, and previous petroglyph dating techniques have used characteristics of this revarnishing, such as increasing darkness (Grant 1968), thickness (Turner 1963), or concentration of manganese (Bard 1979). However, these characteristics are controlled more by microenvironmental factors affecting manganese-concentrating microorganisms (Dorn 1983) and perhaps the distribution of desert dust (e.g., Elvidge and Collet 1981) than by age. In contrast, cation-ratio dating relies on minor elements in varnish, which have different geochemical mobilities and are thus dependent on the length of time the varnish has been subjected to leaching.

Cation-ratio Dating

Cation-ratio dating is based on the concept that the mobile cations (e.g., Na, K, Ca, Mg) are more easily leached from varnish cation-exchange complexes, which are present in illite-montmorillonite clays (Potter 1979), and from manganese and iron oxides (Jenne 1968), which are dominant in varnish, than are less mobile cations (e.g., Ti). In this study potassium and calcium rather than other readily exchangeable cations are employed in a ratio with titanium (K+Ca:Ti) because the bulk chemical method used (i.e., particle-induced X-ray emission (PIXE) analysis performed at the University of California, Davis, Crocker Nuclear Laboratory (Cahill 1981)) gives the most reliable results for this ratio. Furthermore, K and Ca are probably not preferentially adsorbed by iron and manganese oxides (Speidel and Agnew 1982, 71). Titanium is used here as the immobile cation because it is not affected by manganese-concentrating microorganisms, it is present in readily measurable quantities, it is not preferentially adsorbed by iron or manganese oxides (Speidel and Agnew, 1982, 71, 127), and it is immobile in semiarid and arid environments (Marchand 1974; Gardner 1980; Coleman 1982).

Samples are prepared by careful detachment of varnish from the underlying rock with a tungsten-carbide needle under 10× to 45× stereomagnification. This scraping process yields a large sample for bulk chemical analysis by the PIXE method (Cahill 1981). Electron microprobe and other high-resolution analytical techniques are inappropriate because they include only a small portion of the varnish, and an analysis of the entire coat is needed to compare varnish cation ratios.

A reduction of a ratio between mobile and immobile varnish cations (e.g., K+Ca:Ti) indicates a relative chronological sequence of rock varnishes from similar microenvironmental settings at a given site. By calibration of varnish cation ratios with surfaces of known age, such as K-Ar dated volcanics, it is possible to establish an empirical cation-leaching curve useful in the chronometric age determination of rock varnishes.

Cation-ratio dating has been successfully tested as a relative age-determination technique on colluvial and lacustrine surfaces (Dorn 1983). Its validity is best demonstrated, however, by presenting the cation ratios of varnishes from the Coso volcanic field, a late Cenozoic cover over the Coso Range, Inyo County, eastern California. Well-developed rock varnishes were sampled from Coso volcanics, dated from 39,000 to more than 3,000,000 B.P. by the K-Ar method (Duffield, Bacon, and Dalrymple 1980; Duffield and Bacon 1981), to establish an empirical cation-leaching curve for the Coso region (Fig. 1). The cation ratio for varnishes from each sampled volcanic deposit represents an average of 5 PIXE analyses.

The modern cation ratio used in this study was estimated by the K+Ca:Ti ratio of the clay-sized fraction of soils from 16 sites in the Coso Range (including all the calibration locations in Figure 1) because the detritus in varnish is probably derived from soil deflation (Péwé et al. 1981; Dorn and Oberlander 1981), and the particle size incorporated into varnish is usually under 2 μm (Dorn and Oberlander 1982; Dorn 1983). 100 B.P. is the age assigned to the <2μm surficial soil ratio because our scanning electron microscope and energy-dispersive X-ray analysis studies of historical, human-made surfaces in the central and eastern Mojave Desert show no varnish development after 50 to 70 years, but the presence of incipient varnish after ca. 100 years. Because no volcanics were dated under 39,000 B.P., varnishes on andesite and granitic boulders from the approximate

