ELSEVIER
Palaeogeography, Palaeoclimatology, Palaeoecology 161 (2000) 423–433
PALAEO
www.elsevier.nl/locate/palaeo

Terminal Pleistocene wet event recorded in rock varnish from Las Vegas Valley, southern Nevada

Tanzhuo Liu [a,*], Wallace S. Broecker [a], John W. Bell [b], Charles W. Mandeville [c]

[a] *Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA*
[b] *Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA*
[c] *Department of Earth and Planetary Sciences, American Museum of Natural History, New York, NY 10024, USA*

Received 14 October 1999; accepted for publication 9 March 2000

Abstract

Analyses of rock varnish samples from latest Pleistocene alluvial-fan surfaces in Las Vegas Valley, southern Nevada, reveal replicable lamination patterns that are characterized by low-Mn orange surface layers and high-Mn dark basal layers. Radiocarbon dating from beneath the sampled alluvial-fan surfaces suggests that the Mn-rich basal layers accumulated during a short wet phase 10–11 ^{14}C ka when extensive black mats were deposited throughout the region, and paleolake records in the Great Basin also indicate wet conditions during this time period. In contrast, the Mn-poor orange surface layers formed under relatively dry conditions in the Holocene. Thus, these varnish microlaminations are connected with environmental fluctuations that appear to be related to climate change. Evidence from Las Vegas Valley, together with that from Death Valley and the Mojave Desert, suggests that the deposition of these Mn-rich dark basal layers in rock varnish likely corresponded in time to the terminal Pleistocene Younger Dryas-aged wet event in the Great Basin.

Keywords: alluvial fan; climate change; Pleistocene; rock varnish; the Great Basin; Younger Dryas

1. Introduction

Obtaining climate records in arid terrestrial regions has proven very difficult. These regions are largely occupied by modern deserts where conventional climate proxies are either not applicable or datable. Pollen records in deserts are often confusing due to the influx of grains from neighboring mountains. Raised shorelines in closed basin lakes, while being excellent indicators for moisture condition of the past, provide only a few points in time. Except in rare cases like Searles Lake (Smith, 1979; Benson et al., 1990; Phillips et al., 1994) and Lake Estancia (Allen and Anderson, 1993), lake sediments often lack useful climate proxies. In an attempt to improve this situation, we explore the climate record kept in rock varnish.

Rock varnish, or desert varnish as it was traditionally termed, is a dark coating on rocks of diverse lithology, with a typical thickness rarely exceeding 200 μm (Liu and Broecker, 2000). It is ubiquitous in arid to semiarid regions of the world, and consists mainly of Mn- and Fe oxides, and clay minerals (Engel and Sharp, 1958; Potter and Rossman, 1977). Due to its distinct chemical composition from that of the substrate rock, rock varnish is considered of sedimentary origin (Hooke et al., 1969; Perry and Adams, 1978), and its ingredients are largely supplied from the atmo-

* Corresponding author. Fax: +1-914-365-8155.
E-mail address: tanzhuo@ldeo.columbia.edu (T. Liu)

PII: S0031-0182(00)00097-3

sphere delivered in dust, aerosols, rain or dew (Fleisher et al., 1999). Like a macroscale sedimentary basin, varnish-filled microscale basins (usually 2–4 mm-sized dimples) on subaerially exposed rock surfaces often have sedimentary features such as layered stratigraphy (Liu and Dorn, 1996), which constitutes a recording medium of past environments.

Microlaminations in varnish were first observed by Perry and Adams (1978), who recognized their potential as a paleoenvironmental indicator in drylands. Subsequent studies verified their conclusions that orange layers observed in varnish thin sections are Mn-poor, black layers are Mn-rich, and that these layers are laterally continuous (Dorn, 1992, 1994; Liu, 1994). Recent studies by Liu and Dorn (1996) demonstrated that patterns of varnish microlaminations can be correlated from place to place in a given region, suggesting a possible environmental control on the formation of varnish microlaminations. Over the last two decades, microlaminations in varnish have been frequently used by researchers as supportive evidence for environmental variations in deserts (Dorn, 1988, 1990; Hooke and Dorn, 1992; Liu and Dorn, 1996). However, due to the difficulty in radiometric dating of rock varnish, there is no clear evidence to suggest whether the formation of varnish microlaminations is tied to environmental, especially climatic, fluctuations. In this paper, we document a case study in the western United States to show that microlaminations in rock varnish are likely connected with moisture variations produced by a terminal Pleistocene wet event.

2. Methods

2.1. Study Site and Sample Collection

The upper Las Vegas Valley, southern Nevada (Fig. 1), was chosen as our study site for several reasons. First, the late Quaternary alluvial history is well defined, and radiocarbon-datable organic-rich layers (black mats) are common (Haynes, 1967; Quade, 1986; Quade et al., 1998), providing control on the timing of initiation of varnish formation on alluvial-fan surfaces. Secondly, the studies on black mat formation yield a record of groundwater and paleospring discharge intensity in this area (Quade et al., 1998), providing a means of calibrating the varnish record. Lastly, the study area is located 150 km to the east of Death Valley and about 200 km to the north of the Mojave Desert, California, where detailed late Quaternary varnish lamination sequences have been established and calibrated (Liu and Dorn, 1996), thus offering an opportunity to test whether lamination patterns in varnish from those regions are comparable.

