Holocene rock varnish microstratigraphy and its chronometric application in the drylands of western USA

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Abstract

Analyses of hundreds of rock varnish samples from latest Pleistocene and Holocene geomorphic features in the drylands of western USA reveal a regionally replicable Holocene microlamination sequence. This sequence consists of 12 approximately evenly spaced weak dark layers intercalated with 13 orange/yellow layers. Preliminary radiometric age calibration indicates that six dark layers in the upper portion of the sequence were deposited during the last 6000 yr, diagnostic of the Little Ice Age and late Holocene wet events; five dark layers in the lower portion of the sequence were deposited after the termination of the Pleistocene but slightly before 7000 YBP, indicative of the early Holocene wet events; and one dark layer in the middle portion of the sequence was deposited around 6500 YBP, suggestive of the middle Holocene wet phase. Our age calibration further indicates that the Holocene wet events represented by the dark layers largely correlate in time with the millennial-scale Holocene cooling events in the North Atlantic region. This radiometrically calibrated and climatically correlated Holocene microlamination sequence was then used as a unique correlative dating tool to determine surface exposure ages of geomorphic and geoarchaeological features in western USA deserts. The varnish microlamination (VML) dating of debris flow fan deposits in Death Valley, California, yields minimum ages of 12,500, 11,100, 10,300, 9,400, and 2,800 YBP for six debris flow fan building events, suggesting that such events were more likely to have occurred during relatively wet periods of the Holocene. The VML dating of a prehistoric grinding stone from Chili of northern New Mexico yields a minimum age of 9,000–11,000 YBP for the abandonment of this occupation site by the Anasazi Indians. The VML dating of a prehistoric flaked stone (a primary core) from Ocotillo, southern California, yields a minimum age of 12,500 YBP for the flaking of this stone artifact, suggesting at least a Paleo-Indian human occupation at Ocotillo during the terminal Pleistocene. These results indicate that, when properly applied, the VML dating technique has the great potential to yield numerical age assignments for surface stone tools, petroglyphs, and geoglyphs of prehistoric age in the drylands of western USA.

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1. Introduction

Rock varnish is a dark coating on subaerially exposed rock surfaces. It is probably the world’s slowest accumulating sedimentary deposit, growing at rates of only a few to tens of microns per a thousand years (Liu and Broecker, 2000). Its thickness ranges from <5 μm to 600 μm, with a
typical thickness of $\sim 100 \mu m$. Although found in all terrestrial environments, rock varnish is best developed and preserved in arid to semiarid deserts of the world. It is composed of about 30% Mn and Fe oxides, up to 70% clay minerals, and over a dozen trace and rare earth elements (Engel and Sharp, 1958; Potter and Rossman, 1977, 1979). The building blocks of rock varnish are largely blown in as airborne dust (Fleisher et al., 1999; Moore et al., 2001; Thiagarajan and Lee, 2004).

Microlaminations in rock varnish were first reported by Perry and Adams (1978), who recognized their potential as a paleoenvironmental indicator in drylands. Microlaminitations can be observed in ultrathin sections (5–10 $\mu m$ thick) with a normal polarizing microscope (Fig. 1). Electron microprobe chemical mapping (Hooke et al., 1969; Fleisher et al., 1999; Broecker and Liu, 2001) reveals that dark layers in varnish ultrathin sections are rich in Mn and Ba, but poor in Si and Al; while orange and yellow layers are poor in Mn and Ba, but rich in Si and Al (Fig. 1). These two types of layers are intercalated to form a distinct microstratigraphy in varnish.

A growing body of evidence indicates that varnish microstratigraphy carries a climate record (Dorn, 1984, 1990; Cremaschi, 1996; Liu and Dorn, 1996; Liu et al., 2000; Broecker and Liu, 2001; Lee and Bland, 2003). In the Great Basin of western USA, Mn-poor yellow layers (usually containing 5–15% MnO) formed during dry

![Fig. 1. Electron microprobe element maps (128×128 $\mu m$) of rock varnish from Death Valley, California. The inset image at lower right is an optical microstratigraphy seen in varnish ultrathin section under a polarized light microscope. As seen from the probe maps, silica (Si), aluminum (Al), magnesium (Mg), and potassium (K) achieve their highest concentrations in the yellow layer at the top of the varnish microstratigraphy (interpreted to represent the Holocene; Liu, 2003). In contrast, manganese (Mn), barium (Ba), calcium (Ca), and phosphorus (P) achieve their highest concentrations in the dark layers (interpreted to represent the last glacial time; Liu, 2003). Iron (Fe) shows the smallest glacial to interglacial change in concentration. With some exceptions, sulphur (S) is not generally associated with Ba in varnish microlaminae during both glacial and interglacial time. The line profile of Ba was taken along a vertical traverse and the probe-mapped portion of the varnish microstratigraphy is marked by a square. This varnish contains a layering sequence of LU-1/LU-2/LU-3/LU-4 (WP6), suggesting a minimum varnish-based age estimate of 60,000 YBP (see Liu, 2003, for more discussion on layering pattern interpretation of rock varnish).]
periods of the Holocene and the last interglacial, while Mn-rich black layers (usually containing 25–45% MnO) were deposited during wet periods of the last glacial time; Mn-intermediate orange layers (usually containing 15–25% MnO) formed during periods of climatic transition between extremely dry and extremely wet condition (Broecker and Liu, 2001). Furthermore, the glacial-age black layers in varnish microstratigraphy appear to correlate in time with the cold episodes of the Younger Dryas and Heinrich events (Bond et al., 1993; Broecker, 1994) in the North Atlantic region (Liu and Dom, 1996; Liu et al., 2000; Liu, 2003).

Varnish microstratigraphy as a correlative dating technique (cf. terminology in Colman et al., 1987) is relatively new and different in principle and independent of both cation-ratio and AMS 14C methods (Dorn, 1983; Dorn et al., 1989). It was first used by Dorn (1988) to study the chronostratigraphy of alluvial fan deposits in Death Valley, California. Subsequent studies by others (Liu, 1994, 2003; Liu and Dorn, 1996) have greatly improved the usefulness of the technique. The basic assumption in this dating approach is that the formation of varnish microstratigraphy is largely influenced by regional climatic variations. Since climatic signals recorded in varnish have been proven to be regionally contemporaneous (Liu and Dorn, 1996; Liu et al., 2000), varnish microstratigraphy has the potential to be a tephrachronology-like dating tool. Recently, a rigorous blind test of this method was conducted on late Quaternary lava flows in the Mojave Desert, California (Liu, 2003; Phillips, 2003). The test results demonstrate that varnish microstratigraphy is a valid dating tool to provide surface exposure age for late Pleistocene surficial geomorphic features in the Great Basin of western USA (Marston, 2003).

The purpose of this paper is to extend the utility of the varnish microstratigraphy technique to surficial geomorphic and geoarchaeological features of the Holocene. For this purpose, we need to (i) systematically establish the Holocene varnish microstratigraphy for the Great Basin of western USA; (ii) radiometrically calibrate microlaminations in the varnish microstratigraphy; and (iii) demonstrate the potential use of this dating technique for determining surface exposure ages for various geomorphic and geoarchaeological features in the drylands of western USA.

2. Study region and methods

The Great Basin and its vicinity of western USA have been chosen as our study region for several reasons (Fig. 2). First, previous studies (Liu, 1994, 2003; Liu and Dorn, 1996) have established and radiometrically calibrated the late Pleistocene varnish microstratigraphy for this region, providing a temporal framework for further studying of the Holocene varnish microstratigraphy. Second, fine-grained (<0.1 μm in particle size) and fast-growing (10–20 μm/ka) rock varnish of latest Pleistocene to late Holocene age is well developed in the study region, facilitating generalization of high resolution Holocene varnish microstratigraphy. Third, the study region also hosts numerous latest Pleistocene and Holocene geomorphic features that have been dated by radiometric methods (Table 1), thus providing opportunities for radiometric calibration of the Holocene varnish microstratigraphy.

