Rock varnish microlamination dating of late Quaternary geomorphic features in the drylands of western USA

Tanzhuo Liu *, Wallace S. Broecker

Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA

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Abstract

Varnish microlamination (VML) dating is a correlative age determination technique that can be used to date and correlate various geomorphic features in deserts. In this study, we establish a generalized late Quaternary (i.e., 0–300 ka) varnish layering sequence for the drylands of western USA and tentatively correlate it with the SPECMAP oxygen isotope record. We then use this climatically correlated varnish layering sequence as a correlative dating tool to determine surface exposure ages for late Quaternary geomorphic features in the study region. VML dating of alluvial fan deposits in Death Valley of eastern California indicates that, during the mid to late Pleistocene, 5–15 ky long aggradation events occurred during either wet or dry climatic periods and that major climate shifts between glacial and interglacial conditions may be the pacemaker for alteration of major episodes of fan aggradation. During the Holocene interglacial time, however, 0.5–1 ky long brief episodes of fan deposition may be linked to short periods of relatively wet climate. VML dating of alluvial desert pavements in Death Valley and the Mojave Desert reveals that pavements can be developed rapidly (<10 ky) during the Holocene (and probably late Pleistocene) in the arid lowlands (<800 m msl) of these regions; but once formed, they may survive for 74–85 ky or even longer without being significantly disturbed by geomorphic processes operative at the pavement surface. Data from this study also support the currently accepted, “being born at the surface” model of desert pavement formation. VML dating of colluvial boulder deposits on the west slope of Yucca Mountain, southern Nevada, yields a minimum age of 46 ka for the emplacement of these deposits on the slope, suggesting that they were probably formed during the early phase of the last glaciation or before. These results, combined with those from our previous studies, demonstrate that VML dating has great potential to yield numerical age estimates for various late Quaternary geomorphic features in the western USA drylands.

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1. Introduction

Alluvial fans, desert pavements, and colluvial boulder deposits are the most common landforms in the drylands of western USA and in many other arid to semiarid regions of the world. These features have been of the focus of a lot of research in desert geomorphology over the past century for two reasons. First, they are basic and ubiquitous landforms in desert landscapes that deserve intensive scientific scrutiny (e.g., Blake, 1904; Blackwelder, 1931; Williams, 1958; Bull, 1964, 1977; Malde, 1964; Denny, 1965; Melton, 1965; Hunt and Mabey, 1966; Denny, 1967; Hooke, 1967, 1968; Cooke, 1970;
McFadden et al., 1987; Prokopovich, 1987; Dorn, 1988; Harvey, 1990, 1992; Whitney and Harrington, 1993; Wells et al., 1995; Friend et al., 2000; Quade, 2001; Anderson et al., 2002; Wood et al., 2005; Valentine and Harrington, 2006). Secondly, the geomorphic processes responsible for formation and evolution of these landforms may hold a key to our understanding of past environments, especially climate changes in the world’s deserts (e.g., Lustig, 1965; Wells et al., 1987; Bull, 1991; Throckmorton and Reheis, 1993; Whitney and Harrington, 1993; Dorn, 1994; McFadden et al., 1998; Harvey et al., 1999; Harvey, 2002a; Hanson, 2005; Reheis et al., 2005). However, radiometric dating of these geomorphic features has always been difficult. Although radiocarbon dating is accurate and precise for the past 40 ky, many surficial geologic deposits in arid to semiarid environments rarely contain carbon materials for 14C measurement. Other radiometric means, such as U/Th and OSL (optically stimulated luminescence), can be useful only if datable material and favorable geomorphic/geologic settings exist (e.g., Ku et al., 1979; Stokes, 1999; Sharp et al., 2003; Olley et al., 2004). Furthermore, recent developments in the cosmogenic nuclide age determination technique make it applicable for dating alluvial deposits (Repka et al., 1997; Hancock et al., 1999; Phillips et al., 2003; Woerd et al., 2006), but inherent prior exposure of these materials often requires a systematic age correction (by doing either sample amalgamation or depth profile measurements), which inevitably results in large age uncertainty and also makes the dating practice costly.

Varnish microlamination (VML) dating is a correlative age determination tool (cf. terminology in Colman et al., 1987). It is suitable for dating various desert landforms where rock varnish is formed (Liu and Dorn, 1996; Liu, 2003; Liu and Broecker, 2007). In this paper, we first establish a generalized late Quaternary (i.e., 0–300 ka) varnish layering sequence for the drylands of western USA (Fig. 1) and tentatively correlate it with the SPECMAP oxygen isotope record (Imbrie et al., 1984; Martinson et al., 1987). We then use this climatically correlated varnish layering sequence as a correlative dating tool to determine surface exposure ages for late Quaternary geomorphic features (particularly, alluvial fans, desert pavements, and colluvial boulder deposits) in the study region. Results from these studies intend to shed new light on our understanding of climatic influence on alluvial fan development, formation and evolution of desert pavements, and hillslope stability of colluvial boulder deposits in the study region.

Fig. 1. Map showing location of the study sites in the drylands of western USA (A) and map of the studied alluvial fans in Death Valley (B). Stars and a rectangle in (B) denote rock varnish sampling sites. Abbreviations used are Death Valley (DV), Cima volcanic field (CVF), Silurian Valley (SV), Yucca Mountain (YM), Badwater (BW), Mormon Point (MP), Galena Canyon fan (GC), Hanaupah Canyon fan (HC), Six Spring Canyon fan (SC), and Warm Spring Canyon fan (WC).
2. VML dating

Rock varnish is a slowly accreting (<1 to 40 μm/ky; Liu and Broecker, 2000) dark coating on subaerially exposed rock surfaces in arid to semiarid deserts of the world (Dorn and Oberlander, 1982). Because of its sedimentary origin, rock varnish often displays layered microstratigraphy (Fig. 2). Microlaminations in varnish were first reported by Perry and Adams (1978), who recognized their potential as a paleoenvironmental indicator in drylands. Microlaminations can be observed with a petrographic microscope when thin sections of varnish are polished to about 5–10 μm thick (or with a scanning electron microscope in the backscattered mode). Normal rock thin sections are 25–30 μm thick so we refer to the varnish sections as ultrathin (see Liu, 1994; Liu and Dorn, 1996, for methodology of making varnish ultrathin sections). Microprobe chemical analyses reveal that dark layers in varnish ultrathin section 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. 2). These two types of layers are intercalated to form a distinct microstratigraphy.