Detailed morphostratigraphic mapping of latest Pleistocene and Holocene alluvial fans in the Tule Springs area of Upper Las Vegas Valley (Bell et al., 1998) provided a relative age control for the varnish sample locations (Fig. 1). All of the carbonate boulders on alluvial-fan surfaces tend to be varnish-poor or varnish-free due to their weak surface resistance to weathering. However, we successfully collected a total of 12 varnish samples from the more siliceous portions of these boulders, nine from location A and three from location B (Fig. 1; Table 1). Criteria used to select samples included: (1) only alluvially abraded boulders with well-developed (but patchy) varnish were chosen; (2) boulders had to be large enough (>15 cm in size) to reduce the likelihood of post-depositional burial or turnover; and (3) boulders had to have both dark varnish on top and a reddish stain of iron films on the bottom. The existence of iron films implies the 'in-situ' formation of the top dark varnish and greatly reduces the probability of sampling dark varnish that may have been inherited from the prior exposure.

2.2. Laboratory analyses

In the lab, varnish samples were carefully examined under a 45 × binocular stereo microscope. Based on degree of varnish development and the size, shape and surface texture of varnish-filled microbasins on rock surfaces, the five best varnish samples (three from location A and two from location B) were selected for ultra-thin sectioning (Liu, 1994), microscopic imaging, and further chemical analyses with electron microprobe (Table 1). It should be kept in mind that not all varnish-filled microbasins on a sampled boulder

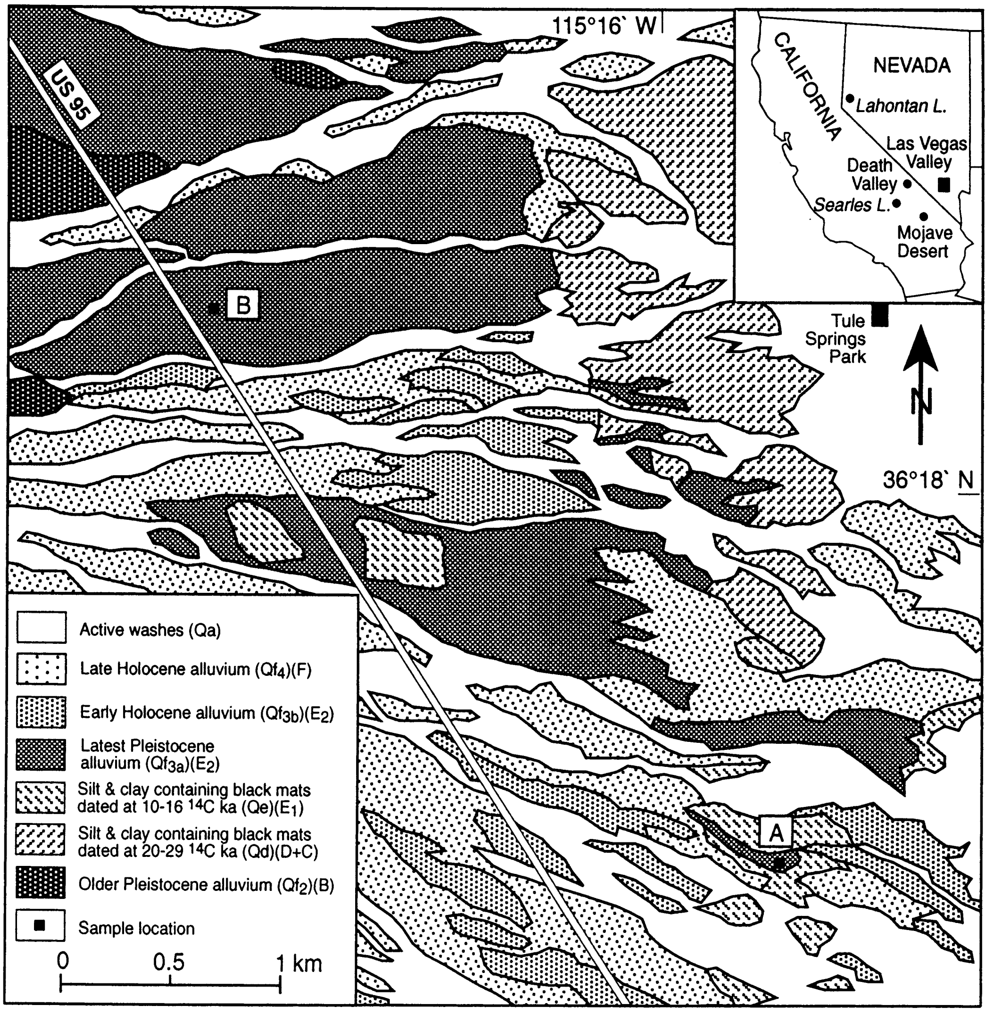


Fig. 1. Location map showing the study site in Upper Las Vegas Valley of southern Nevada. Also shown is a geological map of the Kyle Canyon alluvial fan in the Tule Springs area, modified after Bell et al. (1998). The map units are taken from Bell et al. (1998), and we show the corresponding units D, E, and F of Haynes (1967).

necessarily contain the same microstratigraphy or lamination pattern. Varnish in some microbasins may have formed earlier than in others and thus may contain older lamination patterns. Efforts were made to choose the oldest varnish-filled microbasins on the sampled boulder, which is experience-dependent. In this way, we were able to obtain varnish lamination patterns that are believed to most likely represent the entire exposure history of the sampled fan surfaces.

X-ray mapping and chemical analyses of the varnish samples were done with a Cameca SX100 electron microprobe at the American Museum of Natural History, utilizing an accelerating voltage of 15 keV, 10 nA beam current, and focused beam. The count time was 20 s on peak and 10 s on background. Natural and synthetic mineral and glass standards were used for calibration and checks on precision and accuracy.