In order to establish a complete Holocene varnish microstratigraphy for the study region, varnish samples were intentionally collected from well-dated geomorphic features of latest Pleistocene age (Fig. 2; Table 1). These features include the highstand shorelines of Summer Lake (∼18 ka; see Fig. 3F of this study; Freidel, 1993), Bonneville Lake (∼14.4 14C ka; Cerling and Craig, 1994), Lahontan Lake (∼13.6 14C ka; Benson et al., 1995), Searles Lake (∼14 14C ka; Benson et al., 1990), Silver Lake (10.5–15 14C ka; Wells et al., 1987); the lowstand shorelines of Panamint Lake (∼15 14C ka; Jayko et al., 2001); and the Owens River Dry Falls in Owens Valley (∼15.9 3He ka; Cerling, 1990). For some localities in central Arizona (i.e., McDowell Mountains) and southern California (i.e., Blythe) where such well-dated geomorphic features do not exist, samples were collected from alluvial fan surfaces of latest Pleistocene age based on field observation and judgment (Fig. 2; Table 1).

To radiometrically calibrate the Holocene varnish microstratigraphy, samples were collected from well-dated geomorphic features of Holocene age in the study region (Fig. 2; Table 2). These features include 14C-dated alluvial fan surfaces in Las Vegas Valley of southern Nevada (∼9.9 14C ka; Bell et al., 1998a), Fish Lake Valley of southern Nevada (0.5–6.5 14C ka; Reheis et al., 1993, 1995), Silurian Valley of southern California (∼1.8 14C ka; Anderson and Wells, 2003), Ajo Mountains of southern Arizona (∼2.5 14C ka; Pohl, 1995), cosmogenic 3He-dated debris flow boulders in the Grand Canyon of northern Arizona (∼1.5 ka; Cerling, University of Utah, personal communication, 1997), and cosmogenic 36Cl-dated Carrizoza lava flows (∼5.2 ka; Dunbar, 2002) and 14C-dated McCartys lava flows (∼3.0 14C ka; Laughlin et al., 1994) in central New Mexico.

To demonstrate the potential use of the varnish microstratigraphy method as a unique geomorphic and geoarchaeological dating tool in the drylands of western USA, varnish samples were also collected from surfaces of varying age on a debris flow fan in Death Valley, a grinding stone (or metate) near Chili in northern New
Mexico, and a stone artifact (or a primary core) near Ocotillo in southern California (Fig. 2; Table 1).

A key to this dating technique is an innovative method of making ultrathin sections of rock varnish (Liu, 1994; Liu and Dorn, 1996), which reduces failure rates from 80% to <5% and permits rapid preparation and hence intercomparison of many sections. The conventional way of making varnish thin sections cannot be employed because the resulting thin sections are too thick (25–30 μm) and do not reveal the microstratigraphy, which is opaque in normal geological thin sections. Ultrathin sections (5–10 μm thick), in contrast, permit identification and analysis of late Pleistocene varnish microstratigraphy (Fig. 1). Unlike pre-Holocene varnish microstratigraphy, however, ultrathin sections need to be made slightly thicker (10–15 μm) in order to see Holocene varnish microstratigraphy. Otherwise, the entire Holocene microstratigraphy turns into a single surface yellow layer (see the inset image of optical varnish microstratigraphy in Fig. 1).

Varnish ultrathin sections were then photographed on Kodachrome™ ASA 64 film using a Leica DMLB light microscope equipped with a Leica MPS 60 Photoautomat system. Polarized light was utilized to increase slide contrast. The use of a 10× eyepiece in combination with a 40× objective lens yields good quality color slides with 400× magnification. Kodak Royal Gold™ ASA 100 color print film was used to make prints of the slides on a slide duplicator. Both slide and color print films were commercially developed after exposure. Color slides and prints thus obtained provide high resolution (~1 μm) images of optical varnish microstratigraphy for layering pattern analysis.

Varnish ultrathin sections that contain clearly defined microstratigraphies were selected for further electron microprobe analysis. X-ray elemental mapping and line profiling were obtained on a fully automated, five-spectrometer CAMECA SX100 electron probe, with the use of the quantitative mode of wavelength dispersive X-ray spectrometry (WDS). Probe mapping provides high-

Fig. 2. Location map showing rock varnish sampling sites in the drylands of western USA. Abbreviations used are: Death Valley (DV), Owens Valley (OV), Panamint Valley (PV), Searles Lake (SL), Silver Lake and Silurian Valley (SV).
resolution (∼2 μm) images of chemical varnish microestratigraphy. Using a combination of both optical and chemical microstratigraphy allows detailed detection of Mn, Ba, and other elemental fluctuations in varnish.

In this study, we collected 138 varnish samples from 20 different localities that cover most parts of the Great Basin and its vicinity in western USA drylands. A total of 414 ultrathin sections were made, and 1078 spot chemical measurements were obtained with the electron microprobe along 25 individual line profiles. These chemical data, together with 754 high resolution (∼1 μm) optical images of varnish microstratigraphy, form the database used to generalize and correlate varnish layering sequences.

3. Results

3.1. Holocene varnish microstratigraphy

By carefully selecting fine-grained (<0.1 μm in particle size) and fast-growing (10–20 μm/ka) varnish and by making slightly thicker (10–15 μm) varnish ultrathin sections, we were able to detect and assess relatively weak signals of Holocene wet phases in western USA drylands. For instance, a fast-growing varnish of Holocene age from the ∼16,800 YBP highstand shorelines of Searles Lake in the Mojave Desert (Table 1) displays 11 approximately evenly spaced weak black layers (Fig. 3A). Similar layering sequences were observed in varnish samples from the latest Pleistocene highstand/lowstand shorelines of Summer Lake (OR), Lahontan Lake (NV), and Panamint Lake (CA) and from the Owens River Dry Falls (CA) in the study region (Fig. 3B, D–F). One varnish sample from an alluvial fan surface of latest Pleistocene age flanking the McDowell Mountains, Arizona, displays the most complete Holocene layering sequence (Fig. 3C).

Based on examination of hundreds of varnish microstratigraphies from the study region, we established a generalized Holocene layering sequence in varnish (Fig. 4). This sequence contains 12 approximately evenly spaced Mn- and Ba-rich weak black layers intercalated with 13 Mn- and Ba-poor orange/yellow layers. Six of these black layers, here designated as WH1 to WH6 (WH stands for “wet event in Holocene”), occur in the upper portion of the sequence, likely indicative of the Little Ice Age and late Holocene wet phases in the study region. Five of these black layers, WH8 to WH12, appear in the lower portion of the sequence, probably indicative of early Holocene wet phases. One relatively weak dark layer, WH7, is roughly located in the middle of the sequence, likely indicative of a middle Holocene weak wet phase. Other orange/yellow layers in the sequence appear to be diagnostic of Holocene dry phases in the study region. Table 3 presents a detailed description of characteristics of these black and orange/yellow layers in the Holocene varnish layering sequence.

