AMS RADIOCARBON AND CATION-RATIO DATING OF ROCK ART IN THE BIGHORN BASIN OF WYOMING AND MONTANA

Julie E. Francis, Lawrence L. Loendorf, and Ronald I. Dorn

Samples of organic matter and rock varnish from seven rock-art sites in the Bighorn Basin of Wyoming and Montana were collected for dating purposes. Petroglyphs sampled include Dinwoody-style figures, shield-bearing warriors, and other well-known Plains rock-art motifs. Accelerator mass spectrometry (AMS) dating of 10 petroglyphs yielded dates from the Early Archaic to the Protohistoric periods. A strong numerical relation between varnish leaching and time was found for petroglyphs older than 1,000 years, permitting the derivation of a cation-leaching curve (CLC) and calibrated cation-ratio (CR) ages for 15 different petroglyphs. No clear numerical relation between varnish leaching and time was found for petroglyphs less than 1,000 years old, possibly due to historical damage or past environmental conditions. As a result, calibrated CR ages could not be derived for six petroglyphs, and they are considered to be only younger than 1,000 years. Although further research is needed to establish whether one CLC can be used for all petroglyphs in the region, these studies constitute the first numerical chronology for rock art in the Bighorn area. Results indicate the occurrence of spatially discrete, but temporally concurrent styles in the Bighorn Basin during the last 800–900 years.

Muestras de material orgánico y barniz de roca provenientes de siete sitios con petroglifos en la Cuenca de Bighorn en Wyoming y Montana fueron recolectadas para datación. Los petroglifos muestreados incluyen figuras estilo Dinwoody, guerreros con escudo, así como otros motivos artísticos bien conocidos en las Llanuras. La datación de 10 petroglifos en el acelerador de espectrometría de masas (AMS) produjo fechas desde el período Arcaico Temprano hasta el período Protohistórico. Se encontró una fuerte relación numérica entre la pérdida de barniz y la edad de los petroglifos de más de 1000 años de antigüedad, lo que permitió la derivación de una curva de pérdida de cationes (CLC) y de fechas calibradas por proporción de cationes (CR) para 15 diferentes petroglifos. Esta clara relación numérica entre pérdida de barniz y edad no fue detectada en petroglifos de menos de 1.000 años de antigüedad, posiblemente debido a destrucción histórica o condiciones medioambientales pasadas. Por lo tanto, no fue posible derivar edades calibradas por CR para seis petroglifos, los cuales se consideran de menos de 1.000 años de antigüedad. Se necesita más investigación para determinar si una CLC puede ser utilizada para todos los petroglifos de la región; sin embargo, estos estudios constituyen la primera cronología numérica de petroglifos en el área de Bighorn. Los resultados indican la ocurrencia de estilos espacialmente discretos pero temporalmente concurrentes en la Cuenca de Bighorn durante los últimos 800–900 años.

During the past 10 years, there has been a renewed interest in the study of rock art among North American archaeologists, partially prompted by Old World archaeologists who have developed new approaches (Lewis-Williams 1981; Lewis-Williams and Dowson 1988) that are largely synchronic. These are functional studies designed to understand the meaning of rock art in hunting and gathering societies, and they are accomplished without any need to know the age of the rock art.

The basic research paradigm in North American archaeology is one that includes the temporal, spatial, and formal dimensions of features and artifacts (Chang 1967; Jennings 1989; Rouse 1972). Without question, the primary reason North American archaeologists have been reluctant to study rock art is the difficulty in placing pictographs and petroglyphs into temporal frameworks established by radiocarbon dating in stratigraphic studies. Recently, however, new methods have been developed

Julie E. Francis, Office of the Wyoming State Archaeologist/Wyoming Department of Transportation, Box 1708, Cheyenne, WY 82003-1708
Lawrence L. Loendorf, Loendorf Associates, 985 W. Eucalyptus Place, Tucson, AZ 85704
Ronald I. Dorn, Department of Geography, Arizona State University, Tempe, AZ 85287

American Antiquity, 58(4), 1993, pp. 711–737.

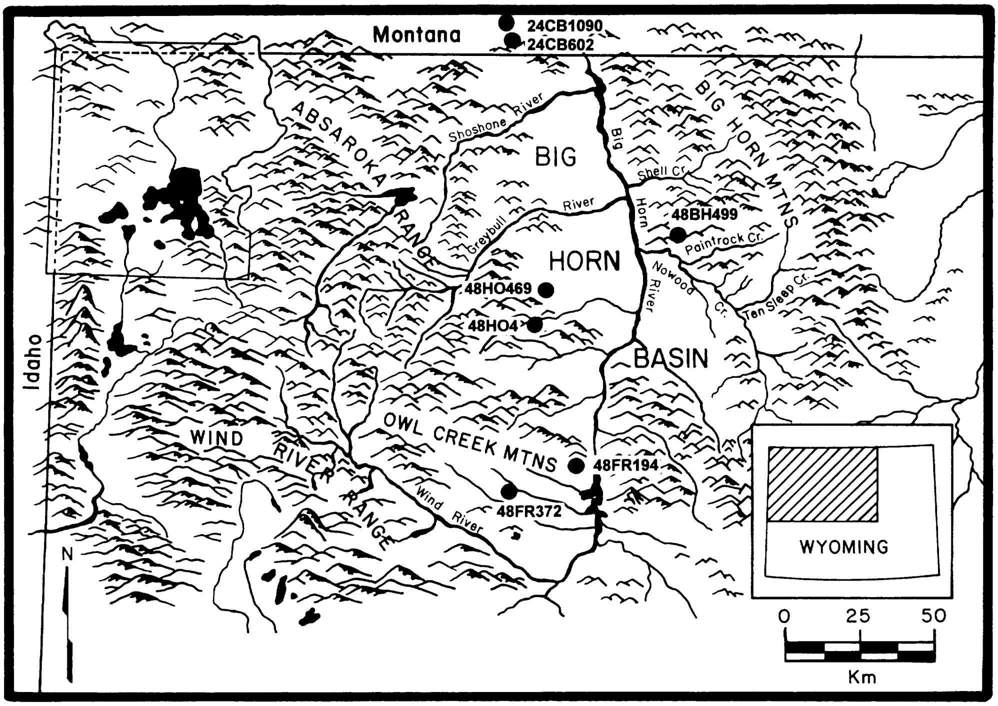

Figure 1. Wyoming and Montana, showing Bighorn petroglyph study area and investigated sites.

that place minimum ages based on dating rock varnish that has accumulated on petroglyphs since their manufacture (Dorn et al. 1986). This method has been successfully used to establish petroglyph chronologies in the Great Basin, southeastern Colorado, and arid south Australia (Dorn and Whitley 1984; Dorn et al. 1988; Loendorf 1991). This approach holds great potential for the study of spatial and temporal variation in rock-art styles and allows the researcher to treat the dimensions of rock-art variability in much the same manner as any other artifact type.

The abundance and diversity of rock art in the Bighorn Basin of Wyoming and southern Pryor Mountains of Montana provide an ideal data base for establishing a chronological sequence of various motifs, and recent archaeological investigations have provided a variety of chronological data. In this paper, we review these data, which are based upon traditional means of rock-art dating, and present a preliminary chronological sequence for rock art in the area. We then offer the calibrated numerical ages, as established through cation-ratio (CR) and accelerator mass spectrometry (AMS) dating, for petroglyphs at seven sites: 24CB602, 24CB1090, 48BH499, 48HO4, 48HO469, 48FR194, and 48FR372 (see Figure 1). Results of the CR and AMS dating generally support the proposed chronology. However, rather than a simple evolution of one style to another, the dating results indicate considerable chronological overlap between styles and the presence of concurrent rock-art traditions in different portions of the study area.

PREVIOUS RESEARCH ON ROCK ART IN THE STUDY AREA

Prehistoric rock drawings are both abundant and diverse within the study area. A variety of pecked, incised, and painted motifs occur, and numerous investigations have taken place over the last 50 years. A rock-art site in the Montana portion of the study area was first examined and photographed by anthropologist John Provinse in the late 1920s or the early 1930s (Loendorf and Porsche 1985). Since that time, dozens of other rock-art sites have been found in the Montana area by a variety of individuals.

Rock art in the Wyoming portion of the study area has been reported since the 1880s (Clark 1885; Mallery 1886, 1893), and several investigators have since suggested chronological schemes, based principally on cases of superimposition of motifs (Gebhard and Cahn 1950; Hendry 1983; Renaud 1936). In general, very recent dates (Protohistoric and Historic periods) were offered for most rock art in Wyoming by these investigators.

The following suggested rock-art chronology has been assembled by using examples of superimposition, associated radiocarbon dates, the recovery of tools that were used to make the art from dated contexts, and the recovery of charcoal in deposits that were superimposed upon the petroglyphs (Loendorf 1990; Walker and Francis 1989). It should be emphasized that this chronology (Francis 1991; Francis and Frison 1990; Loendorf 1988, 1990; Loendorf et al. 1990:5-16, 5-19) was developed prior to the acquisition of the petroglyph-varnish samples.

In 1983, a rock-art site was recorded in Montana north of Frannie, Wyoming (Loendorf 1984). This site, Petroglyph Canyon (24CB602), contains a style of petroglyphs not common north of the Yellowstone River in Montana (Conner and Conner 1971:19; Loendorf 1984:87). Identified as the *en toto* pecked style, these petroglyphs are fairly common in Wyoming and are also found at other sites in southern Montana.

As found at Petroglyph Canyon, the *en toto* pecked style includes a variety of figures that are dominated by humans in association with other humans. It is sometimes possible to differentiate males and females among these human figures. Often one or two male figures are found side by side with one or two female figures. Test excavations at locations near the petroglyphs produced abundant occupational debris from two cultural levels. The upper level had radiocarbon dates of 850 ± 50 B.P., while the lower level had a date of 1270 ± 125 B.P. (Loendorf 1984:113–115). Based on the proximity of the cultural debris to the rock art, tentative ages of 1,200 to 850 years were suggested for the *en toto* pecked style.

At the Bear Shield site in Montana (24CB1090), finely incised figures include a shield with two drawings of large bears on it. These bears and the shield are superimposed on *en toto* pecked anthropomorphic figures, indicating that the incised shield and bear images were made after the *en toto* pecked figures. In actual years, it suggests the incised shield figure and large grizzly bear images were made more recently than 850 years ago.

In 1988, a large rock-art site in Wyoming, known as Legend Rock (48HO4), was intensively recorded (Walker and Francis 1989). This site exhibits several hundred anthropomorphic and zoomorphic petroglyphs. The vast majority of the figures are made by pecking, with a significant percentage made by totally pecking away the interior of the figures' bodies. Numerous other figures exhibit pecked interior lines showing details of torsos and bodies. The majority of the figures at Legend Rock are examples of what Gebhard (1951, 1969) labeled the Dinwoody style. This style is spatially restricted to the Wind River drainage and the southwestern one-quarter of the Bighorn River drainage (see Gebhard 1951). Many figures are extremely elaborate and exhibit bizarre orientations of limbs, bodies, and heads. Other anthropomorphic forms have well-made horns extending out of the tops of their heads. The Dinwoody style is distinctive and considerably different from the *en toto* pecked figures at Petroglyph Canyon.

At Legend Rock, one test unit was placed against the face of a rock-art panel to expose a buried petroglyph. This petroglyph is a fully pecked anthropomorphic figure with horns and can be included in the Dinwoody style. Charcoal from the excavated level burying the feet of the petroglyph yielded an uncalibrated age of 1920 ± 140 B.P. (Francis 1989). Charcoal from levels well below the bottom of the figure was dated at 2180 ± 130 B.P., and 2130 ± 100 B.P. (Francis 1989). Thus, the evidence indicates this figure was manufactured about 2,000 years ago.