2.3. Late Quaternary stratigraphy of the study area

The late Quaternary stratigraphic record in Upper Las Vegas Valley is characterized by

Table 1
Rock varnish samples examined in this study

Sample location in Fig. 1	Best varnish samples culled out in the lab for analyses	Lithology of substrate rock	Ultra-thin sections[a] prepared	Number of varnish microbasins with lamination patterns as shown in Fig. 3
Location A	98-LV-1A	Siliceous limestome	LV-1A-1	2
			LV-1A-2	3
	98-LV-1C	Siliceous limestone	LV-1C-1	2
			LV-1C-2	3 (Fig. 3b)
			LV-1C-3	4 (Fig. 3a)
	98-LV-1G	Siliceous limestone	LV-1G-1	2
			LV-1G-2	3 (Fig. 3c)
			LV-1G-3	2 (Fig. 3d)
Location B	98-LV-3	Sandstone	LV-3-1	2
			LV-3-2	3 (Fig. 3e)
			LV-3-3	3 (Fig. 3f)
	98-LV-4	Siliceous limestone	LV-4-1	2
			LV-4-2	2 (Fig. 3g)
			LV-4-3	3 (Fig. 3h)

[a] Ultra-thin sections are about ~5 μm thick. These are much thinner than regular geological thin sections, which are ~30 μm thick.

repeated cycles of paleospring deposition, fluvial erosion, and fan alluviation. An extensive valley-bottom fill sequence consisting of organic-rich silts, clays, and muds was first divided into units A through F by Haynes (1967). Numerous radiocarbon dates place the ages of these units between 4.5 and >40 ka (Haynes, 1967; Quade, 1986; Bell et al., 1998, 1999). Originally believed by Haynes (1967) to be primarily lacustrine in origin, Quade (1986) and Quade et al. (1995) demonstrated that these units were paludal deposits associated with paleospring discharge during wet climatic periods. The most recent cycle occurred during a late glacial period when extensive Unit E paleospring deposits containing prominent organic layers (black mats) formed throughout the valley; Quade et al. (1998) suggested that this late glacial event was largely Younger Dryas in age (~10.5 ^{14}C ka) (cf. Broecker, 1994).

The cycles of deposition were separated by periods of deep channeling and erosion of the paleospring deposits and by broad alluvial-fan deposition on the piedmonts surrounding the valley. During the late phases of Unit E deposition, a series of alluvial-fan gravels were interbedded with, and capped, the silts and muds. Haynes (1967) differentiated these capping alluvial deposits as Unit E_2 to distinguish them from the underlying silts and muds which he designated Unit E_1. Detailed surficial mapping of the alluvial fans in Upper Las Vegas Valley showed that multiple-age fan deposits comprise the E_2 gravels, and the units were further divided by Bell et al. (1998, 1999). Haynes (1967) estimated the age of the E_2 gravels at 7.5–11.2 ^{14}C ka, based on radiocarbon dating east of our study area, and he suggested that this cycle of deposition was followed by erosion beginning after about 7 ^{14}C ka.

In the study area near Tule Springs Park (Fig. 1), we used the surficial relations mapped by Bell et al. (1998) to provide detailed age control for our sample sites. Unit E_1 paleospring deposits (Qe of Bell et al., 1998; see Fig. 1) are radiocarbon-dated in many locations at between 10–16 ^{14}C ka. The alluvial-fan gravels that we studied (unit Qf_{3a}) are the oldest and topographically highest of the E_2 gravels in the area. The younger E_2 alluvial-fan gravels (Qf_{3b}) are topographically inset 3–5 m below the Qf_{3a} fan surfaces, a relation that establishes the relative ages of the two deposits. At the main sample site A, 0.6 m thick Qf_{3a} fan deposits lie directly over three 5- to 10 cm thick black mats of peat, carbonized wood, and charcoal contained in mud and fluvial silt of Qe (Fig. 2). Radiocarbon ages obtained from these horizons at depths of 2.4, 3.8, and

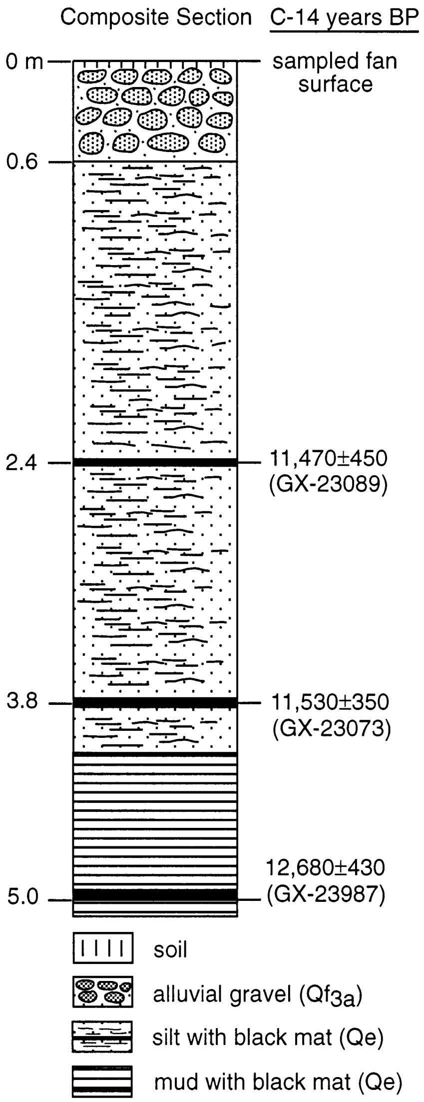


Fig. 2. Composite stratigraphic section and radiocarbon chronology at location A in Fig. 1.

