A New Strategy for Analyzing the Chronometry of Constructed Rock Features in Deserts

Niccole Villa Cerveny,[1,*] Russell Kaldenberg,[2] Judyth Reed,[3] David S. Whitley,[4] Joseph Simon,[4] and Ronald I. Dorn[5]

[1]*Cultural Sciences Department, Mesa Community College, 7110 East McKellips Road, Mesa, Arizona 85282*
[2]*Mojave Desert Cultural and Historical Association, 14044 Hemlock Street, Trona, California 93562*
[3]*Bureau of Land Management, Division of Resource Policy and Management, 5353 Yellowstone Road, Cheyenne, Wyoming 82009*
[4]*W&S Consultants, 447 Third Street, Fillmore, California 93015*
[5]*Department of Geography, Arizona State University, Tempe, Arizona 85287-0104*

The western Great Basin contains thousands of constructed rock features, including rock rings, cairns, and alignments. Unlike subtractive geoglyphs, such as the Nasca Lines of Peru, that remove desert pavement, these surface features alter the location and positioning of cobble- to boulder-sized rocks. The chronology of surface rock features has remained unconstrained by numerical ages because no prior chronometric approach has been able to yield age control. We propose a new strategy for studying these features by analyzing anthropogenic modifications to rock coatings, an approach that permits the use of several dating methods, two of which are assessed here: radiocarbon dating of pedogenic carbonate and rock-varnish microlaminations. Initial results from Searles Valley, eastern California, suggest that constructed rock features may be as old as early Holocene and terminal Pleistocene. Archaeological surveys of desert areas would be greatly enhanced if they noted altered positions of rock coatings. © 2006 Wiley Periodicals, Inc.

INTRODUCTION

From the Paleolithic to the present, humans have acted as agents of aggradation and erosion, altering Earth by building such features as enclosures, mounds, and earth figures. Constructed rock features can also represent important expressions of human behavior (Johnson, 1986; Clarkson, 1994; Doolittle and Neely, 2004), but understanding their significance requires a consideration of both their spatial and temporal contexts (Clarkson, 1990; Doolittle and Neely, 2004). Warm deserts host a large number of earth constructions (Wilson, 1988; Clarkson, 1994; Anati, 2001). While rock rings and cairns may have technological or economic origins, such as sleeping circles (Hayden, 1976) or agricultural features (Evenari et al., 1971; Doolittle

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*Corresponding author; E-mail: ncerveny@mail.mc.maricopa.edu.

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and Neely, 2004), respectively, other structures are more enigmatic. Earth figures are large designs or motifs made on the ground surface, constructed during shamanistic rituals (Whitley, 2000). Representing both negative and positive designs, desert earth figures include geoglyphs, sometimes called intaglios, and rock alignments. Comprising the most well-known earth figures, geoglyphs (Reiche, 1968) require scraping away darker desert pavement to expose underlying lighter-colored silt (Clarkson, 1990, 1994)—yielding a negative design. Rock alignments, in contrast, represent the addition of relief by accumulating larger rocks in patterns on the ground surface, resulting in a positive design (Evenari et al., 1971; von Werlhof, 1989; Hayden, 1994; Doolittle and Neely, 2004). They are, in this sense, structurally analogous to rock rings and cairns.

Generally, the cultural material contained within, on, or under earth figures is used as an index of temporal context. Stratigraphic clues, such as repositioned rocks placed over chronometrically diagnostic pottery, are sometimes available and help to place earthen images within archaeological contexts (Silverman, 1990). Most archaeological surveys in the Great Basin of North America tend to map and then ignore these features because they lack a clear temporal context.

To develop chronological constraints on desert earth figures, researchers have applied experimental techniques, such as cation-ratio dating in Nasca, Peru (Clarkson, 1986, 1990), and in Jordan (Harrington, 1986). Radiocarbon dating of organic matter associated with rock coatings has also been tried (von Werlhof et al., 1995) with the caveat that "[t]hese results must, however, be placed under the cloud of uncertainty that hangs over the entire field of AMS (accelerator mass spectrometry) dating of rock art: the untested assumption surrounding contemporaneity of organics in a surface context" (p. 257). The problem is that extracted carbon includes fragments that are not penecontemporaneous with the exposure of a rock surface (Dorn, 1996b; Whitley and Simon, 2002). Organic pieces associated with rock coatings such as those extracted from petroglyphs in Portugal, for example, derive from older carbon (Watchman, 1997), such as inertinite and vitrinite (Chitale, 1986), molecular fossils (Lichtfouse, 2000), or even old roots (Danin et al., 1987; Whitley and Simon, 2002). Because organic ^{14}C appears to be an open system in rock-art contexts (Whitley and Simon, 2002), just like in soils (Lichtfouse and Rullkotter, 1994; Lichtfouse et al., 1996; Lichtfouse, 1999; Frink and Dorn, 2002), preliminary research reveals some potential for open-system approaches (Frink and Dorn, 2002).

With these difficulties in mind, we use an entirely different strategy to chronometrically constrain desert earth features. Prior attempts at earth-figure dating studied the reformation of rock varnish (Dorn, 2004). Rock features generally and alignments specifically, however, are much more common than geoglyphs in many desert regions. Aerial surveys of just a small portion of the western Great Basin, for example, revealed thousands of rock alignments (von Werlhof, 1989).

Our new strategy to understand rock features derives from prior research that studies spatial variability in biogeochemical landscapes (Perel'man, 1980; Ferring, 1992). The discipline of landscape geochemistry (Perel'man, 1966, 1980) maps spatial variability in soil and regolith geochemistry along hillslope profiles. Similarly,

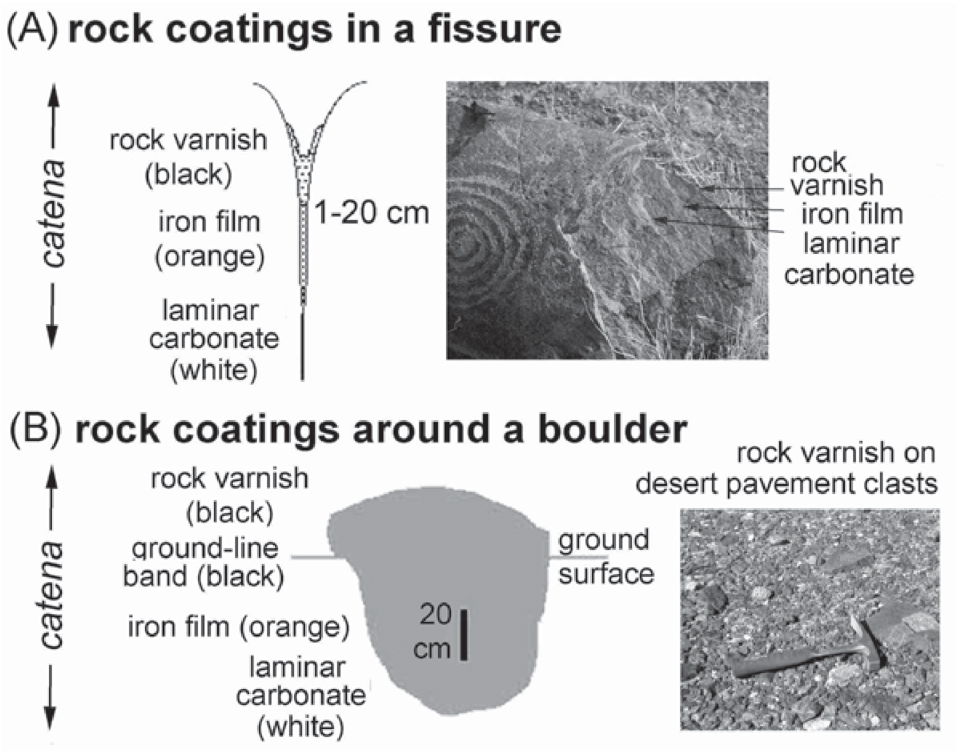

Figure 1. Even though there are many different types of rock-coating sequences that vary over rock surfaces (Dorn, 1998), lateral variability over a scale of centimeters in (A) a rock fissure and (B) around the outside of boulders in desert pavements are the most common rock-coating catenas encountered in warm deserts.