Another important rock-art site in the southern Pryor Mountains of Montana is Valley of the Shields (24CB1094). This site contains at least 16 separate localities with petroglyphs and pictographs, which are dominated by shields and shield-bearing warriors. Test excavation at the base of one panel containing incised and painted shield and shield-bearing warrior motifs produced two sandstone abrading tools used to smooth the sandstone face (Loendorf 1988, 1990). The same red paint used in the pictographs was found adhering to the sandstone tools. A small hearth associated with these artifacts was radiocarbon dated between 950 ± 80 B.P. and 870 ± 80 B.P. (Loendorf

1988, 1990). These data clearly indicate that the shield and the shield-bearing warrior motifs were made about 850 years ago in Montana.

More recent rock art in the Bighorn Basin includes finely incised horses, tipis, and guns. The human figures associated with these motifs are diverse and are not easily categorized into types. Shield-bearing warriors and V-necked human figures are known to be coeval with the horse and the gun, but other anthropomorphic figures are diverse (Magne and Klassen 1991).

The data used to establish the proposed rock-art chronology can be summarized as follows (Figure 2). The evidence from Petroglyph Canyon and Legend Rock suggests that a general pecked tradition occurs across the Bighorn Basin and into Montana, with considerable time depth and morphological variation. In the Wyoming portion of the study area, pecked rock art has a tradition that is longer and more complex than in Montana. Dinwoody-style petroglyphs appear to be the oldest; these complex anthropomorphic and zoomorphic figures were being manufactured by at least 2,000 years ago, extending well into the Late Plains Archaic period (see Frison 1978, 1991). The tradition of pecked figures is first recognized in the Montana portion of the study area as the *en toto* pecked style at about 1,250 years ago. This style is thought to last until about 850 years ago, when a new style of deeply incised and painted figures is prevalent.

It is significant that, along with the change in manufacturing technique, there is a marked change in the motifs that are represented. It is with the incised and painted styles that shield-bearing warriors, V-necked, and simple rectangular-bodied human figures occur. These anthropomorphic forms appear to have no precedents in the earlier pecked rock-art styles. Furthermore, these motifs continue into the Historic period, which can be identified by the fine-line manufacturing technique and the occurrence of horses and guns.

ROCK-VARNISH DATING

Petroglyphs in arid and semiarid regions start to accumulate a coating of rock varnish within about a century after they are engraved. Rock varnish is a dark, thin accretion of manganese and iron oxides, clay minerals, and over 30 major and minor trace elements. Its formation is catalyzed by manganese-oxidizing bacteria (Dorn and Oberlander 1982; Drake et al. 1993; Palmer et al. 1985). The manganese and iron oxides cement the clays to the rock surface (Potter and Rossman 1977). A key advance that permitted the development of rock-varnish dating methods was the finding that varnish is an accretion, rather than a product of the weathering of the underlying rock (e.g., Allen 1978; Dorn and Oberlander 1982; Potter and Rossman 1977). Figure 3 shows several examples of the distinct boundary between the underlying rock and the overlying varnish coating indicative of the accretionary process.

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 provide a minimum age for the underlying petroglyph. Two methods that permit the dating of rock varnishes on petroglyphs have been developed and tested over the last decade. These are AMS radiocarbon dating (Dorn et al. 1986, 1989, 1992; Dorn, Turrin, Jull, Linick, and Donahue 1987) and cation-ratio (CR) dating (Dorn 1983, 1989; Dorn et al. 1990; Dorn, Tanner, Turrin, and Dohrenwend 1987). AMS and CR dating are used together in the age determination of petroglyphs. Use of AMS to obtain ^{14}C measurements of organic matter coated by the accreting varnish provides a minimum radiocarbon age, thus permitting direct dating of some petroglyphs. AMS dates are also used to obtain calibrated ages of varnish CRs. However, not all petroglyphs have subvarnish organic matter that can be collected with existing field methods, and CR dating can be used in these cases.

It is possible to obtain precise and accurate measurements of the chemistry of the varnish on petroglyphs through the use of proton-induced X-ray excitation (PIXE) and the wavelength-dispersive electron microprobe. A ratio of potassium plus calcium, divided by titanium ([K+Ca]/Ti) provides an age, when calibrated by numerical dates. The potassium and calcium leach out of the varnish, thus the ratio of (K+Ca)/Ti decreases systematically over time (Dorn and Krinsley 1991). The CRs are calibrated by measuring radiocarbon dates and the (K+Ca)/Ti ratio from the same varnish.

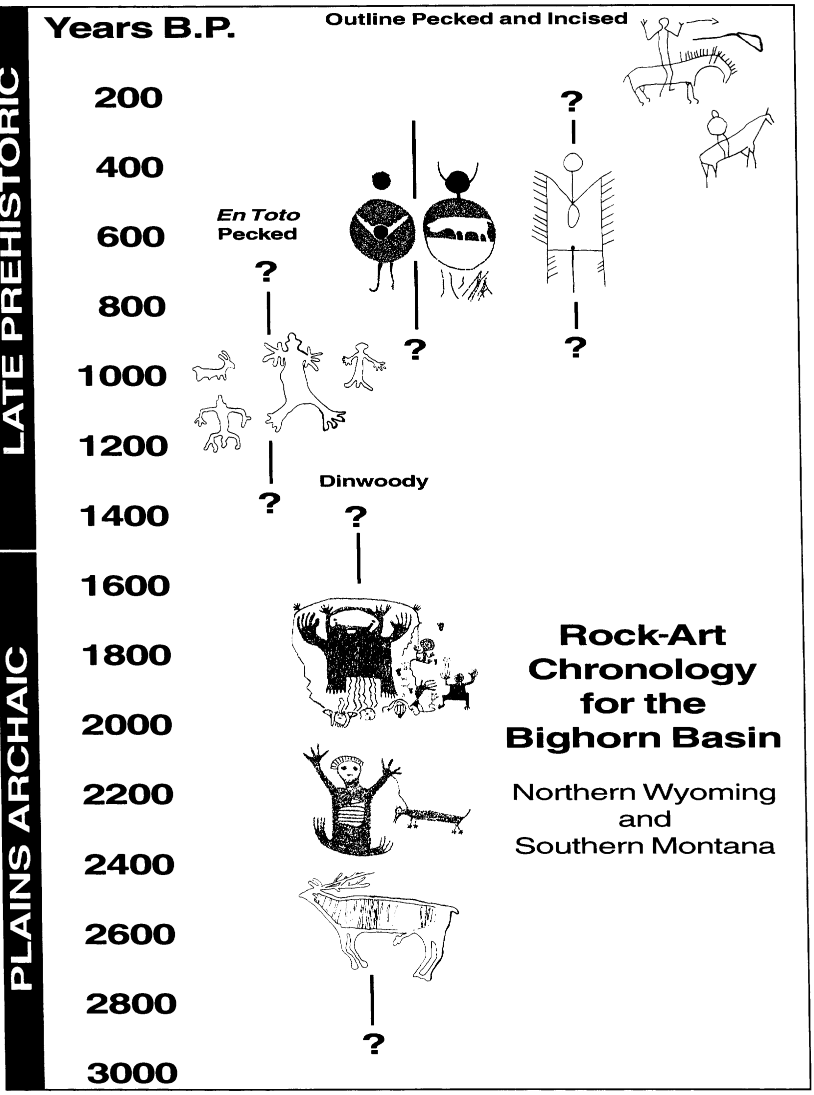

Figure 2. Proposed chronological sequence for rock art in the Bighorn area.

The accuracy of such AMS dates has been the subject of extensive study. The documentation of dozens of tests is presented in Dorn et al. (1986, 1989, 1992) and Dorn, Turrin, Jull, Linick, and Donahue (1987). Tests have been conducted on replicate samples from the same petroglyph, different types of sampling sites within a petroglyph, different types of chemical processing, and different ways of removing the carbon. These tests have shown that AMS dates from organic matter in varnish are often within 10 percent of the age of the control.

Nevertheless, there are uncertainties in the AMS technique. The first is whether carbon that predates the petroglyph can be inadvertently sampled and dated. Dorn et al. (1989) and Reneau et al. (1991) both suggest that it is *theoretically* possible that older organic matter, for example older carbon from nearby soils, could become incorporated into the sample. However, in dozens of test runs, there has never been an AMS date from rock varnish that predates an independent control. Instead, the dominant source of contamination is younger material that could become incorporated

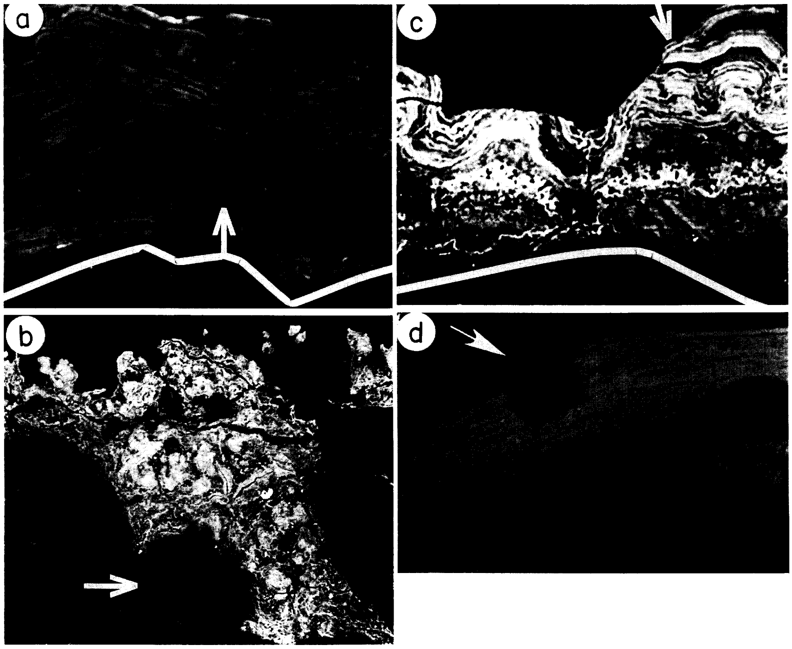

Figure 3. Polished cross sections of rock varnish on Wyoming petroglyphs: (*a*) Layered varnish formed over petroglyph WP-90-28. Arrow shows the porous zone that interrupts the layering, where leaching of the potassium and calcium has taken place (Dorn and Krinsley 1991); (*b*) A thick pocket of varnish formed in a hollow of WP-90-4. Arrow shows a subvarnish deposit of organic matter, which shows up as black in backscatter because of the low atomic number of carbon; (*c*) An "island" of pre-engraving rock varnish that was broken off during the manufacturing of the petroglyph, but not completely removed. Note the truncated layering, where only a little bit of new varnish (arrow) has formed over the original varnish. Remnants of preexisting varnish are very easy to identify and avoid in the field, even with the naked eye; (*d*) A fragment of chalk (arrow) forced into evenly layered varnish on top of petroglyph WP-90-13. The fragment is almost entirely composed of calcium, reflecting the calcium-carbonate composition of the chalk. These scanning-electron-microscope images use a backscatter detector, where brightness indicates atomic number (Krinsley and Manley 1989). Brighter areas shows the manganese- and iron-rich varnish. Darker areas show material with a lower atomic number, either the underlying silica-rich sandstone, or in the case of (*b*), organic matter. The number below the bar indicates the length of the scale bar in μm.

into the varnish well after it started to form (Dorn et al. 1989, 1992; Nagy et al. 1991; Watchman 1992a). Therefore, we feel confident that the AMS ^{14}C ages obtained by this study provide minimum ages for the manufacture of the petroglyphs.

There is also a degree of uncertainty in that an AMS date from rock varnish provides a *minimum* age for the manufacture of the petroglyph, not the actual date of manufacture. This is analogous to inferring the age of an archaeological deposit from a ^{14}C date on organic material in an overlying stratum; a minimum age, not the actual age, for the archaeological deposit is obtained. In the case of rock varnish, organic matter, including remnants of lichens, fungal mats, charcoal, and other unidentifiable matter, can be trapped by the varnish on top of the petroglyph, thus providing an age after which the petroglyph was manufactured.

