How fast does rock varnish grow?

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ABSTRACT

Rates of rock-varnish accumulation have never been systematically documented owing to the difficulty in accurately determining both varnish thickness and age. In this study, we quantitatively assess varnish-accumulation rates through thin sectioning and microscopic examination of rock varnish from radiometrically dated geomorphic features of late Quaternary age in the western United States drylands. Our data indicate that rock varnish grows at rates ranging from <1 to 40 μm/k.y. on subaerially exposed rock surfaces and rarely reaches a thickness exceeding 200 μm regardless of age. Our data also indicate that varnish-accumulation rates vary greatly from sample to sample at a given site, suggesting that varnish thickness does not correlate with the age of the associated geomorphic feature, invalidating the potential use of varnish thickness as a relative age indicator in geomorphology and archaeology. Nevertheless, being the slowest known accumulating terrestrial sedimentary deposit, rock varnish constitutes a unique long-term microscale sedimentary archive of past environmental changes in deserts.

Keywords: rock varnish, thickness, growth rate, age control, microstratigraphy, western United States.

INTRODUCTION

Rock varnish is a dark patina that accumulates on rock surfaces. On the average, it consists of about 30% manganese and iron oxides. The remainder is made up by oxides of Si, Al, Mg, K, and Ca, some of which is contained in clay minerals (Potter and Rossman, 1977). Varnish can form on virtually all lithologies including quartzite; thus, it is believed to be of sedimentary origin, the constituents being supplied from the atmosphere (Fleisher et al., 1999). Although varnish has been found in numerous terrestrial weathering environments including the Antarctic (Dorn et al., 1992b), Iceland (Douglas, 1987), and Hawaii (Dorn et al., 1992a), it is most common in arid to semiarid deserts of the world.

Rock varnish has been a scientific wonder for almost two centuries, dating back to Alexander von Humboldt's travels from 1799 to 1804 in South America (von Humboldt, 1812). However, two basic questions raised by von Humboldt remain unanswered. How long does it take for varnish growth to initiate? Once started how fast does varnish grow? Certainly, there are anecdotal observations useful in answering von Humboldt's questions. In humid environments, rock surfaces may be coated within a few decades (Dorn and Meek, 1995; Klute and Krasser, 1940). For the Mojave Desert, suggestions have been made that varnish formation begins within 25 yr of exposure (Engel and Sharp, 1958). But the most common observation is that once initiated, varnish formation is slow on subaerially exposed rock surfaces (Basedow, 1914; Hayden, 1976; Denny, 1965). Yet, after 200 yr of study, there are only a few qualitative comments on rates of varnish growth where the ages of the archaeological (cf. Pyramids, Lucas, 1905) and geomorphological (cf. paleolake shoreline, Bard et al., 1978) features are known. The purpose of this paper is to present the first quantitative database on rates of varnish formation on landforms that have been radiometrically dated.

METHODOLOGY

Sampling Sites and Sample Collection

The methodology of this study is very simple; it involves collecting varnish-coated rocks from radiometrically dated surfaces and measuring varnish thickness. Our sampling sites are located in the desert regions of the western United States where the environmental setting has fluctuated between arid and semiarid during the Quaternary and where rock varnish is ubiquitous and well preserved. Radiometrically dated geomorphic features of late Quaternary age such as abandoned shorelines of pluvial lakes, lava flows, alluvial-fan and terrace surfaces, debris-flow deposits, fault scarps, and paleolandslides exist in the regions, providing age control on the earliest time at which varnish growth was initiated (Table 1).

As is the case in virtually all Quaternary research, collecting the right type of sample is critical. In order to avoid circular reasoning, we did not sample based on the field appearance of varnish darkness, estimates of thickness in hand samples, or surface coverage of varnish. Rather, we judged varnish samples based only on whether the varnished surface retains primary surface features (cf. Liu and Dorn, 1996). For example, we collected only subaerially exposed rock varnishes on boulders (>15 cm in size) with surfaces abraded by a known geomorphic process, such as alluvial or fluvial polishing, or on lava flows displaying originally formed ropy or aa surface features. Thus, we knew that each varnish started to form sometime after the geomorphic event that created the host surface.