geoarchaeological research has mapped environmental changes from analyses of soils, regoliths, and Quaternary sediments (Fredlund et al., 1988; Ferring, 1992; Goldberg et al., 1994; Bettis and Mandel, 2002), enabling interpretations of landscape changes, such as submergence, reemergence, and then drying in former lacustrine settings (Cabrol and Bettis, 2001, pp. 7810–7811).

Our strategy takes this prior landscape geochemistry perspective and explores spatial variations in biogeochemical coatings on rocks, a variability that has been perceived as analogous to soil catenas (Haberland, 1975). Over the scale of a desert hill, rock coatings display variability up and down slopes similar to the scale of changes seen in a soil catena (Palmer, 2002). Rock-coating catenas also occur over single rock surfaces (Jones, 1991) (Figure 1). For example, unopened rock joints host a colorful lateral sequence of black, orange, and white rock coatings (Coudé-Gaussen et al., 1984; Villa et al., 1995). A similar sequence coats boulders in desert pavements (Walther, 1891). The essence of this study rests in exploring human reorientation of rocks, altering the catena of rock coatings around a boulder.

Prior geoarchaeological studies (Biagi and Cremaschi, 1988; von Werlhof, 1989; Clarkson, 1994; Anati, 2001; Doolittle and Neely, 2004) have explored circumstances where prehistoric people altered natural spatial arrangements of stones. In these settings, we noted that rotating and then thrusting a boulder into the ground alters its rock-coating sequence. In one example, human alignment of stones or construction of rock cairns will sometimes place the former surface of a boulder into the ground, resulting in the formation of pedogenic carbonate over what was once manganese-rich black surface rock varnish. A soil catena conceptually links soils along a hillslope, where topographic position changes environmental variables, such as water movement. A rock-coating catena (cf. Haberland, 1975) occurs where changes in microtopographic position affects environmental variables enough to alter the type of rock coating. We explore here the chronometric potential of anthropogenic changes to rock coating catenas.

STUDY AREA

Searles Valley is part of a chain of lakes that covered eastern California periodically during the late Pleistocene (Figure 2). Between roughly 30,000 and 15,000 yr B.P. (Bischoff and Cummings, 2001) and perhaps briefly again about 10,500 ^{14}C yr B.P. (Smith et al., 1983; Smith and Bischoff, 1993), Searles Lake reached its sill at times that roughly correspond with Heinrich Events in the North Atlantic (Phillips et al., 1996).

Eastern California is the only region in North America that has been surveyed systematically for constructed geoglyphs (von Werlhof, 1989). These surveys, as well as the occurrence of a large beach ridge that separates a small embayment from Searles Lake (and Valley) as a whole (Figure 3), are the reason that we selected the Christmas Canyon part of Searles Lake for our study. The relative isolation of Christmas Canyon had two consequences. First, it contributed to the preservation of an intact late Pleistocene and early Holocene landscape; one that experienced relatively lower rates of erosion and degradation compared with the California Desert as a whole. Second, and most relevant to our study, this ancient landscape contains dense, very well-preserved archaeological sites.

Three general types of constructed rock features are found in the Christmas Canyon area of Searles Valley (Figure 4): rings, cairns, and alignments, or motifs created by the alignment of boulders into a design of some kind. The rock rings occur on a beach ridge of Pleistocene Lake Searles, last desiccated approximately 10,500 ^{14}C yr B.P (Smith, 1979). The two sampled rock rings occur in association with a host of surface lithic-scatter sites and rest close to a mud playa formed behind a large beach ridge, an intermittent marshy environment containing abundant and diverse resources amenable to human exploitation.

We sampled all three types of rock features. Rock rings RR16 and RR17 (Figure 3) each contain over a dozen cobbles composed of basalt, rhyolite, and chert. We initially suspected a cultural origin for these features because of the presence of clasts standing upright. Closer examination revealed clasts with rock-coating catenas that do not occur naturally. Specifically, boulders were thrust into the soil deep enough for pedogenic carbonate to form over what was formerly exposed black surface varnish.

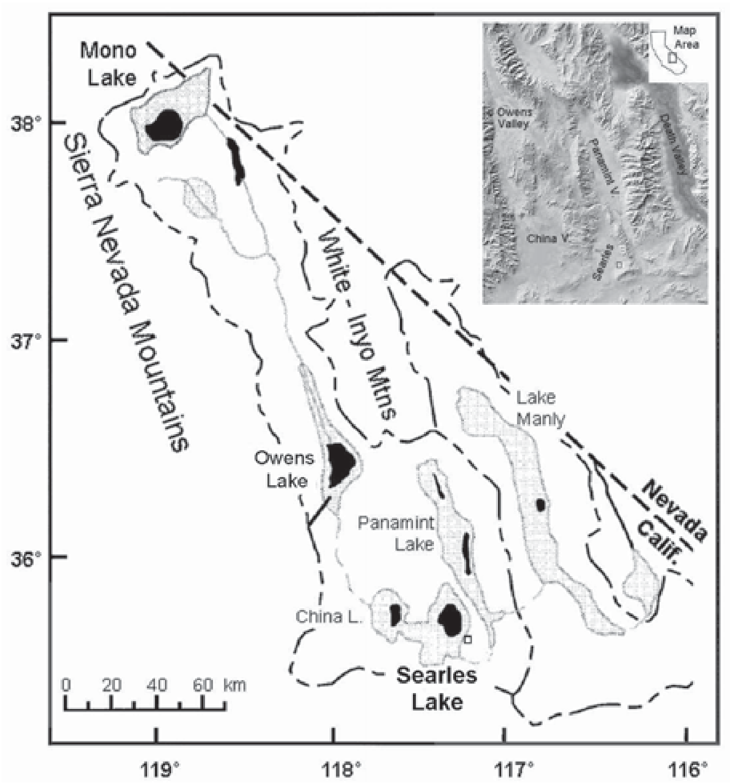

Figure 2. The connected series of closed-basin lakes in the Owens River system during wetter Pleistocene phases that terminated at Death Valley about 140,000 yr B.P. and at Panamint Valley ~30,000–15,000 yr B.P. The timing of these lakes corresponds with glacial advances in the Sierra Nevada (Bischoff and Cummings, 2001) during Heinrich events (Phillips et al., 1996). The small box on the southeast side of Searles Valley indicates the location of the Christmas Canyon field site.

