Understanding the Spatial Variability of Environmental Change in Drylands with Rock Varnish Microlaminations

Tanzhuo Liu* and Ronald I. Dorn**

*Lamont Doherty Earth Observatory, Columbia University
**Department of Geography, Arizona State University

Correlating the timing of events that occurred in different places, though a difficult problem in geographic research, is important for understanding the development of human and physical landscapes. This paper focuses on the evolution of natural arid landscapes and prehistoric human activity in drylands over timescales of 10^3 to 10^5 years. Our approach examines the dark rock coatings called rock varnish that are ubiquitous in arid and semiarid areas (Dorn and Oberlander 1982) and attempts to determine whether layers of rock varnish can serve as a natural GIS (geographic information system). Is it possible, in other words, to map these unique layering patterns for the purpose of establishing temporal correlations?

Orange and black microlaminations in rock varnish were first recognized by Perry and Adams (1978) as miniature sedimentary strata with the potential to record environmental change. As we point out below, orange layers record arid climates, while black layers form in humid settings. We verified Perry and Adams' findings that the black layers are rich in manganese, the orange layers are rich in iron (but not manganese), and layering can be laterally continuous. Subsequently eschewing spatial analysis of these optical sedimentary sequences, investigators turned to microchemical measurements of Mn and Fe along depth profiles using either wavelength dispersive electron microprobes (Dorn 1990; 1994c; Dragovich 1988a; 1988b) or energy dispersive X-ray units attached to electron microscopes (Reneau et al. 1992). Although electron microscopes provide increased resolution of chemistry in these transects, this approach was analogous to restricting analyses of an entire Landsat/SPOT scene to the data from one row or a soil catena in a road cut to samples along one tape measure.

If varnish layers are to be used as a tool for understanding environmental change, it is necessary to move beyond one-dimensional perspectives. To do so requires that we realize the potential of visual microlaminations. Heretofore, these microlaminations have not been assessed principally because of the practical difficulty in making sections that are thin enough (<5–10 μm) to see through the varnish, which in normal thin sections is opaque. Using conventional section preparation techniques, our failure rates exceeded 80 percent, and even then sections were often too thick to see details. Recently, however, the senior author has developed a method of making ultra-thin sections that reduces failure rates to less than 5 percent and permits more rapid sample preparation (Liu 1994). Unlike electron microscope methods of analyzing varnish, optical layering has the advantage of accessibility; samples can be prepared with materials purchased at hardware stores and observed with relatively inexpensive light microscopes.

Our research assesses the reproducibility of patterns in the optical layers of rock varnish and the usefulness of these layers in geographic research. This paper presents our findings on the spatial comparability of visual microlaminations in rock varnishes. It also applies this experimental tool to understand spatial variabilities in environmental change. With this tool, we may be able to correlate the environmental history of different places exposed at the earth's surface and thereby assist students of prehistory, for example, in placing rock engravings in an established cultural se-

Annals of the Association of American Geographers, 86(2), 1996, pp. 187–212

Published by Blackwell Publishers, 238 Main Street, Cambridge, MA 02142, and 108 Cowley Road, Oxford, OX4 1JF, UK.

quence, or students of geomorphology in correlating alluvial fans, glacial moraines, and other landforms having disjunct locations.

Death Valley serves as our main study area. Following a discussion of methods and results, we present the pattern of varnish layering in the Death Valley region, an analysis of the method's uncertainties, and an exploration of its utility for mapping alluvial fans and other cases. We conclude that while this method is still experimental, it seems to have considerable potential for addressing a fundamental problem in geographic research, namely the temporal correlation of different physical and anthropogenic surfaces.

Study Area and Methods

The Death Valley area offers an excellent test case for dating rock varnishes. The area's aridity aids varnish preservation and surfaces of known and variable age are in close proximity. Our evaluation of microlaminations involves comparisons of varnish samples from sites where age control (in the form of radiometric dates) exists and from a large number of undated sites. These samples are then used to note the recurrence of layering patterns on single boulders, on adjacent boulders, on distant boulders on the same geomorphic surface (e.g., transects from the distal to the proximal end of an alluvial-fan unit), and on boulders on landforms of different ages.

Sampling sites with independent age control exist within Death Valley and adjacent areas in the western Basin and Range (Figure 1). Age control is based on: independent ^{14}C data on the genesis of the landform on which the varnish has grown; uranium-series measurements of tufa on shorelines of paleolakes; cosmogenic ^{3}He, ^{10}Be, and ^{26}Al ages; and ^{14}C ages on subvarnish organic matter that record when the time sequence started (Table 1). Figure 2a maps the study area of Death Valley and Figure 2b illustrates, for one alluvial fan, the density of sampling sites that were used to assess the reproducibility of the layering pattern in the 320 km^2 area of southern Death Valley.

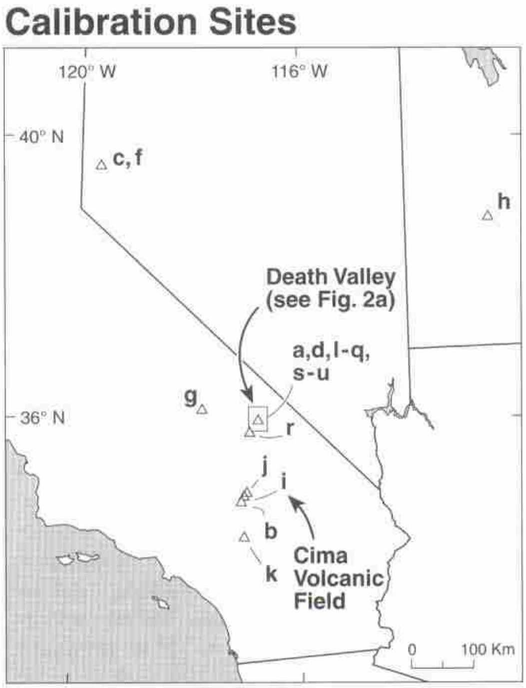


Figure 1. Sampling sites where age control is present. The letters correspond to Table 1 and Figure 4.

The most critical and perhaps the most controversial aspect of this paper concerns rock varnish sampling in the field. There are two schools of thought on how to maximize the chances of collecting the oldest varnish: 1) collection based on visual appearance (cf. Harrington and Whitney 1995; Reneau et al. 1992; Reneau 1993); and 2) collection based on sampling varnishes that have been exposed only to the subaerial environment (Dorn 1994b; 1994d; Liu 1994). While both schools agree that the objective is to sample the oldest varnish, i.e., the varnish most closely related to the exposure of the underlying rock by a geomorphic or archaeological event, they adopt different strategies to achieve that objective.[1] Since different sampling criteria will result in the collection of different types of varnishes and very different types of data, we will return to this issue momentarily.

In all, we prepared 420 ultra-thin sections (each with multiple micro-sedimentary basins) from 360 subaerially exposed rocks. Each section contains several rock-surface depressions where varnish collects, and some 2900 depressions or "microbasins" were analyzed for this study. The different lithologies collected are indicated in figure captions.

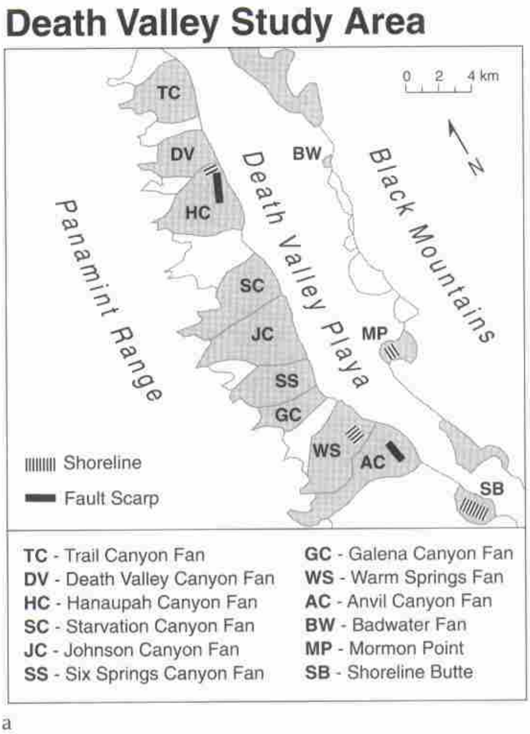
A simple innovation in preparation of ultrathin sections made this research feasible. While geologic thin sections are used routinely in a

Table 1. Numerical Ages that Constrain the Sequence of Optical Microlaminations in Rock Varnish. The letters correspond with sites in Figure 1, ultra-thin sections displayed in Figure 4, and placed in the stratigraphic section in Figure 5.

Figures 1, 4 and 5	Sampling Site and Context	Age Control
a	Hanaupah Canyon fan, Death Valley (Hooke and Dorn 1992)	5980±150 (AA-1303)[1]
b	Ventifact, Cady Mountains, Mojave Desert (Laity 1994)	6480±80 (ETH 5263)[1]
c	Anahoe Island, 1204 m, Pyramid Lake (Benson et al. 1992)	9620±95 (ETH 5265)[1]
d	Mormon Point (–1 m Shoreline), Death Valley (Dorn et al. 1990)	12,970±185 (ETH 2409)[1]
e	Searles Lake Shoreline, 644 m (Benson et al. 1990)	~14,000[2]
f	Lake Lahontan, 1330 m highstand, Pyramid Lake	~14,000[2] (Benson et al. 1990) 13,870±120 (ETH 12814)[1]
g	Dry Falls of Owens River, Rose Valley	~15,500 (^{3}He)[5] (Cerling 1990) 13,000±100 (ETH 12813)[1]
h	Tabernacle Hill flow, Utah	~14,000[2] (Oviatt et al. 1992)
i	Lake Manix Beach Ridge, Mojave Desert	14,200±1,300[2] (Meek 1989) 13,970±100 (AA-2317)[1]
j	Chronese Basin Fan, Mojave Desert (Dorn 1994a)	16,100±800 (AA-714)[1]
k	Blackhawk Landslide, Mojave Desert	17,400±550[2] (Stout 1977) 16,970±155 (AA-2320)[1]
l	Anvil Canyon fan, Death Valley (Hooke and Dorn 1992)	18,340±180 (ETH 12816)[1]
m	Galena Canyon fan, Death Valley (Hooke and Dorn 1992)	21,760±390 (AA-1419)[1]
n	1.7 m beneath the alluvial-fan surface, Hanaupah Cyn fan, Death Valley (Hooke and Dorn 1992)	23,420±660 (Beta 28805)[2]
o	Warm Springs fan, Death Valley (Hooke and Dorn 1992)	>33,200 (±350) (ETH 12815)[1]
p	Galena Canyon fan, Death Valley (Hooke and Dorn 1992)	>34,250 (±350) (ETH 12817)[1]
q	~5 m, Shoreline, north-east side, Hanaupah fan, Death Valley	49,000–70,000[3] (J. Lin 1994)
r	Shoreline, ~355 m, west side, Panamint Valley (Fitzpatrick and Bischoff 1993)	55,000–90,000[3, 4] 35,000±400 (ETH 12819)[1]
s	~55 m, Shoreline, Warm Springs fan, Death Valley (Hooke 1972; Hooke and Dorn 1992; Ku et al. 1994)	~130,000[6]
t	~55 m, Shoreline, Warm Springs fan, Death Valley (Hooke 1972; Hooke and Dorn 1992; Ku et al. 1994)	~130,000[6]
u	Galena Canyon fan, Death Valley (Nishiizumi et al. 1993)	~318,000±12,000[7]

[1] AMS ^{14}C ages on organics entombed by rock varnish sampled underneath imaged sections.
[2] From independently dated ^{14}C material which establishes a maximum age for the varnish sequence.
[3] From uranium-series measurements.
[4] Tufa from shorelines above the sampled unit, hence a maximum age for the varnish sequence.
[5] The ^{3}He age records only the last highly abrasive flow, and not necessarily the last flow event. Since rock varnish would be eroded by the last flood, the ^{14}C age is a closer age constraint for the sequence.
[6] U-series ages on tufa and lake cores indicate desiccation by ~130,000 years ago of the lake that occupied these shorelines (Ku et al. 1994); hence the varnish sequence is younger than ~130,000.
[7] ^{26}Al and ^{10}Be ages for cobble on an eroding fan unit.

variety of earth sciences, rock varnish sections must be ultra-thin, consistently <5–10μm thin, or they become opaque. The preparation proceeds as follows. First, a varnished rock chip is placed in epoxy and a polished cross-section of varnish is made on side 1. Then, the section is placed again in epoxy, and the sample is ground down on side 2. Lastly, the varnish is polished on side 2 until it is thin enough for layering to be visible with light microscope. The key to sample survival in the final thinning is in binding epoxy to epoxy, rather than binding dissimilar materials (epoxy on glass)—an approach used in prior studies (Dorn 1992; Peterson et al. 1995). Unlike prior sections, which frequently were too thick to see the subdivi-



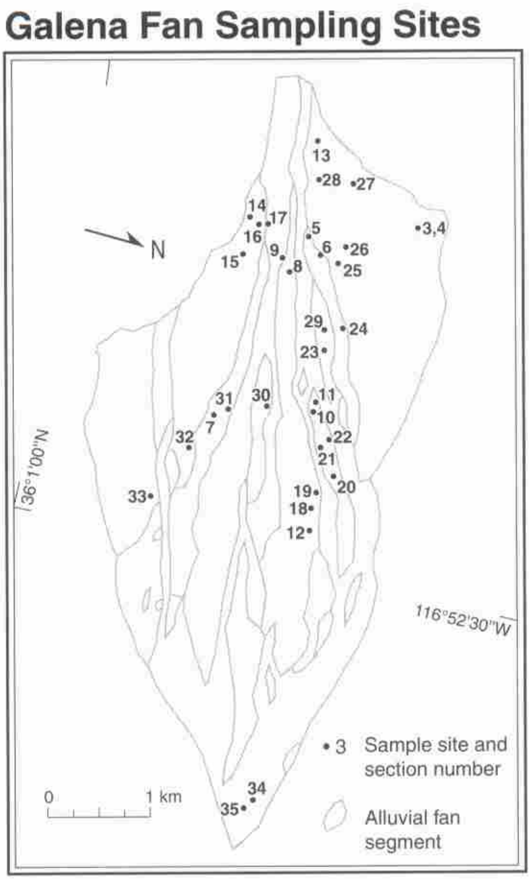


Figure 2. Sampling sites in Death Valley. (a) Alluvial fan, fault, and shoreline sites. (b) Boulder-collection sites on Galena Canyon fan in Death Valley (the location of Galena Canyon fan is indicated by "GC" in Figure 2a).

sions within the Mn-rich bands, the new method produced sections that were thin enough to see all layers—and preparation rates were faster and failures rates (<5 percent) were lower.