The next step was to use a laboratory criterion, independent of thickness, to maximize the chance that we were studying the oldest varnish from a given site. In other words, we wanted to minimize the lag time between surface exposure and the onset of varnishing. Our laboratory criterion is the pattern of layers seen in rock varnish (cf. Liu, 1994; Liu and Dorn, 1996; Cremaschi, 1996; Liu et al., 1998). In the laboratory, we selected layered varnish microbasins (i.e., 1–3-mm-wide varnish-filled dimples) showing the oldest microstratigraphic unit.

Age Control and Thickness Measurement

Varnish ages were inferred from the surface-exposure ages of the sampled geomorphic features. In this study, we collected varnish samples from 27 geomorphic features that have been radiometrically dated (Table 1). The youngest varnish was from basaltic debris-flow deposits in Grand Canyon, Arizona, that were ^{3}He dated as 1.5 ka (T. Cerling, 1997, written commun.). The oldest varnish was from a quartzitic boulder on the oldest alluvial-fan surface in Death Valley, California, that was ^{10}Be/^{26}Al dated as 250 ka (S. Ivy-Ochs, 1998, written commun.). Other varnish samples were from a variety of dated geomorphic features such as the Bandera lava flow in the Zuni-Bandera volcanic field, New Mexico (10 ka [^{14}C]; Laughlin et al., 1994), the Dry Falls in Owens Valley (15.3 ka; Cerling, 1990), the Tabernacle Hill lava flow in Utah (14.4 ka [^{14}C]; Cerling and Craig, 1994), the Blackhawk landslide in the Mojave Desert (17.4 ka [^{14}C]; Stout, 1977), and the shorelines of major pluvial lakes that formed from 10.5 ka (^{14}C) to 120 ka in the Great Basin of the western United States (Table 1). Because all of these dates are for geomorphic events, they provide maximum ages for the initiation of varnish growth.

We collected 42 rock samples, and prepared 74 thin sections, each hosting 1–4 individual microbasins. Thickness measurements were taken on 115 such microbasins. Varnish thickness was accurately measured on thin sections by using an optical microscope. Varnish thin sections were first prepared by using a new thin-sectioning technique[1] (Liu and Dorn, 1996) and then photographed on color print films under the microscope with transmitted polarized light. The measurements of varnish thickness were made on 5" × 3.5" (12.6 cm × 8.7 cm) standard color prints

[1] 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. The varnish is then polished on side 2 until it is thin enough for microstratigraphy to be visible with light microscope.

Data Repository item 200020 contains additional material related to this article.