Single-sample dating is another potential source of uncertainty. The high cost of AMS measurements and the difficulty in finding sufficient organic matter for more than one AMS date from the same petroglyph prohibited us from obtaining replicate measurements from more than one figure.

Field sampling is a final source of uncertainty: mechanical removal of the varnish to look for organic remains underneath is a difficult procedure. The easiest mistake is to inadvertently include younger organic remains growing on top of the varnish. The technique has evolved greatly over the last several years, with the next step being laser extraction of organic matter, if problems associated with the chemical preparation of sections can be overcome (cf. Nobbs and Dorn 1993).

In summary, all available evidence indicates that AMS dates of organic matter from rock varnish closely resemble conventional radiocarbon dates of landforms on which the varnish has formed (Dorn et al. 1989). Furthermore, they always provide a minimum age for the exposure of the underlying surface. What is important to realize is that the CRs are ultimately calibrated by the AMS dates. We view the AMS dates as inherently superior, because CR dating is a chemical-dating method that is influenced by changeable environmental variables, in much the same manner as obsidian-hydration rates are influenced by environmental variables.

While the AMS technique is new, it is not fraught by controversy like the CR approach. Although the controversies over the CR method are reviewed in detail in Dorn (1993), we present Table 1 as a means of summarizing the questions about CR dating for the reader. Many of the controversies in Table 1 likely revolve around the lack of uniformity in the types of varnish samples being used for comparative tests. While one group of researchers examines the "best-looking" varnishes on "smooth" surfaces, another research team does not specify the type of varnish examined. All varnishes are not alike. Detailed criteria have been laid out for the types of varnishes appropriate for dating and how, through light and electron microscopy, to identify bad samples that slip by field collection (Dorn 1989, 1993; Dorn et al. 1990; Krinsley et al. 1990). These criteria have admittedly not been followed by any of the authors that have raised questions over the CR method.

The entire evolution of the CR method has been a process of trial and error—of identifying factors *other than time* that can influence the CR and then trying to control that factor in sample selection. For example, seven of the 34 petroglyphs in this study were considered undatable by CR methods, based on direct observation of residual chalk with a scanning electron microscope, on anomalously high levels of calcium in electron microprobe analyses, or both. Also, we identify a clear inconsistency between radiocarbon ages and CR ages for petroglyphs younger than 1,000 years. We explore possible reasons and anticipate that further research in this age range will identify a set of factors which confound the temporal relation and that can be controlled. Our approach is to treat seriously the ages assigned to the CRs of petroglyphs that have been carefully evaluated for all known sources of error through rigorous field and laboratory testing, and samples in the age range where there is a clear relation betwen time and CRs in the form a of cation-leaching curve.

METHODS

In 1990, samples were collected from 34 petroglyphs at seven sites in the Bighorn Basin (Figure 1), including 20 for AMS and 37 for CR dating. Petroglyphs chosen at each of these sites were good representations of a style and in good condition with little weathering. Only black (manganese-rich) subaerial varnish was collected. Microenvironments with lichens, microcolonial fungi, abundant organic detritus, and other variables (cf. Dorn 1989, 1993; Dorn et al. 1990) that can alter a CR were avoided.

When collecting varnish samples, a tungsten-carbide needle is used to loosen the varnish from five different spots on an individual petroglyph. Each micro-boring is then collected on a tape that lacks potassium, calcium, and titanium. This process results in five pinpoint-sized marks on an individual glyph, which are visible only if one is aware that such samples were taken in the first place and are not noticeable to the casual site visitor. While taking the varnish samples, jeweler's glasses are used to search for organics in the basal layer of the varnish. If organic-rich material is found (Figure 3b), a small plug is removed from the petroglyph for AMS dating.

In addition, dust samples are collected from natural traps, such as rock crevices, at each site to assess local geochemical anomalies of ambient potassium, calcium, or titanium that would influence the CRs of the varnish. None of the local environments sampled in this study exhibit high levels of ambient calcium, potassium, or titanium. If a local eolian anomaly were found, the site would not be datable by the CR method.

For all collected samples, a sliver of at least 3 mm of intact sections is prepared for cross-section examination by light and electron microscopy (cf. Krinsley et al. 1990) in order to evaluate the

Table 1. Issues Under Contention in Cation-Ratio Dating, Discussed in Greater Detail in Dorn (1993).

Issues	Critiques	Discussion
Theory behind cation-ratio dating	Reneau and Raymond (1991) argue that the decline in CR over time is from different amounts of contamination from the rock underlying the varnish, rather than from greater rates of leaching mobile (Ca, K) cations than immobile (Ti) cations. Reneau and Raymond (1991) argue that older varnishes are thicker and have less contamination from the underlying rock, and hence lower CRs. Harry et al. (1992) argue that there is no evidence of CR reduction over time in comparisons of artifacts and bedrock cortical surfaces. Watchman (1992b) questions whether cation-leaching occurs. There is no other proposed alternative to explain the observed CR reduction over time other than differential chemical mobility and differential rock contamination.	1. Five of the six different groups that have found CRs decline with time (Dorn 1983; Glazovskiy 1985; Harrington and Whitney 1987; Pineda et al. 1988, 1990; Zhang et al. 1990; not Bull 1991) have used different rock types—observations inconsistent with the rock-contamination hypothesis. In contrast to their conclusion, Harry et al. (1992:101) also show that varnishes scraped from cultural surfaces have younger (higher) CRs than varnishes scraped on cortical controls. 2. Zones of cation-leaching have been identified in rock varnish (Dorn and Krinsley 1991). 3. Laboratory experiments have verified that cation-leaching occurs from rock varnish (Dorn and Krinsley 1991).
Sampling	Bierman and Gillespie (1991a) argue that forest fires erode varnishes, resetting the varnish clock. Harry et al. (1992) argue that desert pavements are not stable enough for the investigator to know whether the modified surface of the artifact has been exposed continuously, based on qualitative observations at one site in the western Mojave Desert.	Petroglyphs occur on stable talus or bedrock; ones examined in this study are distant from forest fires. We agree that some pavements are not stable. Yet, pavements sampled by Bamforth and Dorn (1988) are felt to be quite stable. Desert pavements in the Mojave Desert have remained in place for 10^4 to 10^5 years (McFadden et al. 1987; Wells et al. 1991).
Sample examination	Watchman (1992a) argues that unlayered samples of varnish are inappropriate for dating, and that layered samples were not found at the south Australian petroglyph site examined.	Dorn and Nobbs (1992) and Nobbs and Dorn (1993) agree that unlayered samples are not appropriate for dating. Yet, the samples used in southern Australia and in this study were found to be layered.
Accuracy of measuring CRs	Bierman and Gillespie (1991b) submitted material to Crocker Nuclear (CNL) at the University of California at Davis for analysis by proton-induced X-ray excitation (PIXE). CNL is the same laboratory used by Dorn in earlier studies of CR dating. Bierman and Gillespie (1991b) reported that CNL did not adequately separate barium from titanium and concluded that because the PIXE method combined barium and titanium, CR [(K + Ca)/Ti] measurements from PIXE are inaccurate.	Cahill (1992) explained that Bierman and Gillespie (1991b) misrepresented PIXE data given to them by CNL to derive invalid conclusions: "The data in Bierman and Gillespie (1991) Table 1, described as 'PIXE UCD' did not in fact come from us" (Cahill 1992:464). Importantly for this study, the wavelength-dispersive electron microprobe technique we used (see Dorn et al. 1990) to measure CRs does separate barium from titanium, as Bierman and Gillespie (1991b) agree.

Table 1. Continued.

Issues	Critiques	Discussion
Calculating CR ages	There is disagreement over the procedure used to assign CR calibrated ages (e.g., Bierman et al. 1991; Lanteigne 1991). One method calculates the mean and variation of multiple CR measurements; this implies that the different samples that are being grouped have the same exposure history. For example, if a petroglyph were to be dated with the approach suggested by Bierman et al. (1991), different collections of varnish from different parts of a petroglyph would be treated as a mean with a variation.	We treat each CR as an independent indicator of age (see Dorn et al. 1990). Each CR is assigned a separate age, based upon a least-squares multiple regression using only radiocarbon ages on petroglyphs as calibration points. These independent calibrated ages for a given surface are then averaged to assign a mean age for the surface. The uncertainty is derived from the standard deviation of these ages. Strictly, the oldest (lowest) CR should represent the closest minimum age for the petroglyph.
Blind tests	Bierman and Gillespie (1992) argue that the blind tests of CR dating in the literature are not truly complete or blind.	The archaeological tests are: (1) comparing varnish CRs with refitted flake-core sequences from the Mojave Desert (Bamforth and Dorn 1988); and (2) Loendorf's (1991) comparison of radiocarbon with CR ages on petroglyphs in southeastern Colorado. Where samples have been calibrated by radiocarbon ages, tests have resulted in a match between the CR ages and newer and independent sources of age control, with the exception of two in situ cosmogenic ^{14}C measurements (see Dorn [1993] for discussion of geological tests). Bierman and Gillespie were invited to test the CR method directly—rather than criticize through inference. Dorn (1992) offered Bierman and Gillespie an opportunity to independently analyze previously measured samples to test their claims. Bierman and Gillespie (1992) stated they were unwilling to complete this independent test of their assertions.

condition of each varnish sample. For AMS dating, we examine the varnish section immediately above or adjacent to any organics that are subsequently extracted. For CR dating, we assume that the section is representative of the entire scraping. Figure 3a shows the type of layered varnish appropriate for dating.

CRs for each of the five varnish samples collected from each petroglyph were established using a wavelength-dispersive electron microprobe. The method of sample preparation is described in detail in Dorn et al. (1990). In brief, a split of each scraping is mounted in epoxy and examined by electron microscopy for the chemistry and quantity of contamination from the underlying rock. Since all samples came from sandstones that appeared to be mostly arenites in section, the amount of chemical contamination by potassium, calcium, and titanium was less than two percent in all samples. The bulk of each scraping is then made into a fused bead, mounted in epoxy, polished, and measured with a 100 μm spot size with a wavelength-dispersive electron microprobe. This permits us to measure bulk samples, rather than micron-scale chemistry. This is to "average" the areas of varnish that have been leached with the areas of varnish that have not been leached.

After AMS dates are obtained, the numerical age and its accompanying CR are used to establish a cation-leaching curve (CLC). This is a semilog least-squares regression of the mean CRs and the mean numerical ages. Calibrated ages for non-radiocarbon-dated petroglyphs are then obtained by comparing the CRs to the CLC. As noted in Table 1, there are two methods used to calculate CR ages. The approach used here treats each CR as an independent indicator of age. Each measured CR of varnish on a petroglyph of unknown age is therefore assigned a *separate* age. These separate CR ages for a given surface are then averaged to assign a mean age for the surface, and the uncertainty is derived from the standard deviation of these ages.

We have chosen to use this method for obtaining calibrated ages because varnish formation is a time-transgressive process; that is varnish does not form on all parts of a petroglyph at the same time. It starts first in one place and grows vertically and horizontally; if a CR age for a petroglyph were anomalously young, this could be from varnish starting to grow long after petroglyph manufacture. By treating each CR as a separate time indicator, intersample variability can be treated as a reflection of the time-transgressive growth process. In addition, treating each separate measurement as an indicator of age requires fewer assumptions: only that the calibration curve is the best estimate of CR age and that CR ages are normally distributed. In essence, this approach keeps the assignment of calibrated ages as close to the raw data as possible, and the lowest CR should ideally provide the closest age. We emphasize that the most critical aspect of varnish methodology is sampling the petroglyph. The objective is to collect varnish that has colonized a rock surface worked by humans as soon after manufacture as possible. Any spot of varnish will not do. The petroglyphs sampled for this study were on sandstone. Varnish starts to grow first on sandstone in peck marks and grain boundaries. These are the microspots where samples should be collected. We also stress that cross sections of varnishes must be evaluated before samples are chemically analyzed in order to avoid varnish microstratigraphies that can yield inaccurate ages (e.g., Dorn 1989; Dorn et al. 1989, 1992; Krinsley et al. 1990). Lastly, we note that it is relatively easy to avoid remnants of natural varnish that predate the manufacture of the petroglyph (Figure 3c).