We also completed wavelength dispersive (WDS) electron microprobe transects in order to test the conclusion that orange layers are Mn-poor and black layers are Mn-rich (Perry and Adams 1978). Quantitative chemical data were obtained by WDS with a fully-automated JEOL JXZ-8600 electron microprobe. Although overlaps are a problem with energy dispersive analyses (such as the Mn-K_β peak resting on the Fe-K_α peak), this problem is resolved by WDS. The probe was set to 10 nA with a counting time of 30 seconds for a focused beam with a diameter of ~2μm.

Results

Our most basic finding (Figures 3 and 4) confirms earlier conclusions that color corresponds with manganese abundance in laminae (Perry and Adams 1978). Orange/yellow (Fe-rich) layers are not as enriched in manganese as are the black layers. We also found that Fe-rich varnish has more clay minerals as reflected in higher totals of [Al+Si]. This is consistent with analyses using infrared mineralogy (Potter and Rossman 1977; 1979) and scanning electron microscopy (Dorn 1986).

An important observation (Figures 4, 5 and 6) is that the surface layer is universally orange/yellow (Mn-poor). This applies to all samples of subaerial rock varnishes examined from

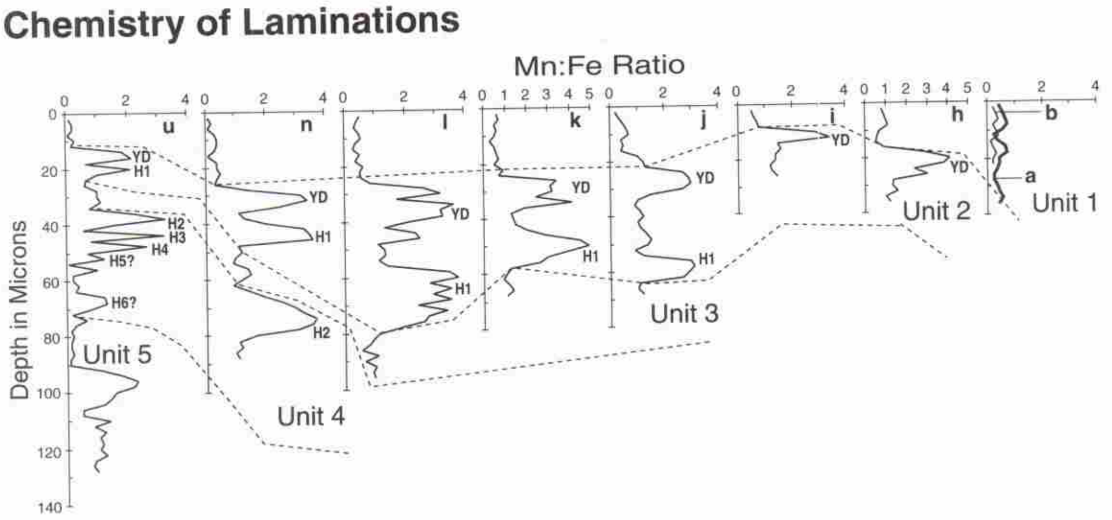


Figure 3. Electron microprobe profiles along transects (identified by lines in Figures 4a, b, h–l, n, and u) show the correspondence of high Mn:Fe ratios with black layers. The black layers are found in even-numbered units, with specific black layers possibly correlated to the younger Dryas (YD) and Heinrich Events H1–H6.

areas that were arid during the Holocene (last 10,000 years). In contrast, black (Mn-rich) surface layers occur only on subaerial varnishes in humid regions (Figure 7a–c) and non-subaerial varnishes in arid regions (Figure 7d–e).

Underneath this first orange/yellow layer are complex patterns of black and orange microlaminae. It is our aim to assess the reproducibility of these patterns. Our first test focuses on microlaminations developed on rocks at sites with numerical age control (Table 1). The ages in Table 1 provide a maximum age for the onset of the varnish laminae at each site. Sequences were reproducible from place to place on a single boulder and from boulder-to-boulder on these dated landforms. Figure 4 presents an illustrative section from each control site, while Figure 5 presents a "stacked" generalization of the sequence, with basal age control indicated on the side.

After examining the patterns at control sites, we examined those sites which did not have independent age control for the presence of a reproducible *relative* sequence of layering in varnish at sites throughout Death Valley (Figure 6). After examining the 2900 or so sequences, a pattern became apparent. Figure 8 generalizes our identification of the "layering units" that are repeated from site to site in the Death Valley area. These layering units are distinctive stratigraphic patterns. In some cases a layering consists of a distinctive single strata, e.g., the yellow/orange of Unit 1. In other cases, the layering units form multiple layers, e.g., thin black layers separated by a thin orange layer in Unit 2. Figure 8 provides readers with a guide to the layering units that they would see when viewing a section in a light microscope.

Our assignment of ages to layering units is based on data in Table 1. While the ages in Table 1 are state-of-the-art, we realize that our calibration will be refined as dating methods improve. Our calibration thus should be regarded as a first approximation. Unit 1 developed during the last ~10,000 ^{14}C yr B.P; the two black layers in Unit 2 at ~10,000–11,000 ^{14}C yr B.P. and ~14,000 ^{14}C yr B.P.; the prominent orange layer in Unit 3 between 15,000 and 20,000 ^{14}C yr B.P.; the first black layer in Unit 4 at ~21,000 ^{14}C yr B.P.; and the second black layer in Unit 4 before ~24,000 ^{14}C yr B.P.

The timing of black layers in Unit 4 (older than ~24,000 ^{14}C yr B.P.) is not constrained by radiocarbon dating because the ^{14}C ages are infinite for sections o and p (Figure 5; Table 1). The basic pattern of 5 black layers in Unit 4 is repeated in samples throughout Death Valley (Figure 6) where Unit 4 is constrained to be younger than the relatively thick yellow layer underlying it, called here Unit 5. Uranium-series age control (Table 1) reveals that the bot-

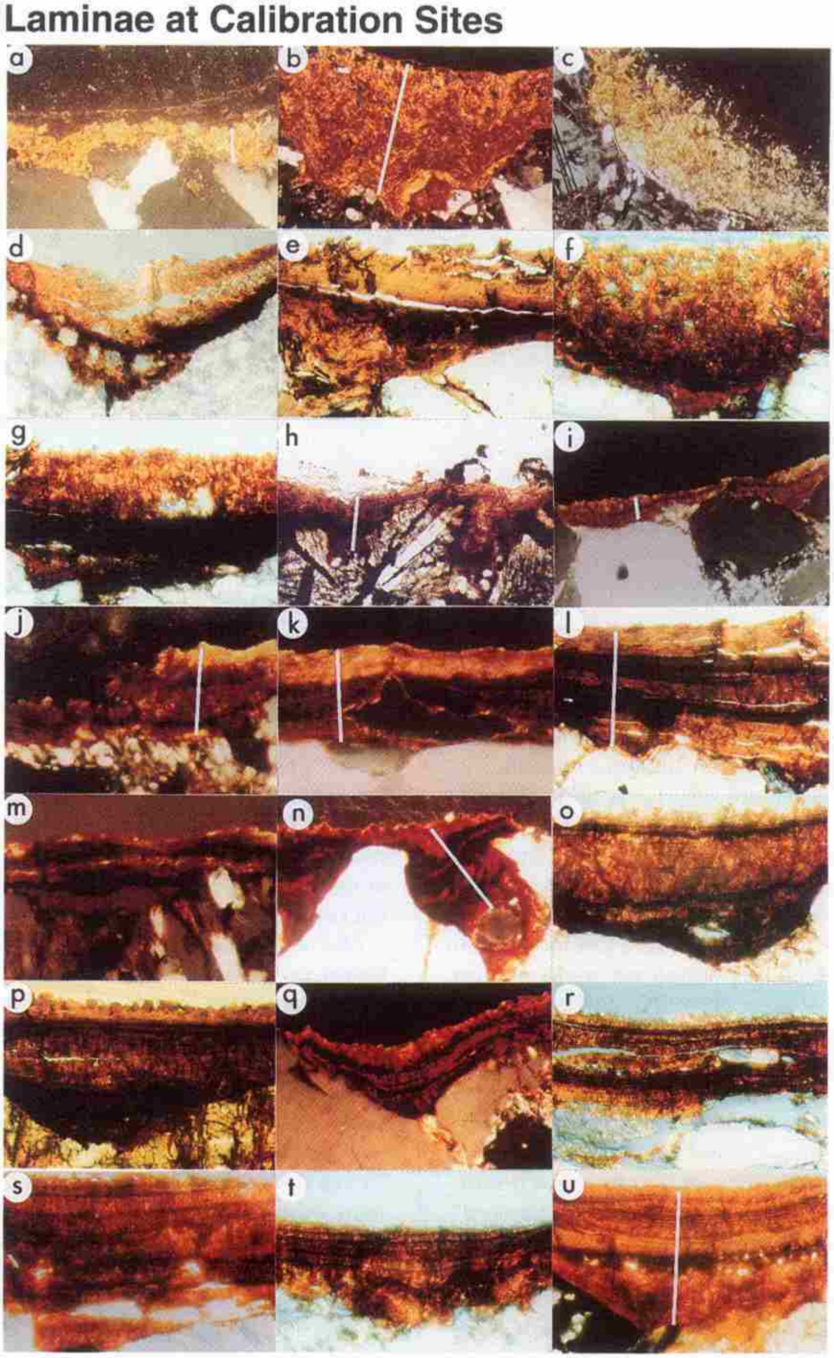


Figure 4. Optical microlaminations seen in ultra-thin sections of rock varnish where age control is available. Letters correspond to Figure 1 and Table 1. The length of each image from top to bottom is ~130 μm save for b, c, and h (~40μm). Lithologies are as follows: a (quarzite), b (basalt), c (andesite), d (chert), e (granodiorite), f (andesite), g (basalt), h (basalt), i (quartzite), j (quartzite), k (sandstone), l (meta-dacite), m (greenstone), n (quartzite), o (meta-diorite), p (meta-dacite), q (quartzite), r (gneiss), s (meta-dacite), t (meta-dacite), and u (meta-dacite).

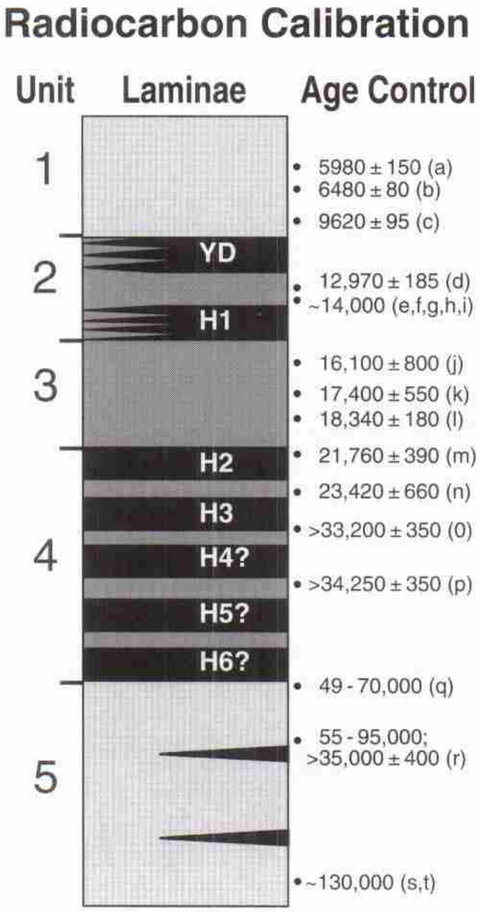


Figure 5. An idealized sequence of varnish layering units identifying the position of the age control in the sedimentary sequence. YD and H1–H6 indicate possible correspondences between black layers and the Younger Dryas (YD) and Heinrich Events H1 through H6. Radiocarbon ages are placed stratigraphically underneath the layering sequence for that varnish. For example, the radiocarbon age for AC-8 (l in Table 1) is 18,340±180 and the bottom layer is Unit 3, hence chronometric placement occurs in Unit 3 in the idealized sequence.

tom four black layers in Unit 4 probably date from between ~24,000 ^{14}C yr B.P. and ~70,000 yr B.P. And Unit 5 probably dates from between ~70,000 and 130,000 yr B.P. (based on uranium-series ages, Table 1, for the high stand of Pleistocene Lake Manly; Hooke and Dorn 1992; also Ku et al. 1994). Units 6, 7, and 8 have no age control except for a single cosmogenic $^{10}Be/^{26}Al$ age at ~318,000 years (Table 1) on a surface on Galena Canyon Fan (Nishiizumi et al. 1993).