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

Fig. 2. Electron microprobe maps of elements (256×256 μm) in rock varnish on a sample from Galena Canyon fan in Death Valley. The image in the lower right corner shows the optical microstratigraphy seen in varnish ultrathin section under polarized light. The element imaged in each panel is shown in the black bar at the bottom of the panel and the color scale of elemental concentration is shown on the right side of the panel. A depth profile of Mn (with ∼2 μm focused beam) was taken along the vertical blue line marked on the inset image. As seen from these probe maps, silica (Si), aluminum (Al), potassium (K), and magnesium (Mg) achieve their highest concentrations in the yellow/orange layers in the middle of the varnish microstratigraphy, which are interpreted to represent the last interglaciation (the Holocene surface yellow layer is absent in this sample because of surface spalling). In contrast, manganese (Mn), barium (Ba), and calcium (Ca) achieve their highest concentrations in the dark layers, which are interpreted to represent the last and penultimate glaciations. This varnish contains a layering sequence of LU-1/.../LU-5/LU-6 (WP12), suggesting a minimum VML age estimate of ∼165 ka for the initiation of varnish formation on the sampled fan surface (see text for discussion).
interglacial, while Mn-rich black layers (usually containing 25–45% MnO) were deposited during wet periods of the last glacial time, and Mn-intermediate orange layers (usually containing 15–25% MnO) were formed during periods of climatic transition between extremely dry and extremely wet conditions (Broecker and Liu, 2001). The wet events represented by glacial-age black layers WP0 to WP6 (WP = wet event in Pleistocene) in varnish microstratigraphy have been shown to correlate in time with the cold episodes of the Younger Dryas and Heinrich events in the North Atlantic region (Liu and Dorn, 1996; Liu et al., 2000; Liu, 2003) (Fig. 3).

Varnish microlaminations as a correlative dating technique are relatively new and different in principle from and independent of both cation-ratio and AMS 14C methods (Dorn, 1983; Dorn et al., 1989). This technique was first used by Dorn (1988) to study the chronostratigraphy of alluvial fan deposits in Death Valley. Subsequent studies (Liu, 1994; Liu and Dorn, 1996; Liu, 2003) 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. Because climatic signals recorded in varnish are regionally contemporaneous (Liu and Dorn, 1996; Liu et al., 2000), VML can be used as a correlative dating tool to provide minimum-limiting surface exposure ages for varnished geomorphic surfaces in deserts. 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 nearly identical convergence of cosmogenic 36Cl ages and varnish-based age estimates for three basalt flows in the Pisgah, Cima, and Amboy volcanic fields demonstrates that VML is a valid tool for providing surface exposure ages of late Pleistocene (i.e., 12–85 ka) surficial geomorphic features.

Fig. 3. Temporal correlation of the late Pleistocene varnish climate record in the drylands of western USA with the GISP2 Greenland ice core record. Radiometric age calibration (Liu et al., 2000; Liu, 2003) indicates that wet events represented by Mn- and Ba-rich dark layers (WP0–WP6) in the varnish record largely correlate with cold periods of the Younger Dryas (YD) and Heinrich events (H1–H6) represented by the oxygen isotopic troughs (marked with shorthand arrows) in the ice core record (Grootes et al., 1993; Bond et al., 1999). The GISP2 timescale is from Meese et al. (1994) and Bender et al. (1994). The chronology of the YD and H1–H6 is from Bond et al. (1999). The color scheme represents relative concentrations of Mn and Ba in varnish microstratigraphy: black = Mn- and Ba-rich; orange = Mn- and Ba-intermediate; yellow = Mn- and Ba-poor. LU = layering unit, MIS = marine isotope stage, WP = wet event in Pleistocene.
in the Great Basin of western USA (Marston, 2003). New studies in the Great Basin (Liu and Broecker, 2007) have shown that varnish microstratigraphy also records Holocene wet events that largely correlate in time with Holocene cooling events uncovered in North Atlantic deep sea sediments (Bond et al., 1997, 1999) (Fig. 4). As a result, this radiometrically calibrated and climatically correlated Holocene varnish microstratigraphy has extended the VML dating potential to surficial geomorphic (and geoarchaeological) features of the Holocene (0–12 ka) (Liu and Broecker, 2007).

3. Late Quaternary varnish microstratigraphy

To further explore the potential of VML dating for surficial geomorphic features older than ∼85 ka, we herein establish a late Quaternary varnish microstratigraphy (Figs. 5 and 6). This generalized layering sequence contains a total of eight layering units (i.e., LU-1 to LU-8, from youngest to oldest), covering a time span of roughly 0–300 ka. LU-1 represents an overall thick surface yellow layer, indicative of the Holocene interglacial dry climate (ca. 0–12 ka) (Broecker and Liu, 2001). Earlier units LU-2, LU-3, and LU-4 altogether contain seven dark layers (WP0 to WP6) intercalated with six orange layers, indicative of a generally wet climate during the last glacial (ca. 12–74 ka) (Liu and Dorn, 1996; Liu, 2003). LU-5 contains three relatively thick yellow layers intercalated with two relatively thin dark layers (WP7 and WP8). LU-6 comprises five approximately evenly spaced dark layers (WP9 to WP13) intercalated with four orange layers. LU-7 may contain three thick orange layers intercalated with two relatively thin dark layers (WP14 and WP15), but further examination of more high-resolution and older (≥LU-7) varnish microstratigraphies is needed to confirm this observation. Like LU-4 and LU-
6, LU-8 also comprises five approximately evenly spaced dark layers (WP16 to WP20) intercalated with four orange layers. A detailed description of the characteristics of these layering units is given by Liu and Dorn (1996).