AMS DATING RESULTS

Subvarnish organic matter was collected from 20 petroglyphs in the study area. Material still attached to the underlying rock was subjected to hydrochloric acid (HCl) and hydrofluoric acid (HF), as described by Dorn et al. (1992), in order to remove possible contamination from inorganic carbonate and organics adsorbed onto clays. Eleven of the samples, examined and processed in the laboratory, were determined to have sufficient amounts of organic material and were submitted to the Facility for Radioisotope Dating at the University of Arizona (Table 2). A second sample from WP-90-4 was submitted at a later date. Because $\delta^{13}C$ values were not measured, none of these AMS dates have been corrected for $\delta^{13}C$ isotopic fractionation.

As can be seen from Table 2, the two AMS dates from petroglyph WP-90-4 overlap at two sigma, as do many, but not all, replicate radiocarbon measurements (Dorn et al. 1989; Nobbs and Dorn

Table 2. Accelerator Radiocarbon Dating of Organic Matter Encapsulated by Rock Varnish, Bighorn Area Petroglyphs.

Site	Sample Number	Lab Number	Radiocarbon Age[a] (years B.P.)	Calibrated Age[b]
48HO469	WP-90-1	AA-6545	225 ± 60	A.D. 1650 (1660) 1950
Coal Draw	WP-90-2	AA-6535	325 ± 70	A.D. 1480 (1640) 1660
48HO4	WP-90-4	AA-6536	5,775 ± 80	4758 (4670, 4640, 4610) 4522 B.C.
Legend Rock	WP-90-4[c]	AA-6552	6,005 ± 105	5041 (4910, 4870) 4783 B.C.
	WP-90-17	AA-6542	295 ± 55	A.D. 1520 (1640) 1660
48FR372	WP-90-20	AA-6538	1,820 ± 65	A.D. 126 (230) 322
48BH499	WP-90-21	AA-6541	325 ± 70	A.D. 1474 (1530, 1550, 1630) 1655
Medicine Lodge Creek	WP-90-22	AA-6540	70 ± 60	A.D. 1690 (1950) 1955+
24CB602	WP-90-28	AA-6544	1,250 ± 65	A.D. 681 (780) 882
Petroglyph Canyon	WP-90-30[d]	AA-6537	15,695 ± 135	16,793 (16,640) 16,489 B.C.
24CB1090	WP-90-32	AA-6539	1,470 ± 75	A.D. 542 (610) 656
Bear Shield	WP-90-35	AA-6543	1,595 ± 60	A.D. 412 (440) 547

[a] Uncorrected for $\delta^{13}C$ isotopic fractionation (see text).

[b] Calibrated ages from Stuiver and Reimer (1993), CALIB version 3.0.2, Method A, presented as minimum of calendar-age ranges on the left, calibrated ages in parentheses), and maximum of calendar-age ranges on the right.

[c] Two AMS measurements were made on WP-90-4, with the second submitted to the laboratory at a later date.

[d] Sample WP-90-30 is not on a petroglyph, but on a geomorphic surface of arenite sandstone, exposed by cuesta scarp retreat.

1993). The lack of a one-sigma overlap does not contradict our basic interpretation that the dates provide reliable minimum ages for a petroglyph. An appropriate analogy can be made to a paleosol buried by slowly accumulating alluvium. Under conditions of gradual burial, some organisms would remain exposed and would continue to exchange CO_2 with the atmosphere. These organisms would naturally yield younger ages than would organisms buried earlier. While we try to sample places where the varnish would grow first (see Dorn et al. 1992), the sampling criteria are constantly being refined, and we anticipate that offsets such as WP-90-4 should occur. However, the fact that the two AMS dates from WP-90-4 (and other replicate tests) are offset by less than 10 percent suggests that the sampling criteria are consistent.

Some of the samples contained excellent organic matter with such a high carbon content that it may actually be charcoal. Petroglyphs may have been outlined or filled in with charcoal or a charcoal-base paint, which would account for the high carbon content. Figure 4 presents cross sections of the samples from WP-90-4. This reveals that charcoal is sometimes found sandwiched between the varnish and the underlying rock. Much of the charcoal has been replaced with manganese and iron that have been mobilized from the varnish (in the areas of cation-leaching), and reprecipitated to replace some of the charcoal structure. The charcoal that has not been replaced can be collected for AMS dating purposes.

AMS dates from this study include one control sample (WP-90-30-Control) and 10 petroglyphs. The control sample was collected from a naturally varnished, unpecked surface next to a petroglyph at 24CB602, the Petroglyph Canyon site. This sample was collected in order to obtain an older age for the purposes of developing the calibration curve.

Out of all the ^{14}C measurements, one is inconsistent with the archaeological context. Petroglyph WP-90-22 yielded a modern age. It was collected from an outline-pecked anthropomorphic figure at 48BH499, the Medicine Lodge Creek site. This figure has experienced a great deal of historical damage, including heavy chalking. Chalking erodes both the varnish and the rock, however it should not have influenced the radiocarbon date, because the sample was treated with HCl. There are, however, a wide variety of other recording techniques that could have introduced recent organic materials, for example modern outlining of the petroglyph with charcoal. Such destructive treatment

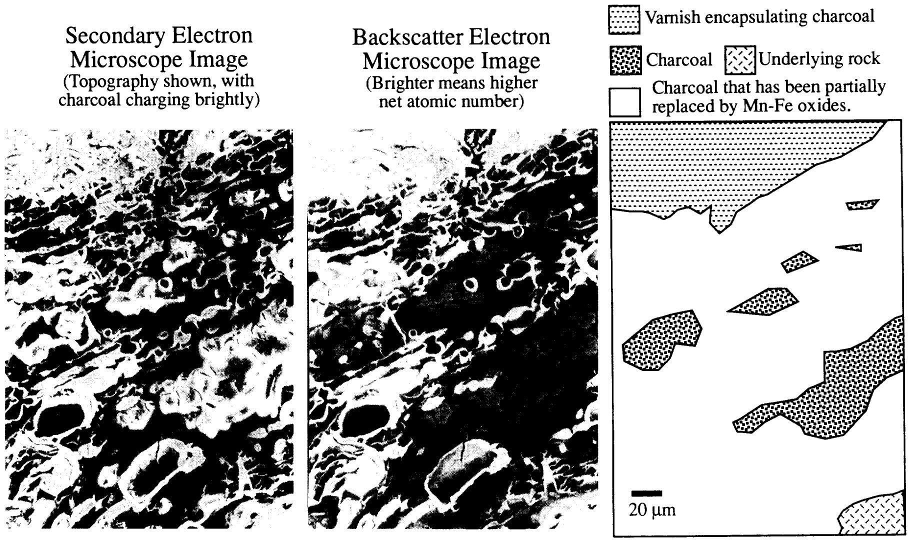

Figure 4. Electron-microscope examination of cross sections of organic matter reveals presence of charcoal, trapped between the varnish and the underlying rock, from petroglyph WP-90-4. Both backscatter and secondary images are shown to highlight the replacement of charcoal with manganese and iron oxides that are leached from the varnish and reprecipitated in the charcoal structure. The organic charcoal that is left is what is being dated.

could have contaminated the sample. It is also possible that the petroglyph was manufactured within the last 100 years. However, this explanation does not fit with the amount of varnish formation observed in the field and with light and electron microscopy, which suggested an age greater than 100 years. In other semiarid regions, approximately 100 years are required for the onset of varnish formation. It may be the case that local environmental conditions in the Bighorn Basin are conducive to more rapid varnish formation. Analysis of varnish samples from surfaces of known historical age in the area is necessary to evaluate this. Regardless of the cause, at two sigma (necessary to obtain a 95 percent confidence interval) the error factor is greater than the mean age, indicating that this date should be considered anomalous.

Of the remaining nine petroglyphs, four are from Dinwoody-style figures (samples WP-90-1, -2, -4, and -20) at three different archaeological sites. These include both the oldest and youngest dates, extending from ca. 6,800 to 300 years ago. Although the sample is small, this range of dates suggests that Dinwoody-style figures were manufactured for an extremely long period of time, from the Early Archaic through the Protohistoric periods (see Frison 1978, 1991).

Four radiocarbon-dated petroglyphs are all *en toto* pecked figures at Petroglyph Canyon (WP-90-28 and -32) and the Bear Shield site (sample WY-90-35) in Montana and the Legend Rock site (sample WP-90-17) in Wyoming. These ages extend from around 1,500 to 300 years ago. Based on the accepted cultural chronologies for the northwestern Plains (Frison 1978, 1991), these dates range from the terminal Late Archaic through the Late Prehistoric and Protohistoric periods. The one date from an outlined-pecked figure (WP-90-21) also yielded a Late Prehistoric or Protohistoric date.

Two of these dates (WP-90-21 and -17) merit further discussion. Petroglyph WP-90-21 showed extensive physical damage from chalking, charcoal outlining, latex molds, and other historical damage. In the laboratory, varnish CRs from WP-90-21 showed evidence of chalking, as did varnish CRs from WP-90-17. WP-90-17 may well have been subjected to other forms of modern damage other than chalking. The two radiocarbon ages from these figures are not out of line with their expected dates, and it is entirely possible that they are accurate minimum estimates for the ages of these two petroglyphs. However, we feel that, because of the historical damage apparent in the field and the laboratory, and the presently unknown effects of such damage to radiocarbon dates, it is best to treat these dates with extreme caution.

CATION-RATIO DATING RESULTS

Effects of Chalking and Other Recording Techniques

Analysis of the AMS dates and CRs for varnish on the Bighorn area petroglyphs revealed potential problems and raised some interesting new questions. The principal problem discovered was the effect of chalking. Unquestionably, chalking and possibly other recording techniques erode and damage varnish. As noted above, five samples were collected from each petroglyph for CR estimates; Table 3 presents the CRs for each of these samples. Full microprobe geochemical data have not been included because of space limitations. They are, however, available by writing the authors.

For many of the petroglyphs, the five samples deviate only slightly from one another, with extremely small standard deviations. However, in others the difference in CR estimates is much greater than expected, with some values being inordinately high. Typically, CRs on samples suitable for dating can range from around 15 to 3. The range of CRs in this study falls in the middle of the established literature (see summary of curves in Bull [1991]; Dorn [1989]; Glazovskiy [1985]; Loendorf [1991]; Pineda et al. [1988, 1990]; and Zhang et al. [1990]). However, a few of the CRs in this study were as high as 58.00 (WP-90-22), with others from several other petroglyphs ranging from 10.25 to 47.31. These are clearly inordinately high, far outside the expected range of variation. The microprobe data indicate that these extremely high CRs appear to have been influenced by additions of calcium from chalking of the petroglyphs. The CR is the ratio of (K+Ca)/Ti, and addition of calcium from the chalk would create an artificially high CR. In fact, when the samples were thin sectioned, chalk was visible on some petroglyphs in the bottom of peck marks (Figure 3d).

Several other petroglyphs, especially from 48BH499, Medicine Lodge Creek, may have been influenced by other recording techniques, such as rubbing or casting. In earlier research where varnish samples were collected both before and after latex molds and rubbings on cloth and paper were made, the "before" and "after" CR estimates varied somewhat (Loendorf 1989:161–164; Loendorf et al. 1992), and the varnish appeared damaged in the lab. Experiments have shown, however, that it is possible to distinguish damaged from undamaged varnish in the laboratory (Loendorf et al. 1992) and use only the undamaged samples in the calculation of calibrated CR ages.