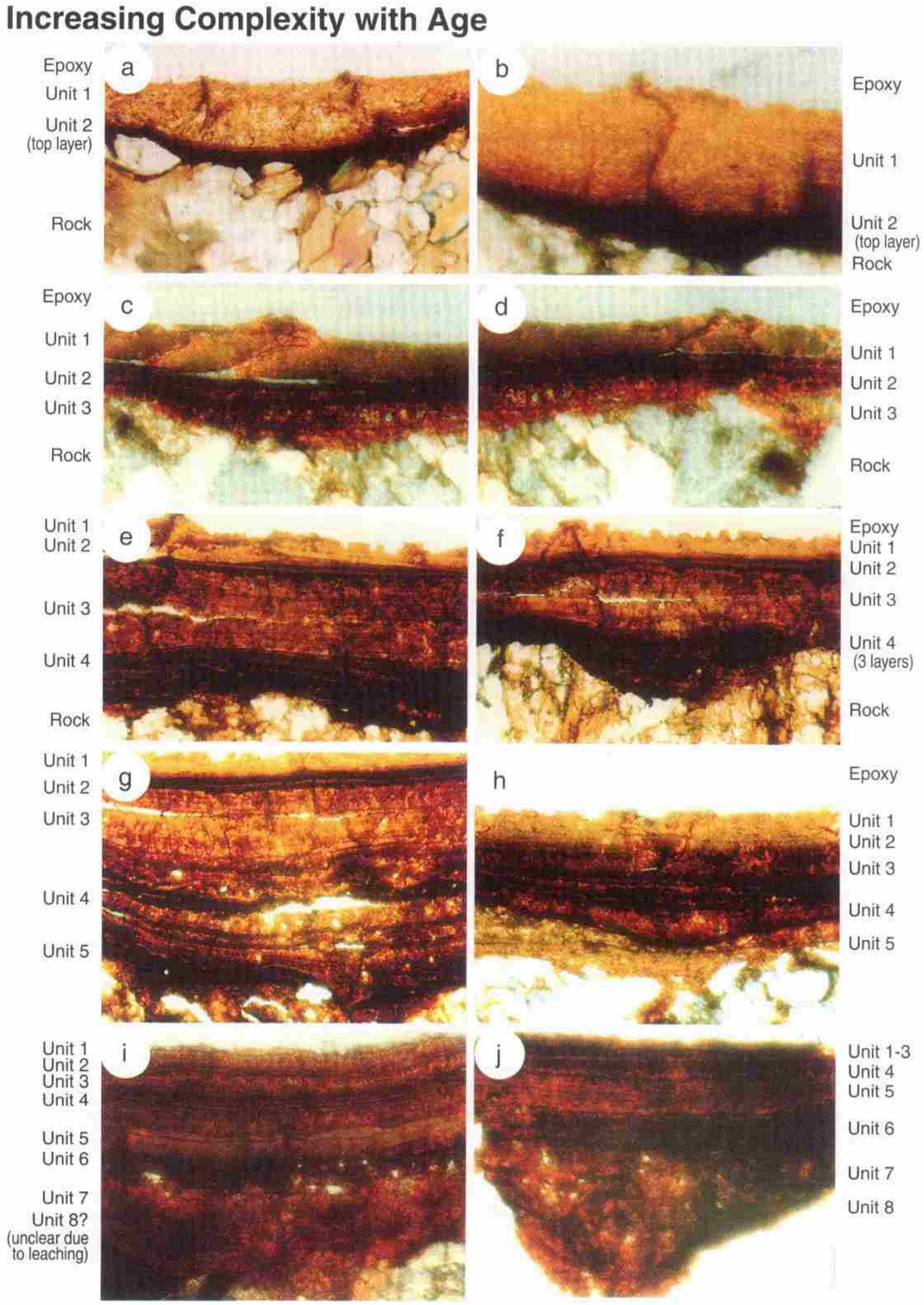
Interpretation of Layering Units and Environmental Conditions

We interpret orange/yellow (Mn-poor, clay-rich) layers as indicative of a dry climate and black (Mn-rich) layers to indicate a wetter climate. Our interpretation is based on both empirical data and theory.

Empirically, the orange/yellow (Mn-poor) uppermost layer formed during the Holocene (Table 1; Figure 4) in areas that have been arid for the last 10,000 years (Benson et al. 1990; Spaulding 1985; Wells and Woodcock 1985). In arid climates, Mn-poor varnish is universally found at the top of the sequence of varnish layers on landforms older than Holocene (Figures 4 and 6). Moreover, varnish that is presently forming in more moist areas is Mn-rich (Dorn 1990) and black (Figure 7a–c).

The assignment of *orange to arid* and *black to humid* is also consistent with what is known about climatic changes in the western United States for the last 24,000 ^{14}C years (Figure 4 and Table 1). The orange/yellow layer, Unit 1, formed in the last 10,000 ^{14}C years when the western United States has been quite arid (COHMAP 1988). As for the three black layers that formed between 10,000 ^{14}C yr B.P. and 24,000 ^{14}C yr B.P., the top black layer is Unit 2 corresponds in time with a wet pulse about 10,000–11,000 ^{14}C yr B.P. (Benson et al. 1992; Elliott-Fisk 1987; Gosse et al. 1995b); the second black layer in Unit 2 corresponds in time with a wet pulse about 14,000 ^{14}C yr B.P. (Benson et al. 1990); the distinctive orange layer of Unit 3 may correlate with a period of warming in the western United States near the end of Pleistocene (Cerling et al. 1994) when glaciers were retreating from their maximum positions (Dorn et al. 1990; Zreda and Phillips 1994; Zreda et al. 1994); and the uppermost black layer in Unit 4 (third black layer) corresponds to the last glacial maximum about 20–21,000 ^{14}C yr B.P. (Bach and Elliott-Fisk 1995; Dorn et al. 1991; Gosse et al. 1995a; Phillips et al. 1990).

From the standpoint of theory, our interpretation of layers focuses on factors that control manganese enhancement in rock varnish. The two extant models of manganese enhancement—the abiotic and the biotic—relate changes in Mn concentration to fluctuations in pH. The abiotic model of manganese enhancement (Hooke et al. 1969; Moore and Elvidge


Increasing Complexity with Age
a
Epoxy
Unit 1
Unit 2
(top layer)
Rock
b
Epoxy
Unit 1
Unit 2
(top layer)
Rock
c
Epoxy
Unit 1
Unit 2
Unit 3
Rock
d
Epoxy
Unit 1
Unit 2
Unit 3
Rock
e
Unit 1
Unit 2
Unit 3
Unit 4
Rock
f
Epoxy
Unit 1
Unit 2
Unit 3
Unit 4
(3 layers)
Rock
g
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
h
Epoxy
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
i
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Unit 8?
(unclear due
to leaching)
j
Unit 1-3
Unit 4
Unit 5
Unit 6
Unit 7
Unit 8

1982; Whalley 1983) posits that Mn (II) ions, but not Fe, are released from dust or rock material by small pH-Eh (redox potential) fluctuations from acidic rain or dew. Under the redox constraints of the abiotic model, an environment that is too alkaline retards the reduction of Mn(IV) from source material (dust); hence varnish formed during arid-alkaline periods of high pH are poor in Mn. The biotic models of Mn-enhancement in varnish (Drake et al. 1993; Dorn and Oberlander 1981; Jones 1991; Krumbein and Jens 1981; Nagy et al. 1991; Palmer et al. 1985) posit that bacteria and perhaps other organisms result in the bioaccumulation of Mn. Note however that experimental data on cultured Mn-bacteria indicate that pH values higher than 7.5 inhibit Mn bioaccumulation (Bromfield and David 1976; Dorn and Oberlander 1981; Schweisfurth et al. 1980; Uren and Leeper 1978; van Veen 1972).

Jones's (1991:127) working model of biomineralization in rock varnish combines aspects of the abiotic and biotic models:

> During wetter times eolian clay minerals spend more time in contact with dew and fog, thus increasing the amount of Mn put into solution. At the same time, wetter soils, increased plant cover, and flooded playa lakes decrease the total amount of alkaline eolian material settling on varnish surfaces. Less alkaline surface conditions favor Mn precipitating bacteria . . . thus allowing them to take full advantage of the increased levels of dissolved Mn in the varnishing solutions. A reduction in circulation of eolian clays may also reduce the amount of clay minerals incorporated into the varnish, thus reducing the amount of Fe in the varnish as well. High Mn production and precipitation plus less Fe incorporation yields a higher Mn:Fe ratio. Conversely, drier conditions reduce the contact time between clay minerals and varnishing solutions, inhibit Mn-precipitating bacteria through increased deposition of alkaline eolian materials, and increase the amount of Fe-bearing eolian clay minerals incorporated into varnish. A low Mn:Fe ratio results.

In summary, biotic and abiotic mechanisms of Mn-enhancement seem to have been "turned off" or "reduced" in deserts during the Holocene, which is supported by empirical observations of Mn-poor varnishes formed in the arid western United States during the last 10,000 years.

Figure 6. Optical microlaminations showing the progressive development of layers over time. Varnish layers display the same stratigraphic sequence as in Figure 5, but from sites without numerical age control. This figure depicts just a few of the >2000 microbasins examined within a 320 km^2 area in Death Valley. On Holocene varnishes, only the yellow/orange layer is found. A basal black layer occurs in varnishes on terminal Pleistocene landforms (a, b). Unit 2 (two black layers) occurs between Unit 1 (Holocene) and Unit 3 (relatively thicker orange layer) (c, d). The number of tightly-layered black bands in Unit 4 depends upon sample age (e, f). Unit 4 is underlain by Unit 5, a yellow layer that is optically similar to the Holocene (g, h). Under Unit 5 are Unit 6 (black layers), Unit 7 (orange layer), and Unit 8 (black layers). The different layering units (annotated on the margins) are described in more detail in the text and in Figure 8. Mean varnish thickness and section numbers are 40µm-HC30 (a), 50µm-MP1 (b), 50µm-DV11a (c), 50µm-DV11b (d), 80µm-GC7 (e), 60µm-WS23 (f), 120µm-GC9 (g), 80µm-GC11 (h), 120µm-GC29 (i), SS-1a (j).

Analysis of Uncertainties

While the foregoing data and interpretations suggest the methodological potential of layering in rock varnish, the method is not yet a "mature" research tool. Significant uncertainties remain.

Continuity in Layering

One set of complications arise in the examination of ultra-thin cross sections (Figure 9):

Section Thickness. Layering disappears altogether in sections that are ground too thin (Figure 9a). Conversely, when the section is too thick, black layers merge optically (Figure 9l).

Erosional Unconformities. Rock varnish is soft, having a Moh's hardness of ≤4–1/2 (Dorn and Oberlander 1982). Abrasion thus can remove layers, which is easiest to see when the unconformity is angular. In Figure 9b, for example, the orange layer of Unit 3 rests on an abrasion surface that truncates the underlying layers. Conversely, abrasion is sometimes conformal as in Figure 9g. In this case, the double black layer of Unit 2 present in the middle of the section is "shaved" down to only one black layer on the sides. The complete erosion of Unit 2, not uncommon in Death Valley (Figure 9h), hints at widespread aeolian abrasion event(s) in the early part of the Holocene. These discontinuities in optical varnish layers also occur at

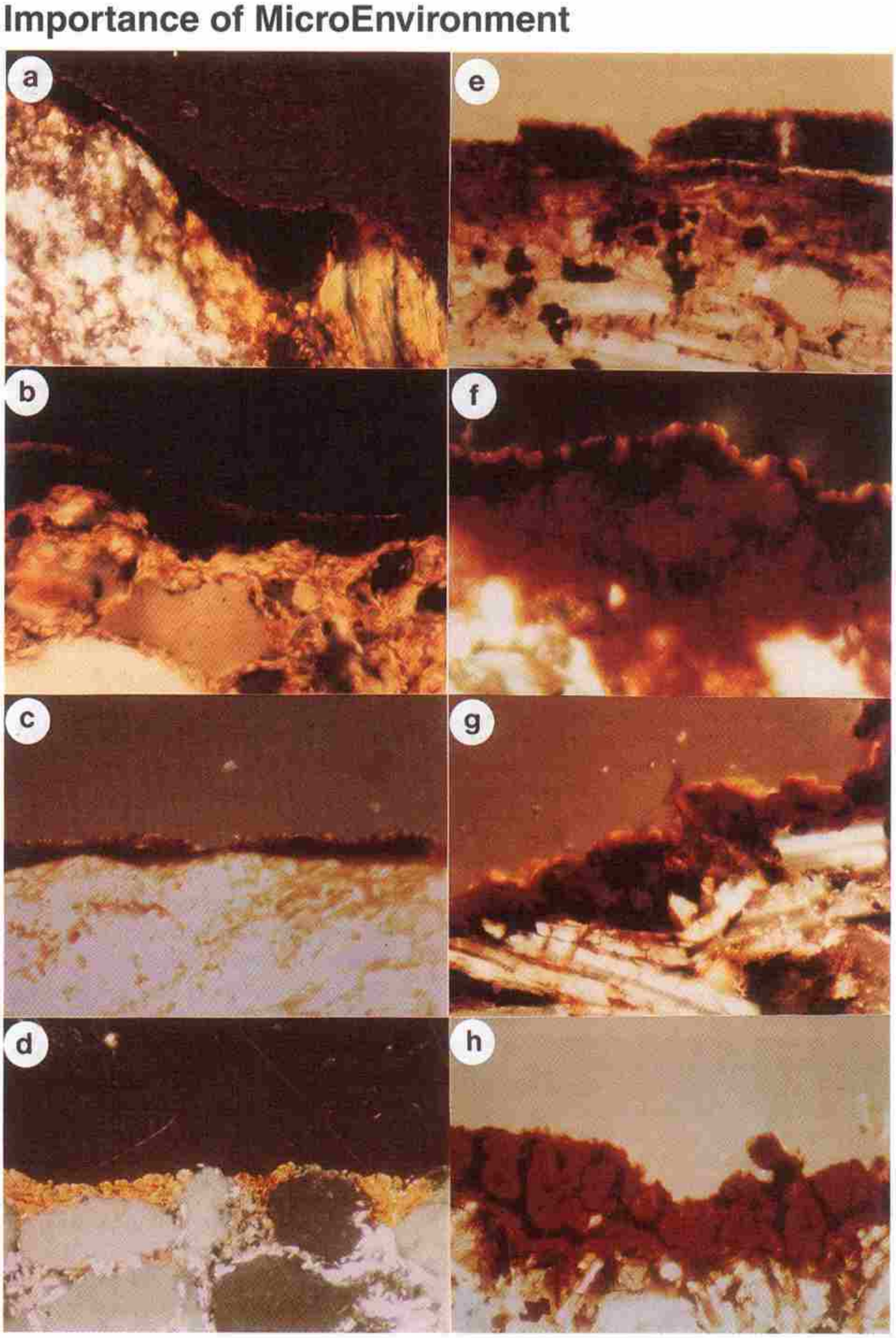
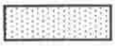
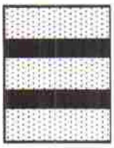
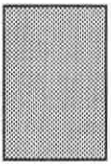


Figure 7. Varnish cross sections in different environmental contexts. The scale is ~130µm from top to bottom. (a) Sample from the terminal moraine of Khumbu Glacier, Nepal, on gneiss; (b) sample from the most recent moraine of Angel Glacier, Canada, on quartzite; (c) sample from ~2900 m in Panamint Range west of Death Valley in a grove of Limber Pines (*Pinus flexilis*), in drainage above Hanaupah Canyon fan, on quartzite; (d) sample from ~400 m next to the current channel of Hanaupah Canyon fan, Death Valley, on quartzite; (e) a forced open spall, Cima Volcanic Field, I-Cone Flow (Turrin et al. 1985), on basalt; (f) a natural spall, Cima volcanic field, A-cone flow (Turrin et al. 1985), on basalt; (g) an old ground-line band varnish, now in a subaerial position, on phyllite, from Qf1 surface at Silver Lake piedmont (Reneau 1993); and (h) basalt clast collected with J. Hayden from desert pavement cobble flipped over in the manufacturing of a sleeping circle, Sierra Pinacate, Mexico (Hayden 1976).