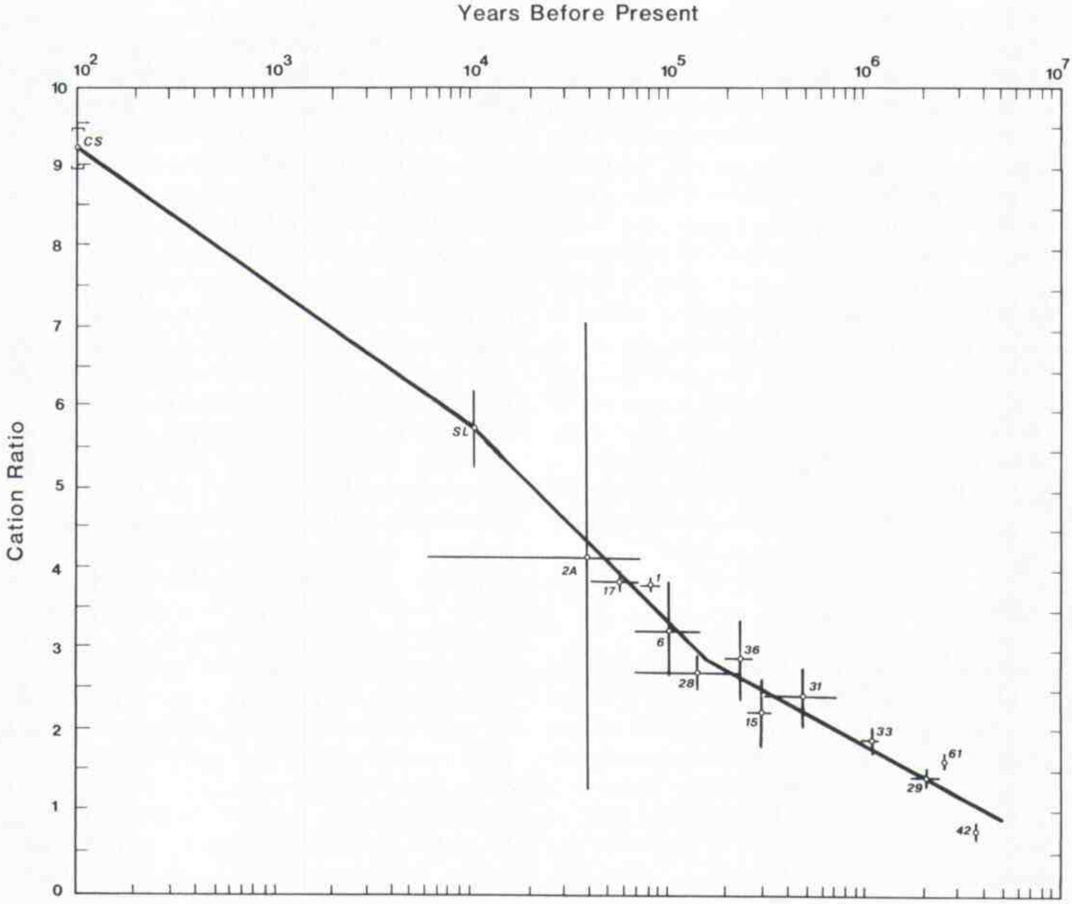

Figure 1. Varnish cation-leaching curve for the Coso region. The cation ratio used is K+Ca:Ti. The numbers represent K-Ar dated volcanic surfaces in the Coso region identified in Duffield and Bacon (1981). The horizontal and vertical bars indicate the K-Ar age uncertainties and cation ratio standard deviations, respectively. SL is the varnish ratio for the Searles Lake late-Pleistocene high stand. CS represents the clay-sized cation ratio of 16 Coso soils, collected near the analyzed volcanic rocks. The brackets on the left hand margin of the graph represent the standard error of the soil cation ratios. The lines from SL to 36 and 36 to 42 are semi-log regression lines with correlation coefficients of −0.99 and −0.98, respectively. The line from SL to CS is drawn between end points because of the lack of Holocene dated surfaces in the region.

10,500-year-old high stand of nearby Searles Lake (Smith 1976, 1979) were sampled to establish a late-Pleistocene/early-Holocene calibration point. Soils and varnish on other lacustrine terraces in the Searles Lake basin were also collected in a separate study to determine the usefulness of cation-ratio dating as a relative age-determination technique (Dorn 1983). However, the cation ratios of soils on the Searles Lake terraces are slightly higher than those of the Coso soils. To compensate for this different input the cation ratio from the Searles Lake high stand was multiplied by a correction factor: Coso soil ratio/Searles soil ratio, or 9.17/9.65. Figure 1 presents the empirical cation-leaching curve for varnish of the Coso-Searles Lake region. Further details on the construction of this curve are presented in Dorn (1983). Figure 1 can be described by the following equation:

$$Y = \begin{cases} 7.468 - 0.170\log X, & \\ \qquad 10^2 < X < 1.05 \times 10^4 & \\ 8.211 - 2.433\log X, & \\ \qquad 1.05 \times 10^4 < X < 1.50 \times 10^5 & \\ 5.724 - 1.296\log X, & \\ \qquad 1.50 \times 10^5 < X < 10^7, & \end{cases}$$

where X is in years B.P. and Y is the K+Ca:Ti rock varnish cation ratio.

Although an empirical relationship has

been demonstrated between varnish K+Ca:Ti ratios on the Coso volcanics and their K-Ar ages, little is known about the processes involved in cation-ratio dating. The reduction of the K+Ca:Ti ratio with time may be due to the replacement of K and Ca (or other mobile cations) by Ti or to the leaching of K and Ca. There are many factors that may influence the leaching or replacement rate, including varnish thickness, micromorphology, hydration, and permeability; wetting amount, type, and frequency; and leaching water geochemistry and temperature. Variations in any one of these factors poses potential problems for the necessary assumptions that the rates of removal of mobile cations from varnish are similar for all samples analyzed for dating, and that any changes in the leaching rate are synchronous in time and amplitude. For instance, thinner coatings are probably more thoroughly leached than thicker varnishes. So long as varnishes are sampled from microenvironments where thickness is mostly time dependent, this is not a problem. However, the thickness of a varnish is also controlled by the rate of accumulation of desert dust and the activity of manganese-concentrating microorganisms—factors other than time that usually vary from site to site (Dorn 1983). We have sampled from similar microenvironments and assumed that all the factors affecting varnish thickness vary in similar ways and amounts at the compared sites. Further research is needed on the mechanics of varnish cation exchange.

An important issue in cation-ratio dating is the notion that varnish forms only during warm and dry periods (e.g., Grant 1967, 1968; Glennie 1970; Hayden 1976; Allen 1978). To support this view, Grant (1968) cited an experiment by D. Martin, where varnish from the Coso area was brought to Santa Rosa, northern California. Grant reported varnish erosion within a few years, and other researchers have cited this experiment to support a warm-dry hypothesis of formation (e.g., Bard 1979; Elvidge, 1979). Unfortunately, it was not mentioned whether the varnish was exposed to anything other than precipitation, such as decaying organic matter in a garden. We will discuss this issue in detail because erosion of varnish in previous periods of greater precipitation would confute the correlation of varnish cation-ratios from the Coso volcanic field with the K-Ar ages of these deposits, thus invalidating the Coso leaching curve in Figure 1.

Dorn and Oberlander (1982) performed an experiment similar to Martin's, exposing Death Valley varnish only to rainfall in Berkeley, northern California. No chemical, optical, or micromorphological changes were observed. Subsequently, some of these varnished rocks were placed under acidic leaf litter. After two years, substantial chemical erosion occurred. In an additional experiment the first author exposed varnish chips from the Negev Desert (Israel), Death Valley, and the Barstow area (Mojave Desert) to running tap water in an open system for one year. The pH of the tap water varied from 6.8 to 8.4. Scanning electron microscopy and energy-dispersive analysis of X-rays (EDAX) of the fresh, six-month-exposed, and one-year-exposed varnishes showed no significant changes in color, chemistry (Fig. 2) or micromorphology (Figs. 3A and 3B), except for the growth of 1-μm to 10-μm diameter manganese-rich botryoids (Fig. 3C).