Fig. 5 shows a comparison between optical and chemical microstratigraphies in varnish samples from

| Table 1 Rock varnish samples collected in the drylands of western USA |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Sampling site   | Geomorphic context | Age control (cal YBP) | Age type and source |
| Summer Lake, OR | Highstand shorelines of Summer Lake | ∼18,000 | VML; this study |
| Tabernacle Hills, UT | Highstand shorelines of Bonneville Lake | ∼17,800 | 14C; Cerling and Craig (1994) |
| Lahontan Lake, NV | Highstand shorelines of Lahontan Lake | ∼16,300 | 14C; Benson et al. (1990) |
| Las Vegas Valley, NV | Alluvial fan surfaces | 11,400–13,400 | 14C; Liu et al. (2000) |
| Fish Lake Valley, NV | Alluvial fan surfaces | 540–7450 | 14C; Reheis et al. (1993, 1995) |
| Owens Valley, CA | Owens Valley Dry Falls | ∼15,900 | He; Cerling (1990) |
| Searles Lake, CA | Highstand shorelines of Searles Lake | ∼16,800 | 14C; Benson et al. (1990) |
| Panamint Lake, CA | Lowstand shorelines of Panamint Lake | ∼18,400 | 14C; Jayko et al. (2001) |
| Death Valley, CA | Lowstand shorelines of Manly Lake | ∼10,000–35,000 | U-series; Ku et al. (1998) |
| Silurian Valley, CA | Alluvial fan surfaces | 1700±70 | 14C; Anderson and Wells (2003) |
| Silver Lake, CA | Highstand shorelines of Silver Lake | ∼12,500 | 14C; Wells et al. (1987) |
| Blythe, CA | Alluvial fan surfaces | ∼12,500 | VML; this study |
| Ocotillo, CA | Stone artifact | To be dated | VML; this study |
| Grand Canyon, AZ | Debris flow fan surfaces | ∼1500 | He; Cerling, University of Utah, personal communication (1997) |
| McDowell Mtn., AZ | Alluvial fan surfaces | Latest Pleistocene | VML; this study |
| Ajo Mtn., AZ | Alluvial terrace surfaces | 2600±110 | 14C; Pohl (1995) |
| Chili, NM | Grinding stone | To be dated | VML; this study |
| McCartys Flow, NM | Basaltic lava flows | 3180±90 | 14C; Laughlin et al. (1994) |
| Carrizo Flow, NM | Basaltic lava flows | 5200±700 | 36Cl; Dunbar (2002) |

Note: VML = varnish microlamination dating.
three locales along a N–S traverse in southern California. For a given varnish microstratigraphy, chemical signals of Mn and Ba in the Holocene portion of the layering sequence are generally weaker than those in the pre-Holocene sequence. Compared to the pre-Holocene black layers that contain 25–45% MnO and 1–6% BaO, the Holocene black layers often contain only about 15–25% MnO and less than 1–4% BaO. This observation is consistent with the fact that the overall climate during the last glacial was wetter than during the current interglacial in the drylands of western USA (Broecker and Liu, 2001). Moreover, black layers WH1 to WH12 observed in the optical microstratigraphy can be clearly identified as minor Mn- and Ba-rich peaks in the chemical microstratigraphy.

Also seen in Fig. 5 are regional variations of Mn and Ba content in the Holocene varnish layers along the traverse. On average, the Holocene layers in varnish from Death Valley contain <10% MnO and <0.5% BaO; while those from Blythe (CA) contains about 10% MnO and 0.5–1.0% BaO, and those from Ocotillo (CA) contain >10–15% MnO and >1.0–1.5% BaO. Such variations of Mn and Ba content seem to reflect the present day effective moisture gradient along the traverse: from the most arid land with less summer monsoonal precipitation in Death Valley to a relatively less arid region with more summer monsoonal precipitation in Ocotillo.

Fig. 6 presents chemical microstratigraphies of Ba for varnish samples of a range of ages, and intersample correlations of Holocene dark layers WH1–WH12 represented by Ba peaks. We found that the chemical signals of Ba in the lower portion of the Holocene microstratigraphy are generally stronger than in the upper portion (Fig. 6A, B). This probably indicates an overall wetter climate condition during the early Holocene. Because of slower varnish growth, the Ba peaks of dark layers WH1–WH6 in varnish of early Holocene age are often more likely to be squeezed up than those in varnish of late Holocene age, which may cause some ambiguity in intersample correlation (Fig. 6A, C). In most cases, the use of both optical and chemical microstratigraphies (see Fig. 5) helps reduce such ambiguity and assures correct identification.

Table 2

<table>
<thead>
<tr>
<th>Figs. 7 and 8</th>
<th>Varnish sample</th>
<th>Oldest LU observed</th>
<th>Age used for calibration</th>
<th>Calibrated 14C age</th>
<th>14C age control</th>
<th>Sample context and depth (m)</th>
<th>Source of age control</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>99-TC-1</td>
<td>WH1</td>
<td>340±30</td>
<td>540±30</td>
<td>520±50</td>
<td>Alluvium (1)</td>
<td>Reheis et al. (1993)</td>
</tr>
<tr>
<td>B</td>
<td>99-TC-2</td>
<td>WH2</td>
<td>1120±190</td>
<td>1320±190</td>
<td>1410±200</td>
<td>Alluvium (1)</td>
<td></td>
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<tr>
<td>C</td>
<td>93-LVA-20±8</td>
<td>WH2+</td>
<td>ca. 1300</td>
<td>ca. 1500</td>
<td>³He age</td>
<td>Alluvium (0)</td>
<td>see Table 1</td>
</tr>
<tr>
<td>D</td>
<td>99-LC-11</td>
<td>WH3</td>
<td>1310±70</td>
<td>1510±70</td>
<td>1620±60</td>
<td>Alluvium (2.5)</td>
<td>Reheis et al. (1995)</td>
</tr>
<tr>
<td>E</td>
<td>05-SV-2</td>
<td>WH3</td>
<td>1500±70</td>
<td>1700±70</td>
<td>1780±50</td>
<td>Alluvium (0.3)</td>
<td>Anderson and Wells (2003)</td>
</tr>
<tr>
<td>F</td>
<td>99-Ajo-1</td>
<td>WH3+</td>
<td>2430±120</td>
<td>2630±120</td>
<td>2510±60</td>
<td>Alluvium (0.7)</td>
<td>Pohl (1995)</td>
</tr>
<tr>
<td>G</td>
<td>98-McC-1</td>
<td>WH4+</td>
<td>2970±140</td>
<td>3170±140</td>
<td>2987±92</td>
<td>Lava flow</td>
<td>Laughlin et al. (1994)</td>
</tr>
<tr>
<td>H</td>
<td>99-LC-6</td>
<td>WH4+</td>
<td>3430±80</td>
<td>3630±80</td>
<td>3380±60</td>
<td>Alluvium (3)</td>
<td>Reheis et al. (1995)</td>
</tr>
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<td>I</td>
<td>99-TC-5</td>
<td>WH5</td>
<td>4080±150</td>
<td>4280±150</td>
<td>3860±100</td>
<td>Alluvium (5)</td>
<td>Reheis et al. (1993)</td>
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<tr>
<td>J</td>
<td>99-LC-12</td>
<td>WH5+</td>
<td>5550±90</td>
<td>5750±90</td>
<td>5010±60</td>
<td>Alluvium (3)</td>
<td>Reheis et al. (1995)</td>
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<tr>
<td>L</td>
<td>99-TC-4</td>
<td>WH7+</td>
<td>6980±120</td>
<td>7180±120</td>
<td>6260±100</td>
<td>Alluvium (0.95)</td>
<td>Reheis et al. (1993)</td>
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<tr>
<td>M</td>
<td>99-IC-3</td>
<td>WH8</td>
<td>7250±80</td>
<td>7450±80</td>
<td>6550±100</td>
<td>Alluvium (3.3)</td>
<td>Reheis et al. (1993)</td>
</tr>
<tr>
<td>N</td>
<td>00-LV-2</td>
<td>WH12</td>
<td>11,220±460</td>
<td>11,420±460</td>
<td>9920±280</td>
<td>Alluvium (1.5)</td>
<td>Liu et al. (2000)</td>
</tr>
<tr>
<td>O</td>
<td>98-LV-1</td>
<td>WP0</td>
<td>13,190±470</td>
<td>13,390±470</td>
<td>11,470±450</td>
<td>Alluvium (2.4)</td>
<td></td>
</tr>
</tbody>
</table>

a All ages are reported in cal YBP (±1σ), except for radiocarbon ages that are reported in ¹⁴C YBP (±1σ).