Electron microprobe analyses indicate that dark layers in layering units LU-5 through LU-8 are relatively enriched in Mn and Ba (about 25–45% for Mn and 2–4% for Ba); yellow layers are relatively depleted in Mn.

Fig. 5. Optical varnish microstratigraphies from late Quaternary alluvial fan surfaces in Death Valley. Note that similar layering patterns are replicated in different varnish microbasins on the same boulder (C and D; E and F) and on boulders from different fan surfaces (A and B), suggesting that microlaminations in varnish record regional environmental fluctuations, especially climate changes. Also note that varnish layering sequences in (E) and (F) are from a quartzite boulder on the oldest fan unit (Qu8) of Six Spring Canyon fan. This same varnished boulder has been cosmogenically $^{10}$Be dated at 297±11 ka, thus making these layering sequences the oldest varnish climate record yet uncovered and dated in the western USA drylands. See Figs. 1 and 8 and Table 1 for locations of these varnish samples.
and Ba (about 5–15% for Mn and <1–2% for Ba); orange layers often contain intermediate amounts of Mn and Ba (about 15–25% for Mn and 1–2% for Ba) (Figs. 2 and 10F). Thus, the chemical signatures of Mn and Ba in the older varnish microstratigraphy (≥LU-5) are similar to those in the younger varnish microstratigraphy (<LU-4) (Broecker and Liu, 2001), suggesting the same climatic origin for formation of these varnish microstratigraphies (Liu et al., 2000).

### 4. Climatic correlation

As a correlative age determination technique, VML dating depends largely on radiometric age calibration of varnish microstratigraphy. However, such age calibration has not been accomplished for late Quaternary varnish microstratigraphy for several reasons. First, collecting varnish samples from old geomorphic surfaces (≥LU-5) for microstratigraphic analysis is often difficult (see Liu and Dorn, 1996, for varnish sampling criteria). Most varnish from clasts and boulders on old surfaces is much younger than the geomorphic ages of the surfaces themselves. This is largely attributed to wind abrasion and/or spalling that commonly reset the varnish clock. Secondly, relatively few old geomorphic surfaces have been radiometrically dated or are potentially datable by available radiometric means. Thirdly, even on those old geomorphic surfaces that have been radiometrically dated, the accuracy and precision of the resulting ages are often too low (on an order of 10^3–10^4 yr) to provide definitive age.

![Graph showing correlation of varnish microstratigraphy with SPECMAP oxygen isotope record](image.png)

**Fig. 6.** A generalized late Quaternary varnish microstratigraphy and its tentative correlation with the SPECMAP oxygen isotope record. Evidence from this and other studies (Liu, 2003; Liu and Broecker, 2007) indicates that wet events represented by dark layers (WP0–WP20) in the varnish record most likely correlate with cold periods represented by oxygen isotopic troughs in the SPECMAP record during the past three glacial–interglacial cycles (i.e., 0–300 ka). The SPECMAP chronology is from Imbrie et al. (1984) and Martinson et al. (1987). Age assignments for dark layers WP0–WP6 are from Liu (2003) (see Fig. 3), and those for WP7–WP20 are largely based on the tentative correlation of the varnish record with the SPECMAP record (also see Fig. 7). The shorthand arrows identify cold periods (represented by substage isotopic troughs in the SPECMAP record) that likely correlate with dark layers within each layering unit. The color scheme represents relative concentrations of Mn and Ba in varnish microstratigraphy (see Fig. 3 for explanation). H = Heinrich event, LU = layering unit, MIS = marine isotope stage, WH = wet event in Holocene, WP = wet event in Pleistocene, YD = Younger Dryas.
calibration, which generally requires age accuracy and precision on an order of 10^2–10^3 yr (Liu, 2003; Liu and Broecker, 2007).

In order to build up a reasonable numerical chronology for late Quaternary varnish microstratigraphy, we pursue a temporal correlation between the varnish climate record and other well-established global climate proxies such as the SPECMAP oxygen isotope record (Imbrie et al., 1984; Martinson et al., 1987), as depicted in Fig. 6. Several lines of evidence support such a correlation. First, previous studies (Liu and Dorn, 1996; Liu et al., 2000; Liu, 2003; Liu and Broecker, 2007) have shown that LU-1 in varnish

<table>
<thead>
<tr>
<th>Sample site and label</th>
<th>Latitude (N) and longitude (W)</th>
<th>Altitude (m msl)</th>
<th>Oldest varnish layering sequence observed</th>
<th>VML age (ka)</th>
<th>Type VML image</th>
<th>Reference age (ka)</th>
<th>Geomorphic context and reference</th>
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<td>Fig. 9A</td>
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<td>Fig. 9D</td>
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*a Estimate is based on the altitude reading of each sampling site from Google Earth’s Europa satellite images (2007) and may be subject to an uncertainty of ±5 m.
microstratigraphy represents the Holocene interglacial, which by definition correlates with marine isotope stage one (MIS 1) (ca. 0–12 ka), and that LU-2, LU-3, and LU-4 collectively represent the last glaciation (ca. 12–74 ka), which correlates with MIS 2, 3, and 4 altogether (also see Figs. 3 and 4). Secondly, LU-5 is a layering unit that stratigraphically directly underlies LU-4 and contains three major Mn- and Ba-poor yellow layers intercalated with two minor Mn- and Ba-rich dark layers. Both optical and chemical signatures of this layering unit are remarkably similar to that of LU-1 (Figs. 2 and 5C,D), suggesting that LU-5 may represent the overall dry period of the last interglacial that correlates with MIS 5 (ca. 74–128 ka). Moreover, the two minor dark layers WP7 and WP8 within LU-5 represent two relatively short periods of wet climate, most likely correlating with two well-known cold reversals of substage MIS 5b (ca. 85–95 ka) and MIS 5d (ca. 105–115 ka) (Fig. 6). Thirdly, because a general correlation between the varnish climate record and the SPECMAP record exists for the most recent glacial–interglacial cycle (as discussed above), by the same token, the penultimate and antepenultimate glacial–interglacial cycles represented by LU-5/LU-6 and LU-7/LU-8 should correlate with MIS 5/6 and MIS 7/8, respectively (Fig. 6).