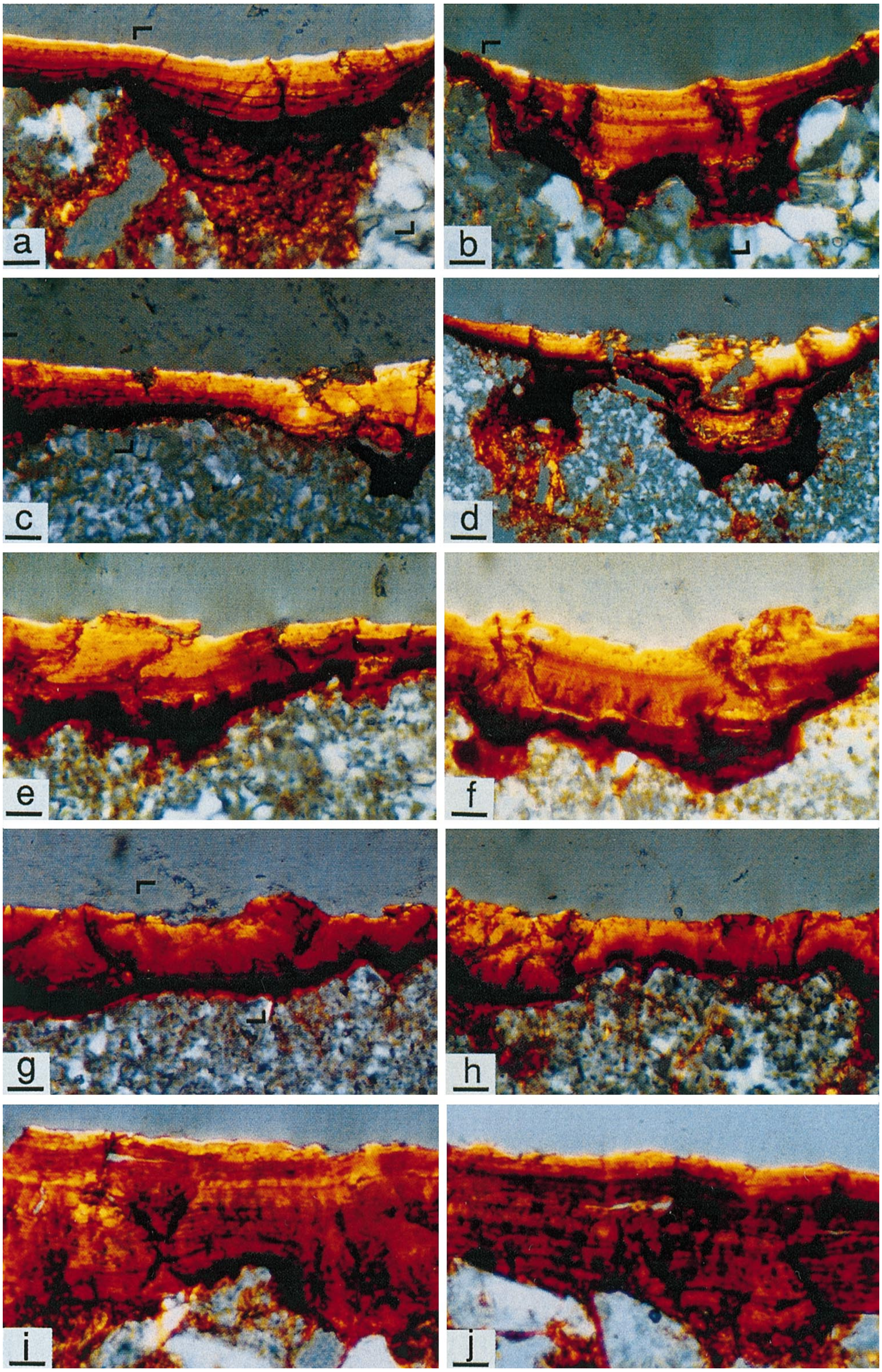
5.0 m below the fan surface were 11 470±450 (GX-23089), 11 530±350 (GX-23073), and 12 680±430 (GX-23987) ^{14}C yr BP, respectively (Bell et al., 1998). The ages of the upper two black mats are in consistent stratigraphic order, but they are virtually identical within the range of dating uncertainty, suggesting that the deposition of the fluvial silt containing the dated layers was relatively rapid (~2 m/100 yr).

Based on the conformable contact between the Qf_{3a} gravels and the underlying Qe paleospring deposits, we infer that the sampled fan surface aggraded shortly after the deposition of the black mats at ~11.5 ^{14}C ka. This age is consistent with that estimated by Haynes (1967) for the oldest E_2 gravels. It is also consistent with soils developed in the sampled deposits: cambic B_w and stage II B_k horizons indicative of a latest Pleistocene to early Holocene age in the southern Great Basin (cf. Harden et al., 1991). At a minimum, this oldest fan surface developed after 11.5 ^{14}C ka and before deposition of the next youngest fan deposit (Qf_{3b}). Based on detailed mapping 10 km north of the study area, Qf_{3b} fan gravels were deposited shortly after 9920±280 (GX-23087) ^{14}C yr BP (Bell et al., 1999).

In summary, stratigraphic relations and the maximum-limiting ages of 11.5 and 9.9 ^{14}C ka for Qf_{3a} and Qf_{3b}, respectively, strongly suggest that the sampled fan gravels Qf_{3a} are no younger than earliest Holocene (~10 ^{14}C ka).