b Letters are keyed to those in Figs. 7 and 8.

c Varnish samples were collected from subaerially exposed alluvial boulders or lava flows. Abbreviations of sample labeling: Trail Canyon (TC), Indian Creek (IC), Leidy Creek (LC), Silurian Valley (SV), Ajo Mountains (Ajo), McCays flow (McC), Carrizozo flow (CR), and Las Vegas Valley (LV).

d Given a varnish lag time of about 200 yr, ages used for calibration of varnish layering sequence in this study were calculated as calibrated ¹⁴C age minus 200 yr.

e The calibrated ¹⁴C ages were obtained through Fairbanks et al.’s (2005) radiocarbon calibration program (version: Fairbanks0805) that is publicly accessible at http://www.radiocarbon.LDEO.columbia.edu.

f This age was from radiocarbon-dated alluvial fan unit Qfcm in Indian Creek of Fish Lake Valley (Reheis et al., 1993).

g Varnish sample was collected from Thure Cerling from debris flow fan surfaces in the Grand Canyon of northern Arizona.

h This age was from radiocarbon-dated alluvial fan unit Qfl in Perry Aiken Creek of Fish Lake Valley (Reheis et al., 1995).
3.2. Age calibration

In order to fully explore the climate record kept in rock varnish, we need to build a reliable radiometric chronology for the Holocene varnish microstratigraphy. Unlike the pre-Holocene layering sequence that has been radiometrically calibrated (Liu, 2003), it is more difficult to calibrate the Holocene sequence for the following reasons. First, the Holocene sequence contains a total of 25 black and orange/yellow layers within a time period of ~12,000 yr. This suggests an average duration of nearly 500 yr for each individual varnish layer and thus requires much more accurate and precise radiometric age constraints for calibration. Secondly, although it would be ideal to date each individual layer within varnish microstratigraphy, such a breakthrough has not yet been accomplished. So our approach to dating varnish layers is still indirect: examining samples from sites with radiometric age control for the underlying landform. Such ages are maxima for the

Fig. 3. Replicated Holocene varnish microstratigraphies from the drylands of western USA. Age constraints (in cal YBP) are maximum-limiting ages for varnish, and age sources are given in Table 1. WH = wet event in Holocene, and WP = wet event in Pleistocene. See Table 3 and text for discussion.
start of the layering sequence because the varnish started to form only after the dated landform was created. Lastly, only a few localities exist in western USA drylands where varnished Holocene geomorphic features have been dated with sufficient precision by radiometric means to provide unambiguous age constraints (Table 1).

The results of our preliminary age calibration for the Holocene varnish microstratigraphy are however very promising (Figs. 7 and 8). Most of our calibration samples were from $^{14}$C-dated Holocene alluvial fan surfaces (500–7500 YBP) in Indian Creek, Leidy Creek, and Trail Canyon of Fish Lake Valley, NV (Table 2; Reheis et al., 1993, 1995). Varnish from the youngest $^{14}$C-dated alluvial fan surface (540 ± 30 YBP) in Trail Canyon displays a latest Holocene layering sequence LU-1 (WH1) (Fig. 7A), which stands for “layering unit 1 with basal layer WH1” (a similar terminology is also applied to LU-1 (WH2–12) in this paper; Liu, 2003). Taken a lag time of ~200 yr for varnish initiation on subaerially exposed rock surfaces plus a time gap between deposition of the dated materials and deposition of the sampled geomorphic features (see the discussion section for details; Liu, 2003), dark layer WH1 in the varnish was probably deposited around 340±30 YBP. Similarly, varnish from $^{14}$C-dated alluvial fan surfaces in Leidy Creek (1510±70 YBP) and Silurian Valley (1700±70 YBP) displays a well-defined late Holocene layering sequence LU-1 (WH3) (Fig. 7D, E), indicating that dark layer WH3 formed around 1300–1500 YBP. Varnish from $^{14}$C-dated alluvial fan surfaces (4280±150 YBP) in Leidy Creek displays a late Pleistocene layering sequence LU-1 (WH5) (Fig. 7I), suggesting that dark layer WH5 was deposited around 4080±150 YBP. In central New Mexico, varnish from the Carrizozo lava flows displays a late Holocene layering sequence LU-1 (WH6) (Fig. 7K). Dunbar (2002) reported three cosmogenic $^{36}$Cl ages for emplacement of the flows: 4900±500, 5400±1000, and 5600±900 YBP, with a weighted average of 5200±700 YBP. If the maximum age of 5600±900 YBP that probably more closely represents the true flow age is assumed, dark layer WH6 was deposited around ca. 5400±900 YBP. Further, varnish from $^{14}$C-dated alluvial fan surfaces (11,420±460 YBP) in Las Vegas Valley of southern Nevada (Liu et al., 2000) displays a nearly complete Holocene layering sequence LU-1 (WH12) (Fig. 7N), suggesting that dark layer WH12 formed around 11,220±460 YBP.

For dark layers WH2, WH7, and WH8, the results of our preliminary age calibration are also very encouraging. One varnish sample from $^{14}$C-dated latest Holocene alluvial fan surfaces (1320±190 YBP) in Trail Canyon displays a latest Holocene layering sequence LU-1 (WH2) (Fig. 7B). Given a lag time of ~200 yr, dark layer WH2 was likely deposited around 1120±190 YBP (Fig. 8). Another varnish sample from $^{14}$C-dated early Holocene alluvial fan surfaces (7450±80 YBP) in Indian Creek displays a clearly defined layering sequence LU-1 (WH8) (Fig. 7M), indicating that dark layer WH8 likely formed around 7250±80 YBP. In this study, no age control was obtained for WH7, a relatively weak dark layer at the middle of the Holocene layering sequence. However, one varnish sample from $^{14}$C-dated middle Holocene alluvial fan surfaces (7180±120 YBP) in Trail Canyon displays a clearly defined layering sequence LU-1 (WH7+) (Fig. 7L); here, WH7+ stands for the orange layer directly underneath dark layer WH7 (a similar terminology is also applied to WH1+ through WH12+ in this paper) (Fig. 8). This indicates that orange layer WH7+ was likely deposited around 6980±120 YBP, which predates dark layer WH7.
Table 3
Characteristics of a generalized Holocene varnish layering sequence in the drylands of western USA