Finally, during the last glacial time, seven major wet periods represented by dark layers WP0 to WP6 in the varnish record have been shown to correlate in time with the cold periods of the Younger Dryas and Heinrich events (Liu et al., 2000; Liu, 2003), which are manifested as oxygen isotopic troughs in the North Atlantic deep sea sediment records (Bond et al., 1997, 1999; McManus et al., 1999) (Figs. 3 and 4). Similar dark layers, such as WP9 to WP13 in LU-6 and WP16 to WP20 in LU-8, are also observed in the late Quaternary varnish microstratigraphy (Fig. 5). By the same reasoning, wet events represented by these dark layers should correlate in time with cold periods represented by those oxygen isotopic troughs around MIS 6.2, 6.4, 6.42, and 6.6 during the penultimate glaciation (MIS 6), and around MIS 8.2, 8.4, and 8.6 during the antepenultimate glaciation (MIS 8), as depicted in Fig. 7.

One piece of geomorphic evidence that we have seems to support the validity of the above climatic correlation. A varnish sample from a quartzite boulder on the oldest fan unit of Six Spring Canyon fan, Death Valley, displays a layering sequence of LU-1/LU-2/LU-3/LU-4/LU-5/LU-6/LU-7/LU-8 (WP20) (Fig. 5E,F). If LU-8 generally correlates with MIS 8 and if the basal dark layer WP20 specifically correlates with the cold period associated with oxygen isotopic event MIS 8.6, as seen in Fig. 7, this layering sequence suggests a minimum age of ∼295 ka for varnish initiation on the sampled alluvial boulder. The same varnished boulder (a quartzite) has been cosmogenically 10Be dated, yielding a preliminary surface exposure age of 297±11 ka (1σ age uncertainties without correction for possible inherent prior exposure; Ivy-Ochs, ETH-Zurich, personal communication, 2007). This corroborates our climatic correlation of...

![Fig. 7. Tentative correlation of dark layers WP0–WP20 in the varnish record with the oxygen isotopic troughs in the deep sea sediment records of SPECMAP (blue line, right ordinate; Imbrie et al., 1984; Martinson et al., 1987) and ODP 980 (green line, left ordinate; McManus et al., 1999). Previous studies (Liu et al., 2000; Liu, 2003) have shown that such correlation exists for dark layers WP0–WP6, as illustrated in Fig. 3. By the same token, similar correlation likely exists for dark layers WP7–WP20, as depicted in this figure. The shorthand arrows denote the climatic correlation-based ages for the upper boundaries of these dark layers in Fig. 6. Vertical bars represent the marine isotope stage (MIS) boundaries.](image-url)
the late Quaternary varnish microstratigraphy with the SPECMAP record (Figs. 6 and 7).

5. Application

Once radiometrically calibrated and climatically correlated, varnish microstratigraphy can be used as a correlative dating tool to estimate numerical ages of geomorphic features in deserts (Liu and Dorn, 1996; Bell et al., 1998; Friend et al., 2000; Liu, 2003; Douglass et al., 2005; Cerveny et al., 2006; Liu and Broecker, 2007). In the following sections, we present several case studies to demonstrate the potential use of VML dating in studying late Quaternary alluvial fans, desert pavements, and colluvial boulder deposits in the study region. To assign absolute ages, we tentatively use the age scale in Fig. 6. We also point out that any varnish-based age estimates should be interpreted as minimum surface exposure ages for the dated geomorphic feature and the ages are only as good as our radiometric calibration and climatic correlation.

5.1. Dating alluvial fan aggradation events

Alluvial fans are distinct, cone-shaped, terrestrial landforms composed of stream and debris flow deposits; they occur where a canyon exits a mountain range (Bull, 1977; Dorn, 1994). Alluvial fans are built in semiarid, humid–temperate, and proglacial regions (Rachocki, 1981), but they are most dominant in drylands (Cooke et al., 1993). Death Valley is an ideal area for the purpose of this case study. First, a number of large alluvial fans are...
well developed and preserved there, providing a great opportunity to study fan morphostratigraphy (Fig. 1B). Secondly, rock varnish is ubiquitous and formed on alluvial fan surfaces of varying age, from late Holocene to mid Pleistocene, making VML dating of these geomorphic features possible. Thirdly, a great deal of previous research on alluvial fans in Death Valley has yielded a chronological framework of fan morphostratigraphy (e.g., Denny, 1965; Hunt and Mabey, 1966; Hooke, 1972; Dorn, 1988; Bull, 1991; Hooke and Dorn, 1992; Ibbeken et al., 1998; Knott et al., 2005), with which our new VML dating results may be compared and evaluated.

