



# Blind testing of rock varnish microstratigraphy as a chronometric indicator: results on late Quaternary lava flows in the Mojave Desert, California

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## Abstract

Rock varnish is a manganiferous dark coating ubiquitous in desert landscapes. To test the validity of varnish microstratigraphy as a chronometric indicator, varnish samples were collected from radiometrically dated and undated late Quaternary lava flows in Amboy, Cima, and Pisgah volcanic fields (AVF, CVF, PVF) in the Mojave Desert of California, western United States. Varnish microstratigraphies show a replicable layering sequence that appears to record regional climate changes that likely correspond in time to the Younger Dryas and Heinrich events in the North Atlantic region. Microstratigraphic patterns on these volcanic fields match patterns found in varnishes from other western US sites with available radiometric age constraints. Based on this regional chronology, varnishes from the A flow, H flow, and a stone pavement surface in the Cima volcanic field were estimated to be 16.5–24, 74–85, and 74–85 ka, respectively; these ages are consistent with previously published cosmogenic  $^3\text{He}$  ages of 18–20, 72–74, and 80–85 ka for these geomorphic surfaces. Varnishes from the I flow at Cima yielded a puzzling age estimate of 39 ka, which is consistent with an older  $^3\text{He}$  age of  $37 \pm 6$  ka reported for the I flow, but inconsistent with a younger  $^3\text{He}$  age of  $31 \pm 7$  ka and a cosmogenic  $^{36}\text{Cl}$  age of  $27 \pm 1.3$  ka for the same flow. Reinterpretation of the original varnish age data, with knowledge of then available field mapping results of the I flow, suggests that the I cone is polycyclic and different flow units were probably unintentionally sampled in the field. The revised varnish ages of 30 and 39 ka for the I flow thus may be in good agreement with their corresponding  $^3\text{He}$  and  $^{36}\text{Cl}$  ages. In a blind test of the method, varnishes from the Phase 1 flow at Pisgah, an unnamed flow (called here the *I'* flow) at Cima, and the Amboy flow were estimated to be 24–30, 46–60, and 74–85 ka, respectively; these ages agree well with  $^{36}\text{Cl}$  ages of  $22.5 \pm 1.3$ ,  $46 \pm 2$ , and  $79 \pm 5$  ka reported for the same flows by Phillips [Geomorphology (2002)]. These test results provide convincing evidence that varnish microstratigraphy, once radiometrically calibrated, can be used as a valid dating tool to estimate surface exposure ages of desert landforms in the western US drylands.

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## 1. Introduction

Rock varnish is a dark coating on subaerially exposed rock surfaces. It accretes at rates of a few

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micrometers per millennium, and its thickness rarely exceeds 200  $\mu\text{m}$  (Liu and Broecker, 2000). Although found in virtually all terrestrial environments, rock varnish is mostly developed and best preserved in arid to semiarid deserts of the world. It consists mainly of Mn and Fe oxides and clay minerals (Engel and Sharp, 1958; Potter and Rossman, 1977, 1979). Because varnish is chemically, structurally, and morphologically distinct from the underlying substrate rock, it forms like other sedimentary deposits, with its ingredients largely delivered from the atmosphere by precipitation, aerosols, dust, and dew (Fleisher et al., 1999; Bao et al., 2001; Moore et al., 2001).

Micro laminations in rock varnish were first reported by Perry and Adams (1978), who recognized their potential as a paleoenvironmental indicator in drylands. Under transmitted light, manganese-poor layers in varnish are orange in color and manganese-rich layers black (Perry and Adams, 1978). Subsequent studies demonstrated that the chemical composition of rock varnish changes markedly with climate: during dry periods, it is manganese-poor and during wet periods manganese-rich (Dorn, 1984, 1990; Liu, 1994; Cremaschi, 1996; Liu and Dorn, 1996; Zhou et al., 2000). In the drylands of the western US, changes of manganese content in varnish range from <5% for arid periods of the Holocene to >40% for wet periods of the late glacial time (Fleisher et al., 1999).

Like a macroscale sedimentary basin, varnish-filled microscale “basins” (i.e., a dimple usually 0.1–0.3 mm deep and 1–3 mm in diameter) on rock surfaces often contain stratigraphically layered microlaminations. Also, just like macroscale sedimentary basins, the stratigraphic sequences reflect a combination of regional and local environmental influences. Although some have had difficulty separating the two (Reneau et al., 1992), the trick to extracting the regional signal rests in site selection and analyzing enough micro-basins to develop a reliable regional record.

Recent studies (Liu et al., 2000; Broecker and Liu, 2001) showed that varnish microstratigraphy appears to carry a unique wetness record in deserts, and that this record is likely tied to the ice rafting record in deep sea sediment from the North Atlantic region (Bond et al., 1993, 1997, 1999). Studies have also shown that varnish microstratigraphy, once radiometrically calibrated, may be useful in dating geomorphic

and geoarchaeological features in deserts (Liu and Dorn, 1996; Bell et al., 1998a; Friend et al., 2000).

In the past decade, however, there have been concerns over the validity of varnish microstratigraphy as a reliable dating tool (Reneau et al., 1992; Reneau, 1993). Such concerns have been intensified in the wake of a recent debate regarding AMS radiocarbon dating of subvarnish organic matter (Dorn et al., 1989; Dorn, 1996, 1998; Beck et al., 1998). As a result, the geological community has become suspicious about the scientific merit of rock varnish dating. Some workers have even claimed that earth scientists should abandon the use of rock varnish dating in their research (Bierman, personal communication, 1998).

In order to retain the reputation of varnish microstratigraphy as a reliable geochronometer, its validity must be rigorously tested. In collaboration with Fred M. Phillips (New Mexico Tech., Socorro), I conducted a blind test on the validity of this dating approach in the western US drylands. My strategy was as follows: (i) document varnish microstratigraphies on a number of radiometrically dated and undated lava flows of late Quaternary age in the Mojave Desert of California, western US; (ii) assume that a common varnish microstratigraphy exists in the western US drylands; (iii) use existing age data to assign a chronology to this microstratigraphy; (iv) use this calibrated microstratigraphy to predict the ages of the varnishes and lava flows from the Mojave Desert; (v) compare these age predictions with the actual ages for the lava flows as determined by cosmogenic  $^{36}\text{Cl}$  method (Phillips, 2002). The purpose of this paper was to present the blind test results and argue that the varnish microstratigraphy method, if applied properly, may have potential as a unique dating tool to study geomorphology, geoarchaeology, and late Quaternary environmental changes in deserts.

## 2. Study sites

Several research concerns were involved in the selection of the Mojave Desert as the study area. First, rock varnishes in the Mojave Desert have been extensively investigated in the past two decades (e.g., Dorn and Oberlander, 1981, 1982; Dorn, 1988, 1990; Reneau et al., 1992; Reneau, 1993; Liu and Broecker, 2000) and their microstratigraphies have

been well understood (Liu, 1994; Liu and Dorn, 1996; Liu et al., 2000; Liu and Broecker, 1999; Broecker and Liu, 2001). Second, the Mojave Desert and its vicinity contain numerous geomorphic features that have been radiometrically dated, providing age constraints for calibration of these varnish microstratigraphies (e.g., Stout, 1977; Benson et al., 1990; Meek, 1990; Wells et al., 1995; Bell et al., 1998b; Heizler et al., 1999). Third, the Mojave Desert also contains a number of late Quaternary basalt flows that are radiometrically datable but have not yet been dated, offering excellent geomorphic settings to conduct the proposed blind test.

Three volcanic fields in the Mojave Desert were included in this study. The Cima volcanic field (CVF), located ~ 25 km SE of Baker, CA (Fig. 1), covers an area of ~ 150 km<sup>2</sup> and contains over 40 basaltic scoria cones and over 60 associated lava flows. It has aa- and pahoehoe-type lava flows that range in age from late Tertiary to latest Pleistocene (Dohrenwend et al., 1984; Turrin et al., 1985). Flows older than 200 ka are often mantled by aeolian deposits and covered with a desert pavement of basalt clasts; but those younger than 200 ka still retain much of their initial flow morphology, such as leveed channels, pressure ridges, collapse depressions, and rafted spines and spires (Wells et al., 1985), thus permitting sample collection from primary flow structures. Furthermore, a previous study by Wells et al. (1995) provided cosmogenic <sup>3</sup>He surface exposure ages for three lava flows (i.e., A flow, I flow, and H flow) and a stone pavement surface (Fig. 2), allowing a direct comparison between these cosmogenic ages and varnish microstratigraphies for these geomorphic features.

The Pisgah volcanic field (PVF), ~ 65 km ESE of Barstow, CA (Fig. 1), covers an area of ~ 83 km<sup>2</sup> and contains basaltic lava flows and a cinder cone (Dibblee, 1966; Wise, 1966; Dellwig, 1969). The cinder cone reaches about 100 m above its surroundings with a basal diameter of ~ 500 m (Fig. 2G). Numerous thin basaltic flows with vesicular pahoehoe, transitional, and aa flow textures comprise the adjacent lava field. As described by Wise (1966), the Pisgah lava erupted in three phases: (i) largely pahoehoe; (ii) aa flow on the eastern side and pahoehoe on the far western side; and (iii) mostly pahoehoe (Figs. 1 and 2G). Although Dibblee (1966) thought Pisgah lava flows were “very late Pleistocene or Holocene”

in age, to the best of my knowledge, Phillips (2002) presents the first radiometric ages for these flows. These were determined by the cosmogenic <sup>36</sup>Cl method.

The Amboy volcanic field (AVF) is located ~ 2 km west of Amboy in California (Fig. 1). About 70 km<sup>2</sup> in area, AVF contains primarily vesicular pahoehoe lava flows and a prominent cinder cone (Fig. 2H). The complex cone, rising 75 m above its surrounding lava field with a basal diameter of about 460 m, contains evidence of at least four nearly coaxial nested cones (Parker, 1963). While outer slopes on the east side of the main cone host abundant and fairly deep gullies, west side slopes remain only slightly gullied (Fig. 2H). Based on cone morphology and petrologic and stratigraphic evidence of the lava flows, Parker (1963) concluded that at least six distinct episodes of eruption occurred at the Amboy Crater and that the timing of such eruptions was probably of post-Tioga age, at the time thought to be younger than 6.0 <sup>14</sup>C ka. As for the Pisgah lava flows, I was not aware of any previously published radiometric dates prior to the cosmogenic <sup>36</sup>Cl dating of the Amboy flow by Phillips (2002).

Although the lava flows in these volcanic fields provide excellent geomorphic settings for a blind test of the validity of the varnish microstratigraphy method, a complication is associated with post-flow aeolian activity in these sites. Field evidence indicates that Amboy and Pisgah flows and some older flows at Cima have experienced substantial aeolian activity in the form of aeolian abrasion sufficient to form ventifacts (Williams and Greeley, 1981; Greeley and Iversen, 1986; this study). Further, sand transport currently occurs across these lava fields; thus, the potential exists for periodic burial of flows that interrupts the accumulation of varnish and cosmogenic nuclides. Although my sampling avoided evidence of aeolian abrasion and deposition, aeolian interference is possible and will push varnish ages in a younger direction.

### 3. Sample collection and methods

Examination of basaltic clasts and flow outcrops in the field shows well-developed rock varnish on most late Quaternary lava surfaces in the study sites.