Above the high shoreline of Searles Lake on an alluvial terrace, we sampled a geoglyph about 2 m across with a cruciform shape (Figure 4C). Composed mostly of rhyolite clasts, a few of the meter-sized boulders had inverted rock-coating catenas. Formerly black surface varnish was thrust into the ground deep enough to reach a depth of carbonate precipitation, resulting in the microstratigraphic overprint of pedogenic carbonate on black surface varnish.

Cairns represent a third type of rock feature found in the area, and they are commonly in desert regions (Evenari et al., 1971; Anati, 2001). The cairn chosen for study contains rocks that were flipped over, allowing study of (a) black surface varnish reformed on the orange varnish normally found on the underside of desert pavement clasts, and (b) pedogenic carbonate formed on top of the black surface varnish. This rock cairn occurs close to a locality known as Christmas Ridge, where a projectile-point base was found embedded in desert pavement (Figure 3).

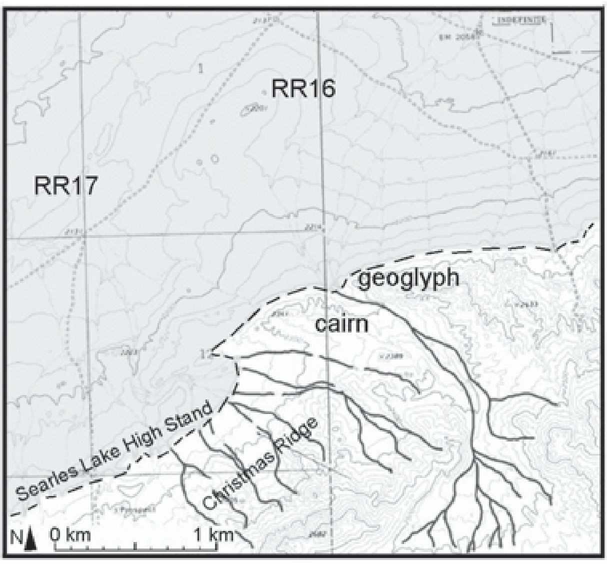

Figure 3. Map of the Christmas Canyon study area (see box in Figure 2) identifying the locations of study sites: rock alignment sites RR16 and RR17; geoglyph; and the cairn site. Shading and the dashed line indicate the area that would have been underwater during the terminal Pleistocene high stand of Searles Lake.

METHODS

We collected entire boulders where field evidence indicated alteration in undisturbed rock-coating catenas (Figure 5A). In particular, we looked for boulders where white pedogenic carbonate coats have formed over black (formerly surface) varnish. Some of these boulders had been rotated only 90 degrees, generating a series of new rock-coating stratigraphies. Other boulders had been flipped over entirely (Figure 5B). Three of these new microstratigraphies (identified by the bold text in Figure 5C) yielded samples with chronometric potential. We have a cautionary note in sampling; boulder manipulation during geoglyph manufacturing can generate spalls in rock fissures, so it is important to distinguish rock-coating catenas formed in fissures from those formed around a boulder (Figure 1).

Pedogenic Carbonate Inversion

An important methodological concern in the radiocarbon dating of carbonate is the potential for old carbonate to dissolve and reprecipitate in the dated material. Paleozoic limestone exists in upstream drainages. In addition, tufa, with a sample radiocarbon age of 20,820 ± 130 yr B.P. (Beta 163526), occurs as beach-ridge cobbles scattered around the rock-ring sites (Figure 3).

Our first methodological task involved assessing whether or not old carbonate contaminated the age of pedogenic carbonate on the boulders we studied. In the

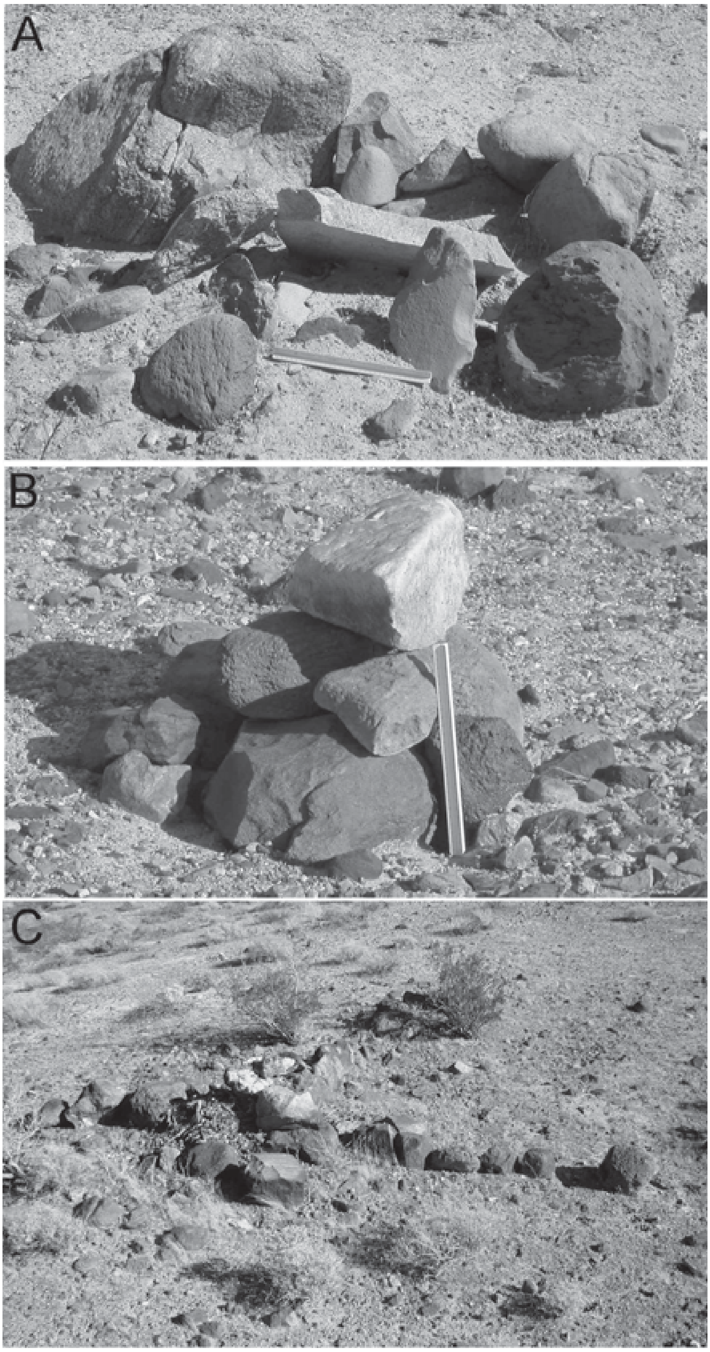

Figure 4. Analyzed constructed rock features include (A) rock ring RR17, (B) a cairn, and (C) a geoglyph. Foot ruler provides scale in A and B, and 0.7-m-tall *Larrea tridentata* scrub provides scale in (C).