Layering Unit Number	Generalized Layering Unit†	Characteristics of Layering Units (LU)
1		LU-1 contains only one yellow layer --- an upper layer in varnish. Its entire thickness ranges from 2 to 150 µm. Age control is from images a,b,c in Figure 4 and rows in Table 1.
2		LU-2 occurs immediately under LU-1 and contains two black layers separated by one orange layer. Each black layer may be subdivided into minor black layers in varnishes with fast accumulation rates. LU-2 is sometimes missing on the older varnishes (≥ LU-4). Entire thickness ranges from 0 to 50 µm. Age control is from images d-i in Figure 4 and rows d-i in Table 1.
3		LU-3 often appears as one major orange layer which separates LU-2 from LU-4. Several minor black layers within it were observed on fast growing varnishes. Its entire thickness ranges from 4 to 60 µm. Age control is from from images j-l in Figure 4 and rows j-l in Table 1.
4		LU-4 is the most prominent layering unit in the Death Valley varnishes and often contains 5 black layers separated by 4 orange layers. Each black layer may consist of minor black layers. The bottom black layer of this unit rests directly on a yellow (or orange) layer, LU-5 which is similar to LU-1. Its entire thickness ranges from 20 to 90 µm. Age control is from images m-q in Figure 4 and rows m-g in Table 1.
5		LU-5 contains three yellow (or orange) layers separated by two black layers. These black layers may consist of 2 or more minor black layers. The relative thickness of this layering unit is less than or equal to that of LU-4. Its entire thickness ranges from 20 to 50 µm. Age control is from images r-t in Figure 4 and rows r-t in Table 1.
6		LU-6 can consist of 5 or more evenly spaced black layers separated by 4 or more orange layers. The ratio of relative thickness between LU-6 and LU-4 approximates 1 in the sections where LU-6 occurs. Its entire thickness ranges from 20 to 50 µm.
7		LU-7 is an orange unit which directly follows the bottom black layer of LU-6. There may be one or more black layers in the middle of LU-7, but they are hard to see due to leaching in lower parts of the oldest ultra-thin sections. The ratio of relative thickness between LU-7 and LU-6 is about 1. Its entire thickness ranges from 20 to 50 µm.
8		LU-8 is the oldest layering unit observed in the Death Valley varnishes. It consists of at least 5 evenly spaced black layers. However, it is hard to discern these black layers due to leaching in the lower part of the oldest ultra-thin sections. LU-8's thickness ranges from 20 to 60 µm. Age control is from image u in Figure 4 and row u in Table 1.

† The graphic illustration of the generalized layering units was made roughly on the scale of relative thickness of each layering unit observed in varnish ultra-thin sections.

Figure 8. Idealized sequence of varnish layering units (LU) in Death Valley.

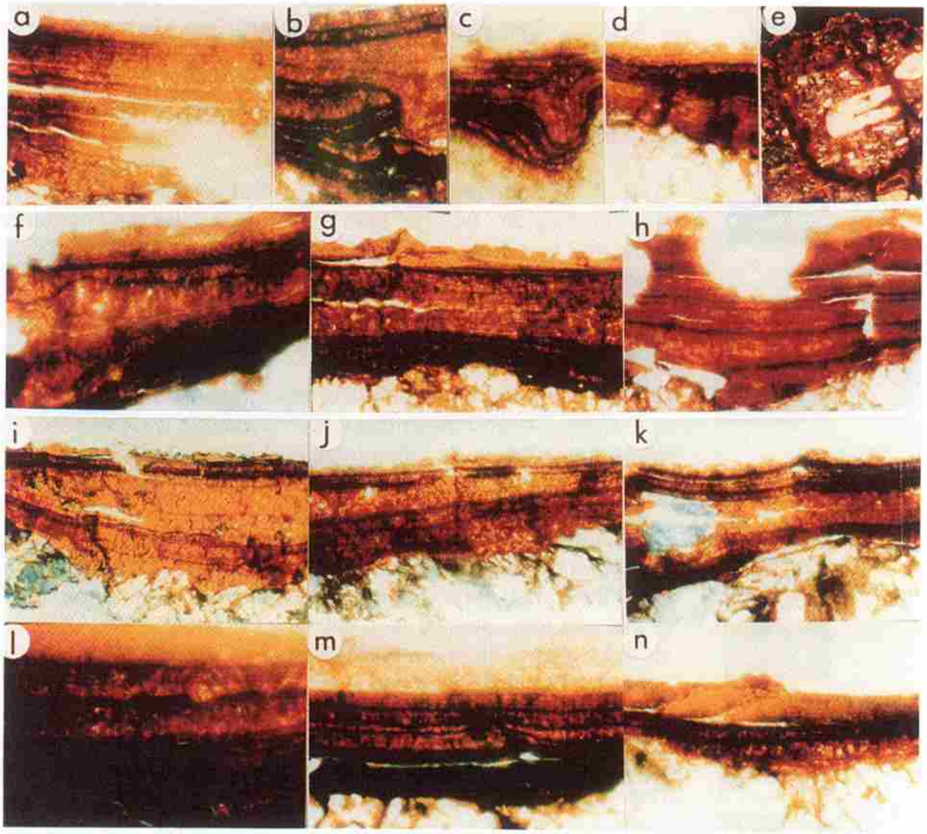

Complications in Interpretation

Figure 9. Sections illustrating complications in the interpretation of microlaminations. All images are from Death Valley except (e) which is from the Cima Volcanic Field. Section numbers and lithologies are: (a) GC-12 (quartzite), (b) GC-14 (meta-dacite), (c) GC-21 (meta-dacite), (d) GC-22 (greenstone), (e) Cima-i2-1 (basalt), (f) WS-23 (quartzite), (g) GC-7 (meta-dacite), (h) GC-11 (greenstone), (i) GC-5 (meta-dacite), (j) GC-5 (meta-dacite), (k) GC-5 (meta-dacite), (l) SS-1 (quarzite), (m) DV-11 (quarzite), and (n) DV-11 (quarzite). The scale from top to bottom is ~130 μm.

finer resolutions observable by scanning (Krinsley et al. 1990) and transmission (Krinsley et al. 1995) electron microscopes.

Leaching. Under wetter conditions in arid lands, capillary water flow through the varnish leaches Mn, Fe and other cations (Krinsley et al. 1990). Areas of leaching often exist as pockets that interrupt varnish layering (Figures 9c, 9d, and 9f). In wetter regions, however, entire varnishes can display evidence of leaching—and thus varnish layering cannot be used in these circumstances.

Facies Changes. These changes occur when depositional rates vary laterally. Our examples in Figures 9i, 9j, and 9k all come from the same thin section. Note how Unit 3 varies in thickness, and subdivisions of the two black bands in Unit 2 can be seen in Figure 9k.

Variable Sedimentation Rates. When sedimentation rates are too slow (<~0.5 μm/ka), some layers may not occur. In contrast, when rates of sedimentation are extremely fast, the continuity of the layering may be interrupted by the development of botryoidal growth forms—diagnostic of varnish growth in wetter conditions (Dorn 1986), e.g., in Figure 4f where black varnish tends to grow in columns making a wavy boundary with Unit 1. Rates of varnish accretion at this site are ~15 μm/ka.

Spalling of Weathering Rind. Rapid spalling of the rock by fire (Dragovich 1994), for example, resets the varnish clock. Although

Figure 9m and 9n are from the same boulder, the latter displays a less complete record because of rock spalling at the place where the sample was collected.

Sampling Non-subaerial Varnishes. The layering sequence described above occurs only in varnishes formed in a subaerial environment. There are, however, many other types of varnishes (Dorn 1994b; 1994d; Engel and Sharp 1958), e.g., "crack varnishes" starting to form in a rock crevice and later exposed by spalling (Figures 7e, 7f, and 9e).

The difficulties in interpretation occur in about half of the microbasins that we have studied. In about ten percent of these cases, problems prevent identification of a layering sequence. On the other hand, in most of the sections complications are limited in area to a rock-surface depression or a portion of a depression. Ninety percent of the time, it is still possible to identify varnish layering patterns.

A Local or Regional Signal?

A second set of complications has to do with the general issue of local or regional controls on a paleoenvironmental record. Similar problems arise when mapping vegetation change through pollen or macrofossils, profiling ice-volume changes with oxygen isotopes in different marine cores, or mapping soils.

One side in the debate over local or regional controls on the chemistry of varnish layers is represented by researchers at Los Alamos National Laboratory. They stress the lack of consistency in Mn-concentration in the surface layers of varnishes chemically profiled in the Cima Volcanic Field in the Mojave Desert (Figure 1). Reneau et al. (1992:719) suggest "that local conditions on the varnish surface play a larger role in determining the composition of accreting varnish than regional climatic fluctuations."

The other side of the debate is based on our analyses of data from the same field area (Figure 1). The presence in ~2900 microbasins of a surface-orange layer that is Mn-poor (e.g., Figures 3–6, 8, and 9) contradicts the Los Alamos findings. Our explanation of this empirical contradiction is that the two sides in the debate have used different sampling criteria and these have resulted in the collection of different types of samples[2] (See Dorn 1994b; 1994d for further discussion on different types of varnishes). When we collected samples that did *not* develop in a subaerial environment, we replicated the Los Alamos results and we also failed to obtain a consistent signal. In these cases of varnish formation (Figure 7e–7h), local influences appear to be a dominant factor:

Crack Varnish. When a rock crevice opens wide enough to permit the influx of clay micelles and solutes, an orange crack varnish may grow (Tricart and Cailleaux 1964). As the crevice opens further and clays are washed from the walls, a black crack varnish grows on top of the orange varnish—as seen in samples from sites where we forced open the rock crevices (Figure 7e) or where natural spalls exposed the walls of rock crevices (Figure 7f).

Ground-Line Band (GLB). Processes that move cobbles in desert pavements (e.g., upthrusting, overland flow, flotation on aeolian dust, and net soil erosion) (Mabbutt 1979) can move GLB varnish originally formed at the air-soil-rock interface (Engel and Sharp 1958) into a subaerial position. Varnish on a cobble that started out in a GLB position but is now 2 cm above the current soil surface provides an unclear Mn signal (Figure 7g).

Small Cobbles. When a desert pavement clast (8cm × 5cm × 2cm) was exposed by the manufacturing of a sleeping circle in the Sierra Pinacate, northern México (Hayden 1976), a black subaerial varnish developed within a few centimeters of the soil surface. In cross-section, however, it presents an inconsistent pattern of Mn-enhancement (Figure 7h).

All of our *subaerial* samples display, in contrast, an overwhelmingly clear signal. These varnishes were collected from the tops of boulders where they would be *most* sensitive to a regional signal of eolian fallout.[3] Subaerial varnishes collected from western U.S. deserts have a surface layer that is poor in manganese and orange/yellow in color (Figures 3–6, 8, 9). Those surface layers with high manganese concentrations in subaerial rock varnishes are correlated with lower soil pH, lower varnish pH, and a positive water balance (Dorn 1990). Manganese in currently forming varnishes is more plentiful, for example, in wetter regions with coniferous forests (Figure 7c) than in drier areas with desert scrub vegetation (Figure 7d). We emphasize that such a clear signal could not occur if "local" influences were dominant on subaerial varnishes.

Our study is limited to the western United States, hence our findings may not necessarily apply to other regions because varnish layering patterns vary with different paleoenvironmental histories. Orange (Mn-poor) surfaces are found in varnishes on the flanks of the Tien Shan in western China and on glacial moraines in Patagonia, and a low-manganese signal is also found in the hyper-arid Peruvian coastal desert (Jones 1991) and the Sahara (Haberland 1975; White 1990). Yet in the drylands of Australia, the surface layer can be comparatively enriched in Mn (Dragovich 1988b; Nobbs and Dorn 1993). Manganese-rich varnishes meanwhile are found in wetter areas, e.g., Iceland (Douglas 1987) and the European Alps (Höllerman 1963).

Case Studies and Implications

Varnish microlaminations will never have the high temporal resolution of such techniques as tree rings or coral. This is because varnish layers form at variable rates in response to environmental changes. Nor can current analyses of varnish layers provide the type of internal age controls that are available in analyses of marine or lacustrine cores. Additional analytical and methodological refinements will be required before varnish microlaminations can move beyond the stage of an experimental method. Perhaps the key problem involves internal age controls for specific layers—a problem on which we are working. While these shortcomings limit our ability to make definitive environmental assertions, we believe that optical microlaminations provide a means for correlating surfaces at a level of resolution heretofore unavailable.