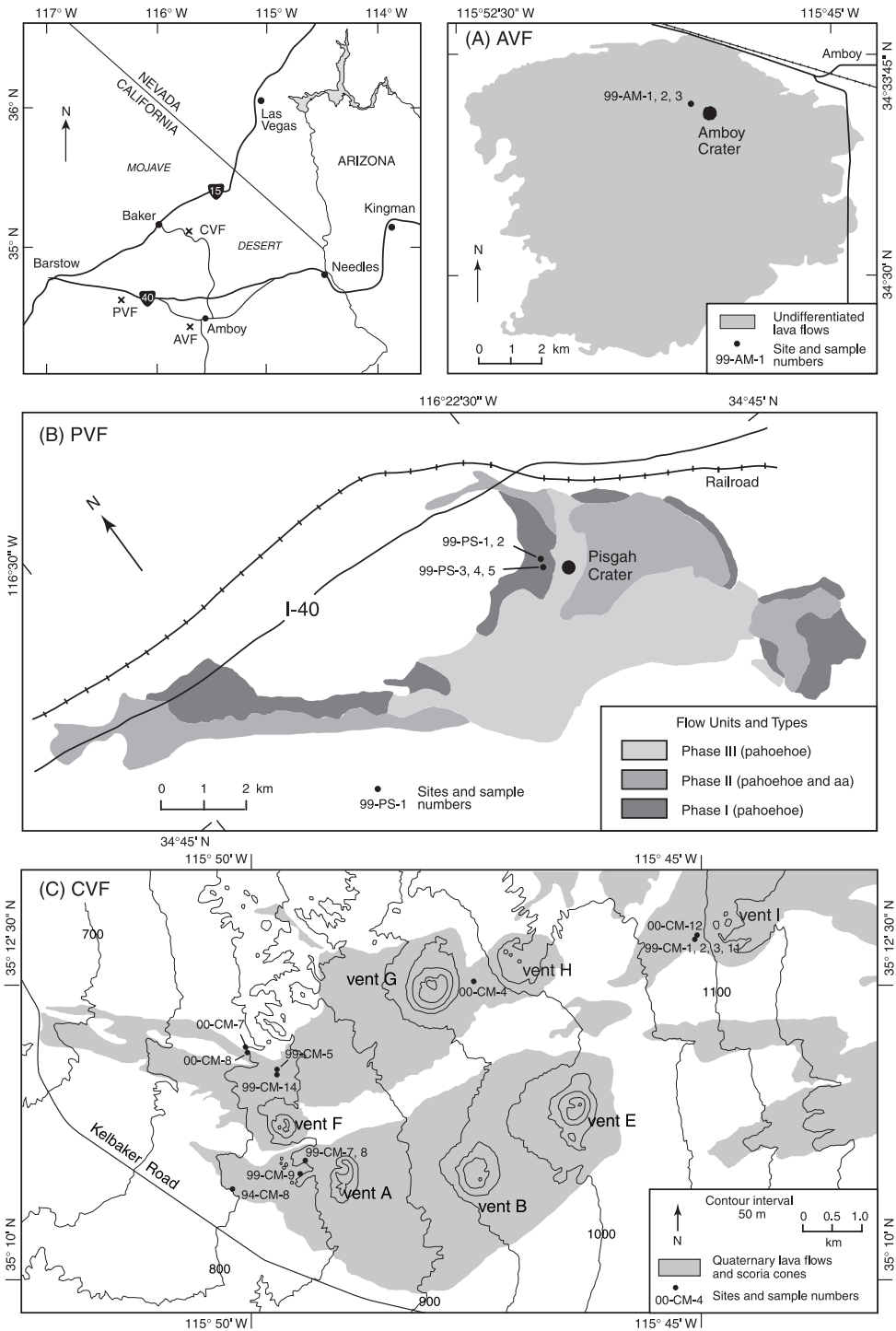


Fig. 1. Location maps of rock varnish samples from late Quaternary lava flows in the Mojave Desert of California, western United States. (A) Amboy volcanic field (AVF); (B) Pisgah volcanic field (PVF); (C) Cima volcanic field (CVF) (geological map of the lava flows in (B) after Greeley et al., 1988).

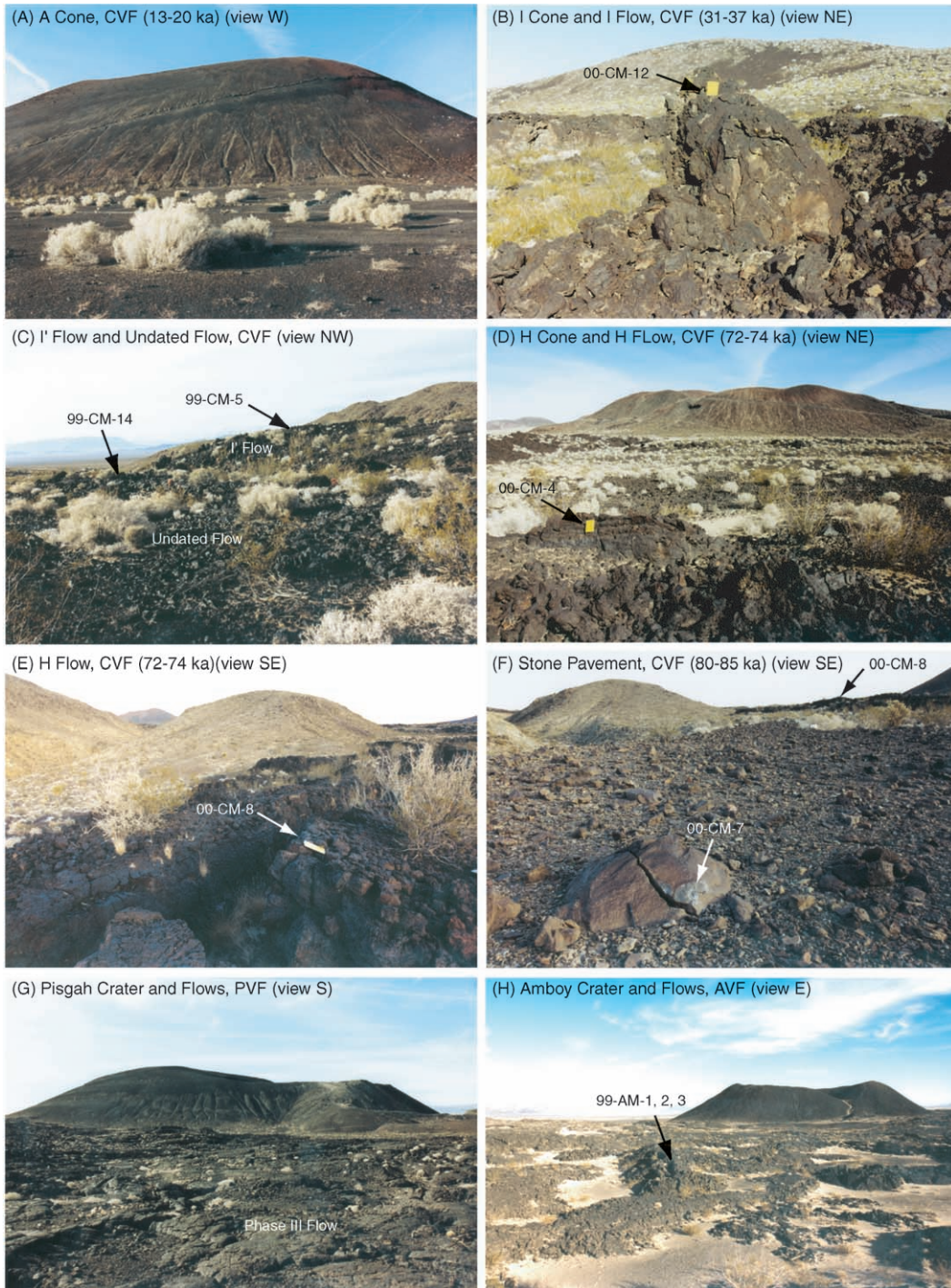


Fig. 2. Field photographs of volcanic cinder cones and rock varnish sampling sites in the Mojave Desert, California. A notebook in B, D, E, a pen in F, and desert bushes in the other photographs are for scale.

Because of weathering and rubbling of flow surfaces and the time-transgressive nature of varnish growth, however, any particular patch of varnish on flow surfaces could range from the age of the flow to a few hundred years old. In order to maximize the likelihood of sampling the oldest possible varnish on a given flow surface, varnish collection was restricted to sampling constructional flow surfaces that still retain primary volcanic features or well-preserved, large (>0.3 m in size) volcanic bombs (Fig. 2). Although preferred by some workers (Reneau et al., 1992), the best-looking (i.e., smoothest, darkest, and thickest) varnishes on either flow surfaces or rubbled basalt clasts were avoided, because generally the best looking varnishes are not the oldest for the sampled lava flows and thus are unsuitable for varnish age dating (Liu and Dorn, 1996). Best looking varnishes reflect more local environmental factors favoring rapid and fast accumulation rates but not necessarily the oldest varnish.

In this study, due to logistics of fieldwork and site conditions, 21 varnish samples were collected, 13 from the Cima volcanic field, 5 from the Pisgah volcanic field, and 3 from the Amboy volcanic field. Table 1 gives details on sites, the lava flows sampled, the geomorphic context, and the available radiometric age constraints.

In the laboratory, the oldest stratigraphically layered varnish microbasins were selected under a 45 × stereo binocular microscope. Ultra-thin sections (~5–10 μm thick) of the selected varnish microbasins, still attached to the rock substrate, were prepared with the use of a special thin-sectioning technique (Liu, 1994) that permitted visual examination of the varnish microstratigraphy. For each of the 21 samples, 3 to 10 ultra-thin sections were made in order to obtain the oldest layering sequence. These thin sections were photographed under a petrologic microscope (with transmitted polarized light) to obtain high-resolution (400 ×) images of varnish microstratigraphy and were then carbon coated for further chemical analysis with an electron microprobe.

For each sample, only the well-defined varnish microstratigraphies lacking or with less surface erosion and unconformities were selected for microprobe chemical analyses. Elemental line profiles of varnish ultra-thin sections were acquired on a fully automated, five-spectrometer CAMECA SX100 electron

probe, with the use of wavelength dispersive X-ray spectrometry (WDS). Probe conditions were set to 15 keV and 10 nA with a counting time of 20 s for quantitative line profile analyses at ~1.5-μm resolution. Natural and synthetic mineral and glass standards were used for calibration and checks on precision and accuracy. These line profiles were used to chemically document the varnish microstratigraphy. Notably, the use of WDS for quantitative chemical analyses permits the precise separation of Ti and Ba, a serious analytical problem for some previous microchemical analyses of varnish with energy dispersive X-ray spectrometry (EDS) (see Bierman and Kuehner, 1992, for a review).

In all, for the 21 varnish samples collected in this study, 133 ultra-thin sections were made and a total of 2056 spot chemical measurements were obtained along 31 individual line profiles. These chemical data, together with some 900 or so optical images (400 ×) of varnish microstratigraphy, form the database used to identify and correlate varnish microstratigraphic patterns.

## 4. Results

### 4.1. Types and chemical features of varnish layers

Optical examinations of ultra-thin sections revealed stratigraphic layering in varnish samples from lava flow surfaces in the Mojave Desert. Generally, three types of layers exist in varnish ultra-thin sections: yellow, orange, and black (Fig. 3). The yellow layers occur at surfaces of all the varnish samples examined regardless of their basal ages. Underneath these yellow layers are alternating black and orange layers. In the oldest varnish samples, a second yellow layer lies underneath the orange and black layer sequence. Individual layers are often laterally continuous for hundreds of micrometers (Figs. 4 and 5).