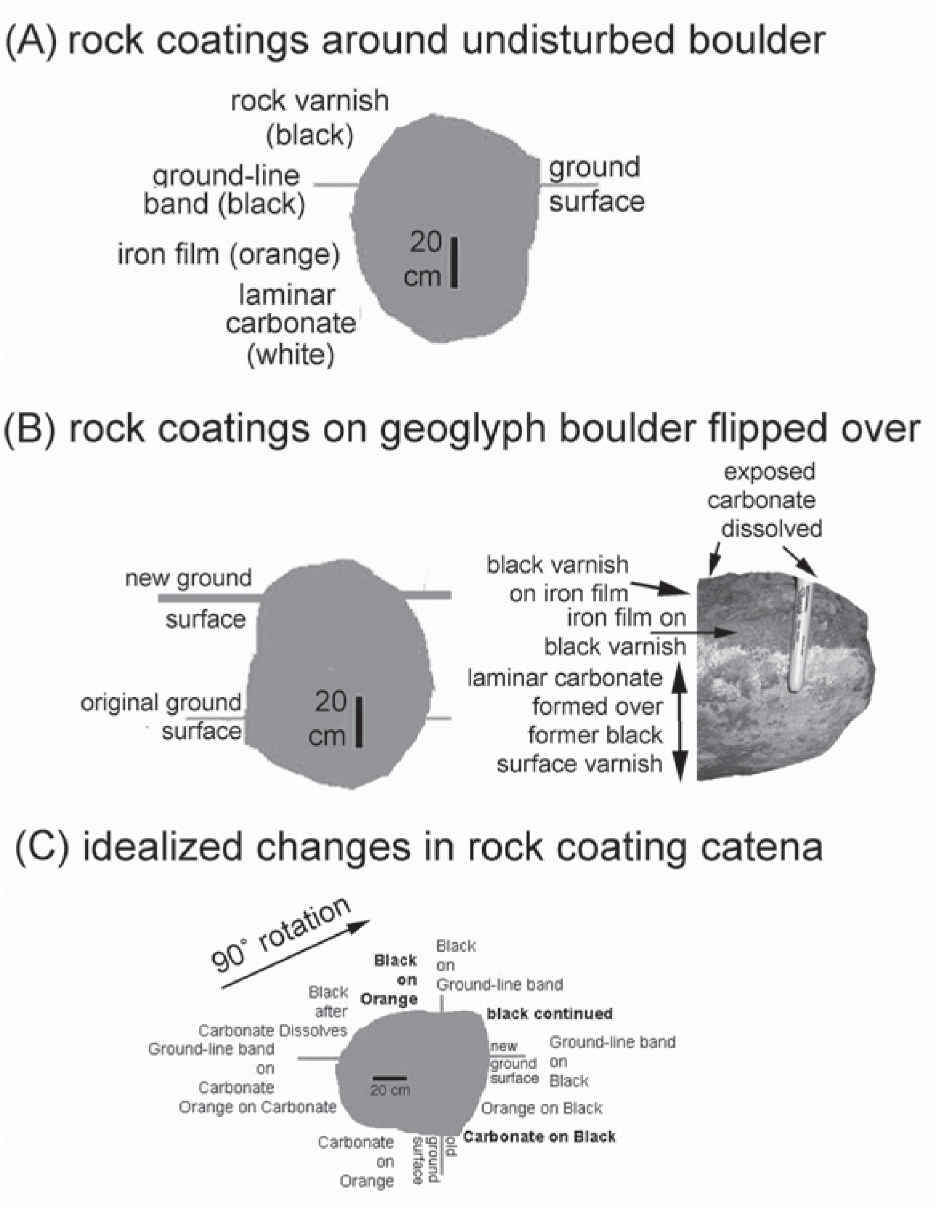

Figure 5. Boulder rotation superimposes different types of rock coatings on the older catena. (A) Idealized catena of rock coatings found on a boulder in a desert pavement. (B) Example of superimposition of rock coatings on a boulder flipped over in making the cruciform geoglyph. (C) An idealized sequence of changes that would happen if a boulder were rotated 90 degrees. The bolded font in (C) highlights the three microstratigraphic sequences explored in this article: microlaminations of black varnish formed over what was once orange-colored iron film; black varnish that shows a continual record of microlaminations because it has remained in a subaerial position after the disturbance; and pedogenic carbonate that forms over what was once black surface varnish.

laboratory, we washed rocks with distilled water and used a soft-bristled brush to remove loose surface materials. Tungsten carbide dental tools then scraped off test samples of soft, loosely cemented carbonate that would represent the outermost deposit. This loosely cemented carbonate yielded two modern ages on two different inverted boulders (Beta 164601; Beta 164603). Thus, the most recent precipitates do not show evidence of contamination from ancient carbonate in the area.

Having no evidence, for now, of contamination by dissolved and reprecipitated ancient limestone and tufa does not eliminate known uncertainties in the radiocarbon dates of carbonate (Chen and Polach, 1986; Stadelman, 1994). However, radiocarbon dating of pedogenic carbonate generally carries the assumption that pedogenic radiocarbon can still be used as a chronometric tool with success if one is cautious (Amundson et al., 1994; Wang et al., 1994; Deutz et al., 2001). Wang et al. (1996) concluded that ^{14}C dating of “pedogenic carbonate laminations is a useful additional tool in Quaternary studies” (p. 379). We, therefore, focused on laminated carbonate.

The laminated form of pedogenic carbonate around the boulders sampled in the study experienced partial replacement of the calcite with silica—seen in electron microscope observations. The silica replacement gives the carbonate a more brittle texture, and mechanical removal results in the popping off of small “shells.” After washing loose sediment with distilled water and scraping the outer loose pedogenic carbonate deposits, we removed the laminar carbonate. We made every attempt to collect the bottom-most laminar carbonate but only where the laminar carbonate could be seen forming over black varnish. Sample sizes were not sufficient for conventional ^{14}C, so we used AMS.

The key to our pedogenic-carbonate-inversion (PCI) dating strategy rests in collecting carbonate that definitively formed on what was once the exposed surface of the boulder; in this way, we know that carbonate formation started after human(s) rotated the rock and thrust it deep enough in the soil to accumulate pedogenic carbonate. Thus, we also took samples for electron microscope observations—to independently assess field and optical microscope observations that the pedogenic carbonate rests microstratigraphically on formerly black surface varnish. We used backscattered electron microscopy (BSE) and energy-dispersive (EDS) X-ray analysis (Dorn, 1995) to analyze these samples.

As a comparison with the rock ring ages, we also removed the innermost laminated carbonate from a chert flake buried at RR16 (Figure 3). The chert flake was found underneath a ring basalt boulder that was picked up to investigate whether the rotation had altered its rock-coating catena. Although the boulder position was not rotated enough to permit its use in this study, the chert tool was found under the boulder at a depth of 90 cm. We speculate that this depth was attained because of rock ring construction. After washing and removal of the loose pedogenic carbonate, laminar carbonate was removed from the bulb-of-percussion surface and measured for radiocarbon content by AMS.