Mapping Alluvial Fans in Death Valley

Geomorphologists have used many different approaches to the mapping and correlation of alluvial-fan deposits, for example, morphostratigraphy (Hooke 1972), remote sensing (White 1993), and weathering and soils (Bull 1991). Although various properties of rock varnish have been used in alluvial-fan research (Dorn 1994a; Hooke and Dorn 1992), the technique of microlaminations may offer more precise correlations than previous approaches.

In our remapping of alluvial-fan units in Death Valley using varnish microlamination patterns, we assume that alluvial-fan surfaces are correlated if the varnish microlamination stratigraphy has the same basal unit, that is, in the longest layering sequences. The layering unit at the bottom of the varnish thus approximates most closely the time of alluviation. Of course, the basal unit provides a *minimum-limiting* time signal because varnishing must follow deposition of a fan unit. It is also important to remember that the temporal resolution of varnish layers is on the order of thousands of years.

Figures 10a and 10b present our mapping of fans debauching respectively from Galena Canyon (Figure 2) and Six Springs Canyon in Death Valley (Figure 2). In describing the general characteristics of these fans, the term layering unit (LU) denotes both the basal microlamination and the geomorphic unit on which this microbed is in the basal bed:

Fan Unit LU-1. LU-1, the youngest fan surface, is located mainly at the toes of the fans and adjacent to the active channel in fan-head trenches. Some LU-1's consist of deposits abandoned so recently that only brown or orange varnish has formed; black patchy varnish (which is orange/yellow in thin section) is barely visible to the naked eye.

Fan Unit LU-2. LU-2's typically consist of deposits with a rough bouldery bar-and-swale topography. On the mapped fans, these units often constitute inset deposits next to the trunk stream channels. Millimeter-scale patches of dark varnishes grow on boulders—but again, the uppermost varnish layer is always yellow/orange in thin section.

Fan Unit LU-3. Most of LU-3 surfaces are reworked from older fan units. Some LU-3 surfaces have developed a smooth desert pavement. More often, the pavement has not completely smoothed out and original depositional bar-and-swale features can still be seen. Black varnish has spread more evenly over the surface boulders.

Fan Unit LU-4. LU-4 surfaces have the best-developed desert pavements, and to the naked eye very well developed varnishes. Incipient drainage systems have started to develop on these surfaces. Soil development is restricted to cambic, argillic, and calcic horizons; no petrocalcic horizon can be observed beneath the pavements.

Fan Unit LU-5. LU-5 surfaces are characterized by well-varnished desert pavements. Well-developed petrocalcic horizons (stage-4) can be observed beneath the pavements where they are undercut by active fluvial incision. Varnishes appear dark on boulders, but cobbles are often too weathered to preserve a dark varnish.

Fan Units LU-6 and LU-7. LU-6 and LU-7 surfaces are characterized by dissected desert pavements. Beneath the pavements there are well-developed petrocalcic horizons; some calcrete rubble (representing erosion of overlying soil horizons) has been incorporated into the pavements. Although erosion of the pavement occurs, varnishes with LU-6 and LU-7 layering sequences can be found on boulders that have retained their fluvially-rounded surfaces. In the field, LU-7 fan surfaces are differentiated from LU-6 surfaces by two features: well-varnished larger boulders are far less frequent on LU-7 than on LU-6, and LU-6 surfaces are often inset into LU-7.

Fan Unit LU-8. LU-8 surfaces are topographically well above any of the younger fan units. They are characterized by ridge-and-ravine (ballena) topography. Most of the surface deposits consist of rubble from the erosion of the petrocalcic soil horizons beneath the original fan surfaces. Well-developed varnishes can be seen only where isolated patches of flat desert pavement remain. Fan surfaces of ≥LU-8 are the oldest observable Quaternary deposits in Death Valley. They are most commonly located in fan-head embayments and tucked up against bedrock outcrops. Varnishes older than LU-8 could not be sampled on these surfaces because the boulders on them retain no original (abraded) surfaces.

Although a full examination of the geomorphic implications of these findings is beyond the scope of this paper, this case study suggests the method's utility for correlating the relative age of geomorphic units and its potential for assigning correlative ages to the layering sequence. Finally, we note that alluvial-fans elsewhere in the southwestern U.S. have surfaces with different degrees of varnish development (Bull 1991), and these too may be mappable with varnish microlaminae.

Connection with Heinrich Events?

There is growing evidence that global climate in the last ice age changed suddenly and dramatically to the unsteady beat of Heinrich Events—those "armadas" of icebergs released episodically from the Laurentide ice sheet into the northern Atlantic (Bond et al. 1993; Broecker 1994). The most recent Heinrich Event correlates with the Younger Dryas (Keigwin and Lehman 1994), a globally synchronous cold snap thought to have occurred about 10,500 ^{14}C yr B.P. (Denton and Hendy 1994; Hodell et al. 1991; Kudrass et al. 1991; Wright 1989). Heinrich Events H1 through H6 from ~14,000 to ~65,000 years ago (Bond et al. 1993; Broecker 1994) are correlated with distinctive characteristics of Greenland ice cores (Bond et al. 1993), Florida pollen cores (Watts and Hansen 1994), French lake deposits (Thouveny et al. 1994), New Zealand glacial advances (Denton and Hendy 1994), and possibly with glacial advances in western North America (Clark and Bartlein 1995; Gosse et al. 1995a; 1995b). These correlations suggest a link between the iceberg armadas and sudden changes in global climate (Birchfield et al. 1994; Broecker 1994).

Much to our surprise, we discovered that varnish microlaminations in Death Valley grossly corresponded with the sequence and timing of Heinrich Events (Figures 5, 6, and 11). The two black layers in Unit 2 seem to correlate with the Younger Dryas and H1 (Broecker 1994). The next black layer (uppermost in varnish Unit 4) occurs at ~21,000 ^{14}C years ago, the age of Heinrich Event H2 (Broecker 1994). The correlation of the next four black layers in Unit 4 with H3–H6 is more speculative, however, because our chronology is not sufficiently precise at the present time (Figure 5). An important point is that the ubiquitous distribution of rock varnish in drylands makes them potential tools for evaluating general hypotheses about the "global extent" (Broecker 1994:421) of sudden climatic changes, e.g., by mapping the distribution of wet periods in desert areas.

Petroglyphs and Artifacts

Rock varnish is removed when humans disturb rock surfaces. This means that artifacts such as stone tools, rock engravings, and giant

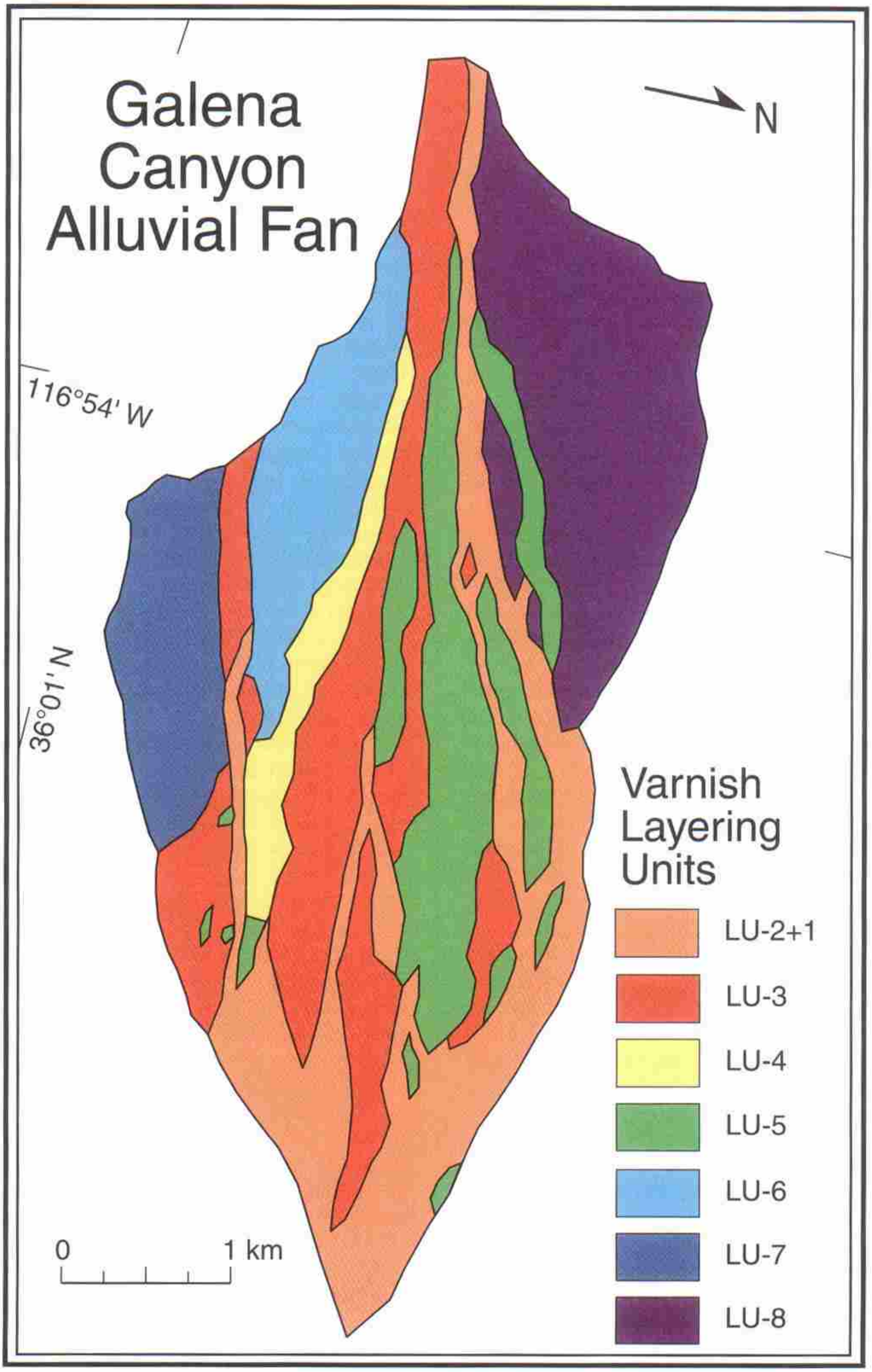


Figure 10a. Map of Galena fan (a) (see Figure 2 for location). Geomorphic units on the fan are correlated with the use of the basal layering unit in the varnish.

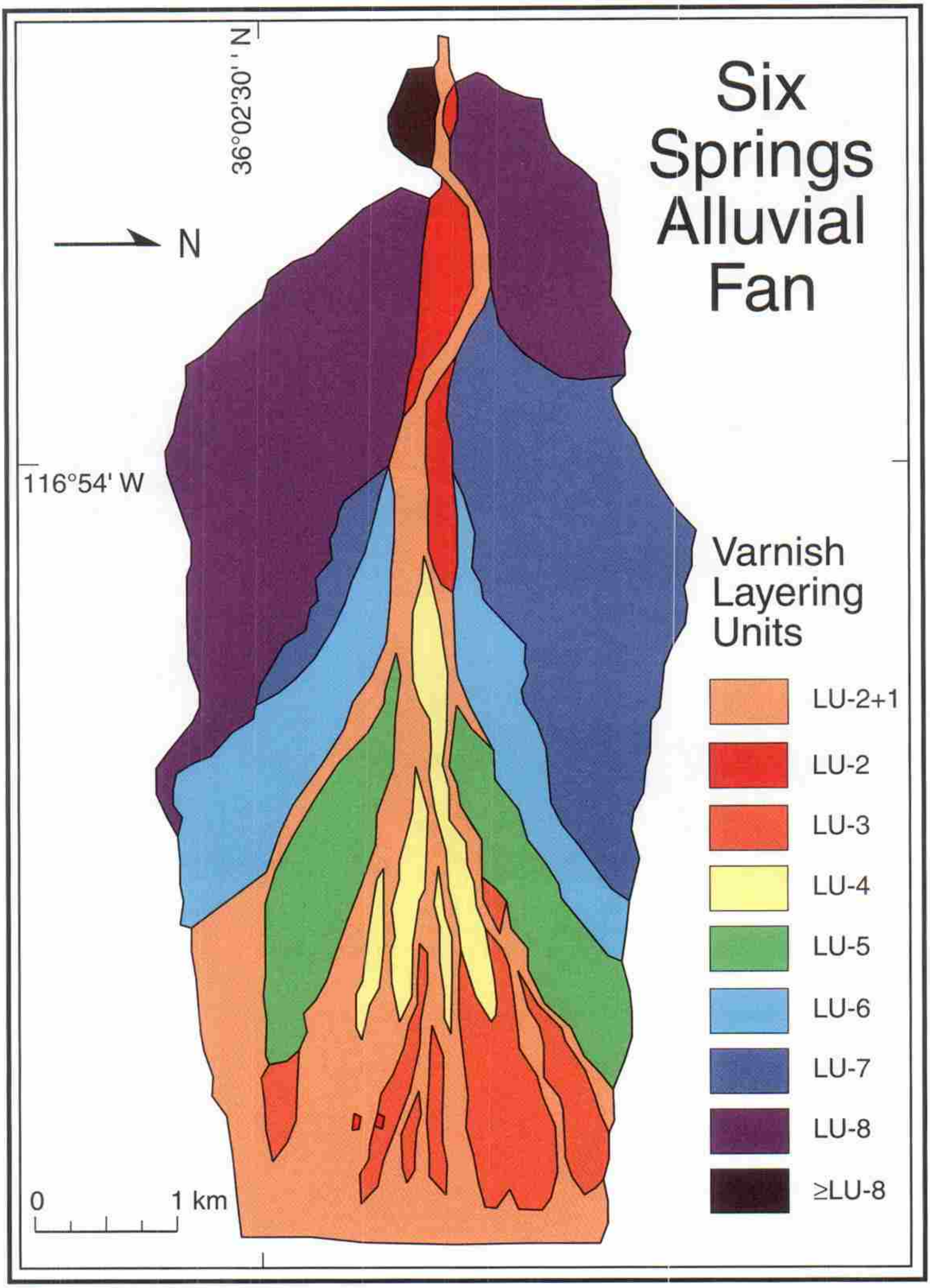


Figure 10b. Map of Six Springs fan (see Figure 2 for location). Geomorphic units on the fan are correlated with the use of the basal layering unit in the varnish.