For the purposes of this paper, petroglyphs for which only one of the five varnish samples appeared damaged are considered datable (see Table 3). Twenty-two of the 34 petroglyphs sampled showed no evidence of chalking and were dated using all five CR samples. Five petroglyphs were dated using four of the five CR samples collected.

We chose not to date petroglyphs with three or fewer consistent estimates using CR methods. This amounted to seven petroglyphs in this study considered too damaged to permit dating by CR methods. Three of these are from 48HO4, the Legend Rock site. These include WP-90-13 (Figure 3d), a Dinwoody-style anthropomorphic figure; WP-90-16, an *en toto* pecked anthropomorph; and WP-90-17, an *en toto* pecked rabbit. The remainder are from Medicine Lodge Creek (WP-90-21, -22, -23, and -25). As discussed above, both WP-90-17 and WP-90-21 were radiocarbon dated, though the dates are suspect. Unfortunately, the samples from Medicine Lodge Creek comprised the only outline-pecked and shield-bearing warrior figures in this study. Because of the extensive historical damage, we were unable to obtain CR dates for these types of petroglyphs.

It may be no accident that all of the undatable petroglyphs occur at two of the best-known sites in Wyoming. In fact, both Legend Rock and Medicine Lodge Creek have been recently developed as state parks. Petroglyphs at both sites have been widely photographed and extensively recorded, including latex casting in the 1970s.

The effects of chalking also pose problems for the derivation of the CLC when historical damage has altered the CRs from petroglyphs. While a particular petroglyph may be undatable by CR

Table 3. Cation-Ratio Data and Ages for Bighorn-Area Petroglyphs.

Site and Sample Number	CR	Criteria for Acceptance or Rejection of Sample[a]	Mean ± 1 Sigma	CR Ages (B.P.)	Age ± 1 Sigma B.P.
48HO469, Coal Draw					
WP-90-1; Dinwoody interior-line anthropomorph	8.94	a	9.05 ± .09		<1000
	8.99	a			
	9.05	a			
	9.10	a			
	9.16	a			
WP-90-2; Dinwoody interior-line anthropomorph	8.70	a	8.80 ± .09		<1000
	8.70	a			
	8.82	a			
	8.86	a			
	8.90	a			
WP-90-3; Dinwoody interior-line figure	8.73	a	9.04 ± .24		<1000
	8.85	a			
	9.09	a			
	9.20	a			
	9.31	a			
48HO4; Legend Rock					
WP-90-4; Dinwoody bison, panel 48	6.75	a	6.87 ± .08	calibration point	
	6.85	a			
	6.87	a			
	6.91	a			
	6.96	a			
WP-90-5; Dinwoody wavy-line figure, one footed, panel 48	7.79	a	7.88 ± .08	2400	2200 ± 200
	7.83	a		2300	
	7.90	a		2100	
	7.90	a		2100	
	7.99	a		1900	
WP-90-6; Dinwoody horned anthropomorph, panel 48	7.55	a	7.68 ± .10	3000	2700 ± 300
	7.61	a		2900	
	7.68	a		2700	
	7.75	a		2500	
	7.81	a		2300	
WP-90-7; *en toto* pecked anthropomorph	8.42	a	8.55 ± .14	1300	1100 ± 200
	8.45	a		1200	
	8.51	a		1100	
	8.59	a		1100	
	8.76	a		890	
WP-90-8; Dinwoody interior-line elk, panel 48	7.61	a	7.76 ± .13	2900	2500 ± 350
	7.70	a		2600	
	7.75	a		2500	
	7.80	a		2400	
	7.95	a		2000	
WP-90-9; foot of WP-90-6, panel 48	7.55	a	7.64 ± .06	3000	2800 ± 200
	7.61	a		2900	
	7.66	a		2700	
	7.66	a		2700	
	7.71	a		2600	
WP-90-10; antlers superimposed by WP-90-9, panel 48	6.72	a	6.85 ± .12	7100	6200 ± 800
	6.75	a		6800	
	6.88	a		6000	
	6.93	a		5700	
	6.99	a		5400	

Table 3. Continued.

Site and Sample Number	CR	Criteria for Acceptance or Rejection of Sample[a]	Mean ± 1 Sigma	CR Ages (B.P.)	Age ± 1 Sigma B.P.
WP-90-11; lower-right side of Dinwoody figure, panel 57	8.21	a	8.30 ± .07	1500	1400 ± 100
	8.25	a		1500	
	8.29	a		1400	
	8.33	a		1400	
	8.40	a		1300	
WP-90-12; left foot of WP-90-11, panel 57	8.10	a	8.25 ± .12	1700	1500 ± 200
	8.18	a		1600	
	8.22	a		1500	
	8.33	a		1400	
	8.40	a		1300	
WP-90-13; Dinwoody human torso, panel 74	12.29	b			NOT DATABLE
	13.59	b			
	15.29	b			
	16.70	b			
	19.20	b			
WP-90-14; Dinwoody quadruped, panel 74	6.84	a	6.94 ± .09	6200	5400 ± 800
	6.90	a		5900	
	6.94	a		4600	
	7.06	a		5000	
	9.09	b			
WP-90-15; Dinwoody anthropomorph, panel 74	7.61	a	7.61 ± .14	2900	2400 ± 400
	7.70	a		2600	
	7.83	a		2300	
	7.91	a		2100	
	7.95	a		2000	
WP-90-16; *en toto* pecked anthropomorph, panel 74	7.70	a			NOT DATABLE
	7.78	a			
	7.86	a			
	9.60	b			
	10.25	b			
WP-90-17; *en toto* pecked rabbit, panel 78	8.80	a			NOT DATABLE
	8.91	a			
	8.99	a			
	13.60	b			
	16.88	b			
WP-90-18; Dinwoody interior-line anthropomorph, panel 40	7.81	a	7.90 ± .08	2300	2100 ± 200
	7.88	a		2200	
	7.90	a		2100	
	8.00	a		2200	
	14.50	b			
48FR194					
WP-90-19; Dinwoody anthropomorph	8.90	a	9.12 ± .14		<1000
	9.11	a			
	9.15	a			
	9.17	a			
	9.29	a			
48FR372					
WP-90-20; Dinwoody interior-line figure	7.83	a	7.97 ± .11	calibration point	
	7.90	a			
	7.98	a			
	8.01	a			
	8.13	a			

Table 3. Continued.

Site and Sample Number	CR	Criteria for Acceptance or Rejection of Sample[a]	Mean ± 1 Sigma	CR Ages (B.P.)	Age ± 1 Sigma B.P.
48BH499, Medicine Lodge Creek					
WP-90-21, outline-pecked elk	9.23	a			NOT DATABLE
	9.30	a			
	9.44	a			
	13.22	b			
	15.90	b			
WP-90-22, outline-pecked anthropomorph	11.69	b			NOT DATABLE
	14.55	b			
	17.96	b			
	28.20	b			
	58.00	b			
WP-90-23, outline-pecked shield-bearing warrior	8.89	a			NOT DATABLE
	8.94	a			
	9.00	a			
	18.20	b			
	36.27	b			
WP-90-24, arrow	8.10	a	8.23 ± .09		<1000
	8.22	a			
	8.29	a			
	8.29	a			
	40.60	b			
WP-90-25, *en toto* pecked anthropomorph	8.66	a			NOT DATABLE
	8.72	a			
	16.90	b			
	29.70	b			
	47.31	b			
24CB602, Petroglyph Canyon					
WP-90-26, *en toto* anthropomorph	8.30	a	8.41 ± .08	1400	1300 ± 100
	8.37	a		1300	
	8.40	a		1300	
	8.48	a		1200	
	8.48	a		1200	
WP-90-27, *en toto* pecked animal	7.65	a	7.76 ± .10	2700	2500 ± 250
	7.69	a		2600	
	7.76	a		2500	
	7.80	a		2400	
	7.91	a		2100	
WP-90-28, *en toto* pecked anthropomorph	8.45	a	8.54 ± .09	calibration point	
	8.45	a			
	8.59	a			
	8.60	a			
	8.63	a			
WP-90-29, *en toto* pecked anthropomorph	8.50	a	8.62 ± .08	1200	1000 ± 150
	8.57	a		1100	
	8.64	a		1000	
	8.65	a		1000	
	8.72	a		920	
WP-90-30, *en toto* pecked thunderbird	8.69	a	8.79 ± .09		<1000
	8.75	a			
	8.81	a			
	8.90	a			
	12.22	b			

Table 3. Continued.

Site and Sample Number	CR	Criteria for Acceptance or Rejection of Sample[a]	Mean ± 1 Sigma	CR Ages (B.P.)	Age ± 1 Sigma B.P.
WP-90-31, *en toto* pecked anthropomorph	8.31	a	8.42 ± .08	1400	1300 ± 100
	8.38	a		1300	
	8.45	a		1200	
	8.46	a		1200	
	8.50	a		1200	
WP-90-32, *en toto* pecked bison	8.28	a	8.38 ± .08	calibration point	
	8.30	a			
	8.41	a			
	8.45	a			
	8.45	a			
WP-90-33, blood at mouth of WP-90-32	8.72	a	8.81 ± .07		<1000
	8.79	a			
	8.82	a			
	8.90	a			
	10.87	b			
WP-90-34, *en toto* pecked upside-down quadruped	7.55	a	7.70 ± .13	3000	2600 ± 350
	7.63	a		2800	
	7.63	a		2800	
	7.82	a		2300	
	7.85	a		2300	
24CB1090, Bear Shield					
WP-90-35, *en toto* pecked anthropomorph, left leg	8.13	a	8.21 ± .08	calibration point	
	8.17	a			
	8.17	a			
	8.30	a			
	8.30	a			
WP-90-36, right leg of WP-90-35	8.19	a	8.34 ± .13	1600	1400 ± 200
	8.26	a		1500	
	8.33	a		1400	
	8.41	a		1300	
	8.52	a		1100	
WP-90-37, Fine-line-incised bear superimposed over WP-90-35 and -36	9.11	a	9.26 ± .15		<1000
	9.14	a			
	9.28	a			
	9.28	a			
	9.50	a			

[a] a = Microstratigraphy as identified by SEM studies (Dorn 1989; Dorn et al. 1990; Krinsley et al. 1990) indicates sample is appropriate for dating and there are no geochemical anomalies; b = chalk was identified by a high concentration of CaO in microprobe data and sometimes in the SEM cross-section studies.

methods, it still may be possible to obtain an AMS date, as was the case with petroglyphs WP-90-17 and -21. Because of the inaccuracy of the CRs, it is impossible to use the either the AMS dates or the CRs in the construction of the calibration curve.

Petroglyphs Older than 1,000 Years

For petroglyphs older than about 1,000 years, we have observed a good relation between varnish CRs and the radiocarbon age of entombed organic matter. The calibration data are presented in Table 4, with the CLC presented in Figure 5. The semilog, least-squares regression is represented by the following equation:

$$\text{Varnish CR} = 15.42 - 2.26 \log_{10}(\text{Age}).$$

Table 4. Data Used in the Construction of the Cation-Leaching Curve. Errors are 1 Sigma.

Sample	Calibrated Radiocarbon Age (years B.P.)	Cation Ratio
WP-90-28	1,170 ± 80	8.54 ± .09
WP-90-32	1,340 ± 90	8.38 ± .08
WP-90-35	1,510 ± 80	8.21 ± .08
WP-90-20	1,710 ± 80	7.97 ± .11
WP-90-4	6,840 ± 150	6.87 ± .08
WP-90-30[a]	18,590 ± 150	5.71 ± .12

[a] Control sample.