Varnish Microlamination Method

The study of varnish microlaminations (VML; Dorn, 1990; Cremaschi, 1996), refined by extensive independent calibrations of layering patterns (Liu and Dorn, 1996; Liu et al., 2000; Liu, 2003), permits assignment of correlative surface ages into broad time classes that correspond with regional climatic events. A blind test administered by the editor of *Geomorphology* (Marston, 2003) ended with the following conclusion on the VML approach:

> This issue contains two articles that together constitute a blind test of the utility of rock varnish microstratigraphy as an indicator of the age of a Quaternary basalt flow in the Mohave Desert. This test should be of special interest to those who have followed the debate over whether varnish microstratigraphy provides a reliable dating tool, a debate that has reached disturbing levels of acrimony in the literature. Fred Phillips (New Mexico Tech) utilized cosmogenic 36Cl dating, and Liu (Lamont-Doherty Earth Observatory, Columbia University) utilized rock varnish microstratigraphy to obtain the ages of five different flows, two of which had been dated in previous work and three of which had never been dated. The manuscripts were submitted and reviewed with neither author aware of the results of the other. Once the manuscripts were revised and accepted, the results were shared so each author could compare and contrast results obtained by the two methods. In four of the five cases, dates obtained by the two methods were in close agreement. Independent dates obtained by Phillips and Liu on the Cima "I" flow did not agree as well, but this may be attributed to the two authors having sampled at slightly different sites, which may have in fact been from flows of contrasting age. Results of the blind test provide convincing evidence that varnish is a valid dating tool to estimate surface exposure ages microstratigraphy. (p. 197)

Most of the original calibration of VML research took place in the southwestern Great Basin, including a large number of calibration sites in and around our study area. Furthermore, the distinctive wet climatic events responsible for the discrete black layers in varnish produced glacial pulses in the nearby Sierra Nevada (Phillips et al., 1996). Although ongoing research is now attempting to identify discrete Holocene laminae (cf. Cremaschi, 1996) in our study area, at the present time, the calibration in the study area only discriminates Holocene from terminal Pleistocene (Liu et al., 2000) and older (Liu, 2003) ages.

We followed the methods used to develop Liu's calibration (Liu and Dorn, 1996; Liu et al., 2000; Liu, 2003), in terms of broad sampling parameters for a boulder and in terms of the types of millimeter-sized microbasins that are the focus of making ultra-thin sections. In brief, varnish analysis requires stable boulders from loci that address the question of interest; in this case, the loci must be related to alteration of boulder position. Then, the varnish should be collected from positions that were once well drained and not from positions close to a soil context or a ground-line band. The "best-looking" varnish should be avoided, as should varnish at locales where water collects on the cobbles, for water ponding generates local microenvironments that do not reflect the regional climatic signal. Positions close to deceased microcolonial fungi on varnish should also be avoided because of the local biogeochemical signal that they create. However, those now-buried lithobionts have potential for use in radiocarbon dating—if rates of carbon cycling (cf. Dorn, 1998, p. 316) can be resolved.

We applied the VML method in three contexts. First, we examined the lamination sequence underneath pedogenic carbonate (site RR17 in Figure 3) in the carbonate-on-black varnish context in Figure 5B. The hypothesis is that boulder rotation should "freeze" the varnish microlamination sequence, thus providing a maximum age for the rotation event. Second, we analyzed the lamination pattern sampled from the

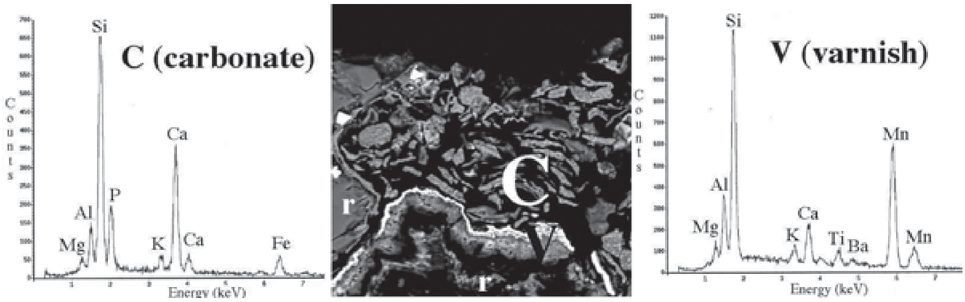

Figure 6. The BSE and EDS analyses confirm the field assessment that pedogenic carbon formed over what was once black surface varnish. In the central BSE view (scale 40 µm across), a defocused (~5 µm) EDS analysis reveals that the carbonate maintains a brecciated texture with a considerable silica component. Mn-rich varnish rests under the pedogenic carbonate and on top of the host rock.

black-on-orange context in Figure 5C of a rotated rock cairn boulder (Figure 4C). The hypothesis is that surface black varnish should start to form on the orange iron-film coating after boulder rotation. Third, as a point of comparison, we also analyzed the VML in the more traditional surface context (Liu et al., 2000; Liu, 2003)—in this case, the projectile-point fragment found in desert pavement a few meters from the rock cairn. This fragment is the base of a large stemmed point. Although the point base does not clearly correspond to any of the established projectile-point types for this region, it is most similar in size and morphology to examples of Western Stemmed Tradition points of early Holocene/terminal Pleistocene age (Willig and Aikens, 1988).

RESULTS

Pedogenic Carbonate Inversion

Electron microscope data confirmed field and optical microscope observations that pedogenic carbonate formed over what was once surface black varnish. Figure 6 illustrates the microstratigraphic context of PCI samples. After mechanical removal of the loosely cemented carbonate that generated modern radiocarbon ages (Beta 164601; Beta 164603), inner carbonate mechanically broke apart into shell-like fragments. EDS analyses (Figure 6C) show a substantial replacement of the calcite with silica in this inner carbonate. The iron spike may reflect the intercalation of rock coatings (Dorn, 1998) in that orange iron films can interdigitate with pedogenic carbonate (Villa et al., 1995). The EDS analysis of the varnish under the carbonate (V in Figure 6) shows peaks typical for clay minerals (Mg, Al, Si), manganese (Mn), and trace elements (K, Ca, Ti, and Ba).

The AMS ^{14}C age for the innermost, silica-enriched pedogenic carbonate of 7260 ± 40 yr B.P. (Beta 164602) is best interpreted as a minimum age for the formation of rock ring RR16. The outermost carbonate yields modern AMS ages (Beta 164601; Beta 164603); thus, at this point, we have not found evidence of contamination from