Chemical analyses along line profiles revealed systematic variations in the concentration of Mn with depth. Figs. 3–6 confirm the conclusion of Perry and Adams (1978) and others (e.g., Dorn, 1990; Liu and Dorn, 1996; Liu et al., 2000) that color corresponds with Mn abundance in varnish laminae. In my varnish samples, black layers are largely enriched in Mn (20–

Table 1  
Rock varnish samples collected from late Quaternary lava flows in the Mojave Desert, California

Sample site and label	Latitude (N) and longitude (W)	Altitude (m)	Age control (ka)	Geomorphic context
<i>Cima volcanic field</i>				
<i>A Flow</i>				
99-CM-7	35°10'55"/115°49'21"	860	13–20 <sup>a</sup>	Varnish is good on primary faces of an ejecta.
99-CM-8	35°10'55"/115°49'21"	860	119 ± 28 <sup>b</sup>	Varnish is good on primary ropy lava faces.
99-CM-9	35°10'55"/115°49'21"	860		Varnish is good on primary faces of an ejecta.
<i>I Flow</i>				
99-CM-1	35°13'00"/115°45'05"	1100	31–37 <sup>a</sup>	Varnish is good on primary ropy lava faces.
99-CM-2	35°13'00"/115°45'05"	1100	110 ± 10 <sup>c</sup>	Varnish is good on primary ropy lava faces.
99-CM-3	35°13'00"/115°45'05"	1100		Varnish is good on rubbled faces of a lava mound.
99-CM-11	35°12'44"/115°45'20"	1095		Varnish is good on primary ropy lava faces.
00-CM-12	35°12'57"/115°45'14"	1100		Varnish is good on primary faces of a lava mound.
<i>I' Flow<sup>d</sup></i>				
99-CM-5	35°11'42"/115°49'39"	830		Varnish is good on primary ropy faces of a pressure ridge.
<i>Undated flow</i>				
99-CM-14	35°11'42"/115°49'39"	825		Varnish is very good on primary ropy lava faces.
<i>H Flow</i>				
00-CM-4	35°12'28"/115°47'35"	975	72–74 <sup>a</sup>	Varnish is good on primary faces of a small pressure ridge.
00-CM-8	35°11'55"/115°49'58"	800	150 ± 60 <sup>c</sup>	Varnish is good on primary faces of a breached pressure ridge.
<i>Stone pavement</i>				
00-CM-7	35°11'59"/115°50'01"	795	80–85 <sup>a</sup>	Varnish is very good on ventifacted faces of an alluvial boulder.
<i>Pisgah volcanic field</i>				
<i>Phase 1 flow</i>				
99-PS-1	34°45'21"/116°22'37"	685		Varnish is good on primary faces of a breached pressure ridge.
99-PS-2	34°45'21"/116°22'37"	685		Varnish is good on primary faces of a breached pressure ridge.
99-PS-3	34°45'15"/116°22'38"	685		Varnish is good on primary faces of a breached pressure ridge.
99-PS-4	34°45'15"/116°22'38"	685		Varnish is good on primary faces of a lava escarpment.
99-PS-5	34°45'15"/116°22'38"	685		Varnish is good on primary faces of a breached pressure ridge.
<i>Amboy volcanic field</i>				
<i>Amboy flow</i>				
99-AM-1	34°32'49"/115°47'47"	235		Varnish is good on primary faces of a breached pressure ridge.
99-AM-2	34°32'49"/115°47'47"	235		Varnish is good on primary faces of a breached pressure ridge.
99-AM-3	34°32'49"/115°47'47"	235		Varnish is good on primary ropy faces of a pressure ridge.

<sup>a</sup> Cosmogenic <sup>3</sup>He age (Wells et al., 1995).

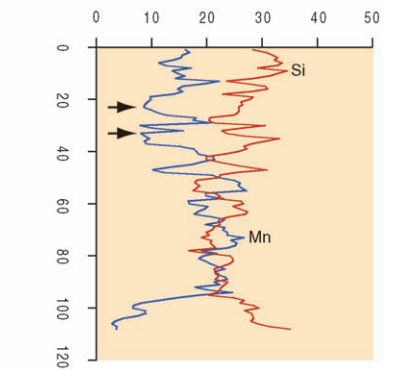
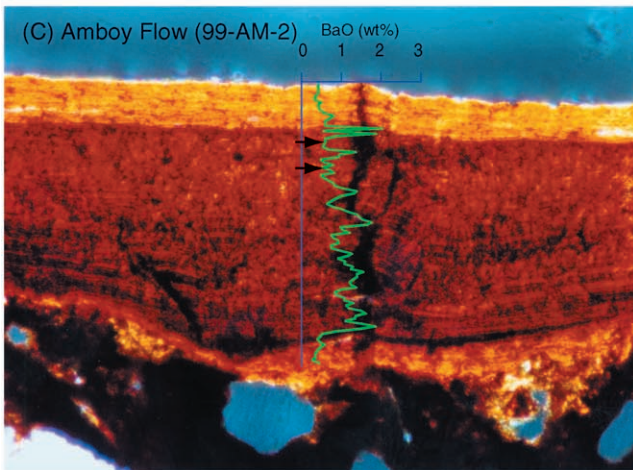
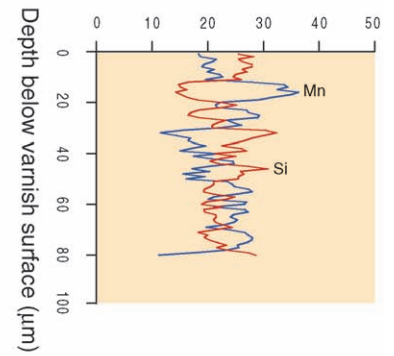
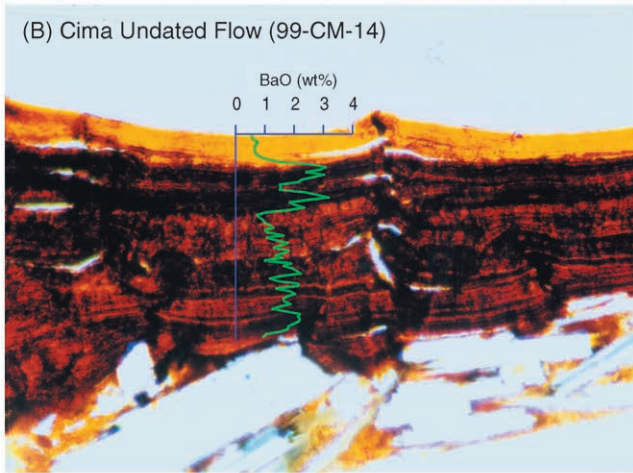
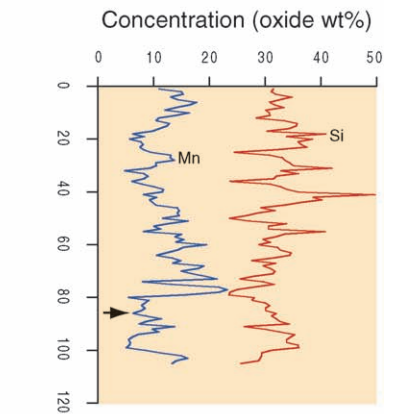
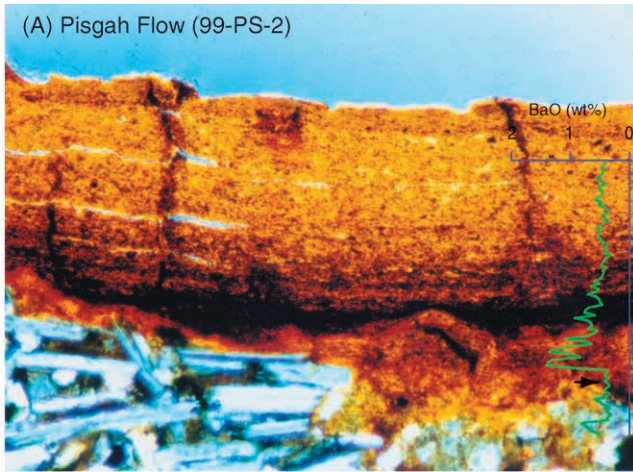
<sup>b</sup> <sup>40</sup>Ar/<sup>39</sup>Ar age (Turrin and Champion, 1991).

<sup>c</sup> K–Ar age (Dohrenwend et al., 1984; Turrin et al., 1985; Turrin and Champion, 1991).

<sup>d</sup> This sampled flow may be an early phase of lava eruption from vent I and was thus named here as I' flow. It is morphologically older than the flows near vent I.

40 wt.%) but depleted in Si (15–25 wt.%), while yellow layers are depleted in Mn (5–15 wt.%) but enriched in Si (30–40 wt.%) (Figs. 3–6). Orange layers often contain intermediate amounts of Mn

(15–25 wt.%) and Si (20–30 wt.%) (Figs. 3–6). The absolute concentrations of Mn, Si, and other elements (such as Ba and Fe; see below) in these varnish layers may vary from sample to sample,



probably reflecting local variations of source material and differential enhancement of these elements in varnish microbasins.

The black layers in these varnishes are also closely associated with high Ba concentrations (1–3 wt.%), while the yellow layers are associated with low Ba concentrations (0.2–1.0 wt.%) (Figs. 3–6). The orange layers generally contain intermediate amounts of Ba (0.75–1.5 wt.%). These observations indicate that Ba is systematically associated with Mn in varnish microstratigraphy, a finding noted previously by other workers (Raymond et al., 1991; Reneau et al., 1992). My data also suggest that (among other major and minor elements in rock varnish such as Si, Fe, Al, Mg, K, Ca, and P) elemental variations of Ba and Mn concentrations along depth profiles may be the best way to chemically characterize varnish microstratigraphy in the western US drylands (Broecker and Liu, 2001; Figs. 3–6).

For most of the varnish samples analyzed in this study, high Fe concentrations (15–25 wt.%) are largely associated with yellow and/or orange layers; while low Fe concentrations (7–15 wt.%) are associated with black layers (Figs. 3–6). This suggests an overall inverse correlation between Fe and Mn in varnish microstratigraphy, thus confirming a similar observation on rock varnish from the Cima volcanic field (Reneau et al., 1992). In some cases, however, high Fe concentrations may be associated with black (or orange) layers that are Mn-poor, rather than Mn-rich as they are in most of the varnish samples studied (Figs. 3C, 4D and 6B). Since such Fe-rich “black layers” often contain anomalously high Ti (up to 2.1 wt.%), they may result from deposition of volcanic-ash-derived detritus in the varnish, as previously suggested by Harrington (1988).

#### 4.2. Layering patterns and layering units

The evidence uncovered by detailed examinations of ultra-thin sections, along with chemical data

obtained from this study, indicates that microstratigraphies in different varnish microbasins often display similarities in their layering patterns, which can be best characterized by layering units. A layering unit is akin to a geological formation in a stratigraphic column.

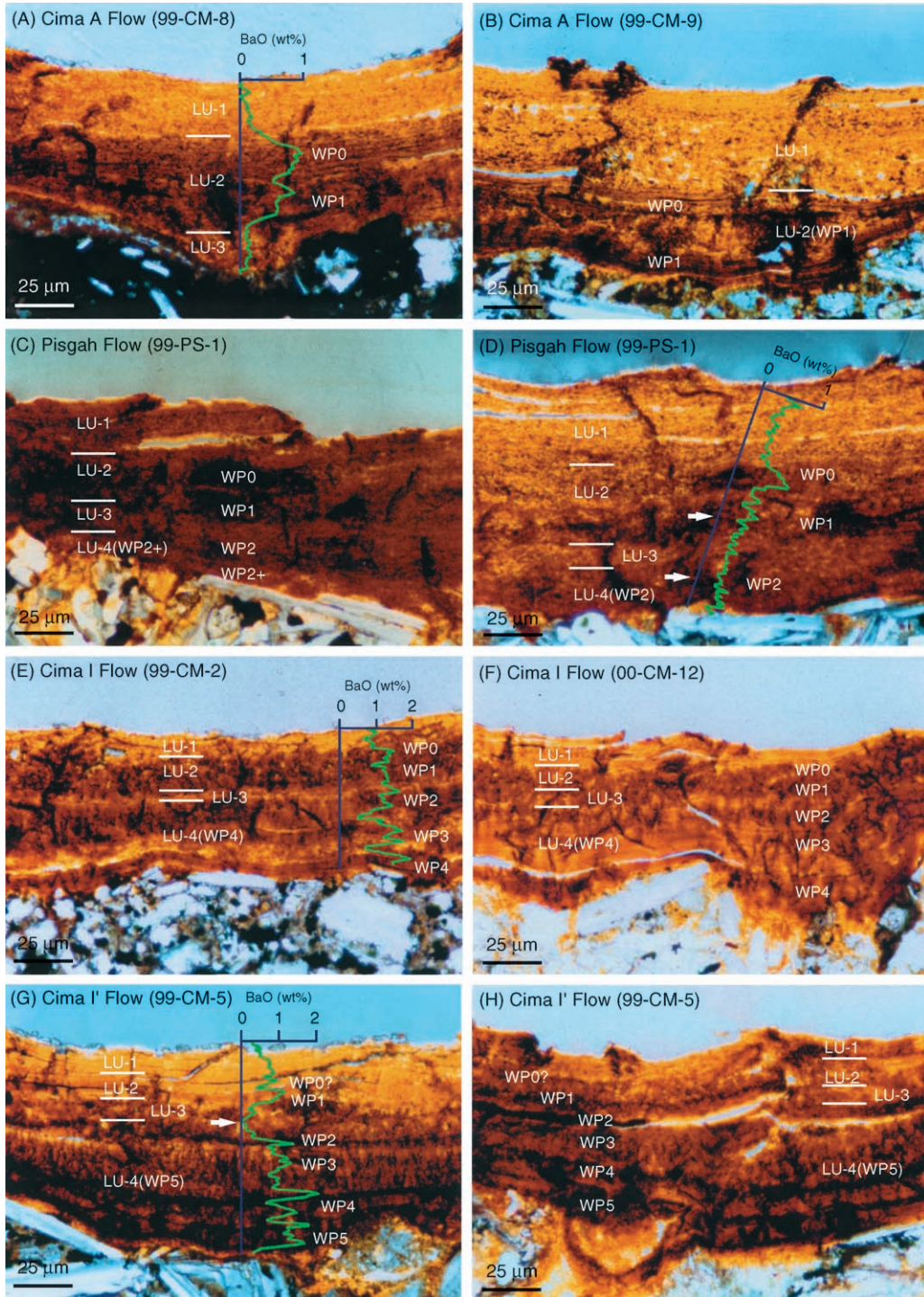
A varnish layering unit (LU) is defined as a distinct configuration of one or more major stratigraphic layers in varnish microbasin and has a unique stratigraphic position (Liu, 1994). Varnish samples from late Quaternary lava flows in the Mojave Desert display, either in part or fully, a generalized layering pattern. This pattern consists of:

- (i) (LU-1), a surface yellow layer;
- (ii) (LU-2), a pair of black layers (called here WP0 and WP1; WP stands for the “Wet event in Pleistocene”) interfingering with a relatively thin orange layer;
- (iii) (LU-3), a relatively thick orange layer;
- (iv) (LU-4), a series of five approximately evenly spaced black layers (i.e., WP2, WP3, WP4, WP5, and WP6) separated from one another by relatively thin orange layers;
- (v) (LU-5), a thick yellow layer directly underneath the basal black layer of LU-4 (i.e., WP6).

For the purpose of discussion, and to guide the reader in reviewing the illustrations in Figs. 3–6, Table 2 presents a detailed description of the generalized layering pattern and layering units observed in Mojave Desert varnishes.

As seen from Figs. 3–6 and Table 2, varnish layering units and layering patterns have the following features. (i) A layering unit as a whole maintains lateral continuity on a scale of hundreds of micrometers. (ii) A layering unit may be correlated visually and chemically from microbasin to microbasin. (iii) Some layering unit(s) may be missing or visually unrecognizable in a varnish microbasin due to post-depositional modification such as aeolian abrasion

Fig. 3. Optical (left) and chemical (right) microstratigraphies in rock varnish from late Quaternary lava flows in the Mojave Desert, California. The black layers in the varnish are enriched in Mn and Ba (but depleted in Si), and the yellow layers are depleted in Mn and Ba (but enriched in Si). The orange layers contain intermediate amounts of Mn and Ba. Note that the absolute concentrations of Mn and Ba in the outermost yellow layers change from sample to sample, but their relative concentrations are generally lower than those in the underlying black and orange layers. Also note that some orange layers in the varnish contain anomalously high content of Fe, as marked by the dark arrows in A and C, leading to extremely low content of Mn and Ba in these layers (see Fig. 6).



(Fig. 5A,B) and chemical leaching (Fig. 5C). (iv) A layering pattern contains one or more layering units that are stratigraphically ordered in either a continuous or a discrete fashion, with younger layering units resting on older ones. (v) A complete layering pattern includes one or several consecutive layering units, with the youngest unit at the top and the oldest one at the base. (vi) The age of a layering pattern is represented by the age of its basal layering unit (and also the basal layer contained therein). (vii) The more the layering units (and also the layers contained in the basal layering unit) of a varnish, the older the varnish. Table 3 presents the oldest layering patterns observed in each of the varnish samples examined in this study.

#### 4.3. Age calibration and climatic correlation

Calibration of varnish microstratigraphy often requires a range of radiometric age constraints from accurately dated geomorphic surfaces that host the varnish (Liu, 1994; Liu and Dorn, 1996; Liu et al., 2000; Broecker and Liu, 2001). However, this is not the case in the study sites. First, not all of the sampled lava flows have been accurately dated by radiometric means. Second, although some lava flows such as the A flow, I flow, and H flow in the Cima volcanic field were dated with cosmogenic  $^3\text{He}$  (Wells et al., 1995), the use of these  $^3\text{He}$  dates for calibrating varnish microstratigraphies in the study area would invalidate the condition for this blind test.

To calibrate varnish microstratigraphy within the context of a blind test, I used other radiometrically calibrated varnish microstratigraphies from the western US drylands, a region that is geographically close and also climatically similar to the study area (Fig. 1; Table 4). My previous studies (Liu and Dorn, 1996; Liu et al., 2000) indicated that while individual layers in varnish microstratigraphy cannot be directly dated at present, it is feasible to build a chronology by obtaining varnish from geomorphic features spanning the age range of interest. For each such sample, a

basal age can be established either through radiocarbon ages for the geomorphic feature itself or by measuring cosmogenic isotopes produced by cosmic ray spallation within the rock that hosts the varnish. I collected varnish samples from a number of geomorphic features in the western US drylands, such as paleoshorelines, paleolandslides, fault scarps, and alluvial-fan and lava surfaces that have been radiometrically dated, with numerical ages ranging from 10.5 ( $^{14}\text{C}$ ) to  $\sim 95$  ka (Fig. 7; Table 4). Using the same methodology employed in the previous studies, I first established a generalized varnish layering sequence, which is similar in both layering pattern and layering unit to the one in the study area (Table 2), and then I constructed its numerical chronology, as shown in Fig. 8.

Based on this preliminary age calibration of the varnish layering sequence, I found that in the drylands of the western US, the Mn-poor yellow layer in LU-1 generally formed during the overall warm and dry period of the Holocene; and the Mn-rich black layers in LU-2 and LU-4 formed during cold and wet periods of the last glacial (Fig. 8 and Table 2; also see Liu and Dorn, 1996; Liu et al., 2000; Broecker and Liu, 2001). In particular, the glacial-age black layers WP0, WP1, WP2, and WP4 in the varnish appear to correlate with the cold episodes of the Younger Dryas and H1, H2, H4 Heinrich events, respectively, in the North Atlantic region (Broecker, 1994; Bond et al., 1999) (Fig. 8). The other three black layers (WP3, WP5, and WP6) may also correlate in time with H3, H5, and H6 Heinrich events, but more radiometric age constraints are needed to demonstrate such correlation. Furthermore, the sharp upward transition in color from the yellow layer in LU-5 to the basal black layer in LU-4 (i.e., WP6) likely corresponds to the end of the last interglacial. Based on varnish microstratigraphy from radiometrically dated lava flows in the Lathrop Wells volcanic field of southern Nevada (Heizler et al., 1999), this transition reasonably has an age slightly younger than  $\sim 77$  ka (Figs. 7K and 8). I tentatively

Fig. 4. Optical images and Ba line profiles of the oldest microstratigraphies uncovered in varnish samples from late Quaternary lava flows in the Cima volcanic field. The white labels are layering pattern interpretation of these microstratigraphies. The white arrows in D and G identify orange layers that contain anomalously high content of Fe but extremely low contents of Ba and Mn (see Fig. 6). Note that sometimes varnish ultra-thin sections were made too thick (as illustrated in C) so the surface yellow layers in LU-1 appear visually as “orange” layers; or too thin (as illustrated in F) so the black layers in LU-2 and LU-4 appear visually as “orange” layers. Also note that the surface layer in C has been modified by postdepositional processes such as wind abrasion and peeling.

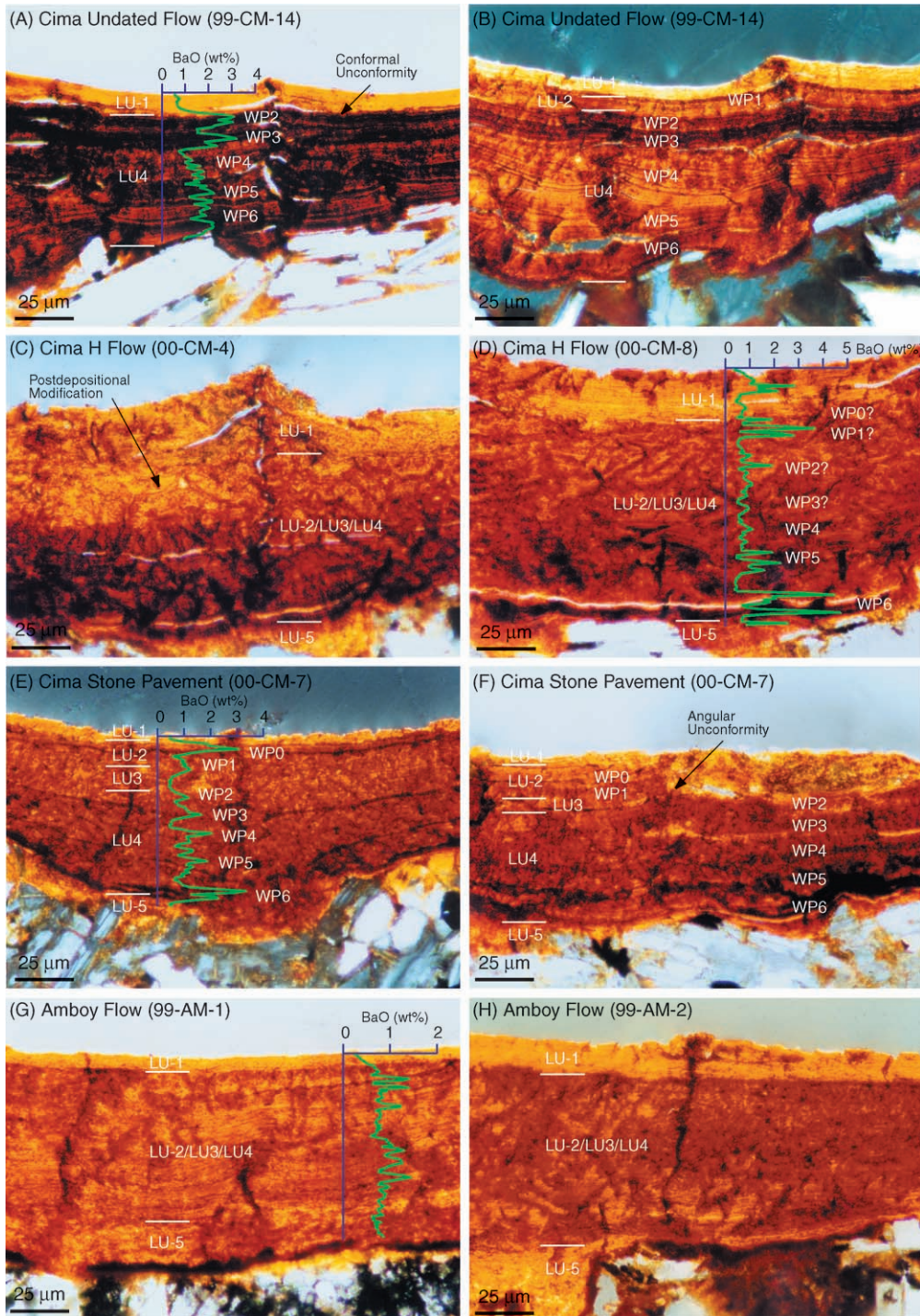


Fig. 5. Optical images and Ba line profiles of the oldest microstratigraphies uncovered in varnish samples from late Quaternary lava flows and stone pavement surface in the Cima, Pisgah, and Amboy volcanic fields. The white labels are layering pattern interpretation of these microstratigraphies. Note that the dark bands in the lower portions of images G and H are not black layers of rock varnish; rather they are Fe- and Ti-rich films of the substrate basalt.

place this boundary at the end of marine isotope stage 5, or  $\sim 74$  ka (Fig. 8; Martinson et al., 1987). Lastly, like its Holocene analog of the yellow layer in LU-1, the yellow layer in LU-5 probably formed during the late phase of the last interglacial or marine isotope stage 5a between 74 and 85 ka (Martinson et al., 1987; Peteet et al., 1992; McManus et al., 1994; Kukla et al., 1997), as suggested by a varnish microstratigraphy from the 55–95-ka highstands of Panamint Lake in California (Fig. 7L).