3. Results and discussion

Microscopic examination of 36 varnish microbasins on 14 ultra-thin sections of the five selected rock samples revealed a clearly defined lamination pattern (Fig. 3). This pattern consists of an orange surface layer that is usually 20–40 μm thick underlain by a dark basal layer that is usually 5–10 μm thick; layers of both types are laterally continuous for hundreds of microns within each individual microbasin. Similar lamination patterns are replicated in varnish from different microbasins on the same boulder face, on different boulders from the same fan surface at the same location, and on different boulders from the same morphostratigraphic fan unit at different locations (Fig. 3a–h, Table 1). High-resolution (~2 μm) X-ray elemental mapping and line profile analyses by electron microprobe revealed that basal dark layers in the varnish contain 30–45% MnO, while the surface orange layers contain 15–25% MnO (Fig. 4; also see Fleisher et al., 1999). Such dramatic variations of Mn content in varnish stratigraphy appear to reflect a major environmental


a
b
c
d
e
f
g
h
i
j

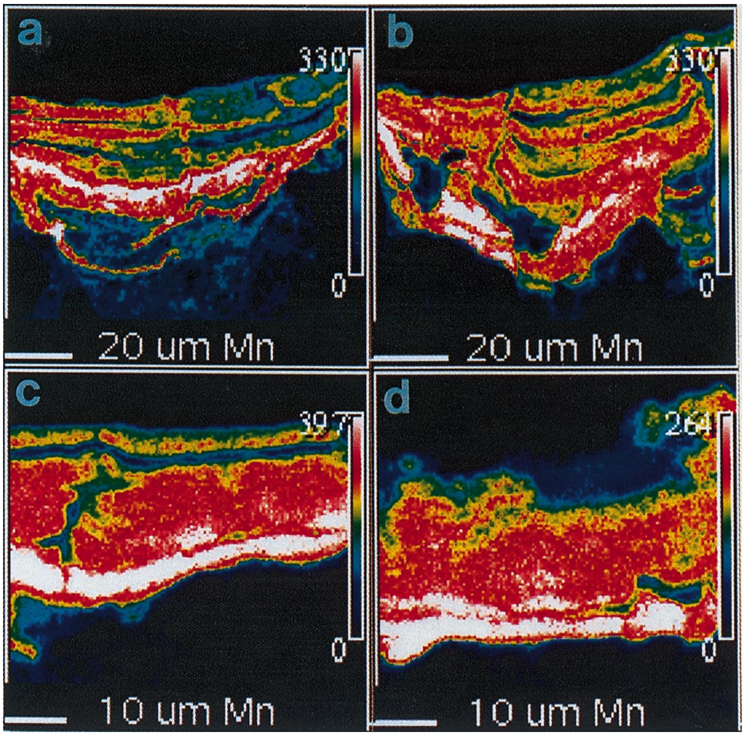


Fig. 4. Chemical microlaminations of Mn in varnish, as mapped by X-ray electron microprobe. The color scale on each image represents relative concentration of Mn: white band indicating 30–45% MnO, red band 15–25%, and green band 5–10%. The corresponding color images in Fig. 3 are: a (Fig. 3a), b (Fig. 3b), c (Fig. 3c), and d (Fig. 3g).

fluctuation in the study area (cf. Perry and Adams, 1978; Cremaschi, 1996).

The timing for the deposition of the Mn-rich dark basal layers can be constrained with available age control. Radiocarbon dating of the black mats underneath the sampled Qf_{3a} fan surface indicates that the fan surface aggraded slightly after ~ 11.5 ^{14}C ka. This is a maximum-limiting age for the onset of varnish formation on the fan surface. Studies on accumulation rates of rock varnish in the western US drylands show that, under certain conditions, decades to a few hundred years may be needed to initiate varnish formation on subaerially exposed stable rock surfaces (Dorn and Meek, 1995; Liu and Broecker, 2000). If a lag time of several hundred years is assumed for varnish to grow on the abandoned fan surface in the study area, the Mn-rich dark basal layers in the varnish probably started to accumulate around ~ 11 ^{14}C ka. Further, we tested this model by collecting rock varnish samples from Qf_{3b} fan surfaces 10 km north of the study area. As discussed above, these fan surfaces are no older than 9.9 ^{14}C ka (Bell et al., 1999). Varnish samples from

Fig. 3. Optical microlamination patterns seen in varnish ultra-thin sections under a microscope with cross-polarized light. Varnish samples of images a–h were from the Qf_{3a} fan surfaces (10–11.5 ^{14}C ka) in the study area, and those of images i and j from the Qf_{3b} fan surfaces (9.9 ^{14}C ka) in a site 10 km north of the study area. Note that similar lamination patterns consisting of a thick orange surface layer underlain by a relatively thin dark basal layer are replicated in images a–h. Also note that no comparable dark basal layers are observed in images i and j; rather, the relatively weak and thin dark layers are seen within the overall thick orange layers, presumably diagnostic of the Holocene wet phases in the Great Basin of the western United States (cf. Liu and Broecker, 1999). Markers on images a, b, c, and g identify opposing cornered areas mapped by electron microprobe and shown in Fig. 4. The scale bar is 13 μm for a, b, e–h, 20 μm for c, d, and 6 μm for i, j.

these fan surfaces display no basal dark layers, only orange surface layers (Fig. 3i and j), suggesting that the deposition of the Mn-rich dark basal layers in the varnish terminated just before the onset of the Holocene.

The deposition of the Mn-rich dark basal layers appears to correspond in time to a terminal Pleistocene wet event. On a local scale, studies by Quade et al. (1998) demonstrated that extensive black mats were formed in Las Vegas Valley between 10 and 11 ^{14}C ka at the same time as the Younger Dryas (Fig. 5f). On a regional scale,