In this case study, varnish samples were collected from different fan units (Qu1 to Qu8) of Galena Canyon fan on the west side of Death Valley (Figs. 1B and 8), using sampling criteria detailed elsewhere (Liu, 1994; Liu and Dorn, 1996). Here, Qu1 to Qu8 are mapped on the basis of oldest layering units LU-1 to LU-8 (respectively) observed in varnish from these fan units. The youngest fan surfaces that we sampled (i.e., younger part of Qu4) comprise alluvial deposits with weakly developed desert pavements, mainly confined within the trunk channel of active washes. The slightly older surfaces (i.e., older part of Qu4) comprise alluvial deposits with clearly delineated fan morphology and well-developed desert pavements, usually located next to the trunk channel. Next older fan units (Qu5) are smooth, well-developed desert pavements with a petrocalcic horizon. Still older (Qu6) are smooth desert pavements with a well-developed petrocalcic horizon that have been dissected. The oldest units (Qu8) that we sampled are often characterized by ridge-and-ravine (ballena) topography, with petrocalcic rubble on surfaces. Table 2 gives a description of all mappable fan units identified in this study, their varnish-based age assignments, and comparison with other previously described fan units in the region (Dorn, 1988; Bull, 1991; Hooke and Dorn, 1992).

VML dating of varnish samples from these fan units yields new time constraints on major episodes of late Quaternary fan aggradation in Death Valley (Figs. 8 and 9). Sample A from the younger part of Qu4 displays a layering sequence of LU-1/LU-2/LU-3/LU-4 (WP3) (Figs. 8 and 9A), which stands for “layering sequence LU-1 through LU-4 with basal layer WP3” (see Liu, 2003, for terminology). Based on the VML age scale in Fig. 6, the basal dark layer WP3 in this sample started to form around 30 ka, which provides a minimum surface exposure age for formation (or abandonment) of the sampled fan surface. Similarly, samples B and C from the older part of Qu4 display a layering sequence of LU-1/LU-2/LU-3/LU-4 (WP6) (Figs. 8 and 9B,C), suggesting that these surfaces were formed around 60 ka, in accord with the timing of a fan aggradation event identified in the lower Colorado River region (Bull, 1991). Samples D and G from Qu5 display a layering sequence of LU-1/LU-2/LU-3/LU-4 (WP6+) (Figs. 8 and 9D; also see Fig. 5C,D), indicating...
that Qu5 was deposited around 74–85 ka. Sample E from Qu6 displays a layering sequence of LU-1/…/LU-5/LU-6 (WP12) (Figs. 8 and 9E), suggesting that Qu6 was deposited around ∼165 ka. Sample F from Qu8 displays a layering sequence of LU-1/…/LU-7/LU-8 (WP19) (Figs. 8 and 9F), implying that Qu8 was deposited around ∼276 ka. Although varnish older than LU-8 could not be sampled from the oldest fan unit Qu8+ because of surface erosion, the morphostratigraphic relationship between Qu8+ and Qu8 indicates that the former is somewhat older than the latter, thus having a VML age estimate of >303 ka (Fig. 8). Nishiizumi et al. (1993) reported two cosmogenic $^{10}$Be dates of 318±12 ka and 320±14 ka for their fan surfaces Q2a and Q1b, respectively. Because these $^{10}$Be-dated fan surfaces morphostratigraphically belong to our fan unit Qu8+ (Fig. 8), it implies that Qu8+ was deposited around 318–320 ka, largely in accord with our VML age estimate of >303 ka for this fan unit.

Clearly, the above VML age estimates are generally consistent with the morphostratigraphic sequence of the sampled fan units shown in Fig. 8. Compared to other previously published fan chronologies in Death Valley (Dorn, 1988; Bull, 1991; Hooke and Dorn, 1992; Table 2), our VML ages for these fan units are
more accurate and have better temporal resolution. Moreover, the fairly close agreement between our 
VML age estimate and two independently derived $^{10}$Be ages for fan unit Qu8+ illustrates the great potential of 
VML dating for late Quaternary alluvial deposits in the drylands of western USA.

5.2. Testing models of desert pavement formation

Desert pavements are common landforms in the arid regions of the world (Cooke et al., 1993). In the Mojave 
Desert, desert pavements are often seen as a continuous, one- to two-clast-thick layer of closely packed and well-
varnished gravel that armors low-relief alluvial fan surfaces (McFadden et al., 1987; Wells et al., 1995). Because 
relatively stronger pavement development is frequently 
observed on late Pleistocene surfaces than on Holocene 
surfaces, as indicated by the degree of associated soil 
formation, varnish coverage, and planarity, desert pave-
ments are widely used as a relative age indicator of 
alluvial fan surfaces in desert geomorphology (e.g., 
Hooke, 1972; Wells et al., 1985, 1987; McFadden et al., 
1989, 1998; Bull, 1991; McDonald et al., 1994; Knott 
et al., 2002; Helms et al., 2003). Early hypotheses 
proposed to explain the origin of desert pavements include wind deflation of fine particles, water erosion of 
fine clasts, or shrink–swell process of soils (e.g., Low-
dermilk and Sundling, 1950; Denny, 1965; Cooke, 1970; 
Johnson and Hester, 1972; Hooke, 1990; Thomas, 1997). 
The currently accepted model of pavement formation 
involves deposition of windblown sediments rather than 
deflation or water erosion of eolian silt and fine sand 
(McFadden et al., 1986, 1987; Wells et al., 1995). 
According to this model, desert pavements remain on an 
accretionary (i.e., vertical growing) mantle of soil-modi-
fied dust. This hypothesis implies that pavement clasts 
have been continuously exposed since cessation of depo-
sition of the underlying gravels; in other words, they are “born at the surface” (McFadden et al., 1987).

Rock varnish microstratigraphy offers a unique way 
to test this hypothesis. First, the apparently continuous 
varnish climate record of the past $\sim 300$ ky discussed 
above indicates that, once initiated, the varnish has been 
continuously exposed on rock surfaces to record envi-
ronmental fluctuations, especially climate changes. Any 
postdepositional burial of varnished clasts would termi-
nate, disrupt, or reset the varnish record. This evidence 
further indicates that the varnished clasts have indeed 
been continuously exposed at the surface since the ces-
sation of their deposition.