#### 4.4. Age estimate

Radiometric age calibration revealed a striking correlation between black layers in varnish microstratigraphy and major climatic variations such as the Younger Dryas and Heinrich events during the last glaciation (Fig. 8). Although such correlation has not been fully verified due to my inability to directly date individual layers in varnish, its implications for varnish layering dating are significant. First, because climatic signals recorded in varnish appear to be regionally correlative, varnish microstratigraphy has the potential as a regional stratigraphic indicator. Second, once calibrated, varnish microstratigraphy will become a useful tool to estimate the ages of varnished geomorphic features. Third, given the above climatic correlation of varnish layers, the ages of the Younger Dryas and Heinrich events can be reasonably assigned to the corresponding black layers in varnish for more accurate age dating. Over the past decade, the radiometric chronology of the Younger Dryas and Heinrich events has been well established by numerous paleoclimatic studies. For instance, the Younger Dryas cold snap has been accurately dated at 12.5 ka; the timing of H1 through H6 Heinrich events has also been constrained at 16.5, 24, 30, 39, 46 and 60 ka, respectively (Bond and Lotti, 1995; Bond et al., 1999). Based on these age assignments, black layer WP0 in varnish likely formed around 12.5 ka when the North Atlantic region was subject to the Younger Dryas cooling. Similarly, black layers WP1 through WP6 likely formed around 16.5, 24, 30, 39, 46 and 60 ka, respectively. The numerical ages thus derived for these black layers determine the temporal framework and resolution of varnish layering dating.

##### 4.4.1. Relative age estimate

Based on stratigraphic relationship of layering units in varnish layering sequences from the study area (Table 3), I estimated relative ages of the sampled lava flows. Of all the lava flows studied, the A flow in the Cima volcanic field is the youngest, with an oldest observed layering pattern of LU-1/LU-2/LU-3 (Fig. 4A). The Phase 1 flow in the Pisgah volcanic field is slightly older than the A flow, with an oldest layering pattern of LU-1/LU-2/LU-3/LU-4 (WP2+) (Fig. 4C). The I flow is older than the Pisgah Phase 1 flow, with an oldest layering pattern of LU-1/LU-2/LU-3/LU-4 (WP4) (Fig. 4E). The I' flow is older than the I flow, as its oldest layering pattern is LU-1/LU-2/LU-3/LU-4 (WP5) (Fig. 4G). The “Undated” flow is older than the I' flow, as its oldest layering pattern is LU-1/LU-2/LU-3/LU-4 (WP6) (Fig. 5A). Both the H flow and the Amboy flow are the oldest lava flows sampled in this study, as they have the same oldest layering pattern of LU-1/LU-2/LU-3/LU-4/LU-5 (Fig. 5C,G). The stone pavement surface in the Cima volcanic field has varnish with an oldest layering pattern similar to those from the H flow and the Amboy flow (Fig. 5E), suggesting that these geomorphic surfaces are similar in age.

##### 4.4.2. Numerical age estimate

Calibrated ages of varnish samples were estimated on the basis of radiometric age calibration of the generalized varnish microstratigraphy in the western US drylands and its possible correlation with major climatic variations in the North Atlantic region (Figs. 7 and 8; Table 3). Due to lag times and the time-transgressive nature of varnish growth on subaerially exposed lava surfaces, however, the oldest varnish age (rather than the arithmetic mean of the varnish ages) obtained for each of the sampled lava flows is interpreted to represent a minimum surface exposure age for the flow (Table 3).

In the Cima volcanic field, three varnish samples (99-CM-7, 8, 9) were collected from the A flow, and they each have oldest basal layering units of LU-3, LU-3, and LU-2 (WP1), respectively, with corresponding calibrated ages of 16.5–24, 16.5–24, and 16.5 ka (Table 3). The oldest of these ages, 16.5–24 ka, is thus interpreted to represent a minimum surface exposure age of the A flow. Similarly, the minimum

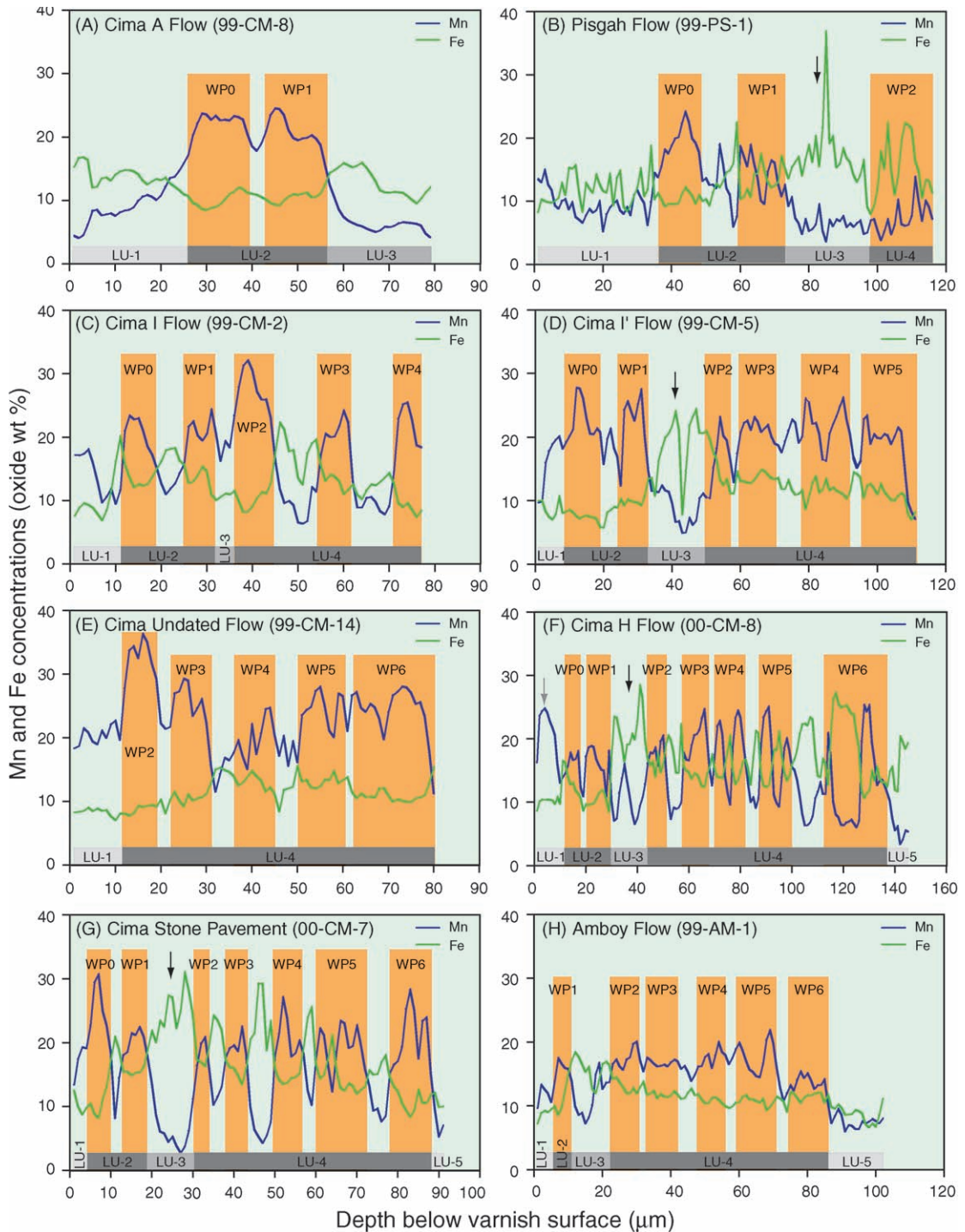







Table 2  
Characteristics of varnish layering units in the Mojave Desert, California

LU number	Generalized layering unit	Characteristics of layering unit (LU)
LU-1		LU-1 is an outermost layering unit in a given varnish microstratigraphy and often contains only one relatively thick major yellow layer. Occasionally, LU-1 may contain a number of minor thin black layers near the varnish surface (Fig. 7). The overall thickness of LU-1 is largely affected by varnish accumulation rate and surface erosion (Figs. 4C, 5F), varying from 5–30 $\mu\text{m}$ on late Pleistocene varnish to 20–100 $\mu\text{m}$ on latest Pleistocene to Holocene varnish.
LU-2		LU-2 occurs immediately underneath LU-1 and often contains two major black layers separated by one orange layer. Sometimes these two black layers each may contain two to five minor black layers (Fig. 5B), or they both may visually merge into one thick black layer due to postdepositional erosion of the orange layer (Fig. 4E). They could also be visually altered into orange layers by postdepositional chemical leaching (Figs. 5C, F). LU-2 is frequently removed by postdepositional erosion on old varnish ( $\geq$ LU-4)(Fig. 5A). Its entire thickness ranges from 0 to 40 $\mu\text{m}$ .
LU-3		LU-3 often occurs as a single orange layer that separates LU-2 from LU-4. This orange layer is relatively thicker on younger varnish ( $\leq$ LU-3) than on old varnish ( $\geq$ LU-4). Sometimes both LU-2 and LU-3 are completely removed from varnish microstratigraphy by postdepositional erosion, leading to a direct contact between LU-1 and LU-4 (Fig. 5A). Its entire thickness ranges from 0 to 20 $\mu\text{m}$ .
LU-4		LU-4 is the most prominent layering unit in varnish from the Mojave Desert and often contains five approximately evenly spaced major black layers separated by four orange layers. Each of these major black layers may occasionally contain two to five minor black layers (Figs. 5A, B), depending on varnish growth rate and the depositional sensitivity of the varnish microbasin. The orange layers in LU-4 are usually much thinner than their neighboring black layers due to postdepositional erosion, making LU-4 visually "compacted" as a series of five major black layers (Fig. 5A). In some cases, the first two black layers of LU-4 (i.e., WP2 and WP3) are altered into orange layers by postdepositional chemical leaching (Figs. 5C, D). The basal black layer of LU-4 often rests on a thick yellow layer that is similar to the yellow layer of LU-1. Its entire thickness ranges from 40 to 130 $\mu\text{m}$ .
LU-5 <sup>a</sup>		LU-5 usually contains one thick yellow layer overlain by a series of major black layers in LU-4. This yellow layer does not show up in varnish samples of latest Pleistocene and Holocene age, but on those of late Pleistocene age (Figs. 5C–H). Its entire thickness ranges from 2 to 60 $\mu\text{m}$ .

<sup>a</sup> A fully developed layering unit of LU-5 in varnish contains three thick yellow layers interbedded with two thin black layers, corresponding roughly to a time span between 70 and 130 ka (Liu, 1994). Since the oldest varnish samples I collected from the study area may be older than 74 ka but slightly younger than 85 ka, as discussed in this paper, they contain only the uppermost yellow layer in LU-5.

surface exposure age of the I flow was estimated to be 39 ka, based on the three oldest basal layering units of LU-4 (WP4) observed in varnish samples 99-CM-2, 99-CM-11, and 00-CM-12 (Table 3). Although only one varnish sample (99-CM-5) was collected from a

well-preserved pressure ridge of the I' flow, its clearly defined and fully developed oldest basal layering unit of LU-4 (WP5) suggests a minimum age of 46 ka for this flow (Figs. 7H and 8). Another varnish sample (99-CM-14) from the "Undated" flow surface dis-

Fig. 6. Chemical microstratigraphies in varnish samples from late Quaternary lava flows and a stone pavement surface in the Cima, Pisgah, and Amboy volcanic fields and their layering pattern interpretation. The dark arrows in B, D, F, and G identify orange layers that contain anomalously high content of Fe but extremely low content of Mn. Note that the Mn-rich peak identified by a gray arrow in F is due to reprecipitation of mobilized Mn along a vertical fracture near the varnish surface (see Fig. 5D), thus it should not be interpreted as a normal Mn-rich black layer in varnish microstratigraphy.