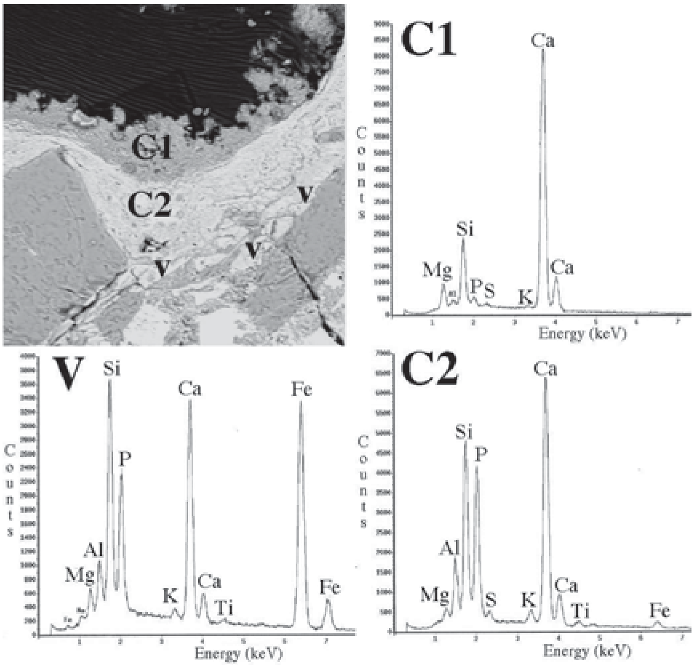

Figure 7A. Replicate samples from rock ring RR16 reveal the same microstratigraphy of pedogenic carbonate that grew on top of manganese-rich varnish. The only way to explain this microstratigraphy is to flip the boulder over and shove it into the ground. (A) The BSE image (scale 140 µm across) of the RR16 subsample with the ^{14}C age of 3860 ± 50 yr B.P. (Beta 168711) shows the two types of pedogenic carbonate. The uppermost layer (C1), yielding modern ^{14}C ages for scrapings from the top, contains less silica and iron than the inner pedogenic carbonate (C2). The inner layers' much lower porosity and iron combine to produce a brighter appearance in backscattered electrons. The varnish (V) is dominated by clays (Si, Al, Mg), phosphorus, iron, and the calcium spike likely comes from X-rays generated from superposed laminar carbonate.

older carbon sources. There are other reasons to interpret PCI ^{14}C as a minimum age for surface rock features: pedogenic carbonate can be in an open system providing a continual source of younger carbon (Stadelman, 1994). Because the mechanically removed sample represents "bulk" sampling of a carbonate deposit that accumulated sequentially over time, much of the bulk sample must postdate boulder inversion. Unfortunately, we do not have a way of estimating the offset in time between rock feature formation and the ^{14}C age because no other method has yet established an independent comparative age for an alignment.

Full stratigraphic contexts of unprocessed samples can be seen in the BSE images in Figure 7A and 7B from rock-ring site RR16 (Figure 4A). Using a similar processing strategy in which we tried to collect the innermost pedogenic carbonate, we obtained two very different ^{14}C ages of 3860 ± 50 yr B.P. (Beta 168711) (Figure 7A) and 8440 ± 60 yr B.P. (Beta 168081) (Figure 7A) in subsamples of the

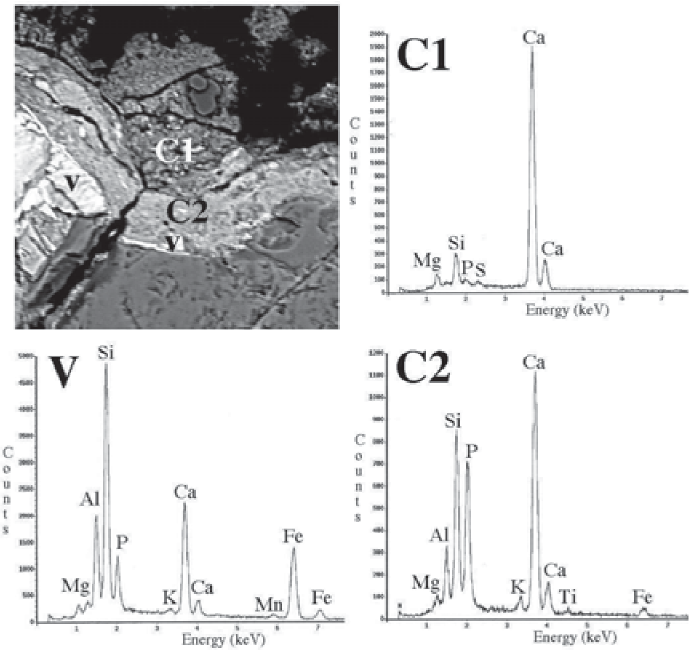

Figure 7B. The BSE image (scale 140 µm across) of the RR16 subsample with the ^{14}C age of 8440 ± 60 yr B.P. (Beta 168081) shows the two types of pedogenic carbonate. The uppermost layer (C1) contains less silica and less iron than the inner pedogenic carbonate (C2). The varnish (V) is dominated by clays, phosphorus, and iron, and the calcium spike derives from X-rays generated from the pedogenic carbonate.

same boulder. The carbonate displayed similar BSE textures and chemistry in both samples. The outermost poorly cemented carbonate had a minimal iron and silica signature (C1 in Figure 7A and 7B) with high porosity; the high porosity at the micrometer scale explains the darker BSE texture. The inner carbonate (C2 in Figure 7A and 7B) that was sampled for dating displayed higher concentrations of silica—where the silica replacement explains the shell-like texture in mechanically removed samples.

Field examination of an inverted boulder at site RR16 (Figure 3) exposed a chert flake coated with carbonate. After removal of the soft outer carbonate, the dense silica-enriched inner carbonate next to the bulb of percussion yielded a ^{14}C age of 5900 ± 50 yr B.P. (Beta 167811).

An inverted rhyolite boulder in the geoglyph (Figure 4C) showed field evidence of carbonate formation over black varnish. The BSE and EDS analyses provided confirmation of the anthropogenic inversion of pedogenic carbonate because humans are the only known agency that can flip a boulder over and place it upside down in a row where pedogenic carbon forms over what was once black surface varnish

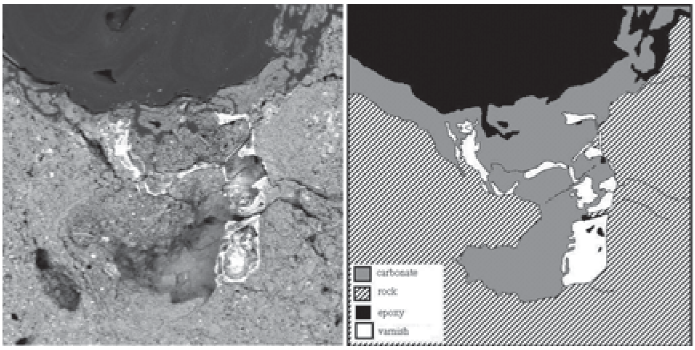

Figure 8. The BSE image (left) of a cruciform-like rock alignment sample (Figure 4C) and the corresponding map (right), based on EDS data, confirms the field identification of pedogenic carbonate over what was once surface varnish.

(Figure 8). The shell-like inner carbonate yielded an AMS ^{14}C age of 4110 ± 40 yr B.P. (Beta 168080). Again, we have no reason to interpret this age as anything other than a minimum limit for the manufacturing of the earth figure.

Varnish Microlaminations

The rock-ring RR17 (Figure 4A) boulder sampled for AMS ^{14}C dating of the pedogenic carbonate revealed a VML chronometry consistent with the ^{14}C age of 7260 ± 40 yr B.P. (Beta 164602). Figure 9 shows that the black surface varnish—underneath the pedogenic carbonate—experienced erosion because the black (Mn-rich) layers are truncated. Emplacement of the rotated boulder into the ground could have eroded the varnish. Then, pedogenic carbonate formed over the truncated surface. Using Liu's (2003) calibration shown in Figure 9, it appears as though boulder rotation took place sometime after 10,500 yr B.P.—the terminal Pleistocene wet phase in the region (Liu et al., 2000).