<table>
<thead>
<tr>
<th>Wet event</th>
<th>Generalized layering sequence</th>
<th>Characteristics of layering pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Ice Age wet event</td>
<td>WH1</td>
<td>WH1 is the outermost dark layer in a given Holocene varnish microstratigraphy (Figs. 3A and 7C, J). In fine-grained and fast-growing mid-to-late Holocene varnish, it often contains 3 secondary dark layers WH1a, b, c (Figs. 7D, E, L and 11), each of which may further consist of 2-4 narrow dark bands (Fig. 7D, E, H). Occasionally, WH1a, b, c appear collectively as a set of 12 evenly spaced weak dark bands (Fig. 7B). In some early Holocene varnish samples, WH1 is absent due likely to postdepositional modification such as wind abrasion and peeling (Fig. 3B, F). The overall thickness of WH1 depends largely on varnish age, growth rate, and surface erosion, varying from 2-10 µm in early Holocene varnish to 10-30 µm in mid-to-late Holocene varnish.</td>
</tr>
<tr>
<td>Medieval Warm wet event</td>
<td>WH2</td>
<td>WH2 occurs underneath WH1 and is separated from it by a narrow yellow/orange layer (WH1+). In fine-grained and fast-growing mid-to-late Holocene varnish, it often contains 2 secondary dark layers WH2a, b; each of which may further consist of 2-4 narrow dark bands (Figs. 7D, E and 11). In most cases, WH2b appears to be more dominant in both thickness and darkness than WH2a (Fig. 7D, E) and therefore makes WH2 visually as one dark layer (Fig. 7L, L). Like WH1, WH2 is sometimes absent in early Holocene varnish samples due to postdepositional modification (Fig. 3B, F). Its entire thickness ranges from 2 to 30 µm.</td>
</tr>
<tr>
<td>Late-Holocene wet events</td>
<td>WH3 through WH6</td>
<td>WH3 through WH6 occur as a set of 4 visually predominant and nearly evenly spaced dark layers in the upper portion of the Holocene layering sequence compared to dark layers WH1 and WH2 (Fig. 3A, N). In some fine-grained and fast-growing late-to-early Holocene varnish, those dark layers each contain 2-5 secondary dark bands (Fig. 3B). In most cases, WH6 is the most dominant dark layer and directly overlies a detritus-rich yellow/orange layer (WH6+) (Fig. 3A, B, E, F, L). Occasionally, WH3 may be visually merged with WH2 as one dark band in some early Holocene varnish samples (Fig. 7M). Sometimes, WH3 and WH4 are not as dark as WH5 and WH6 due probably to postdepositional modification such as leaching (Fig. 3C, E). The thicknesses (in µm) of these dark layers are: WH3 (2-10), WH4 (2-10), WH5 (4-15), WH6 (5-25).</td>
</tr>
<tr>
<td>Mid-Holocene wet event</td>
<td>WH7</td>
<td>WH7 occurs as a relatively weak dark layer roughly at the middle portion of the Holocene layering sequence (Figs. 3B, C, F and 7L). Above and below WH7 are two yellow/orange layers (WH6+ and WH7+) that are diagnostic of the middle Holocene warm period (Broecker and Liu, 2001). WH7 is often subject to postdepositional erosion or is absent in some slowly-growing varnish samples (Figs. 7N and 9C). Its entire thickness ranges from 0 to 5 µm.</td>
</tr>
<tr>
<td>Early-Holocene wet events</td>
<td>WH8 through WH12</td>
<td>WH8 through WH12 occur as a set of 5 prominent and approximately evenly spaced dark layers in the lower portion of the Holocene layering sequence (Fig. 3C, F); each of which may further consist of 2-4 narrowly spaced secondary dark bands in some fine-grained and fast-growing early Holocene varnish (Fig. 3B, F). Compared to dark layers WH1-6, those of WH8-12 appear to be well developed and more enriched in Mn and Ba, thus often having a “fatter and darker” appearance in optical varnish microstratigraphy (Figs. 5B, C, 9C, 10D). In an evenly polished varnish ultrathin section, dark layers WH8-12 are often distinguished from dark layers WH1-6 in that the former are collectively darker than the latter under polarized light (Fig. 9B, C, D). If the varnish ultrathin section is too thick (&gt;15-20 µm), WH8-12 become visually merged as one dominant basal dark layer that is easily misinterpreted as a terminal Pleistocene dark layer WP0 (Liu et al., 2000). If the ultrathin section is too thin (&lt;10-15 µm), dark layers WH8-12 (and WH1-7, too) are visually turned into orange/yellow layers, as illustrated in Fig. 7O. The thicknesses of dark layers WH8-11 each range from 2 to 10 µm, and that of WH12 ranges from 2 to 15 µm.</td>
</tr>
<tr>
<td>Younger Dryas wet event</td>
<td>WP0</td>
<td>WP0 is a terminal Pleistocene dark layer that stratigraphically underlies the entire Holocene layering sequence (Fig. 7O). It often contains 3 evenly spaced secondary dark layers in some fast-growing latest Pleistocene varnish samples (Fig. 3F). Its thickness ranges from 5 to 25 µm.</td>
</tr>
</tbody>
</table>

For those orange/yellow layers in the Holocene layering sequence, our preliminary age calibration provides reasonable time constraints. Varnish from cosmogenic ¹⁷⁷⁷He-dated ~ 1500 YBP debris flow boulders in the Grand Canyon of northern Arizona (Cerling, University of Utah, personal communication, 1997) displays a latest Holocene layering sequence LU-1 (WH2+) (Fig. 7E). Given a lag time of ~200 yr, this suggests an age of ca. 1300 YBP for orange layer WH2+, which predates dark layer WH2 and postdates dark layer WH3. Varnish from ¹⁴C-dated alluvial terraces (2630 ± 120 YBP) in the Ajo Mountains of southern Arizona (Pohl, 1995) displays a late Holocene layering sequence LU-1 (WH3+) (Fig. 7F). This indicates an age of 2430 ± 120 YBP for orange layer WH3+, which postdates dark layer WH4. Similarly, varnish from ¹⁴C-dated McCarty's lava flows (3170 ± 140 YBP) in central New Mexico (Laughlin et al., 1994) and alluvial fan surfaces (3630 ± 80 YBP) in Leidy Creek of Fish Lake Valley displays a late Holocene layering sequence LU-1 (WH4+) (Fig. 7G, H),
suggesting an age of 3000–3400 YBP for orange layer WH4+, which predates dark layer WH4 and postdates dark layer WH5. Furthermore, varnish from 14C-dated alluvial fan surfaces in Leidy Creek (5750 ± 90 YBP) displays a well-defined late Holocene layering sequence LU-1 (WH5+) (Fig. 7J), indicating an age of 5550 ± 90 YBP for orange layer WH5+ that predates dark layer WH5 and postdates dark layer WH6.

In conclusion, although some of the 12 dark layers (such as WH9, WH10, and WH11) in the Holocene varnish layering sequence have not been calibrated because of the lack of appropriate radiocarbon age control in the study region, our preliminary age calibration presented above generally provides good time constraints on most of these varnish layers in the sequence, as summarized in Fig. 8.

Fig. 5. Optical (left) and chemical (right) microstratigraphies in rock varnish from three localities along a N–S traverse in the drylands of western USA. Note that WH1–WH12 and WP0 in the right panel identify Mn-rich peaks on each probe line profile that largely correspond to the Holocene and terminal Pleistocene dark layers seen in the optical microstratigraphies.
3.3. Climatic correlation

The Holocene wetness variations uncovered in varnish microstratigraphy appear to have a striking correlation with the Holocene climate events in the North Atlantic region (Fig. 4). Bond et al. (1997, 1999) discovered a pervasive millennial-scale cycle, with a cyclicity of 1470 ± 500 yr, of Holocene events and abrupt climate shifts during the last glaciation in the North Atlantic deep sea cores. The discovery most interesting to this study is that the Holocene portion of the climate record revealed a total of nine cooling events, with the Little Ice Age (LIA) being the most recent in this series of millennial-scale cycles. For the sake of simplicity, Bond et al. (1997, 1999) named these events (from oldest to youngest) as 8, 7, 6, 5, 4, 3, 2, 1, and 0 cooling events; and their reported ages are ca. 11,100, 10,300, 9400, 8100, 5900, 4100, 2800, 1400, and 650–300 YBP, respectively (Figs. 4 and 8).