In order to determine whether the pH of the tap water in the above experiment was similar to the pH of natural precipitation in the eastern California region, frontal precipitation was sampled from two storms during the 1981-1982 winter, one in Death Valley and the other near Salt Springs, Mojave Desert. At the start of storms pH values were 8.5 and 8.2, respectively. Samples taken near the end of the precipitation had pH levels of 6.7 at both sites. One sample of runoff taken during the middle of the storm near Salt Springs had a pH of 7.2. pH measurements were made in the laboratory with a Beckman pH meter. Unfortunately, the redox potentials that were also measured are probably not valid because they likely represent an undefined combination of uncoupled redox systems (Baas-Becking, Kaplan, and Moore 1960; Morris and Stumm 1967). For the purposes of this investigation, however, we shall assume that redox potential is predominately controlled by pH, as has been indicated by Collins and Buol (1970, 112–13).

Elvidge and Collet (1981) stressed that the alkalinity of a desert is needed for the preservation of varnish. We agree, but with one qualification. That no varnish was removed

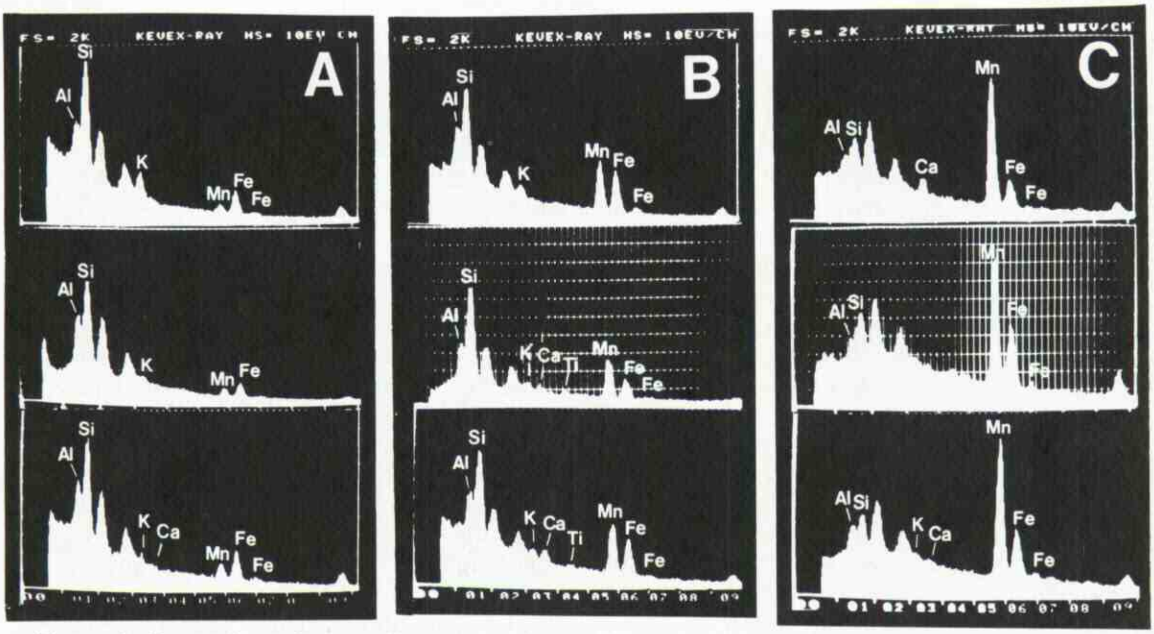

Figure 2. Comparison of energy-dispersive analysis of X-rays of varnish from a one-year experiment to test whether varnish erodes under conditions of greater moisture. All analyses were taken of varnish microridges, not depressions, because ridges are the most susceptible to erosion. (A) From varnish on gneiss from the second darkest flow on a talus cone, just south of Copper Creek alluvial fan, Death Valley National Monument (Dorn 1983). Upper panel is of fresh varnish, middle panel of varnish after six months of exposure to running tap water, and lower panel is after one year of exposure. (B) From varnish collected on volcanic tuff from Rainbow Basin near Barstow, Mojave Desert, California. The sequence is the same as in Figure 2A. (C) From varnish collected from a desert pavement near Wadi Vion, Negev Desert, Israel. The sequence is the same as in Figure 2A. As the experiment progressed there may have been a slight reduction in K and Ca in the varnishes. However, no clearly discernible changes occurred in the relative abundances of manganese and iron. The slight variations are probably due to the point-to-point microchemical variations that are common in arid varnishes (Dorn and Oberlander 1982).

during the year-long exposure to tap water with a pH range similar to desert precipitation suggests that an increase in near-neutral precipitation alone will not chemically erode varnish. For example, the first author has observed active manganese-enhancement by microorganisms in varnishes from semiarid regions with mean annual precipitations well over 300 mm. Acidity from sources such as lichens, decaying organic matter, and acid rain is needed to reduce the manganese in varnish and bring about its chemical decay.

Accurate cation-ratio dating also requires that the initial ambient "input" of K+Ca:Ti has remained relatively constant during the period of varnish deposition. Because varnish accretion is an extremely slow process in arid environments (Elvidge and Collet 1981; Dorn and Oberlander 1982), short-term localized changes in airborne fallout should not significantly disturb the overall input ratio. Long-term exposure to deflated soil material is probably the major mode by which varnish constituents accumulate (Elvidge and Collet 1981; Péwé et al. 1981; Dorn and Oberlander 1982). It must be assumed that the composition of this eolian fallout has remained relatively constant in the Coso Range through the Quarternary, as has probably been the case in central Arizona (Péwé et al. 1981, 182). Although there are no direct data to support this assumption for the Coso Range, energy-dispersive analysis of X-rays of the top layers of five Coso varnishes show K+Ca:Ti ratios that are indistinguishable from EDAX analyses of the <2 μm fraction of the nearby desert soils. Other potential limitations of cation-ratio dating are discussed in Dorn (1983)

Chronometric Age Determination of Coso Petroglyphs

Permission to obtain varnish samples from five petroglyphs in the Coso Range was ob-