The cairn at the Christmas Ridge site included a boulder whose rotation placed orange iron film, formed underground in contact with the Av soil horizon, into an exposed surface position. Because the orange bottom coating has a similar appearance in optical thin section (and in chemistry) to the iron-rich layers in surface varnish, interpretation of the VML sequence must be based on the occurrence of black (Mn-rich) layers. Three different ultra-thin sections showed black layers on top of the orange coating (Figure 10A–C). In another cairn boulder, the construction process chipped black surface varnish—all before the boulder was placed upside down and pedogenic carbonate formed over the surface varnish (Figure 10D). Using Liu's calibration, the presence of the LU-2 terminal Pleistocene event (Liu et al., 2000) suggests that the cairn boulder was rotated sometime in the latest Pleistocene, before the 11,000 yr B.P. microlaminae and after the 14,000 yr B.P. microlaminae.

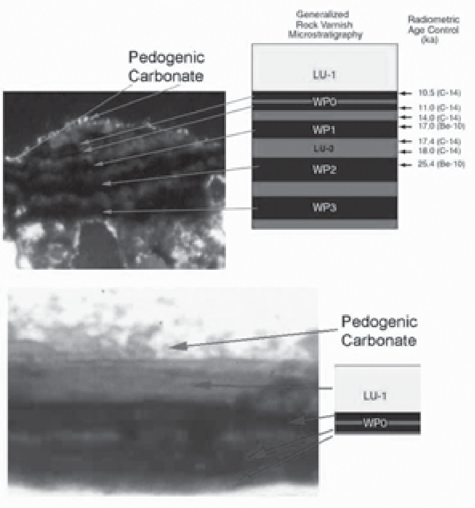

Figure 9. Ultra-thin sections of a boulder in the RR17 rock-ring sample where the very top of the colored section shows the pedogenic carbonate—as confirmed by an energy-dispersive X-ray signal of calcium. Black, formerly surface varnish occurs underneath the pedogenic carbonate. The microstratigraphy of the varnish is juxtaposed next to Liu's (2003) calibration. The uppermost LU-1 layer, even though it is truncated, formed during the Holocene. The pedogenic carbonate was originally thicker, but much of it was lost during sectioning. The varnish thickness is about 80 µm and 40 µm from top to bottom in the upper and lower sections.

The base of a projectile point, found in the desert pavement near the rock cairn, also hosts thin rock varnish. Sectioning was particularly difficult because the varnish rested on the very hard and unweathered siliceous surface. The sample-preparation process regularly generates "failures," where the last stages of thinning a section enough to see the optical VML removes the entire varnish. In this case, the last stages in polishing generated an unusually high number of failures. Only 2 of 14 microbasins survived the last thinning step, and in these microbasins, only a portion of the top LU-1 layer survived, as seen in Figure 11; the rest of the Holocene LU-1 layer was mechanically abraded away in the attempt to resolve discrete black layers. Fortunately, the chronometrically distinct WP0 layer rests at the bottom of the sequence—a 10,500 yr B.P. terminal Pleistocene layer (Liu et al., 2000). Thus, the formation of the point's varnish appears to have occurred between the 11,000 and 10,500 yr B.P. terminal Pleistocene black layers.

DISCUSSION

Stressing Uncertainties

The major contribution of this article rests in providing a new strategy for analyzing constructed rock features in deserts. By learning how to read natural rock-coating cate-

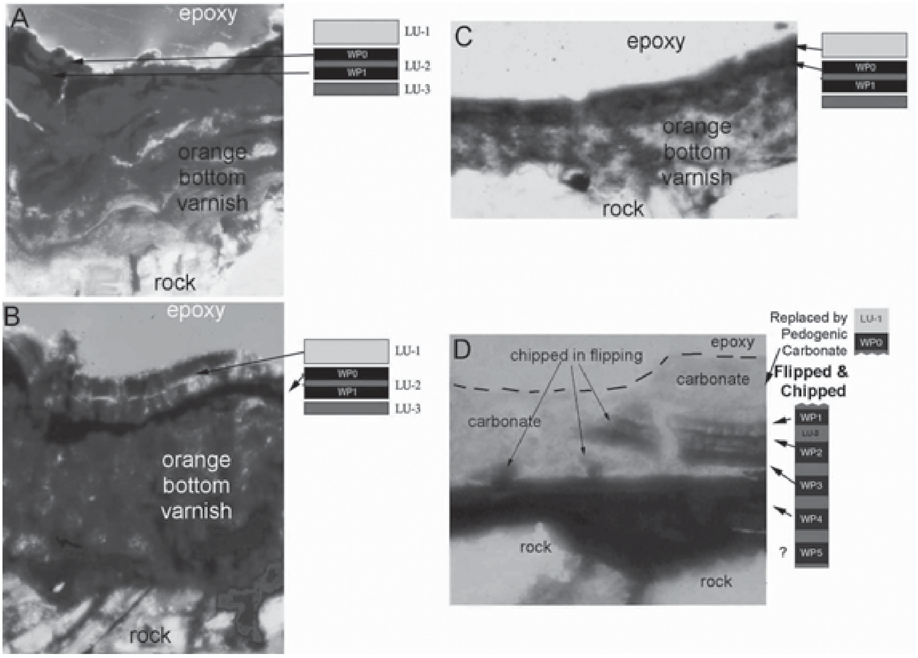

Figure 10. Flipping a boulder in the cairn at the Christmas Ridge site altered the stratigraphy of rock coatings. In images A–C, black surface varnish formed on top of what was once the orange iron film that originally formed in the subsurface. Microlamination sequences from three separate microbasins yield a consistent signal that the boulder was flipped sometime before 11,000 yr B.P. using Liu's (2003) calibration. In image D, the original black surface varnish was chipped in the flipping process, and then pedogenic carbonate formed over fractured varnish—freezing the microstratigraphy sometime about 11,000 yr B.P. using Liu's (2003) calibration. The images display varnish thickness of ~25 µm, 40 µm, 40 µm, and 100 µm, respectively.

nas (e.g., Figure 1) and how we can alter rock-coating sequences (e.g., Figure 5), we can open up a series of new chronometric approaches. In this section, we identify three overarching uncertainties associated with the two chronometric methods tried here.

First, all of our pedogenic carbonate ^{14}C ages and varnish microlamination calibrated ages must be viewed as experimental because we have no independent data on the accuracy of the ages provided here. We are not advocating that the numerical ages are accurate or precise, but only that the general timing and order of magnitude of ages converge to indicate early Holocene or terminal Pleistocene occupants could have constructed these rock features. No other chronometric methods have been able to constrain the ages of rock rings, cairns, or rock alignments. Thus, we are unable to conduct blind tests against methods with independent assumptions similar to those carried out elsewhere (Loendorf, 1991; Herscher, 2000; Marston, 2003).