Several lines of evidence support a possible correlation of the varnish climate record with the deep sea record. First, our previous studies in the Great Basin show that the formation of pre-Holocene dark layers in varnish microstratigraphy was contemporaneous with abrupt climate shifts, such as Heinrich events, during the last glaciation (Liu and Dorn, 1996; Liu et al., 2000; Broecker and Liu, 2001; Liu, 2003). In particular, in the Las Vegas Valley of southern Nevada, black layer WP0 (WP stands for “wet event in Pleistocene”; also see Liu, 2003, for more discussion on this topic) in the latest Pleistocene varnish microstratigraphy has been proven to correlate in time with the Younger Dryas (YD) cold snap in the North Atlantic (Liu et al., 2000). The YD cooling is considered as one of these abrupt climate shifts that manifest the millennial-scale climatic cyclicity (Bond et al., 1997, 1999).

Secondly, the number of wet/cold phases largely matches between the two climate records (Fig. 4). Our current study has documented a total of 12 black layers in varnish microstratigraphy, each representing a Holocene wet phase. Four black layers of the early Holocene (WH12, WH11, WH10, and WH9) presumably match four early Holocene cooling events (8, 7, 6, and 5, respectively), and four late Holocene black layers (WH6, WH5, WH4, and WH3) presumably match four late Holocene cooling events (4, 3, 2, and 1, respectively). Because the topmost black layer (WH1) represents the most recent wet phase during the Holocene, it most likely matches the LIA cooling. Although black layers WH8, WH7, and WH2 have no clear match to any of the nine cooling events identified by Bond et al. (1997, 1999), further examination of the deep sea record suggests that these black layers may match some minor cold peaks in the record, as indicated by question marks in Fig. 4. Specifically, if such climatic correlation exists, the deposition of black layers WH8, WH7, and WH2 likely occurred around 7300, 6500, 1100–900 YBP, respectively.

Thirdly, a close match exists in the cyclicity of the Holocene wet/cold events in both records. Given a well-known duration of ~12,000 yr for the Holocene, a total of 12 roughly evenly spaced black layers in the Holocene varnish microstratigraphy imply a roughly 1000-yr cyclicity of wet events. Such cyclicity overlaps, within ±1σ...
error, the reported cyclicity of 1374±502 yr for the Holocene cooling events, or 1470 ±500 yr for both the Holocene and the last glacial cold events in the North Atlantic region.

Finally, our radiometric age calibration indicates that there is generally a temporal correlation between the varnish climate record and the deep sea record. As seen in Figs. 4 and 8, dark layers WH12, WH6–WH3, and WH1 in the Holocene varnish layering sequence correlate in time with the Holocene cooling events 8, 4–1, and LIA (respectively) in the deep sea record; and dark
layers WH8, WH7, and WH2 correlate in time with minor cooling phases around ca. 7300, 6500, 900–1100 YBP (respectively) that did not qualify as the Holocene cooling events based on the criteria of Bond et al. (1997, 1999). Similar correlation may exist between dark layers WH1–WH12 and cooling events 7–5, but more radiometric age calibration is needed to confirm this correlation.

3.4. Chronometric application

Once established and radiometrically calibrated, varnish microstratigraphy can be used to estimate numerical ages of geomorphic and geoarchaeological features of interest (Liu and Dorn, 1996; Bell et al., 1998b; Friend et al., 2000; Liu, 2003; Douglass et al., 2005). For the purpose of age dating in this study, we tentatively use the age scale in Fig. 8. We also point out that any varnish-based age estimate should be interpreted as minimum surface exposure age for the geomorphic feature and the age is only as good as our calibration. In the following sections, we present several case studies to demonstrate the potential use of varnish microstratigraphy as a unique dating tool in western USA drylands.

3.4.1. Geomorphic use

Debris flow fan deposits, Death Valley: Debris flow fans are common features in arid to semi-arid environments. In Death Valley, some 10 debris flow fans of various sizes crop out within a distance of about 1 km on the east side of the valley north of Mormon Point (as illustrated by a dramatic one that we studied; Fig. 9). Previous studies (Bull, 1991) classified the deposits of this debris flow fan into five age groups, namely Q2c, Q3a, Q3b, Q3c, and Q4, based largely on differential development of rock varnish on the deposits (Bull, 1991: Fig. 2.26B). Here, Q2c represents the oldest fan unit with dark-brown varnish coverage that formed during the terminal Pleistocene (70–12 ka); Q3a–c represents the subsequent fan units with varying degree of orange varnish coverage that formed during the early-to-late Holocene around 12–8, 8–4, 4–2 ka, respectively; and Q4 represents the modern debris flow deposits that have no varnish coverage and formed during the latest Holocene around 2–0 ka (Bull, 1991: Table 2.13). However, because of the extreme difficulty in radiometric dating of debris flow fan deposits, no specific numerical chronology exists for the formation and evolution of this debris flow fan.

In this study, varnish microlamination (VML) dating was used to provide numerical age estimates for the deposits. Based on fan morphology and varying degree of varnish development, we identified seven units (i.e., Df1 through Df7), with Df1 being the oldest and Df7 the youngest (Fig. 9). Varnish samples were collected from all but the youngest (i.e., Df7) units. Table 4 summarizes these units, samples collected, oldest varnish layering patterns observed, varnish-based age estimates, and their correlation to Bull’s (1991) generalized alluvial fan units. Varnish from Df1 and Df2 displays, respectively, the oldest pre-Holocene LU-1/LU-2 (WP0) and early Holocene LU-1 (WH12+) layering sequences, suggesting a minimum age of 12,500 YBP for Df1 and 11,100–12,500 YBP for Df2 (Fig. 9E, F). Varnish from Df3 and Df4 shows early Holocene layering sequence LU-1 (WH11) (Fig. 9B), suggesting a minimum age of 9400 YBP for Df5. Varnish from Df3 and Df4 shows early Holocene layering sequences LU-1 (WH12) and LU-1 (WH11) (Fig. 9C, D), respectively, indicating a minimum age of 11,100 YBP for Df3 and 10,300 YBP for Df4. Varnish from Df5 and Df6 shows an early Holocene layering sequence LU-1 (WH12) and LU-1 (WH11) (Fig. 9E, F), respectively, indicating a minimum age of 2800 YBP for Df5. Clearly, our preliminary varnish-based age estimates are in close agreement with Bull’s (1991) estimates and also have much better age resolution (Table 4). More importantly, our dating results indicate that debris flow fan building events in Death Valley were more likely to have occurred during
Fig. 9. A debris flow fan (∼ 0.04 km² in size) on the east side of Death Valley, California (upper panel) and optical microstratigraphies of rock varnish from the fan deposits (lower panel). Seven fan units (Df1–Df7) were identified on the basis of fan morphology and degree of varnish coverage (see Table 4). VML dating results (reported in cal YBP) indicate that emplacement of these fan units was more likely to have occurred during relatively wet periods of the Holocene. Note that while optically similar due to thin sections with slightly greater thickness, the Holocene dark layers in these images often contain less Ba than the pre-Holocene dark layers, as illustrated in (C) and (F). The brown burn marks in (C) were made by electron microprobe during line profiling.
relatively wet periods of the Holocene, as evidenced by the basal dark layers in varnish microstratigraphies from four (out of five) sampled Holocene fan units in this case study (Fig. 9).