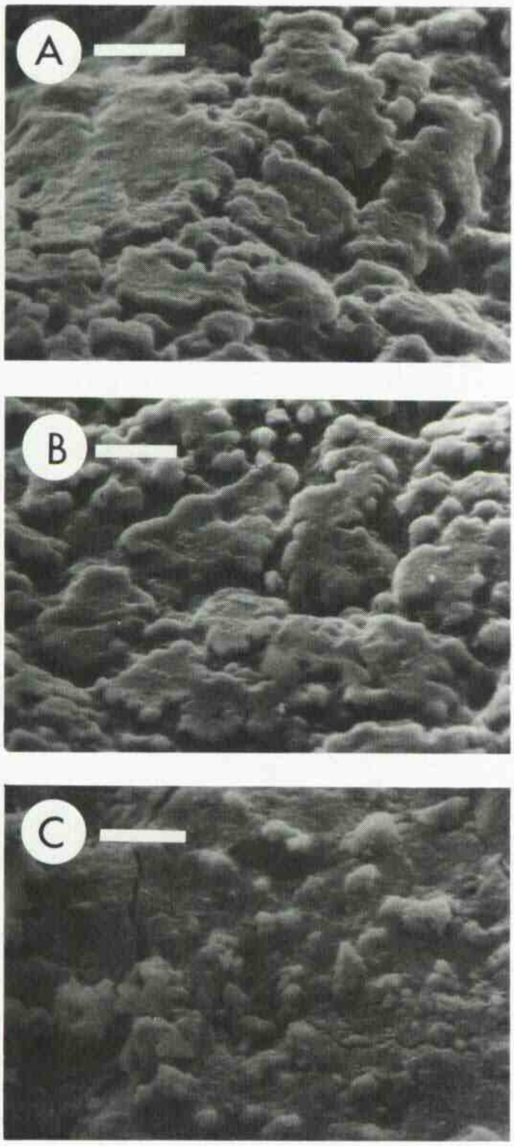

Figure 3. Scanning electron microscope observations of varnish taken from Rainbow Basin near Barstow, Mojave Desert, and exposed to running tap water in an open system for one year. Scale bar is 20 μm in A and B, and 10 μm in C. (A) Fresh varnish showing a typical arid micromorphology of predominantly lamellate separated by furrows. (B) Varnish after one year of exposure showing no clear change, except for some small botryoids rich in manganese developed in the furrows in the upper center of the image. (C) Close-up of newly developed manganese-rich botryoids growing on a lamellate surface.

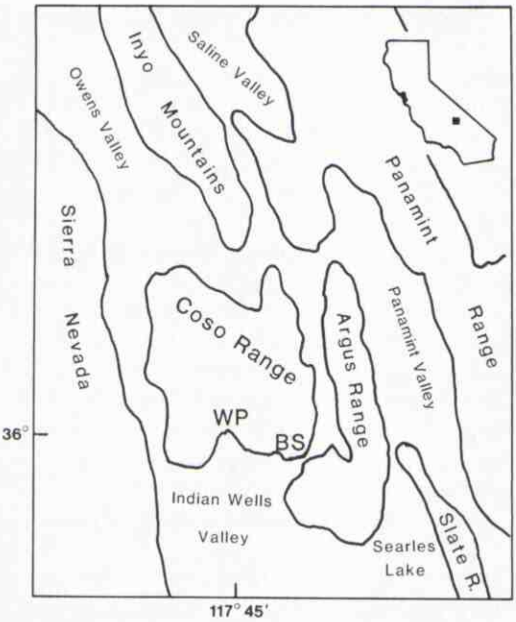

Figure 4. Map outlining the physiography of the Coso Range and vicinity and the location of the Wheeler Prospect (WP) and Birchim Springs (BS) petroglyph sampling sites.

tained from the Environmental Branch, China Lake Naval Weapons Center. The petroglyphs are from the Wheeler Prospect and Birchim Springs sites, located at 36°01′ N, 117°46′ W and 35°55′ N, 117°28′ W, respectively (Fig. 4). Both sites have only small concentrations of pecked motifs, numbering about 50 per site. Much larger petroglyph accumulations occur, and about 20,000 petroglyph motifs have been recorded in the Coso Range (Grant 1968). The Wheeler Prospect and Birchim Springs sites are representative of the Coso Range petroglyph assemblage (Grant 1968), containing Great Basin curvilinear abstract, rectilinear abstract, and representational styles, as defined by Heizer and Baumhoff (1962). All three styles were sampled in this study. The individual petroglyphs were selected on the basis of maximum observed varnishing for a particular style and similar microenvironmental conditions. The inital results were presented by Dorn and Whitley (1983) and are elaborated here.

Rock varnish was sampled from the petroglyphs in the field. The scraping process incorporated some particles from the underlying rock. These fragments were later extracted in the laboratory under 45× stereomagnification. Occasionally, undisturbed surfaces occurred in the middle of an engraving. Such cases were easily distinguished from the petroglyph in the field, and varnishes formed on the unpecked surfaces were not sampled.

One of the potential difficulties in comparing cation ratios of varnishes is the possibility of disparate onset of microbial colonization, implying nonsynchroneity of varnish initiation on surfaces of similar ages. This possibility is significantly reduced in sampling petroglyphs by the presence of nearby natural black varnish. Microbial colonization of petroglyphs is comparatively easy, occurring from natural varnishes only a few millimeters away and relatively soon after the natural surface was removed by pecking. Although the Coso volcanics were not similarly situated with respect to immediate colonization, the error introduced by nonsynchronous varnish initiation is probably minor in terms of their K-Ar ages.

A chronometric age determination for each petroglyph was obtained by correlating the mean K+Ca:Ti ratio for the petroglyph with the age on the Coso Range cation-leaching curve (Fig. 1). For example, the 6.10 average cation ratio for the petroglyph illustrated in Figure 5D (Great Basin curvilinear abstract element) corresponds to 6400 B.P. on the curve. The error margin (EM) is estimated by ±1 standard deviation (SD); the upper SD at 6.31 corresponds to 5600 B.P., and the lower SD at 5.89 is equivalent to 8600 B.P. Therefore, the cation-ratio age of the petroglyph depicted in Figure 5D is 6400 B.P. (EM 5,600 to 8600 B.P.). The four sampled petroglyphs from Wheeler Prospect are displayed in Figures 5A, B, C, and E. A Great Basin curvilinear abstract-style form (Fig. 5C) dates to 6000 B.P. (EM 2250 to 13,500 B.P.), whereas a Great Basin rectilinear image (Fig. 5B) dates to 4300 B.P. (EM 2200 to 8600 B.P.). A second Great Basin curvilinear abstract motif (Fig. 5E) has an estimated date of 1700 B.P. (EM 1350 to 2050 B.P.), and the Great Basin representational side-facing sheep motif (Fig. 5A) correlates to 580 B.P. (EM 120 to 2900 B.P.). The average dates and standard deviations for all petroglyphs except that shown in Figure 5A are derived from three separate PIXE analyses. Owing to the limited revarnishing of the petroglyph in Figure 5A, there was only enough varnish material for one PIXE analysis. The age uncertainty of this petroglyph is based entirely on the estimated experimental error of the PIXE run. Therefore, there is some question concerning the accuracy of its date.