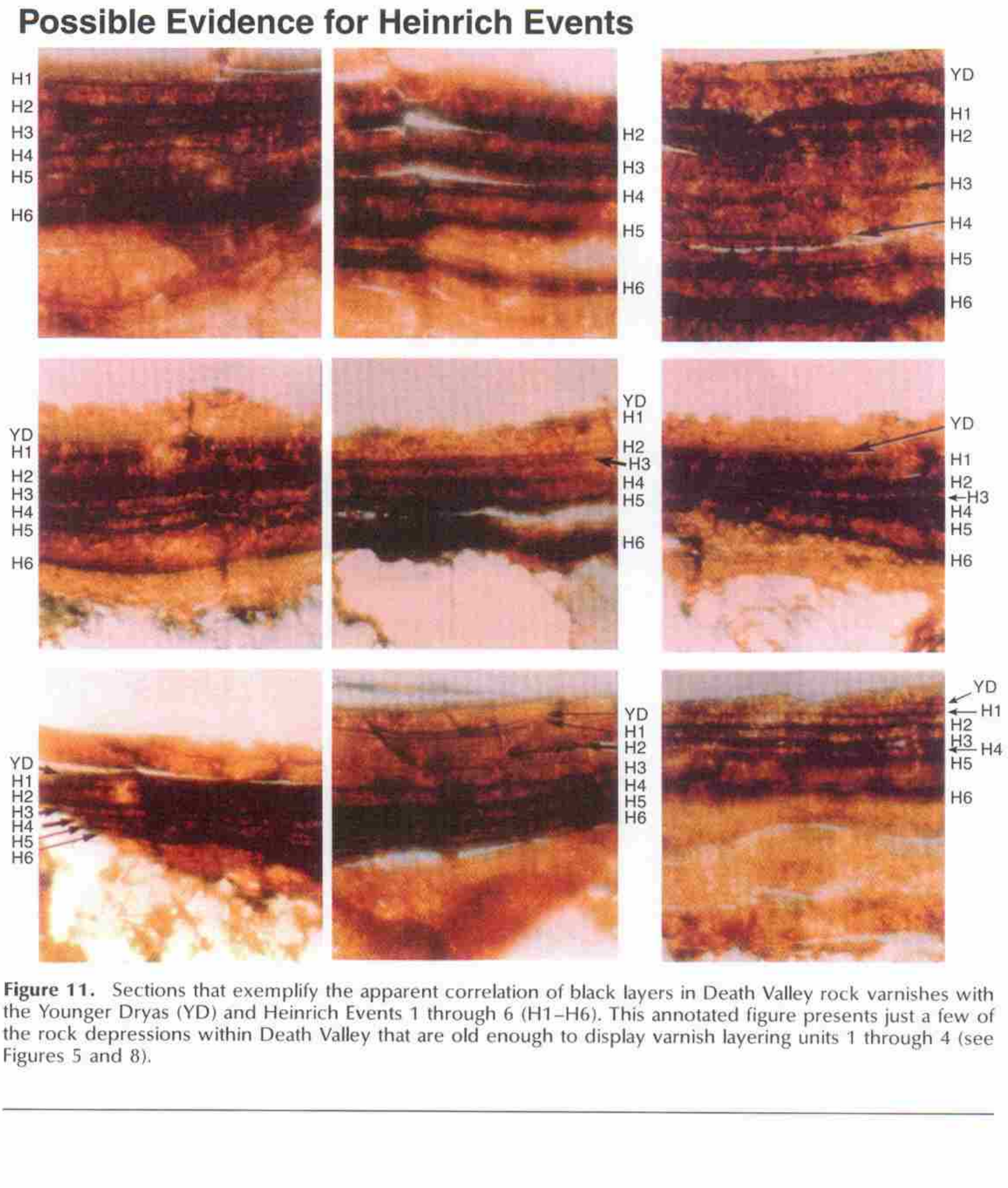


Figure 11. Sections that exemplify the apparent correlation of black layers in Death Valley rock varnishes with the Younger Dryas (YD) and Heinrich Events 1 through 6 (H1–H6). This annotated figure presents just a few of the rock depressions within Death Valley that are old enough to display varnish layering units 1 through 4 (see Figures 5 and 8).

Figure 12. Correspondence between petroglyph appearance in the field, visual microlaminations of rock varnish formed on the petroglyph grooves, and ^{14}C ages for petroglyphs. The width of the petroglyph lines is about 1 cm for all photographs, except for the anthropomorph where the body is about 4 cm wide. Black layers are enriched in Mn, and the orange/red layers are Mn-poor; the different appearances of the Mn-poor layers is due to different effects of the polarizer. The assignment of the annotated layering units is tentative and is based on the sequence in Figure 5. In the western U.S., older ^{14}C ages correspond with more complex layering patterns. The South Australian layering patterns have not yet been calibrated, but the relative antiquity of the petroglyph is consistent with the multiple layers observed. Radiocarbon ages are on organics encapsulated in the weathering rind, beneath the varnish (cf. Dorn 1994b).

Shield Figure, Cow Cove, Mohave Desert: 4990 ± 70 ^{14}C yr B.P. (ETH-12879)

Epoxy

Unit 1 (Holocene)

Rock (under varnish ~15-20 µm thick)

Outlined Animal, Legend Rock, Wyoming: 10,660 ± 50 ^{14}C yr B.P. (Beta-84416)

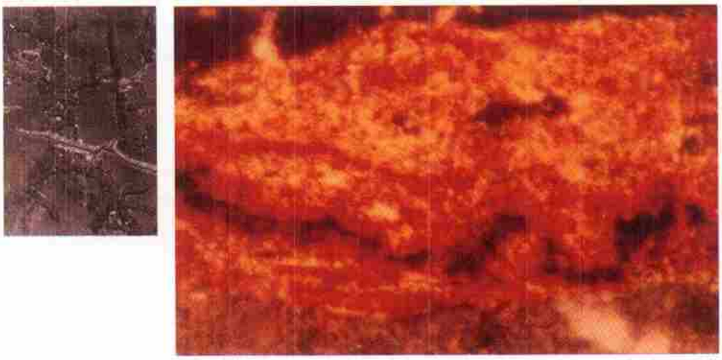
Epoxy

Unit 1 (Holocene)

Upper Layer Unit 2 - Younger Dryas?

Rock (under varnish ~25 µm thick)

Anthropomorph, Southwest, Wyoming: 11,650 ± 50 ^{14}C yr B.P. (Beta-84418)



Unit 1 (Holocene)

Upper Layer Unit 2 - Younger Dryas?

Orange varnish between 2 black layers of Unit 2 (~14-11 ka)

Rock (under varnish ~30 µm thick)

Spiral Figure, Coso Range, California: 14,760 ± 90 ^{14}C yr B.P. (CAMS-20705)

Epoxy

Unit 1 (Holocene)

Upper Layer Unit 2 - Younger Dryas?

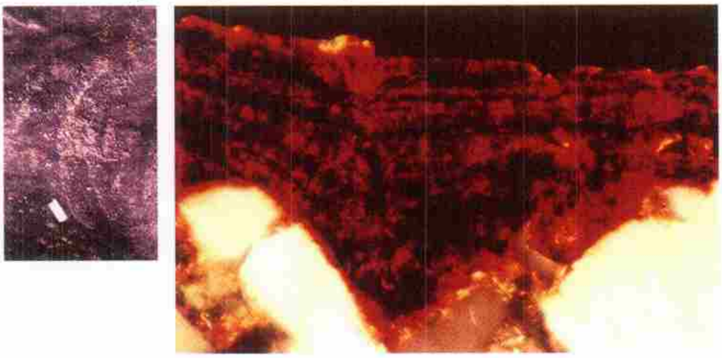
Middle (orange) Layer Unit 2

Lower Layer Unit 2 - Heinrich 1?

Unit 3

Rock (under varnish ~35 µm thick)

Curved Line, Olary Province, South Australia



Epoxy

Varnish layers in South Australia are not calibrated. Subvarnish organic matter yielded AMS radiocarbon ages for this petroglyph of:

43,140 ± 130 (AA 6898) and
> 43,100 (AA 6920)

Rock (under varnish ~50-80 µm thick)

ground figures are amenable to analysis with microlaminations. The time-scale of laminae formation is too coarse for use on recent artifacts, Holocene petroglyphs for example, because the orange/yellow surface layer is diagnostic of the last 10,000 years; see Figure 12a. However, older varnishes with their distinctive layering patterns may permit the dating of older worked stone (see Figures 12b and 12c).

Paleoearthquakes

The determination of future seismic hazards is dependent on information about the timing of past earthquakes. Microlaminations can aid in constraining the timing of past earthquakes in arid regions where age control is frequently lacking because organic remains are typically oxidized. To illustrate this potential, samples were collected from surfaces above, on, and below fault scarps at the base of Hanaupah fan (Figures 2a and 13). If the stratigraphy in Table 1 and Figure 5 are used, varnish layering sequences suggest the occurrence of a major faulting event just after 11,000 to 14,000 ^{14}C yr B.P. (upper black layer in Unit 2) and a minor faulting event sometime after 10,000 ^{14}C yr B.P. (Unit 1).

Implications for Other Varnish Methods

Varnish thickness cannot be used as a dating tool. As Figure 4 illustrates, rates of varnish accretion vary greatly. Microbasins with only Unit 1 can be thicker than microbasins with a much more complex layering pattern. The wetting that fosters faster varnish growth also enhances decay of the underlying rock, which eventually spalls and resets the varnish clock. Slower-growing varnishes have greatest potential for longer-term survival because they exist in the most xeric sites. Quartzite, which provides the longest varnish sequences in Death Valley, appears to be the most stable substrate. That said, even the most stable boulder surfaces are subject eventually to spalling. In the case of Death Valley, we have not found a distinct layering unit more complicated than Unit 8 (Figure 6 and 8)—probably about 300,000 years old (Table 1).

Our data also reveal that, contrary to a recent study in the Mojave Desert (Reneau 1993), neither bulk manganese abundance nor thickness can be used successfully as a tool to date the subaerial exposure of rock surfaces. The mass of manganese per unit surface area depends upon the abundance and thickness of black layers. Varnishes of the same age with thicker black layers will have more Mn than varnishes with thinner black layers.

Implications for Landscape Stability

If even a micron of the underlying rock erodes, the varnish is lost. Some boulder surfaces do not survive long (Figures 9m and 9n), but these easily-eroded boulders may rest next to boulders that have experienced *no* erosion by fluvial, aeolian, or slope processes for 10^4 to 10^5 years (Figure 5). Boulder erosion cannot, therefore, be treated as a constant—a result that should not be surprising to those who have seen glacial polish on bedrock that predates the last-glacial maxima (Dorn et al. 1991; Nishiizumi et al. 1993) or Pleistocene paintings in European caves (Valladas et al. 1992). Our observations on varnish stability are consistent with a maximum uranium-series (non-isochron) age of ≥300,000 yr B.P. on rock varnish (Knauss and Ku 1980).

Doubtless our finding that boulders can remain stable for tens to hundreds of thousands of years will be resisted by scholars who model landform development on the *assumption* that boulder erosion can be treated as a constant (Hallet and Putkonen 1994). However mathematically inconvenient, boulder erosion is not a linear process; it tends to occurs in slabs and at irregular time intervals. Our results imply that only those boulders that remain stable for a long period are useful as tools for dating glacial moraines with cosmogenic nuclides (Brook et al. 1993; Phillips et al. 1990; Zreda and Phillips 1994; Gosse et al. 1995a, 1995b). Accordingly, the process of selecting the most stable boulders for cosmogenic nuclide sampling would be aided by the study of varnish microlaminations.