### Table 4

<table>
<thead>
<tr>
<th>Debris flow fan unit (this study)</th>
<th>Geomorphic feature and varnish coverage</th>
<th>Sample number</th>
<th>Oldest layering sequence observed</th>
<th>Varnish-based age estimate (ka)</th>
<th>Alluvial fan unit and age (ka) (Bull, 1991)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Df₁</td>
<td>Youngest/aggrading debris flow lobe</td>
<td>No varnish coverage</td>
<td>99-DV-14</td>
<td>LU-1 (WH4)</td>
<td>2.8</td>
</tr>
<tr>
<td>Df₂</td>
<td>Young debris flow lobe</td>
<td>Lightest orange varnish coverage</td>
<td>99-DV-9</td>
<td>LU-1 (WH10)</td>
<td>9.4</td>
</tr>
<tr>
<td>Df₃</td>
<td>Intermediate debris flow lobe</td>
<td>Light orange varnish coverage</td>
<td>99-DV-8</td>
<td>LU-1 (WH11)</td>
<td>10.3</td>
</tr>
<tr>
<td>Df₄</td>
<td>Intermediate debris flow lobe</td>
<td>Orange varnish coverage</td>
<td>99-DV-10</td>
<td>LU-1 (WH12)</td>
<td>11.1</td>
</tr>
<tr>
<td>Df₅</td>
<td>Old debris flow lobe</td>
<td>Brown/orange varnish coverage</td>
<td>99-DV-7</td>
<td>LU-1 (WH12+)</td>
<td>11.1–12.5</td>
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<tr>
<td>Df₁</td>
<td>Old debris flow lobe</td>
<td>Brown varnish coverage</td>
<td>99-DV-1</td>
<td>LU-1/LU-2 (WP0)</td>
<td>12.5</td>
</tr>
<tr>
<td>Df₁</td>
<td>Oldest debris flow lobe</td>
<td>Dark-brown varnish coverage</td>
<td></td>
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</tbody>
</table>

3.4.2. Geoarchaeological use

**Grinding stone, Chili, northern New Mexico:** Although the VML method has been previously applied to dating old prehistoric rock art in the Great Basin (e.g.,
Dorn, 1992; Liu and Dorn, 1996), this dating technique is used for the first time herein to estimate the age of young prehistoric stone artifacts in western USA deserts. A varnish sample was obtained from a grinding stone (or metate) found near Chili in northern New Mexico (Figs. 2 and 10A). The presence of hundreds of Anasazi pottery shards (Pueblo II–III pottery; Liu, unpublished data) in a nearby hillslope implies a maximum age of 700–1100 YBP (Lister and Lister, 1978) for the abandonment of this occupation site by the Anasazi Indians. Varnish from the sampled grinding stone displays a latest Holocene layering sequence LU-1/LU-2 (WP0) (Fig. 10B; also see Fig. 6E), suggesting a minimum age of 900–1100 YBP for the varnish initiation. This age estimate appears to be consistent with the available archaeological evidence.

**Stone artifact, Ocotillo, southern California:** In order to demonstrate the great potential of the VML method in dating old prehistoric stone artifacts in western USA deserts, a sample was also obtained from a well-varnished flaked stone, or a primary core, collected by archaeologist Jay von Werlhof near Ocotillo, southern California (Figs. 2 and 10C). This varnish displays a latest Pleistocene layering sequence LU-1 (WH2) (Fig. 10D; also see Fig. 5C), indicating a minimum age of 12,500 YBP for the flaking of this stone artifact and thus suggesting at least a Paleo-Indian human occupation at Ocotillo during the terminal Pleistocene.

4. Discussion

As illustrated above, the VML dating technique is a unique tool in studying desert geomorphology and geoarchaeology in western USA drylands. It can be useful in dating surficial geomorphic features where other radiometric means, such as radiocarbon and cosmogenic radionuclide methods, are not applicable or difficult to use. However, like any other Quaternary dating technique in earth science, it also has some intrinsic problems that deserve further discussion.

4.1. Validity of age calibration

As a correlative dating tool, the VML method also depends on a premise that climate variations are recorded in varnish. Based on our preliminary radiometric age calibration, we found that the Holocene climate record in rock varnish is generally valid and comparable to other climate records in the study region (Table 5). In the Mojave Desert, for example, Enzel et al. (1989) reported three Holocene wet periods in the lacustrine record of Silver Lake. The first wet period occurred around 10,540±140 YBP, in reasonable accord with the early Holocene wet phase WH11 herein dated at 10,300 YBP. The second one occurred around 3930±100 YBP, which correlates with one wet phase WH5 at 4100 YBP. The third occurred around 440±100 YBP, largely overlapping our most recent wet phase WH1 around 300–650 YBP. Miller et al. (2000) documented a wet period in the middle Holocene at 6500±500 YBP (Infrared Stimulated Luminescence or IRSL age) that was concurrent with debris flow building and a short-lived lake stand in the northern Silurian Valley of the Mojave Desert. This wet period correlates favorably with our middle Holocene wet phase WH7 at ~6500 YBP (Fig. 8). Other regional climate proxies [such as a pollen
Table 5
Comparison of rock varnish climate record with other regional climate proxies in the drylands of western USA\textsuperscript{a}

<table>
<thead>
<tr>
<th>Wet event \textsuperscript{b} recorded in rock varnish</th>
<th>Numerical age assignment \textsuperscript{c}</th>
<th>Lake phase</th>
<th>Pollen record</th>
<th>Flow discharge</th>
<th>Highstand/transgression</th>
<th>Black mat/wet phase</th>
<th>Holocene glacier advance</th>
</tr>
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<tbody>
<tr>
<td>WH1a 300</td>
<td>300±160</td>
<td>300</td>
<td>296–375</td>
<td>550</td>
<td>580±70</td>
<td>110–250</td>
<td>100</td>
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<tr>
<td>WH1b 500</td>
<td>440±100</td>
<td>450</td>
<td>465–550</td>
<td>700</td>
<td>580±70</td>
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<td>700</td>
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<td>WH1c 650</td>
<td>575</td>
<td>605–680</td>
<td>700</td>
<td>580±70</td>
<td>700</td>
<td>900</td>
<td>1100</td>
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<tr>
<td>WH2a 900</td>
<td>900</td>
<td>866</td>
<td>1370±50</td>
<td>3100±210</td>
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<td>1350±140</td>
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<td>WH2b 1100</td>
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<td>1100</td>
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<td>WH3 1400</td>
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<td>3770±120</td>
<td>3500</td>
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<td>WH5 4100</td>
<td>3770±120</td>
<td>5900</td>
<td>5940±80</td>
<td>6500±500</td>
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<td>WH7 6500</td>
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<td>9150±270</td>
<td>800±190</td>
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<td>800±190</td>
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<td>10,300</td>
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</tr>
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<td>WH10 9400</td>
<td>11,100</td>
<td>11,530±350</td>
<td>11,530±350</td>
<td>12,090±380</td>
<td>12,470±200</td>
<td>7860±130</td>
<td>7860±130</td>
</tr>
<tr>
<td>WH11 10,300</td>
<td>12,500</td>
<td>12,420±300</td>
<td>12,420±300</td>
<td>12,090±380</td>
<td>12,470±200</td>
<td>7860±130</td>
<td>7860±130</td>
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<tr>
<td>WH12 11,100</td>
<td>12,500</td>
<td>12,420±300</td>
<td>12,420±300</td>
<td>12,090±380</td>
<td>12,470±200</td>
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<tr>
<td>WP0 12,500</td>
<td>12,500</td>
<td>12,420±300</td>
<td>12,420±300</td>
<td>12,090±380</td>
<td>12,470±200</td>
<td>7860±130</td>
<td>7860±130</td>
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</table>

\textsuperscript{a} All ages are reported in cal YBP (±1\sigma), rounded to the nearest 10 yr; and all \textsuperscript{14}C ages are calibrated using Fairbanks et.al.’s (2005) calibration program (version: Fairbanks0805) that is publicly accessible at http://www.radiocarbon.LDEO.columbia.edu. For \textsuperscript{14}C ages that were reported without age errors or interpolated based on published curves of climate proxies, an age error (1\sigma) of 100 yr is assumed for \textsuperscript{14}C dates of 0–6000 and 200 yr for dates of 6001–12,000.