Table 3

Rock varnish layering patterns, pattern-based varnish ages, and their comparison with cosmogenic  $^3\text{He}$  and  $^{36}\text{Cl}$  ages of late Quaternary lava flows in the Mojave Desert, California

Sample site and label	Oldest layering pattern	Number of duplicated pattern	Type image of layering pattern	Pattern-based varnish age (ka)	Estimated flow age (ka) <sup>a</sup>	Cosmogenic surface exposure age	
						$^3\text{He}$ (ka) <sup>b</sup>	$^{36}\text{Cl}$ (ka) <sup>c</sup>
<i>Cima volcanic field</i>							
<i>A Flow</i>							
99-CM-7	LU-1/LU-2/LU-3	5		16.5–24	16.5–24	18–20	21 ± 1.6
99-CM-8	LU-1/LU-2/LU-3	9	Fig. 4A	16.5–24	(12.5–16.5) <sup>d</sup>	13 ± 3	11.5 ± 1.5
99-CM-9	LU-1/LU-2 (WP1)	7	Fig. 4B	16.5			
<i>I Flow</i>							
99-CM-1	LU-1/LU-2/LU-3/LU-4 (WP3)	2		30	(30) <sup>e</sup>	31 ± 7	27 ± 1.3
99-CM-2	LU-1/LU-2/LU-3/LU-4 (WP4)	12	Fig. 4E	39	39	37 ± 6	
99-CM-3	LU-1/LU-2 (WP0+) <sup>f</sup>	3		12.5–16.5			
99-CM-11	LU-1/LU-2/LU-3/LU-4 (WP4)	5		39			
00-CM-12	LU-1/LU-2/LU-3/LU-4 (WP4)	12	Fig. 4F	39			
<i>I' Flow</i>							
99-CM-5	LU-1/LU-2/LU-3/LU-4(WP5)	12	Fig. 4G	46–60	46–60		46 ± 2
<i>Undated flow</i>							
99-CM-14	LU-1/LU-2/LU-3/LU-4(WP6)	39	Fig. 5A	60	60		
<i>H Flow</i>							
00-CM-4	LU-1/LU-2/LU-3/LU-4/LU-5	12	Fig. 5C	74–85	74–85	72–74	
00-CM-8	LU-1/LU-2/LU-3/LU-4/LU-5	19	Fig. 5D	74–85			
<i>Stone pavement</i>							
00-CM-7	LU-1/LU-2/LU-3/LU-4/LU-5	31	Fig. 5E	74–85	74–85	80–85	
<i>Pisgah volcanic field</i>							
<i>Phase 1 flow</i>							
99-PS-1	LU-1/LU-2/LU-3/LU-4 (WP2+) <sup>g</sup>	3	Fig. 4C	24–30	24–30		22.5 ± 1.3
99-PS-2	LU-1/LU-2 (WP1)	2		16.5			
99-PS-3	LU-1/LU-2/LU-3/LU-4 (WP2)	3		24			
99-PS-4	LU-1/LU-2/LU-3/LU-4 (WP2)	10		24			
99-PS-5	LU-1/LU-2/LU-3/LU-4 (WP2)	2		24			
<i>Amboy volcanic field</i>							
<i>Amboy flow</i>							
99-AM-1	LU-1/LU-2/LU-3/LU-4/LU-5	6	Fig. 5G	74–85	74–85		79 ± 5
99-AM-2	LU-1/LU-2/LU-3/LU-4/LU-5	9	Fig. 3C	74–85			
99-AM-3	LU-1/LU-2/LU-3/LU-4/LU-5	11		74–85			

<sup>a</sup> The estimated flow age was based on the oldest pattern-based varnish age of each flow and interpreted as a minimum-limiting age for the surface exposure of the flow.

<sup>b</sup> The cosmogenic  $^3\text{He}$  ages of Wells et al. (1995) on either flow features or cone scoria (not on pavement surfaces) were used.

<sup>c</sup> The cosmogenic  $^{36}\text{Cl}$  ages of the sampled flows are reported by Phillips (2002).

<sup>d</sup> Age estimate in parentheses was made for the younger phase of the A flow based on an earlier study (Liu, 1994); see text for discussion.

<sup>e</sup> Age estimate in parentheses was made for the younger phase of the I flow based on reinterpretation of the original varnish age data; see text for discussion.

<sup>f</sup> “WP0+” is used here to represent the orange layer that is directly underneath black layer WP0.

<sup>g</sup> “WP2+” is used here to represent the orange layer that is directly underneath black layer WP2.

Table 4

Radiometric age constraints used for calibration of a generalized varnish layering sequence in the western US drylands

Figs. 7 and 8 <sup>a</sup>	Sampling site and geomorphic context	Age control (ka)	Age type and source
A	Silver Lake shoreline A, Mojave Desert, California	10.5–15.0	<sup>14</sup> C; Wells et al., 1987
B	Alluvial-fan surface, Las Vegas Valley, Nevada	11.0	<sup>14</sup> C; Bell et al., 1998b
C	Searles Lake shoreline at ~ 644 m, Mojave Desert, California	14.0	<sup>14</sup> C; Benson et al., 1990
D	Tabernacle Hill lava flow, Utah	14.0	<sup>14</sup> C; Oviatt et al., 1992
E	Lone Pine Creek fault scarp, Owens Valley, California	17.0–17.8	<sup>10</sup> Be; Bierman et al., 1995
F	Blackhawk paleo-landslide, Mojave Desert, California	17.4	<sup>14</sup> C; Stout, 1977
G	Manix Lake shoreline at ~ 538 m, Mojave Desert, California	18.0	<sup>14</sup> C; Meek, 1990
H	Lone Pine Creek fan surface (Qg3), Owens Valley, California	25.4	<sup>10</sup> Be; Bierman et al., 1995
I	Socorro Fault Scarp, New Mexico	40.0	<sup>36</sup> Cl; Phillips et al., 1998
J	Red Hill lava flow, Owens Valley, California	57.1	<sup>3</sup> He; Cerling, 1990
K	Lathrop Wells lava flow (Q11), Nevada	77.3	<sup>40</sup> Ar/ <sup>39</sup> Ar; Heizler et al., 1999
L	Panamint Lake shoreline at ~565 m, Panamint Valley, California	55–95	U-series; Fitzpatrick and Bischoff, 1993

<sup>a</sup> The letters correspond to those in both Figs. 7 and 8.

plays a fully developed basal layering unit of LU-4 (WP6), suggesting a minimum age of 60 ka for the flow (Fig. 5A,B). Since the “Undated” flow is morphologically and also stratigraphically older than the I’ flow, as observed at the sampling locality (see Fig. 2C), the age of the former should predate the age of the latter. Therefore, the age of the I’ flow most likely falls between 46 and 60 ka.

Two varnish samples from the H flow [one near the H cone (00-CM-4) and the other at the westernmost end of the H flow (00-CM-8)] have an oldest basal layering unit of LU-5 in their varnish layering sequences (Fig. 5C,D), suggesting a minimum surface exposure age of 74–85 ka for the H flow. The stone pavement surface in the Cima volcanic field is stratigraphically overlapped by, and is thus older than the H flow (Wells et al., 1995). One varnish sample (00-CM-7) from a large alluvial boulder 0.3 m above the pavement surface (Fig. 2H) has an oldest basal layering unit of LU-5 (Fig. 5E,F), which is similar in age to that of the H flow (74–85 ka).

As noted in the field (Table 1) and illustrated in Fig. 2H, this varnish sample formed on ventifacted boulder faces, indicating a prolonged episode of wind abrasion in the Cima volcanic field after the deposition of the alluvial boulder and before the onset of the recorded episode of varnish formation. Thus, the true age of the stone pavement surface should certainly be older than the age of the varnish (or the age of the H flow), even though their layering pattern-based ages (74–85 ka) are indistinguishable. This result is consistent with the stratigraphic overlapping between the H flow and the stone pavement surface (Wells et al., 1995).

In the Pisgah volcanic field, five varnish samples were collected from the Phase 1 flow surfaces ~ 400 m NW of the Pisgah Crater (Fig. 1; Table 1). Although one of these varnish samples (99-PS-2) contains a relatively younger basal layering unit of LU-2 (WP1) and three others (99-PS-3, 4, 5) contain a moderately older basal layering unit of LU-4 (WP2), sample 99-PS-1 has the oldest basal layering

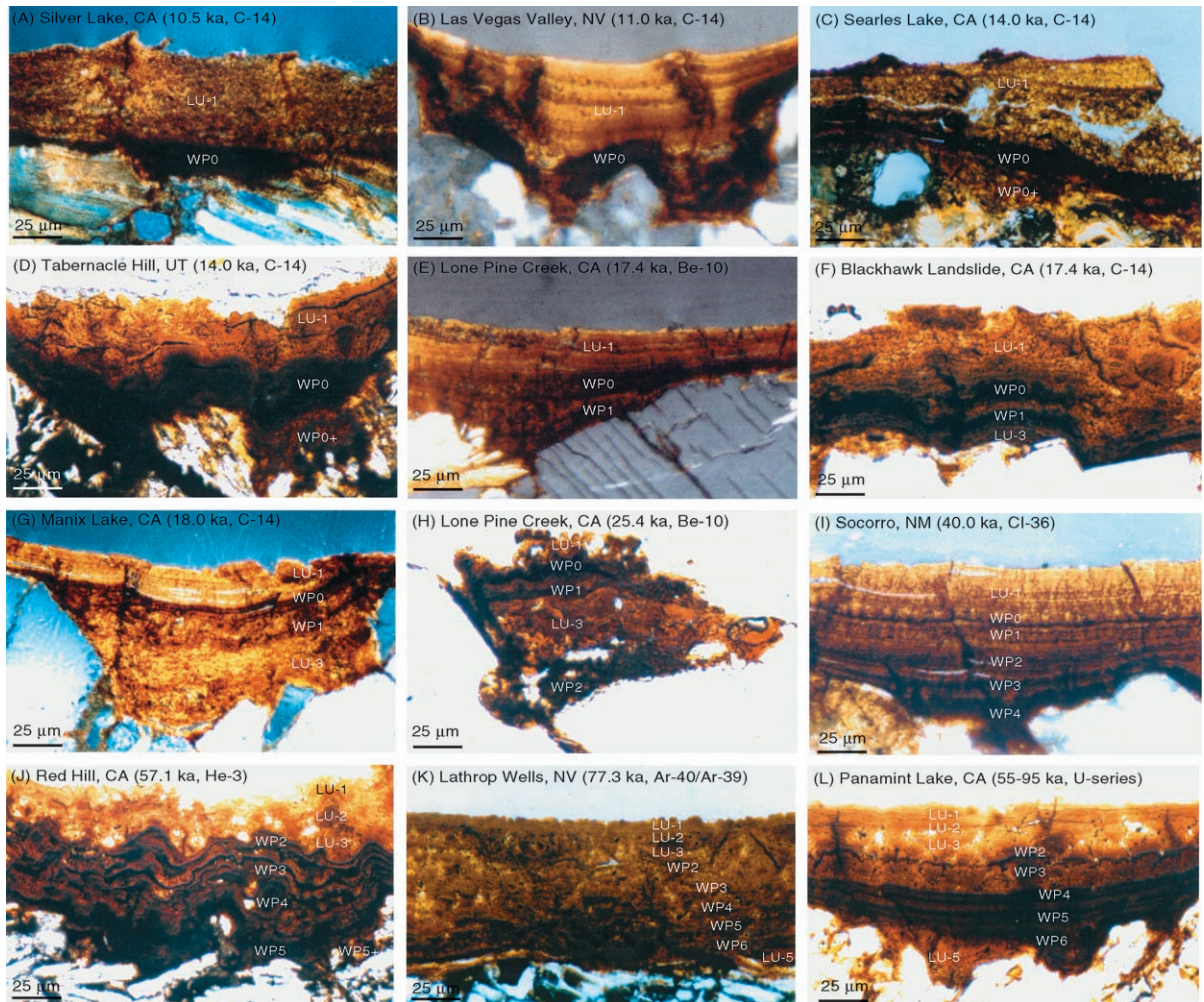


Fig. 7. Optical microstratigraphies in rock varnish samples from radiometrically dated geomorphic features in the western US drylands. Sources of age control are listed in Table 4. Letters in the varnish images correspond to those in both Table 4 and Fig. 8. Note that black layers of WP0 and WP1 in images J and L and those of WP2 and WP3 in image L have been altered to orange layers by postdepositional chemical leaching (see Liu and Dorn, 1996, for detailed discussion).

unit of LU-4 (WP2+), suggesting a minimum surface exposure age of 24–30 ka for the Phase 1 flow of the Pisgah lava (Fig. 4C; Table 3).