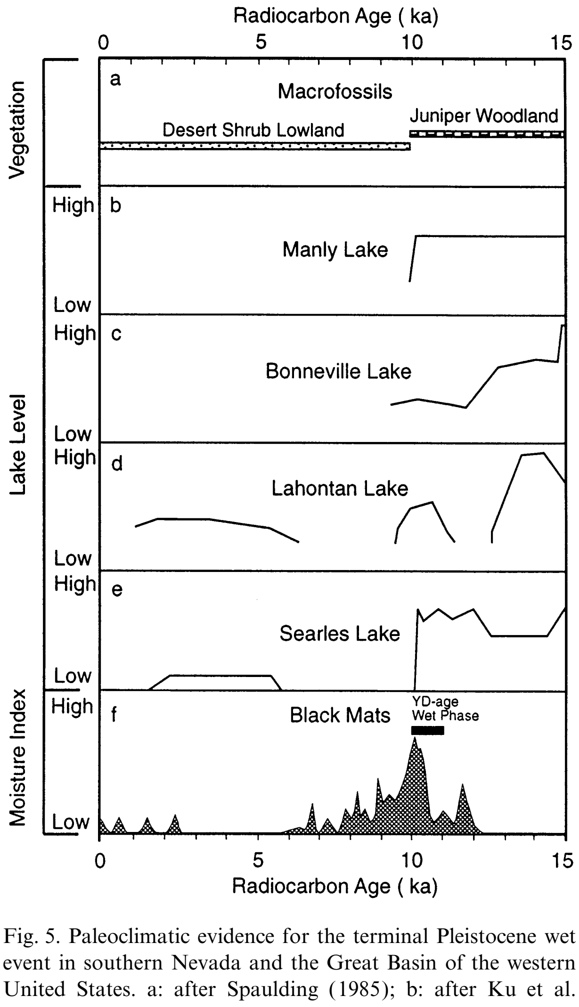


Fig. 5. Paleoclimatic evidence for the terminal Pleistocene wet event in southern Nevada and the Great Basin of the western United States. a: after Spaulding (1985); b: after Ku et al. (1998); c: after Oviatt et al. (1992); d: after Benson et al. (1995); e: after Smith (1979); f: after Quade et al. (1998). YD: Younger Dryas.

lakes in the Lahontan basins formed the Russell shoreline complex between 10 and 11 ^{14}C ka (Currey, 1990) (Fig. 5d). Searles Lake in the Mojave Desert rejuvenated for a short period of time around 10.5 ^{14}C ka (Smith, 1979) (Fig. 5e). A 64–78 m deep Lake Manly in Death Valley existed between 10 and 35 ka (Hooke, 1972; Ku et al., 1998) (Fig. 5b). In the Bonneville basin, a small lake rose to occupy the Gilbert shorelines between 10.3 and 10.9 ^{14}C ka (Currey, 1990) (Fig. 5c). In contrast, evidence from Owens Lake, California is supportive of dry conditions at this time (Benson et al., 1997). In summary, both black mats and most paleolake records suggest a short phase of wet climate at the termination of the Pleistocene in the present-day drylands of the Great Basin. Taking all the evidence together, we conclude that the Mn-rich dark basal layers in the varnish from Las Vegas Valley accumulated under a relatively wet climate around 10–11 ^{14}C ka.

Our data also indicate that the Mn-poor orange surface layers in the varnish accumulated under a drier climate during the Holocene. Of a total of 36 varnish microbasins examined, all displayed Mn-poor orange surface layers, which overlie the Mn-rich dark basal layers. Based on this microstratigraphic relationship and the timing for the formation of the basal varnish layers, the Mn-poor orange surface layers should be younger than ~ 10 ^{14}C ka; thus, they formed during the Holocene. In Las Vegas Valley, the overall climate was relatively drier in the Holocene than in the terminal Pleistocene, as indicated by the decline in black mat formation after ~ 10 ^{14}C ka (Quade et al., 1998) (Fig. 5f). Other evidence also indicates similar dry conditions in the Great Basin during the Holocene. The plant macrofossil record suggests that a widespread juniper woodland below 1800 m in the Yucca Mountains area of southern Nevada was replaced by what are now desert shrub lowlands after ~ 10 ^{14}C ka (Spaulding, 1985) (Fig. 5a). Closed-basin lakes such as Searles Lake and Lake Manly desiccated after 10 ^{14}C ka (Hooke, 1972; Smith, 1979; Ku et al., 1998) (Fig. 5b and e); large lakes such as Lake Lahontan and Lake Bonneville dropped below their latest Pleistocene maximum water levels at this time (Oviatt et al., 1992; Benson et al., 1995) (Fig. 5c and d). Therefore, the Holocene dry climate is likely to be responsible for the formation of the Mn-poor orange surface layers in the varnish.

More evidence from Death Valley and the Mojave Desert supports that the climate signals recorded in rock varnish are of regional extent. In Death Valley, varnish from the abandoned shorelines of Lake Manly dated at <18 ka (Ku et al., 1998) and alluvial-fan surfaces of latest Pleistocene age displays a lamination pattern that consists of a thick orange surface layer underlain by a thin dark basal layer (Fig. 6a and b). Similar patterns are also observed in varnish from shoreline A of Silver Lake in the Mojave Desert that is dated at 10.5–15 ^{14}C ka (Wells et al., 1987) (Fig. 6c and d). These age constraints further suggest that the dark basal layers in the varnish formed around 10–11 ^{14}C ka in response to the terminal Pleistocene wet event in the Great Basin.

The climatic correlation of varnish microlaminations is consistent with models of varnish formation. In the desert regions of the western US, the Mn content in dust and soils is about 0.1% or less (Lakin et al., 1963); in comparison, the Mn content in rock varnish is greatly enriched and can be as high as 40–45% (Fleisher et al., 1999). Two models have been proposed to explain how Mn is concentrated so effectively in varnish (see Dorn, 1990 and Jones, 1991 for detailed discussions on this topic). The biotic model assumes that bacteria capable of bioconcentrating Mn favor a relatively wet environment with low pH and alkalinity, whereas the abiotic model proposes that, in a relatively dry environment that has high pH and alkalinity, there is no effective way to release Mn from airborne dust. Though different in mechanism, both models suggest a climatic control over the enhancement and depletion of Mn in varnish.