Secondly, if clasts have been continuously exposed at 
the surface since the cessation of deposition on that 
surface, they should have a surface exposure age close 
to that of the surface itself. To test this scenario, we 
collected varnish samples from a pavement surface in 
the Cima volcanic field of the Mojave Desert (Figs. 1 
and 10E; Table 1). This pavement was developed on a 
late Quaternary alluvial fan surface ($\sim 795$ m msl) that 
has been partially buried by a basalt flow. Cosmogenic 
$^3$He dating yielded two surface exposure ages of $72 \pm 7$ 
and $74 \pm 7$ ka for the flow emplacement (Wells et al., 
1995). This implies that the material on the fan surface 
was deposited before $72–74$ ka because it is stratogra-
phically older than the flow surface. The pavement 
surface was also cosmogenically $^3$He dated, yielding 
two maximum-limiting surface exposure ages of $80 \pm 10$ 
and $85 \pm 9$ ka (Wells et al., 1995). Varnish from the same 
$^3$He-dated pavement surface displays a layering se-
quency of LU-1/…/LU-4/LU-5 (WP6+), yielding a 
minimum age of $74–85$ ka for the pavement clasts 
(Fig. 10F). This VML age estimate perfectly falls in 
between the $^3$He age bracket of $72–85$ ka for the 
pavement formation, lending strong support for the 
“being born at the surface” model of desert pavement 
formation (McFadden et al., 1987).

Varnish samples were also collected from relatively 
young desert pavements in the study region to assess 
how fast pavements are formed. Samples from a late 
Pleistocene pavement surface ($12–70$ ka, about $30$ m 
below sea level; see Fig. 2.25 of Bull (1991)) at the foot 
of Hanaupah Canyon fan in Death Valley display a 
layering sequence of LU-1/LU-2/LU-3/LU-4 (WP3), 
yielding a VML age estimate of $30$ ka for the pavement 
(Figs. 10C,D). Samples from an incipient pavement 
surface ($\sim 215$ m msl) of early Holocene to latest 
Pleistocene age in Silurian Valley of the Mojave Desert 
(Mahan et al., in press) display a layering sequence of 
LU-1 (WH10), yielding a VML age estimate of $9.4$ ka 
for the pavement (Figs. 10A,B). These data, together 
with other VML age data presented in this study (see 
Figs. 8 and 9; Table 1), indicate that desert pavements 
can be developed rapidly (i.e., $<10$ ky) during Holocene 
(and probably late Pleistocene) in this environment; but 
one formed, they may survive for $74–85$ ky or even 
longer without being significantly disturbed by geo-
morphic processes operative at the pavement surface. 
This is largely consistent with the observed longevity of 
Pleistocene desert pavements at Lathrop Wells and Red 
Cone volcanoes in southern Nevada (Valentine and 
Harrington, 2006), but it casts considerable doubt on 
a previous claim that no alluvial desert pavements 
above $\sim 400$ m in Death Valley and the Mojave 
Desert are older than the latest Pleistocene ($\sim 15$ ka) 
(Quade, 2001).
5.3. Dating hillslope stability of colluvial boulder deposits

Colluvial boulder deposits are relatively stable colluvium, consisting of linear fields of well-varnished hillslope boulders (Dorn and Krinsley, 1994). They are ubiquitous on desert hillslopes in the arid regions of the world (e.g., Melton, 1965; Prokopovich, 1987; Nials and Davis, 1990; Whitney and Harrington, 1993; Dorn and Krinsley, 1994; Friend et al., 2000). Due largely to the well-developed varnish coverage associated with these deposits, they are often considered to be “stabilized or relict landforms” (Cooke et al., 1993). In the Yucca Mountain area of southern Nevada, Whitney and Harrington (1993) reported some oldest colluvial boulder deposits that are probably early to middle Pleistocene in age (i.e., \( \sim 660 \) ka) based on cosmogenic \(^{36}\)Cl dating of the deposits.

In order to evaluate the great antiquity of these deposits, we collected varnish samples from the largest boulder stripe on the west slope of the Yucca Mountain (Fig. 11A). The oldest varnish sample that we obtained from this site displays a layering sequence of LU-1/LU-2/LU-3/LU-4 (WP5), yielding a minimum VML age of 46 ka for the emplacement of these deposits on
the slope (Fig. 11B). Obviously, our VML age estimate is about an order younger than the reported $^{36}$Cl age of $\sim 660$ ka for similar colluvial boulder deposits in the same area (Whitney and Harrington, 1993), suggesting that either the varnish clock has been reset at least once and perhaps several times over the past 660 ky by surface spalling of the sampled boulder faces, or the $^{36}$Cl age is significantly biased by inherent prior exposure (Dorn and Krinsley, 1994), or both. In any case, our VML age estimate indicates that these boulder deposits have remained stable in their present geomorphic position for at least 46 ky, implying that they were probably formed during the early phase of the last glaciation or before.

6. Discussion

6.1. VML age scale

As demonstrated in the above three case studies, the VML age scale plays a critical role in VML age dating. Over the dating range of 0–85 ka, it depends largely on radiometric calibration and climatic correlation of varnish microstratigraphy well established by our previous studies (Liu et al., 2000; Liu, 2003; Liu and Broecker, 2007) (Figs. 3 and 4). For samples older than 85 ka, however, it depends largely on a proposed temporal correlation of the varnish climate record with the SPECMAP $\delta^{18}$O record (Figs. 6 and 7). In...
this study, we tentatively use the SPECMAP orbitally tuned chronology of 0–300 ka (Imbrie et al., 1984; Martinson et al., 1987) to assign specific numerical ages to the boundaries of layering units in varnish microstratigraphy (Figs. 6 and 7). Many paleoclimatic studies (e.g., Gallup et al., 1994; Tzedakis et al., 1997, 2001, 2003; McManus et al., 1999; Bard et al., 2002; Kukla et al., 2002; Cutler et al., 2003) have shown that the SPECMAP chronology is generally valid for global climatic correlation, with possible age uncertainty of about ±5 ky for the past 300 ky (Martinson et al., 1987). We also notice that some controversy exists regarding the SPECMAP age of 128 ka for the MIS 5/6 boundary or Termination II (Broecker and van Donk, 1970). A study from high-precision U/Th dating of aragonite-rich marine sediment in the Bahamas suggests that Termination II should be placed at 135 ka (Henderson and Slowey, 2000). Studies of deep sea sediments and cave deposits from other regions of the world appear to support such a suggestion (Spätl et al., 2002; Holzkämper et al., 2005). For the sake of internal consistency within the SPECMAP chronology, however, we continue to use 128 ka for the MIS 5/6 boundary.