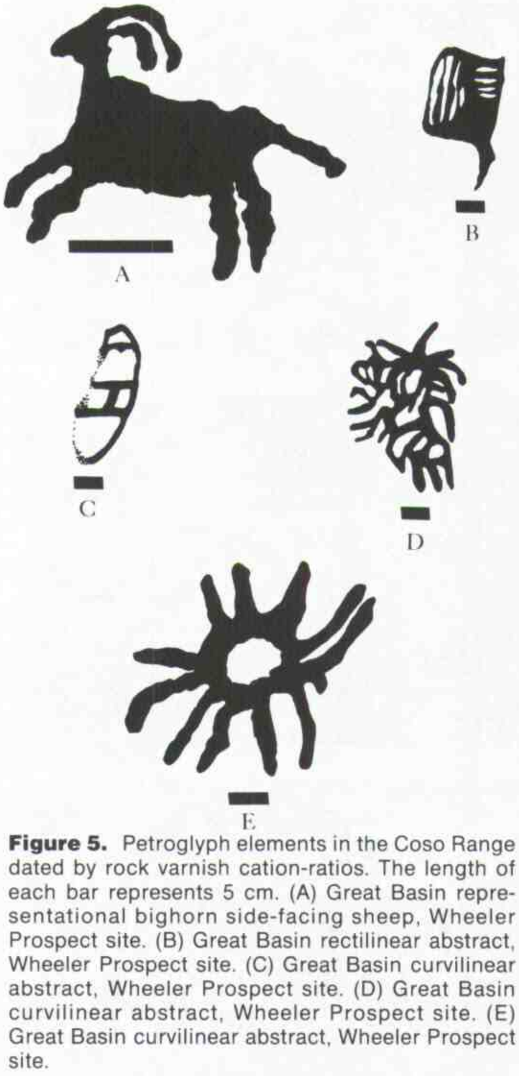

Figure 5. Petroglyph elements in the Coso Range dated by rock varnish cation-ratios. The length of each bar represents 5 cm. (A) Great Basin representational bighorn side-facing sheep, Wheeler Prospect site. (B) Great Basin rectilinear abstract, Wheeler Prospect site. (C) Great Basin curvilinear abstract, Wheeler Prospect site. (D) Great Basin curvilinear abstract, Wheeler Prospect site. (E) Great Basin curvilinear abstract, Wheeler Prospect site.

Because the regression line on which these dates are based is drawn between end points, the only known error is based on sample measurements. It is likely that additional uncertainty exists in the Coso leaching curve after 10,500 B.P. More Holocene data points are needed to derive an accurate idea of the error in this part of the curve. However, the high correlation coefficients ($r = -0.99$; $r = -0.98$) for the least-squares regression lines before 10,500 B.P. (Fig. 1) imply that the uncertainty in the Coso leaching curve is probably far less than the uncertainty in the sample measurements.

The structure of petroglyph varnishes also suggests a Holocene age. Varnishes formed within the Coso rock engravings have surface micromorphologies that are similar to varnishes formed on nearby rock outcrops (e.g., Figs. 6A and 6B). Dorn (1983) observed that most varnishes in the Coso Range that have formed on surfaces at least 20,000 years old have a varnish micromorphological stratigraphy of botryoidal (associated with less dusty, semiarid environments) under a surficial layer of mostly lamellate varnish (associated with more arid and/or eolian environments rich in clay). The current surface of varnish in the Coso Range, a mostly lamellate micromorphology, is probably a product of long-lasting and relatively drier Holocene conditions. The underlying botryoidal varnish may be from the Wisconsin glacial interval environmental conditions (Fig. 6C). Therefore, a Holocene age for the petroglyphs is also suggested by the completely lamellate micromorphological stratigraphy of the varnish formed within the Coso petroglyphs (e.g., Fig. 6D).

We should stress that the geographic applicability of the calibration curve in Figure 1 is probably limited to the region around the Coso Range. Unknown differences in the initial K + Ca:Ti ratios and differences in the environmental factors that affect the leaching rate would make the results of any attempt to date varnish away from the Coso-Searles Lake area using Figure 1 highly suspect. It is likely that a new calibration curve will be needed in every region in which cation-ratio dating is applied. However, it might be possible to apply an established curve to another region if a quantitative understanding exists for differences in input ratios, environmental factors affecting the leaching rates, cation-exchange capacities, and the processes involved in cation leaching.

Cultural Interpretation of the Coso Petroglyphs

Prior rock art research in the Great Basin has suggested a relative stylistic chronological ordering with Great Basin curvilinear abstract as oldest, followed successively by Great Basin rectilinear abstract and Great Basin representational. Steward (1929), Heizer and Baumhoff (1962), and von Werlhof (1965) hypothesized the following absolute ranges for the above styles: ca. 1000 B.C. to A.D. 1500, A.D. 1 to A.D. 1500, and A.D. 1 to A.D. 1500. Within the Coso Range a chronological sequence of three time periods (early, transitional, and late) was proposed for the representational style by Grant (1968), with the hypothesized absolute age spans being ca. 1000 B.C. to 200 B.C., 200 B.C. to A.D. 300, and A.D. 300 to A.D. 1000, respectively. However, the reasoning of these investigators was based on questionable assumptions.