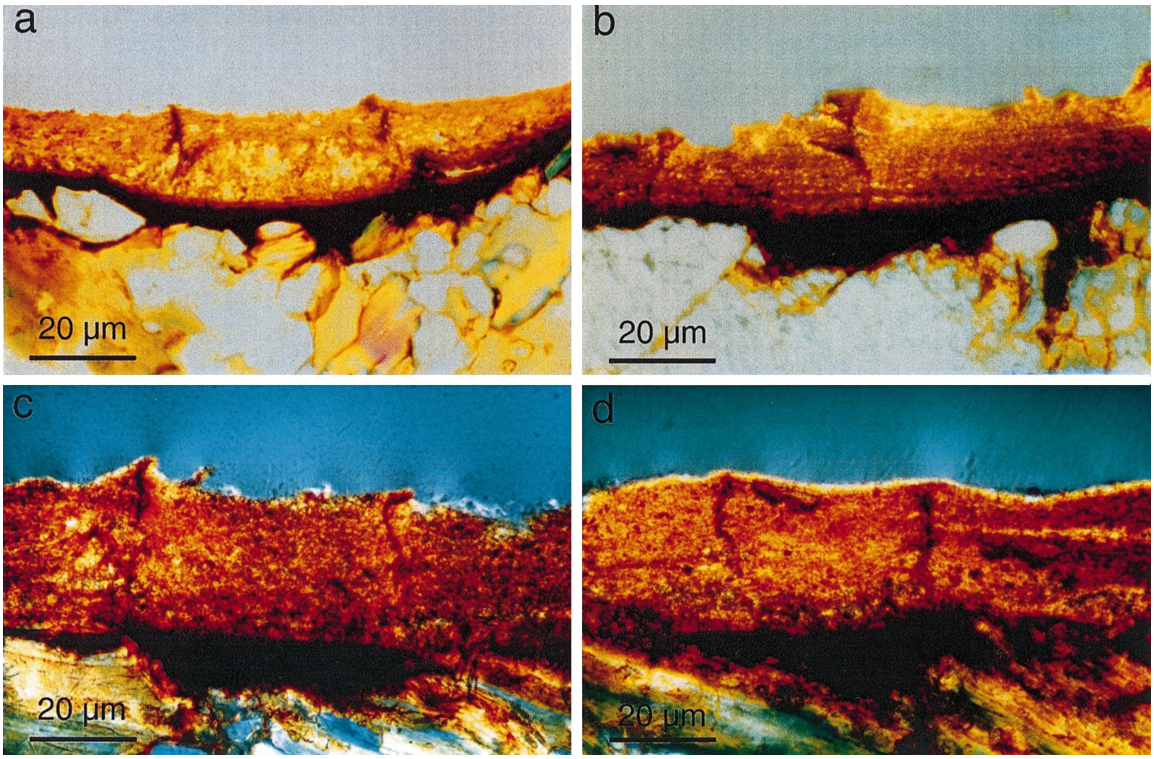


Fig. 6. Optical microlamination patterns in varnish from: (a) latest Pleistocene alluvial-fan surface at Hanaupah Canyon in Death Valley (elevation: −5 m; <13 ^{14}C ka; see Hooke and Dorn, 1992); (b) lowest shoreline of Lake Manly at Mormon Point in Death Valley (elevation: −30 m; <18 ka; see Ku et al., 1998); (c) and (d) shoreline A of Silver Lake in the Mojave Desert (<10.5–15 ^{14}C ka; see Wells et al., 1987).

4. Conclusions

Changes in rock varnish composition, as revealed by both optical and chemical microlaminations, reflect paleoclimatic fluctuations. High-Mn dark layers in varnish form under relatively wet conditions and low-Mn orange layers under drier conditions. Evidence from Las Vegas Valley, together with that from Death Valley and the Mojave Desert, indicates that the Mn-rich dark basal layers in the varnish deposited around 10–11 ^{14}C ka, probably corresponding to the terminal Pleistocene Younger Dryas-aged wet event in the Great Basin of the western United States.

Acknowledgements

This research was funded by the US Department of Energy. The authors thank Roger Leb. Hooke and Jay Quade for constructive comments on the earlier version of this paper. Thanks also go to G.J. Retallack and an anonymous reader for critical reviews. Lamont–Doherty Earth Observatory contribution 6408.

References

Allen, B.D., Anderson, R.Y., 1993. Evidence from western North America for rapid shifts in climate during the last glacial maximum. Science 260, 1920–1923.

Bell, J.W., Ramelli, A.R., Caskey, S.J., 1998. Geologic Map of the Tule Springs Park Quadrangle. Nevada Bureau of Mines and Geology Map 113, 1:24,000 Scale.

Bell, J.W., Ramelli, A.R., dePolo, C.M., Maldonado, F., Schmidt, D.L., 1999. Geologic Map of the Corn Creek Springs Quadrangle. Nevada Bureau of Mines and Geology Map 121.

Benson, L.V., Currey, D.R., Dorn, R.I., Lajoie, K.R., Oviatt, C.G., Robinson, S.W., Smith, G.I., Stine, S., 1990. Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 78, 241–286.

Benson, L., Kashgarian, M., Rubin, M., 1995. Carbonate deposition, Pyramid Lake subbasin, Nevada: 2. Lake levels and polar jet stream positions reconstructed from radiocarbon ages and elevations of carbonates (tufas) deposited in the Lahontan basin. Palaeogeography, Palaeoclimatology, Palaeoecology 117, 1–30.

Benson, L., Burdett, J., Lund, S., Kashgarian, M., Mensing, S., 1997. Nearly synchronous climate change in the Northern Hemisphere during the last glacial termination. Nature 388, 263–265.

Broecker, W.S., 1994. Massive iceberg discharges as triggers for global climate change. Nature 372, 421–424.

Cremaschi, M., 1996. The rock varnish in the Messak Settafet (Fezzan, Libyan Sahara), age, archaeological context and paleo-environmental implication. Geoarchaeology 11, 393–421.