Calibrated ages (Table 3) range from around 6,200 to 1,000 years ago. Breaking these dates down by style, they include 10 CR dates for eight Dinwoody-style figures, seven CR dates for *en toto* pecked figures, and one date associated with outline pecking. Dinwoody-style CR dates extend from about 6,200 to 1,400 years ago. These include two Early Archaic dates (WP-90-10 and -14), six Late Archaic dates (WP-90-5, -6, -8, -9, -15, and -18), and two dates from one petroglyph (WP-90-11 and -12) falling in the very early portion of the Late Prehistoric period. *En toto* pecked dates (WP-90-7, -26, -27, -29, -31, -34, and -36) range from 2,600 to 1,000 years ago, spanning the Late Archaic and Late Prehistoric periods, ending at the 1,000-year cutoff assigned for calibrated ages. The one date for a petroglyph associated with outline pecking (WP-90-24) falls into the early portion of the Late Prehistoric.

Petroglyphs Less than 1,000 Years Old

No clear numerical relation was found between radiocarbon age and varnish CRs for petroglyphs AMS dated to less than 1,000 years old (Table 5). For these four petroglyphs, three observations in Table 5 stand out and concern us. The first is the CR estimate from WP-90-21, the outline-pecked elk at Medicine Lodge Creek. This petroglyph has the oldest radiocarbon age, but the largest (and therefore less-leached or youngest) CR age. In contrast, the other three petroglyphs (two interior-line Dinwoody-style figures from the Coal Draw site and WP-90-17 from Legend Rock) do show a negative correlation between CR and age, as would be expected from progressive leaching with time. However, the numerical relation between CR and radiocarbon age is different from samples

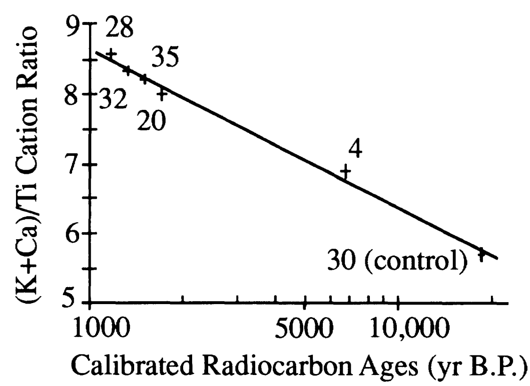

Figure 5. Preliminary cation-leaching curve for Bighorn area, Wyoming and Montana. Sample numbers shown on the curve correlate to Table 3.

Table 5. Mean Cation Ratios for AMS-Dated Petroglyphs Less Than 1,000 Years Old. Errors are 1 Sigma.

Sample	Uncalibrated Radiocarbon Age (years B.P.)[a]	Mean Cation Ratio
WP-90-21	325 ± 70	9.27 ± .05
WP-90-2	310 ± 70	8.80 ± .09
WP-90-17	295 ± 55	8.86 ± .08
WP-90-1	225 ± 60	9.05 ± .09

[a] At 2 Sigma, all dates could be modern.

older than 1,000 years. Finally, all four of these petroglyphs have radiocarbon ages that cluster closely around cal A.D. 1600 (Table 2).

We suspect that either historical damage or local environmental conditions may be acting as confounding factors to obscure the relationships between age and leaching of the varnish. Both WP-90-17 and WP-90-21 showed indications of historical damage. Because of this damage, we do not have confidence that the analytical measurements reflect the figures' true age. This is certainly the case for the CRs, by which both figures are considered completely undatable. And, as noted previously, the radiocarbon ages should be treated cautiously.

Second, all four AMS dates can be considered contemporaneous, which poses problems for the derivation of a CLC. The clustering of ages around cal A.D. 1600 could reflect the more moist conditions that existed in western North America during the "Little Ice Age" (cf. Luckman et al. 1993; Scuderi 1987). If these conditions during this period brought a bloom of lichens and cyanobacteria, samples of subvarnish organic matter might reflect this time interval, rather than the age of exposure of the underlying rock surface. In other words, a radiocarbon date for a petroglyph may be biased toward recording a time interval that favors the growth of rock-surface organisms that would be encapsulated by the accreting varnish. Such a bias would be most noticeable in the youngest samples. We stress that this analysis does not invalidate the interpretations of AMS ^{14}C ages as minimum-limiting dates.

Because of these uncertainties, we have concluded that additional sampling is needed before we can treat CRs for petroglyphs greater than about 8.6 (younger than 1,000 years) as anything other than highly speculative. Rather than assign calibrated ages, we present a relative ordering of the petroglyphs, from oldest to youngest, based upon the mean CR (Table 6). This is presented largely for illustrative purposes; it should be acknowledged that all the AMS dates overlap and that, without

Table 6. Relative Ordering of Petroglyphs Less than 1,000 Years Old Based on Cation Ratios and AMS Dates.

Sample	Style	Mean CR	Uncalibrated Radiocarbon Age (years B.P.)
WP-90-21	outline pecked	NOT DATABLE	325 ± 70
WP-90-30	*en toto* pecked	8.79 ± .09	-
WP-90-2	Dinwoody	8.80 ± .09	310 ± 70
WP-90-33	*en toto* pecked	8.81 ± .07	-
WP-90-17	*en toto* pecked	NOT DATABLE	295 ± 55
WP-90-3	Dinwoody	9.04 ± .24	-
WP-90-1	Dinwoody	9.05 ± .09	225 ± 60
WP-90-19	Dinwoody	9.12 ± .14	-
WP-90-37	fine-line incised	9.26 ± .15	-

knowing the exact nature of the numerical relation between age and varnish leaching, many of these figures may be contemporaneous.

Nine petroglyphs are considered to be less than 1,000 years in age. Four Dinwoody-style glyphs (WP-90-1, -2, -3, and -19) fall into this age grouping, three of which are from the Coal Draw site. All are extremely elaborate, finely executed, interior-line figures, as opposed to the fully pecked Dinwoody anthropomorphs. Two *en toto* pecked animals from Petroglyph Canyon (WP-90-30 and -33) and one *en toto* pecked animal from Legend Rock (WP-90-17) are considered to be less than 1,000 years old. It is also significant that the finely incised bear from the Bear Shield site has the highest (youngest) CR. This is consistent with the proposed chronology, in that finely incised figures should date to the Protohistoric and Historic periods. It should also be noted that petroglyph WP-90-23, an outline-pecked, shield-bearing warrior, had three undamaged CR estimates with a mean of 8.94, which if accurate, may indicate an age of less than 1,000 years.

DISCUSSION

This research has provided one of the first tests of the AMS and CR dating methods against rock art, the age of which can be reliably inferred based on independent archaeological data (see Loendorf [1991] for other tests of the method). It should be emphasized that the AMS and CR dating methods are still yet considered experimental, with numerous questions remaining to be answered, and the dates obtained from this project are considered preliminary. Questions raised by this research include the effects of environmental fluctuations on the formation of the varnish on relatively recent petroglyphs and the related bias that may affect the associated radiocarbon dates, the effects of chalking, latex molds, rubbings, and other traditional recording techniques on both AMS dates and CRs, and the use of such extremely small samples of organic matter for AMS dates. With additional research, questions regarding the anomalies found with petroglyphs less than 1,000 years in age and whether one calibration curve may be used for all rock art within the study area can be addressed.

It should also be emphasized that the results of the CR and AMS dating are generally consistent with the proposed rock-art chronology in the Bighorn area and that the samples themselves show remarkable internal consistency. For example, Francis (1989:195–197) suggested that the oldest rock art (dating sometime prior to 2,000 years ago) at Legend Rock should consist of outline-pecked zoomorphic figures. Two separate radiocarbon dates of one of these figures (an outline-pecked bison) yielded the oldest dates of the entire project, Early Archaic ages of cal 6840 and 6590 B.P. (Table 2). Dates of around 2,000 years old were suggested for fully pecked Dinwoody-style anthropomorphic figures (Francis 1989:199–200). The two figures of this type dated by this project (WP-90-6 and -15) were made by about 2700 to 2400 B.P.

Loendorf (1984) suggested that *en toto* pecked style figures were manufactured by at least 1,000 years ago. AMS and CR dates for seven of the 12 *en toto* pecked figures range from 1000 to 1500 B.P.; two other dates are slightly older than 2,000 years B.P. (Tables 2 and 3), and three dates are less than 1,000 years (Table 6). Again the AMS and CR estimates are consistent with independent data. Finally, the one fine-line incised figure, thought to be of Historic age, yielded the highest CR or youngest date (most likely less than 300 years old) of any of the petroglyphs investigated (Table 5).

Several figures and panels were sampled at more than one place in order to check for internal consistency. Samples WP-90-5, -6, -8, -9, and -10 (Table 3) were all taken from the same panel (panel 48) at the Legend Rock site (Figure 6). Sample WP-90-6 was taken from the upper torso of a large, fully pecked, Dinwoody anthropomorphic figure. Sample WP-90-9 was taken from the left foot of that same figure. Taking into account the standard deviation of the CR estimates, the dates for these two samples range from 3000 to 2300 B.P. and 3000 to 2600 B.P. respectively. These dates exhibit almost complete overlap, as would be expected of two samples from the same figure. Sample WP-90-8 is from the elk to the right of the anthropomorphic figure. Its CR dates range from 2,900 to 2,000 years ago, suggesting a direct association with the anthropomorph. Sample WP-90-5 is from a wavy-lined anthropomorphic figure (see Francis 1989:181) superimposed over the right arm of WP-90-6. The CR estimate for WP-90-5 is about 2,200 years ago, consistent with its superimposition. Finally, sample WP-90-10 is from a set of antlers superimposed by the foot of

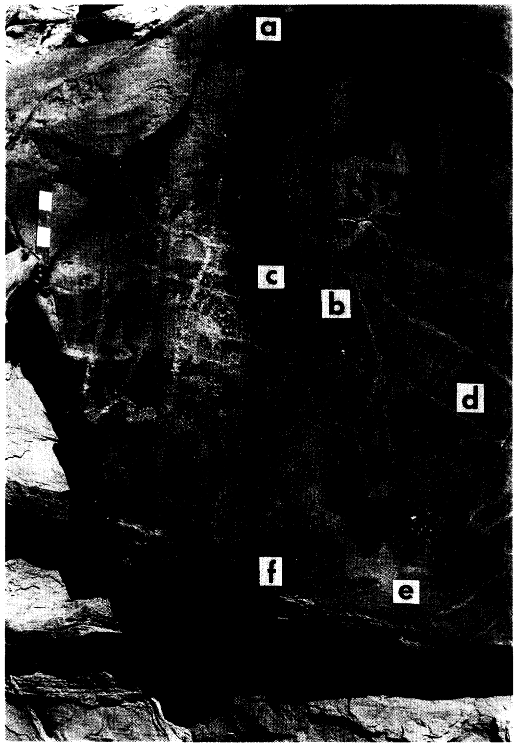

Figure 6. Panel 48, Legend Rock site (48HO4), showing locations of varnish samples on individual Dinwoody figures: (*a*) WP-80-4; (*b*) WP-90-5; (*c*) WP-90-6; (*d*) WP-90-8; (*e*) WP-90-9; (*f*) WP-90-10.

WP-90-6. Its CR age is approximately 6,200 years old. In other words, all of the CR estimates from this panel are consistent with relative ages based upon superimpositions.

The same internal consistency is also apparent in samples taken from other panels and sites investigated as part of this project. Samples from the body and left foot of the main human figure in panel 57 at Legend Rock overlap completely (Table 3). Samples WP-90-32 and -33 are from an *en toto* pecked bison and "blood" dripping from its mouth at the Petroglyph Canyon site (Figure 7). Based upon visual estimates of the amount of varnish formation, the blood was added to the figure at a later date. The AMS date from the bison is about 1,340 years ago (Table 2), while the CR estimate for the blood is less than 1,000 years (Table 3). Finally, the left and right leg of an *en toto* pecked figure superimposed by the finely incised bear at the Bear Shield site (Figure 8) were both sampled. The calibrated AMS date from the left leg is about 1,510 years ago; the CR date from the right leg is about 1,400 years old (see Table 3). The CR estimate from the superimposed bear falls into the less-than-1,000-years-old category (Table 3). These data strongly support the efficacy and reliability of both dating techniques.