Heizer and Baumhoff (1962, 284), for example, based their chronology on two assumptions, which were presented without any supporting evidence. These assumptions were that the youngest petroglyphs are between 150 and 200 years old and that the petroglyphs with the best developed varnish may be 15 to 20 times older than the youngest rock engravings. Grant's (1968) view that no petroglyphs in the Coso Range are older than about 3,000 years based on the implicit assumption that varnish is eroded in "pluvial" periods of greater precipitation. Because Grant felt the "little pluvial" occurred about 3000 to 4000 B.P., the petroglyphs etched into the Coso Range varnishes must therefore postdate this climatic period. Grant's assumption has been criticized in an earlier section.

Though we have chronometrically estimated the ages of only a few Coso Range petroglyphs, and these dates have large uncertainties, some preliminary interpretations are in order. First, these cation-ratio dates roughly substantiate the relative chronological ordering of the Great Basin styles. The two oldest samples illustrated in Figures 5C (ca. 6000 B.P.) are from curvilinear-style elements, and the rectilinear-style element depicted in Figure 5B (ca. 4300 B.P.) is about 2,000 years younger. The curvilinear style continued until at least ca. 1700 B.P. (Fig. 5E), indicating that its production probably overlapped the engraving of the rectilinear style. Finally, the representational-style element (Fig. 3A) is indicated to be the youngest in the chronological sequence.

Our chronometric dates are significantly older than those proposed by earlier researchers. The date for the petroglyph in Figure 5D argues for the initiation of petro-

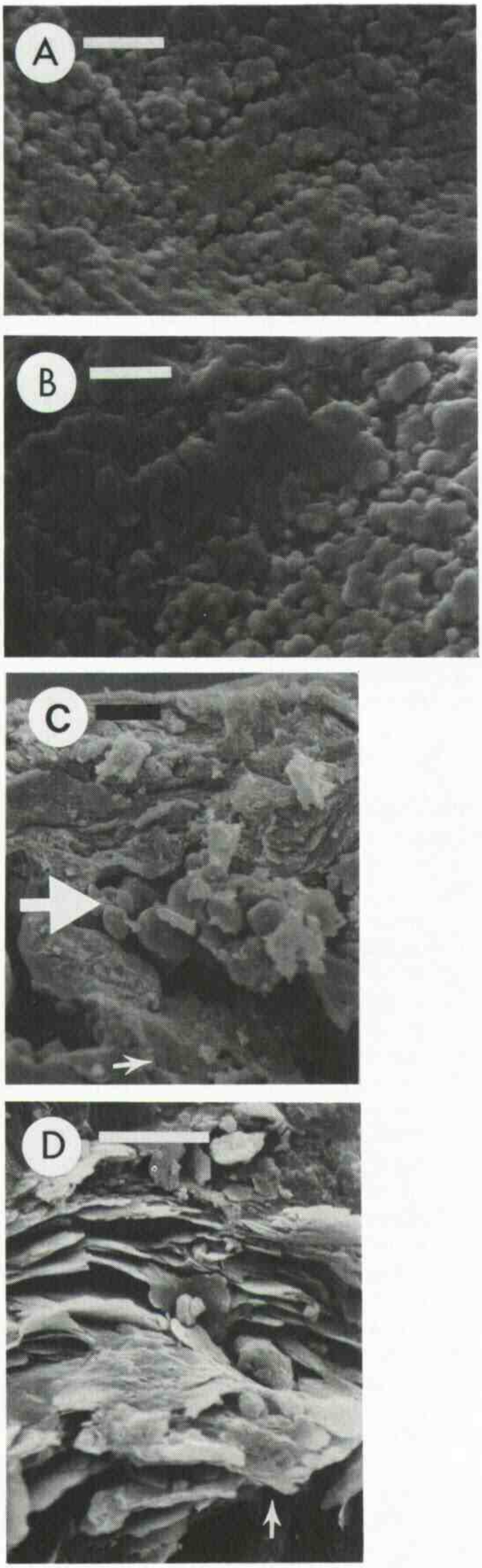

Figure 6. Scanning electron microscope images of rock varnishes formed on petroglyphs and natural outcrops in the Coso Range. Scale bar is 20 μm in A and B, and 5 μm in C and D. (A) Rock varnish with a surface micromorphology between lamellate and botryoidal, where lamellate platelets are covering and obscuring an underlying botryoidal structure. Varnish from Coso volcanic #31 (see Duffield and Bacon 1981). (B) Rock varnish with a more lamellate micromorphology than illustrated in Figure 6A, where clay-rich lamellate varnish is more dominant than botryoidal forms. Varnish from a chip taken from petroglyph depicted in Figure 5D. (C) Image of a broken edge of natural varnish on Coso rhyolite dome 1, with a K-Ar age of 81,000 ± 8,000 B.P. (Duffield and Bacon 1981). A sequence of three layered varnish micromorphologies can be seen from the varnish surface down to the underlying rock (lower arrow): surface lamellate, subsurface botryoidal (upper arrow), and subsurface lamellate just above the underlying rock. Considering the K-Ar age of the basalt flow, the lamellate strata may be associated with interglacial conditions, and the botryoidal layer may have developed during the relatively more moist Wisconsin glaciopluvial conditions in the western United States. (D) Image of the broken edge of varnish formed on the petroglyph shown in Figure 5B, illustrating a micromorphological stratigraphy of entirely lamellate micelles from the surface of the varnish at the top of the image down to the rock underlying the varnish (arrow).

glyph production in the Coso Range at ca. 6400 B.P., or about 3,400 years earlier than previously hypothesized. The petroglyph in Figure 5C has an approximate age of 6,000 years, further substantiating the relatively great antiquity of the curvilinear style. The petroglyph in figure 5B, which is from a rectilinear motif, is similarly suggested to be approximately 2,300 years older than the conjectured maximum age of A.D. 1.

The assigned date of 580 B.P. for the petroglyph depicted in Figure 5A, which is from a side-facing bighorn sheep (representational style), indicates a chronometric age for the production of this style in accord with those proposed for the Great Basin as a whole. However, this date is at odds with the suggested termination of rock art in this region at ca. A.D. 1000 (Grant 1968). Recent work on the Coso petroglyph assemblage (Whitley 1982a) indicates that Euro-American petroglyphs (i.e., depictions of Historic-period items) are present within the corpus of the motifs. Consequently, the late date for the petroglyph in Figure 5A falls within this extended period of rock art production. More samples of bighorn sheep and other representational elements need to be gathered before any firm conclusions can be drawn, especially as the date of the petroglyph in Figure 5A is based on only one PIXE analysis.