For dark layers WP9–13 and WP16–20 within layering units LU-6 and LU-8, we tentatively use the SPECMAP chronology of substage isotopic troughs for age assignments, with a contention that wet events represented by these approximately evenly spaced dark layers generally correlate with cold events associated with those roughly evenly spaced substage isotopic troughs (Figs. 6 and 7). Similarly, for dark layers WP7–8 and WP14–15 within layering units LU-5 and LU-7, we use the SPECMAP chronology of MIS 5b, 5d and MIS 7b, 7d, respectively, for age assignments (Figs. 6 and 7). Because we do not know the time interval requested by the formation of each dark layer in the varnish microstratigraphy, we conservatively assign the youngest possible ending ages of these substage isotopic troughs to the upper boundary of each dark layer, as depicted in Fig. 7 (see, for example, WP9). The VML age scale thus derived is preliminary and somewhat speculative at this stage. Further studies on radiometric age calibration of late Quaternary varnish microstratigraphy are needed to refine our climatic correlation-based chronology.

6.2. Modulation of alluvial fan deposition by climatic changes

A fundamental issue in the study of alluvial fans is how they develop over time and how environmental factors, especially climatic changes, influence their development. The question of whether fan aggradation is favored by wetter or drier climates has been in debate for several decades. Studies in the Death Valley and lofty Sierra Nevada regions (e.g., Lustig, 1965; Dorn, 1988, 1994; Bull, 1991; Benn et al., 2006) indicate that fan aggradation events largely occurred during (glacial) humid climatic periods. Studies in the Mojave Desert and lower Colorado River regions (e.g., Wells et al., 1987; Bull, 1991; Harvey et al., 1999; McDonald et al., 2003) suggest that most fan aggradation occurred during transitions to interglacial (drier) climatic environments. Still, other studies in Death Valley (e.g., Hooke, 1967, 1972) indicate that fan aggradation may be as continuously as the climate changes represented by changes in rate of accumulation.

Our VML dating reveals that, during the mid to late Pleistocene, 5–15 ky long aggradation events occurred during either wet or dry climatic periods. Given the mapped fan units Qu1 through Qu8 in Death Valley, at least eight different aggradation events have been noted in the past 300 ky (Figs. 8 and 9; also see Liu and Dorn, 1996). Events that led to deposition of fan units Qu8, Qu6, Qu4, and Qu2 occurred during relatively wetter climatic periods represented in rock varnish by layering units LU-7, LU-5, LU-3, and LU-1, respectively. In other words, fan surfaces of these eight different units indicate that aggradation of alluvial fans has been fairly continuous for the past 300 ky. These results are consistent with many studies in global research on desert alluvial fans (Harvey, 2002b), particularly with studies finding specific connections to fan aggradation during wet Milankovitch-scale periods (Ritz et al., 2003; Bhandari et al., 2005; Owen et al., 2006), dry Milankovitch-scale periods (Chamyal et al., 2003; Hetzel et al., 2004; Pope and Wilkinson, 2005), and transitions from wet to dry (Carignano, 1999; Klingler et al., 2003) and dry to wet (Roberts and Barker, 1993; Eriksson et al., 2000; Jain and Tandon, 2003; Al Farraj and Harvey, 2004).

Our VML dating also reveals that major climate shifts between glacial and interglacial conditions may be the pacemaker for alteration of major episodes of fan aggradation (Figs. 8 and 9; also see Liu and Dorn, 1996). For instance, fan units Qu8 and Qu6 were deposited during the antepenultimate (MIS 8) and penultimate (MIS 6) glaciations, respectively; fan units Qu7 and Qu5 were deposited during the antepenultimate (MIS 7) and penultimate (MIS 5) interglaciations, respectively. During the last glaciation that
is represented collectively by MIS 4, MIS 3, and MIS 2, fan units Qu4, Qu3, and Qu2 were formed altogether. The present-day interglacial period (MIS 1) has witnessed deposition of fan unit Qu1.

During the Holocene interglacial time, however, 0.5–1 ky long brief episode of fan deposition may be linked to short-term periods of relatively wet climate. For example, the varnish from the incipient desert pavement in Silurian Valley displays a layering sequence of LU-1 (WH10) (Figs. 10A,B), suggesting that deposition of the alluvium underlying this pavement likely occurred during a relatively wet period around 9.4 ka, represented by the basal dark layer WH10 in the layering sequence (Figs. 4 and 10B). Our previous studies (Liu and Broecker, 2007) also indicated that buildup of small debris flow fans in Death Valley was more likely tied to the Holocene millennial-scale wet events in the region, as illustrated in Fig. 12.

Notably, some inherent limitations exist in the use of VML results to connect geomorphic events with climatic change. First, diachronous geomorphic events could have taken place during decadal or centennial wet or dry periods within a millennial-scale VML signal; when viewed across a time period of $\sim 10^3$ yr, these events may appear synchronous (Thomas, 2004). Secondly, the climatic conditions needed to cause a change in varnish layering may not necessarily match the threshold needed to alter geomorphic systems such as alluvial fans. Thirdly, the response time of geomorphic systems to climatic change in arid to semiarid environments, which is probably on an order of $10^2–10^4$ yr (Bull, 1991), may be different from that of rock varnish, which is generally on an order of $10^2–10^3$ yr (Liu, 2003; Liu and Broecker, 2007). Finally, single chronometric tools should always be viewed as needing verification, especially when attempting correlations with sub-Milankovitch-scale events. The use of multiple chronometric tools, such as cosmogenic nuclides or optically stimulated luminescence (OSL) with VML, would assist in identifying definitive clustering of fan-altering climatic events.