Despite the preliminary nature of the AMS and CR dates from this project, the results hold some interesting anthropological implications for the prehistory of this area. As noted previously, a relatively simple chronological sequence of petroglyph styles had been posited. This included, from oldest to youngest, Dinwoody-style glyphs, replaced by *en toto* pecked figures, replaced by outline-pecked and incised shield-bearing warriors and V-necked figures, replaced by finely incised historical-period figures. Rather than a simple evolutionary sequence, the results of this project suggest a complex pattern of concurrent rock-art styles in different parts of the study area (Figure 9).

It is apparent that the Dinwoody style extends from at least Early Plains Archaic to the Protohistoric period. This inference is based upon the AMS dates, which range from at least 6,800 years

Figure 7. ***En toto*** **pecked bison and "blood" from Petroglyph Canyon (24CB602). The darker body of the bison shows some varnish development compared to the "fresh" surface of the blood. Sample WP-90-32 from the bison was AMS dated to 1470 ± 75 B.P. (AA-6539). The CR age for the blood is less than 1,000 years.**

old to sometime around 300 years old. The CR estimates largely fall between these extremes. Thus far, the earliest dates pertain to both interior-lined and fully-pecked animal figures. However, it is also clear that these types of animal figures are closely associated with much younger anthropomorphic figures. It is perhaps even more significant that Dinwoody-style petroglyphs are spatially restricted to the Wind River and upper Bighorn River drainage, essentially corresponding to the southwestern one-quarter of the study area (Gebhard 1951). No Dinwoody-style petroglyphs are known east of the Bighorn River.

The *en toto* pecked style apparently has a slightly longer time span than originally thought. AMS

Figure 8. Finely incised bear and shield superimposed over an ***en toto*** **pecked figure in the body of the bear at the Bear Shield site (24CB1090). Sample WP-90-35 was AMS dated to 1595 ± 60 B.P. (AA-6543). The calibrated CR age from the right leg (WP-90-36) is 1400 ± 200 B.P. The CR for the incised bear falls into the less-than-1,000-years-old category and is the youngest (highest) recorded on this project.**

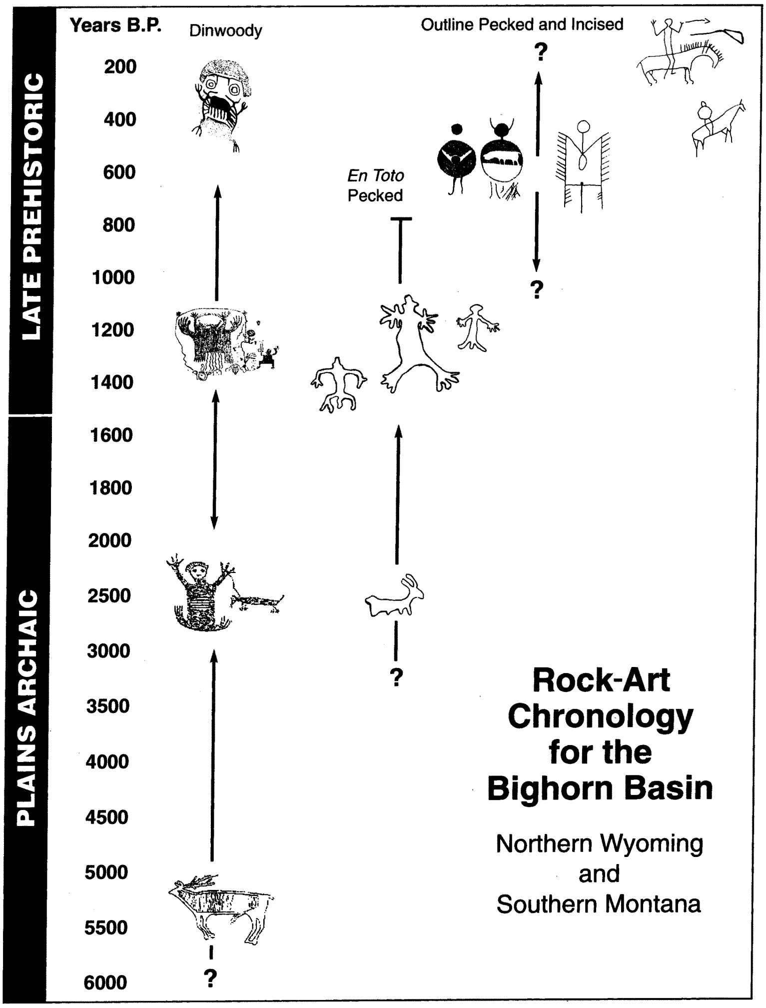

Figure 9. Revised chronological sequence for rock art in the Bighorn area.

dates indicate manufacture of this style by at least 1,500 years ago, with CR estimates as early as about 2,600 years old. The majority of the *en toto* pecked figures date to slightly before 1,000 years ago, with a few such figures less than 1,000 years old. A future issue to explore is whether the "popularity" of this style was declining by 1,000 years ago. *En toto* pecked figures have a much wider spatial distribution than Dinwoody style. A few of these figures occur at Legend Rock and other Dinwoody sites. Some *en toto* pecked figures also occur on the east side of the Bighorn River, in particular at the Medicine Lodge Creek site. *En toto* pecked style also occurs in the Montana portion of the study area.

Although chalking presented obstacles in dating outline-pecked and incised shield-bearing warriors and associated figures, there is no information currently available to suggest that shield-bearing warriors are any greater than 1,000 years old. The one extremely tentative CR estimate on a shield-bearing warrior from Medicine Lodge Creek (WP-90-23) falls into the less-than-1,000-years-old category. At present, the evidence from Valley of the Shields (Loendorf 1990) that such figures were being manufactured as of 800 to 900 years ago is the most definitive. Shield-bearing warriors also have a broad spatial distribution. They are extremely common in Montana and east of the Bighorn

River. They are almost unknown from the Dinwoody portion of the study area (Francis 1989:170–171).

What is important to emphasize is that Dinwoody-style figures, *en toto* pecked figures, and finely incised figures all occur within the less-than-1,000-years-old category. In fact, the ^{14}C dates suggest that many of these figures may be contemporaneous; in other words, during the last 1,000 years, all different types of rock art were being manufactured in different portions of the study area. This suggests that concurrent rock-art styles or traditions occurred in different parts of the Bighorn Basin and surrounding mountains for the last 800 to 900 years.

CONCLUSIONS

There are many potential explanations for the long-term persistence of one rock-art style or tradition in one portion of the Bighorn area, along with presence of spatially disparate, but temporally concurrent styles and traditions for the last 800 to 900 years in other portions of the area. Additional research, which relates rock art to other classes of archaeological remains, along with additional dates on rock art, are needed to start answering questions raised by this research.

This project demonstrates the potential utility of AMS radiocarbon and CR dating of rock art, and it opens several new avenues of inquiry necessary to perfect the techniques. Within the study area, there is a systematic relation between the leaching rates of rock varnish and time for petroglyphs older than 1,000 years, which can be used to derive calibrated ages. This relation does not hold for petroglyphs younger than 1,000 years, and it is not yet possible to derive calibrated ages for figures less than 1,000 years old. Past environmental conditions and modern damage to petroglyphs are two possible explanations. The results of this research provide an example of how the different approaches of AMS and CR can be used together to identify anomalies and refine the different dating techniques. It is clear that this project has raised many more questions than it has answered, both from the standpoint of developing new dating techniques and from the anthropological issues raised. Nonetheless, the use of new dating methods allows us to investigate rock art in a far more systematic fashion than has been possible in the past.

Acknowledgments. Funding for the fieldwork phase of the study was provided by the Bureau of Reclamation, the University of North Dakota, the Wyoming State Historic Preservation Office, the State Parks and Historic Sites Division of the Wyoming Department of Commerce, and by an NSF PYI award. The bulk of financial assistance for laboratory analyses, AMS dating, and CR dating was provided by the Bureau of Land Management, Wyoming State Office. Thanks to A. J. T. Jull, L. Toolin, and D. Donahue at the Arizona accelerator for measuring the radiocarbon content of our samples. Special thanks go to George C. Frison of the University of Wyoming, and Mike Bies and John Whitehurst of the Bureau of Land Management, Worland, Wyoming, the Office of the Wyoming State Archaeologist, and the Wyoming Transportation Department for their support. Figures were prepared with the assistance of Larry Edgar, Lucy Ganje, and Kurt Peterson. Thanks also to Thomas A. Dowson, Ann Johnson, Martin Magne, and three anonymous reviewers for their useful comments on drafts of this paper.

REFERENCES CITED

Allen, C. C.
1978 Desert Varnish of the Sonoran Desert: Optical Electron Probe Microanalysis. *Journal of Geology* 86: 743–752.

Bamforth, D. B., and R. I. Dorn
1988 On the Nature and Antiquity of the Manix Lake Lithic Industry. *Journal of California and Great Basin Anthropology* 10:209–226.

Basedow, H.
1914 Aboriginal Rock Carvings of Great Antiquity in South Australia. *Journal of the Royal Anthropological Institute* 44:195–211.

Bierman, P., and A. Gillespie
1991a Range Fires: A Significant Factor in Exposure-Age Determination and Geomorphic Surface Evolution. *Geology* 19:641–644.
1991b Accuracy of Rock-Varnish Chemical Analyses: Implications for Cation-Ratio Dating. *Geology* 19: 196–199.