Most of the Coso Range petroglyphs are not revarnished beyond a few incipient spots of dusky-brown varnish. Based solely on the approximate percentage of petroglyph area covered with varnish, Figures 5C and 5D illustrate the best revarnished petroglyphs in the Coso Range that we have observed. Therefore, these two samples are probably among the oldest petroglyphs extant in the Coso Range assemblage. The age determinations of the varnish from these samples (ca. 6400 and 6000 B.P.) suggest that petroglyph production began during an arid period of warm and/or dry climatic conditions lasting from ca. 7500 to 4000 B.P. (Antevs 1955; Baumhoff and Heizer 1965; Irwin-Williams and Haynes 1970; Mehringer 1977; Byrne, Busby, and Heizer 1979).

The presence of dated petroglyphs in the Coso Range during this arid phase is problematical, given the hiatus in occupation during this period hypothesized by certain researchers (e.g., Baumhoff and Heizer 1965). However, Bettinger and Taylor (1974) have argued that there is little evidence for such a gap in the continuity of California Desert cultural history. Further, Mehringer (1977) argued that more data are required before Great Basin climatic changes from 7500 to 4000 B.P. and their effects on human occupation of the region are fully understood. Finally, Hillebrand (1972) has speculated that the initial occupation of the Coso Range occurred during the period from around 7000 to 5000 B.P. The chronometric dates for the motifs depicted in Figures 3C and 3D support the contentions of both Bettinger and Taylor (1974) and Hillebrand (1972). Similarly, it should be noted that, as most of the Coso petroglyphs are not sufficiently revarnished to be cation-ratio dated, the majority of them probably postdate the mid-Holocene arid phase terminating around 4000 B.P. Therefore, they correspond to the Great Basin Archaic Period, a time of increased archaeological remains and inferred greater population in the Great Basin (Baumhoff and Heizer 1965; Irwin-Williams and Haynes 1970; Hester 1973; Elston 1982).

Concerning temporal patterns in the production of the Coso rock art, our preliminary dates provide us with only approximate starting points for the three Great Basin styles. However, if we assume that this production was constant, we can derive a preliminary estimate of the approximate rate of petroglyph manufacture. First, taking the date of 6400 B.P. for the petroglyph in Figure 5D as the approximate initial date of rock art production, and A.D. 1550 as the terminal date for the pecked art (based on the presence of Euro-American motifs within the assemblage (Whitley 1982a)), we estimate a period of approximately 6,000 years of petroglyph manufacture. Second, Grant (1968) estimated that there are approximately 20,000 petroglyphs in the Coso Range. Therefore, we estimate that slightly more than 3.3 petroglyphs were produced on average per year in the Coso Range. We should emphasize that the notion of about 3.3 pertroglyphs/year is based on the assumption that the production rate was constant for the duration of the rock art manufacture.

The rate of petroglyph manufacture is significant in interpreting the cultural history of the Coso region. Grant (1968) viewed the large quantity of Coso petroglyphs as evidence of a prehistoric religious cult based on hunting bighorn sheep. Grant proposed that over-hunting by this cult brought about the decimation of the bighorn sheep herds, which in turn brought about a quiescence of the sheep cult. Steward (pp. vii-x in Grant (1968)) observed that this hunting-cult hypothesis implies a substantial "deculturation" from a well-organized religious cult (presumed to have included formalized ceremonial activities, intensive sheep hunting, and more extensive petroglyph manufacture) to the ethnographic situation recorded in the first part of this century by Steward (1934), namely a society of hunters and gatherers who lacked any form of ceremonialism.

Even if our estimate of about 3.3 petroglyphs/year is off by an order of magnitude, these still could have been generated easily by a population size and structure similar to that recorded by Steward in his ethnographic field work. We see no reason to presume that the prehistory of the Coso Range differed significantly from that of other areas of the Great Basin in North America, as would be required to accept the hunting-cult hypothesis. Rather, we argue that the large quantity of Coso petroglyphs probably results from their antiquity, and not from an origin in a religious cult that has no apparent parallel in the ethnography and archaeology of the Great Basin in general, nor in the ethnography and archaeological record from the Coso Range in particular (Whitley 1982b).

Chronometric Age Determination in the Central Mojave Desert

Dorn et al. (in preparation) have established a cation-leaching curve in the Mojave River basin, potentially applicable from Yermo to the Cima volcanic field, Mojave Desert, California. This new curve is based on the correlation of varnish K+Ca:Ti ratios with K-Ar dated basalt flows in the Cima field (Turrin, Dohrenwend, McFadden, and Wells 1984), a late Pleistocene shoreline of Lake Mohave (Ore and Warren 1971), and the first tandem accelerator mass spectroscopy (TAMS) ^{14}C date by the NSF Regional Facility for Radioisotope Dating at the Univeristy of Arizona on the organic matter in rock varnish.

Using this still preliminary curve, we are in the process of cation-ratio dating petroglyphs in the central Mojave Desert. For example, varnish on a curvilinear abstract petroglyph has been assigned a tentative age of 2300 B.P. (EM 2100–2500 B.P.) based on 3 PIXE analyses. The engraving is in the Cima volcanic field, about 20 km southeast of Baker, California. Future modifications of this curve will probably not change this date substantially. This indicates the curvilinear abstract style was extant in the Mojave Desert in the late-Holocene, like the Coso Range example dated at ca. 1700 B.P.

The Mojave River basin curve (Dorn et al., in preparation) demonstrates that chronometric cation-ratio dating is feasible in more than one locality. Though the organic matter in the varnish on petroglyphs is insufficient for a TAMS analysis, it is now possible to radiocarbon date more extensive varnish deposits on desert landforms. This also implies that cation-leaching curves, useful in dating the milligram quantities of varnish on petroglyphs, can now be generated in regions where there are no K-Ar dated Quaternary volcanic fields.

Relative Age Determination of Petroglyphs

Few areas have calibrated surfaces like the Coso and Cima volcanic fields where a cation-leaching curve can be established to date rock engravings chronometrically. Still, relative age determinations using cation-ratios are possible, as older varnishes at a given site would have more leached (lower) ratios. In this section we will discuss the potential of using cation ratios for relative dating of petroglyphs from Nevada and Arizona.