In the Amboy volcanic field, three varnish samples were collected from the breached pressure ridge of a lava flow ~ 400 m NW of the Amboy Crater: one (99-AM-3) from the flow-top surface of the pressure ridge and the other two (99-AM-1, 2) from

the nearly vertically breached faces of the pressure ridge (Fig. 2H). Although containing less-defined layering units of LU-2, LU-3, and LU-4, all three samples display well-defined and unambiguous yellow layers of LU-1 and LU-5 in their microstratigraphies (Figs. 3C and 5G,H), indicating a minimum surface exposure age of 74–85 ka for this Amboy lava flow.

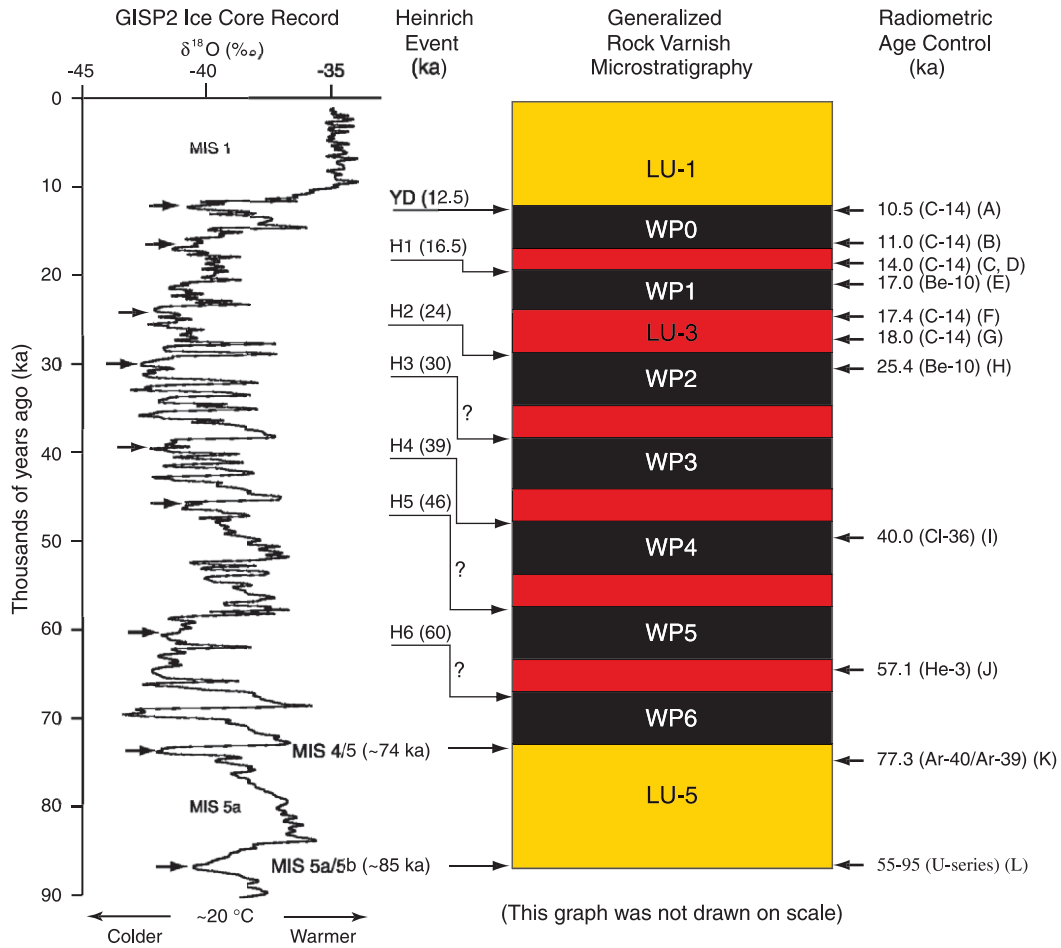


Fig. 8. Radiometric age calibration of a generalized late Quaternary varnish microstratigraphy in the western US drylands and its temporal correlation with the Younger Dryas (YD) and the Heinrich events (H1–H6) seen in Greenland’s GISP2 ice core record (Grootes et al., 1993; Bond et al., 1999). The GISP2 time scale is from Meese et al. (1994) and Bender et al. (1994). The chronology of the YD and H1–H6 is from Bond et al. (1999). The sources of radiometric age control are listed in Table 4, and letters are keyed to those in both Table 4 and Fig. 7. MIS = Marine Isotope Stage.

Table 3 provides a summary of the estimated ages for both varnishes and sampled geomorphic features in the study area.

## 5. Discussion

### 5.1. Validity of varnish layering dating

The best way to test the validity of varnish layering dating is to compare the varnish-based age estimates

with those determined by the cosmogenic <sup>36</sup>Cl method for the same previously undated lava flows. In the Cima volcanic field, the previously undated I’ flow was sampled from the same flow feature for both varnish layering and <sup>36</sup>Cl dating (Table 1; Fig. 2C). The varnish-based age estimate for the I’ flow is 46–60 ka (Table 3), in good agreement with a single <sup>36</sup>Cl measurement of 46 ± 2 ka reported for his “unidentified flow” by Phillips (2002). Although the Pisgah lava flows were considered to be “very late Pleistocene or Holocene” in age (Dibblee, 1966), they were

not radiometrically dated prior to this study. The varnish-based age estimate for the sampled Pisgah Phase 1 flow is 24–30 ka (Table 3), closely matching a mean  $^{36}\text{Cl}$  age of  $22.5 \pm 1.3$  ka ( $n=3$ ) for the same flow (Phillips, 2002). The Amboy lava flows have long been considered very young and probably of “post-Tioga age or 6000 ( $^{14}\text{C}$ ) years” (Parker, 1963). However, the varnish layering dating yielded a much older age of 74–85 ka for the sampled Amboy flow (Table 3), and such age is well consistent with a mean  $^{36}\text{Cl}$  age of  $79 \pm 5$  ka ( $n=3$ ) for the same flow (Phillips, 2002). Given the reported analytical errors ( $1\sigma$ ) of these  $^{36}\text{Cl}$  ages and their possible 10–15% total age uncertainty (Phillips et al., 1996), the varnish-based age estimates nearly perfectly overlap for the  $^{36}\text{Cl}$  ages—a blind test result that appears to justify the validity of varnish layering dating (Fig. 9).

More varnish age data from other previously dated geomorphic features in the study area further support the validity of varnish layering dating (Fig. 9). In the Cima volcanic field, previous field mapping by Wells (quoted in Royek, 1991) distinguished two flow units that were associated with the latest Pleistocene eruption of the A cone. Subsequent dating by Wells et al. (1995) yielded three cosmogenic  $^3\text{He}$  ages:  $18 \pm 12$  and  $20 \pm 10$  ka for the older flow unit and  $13 \pm 3$  ka for the younger flow unit. Based on the above field mapping, varnish samples (99-CM-7, 8, 9) collected in this study appeared to be from the older flow unit, rather than from the younger one as thought in the field (Fig. 1C). These samples yielded a varnish-based age estimate of 16.5–24 ka, in good agreement with the  $^3\text{He}$  age of 18–20 ka and a  $^{36}\text{Cl}$  age of  $21 \pm 1.6$  ka for the older flow unit (Phillips, 2002; Table 3). In an

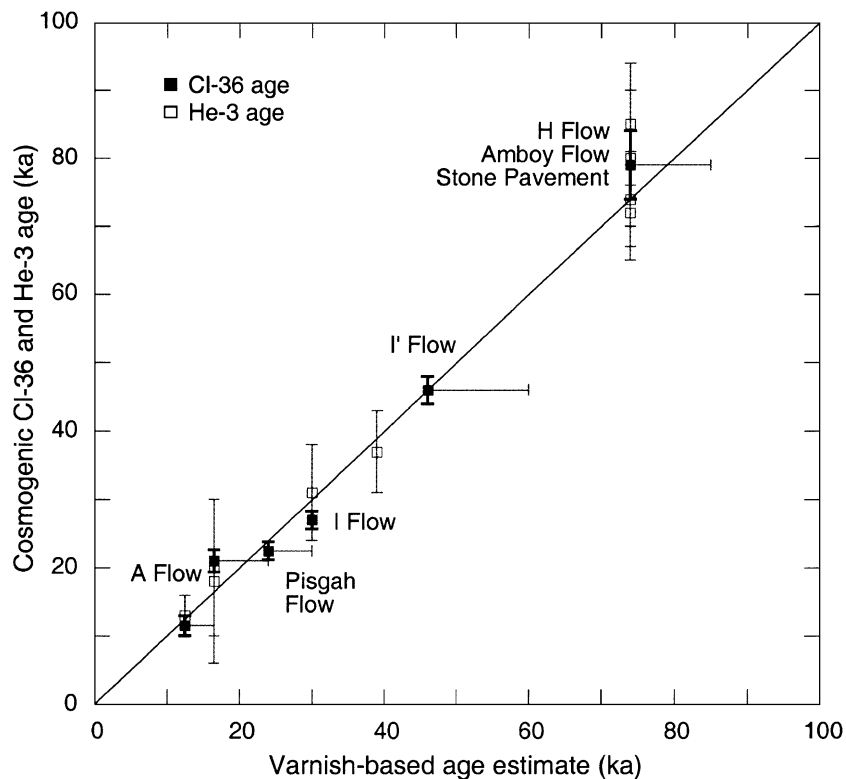


Fig. 9. Comparison of varnish-based age estimates with cosmogenic  $^{36}\text{Cl}$  and  $^3\text{He}$  ages for samples from the Amboy, Cima, and Pisgah volcanic fields. For each lava flow and stone pavement, the minimum varnish-based age estimates in Table 3 were used to make this scatter plot. Error bars for  $^{36}\text{Cl}$  and  $^3\text{He}$  ages represent  $1\sigma$  uncertainty (Wells et al., 1995; Phillips, 2002), while those for varnish ages represent the full range of age estimate.

earlier study (Liu, 1994), varnish from the younger flow unit (i.e., 94-CM-8 in Fig. 1C) yielded a layering pattern of LU-1/LU-2 (WP0+), or a varnish-based age estimate of 12.5–16.5 ka (see the layering image of 94-CM-8 in Fig. 3.3 of Liu, 1994). This age is also consistent with the  $^3\text{He}$  age of  $13 \pm 3$  ka and a possible  $^{36}\text{Cl}$  age of  $11.5 \pm 1.5$  ka suggested for the younger flow unit of the A cone (Phillips, 2002). Both the H flow and the stone pavement surface at Cima were estimated to have a varnish-based age of 74–85 ka (Table 3), which is closely tied to the previously published  $^3\text{He}$  ages of 72–74 ka for the H flow and 80–85 ka for the stone pavement surface (Wells et al., 1995; Fig. 2E,F).