6.3. Implications for cosmogenic surface exposure dating

Abundant data in the literature of cosmogenic dating indicate that some rock surfaces remain stable for $\sim 10^4$ yr or more. In a classic example of the inherent spatial variability of postglacial erosion, Cerling and Craig (1994) measured $^3$He in rock polished at $\sim 13$ ka by the Makanaka glacier in Hawaii. This result is similar to that obtained by Dorn et al. (1991) using $^{36}$Cl. The almost identical convergence of $^{36}$Cl and $^{10}$Be/$^{26}$Al ages of $\sim 50$ ka for the same boulders at Meteor Crater, Arizona (Nishiizumi et al., 1991a; Phillips et al., 1991), similarly implies close to zero rates of erosion — as does the convergence of $^3$He (Cerling and Craig, 1994) and $^{38}$Cl ages of $\sim 80$ ka (Zreda et al., 1993) for Lathrop Wells volcano in southern Nevada. Erosion rates would have to be $< 1$ mm/ky for the ages yielded by these different cosmogenic isotopes to converge so well. In a different example, Nishiizumi et al. (1991b) also documented close to zero rates of erosion in the harsh periglacial environment of Antarctica. This does not imply that cosmogenic data reveal that all surfaces are so stable; other results are consistent with rapid rates of erosion (Cerling and Craig, 1994). A reasonable claim can be made here that some boulder surfaces may remain extremely stable at the land surface for tens to hundreds of thousands years.

Varnish data obtained from this study strongly support this claim. Rock varnish is a kind of sedimentary accumulation on subaerially exposed rock surfaces. The development of rock varnish on alluvial boulder faces implies basically zero rates of erosion since the onset of the varnish. Even a micron of boulder erosion would result in a loss of the overlying varnish. Thus, dating the onset of rock varnish indicates the last time a boulder erosion event occurred, either by spalling, biochemical activity (e.g., lichens), or mechanical abrasion. Our finding that varnish can continuously accumulate over periods of $10^4–10^5$ yr (see Figs. 5 and 9, 10, 11) is consistent with the cosmogenic data. This suggests that, in the drylands of western USA, zero rates of erosion should be used in calculating surface exposure ages of late Quaternary (0–300 ka) alluvial boulders with cosmogenic dating if they still retain fluviually polished faces.

VML dating may also be used to assess the inherent prior exposure associated with cosmogenic dating of alluvial deposits. As a conservative age determination tool, VML dating always yields minimum-limiting surface exposure age for a given geomorphic feature. Because of the existence of a certain amount of inherent prior exposure in alluvial boulders, however, cosmogenic dating often yields maximum-limiting surface exposure age for these deposits. By dating the same boulder with both methods, we may be able to determine the age bias associated with the inherent prior exposure of the boulder. This would greatly improve our understanding of the prior exposure history of alluvial boulders, a costly task that is presently done by doing sample amalgamation or depth profile measurements in cosmogenic dating.
6.4. Limitations of VML dating

As is the case for any Quaternary age determination technique, VML dating has some intrinsic limitations that may hinder its application. First, this method can be applied only in desert regions where rock varnish is formed and well preserved. Secondly, because of spatial variations of late Quaternary climate changes on a...
global scale (for example, glacial-time wet periods in the Great Basin vs. dry periods in the Lake Eyre Basin of Australia; see Benson et al., 1990; Hesse et al., 2004), the varnish microstratigraphy that we have constructed herein may not be applicable in other deserts of the world. For the method to be used there, a regional varnish microstratigraphy must be established, radio metrically calibrated, and climatically correlated. Thirdly, learning how to do VML dating is a long, apprentice-like process and many years of field/laboratory training and experience are needed to master the technique. Fourthly, although making varnish ultrathin sections is difficult and time-consuming, the most difficult task in VML dating is sampling the oldest possible varnished boulders on a given geomorphic surface in the field and selecting the oldest possible varnish-filled microbasins on a specimen in the lab. This has to be done even before one knows how old a geomorphic surface of interest really is. Lastly, correct interpretation of varnish microstratigraphy is always a challenging task, which is largely experience-dependent. Complications, such as postdepositional leaching, abrasion of surface varnish layers (by natural processes or during sample preparation), spatial and altitudinal variations of varnish chemistry (particularly Mn and Ba contents), multiple/missing layers, and differential varnish growth, often make the interpretation indefinite and thus more subjective (Liu and Dorn, 1996; Liu, 2003). A simple way of dealing with these problems is just making more varnish ultrathin sections to uncover the most unambiguous and replicable layering patterns.

7. Conclusion

After nearly three decades of serious research, acrimonious debates, and rigorous blind testing, rock varnish microstratigraphy has finally emerged as probably the most reliable (and also least controversial) dating technique among varnish methods. When properly applied, the VML approach can be used to date late Quaternary surficial geomorphic and geoarchaeological features, with a possible age resolution of 500–1000 years in the Holocene and a few thousands of years in the mid to late Pleistocene. Although future progress in high-resolution radiometric dating of paleoclimatic records will unavoidably lead to some refinement and modification of the VML age scale used in this study, the generalized late Quaternary varnish layering sequence should basically remain the same and can be used independently as a regional correlation and mapping tool. As demonstrated in this and other studies (Liu and Dorn, 1996; Bell et al., 1998; Friend et al., 2000; Liu, 2003; Cerveny et al., 2006; Liu and Broecker, 2007; also see VML Dating Lab’s website at www.vmldatinglab.com for more examples), application of the VML dating will surely open new research avenues in studies of desert geomorphology, geoarchaeology, and neotectonics in the western USA drylands.

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