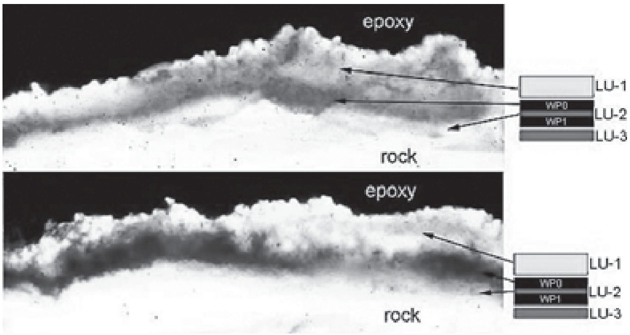

Figure 11. Two microbasins of rock varnish formed on top of a Paleo-Indian projectile-point base reveal a sequence of microlaminations consistent with an age older than 10,500 yr B.P. but younger than 11,000 yr B.P. using Liu's (2003) calibration. Varnish thickness is about 20 µm in each microbasin.

A cautionary example on the need for tests using independent methods with different assumptions is the ^{14}C dating of organic matter associated with petroglyphs. The method was subjected to a blind test (Bednarik, 1995) when Dorn (1996a, 1996b) and Watchman (1996, 1997) independently found organics of vastly different ages in the same dated samples. Dorn rejected the method after that discovery (Dorn, 1996a, 1996b); but Watchman continued to apply the technique (Huyge et al., 2001), explaining, "I am currently testing the reliability of the AMS ^{14}C dating method on rock varnishes at selected sites" (Watchman, 2002, p. 11). The decision to reject or retain the method was not settled by a blind test of two investigators using a similar strategy and finding remarkably similar (Bednarik, 1995) and completely unexpected (Clottes, 1995) mid-Holocene ages. Instead, it took the independent method of archaeological excavation (Herscher, 2000) to demonstrate that petroglyph radiocarbon results can be grossly misleading.

Blind testing against an independent method has not occurred in this case; but we view such testing as a critical next step, and thus we offer a few ideas. One comparative method might be OSL dating (Dragovich and Susino, 2001; Olley et al., 2004) on quartz fragments trapped between black varnish and the encapsulating pedogenic carbonate. Another approach might be ^{14}C dating of the microcolonial fungi that grew on top of the varnish before it was entombed by the pedogenic carbonate. However, both of these comparative methods would likely provide maximum ages for the rock alignment. There could be concerns about "inherited" OSL signals, and the fungi that rest on top of present-day varnish can grow so slowly that it yields nonmodern ^{14}C ages (Staley et al., 1991)—perhaps from "refractory" organics observed by Staley and others (1991). Still, even comparisons of maximum-limiting ^{14}C ages on buried lithobionts and OSL ages on trapped quartz would provide useful independent upper constraints.

A second major concern is the divergent range of ^{14}C ages for rock ring RR16, 3860 ± 50 yr B.P. and 8440 ± 60 yr B.P. We have no reason to doubt that each age provides a minimum limit; but it is unclear why the two ages differ. Both samples were processed in an equivalent fashion. Both samples had similar microstratigraphic textures, as revealed by BSE and EDS analyses. Perhaps an earlier event caused the pedogenic carbonate to flake off the boulder and the 3860 ± 50 yr B.P. sample formed after this event. Perhaps localized micron-scale solution and reprecipitation occurred in the younger sample. Alternatively, some of the modern powdery carbonate may have washed into a crevice in the sampled innermost carbonate, or there might be another explanation. Even though both minimum ages provide the first insight into the potential antiquity of rock rings in southwestern North America, the obvious implication is that a single radiocarbon age can provide grossly misleading interpretations. The rock ring RR16 is likely at least early Holocene in age; yet a single 3860 ± 50 yr B.P. age could have led others to associate the rock-ring feature with mid-Holocene occupations.

A third uncertainty that the reader must keep in mind is the relatively few ultrathin sections made for VML dating. An advantage of the VML method is that many sections can potentially be generated, each yielding its own calibrated microstratigraphic age; but we experienced a large number of failures where the last abrasion needed to see through the varnish eroded away the entire section. A next step in the research process would be to set aside the months required to make dozens of microstratigraphic sections from several altered boulders—to get a handle on the precision of the VML method in understanding rock features. Such a study, however, is beyond the scope of this work that is designed to accomplish something very different: to explain the general strategy of dating rock alignments by the altered stratigraphy of rock-coating catenas.

Derived Empirical Ages

The empirical ages obtained with these experimental techniques are unremarkable in the sense that they pertain to archaeological periods that are well represented in the regional archaeological record. Indeed, several decades ago, archaeologists speculated that rock alignments from this area might date to Paleo-Indian times (Davis and Winslow, 1965). Our chronometric minimum age of 4110 ± 40 yr B.P. obtained on a rock alignment is substantially short of this mark, but it provides the first numerical age supporting the estimate of substantial time depth for the rock alignment tradition in the southwestern Great Basin. Similarly, while our terminal Pleistocene ages on a cairn are unverified by independent techniques, additional evidence from the immediate area in the form of a diagnostic projectile-point base demonstrates occupation and use extending back to Paleo-Indian times. Perhaps more importantly, ongoing surface surveys of this area reveal a notable absence of evidence for any substantial late Holocene use of the sub-basin containing our study sites. Although the results we have obtained fit well with the local archaeological record, as it is currently understood, the strategy of obtaining age insight from rock alignments also has the potential to provide age estimates in areas with a complete lack of chronometry.

CONCLUSIONS

Prehistoric constructions of rock rings, rock cairns, and alignments have long been ignored in substantive archaeological interpretations of regions outside of Nasca, Peru. The inability to place these surface features in a chronometric context has left them with "... an inert quality, a certain spinelessness when unaccompanied by a more or less definite chronological background" (Tozzer, 1926, p. 283).

We present a general strategy by which desert rock alignments can be dated. Human movement of boulders alters the catenas of rock coatings, resulting in a sequence of new rock coatings formed on top of the natural catena. We used three of these anthropogenically caused superpositions to provide the first chronometric insights into rock rings, rock cairns, and a rock alignment motif in the western Great Basin of North America.

Anthropogenic boulder rotation resulted in the formation of (a) ^{14}C-datable pedogenic carbonate over a type of rock varnish that forms in a surface environment, (b) datable varnish microlaminations in what was once surface rock varnish covered by pedogenic carbonate, and (c) datable varnish microlaminations covering what was once a subsurface orange iron film. Results from the experimental application of these methods suggests that (1) rock rings in the Christmas-Canyon area of the Searles Valley in eastern California are at least early Holocene in age, (2) a rock alignment is at least mid-Holocene in age, and (3) a rock cairn is perhaps terminal Pleistocene in age.

Microstratigraphic layers in desert rock coatings reflect regional changes in the geographic distribution of these coatings, thus permitting interpretation of long-term records of environmental changes in deserts (Cremaschi, 1996; Russ et al., 2000; Lee and Bland, 2003; Liu, 2003). Similar geographic variability in rock coatings occurs outside of deserts, for example, in a climatic transect from the Khumbu of Nepal to the rainshadow in the Tibetan Plateau (Dorn, 1998). Although there has been an increase in the understanding of rock coatings in humid areas (Reams, 1990; Darmody et al., 2002; Dixon et al., 2002; Arocena and Hall, 2003), detailed studies establishing contemporary relationships (Dorn, 1990) are largely lacking in wetter regions (Krumbein and Urzi, 1993). We hope that this study also stimulates research on the relationship between catena changes in humid-area rock coatings and the manner in which prehistoric peoples altered stone.

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