As is the case in any intercomparison of Quaternary dating methods, anomalous results do occur. In this study, the I flow at Cima was estimated to be 39 ka based on an oldest layering pattern of LU-1/LU-2/LU-3/LU-4 (WP4) observed in five varnish samples from the I flow (Fig. 4E,F; Table 3). On one hand, this age estimate is consistent with an older  $^3\text{He}$  age of  $37 \pm 6$  ka reported for the I flow (Wells et al., 1995); on the other hand, it is largely inconsistent with a younger  $^3\text{He}$  age of  $31 \pm 7$  ka and a mean  $^{36}\text{Cl}$  age of  $27 \pm 1.3$  ka ( $n=3$ ) reported for the same flow (Wells et al., 1995; Phillips, 2002). As discussed below, the most likely explanation for such age discrepancy is that different flow units were unintentionally sampled in the field. This scenario, if true, would necessitate a reinterpretation of the single age estimate of 39 ka that I originally made for the I flow (Table 3).

Previous field mapping by Wells (quoted in Royek, 1991) indicated that the I cone is polycyclic, with three flow units (i1, i2, and i3) cropping out within ~200 m west of the cone. The bimodal  $^3\text{He}$  age distribution on lava samples from this locality (see Fig. 2 and Table 1 of Wells et al., 1995) appeared to support such field observation. At this locality, two varnish samples (99-CM-1, 3) were from the southern margin of the I flow (i.e., i1), each within 0.5 m of its paired  $^{36}\text{Cl}$  sampling spot; they yielded age estimates of 30 and 12.5–16.5 ka, respectively (Table 3). Since these two samples were indeed from the same flow unit, as suggested by the  $^{36}\text{Cl}$  dating results, the best varnish-based age estimate for this sampled flow should be 30 ka, thus in good agreement with the corresponding  $^{36}\text{Cl}$  age of  $27 \pm 1.3$  ka (Phillips, 2002) and the younger  $^3\text{He}$  age of  $31 \pm 7$  ka (Wells et al.,

1995). Three other samples (99-CM-2, 11 and 00-CM-12) were from flow surfaces at the same locality, but 5–50 m further north of the  $^{36}\text{Cl}$  sampling spots (Fig. 2B). They all yielded an identical varnish-based age estimate of 39 ka, suggesting that these samples were probably from an older flow unit (i.e., i3). Moreover, the varnish-based age for this unintentionally sampled older flow unit fairly matches the older  $^3\text{He}$  age of  $37 \pm 6$  ka reported for the I flow (Wells et al., 1995).

In summary, both varnish and  $^{36}\text{Cl}/^3\text{He}$  age data from previously undated and dated geomorphic features in the Mojave Desert provide convincing evidence that varnish microstratigraphy, once radiometrically calibrated, can be used as a valid dating tool to estimate surface exposure ages of desert landforms such as lava flows, alluvial fans, and stone pavements in the western US drylands. Although some anomalous varnish ages were obtained for the I flow at Cima, reinterpretation of these age data with knowledge of the previous field mapping of the I flow by Wells (quoted in Royek, 1991) appears to yield more evidence in support of the above conclusion.

## 5.2. Uncertainties in varnish layering dating

Varnish layering dating is by definition a calibrated dating method (Colman et al., 1987). Like other calibrated dating tools such as lichenometry (Bull, 2000), varnish layering dating has similar problems or uncertainties (such as lag time, age calibration, and sample selection). These uncertainties, if not well understood or properly handled, could hamper the potential use of this dating technique.

### 5.2.1. Lag time of varnish growth

The lag time of varnish growth is a key factor that influences the accuracy of varnish layering dating. This is because, for any varnish sample to be dated, an unknown lag time always exists between varnish initiation and surface exposure of the substrate rock. Furthermore, aeolian abrasion resets the varnish clock, which increases the lag time. Traditionally, many believe that varnish may take a few thousands of years to initiate on subaerially exposed rock surfaces in arid to semi-arid deserts (Hunt, 1975; Moore and Elvidge, 1982; Bull, 1991). Under favorable conditions, however, only a few decades to hundreds of years

may be needed for varnish to grow on subaerially exposed stable rock surfaces. For instance, rock varnish as young as 35 years old has been reported on slag piles at San Bernardino, southern California (Dorn and Meek, 1995). In the arid zone of southern Australia near Karolita, incipient varnish has developed on a 100-year-old letter inscription on a rock surface (Nobbs and Dorn, 1988). A grinding stone or metate believed to be of pre-Columbus age (ca. 500–1000 YBP) near Chili, northern New Mexico, has been coated with 60- $\mu\text{m}$ -thick patchy varnish (Liu, unpublished data). Well-developed, patchy varnish was also observed on an  $\sim$  1900-year-old rocky ramp west of Masada, Israel (Bull, 1991). These pieces of evidence indicate that the lag time of varnish growth may be on an order of a few hundred years. Based on my experience, by carefully sampling the oldest possible varnish on geomorphic features of interest, controlling this lag-time-related age uncertainty is practically feasible within a few hundred years for varnish of Holocene and latest Pleistocene age and within several thousand years for varnish of late Pleistocene age.

### 5.2.2. Age calibration

Radiometric age calibration of varnish layering sequences remains the most difficult problem in varnish layering dating for several reasons. First, varnish material is not directly datable by available radiometric means at present, which makes it impossible to radiometrically calibrate the ages of internal layers within varnish microstratigraphy. Second, although ages may be obtained for basal varnish layers through radiometric dating of varnished geomorphic features, such age calibration is indirect and often involves an assumption that the lag time of varnish growth is relatively small compared to the age of the dated geomorphic feature. Such an assumption, while probably true, cannot be definitively justified. Third, the temporal resolution of such calibrations may be predetermined by the distribution of the timing of major climatic fluctuations recorded in the varnish that were likely associated with the Younger Dryas and Heinrich events. Finally, the age distribution of radiometrically datable geomorphic features in the western US drylands (such as lava flows, alluvial-fan deposits, and glacial moraines) is discrete, which also prevents a detailed calibration of varnish layering

sequence. Clearly, new calibration means and further research are desperately needed to improve this situation.

### 5.2.3. Sampling oldest varnish

Sampling rock varnish has proven to be a tricky task and also the most debatable topic in varnish research (Krinsley et al., 1990; Reneau, 1993; Whitney and Harrington, 1993; Dorn, 1994; Liu and Dorn, 1996). Just like the fact that not every tree in a forest may be appropriate for tree ring analysis, not every varnish microbasin on a rock surface may be suitable for microstratigraphic analysis. For age dating, only the oldest possibly varnish microbasins on well-preserved primary geomorphic surfaces should be selected. Although somewhat “subjective”, such selection is very critical and often requires iterative training both in the field and in the laboratory. Because surficial geomorphic processes such as rock weathering, spalling, wind abrasion, and bioturbation all contribute to resetting the varnish clock, young varnish is easily collected from an old surface. On the other hand, collecting varnish as old as or slightly younger than the age of the surface ( $\leq$  250 ka) is always difficult (but still possible) (Liu and Broecker, 2000). Extreme caution should be taken when one samples rock varnish from a flow surface. Varnish on primary pahoehoe or aa features may not always be the oldest for the flow, as indicated by my varnish data on both the I flow at Cima and the Phase 1 flow at Pisgah (Figs. 3A and 4C,D; Table 3).

### 5.2.4. Sampling fine-grained and layered varnish

Not every varnish-filled microbasin on a rock surface contains a fine-grained (i.e., submicrometer) and layered microstratigraphy. Rather, some contain varnish deposits that are either coarse-grained or unlayered, or both; such deposits are inappropriate for layering pattern analysis and varnish layering dating. This is especially true for varnish microbasins in deep ( $>$ 2 mm) sheltered vesicular voids on lava surfaces where water and probably dew are easily collected, promoting chemical leaching that often alters partially or completely the primary microstratigraphy of varnish deposit (Fig. 5B). Large grain-sized detritus and dirt are also frequently collected in these voids, introducing internal sedimentary disturbance during varnish accretion. Such disturbed varnish microstra-

tigraphies are usually difficult for layering pattern interpretation. I recommend that varnishes in shallow microdepressions (about 0.1–0.3 mm deep and 1–3 mm in diameter) that contain fine-grained and layered microstratigraphies be selected for varnish layering dating.

#### 5.2.5. *Ultra-thin sectioning of varnish microbasin*

In varnish layering dating, samples must be thin-sectioned to a certain thickness (usually about 5–10  $\mu\text{m}$  thick) to visually see varnish microstratigraphies, which are opaque in regular geological thin sections (25–30  $\mu\text{m}$  thick). In practice, however, it is not an easy task to make varnish sections so thin by using conventional thin-sectioning techniques. A special ultra-thin sectioning method (Liu, 1994) should be employed for this purpose. In well-made ultra-thin sections that are about 5–10  $\mu\text{m}$  thick, all black, orange and yellow layers in varnish microstratigraphy can be simultaneously observed under a petrologic microscope (with transmitted polarized light). These layers may be optically altered into yellow layers when sections are made too thin (<5  $\mu\text{m}$ ), or black layers when sections are made too thick (>10  $\mu\text{m}$ ) (Liu and Dorn, 1996). In unevenly polished ultra-thin sections, a “fake” yellow layer may occur at the upper portion of a varnish microstratigraphy. Sometimes uneven polishing could partially distort the original varnish microstratigraphy or even completely destroy it. All these would introduce uncertainties in layering pattern interpretation and varnish layering dating. Therefore, great cares such as delicate polishing moves and frequent microscopic checking must be taken to make precise and even polishing during ultra-thin section preparation.

#### 5.2.6. *Postdepositional modification of varnish layers*

Varnish microstratigraphies are occasionally modified in situ by postdepositional processes such as bioturbation, chemical leaching, and physical erosion (Dorn and Krinsley, 1991; Liu, 1994; Liu and Dorn, 1996). In this study, postdepositional bioturbation and chemical leaching frequently occur in most of the varnish microbasins examined, resulting in ambiguous microstratigraphies (Fig. 5C,H). Because of past aeolian activity and weathering, physical erosion of varnish layers by wind abrasion and surface peeling are also common and of similar magnitude in the three

volcanic fields, as evidenced by stratigraphic unconformities in varnish microstratigraphies (Fig. 5A,F). Accordingly, varnish microbasins sometimes contain layering sequences that lack one or more layering units (Fig. 5A). All these complications have prevented identification of varnish layering patterns in about 30% of the microbasins examined in this study. Because postdepositional modification inevitably introduces stratigraphic uncertainties in layering pattern interpretation, more ultra-thin sections (at least 3 to 10) should be made for any given sample to minimize these uncertainties and to get the most unambiguous layering pattern for age dating.

## 6. Conclusion

Rock varnish microstratigraphy is a useful dating technique that, when applied properly, can provide calibrated age constraints on surficial geomorphic features such as lava flows, alluvial-fans, and pavement surfaces in deserts. In both blind and nonblind tests of this study, the close match between varnish-based age estimates and cosmogenic  $^{36}\text{Cl}/^3\text{He}$  ages for lava flows and stone pavement surface in the Mojave Desert, California supports the validity as well as the feasibility of varnish layering dating in the drylands of the western US.

The true value of this dating technique rests in the ubiquitous distribution of rock varnish in the world's deserts where other available dating approaches are either not applicable or difficult to use. In particular, this dating technique can be used to evaluate the antiquity and cultural significance of varnished artifacts such as petroglyphs, geoglyphs, and stone flakes in deserts. Although I am not sure whether my calibrated varnish layering sequence in the western US drylands is applicable worldwide, the principle and methodology that I used to develop this dating technique should work in any desert regions where rock varnish forms. Further, Mn-rich black and Mn-poor orange/yellow layers are observed in rock varnishes from arid regions of western China (Zhou et al., 1999), Australia (Nobbs and Dorn, 1988, 1993), the Dead Sea region of the Middle East (Liu, unpublished data), the Patagonia Desert in South America (Liu, unpublished data), and even from the Dry Valley of the Antarctic (Dorn et al., 1992). When proper radio-

metric calibration is accomplished, the varnish layering method will serve as a unique dating tool to study geomorphology, geoarchaeology, and late Quaternary environmental changes in the world's deserts.

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