1992 Reply to T. A. Cahill's Comment on Accuracy of Rock-Varnish Chemical Analysis: Implications for Cation-Ratio Dating. *Geology* 20:471–472.
Bierman, P., A. Gillespie, and S. Kuehner
1991 Precision of Rock-Varnish Chemical Analyses and Cation-Ratio Ages. *Geology* 19:135–138.
Bull, W. B.
1991 *Geomorphic Responses to Climatic Change.* Oxford University Press, Oxford.
Cahill, T. A.
1992 Comment on "Accuracy of Rock-Varnish Chemical Analyses: Implications for Cation-Ratio Dating." *Geology* 20:469.
Chang, K. C.
1967 *Rethinking Archaeology.* Random House, New York.
Clark, W. P.
1885 *The Indian Sign Language, with Brief Explanatory Notes of the Gestures Taught Deaf-Mutes in Our Institutions for Their Instruction, and a Description of Some of the Peculiar Laws, Customs, Myths, Superstitions, Ways of Living, Code of Peace and War Signals of Our Aborigines.* Hamersly, Philadelphia.
Conner, S. W., and B. L. Conner
1971 *Rock Art in the Montana High Plains.* The Art Galleries, University of California, Santa Barbara.
Dorn, R. I.
1983 Cation-Ratio Dating: A New Rock Varnish Age Determination Technique. *Quaternary Research* 20: 49–73.
1989 Cation-Ratio Dating of Rock Varnish: A Geographical Perspective. *Progress in Physical Geography* 13:559–596.
1992 Comment on "Accuracy of Rock-Varnish Chemical Analyses: Implications for Cation-Ratio Dating." *Geology* 20:470–471.
1993 Dating Petroglyphs with a Three-Tier Rock Varnish Approach. In *New Light on Old Art: Advances in Hunter-Gatherer Rock Art Research*, edited by D. S. Whitley and L. Loendorf. UCLA Institute of Archaeology, Los Angeles, in press.
Dorn, R. I., and D. H. Krinsley
1991 Cation-Leaching Sites in Rock Varnish. *Geology* 19:1077–1080.
Dorn, R. I., and M. Nobbs
1992 Further Support for the Antiquity of South Australia Rock Engravings. *Journal of the Australian Institute of Aboriginal and Torres Strait Islander Studies* 1:56–60.
Dorn, R. I., and T. M. Oberlander
1982 Rock Varnish. *Progress in Physical Geography* 6:317–367.
Dorn, R. I., and D. S. Whitley
1984 Chronometric and Relative Age Determination of Petroglyphs in the Western United States. *Annals of the Association of American Geographers* 74:308–322.
Dorn, R. I., M. Nobbs, and T. A. Cahill
1988 Cation-Ratio Dating of Rock Engravings from the Olary Province of Arid South Australia. *Antiquity* 62:681–689.
Dorn, R. I., D. Tanner, B. D. Turrin, and J. C. Dohrenwend
1987 Cation-Ratio Dating of Quaternary Materials in the East-Central Mojave Desert, California. *Physical Geography* 8:72–81.
Dorn, R. I., P. Clarkson, M. F. Nobbs, L. L. Loendorf, and D. S. Whitley
1992 Radiocarbon Dating Inclusions of Organic Matter in Rock Varnish, with Examples for Drylands. *Annals of the Association of American Geographers* 82:136–151.
Dorn, R. I., A. J. T. Jull, D. J. Donahue, T. W. Linick, and L. T. Toolin
1989 Accelerator Mass Spectrometry Radiocarbon Dating of Rock Varnish. *Geological Society of America Bulletin* 101:1363–1372.
Dorn, R. I., B. D. Turrin, A. J. T. Jull, T. W. Linick, and D. J. Donahue
1987 Radiocarbon and Catio-Ratio Ages for Rock Varnish on Tioga and Tahoe Morainal Boulders of Pine Creek, Eastern Sierra Nevada in California, and Paleoclimatic Implications. *Quaternary Research* 28:38–49.
Dorn, R. I., T. Cahill, R. Eldred, T. E. Gill, B. H. Husko, A. J. Bach, and D. Elliot-Fisk
1990 Dating Rock Varnishes by the Cation-Ratio Method with PIXE, ICP, and the Electron Microprobe. *International Journal of PIXE* 1:157–195.
Dorn, R. I., D. B. Bamforth, T. A. Cahill, J. C. Dohrenwend, B. D. Turrin, D. J. Donahue, A. J. T. Jull, A. Long, M. E. Macko, E. B. Weil, D. S. Whitley, and T. H. Zabel
1986 Cation-Ratio and Accelerator Dating of Rock Varnishes on Archaeological Artifacts and Landforms in the Mojave Desert, Eastern California. *Science* 231:830–833.
Drake, N. A., M. T. Heydeman, and K. J. White
1993 Distribution and Formation of Rock Varnish in Southern Tunisia. *Earth Surface Processes and Landforms* 18:31–41.

Francis, J. E.
1989 Rock Art at Legend Rock. In *Legend Rock Petroglyph Site (48HO4), Wyoming: 1988 Archaeological Investigations*, edited by D. N. Walker and J. E. Francis, pp. 151–208. Office of the Wyoming State Archaeologist, Laramie. Submitted to the Wyoming Recreation Commission, Cheyenne.
1991 An Overview of Wyoming Rock Art. In *Prehistoric Hunters of the High Plains*, 2nd ed., by G. C. Frison, pp. 397–430. Academic Press, New York.
Francis, J. E., and G. C. Frison
1990 Age and Chronology of Rock Art in Northwestern Wyoming. Paper presented at the 55th Annual Meeting of the Society for American Archaeology, Las Vegas.
Frison, G. C.
1978 *Prehistoric Hunters of the High Plains.* Academic Press, New York.
1991 *Prehistoric Hunters of the High Plains.* 2nd ed. Academic Press, New York.
Gebhard, D. S.
1951 Petroglyphs of Wyoming: A Preliminary Paper. *El Palacio* 58(3):67–81.
1969 *The Rock Art of Dinwoody, Wyoming.* The Art Galleries, University of California, Santa Barbara.
Gebhard, D. S., and H. A. Cahn
1950 The Petroglyphs of Dinwoody, Wyoming. *American Antiquity* 15:219–228.
Glazovskiy, A. F.
1985 Rock Varnish in the Glacierized Regions of the Pamirs. *Data of the Glaciological Studies* 54:136–141.
Harrington, C. D., and J. W. Whitney
1987 Scanning Electron Microscope Method for Rock Varnish Dating. *Geology* 15:967–970.
Harry, K., P. R. Bierman, and L. Fratt
1992 *Lithic Procurement and Rock Varnish Dating: Investigations at CA-KER-140, a Small Quarry in the Western Mojave Desert.* Technical Series No. 36. Statistical Research, Tucson.
Heizer, R. F., and M. A. Baumhauf
1962 *Prehistoric Rock Art of Nevada and Eastern California.* University of California Press, Berkeley.
Hendry, M. H.
1983 *Indian Rock Art in Wyoming.* Augstums Printing Service, Lincoln, Nebraska.
Jennings, J. D.
1989 *Prehistory of North America.* 3rd ed. Mayfield, Mountain View, California.
Krinsley, D. H., and C. R. Manley
1989 Backscattered Electron Microscopy as an Advanced Technique in Petrography. *Journal of Geological Education* 37:202–209.
Krinsley, D. H., R. I. Dorn, and S. Anderson
1990 Factors that May Interfere with the Dating of Rock Varnish. *Physical Geography* 11:97–119.
Lanteigne, M.
1991 Cation-Ratio Dating of Rock Engravings: A Critical Appraisal. *Antiquity* 65:292–295.
Lewis-Williams, D. S.
1981 *Believing and Seeing: Symbolic Meanings in Southern San Rock Paintings.* Academic Press, London.
Lewis-Williams, D. S., and T. A. Dowson
1988 The Signs of All Times: Entoptic Phenomena in Upper Palaeolithic Art. *Current Anthropology* 29: 201–245.
Loendorf, L. L.
1984 *Documentation of Rock Art: Petroglyph Canyon, Montana.* Contribution No. 207. Department of Anthropology, University of North Dakota, Grand Forks.
1988 Rock Art Chronology in Carbon County, Montana and the Valley of the Shields Site, 24CB1094. Paper presented at the Montana Archaeological Society Meetings, Missoula.
1989 *Nine Rock Art Sites in the Pinon Canyon Maneuver Site, Southeastern Colorado.* Contribution No. 248. Department of Anthropology, University of North Dakota, Grand Forks.
1990 A Dated Rock Art Panel of Shield Bearing Warriors in South Central Montana. *Plains Anthropologist* 35:45–54.
1991 Cation-Ratio Varnish Dating and Petroglyph Chronology in Southeastern Colorado. *Antiquity* 65:247–255.
Loendorf, L. L., and A. Porsche
1985 *The Rock Art Sites in Carbon County, Montana.* Contribution No. 224. Department of Anthropology, University of North Dakota, Grand Forks.
Loendorf, L. L., J. E. Francis, and R. I. Dorn
1992 Petroglyphs: Are We Loving Them to Death? Paper presented at the 50th Plains Conference, Lincoln, Nebraska.
Loendorf, L. L., K. Hackett, J. D. Benko, D. M. Penny, J. K. Michaelsen, and T. K. Larson
1990 *The Cottonwood Creek Rock Art Survey.* Larson-Tibesar Associates, Laramie, Wyoming. Submitted to the USDI Bureau of Land Management, Montana State Office, Billings. Copies available from Larson-Tibesar Associates, Laramie, Wyoming.
Luckman, B. H., G. Holdworth, and M. Jercinovich
1993 Neoglacial Glacier Fluctuations in the Canadian Rockies. *Quaternary Research* 39:144–153.

McFadden, L. D., S. G. Wells, and M. Jercinovich
1987 Influences of Eolian and Pedogenic Processes on the Origin and Evolution of Desert Pavements. *Geology* 15:504–508.
Magne, M. P. R., and M. A. Klassen
1991 A Multivariate Study of Rock Art Anthropomorphs at Writing-on-Stone, Southern Alberta. *American Antiquity* 56:389–418.
Mallery, G.
1886 Pictographs of the North American Indians: A Preliminary Paper. *Fourth Annual Report of the Bureau of Ethnology* 4:3–256. Smithsonian Institution, Washington, D.C.
1893 Picture-Writing of the American Indians. *Tenth Annual Report of the Bureau of Ethnology* 10:1–822. Smithsonian Institution, Washington, D.C.
Nagy, B. L., A. Nagy, M. J. Rigali, W. D. Jones, D. H. Krinsley, and N. A. Sinclair
1991 Rock Varnish in the Sonoran Desert: Microbiologically Mediated Accumulation of Manganiferous Sediments. *Sedimentology* 38:1153–1171.
Nobbs, M., and R. I. Dorn
1993 New Surface Exposure Ages for Petroglyphs from the Olary Province, South Australia. *Archaeology in Oceania*, in press.
Palmer, F. E., J. T. Staley, R. G. E. Murray, T. Counsell, and J. B. Adams
1985 Identification of Manganese-Oxidizing Bacteria from Desert Varnish. *Geomicrobiology Journal* 4:343–360.
Pineda, C. A., L. Jacobson, and M. Peisasch
1988 Ion Beam Analysis for the Determination of Cation-Ratios as a Means of Dating Southern African Rock Varnishes. *Nuclear Instruments and Methods in Physics Research* B35:463–466.
Pineda, C. A., M. Peisach, L. Jacobson, and C. G. Sampson
1990 Cation-Ratio Differences in Rock Patina on Hornfels and Chalcedony Using Thick Target PIXE. *Nuclear Instruments and Methods in Physics Research* B49:332–335.
Potter, R. M., and G. R. Rossman
1977 Desert Varnish: The Importance of Clay Minerals. *Science* 196:1446–1448.
Renaud, E. B.
1936 Pictographs and Petroglyphs of the High Western Plains. *Archaeological Survey of the High Western Plains, Eighth Report.* Department of Anthropology, University of Denver, Denver.
Reneau, S. L., and R. J. Raymond
1991 Cation-Ratio Dating of Rock Varnish: Why Does It Work? *Geology* 19:937–940.
Reneau, S. L., T. M. Oberlander, and C. D. Harrington
1991 Accelerator Mass Spectrometry Radiocarbon Dating of Rock Varnish: Discussion and Reply. *Geological Society of American Bulletin* 103:310-314.
Rouse, I.
1972 *Introduction to Prehistory: A Systematic Approach.* McGraw-Hill, New York.
Scuderi, L.
1987 Late-Holocene Upper Timberline Variation in the Southern Sierra Nevada. *Nature* 325:242–255.
Stuiver, M., and P. J. Reimer
1993 Extended ^{14}C Data Base and Revised Calib 3.0 ^{14}C Age Calibration Program. *Radiocarbon* 35:215–230.
Walker, D. N., and J. E. Francis (editors)
1989 *Legend Rock Petroglyph Site (48HO4), Wyoming: 1988 Archaeological Investigations.* Office of the Wyoming State Archaeologist, Laramie. Submitted to the Wyoming Recreation Commission, Cheyenne. Copies available from the Office of the Wyoming State Archaeologist, Laramie.
Watchman, A.
1992a Doubtful Dates for Karolta Engravings. *Journal of the Australian Institute of Aboriginal and Torres Strait Islanders Studies* 1:51–55.
1992b Comment on "Cation-Leaching Sites in Rock Varnish." *Geology* 20:1050.
Wells, S. G., L. D. McFadden, and C. T. Olinger
1991 Use of Cosmogenic He-3 and Ne-21 to Understand Desert Pavement Formation. *Geological Society of American Abstracts with Programs* 23(5):206.
Zhang, Y., T. Lie, and S. Li
1990 Establishment of a Cation-Leaching Curve of Rock Varnish and Its Application to the Boundary Region of Gansu and Xinjiang, Western China. *Seismology and Geology* 12:251-261.

Received March 30, 1992; accepted May 19, 1993