Bard (1979) studied the chemistry of natural and petroglyph varnish and the underlying rock at the Grimes Point petroglyph site near Fallon, Nevada. Although Bard did not use cation-ratio dating, he presented neutron activation analyses (NAA) of varnishes. Unlike PIXE, NAA is sensitive to sodium and not potassium, so the Na+Ca:Ti ratio will be used here. Table 19 in Bard (1979, 359–60) presents NAA analyses of three petroglyph styles at the Grimes Point site: pit-and-groove, Great Basin curvilinear abstract, and Great

Basin representational. We have no way of estimating the degree of contamination from the underlying rock that was incorporated into Bard's samples, but an examination of the major and trace elements in his data tables suggests it is significant. Therefore, comparisons of the petroglyph Na + Ca:Ti ratios with any pure varnish samples is unwarranted. Yet, if an equal proportion of contamination from the underlying andesitic rock is assumed, a comparison of the relative petroglyph ratios may be valid.

The average Na + Ca:Ti ratio for the six pit-and-groove petroglyphs is 13.3, with a standard deviation of 2.6. (His sample RGPS 16 was excluded because the calcium analysis suggests an anomalously high amount of contamination from either much Ca-rich detritus or a Ca-rich crystal from the underlying andesite.) The average ratio for 10 Great Basin curvilinear petroglyphs is a less leached 18.4 ± 5.3. Unfortunately, the chemistry of the two Great Basin representational elements sampled indicates that little or no varnish was incorporated into the sample. The findings of Heizer and Baumhoff (1962), von Werlhof (1965), Rusco (1970), Nissen (1975), and Bard (1979) suggest that Great Basin petroglyphs maintain a progression in time from pit-and-groove, to Great Basin curvilinear, and lastly to Great Basin representational. Our cation-ratio reanalysis of Bard's (1979) data supports this relative chronology at the Grimes Point petroglyph site, as the representational samples lacked any varnish. Note that no pit-and-groove samples were analyzed from the Coso Range.

J. Simon Bruder collected natural and petroglyph varnish from the Hedgepeth Hills near Phoenix, Arizona. Curvilinear, footprint, and bighorn sheep elements were sampled, all representative of the so-called Gila Petroglyph Style (Schaafsma 1980). A description of the field sampling procedure and the Hedgepeth Hills site is provided by Bruder (1983). Contaminants from the underlying rock were extracted by the first author in the laboratory under 45 × stereomagnification, and enough material was gathered for one PIXE analysis per element. The natural varnish sampled from two separate boulders has similar K + Ca:Ti ratios of 8.29 ± 1.53 and 8.42 ± 1.00. The curvilinear element sampled has a less-leached cation ratio of 9.85 ± 0.79, and a footprint element measured13.13 ± 1.31. Scrapings of a second footprint motif and a bighorn sheep figure were analyzed, but there was not enough titanium to measure accurately by the PIXE technique. More elements should be sampled before any definite conclusions can be drawn. However, at the Hedgepeth Hills site, cation-ratio dating suggests that the footprint motif is younger than the curvilinear element, which postdates adjacent natural varnish. Thus it is possible that internal chronological variation is present within the Gila Petroglyph style. Such chronologic variation has not been previously recognized (Schaafsma 1980, 54).

Conclusion

This paper presents the first direct chronometric and relative age determinations of petroglyph rock art using a new rock varnish age-determination technique called cation-ratio dating. Calibrated with surfaces of known age in the Coso Range and in the Cima-Lake Mohave areas of eastern California, the varnish cation-ratio of K + Ca:Ti has been used to establish cation-leaching curves that are useful in dating surfaces of unknown age in these regions. For petroglyph sites in Nevada and Arizona where calibrations have not been developed, we demonstrate that the technique is useful in establishing a relative sequence of engravings.

Five petroglyphs of the Great Basin curvilinear, rectilinear, and representational styles have been dated using the Coso cation-leaching curve. The curvilinear petroglyphs are the oldest style, starting as early as 6400 B.P. (EM 5600 to 8600 B.P.) and lasting until at least 1700 B.P. (EM 1350 to 2050 B.P.). The earlier curvilinear forms are followed by the rectilinear style (approximately 4300 B.P.), and lastly the representational style (approximately 580 B.P.). These age estimates support the established relative stylistic chronological ordering, but indicate that the initiation was almost twice as early as previously proposed. The problem of using subjective dating methods to derive conservative ages is not unique to the western United States. Context dating in South Africa by Butzer et al. (1979) and Thackeray et al. (1981), for example, has trebled the ages originally assigned to rock engravings.

The onset of petroglyph manufacture around 6400 B.P. during a major arid phase from ca. 7500 to 4000 B.P. is in accord with recent speculation concerning the time of inital occupance of the Coso Range. A previous hypothesis that a prehistoric hunting cult was responsible for the production of much of the 20,000 petroglyphs in the Coso Range seems unwarranted. Instead, the large number of petroglyphs can be explained by a slow average rate of manufacture by peoples in a cultural context similar to that observed in the early part of this century. There is no need to invoke a deculturation in the Coso region, especially as such a devolution would be unique within the cultural history of the Great Basin. More extensive petroglyph age determinations in the Coso Range and elsewhere in the Great Basin of North America would shed further light on these questions.

The chronometric dates reported here have implications for the general rate of varnish formation in moderately arid environments. The petroglyphs we observed in the Coso Range are not completely coated with varnish. The varnish consists of millimeter-wide dots that in some cases are coalescing. The petroglyph illustrated in Figure 5C had the most extensive cover of 80 to 90 percent varnish. Even the surfaces of boulders and cobbles on the 10,500-year-old high stand of Searles Lake are not yet entirely varnished. These results are compatible with opinions expressed by Blackwelder (1948), Hunt and Mabey (1966), Hayden (1976), and Carter (1980) that it usually takes 10,000 years or more for a rock to become completely varnished in an arid environment. Because rock varnish develops so slowly in deserts, cation-ratio dating may also be useful in estimating the absolute and relative ages of artifacts and in studying arid geomorphology.

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