Conclusion

We are approaching the bicentennial of scholarly research on manganese-iron coatings on rocks. Since Alexander von Humboldt's (1812) explorations on the Orinoco River, the literature on rock varnish has been filled with

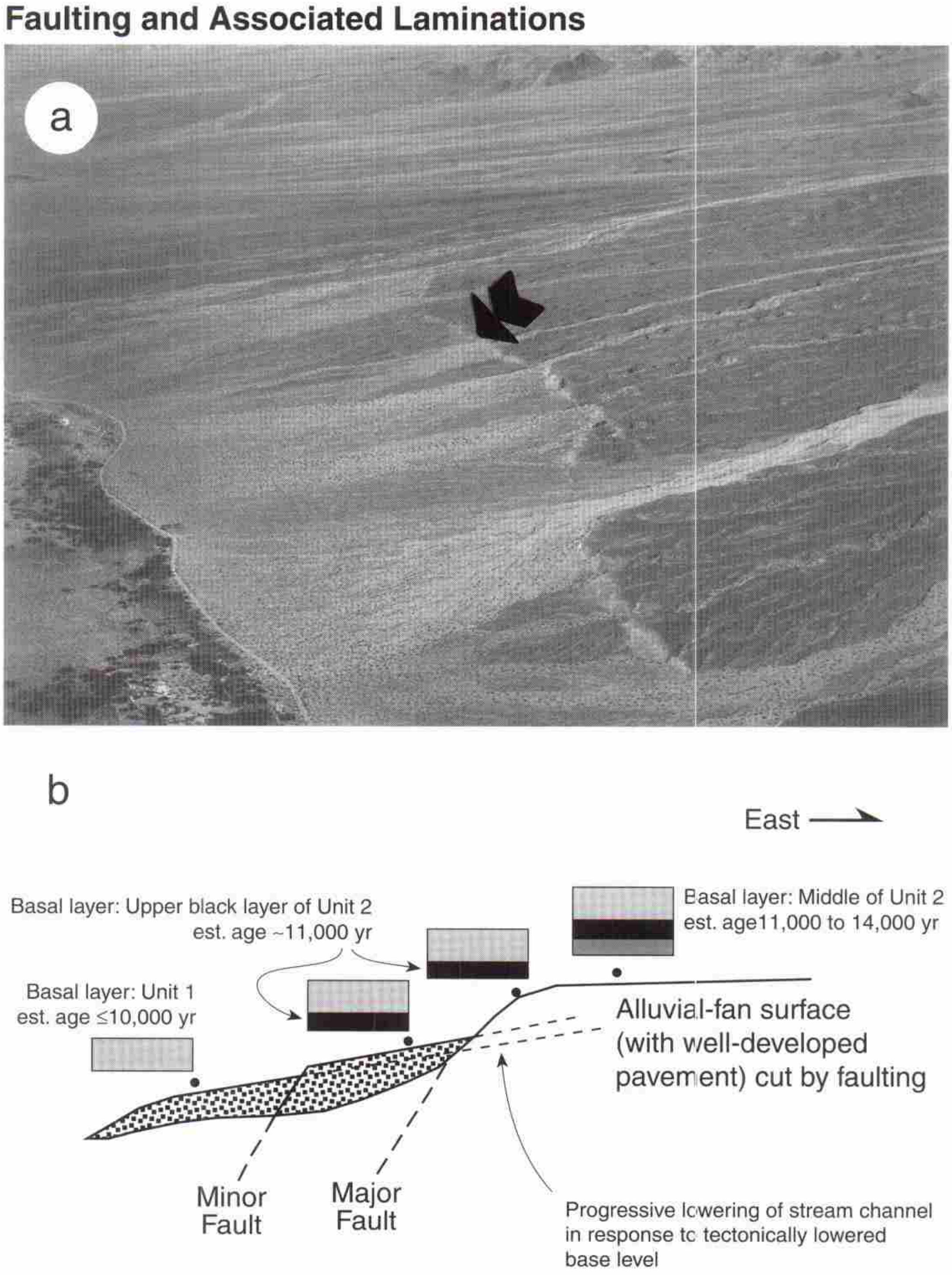


Figure 13. Using varnish laminae to study faulting. (a) Oblique aerial photograph (south-looking) of the fault scarp at the base of Hanaupah Canyon fan (see Figure 2a for the location). The road on the left side (west) of the photograph conveys a sense of scale. The major fault scarp offsets a darkly-varnished fan unit, but a newer fault scarp offsets younger inset fan deposits. The arrow points to the location of the sampling. (b) Idealized cross-section illustrating the microlamination sequences found at different locales above and below the fault scarps.

speculation on its potential as an indicator of time and environmental change, propelled by intuitive interpretations of the variable darkness of varnish, and driven by the need for a technique for correlating exposed surfaces. Of the fourteen methods for analyzing the time signals within rock varnish devised thus far (Dorn 1994d), we believe that the method of visual microlaminae has the most potential for widespread use because: first, "a picture is worth a thousand words," especially when thousands of rock depressions replicate a pattern; second, material costs are minimal; third, the manufacturing of ultra-thin sections (Perry and Adams 1978; Dorn 1992) has become efficient and reliable (Liu 1994); fourth, conventional transmitted light microscopes are readily available; and fifth, sampling is not difficult once investigators realize that, like any sample collected for dating, "not all samples are alike" and in the case of varnish the "best looking" is not necessarily the best for dating purposes.[4] Collection requires a rock hammer, an understanding of different types of rock varnish (Dorn 1994d; Liu 1994), and an appreciation of the field relationships of surface textures and geomorphic or archaeological processes of interest. If, for example, an investigator is interested in the age of an alluvial-fan unit, fluvially abraded cobbles should be collected—not smooth planar surfaces that are characteristic of joints exposed by spalling.

The method has a further advantage in that it is a "conservative" technique. First, the varnish layering pattern always provides a *minimum* time signal for the exposure of the underlying rock because aeolian abrasion, lacustrine action, spalling of weathering rinds or along joints, and biochemical erosion all "reset" the varnish clock. Second, even without precise temporal "calibrations" (Figure 5 and Table 1), the technique can be used to correlate the relative ages of surfaces. And once calibrations are established, the technique has the potential to be used to assign correlated-ages. While we do not know if it is possible to establish calibrations outside of the Death Valley region, continuous optical microlaminations in varnishes are evident throughout the drylands of the western U.S. as well as in Antarctica, the Kunlun Mountains, Negev Desert, Patagonia, the Sinai Peninsula, South Australia, southern Peru and the Tien Shan Mountains.

Our optimism for optical microlaminations as a chronometric tool is tempered, however, by the realization that this method is still in the experimental stage. Yet, we remain confident that this approach will yield precise and accurate age-determinations and low-cost correlations of non-contiguous surfaces in drylands. A potentially powerful record of place-specific and long-term environmental change thus lies literally beneath our feet.

Acknowledgments

We thank A. Bach, W. Broecker, P. Beyer, J. Clark, R. LeB. Hooke, M. Marcus, G. Pope, and S. Reynolds for comments; T. Holcomb, J. Francis, M. Nobbs, and D. Whitley for permission to use petroglyph samples; J. Clark for microprobe assistance; and I. Hajdas and G. Bonani for ^{14}C analyses. This research was supported by the NSF Doctoral Dissertation Improvement Grant SBR94-04718 and Sabbatical Support from Arizona State University. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the National Science Foundation.

Note

1. The visual school of varnish collection, promoted mostly by varnish researchers at Los Alamos National Laboratory, is best summarized in their papers.

> [O]ur sampling protocol, based on the assumption that clasts most closely representing the exposure age of a surface are those with the most developed (oldest) varnish (Harrington and Whitney 1987; Whitney and Harrington 1994). To maximize the probability of selecting the oldest clasts on a surface we originally collected ~20 clasts from a deposit or surface and then culled them to the best 8 to 10 clasts, based on the macroscopic quality of each varnish coat . . . (Harrington and Whitney 1995:168–169)

> . . . relative darkness may be the best field criteria for relative age. (Reneau et al. 1992:687)

> Sample collection at each site involved repeated traverses across the surface, selecting clasts whose varnish appeared exceptionally dark or continuous when compared with other clasts on the same surface. These clasts were then culled by roughly half, those with less-developed varnish being rejected, thereby resulting in sample collections of 21 to 49 clasts from each sample site. . . . Typically, the best varnish on each geomorphic surface of the Soda Mountains piedmont occurs 1–2 cm above the soil surface on relatively small clasts having intermediate axes generally less than 10 cm. (Reneau 1993:311)

The notion that appearance is equivalent to age is intuitively appealing, but appearance is influenced by many factors other than age, e.g., varnish chemistry, lithology, the underlying weathering rind, patterns of water flow over surfaces, other rock coatings, epilithic organisms, surface roughness, soil proximity, and, most importantly, the type of rock varnish (cf. Dorn 1994b; 1994d). We agree that darker varnishes are the oldest, but only when time is the only variable.

We tried to collect only varnishes that have remained exposed to the atmosphere. We collected rounded cobbles, because these had the highest likelihood of relating to the geomorphic event (e.g., flooding, wave abrasion) of interest. Salt-weathering and other types of rock weathering tend to shatter rocks along angular planes of weakness, both in the subsurface and at the surface. Varnishes were collected from the tops of boulders because these have been exposed only to airborne fallout. We purposely avoided the "best looking" varnishes, because these start in unopened rock fractures and at ground lines on desert pavement cobbles (Dorn 1994b; 1994d). These positions allow rapid and thick cementation of clays to rock surfaces—all the while avoiding exposure to the acidity of rainfall and rock-surface organisms. Varnishes formed in rock crevices and too close to the ground surface are influenced by local microenvironmental changes—not a regional climatic signal. In contrast, truly subaerial positions are exposed to alternating conditions of dust deposition, precipitation, and organic acids. In essence, exposure to the elements means that subaerial varnishes do not look the darkest, but they do provide the records reported here. Discussion and tables detailing sampling criteria are presented elsewhere (Dorn 1994b; Dorn 1994d; Liu 1994).

2–4. See note 1.

References

Bach, A., and Elliott-Fisk, D. L. 1995. Pleistocene Glacial Moraine Complex at Pine Creek, East-central Sierra Nevada, CA. Forthcoming in *Physical Geography* 16.

Benson, L., Currey, D., Lao, Y., and Hostetler, S. 1992. Lake-Size Variations in the Lahontan and Bonneville Basins between 13,000 and 9000 ^{14}C yr B.P. *Palaeogeography, Palaeoclimatology, Palaeoecology* 95:18–32.

Benson, L. V., Currey, D. R., Dorn, R. I., Lajoie, K. R., Oviatt, C. G., Robinson, S. W., Smith, G. I., and 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.

Birchfield, E. G., Wang, H., and Rich, J. 1994. Century/Millennium Internal Climate Oscillations in an Ocean-Atmosphere-Continental Ice Sheet Model. *Journal of Geophysical Research* 99(C6):12,459–12,470.

Bond, G., Broecker, W., Johnson, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G. 1993. Correlations between Climate Records from North Atlantic Sediments and Greenland Ice. *Nature* 365:143–147.

Broecker, W. S. 1994. Massive Iceberg Discharges as Triggers for Global Climate Change. *Nature* 372:421–424.

Bromfield, S. M., and David, D. J. 1976. Sorption and Oxidation of Manganous Ions and Reduction of Manganese Oxide by Cell Suspensions of Manganese Oxidizing Bacterium. *Soil Biology Biochemistry* 8:37–43.

Brook, E. J., Kurz, M. D., Ackert, R. P., Denton, G. H., Brown, E. T., Raisbeck, G. M., and Yiou, F. 1993. Chronology of Taylor Glacier Advances in Arena Valley, Antarctica, using in situ Cosmogenic ^{3}He and ^{10}Be. *Quaternary Research* 39:11–23.

Bull, W. B. 1991. *Geomorphic Responses to Climatic Change*. Oxford: Oxford University Press.

Cerling, T. E. 1990. Dating Geomorphic Surfaces using Cosmogenic ^{3}He. *Quaternary Research* 33:148–156.

Cerling, T. E., Poreda, R. J., and Rathburn, S. L. 1994. Cosmogenic ^{3}He and ^{21}Ne Age of the Big Lost River Flood, Snake River Plain, Idaho. *Geology* 22:227–230.

Clark, P. U., and Bartlein, P. J. 1995. Correlation of Late Pleistocene Mountain Glaciation in Western United States with North Atlantic Heinrich Events. *Geology* 23:483–486.

COHMAP. 1988. Climatic Changes in the Last 18,000 Years: Observations and Model Simulations. *Science* 241:1043–1052.

Denton, G. H., and Hendy, C. H. 1994. Younger Dryas Age Advance of Franz Josef Glacier in the Southern Alps of New Zealand. *Science* 264:1434–1437.

Dorn, R. I. 1986. Rock Varnish as an Indicator of Aeolian Environmental Change. In *Aeolian Geomorphology*, ed. W. G. Nickling, pp. 291–307. London: Allen & Unwin.

——. 1990. Quaternary Alkalinity Fluctuations Recorded in Rock Varnish Microlaminations on Western U.S.A. Volcanics. *Palaeogeography, Palaeoclimatology, Palaeoecology* 76:291–310.

——. 1992. Paleoenvironmental Signals in Rock Varnish on Petroglyphs. *American Indian Rock Art* 18:1–17.

——. 1994a. Alluvial Fans as an Indicator of Climatic Change. In *Geomorphology of Desert Environments*, ed. A. D. Abrahams and A. J. Parsons, pp. 593–615. London: Chapman and Hall.

——. 1994b. Dating Petroglyphs with a 3-Tier Rock Varnish Approach. In *New Light on Old Art: Advances in Hunter-Gatherer Rock Art Research*, ed. D. S. Whitley and L. Loendorf, pp. 12–36. UCLA Institute for Archaeology Monograph Series No. 36.

——. 1994c. Rock Varnish as an Indicator of Climatic Change. In *Geomorphology of Desert Environments*, ed. A. Abrahams and A. Parsons, pp. 539–552. London: Chapman and Hall.

——. 1994d. Surface Exposure Dating with Rock Varnish. In *Dating in Exposed and Surface Contexts,* ed. C. Beck, pp. 77–113. Albuquerque: University of New Mexico Press.

Dorn, R. I., and Oberlander, T. M. 1981. Microbial Origin of Desert Varnish. *Science* 213:1245–1247.

——, and ——. 1982. Rock Varnish. *Progress in Physical Geography* 6:317–367.

Dorn, R. I., Jull, A. J. T., Donahue, D. J., Linick, T. W., and Toolin, L. T. 1990. Latest Pleistocene Lake Shorelines and Glacial Chronology in the Western Basin and Range Province, USA: Insights from AMS Radiocarbon Dating of Rock Varnish and Paleoclimatic Implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 78:315–331.

Dorn, R. I., Phillips, F. M., Zreda, M. G., Wolfe, E. W., Jull, A. J. T., Kubik, P. W., and Sharma, P. 1991. Glacial Chronology of Mauna Kea, Hawaii, as Constrained by Surface-Exposure Dating. *National Geographic Research and Exploration* 7:456–471.

Douglas, G. R. 1987. Manganese-Rich Rock Coatings from Iceland. *Earth Surface Processes and Landforms* 12:301–310.

Dragovich, D. 1988a. Desert Varnish and Environmental Change near Broken Hill, Western New South Wales. *Earth-Science Review* 25:399–407.

——. 1988b. A Preliminary Electron Probe Study of Microchemical Variations in Desert Varnish in Western New South Wales, Australia. *Earth Surface Processes and Landforms* 13:259–270.

——. 1994. Fire, Climate, and the Persistence of Desert Varnish near Dampier, Western Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 111:279–288.

Drake, N. A., Heydeman, M. T., and White, K. H. 1993. Distribution and Formation of Rock Varnish in Southern Tunisia. *Earth Surface Processes and Landforms* 18:31–41.