\textsuperscript{b} Wet event WH1 contains three secondary wet phases WH1a, WH1b, and WH1c; and wet event WH2 contains two secondary wet phases WH2a and WH2b (see Fig. 11).

\textsuperscript{c} Numerical age assignments of 300, 500, 650, and 900 for WH1a, WH1b, WH1c, and WH2a, respectively, are based on a possible correlation of the Mono Lake record (Stine, 1990) with the varnish record (see Fig. 11); the other age assignments are from Fig. 8.

\textsuperscript{d} The Silver Lake records were from Enzel et al. (1989) and Wells et al. (1987); the reported and interpolated \textsuperscript{14}C dates are 390±90, 3620±70, 9330±95, and 10,500±200.

\textsuperscript{e} The pollen record was from Fig. 8 of Davis (1990); the reported and interpolated \textsuperscript{14}C dates for the pollen record are ca. 260, 390, 2800, 3800, and 7000. The calibrated age of 300±160 for an interpolated \textsuperscript{14}C date of 260±100 was obtained from CALIB Rev 5.0.2 (Stuiver and Reimer, 1993).

\textsuperscript{f} The flow discharge record of the Sacramento River was from Meko et al. (2001) and Yuan et al. (2004).

\textsuperscript{g} From Stine (1990).

\textsuperscript{h} From Adams (2005).

\textsuperscript{i} From Benson et al. (2002).

\textsuperscript{j} The black mat record in southern Nevada was from Fig. 5 of Quade et al. (1998); the interpolated \textsuperscript{14}C dates for peak black mat formation during the Holocene are ca. 580, 1500, 6600, 7200, 8200, 8900, 10,000, 10,300.

\textsuperscript{k} The black mat in Panamint Valley was from Peterson (1980), with a reported \textsuperscript{14}C date of 10,520±140. The black mat in Silurian Valley was from Anderson and Wells (2003), with a reported \textsuperscript{14}C date of 5180±70. The infrared stimulated luminescence age of 6500±500 for a short-lived lake stand in Silurian Valley was from Miller et al. (2000).

\textsuperscript{l} The morainal record was from Curry (1969); the calibrated age of 7860±130 was derived from a reported \textsuperscript{14}C date of 7030±130 for early Holocene tills. The calibrated age of 1350±140 for a possible Recess Peak advance was obtained from a reported \textsuperscript{14}C date of 1440±150 after Porter and Denton (1967).

\textsuperscript{m} The lake sediment record of Holocene glacier advances in the Sierra Nevada was from Bowerman (2005).
record from San Joaquin Marsh (Davis, 1990), a flow discharge record from Sacramento River (Meko et al., 2001; also see Yuan et al., 2004), lake sediment records from Walker Lake (Adams, 2005) and Owens and Pyramid Lakes (Benson et al., 2002), black mat records from southern Nevada (Quade et al., 1998), Panamint Valley (Peterson, 1980), and Silurian Valley (Anderson and Wells, 2003), and morainal and lake sediment records of Holocene glacier advances in the Sierra Nevada (Curry, 1969; Bowerman, 2005)] provide complementary Holocene wetness records in western USA drylands that correlate well in time with our 12 Holocene wet phases (Table 5).

It is also noteworthy that varnish microstratigraphy may have the potential to carry a high resolution (centennial scale) Holocene wetness record in western USA drylands. As illustrated in Fig. 11 (right panel), one fine-grained and fast-growing varnish sample from 14C-dated alluvial fan surfaces in Leidy Creek of Fish Lake Valley (1510 ± 70 YBP; Table 2) hosts a high resolution optical microstratigraphy. Here, dark layer WH1 contains three secondary dark layers (WH1a, WH1b, and WH1c), and dark layer WH2 contains two secondary dark layers (WH2a and WH2b); each of these secondary dark layers further consists of 2–4 narrowly spaced dark bands. Given a lag time of ~200 yr for varnish initiation on the sampled alluvial boulder, the basal dark layer WH3 in the microstratigraphy was likely deposited around 1310 ± 70 YBP. If these dark layers are interpreted as a climatic proxy of wetness (Liu et al., 2000; Broecker and Liu, 2001; Liu, 2003), the varnish microstratigraphy provides a centennial-scale wetness record of the past 1300–1400 yr for Fish Lake Valley (NV). A comparison of this varnish record with a nearby 2000-yr-long Mono Lake record (Stine, 1990) suggests a fascinating correlation (Fig. 11). Specifically, three secondary dark layers (WH1a, WH1b, and WH1c) in the varnish record likely correlate in time with three LIA highstands (HS) of Mono Lake (i.e., Clover Ranch, Danberg Beach, and Rush Delta), one secondary dark layer (WH2a) correlates with a Medieval Warm Period (MWP) (ca. 800–1200 YBP; Soon et al., 2003) highstand (i.e., Post Office), and one major dark layer (WH3) with a pre-MWP highstand (i.e., Mill Creek-East). The secondary dark layer (WH2b) in the varnish record may correlate in time with a short-lived wet period (~1100 YBP) during

![Fig. 11. A possible correlation of rock varnish climate record with the lake-level record of Mono Lake (CA). The varnish record is from Leidy Creek in Fish Lake Valley (NV), with radiometric age control of 1310 ± 70 YBP for WH3 (Fig. 7D; Table 2). The Mono Lake record is from Stine (1990). HS = highstands. See text for discussion.](image-url)
the MWP that has been well-documented in other regional climate records from western USA drylands (Table 5), but this wet period is not discernible in the Mono Lake record (Fig. 11). Clearly, without detailed radiocarbon age calibration of these dark layers, the above mentioned correlation is, at best, conjectural. However, if such correlation indeed exists, dark layers WH1a, WH1b, and WH1c are most likely to be deposited (respectively) around ca. 300, 500, and 650 YBP and dark layers WH2a and WH2b around ca. 900 and 1100 YBP (Fig. 11; Table 5). More studies in the future are needed to refine this correlation.

5. Conclusion

Rock varnish microstratigraphy is a useful geomorphic and geoaarchaeological dating tool. Without radiometric age calibration, varnish microstratigraphy can stand alone as a regional correlation and mapping tool (Liu, 1994; Liu and Dom, 1996). With age calibration, it can provide numerical age constraints on surficial geomorphic and geoaarchaeological features, with a possible age resolution of 500–1000 yr in the Holocene and a few thousand years in the late Pleistocene (Liu, 2003; also see VML Dating Lab’s website at www.vmldatinglab.com for more examples). Moreover, when detailed radiometric age calibration is accomplished for the Holocene varnish layering sequence, the technique has the potential to yield numerical age assignments for surface stone tools, petroglyphs, and geoglyphs that may be related to major cultural periods and phases of American prehistory in western USA deserts.

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References


of the Davis Mountain 15′ Quadrangle, Esmeralda County, Nevada. U.S. Geological Survey MAP I-2342, 1:24,000 Scale, Denver, Colorado.