Currey, D., 1990. Quaternary paleolakes in the evolution of semidesert basins, with special emphasis on Lake Bonneville and the Great Basin, U.S.A. Palaeogeography, Palaeoclimatology, Palaeoecology 76, 189–214.

Dorn, R.I., 1988. A rock varnish interpretation of alluvial-fan development in Death Valley, California. National Geographic Research 4, 56–73.

Dorn, R.I., 1990. Quaternary alkalinity fluctuations recorded in rock varnish microlaminations on western U.S.A. volcanics. Palaeogeography, Palaeoclimatology, Palaeoecology 76, 291–310.

Dorn, R.I., 1992. Paleoenvironmental signals in rock varnish on petroglyphs. American Indian Rock Art 18, 1–17.

Dorn, R.I., 1994. Rock varnish as an indicator of climatic change. In: Abrahams, A., Parsons, A. (Eds.), Geomorphology of Desert Environments. Chapman & Hall, London, pp. 539–552.

Dorn, R.I., Meek, N., 1995. Rapid formation of rock varnish and other rock coatings on slag deposits near Fontana. Earth Surface Processes and Landforms 20, 547–560.

Engel, C.G., Sharp, R.S., 1958. Chemical data on desert varnish. Geological Society of America Bulletin 69, 487–518.

Fleisher, M., Liu, T., Broecker, W.S., Moore, W., 1999. A clue regarding the origin of rock varnish. Geophysical Research Letters 26, 103–106.

Harden, J.W., Talor, E.M., Hill, C., Mark, R.K., McFadden, L.D., Reheis, M., Sowers, J.M., Wells, S.G., 1991. Rates of soil development from four soil chronosequences in the southern Great Basin. Quaternary Research 35, 383–399.

Haynes Jr., C.V., 1967. Quaternary geology of the Tule Springs Area Clark County Nevada. In: Wormington, H.M., Ellis, D. (Eds.), Pleistocene Studies in Southern Nevada Paper 13. Nevada State Museum of Anthropology, Carson City, NV, pp. 1–128.

Hooke, R.L., Yang, H., Weiblen, W., 1969. Desert varnish: an electron probe study. Journal of Geology 77, 275–288.

Hooke, R.L., 1972. Geomorphic evidence for late Wisconsin and Holocene tectonic deformation, Death Valley, California. Geological Society of America Bulletin 83, 2073–2098.

Hooke, R.L., Dorn, R.I., 1992. Segmentation of alluvial fans in Death Valley, California: New insights from surface-exposure dating and laboratory modeling. Earth Surface Processes and Landforms 17, 557–574.

Jones, C.E., 1991. Characteristics and origin of rock varnish from the hyperarid coastal deserts of northern Peru. Quaternary Research 35, 116–129.

Ku, T.L., Luo, S., Lowenstein, T.K., Li, J., Spencer, R.J., 1998.

U-series chronology of lacustrine deposits in Death Valley, California. Quaternary Research 50, 261–275.

Lakin, H.W., Hunt, C.B., Davidson, D.F., Oda, U., 1963. Variation in minor-element content of desert varnish. US Geological Survey Professional Paper 475, 28–31.

Liu, T., 1994. Visual microlaminations in rock varnish: a new paleoenvironmental and geomorphic tool in drylands. Ph.D. thesis, Tempe, Arizona State University, 173 pp.

Liu, T., Dorn, R.I., 1996. Understanding the spatial variability of environmental change in drylands with rock varnish microlaminations. Annals of the Association of American Geographers 86, 187–212.

Liu, T., Broecker, W.S., 1999. Rock varnish evidence for Holocene climate variations in the Great Basin of western United States. GSA Abstracts with Programs 31 (7), 418

Liu, T., Broecker, W.S., 2000. How fast does rock varnish grow? Geology 28, 183–186.

Oviatt, C.G., Currey, D.G., Sack, D., 1992. Radiocarbon chronology of Lake Bonneville, Eastern Great Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 99, 225–241.

Perry, R.S., Adams, J., 1978. Desert varnish: evidence of cyclic deposition of manganese. Nature 276, 489–491.

Phillips, F.M., Campbell, A.R., Smith, G.I., Bischoff, J.L., 1994. Interstadial climatic cycles: a link between western North America and Greenland? Geology 22, 1115–1118.

Potter, R.M., Rossman, G.R., 1977. Desert varnish: The importance of clay minerals. Science 196, 1446–1448.

Quade, J., 1986. Late Quaternary environmental changes in the upper Las Vegas Valley, Nevada. Quaternary Research 26, 340–357.

Quade, J., Mifflin, M.D., Pratt, W.L., McCoy, W., Burckle, L., 1995. Fossil spring deposits in the southern Great Basin and their implications for changes in water-table levels near Yucca Mountain, Nevada, during Quaternary time. Geological Society of America Bulletin 107, 213–230.

Quade, J., Forester, R.M., Pratt, W.L., Carter, C., 1998. Black mats, spring-fed streams, and late-glacial-age recharge in the southern Great Basin. Quaternary Research 49, 129–148.

Smith, G.I., 1979. Subsurface stratigraphy and geochemistry of late Quaternary evaporites, Searles Lake, California. US Geological Survey Professional Paper 1043, 1–130.

Spaulding, W.G., 1985. Vegetation and climates of the last 45,000 years in the vicinity of the Nevada Test Site, south-central Nevada. US Geological Survey Professional Paper 1329, 1–83.

Wells, S.G., McFadden, L.D., Dohrenwend, J.C., 1987. Influence of late Quaternary climatic changes on geomorphic and pedogenic processes on a desert piedmont, eastern Mojave Desert, California. Quaternary Research 27, 130–146.