Elliott-Fisk, D. L. 1987. Glacial Geomorphology of the White Mountains, California and Nevada: Establishment of a Glacial Chronology. *Physical Geography* 8:299–323.

Engel, C. G., and Sharp, R. S. 1958. Chemical Data on Desert Varnish. *Geological Society of America Bulletin* 69:487–518.

Fitzpatrick, J. A., and Bischoff, J. L. 1993. Uranium-Series Dates on Sediments of the High Shoreline of Panamint Valley, California. *U.S. Geological Survey Open-File Report* 93-232:1–15.

Gosse, J. C., Klein, J. Evenson, E. B., Lawn, B., and Middleton, R. 1995a. Beryllium-10 Dating of the Duration and Retreat of the last Pinedale Glacial Sequence. *Science* 268:1329–1333.

Gosse, J. C., Evanson, E., Klein, J., Lawn, B., and Middleton, R. 1995b. Precise Cosmogenic ^{10}Be Measurements in Western North America: Support for a Global Younger Dryas Cooling Event. *Geology* 23:877–880.

Haberland, W. 1975. Untersuchungen an Krusten, Wustenlacken und Polituren auf Gesteinsoberflachen der nordlichen und mittlerent Saharan (Libyen und Tchad). *Berliner Geographische Abhandlungen* 21:1–77.

Hallet, B., and Putkonen, J. 1994. Surface Dating of Dynamic Landforms: Round Boulders on Aging Moraines. *Science* 265:937–940.

Harrington, C., and Whitney, J. 1995. Comment on Evidence Suggesting that Methods of Rock-Varnish Cation Ratio Dating are Neither Comparable nor Consistently Reliable. *Quaternary Research* 43:268–271.

Hayden, J. 1976. Pre-Altithermal Archaeology in the Sierra Pinacate, Sonora, Mexico. *American Antiquity* 41:274–289.

Hodell, D. A., Curtis, J. H., Jones, G., Higuera-Gundy, A., Brenner, M., Binford, M., and Dorsey, K. 1991. Reconstruction of Caribbean Climate Change over the Past 10,500 Years. *Nature* 352:790–793.

Höllerman, P. 1963. "Verwitterungsrinden" in den Alpen. *Zeitschrift für Geomorphologie* 7:172–177.

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., and Dorn, R. 1992. Segmentation of Alluvial Fans in Death Valley, California: New Insights from Surface-Exposure Dating and Laboratory Modelling. *Earth Surface Processes and Landforms* 17:557–574.

Hooke, R. L., Yang, H., and Weiblen, P. W. 1969. Desert Varnish: An Electron Probe Study. *Journal of Geology* 77:275–288.

Jones, C. E. 1991. Characteristics and Origin of Rock Varnish from the Hyperarid Coastal Deserts of Northern Peru. *Quaternary Research* 35:116–129.

Keigwin, L. D., and Lehman, S. J. 1994. Deep Circulation Change linked to HEINRICH Event 1 and Younger Dryas in a Middepth North Atlantic Core. *Paleoceanographic Currents* 9:185–194.

Knauss, K. G., and Ku, T. L. 1980. Desert Varnish: Potential for Age Dating via Uranium-Series Isotopes. *Journal of Geology* 88:95–100.

Krinsley, D., Dorn, R. I., and Anderson, S. 1990. Factors that May Interfere with the Dating of Rock Varnish. *Physical Geography* 11:97–119.

Krinsley, D. H., Dorn, R. I., and Tovey, N. K. 1995. Nanometer-Scale Layering in Rock Varnish: Implications for Genesis and Paleoenvironmental Interpretation. *Journal of Geology* 103:106–113.

Krumbein, W. E., and Jens, K. 1981. Biogenic Rock Varnishes of the Negev Desert (Israel): An Ecological Study of Iron and Manganese Transformation by Cyanobacteria and Fungi. *Oecologia* 50:25–38.

Ku, T. L., Luo, S., Lowenstein, T. K., Li, J., and Spencer, R. J. 1994. U-Series Chronology for Lacustrine Deposits of Death Valley, California: Implications for Late Pleistocene Climate Changes. *Geological Society of America Abstracts with Programs* 26(7):A-169.

Kudrass, H. R., Erlenkeuser, H., Vollbrecht, R., and Weiss, W. 1991. Global Nature of the Younger Dryas Cooling Event Inferred from Oxygen Isotope Data from Sulu Sea Cores. *Nature* 349:406–409.

Laity, J. E. 1994. Landforms of Aeolian Erosion. In *Geomorphology of Desert Environments,* ed. A. D. Abrahams and A. J. Parsons, pp. 506–535. London: Chapman and Hall.

Lin, J. 1994. Personal Communication. Lamont Doherty Earth Observatory, Columbia University.

Liu, T. 1994. Visual Microlaminations in Rock Varnish: A New Paleoenvironmental and Geomorphic Tool in Drylands. Ph.D. Dissertation, Department of Geography, Arizona State University, Tempe.

Mabbutt, J. A. 1979. Pavements and Patterned Ground in the Australian Stony Deserts. *Stuttgarter Geographische Studien* 93:107–123.

Meek, N. 1989. Geomorphic and Hydrologic Implications of the Rapid Incision of Afton Canyon, Mojave Desert, California. *Geology* 17:7–10.

Moore, C. B., and Elvidge, C. D. 1982. Desert Varnish. In *Reference Handbook on the Deserts of North America,* ed. G. L. Bender, pp. 527–536. Westport, Connecticut: Greenwood Press.

Nagy, B., Nagy, L. A., Rigali, M. J., Jones, W. D., Krinsley, D. H., and Sinclair, N. 1991. Rock Varnish in the Sonoran Desert: Microbiologically Mediated Accumulation of Manganiferous Sediments. *Sedimentology* 38:1153–1171.

Nishiizumi, K., Kohl, C., Arnold, J., Dorn, R., Klein, J., Fink, D., Middleton, R., and Lal, D. 1993. Role of in situ Cosmogenic Nuclides ^{10}Be and ^{26}Al in the Study of Diverse Geomorphic Processes. *Earth Surface Processes and Landforms* 18:407–425.

Nobbs, M., and Dorn, R. I. 1993. New Surface Exposure Ages for Petroglyphs from the Olary Province, South Australia. *Archaeology in Oceania* 28:18–39.

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

Palmer, F. E., Staley, J. T., Murray, R. G. E., Counsell, T., and Adams, J. B. 1985. Identification of Manganese-Oxidizing Bacteria from Desert Varnish. *Geomicrobiology Journal* 4:343–360.

Perry, R. S., and Adams, J. 1978. Desert Varnish: Evidence of Cyclic Deposition of Manganese. *Nature* 276:489–491.

Peterson, F., Bell, J., Dorn, R., Ramelli, A., and Ku, T. L. 1995. Late Quaternary Geomorpholgy and Soils in Crater Flat, Yucca Mountain area, Southern Nevada. *Geological Society of America Bulletin* 107:379–395.

Phillips, F. M., Zreda, M. G., Smith, S. S., Elmore, D., Kubik, P. W., and Sharma, P. 1990. A Cosmogenic Chlorine-36 Chronology for Glacial Deposits at Bloody Canyon, Eastern Sierra Nevada, California. *Science* 248:1529–1532.

Potter, R. M., and Rossman, G. R. 1977. Desert Varnish: The Importance of Clay Minerals. *Science* 196:1446–1448.

——, and ——. 1979. The Manganese- and Iron-Oxide Mineralogy of Desert Varnish. *Chemical Geology* 25:79–94.

Reneau, S. L. 1993. Manganese Accumulation in Rock Varnish on a Desert Piedmont, Mojave Desert, California, and Application to Evaluating Varnish Development. *Quaternary Research* 40:309–317.

Reneau, S., Raymond, R., and Harrington, C. 1992. Elemental Relationships in Rock Varnish Stratigraphy, Layers, Cima Volcanic Field, California: Implications for Varnish Development and the Interpretation of Varnish Chemistry. *American Journal of Science* 292:684–723.

Schweisfurth, R., Jung, W., and Jacobs, M. 1980. Manganese-Oxidizing Microorganisms and their Importance for the Genesis of Manganese Ore Deposits. In *Geology and Geochemistry of Manganese. Volume III. Manganese on the Bottom of Recent Basins,* ed. I. M. Varentsov and G. Grasselly, pp. 279–283. Stuttgart, Germany: E. Schweizerbart'sche Verlagsbuchhandlung.

Spaulding, W. G. 1985. Vegetation and Climates of the Last 45,000 Years in the Vicinity of the Nevada Test Site, South-Central Nevada. *U.S. Geological Survey Professional Paper* 1329:1–83.

Stout, M. L. 1977. Radiocarbon Dating of Landslides in Southern California. *California Geology* 30:99–105.

Thouveny, N., de-Beaulieu, J.-L., Bonifay, E., Cree, K., Guiot, J., Icole, M., Johnsen, S., Jouzel, J., Reille, M., Williams, T., and Williamson, D. 1994. Climate Variations in Europe over the Past 140 kyr Deduced from Rock Magnetism. *Nature* 371:503–506.

Tricart, J., and Cailleaux, A. 1964. *Le modèle de régions sèches. Fascicule I. Le Milieu morphoclimatique Les mécanismes morphogénétiques de regions sèches.* Paris: Centre de Documentation Universitaire.

Turrin, B. D., Dohrenwend, J. C., Drake, R. E., and Curtiss, G. H. 1985. K-Ar Ages from the Cima Volcanic Field, Eastern Mojave Desert, CA. *Isochron West* 44:9–16.

Uren, N. C., and Leeper, G. W. 1978. Microbial Oxidation of Divalent Manganese. *Soil Biology and Biochemistry* 10:86–87.

Valladas, H., Cachier, H., Maurice, P., de Quiros, F. B., Clottes, J., Valdes, V. C., Uzquiano, P., and Arnold, M. 1992. Direct Radiocarbon Dates for Prehistoric Paintings at the Altamira, El Castillo and Niauz Caves. *Nature* 257:68–70.

van Veen, W. L. 1972. Factors Affecting the Oxidation of Manganese by Sphaerotilus discophorus. *Antonie van Leeuwenhoek* 39:657–662.

von Humboldt, A. [1812] 1907. *Personal Narrative of Travels to the Equinoctial Regions of America During the Years 1799–1804,* Vol. 2. Trans. and ed. T. Ross. London: George Bell & Sons.

Watts, W. A., and Hansen, B. C. S. 1994. Pre-Holocene and Holocene Pollen Records of Vegetation History from the Florida Peninsula and their Climatic Implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 109:163–176.

Wells, P. V., and Woodcock, D. 1985. Full-Glacial Vegetation of Death Valley, California. Juniper Woodland Opening to Yucca Semidesert. *Madrono* 32:11–23.

Whalley, W. B. 1983. Desert Varnish. In *Chemical Sediments and Geomorphology: Precipitates and Residua in the Near Surface Environment,* ed. A. S. Goudie and K. Pye, pp. 197–226. London: Academic Press.

White, K. 1990. Spectral Reflectance Characteristics of Rock Varnish in Arid Areas. *School of Geography University of Oxford Research Paper* 46:1–38.

——. 1993. Image Processing of Thematic Mapper Data for Discriminating Piedmont Surficial Materials in the Tunisian Southern Atlas. *International Journal of Remote Sensing* 14:961–977.

Whitley, D. S., and Dorn, R. I. 1987. Rock Art Chronology in Eastern California. *World Archaeology* 19:150–164.

Wright Jr., H. E. 1989. The Amphi-Atlantic Distribution of the Younger Dryas Paleoclimatic Oscillation. *Quaternary Science Reviews* 8:295–306.

Zreda, M. G., and Phillips, F. M. 1994. Surface Exposure Dating by Cosmogenic Chlorine-36 Accumulation. In *Dating in Exposed and Surface Contexts,* ed. C. Beck, pp. 161–183. Albuquerque: University of New Mexico Press.

Zreda, M. G., Phillips, F. M., and Elmore, D. 1994. Cosmogenic ^{36}Cl Accumulation in Unstable Landforms. 2. Simulations and Measurements on Eroding Moraines. *Water Resources Research* 30:3127–3136.

Submitted 3/95; Revised 7/95; Accepted 10/95.

Liu, Tanzhuo, and Dorn, Ronald I. 1996. Understanding the Spatial Variability of Environmental Change in Drylands with Rock Varnish Microlaminations. *Annals of the Association of American Geographers* 86(2):187–212. *Abstract.*

A fundamental problem in the analysis of landforms and surface artifacts is how to correlate the ages of non-contiguous surfaces. One solution to this problem may lie within the varnish coatings on desert rocks. When viewed with a light microscope in ultra-thin cross-sections, rock varnish reveals orange and black layers that record drier and wetter climates, respectively. Consistent patterns of alternating orange and black microlaminae are evident in some 2900 rock-surface depressions in 420 ultra thin sections from 360 rocks in Death Valley and the surrounding region. Microlaminae are organized into distinct layering units that provide relative ages for geomorphic and archaeological surfaces. The largest uncertainty in developing calibrated chronologies for layering units is the inability to date specific layers; we resolve this problem by correlating layering units with independent numerical ages. Because rock varnishes are ubiquitous in deserts, their visual microlaminations have great potential as a tool to assess temporal and spatial variations in dryland environments. This potential is illustrated for alluvial-fan deposits in Death Valley, petroglyphs, and fault scarps. One of the most surprising, if speculative, findings is that the ages of black laminations (wetter periods) in Death Valley coincide with the timings of iceberg armadas in the North Atlantic (Heinrich Events). **Key Words:** alluvial fans, climatic change, Death Valley, deserts, drylands, environmental change, faulting, geomorphology, Heinrich Events, petroglyphs, rock varnish.

Correspondence: Lamont Doherty Earth Observatory, Columbia University, Box 1000, Route 9W, Palisades, New York, 10964-8000 (Liu); Department of Geography, Arizona State University, Box 870104, Tempe, Arizona, 85287-0104 (Dorn).