TABLE 1. ROCK-VARNISH AGE CONTROL, MEASURED LARGEST THICKNESS, AND APPARENT ACCUMULATION RATES

Fig. 2	Sample site and geomorphic context	Sample number	Age* ka (cal yr)	Thickness† (μm)	Rate (μm/k.y.)	Cited age (or age type) and source
A	Grand Canyon debris flow deposit, AZ	93-LVA FLS 20§	1.5	60	40.0	^{3}He (T. Cerling, 1997, written commun.)
B	McCartys lava flow, Zuni-Bandera VF, NM	98-McCartys-1	3.2	52	16.3	2987 ± 92 ^{14}C (Laughlin et al., 1994)
C	Carrizozo lava flow, NM	99-Carrizozo-1	5.0-7.0#	100	14.3	^{36}Cl (F. Phillips, 1998, oral commun.)
D	Bandera lava flow, Zuni-Bandera VF, NM	99-Bandera-1	11.0	130	11.8	9810 ± 60 ^{14}C (Laughlin et al., 1994)
E	Silver Lake, A shoreline, Mojave Desert, CA	98-Silver Lake-3	12.5	212	17.0	10 500-15 500 ^{14}C (Wells et al., 1987)
F	Coyote Lake shoreline, Mojave Desert, CA	98-Coyote Lake-1	13.4	68	5.1	11 360 ± 340 ^{14}C (Meek, 1990)
G	Alluvial fan, Las Vegas Valley, NV	98-Las Vegas-1G	13.5	92	6.8	ca. 11 500 ^{14}C (Bell et al., 1998)
H	Aberdeen lava flow, Owens Valley, CA	96-Aberdeen-1	11.8-13.6#	138	10.1	^{3}He (Cerling, 1990)
I	Dry Falls, Owens Valley, CA	96-Dry Fall-2	15.9	202	12.7	^{3}He (Cerling, 1990)
J	Lahontan Lake shoreline at Oling House, NV	95-Oling House-5	16.3	239	14.7	ca. 13 600 ^{14}C (Benson et al., 1995)
K	Searles Lake shoreline, Mojave Desert, CA	94-Searles Lake-1	16.8	244	14.5	ca. 14 000 ^{14}C (Benson et al., 1990)
L	Tabernacle Hill lava flow, UT	96-TH-14A	17.8	121	6.8	14 400 ± 100 ^{14}C (Cerling & Craig, 1994)
M	Lone Pine fault scarp, Owens Valley, CA	98-Lone Pine-7a	17.0-17.8#	56	3.1	^{10}Be/^{26}Al (Bierman et al., 1995)
	Provo shoreline at Delta, Bonnevill Lake, UT	95-Delta-1	17.8	85	4.8	14 400 ± 100 ^{14}C (Cerling and Craig, 1994)
	Organ Pipe alluvial terrace, AZ	98-Organ Pipe-4	17.8	126	7.1	14 880 ± 100 ^{14}C (Pohl, 1995)
N	Walters bars, Bonneville Flood, ID	95-Walters Bar-19	18.0	192	10.7	14 500 ± 100 ^{14}C (Cerling & Craig, 1994)
O	Aden lava flow, Patrillo VF, NM	98-Aden-3	15.7-18.9#	241	12.8	^{3}He (Anthony & Poths, 1992)
P	Blackhawk landslide, Mojave Desert, CA	98-Blackhawk-3	20.7	210	10.1	17 400 ± 550 ^{14}C (Stout, 1977)
Q	Manix Lake shoreline, Mojave Desert, CA	98-Manix Lake-4	21.4	106	5.0	ca. 18 000 ^{14}C (Meek, 1990)
R	Harper Lake shoreline, Mojave Desert, CA	98-Harper Lake-2	27.5	120	4.4	24 440 ± 2190 ^{14}C (Meek, 1997)
S	Socorro fault scarp, NM	98-Socorro-6	40	120	3.0	^{36}Cl (Phillips et al., 1998)
T	Red Hill lava flow, Owens Valley, CA	96-Red Hill- 5	57.1	110	1.9	^{3}He (Cerling, 1990)
U	Lathrop Wells lava flow, NV	96-LW-3	81	160	2.0	^{36}Cl (Zreda et al, 1993)
V	Panamint Lake shoreline, Panamint Valley, CA	95-PL-5	55-95#	104	1.1	U-series (Fitzpatrick & Bischoff, 1993)
W	Manly Lake shoreline, Death Valley, CA	96-SB-13	120	150	1.3	U-series (Hooke and Dorn, 1992)
	Socorro alluvial fan, NM	98-Socorro-1	140	242	1.7	^{36}Cl (Phillips et al., 1998)
X	Six Spring alluvial fan, Death Valley, CA	91-SS-1	250	160	0.6	^{10}Be (S. Ivy-Ochs, 1998, written commun.)

Note: The full data set of varnish-thickness measurements and accumulation rates is available (see footnote 2).
VF - Volcanic Field; AZ - Arizona; CA - California; ID - Idaho; NV - Nevada; NM - New Mexico; UT - Utah.
* The calibrated radiocarbon ages were either from the cited references or estimated from Stuiver and Reimer (1993).
† The images of varnish microbasins displaying the measured largest thickness are shown in Figure 2.
§ This sample was collected by Thure Cerling.
\# The older date was used to calculate varnish-accumulation rate.

with 477 × magnification of the varnish thin sections. The apparent varnish thickness was measured in millimeters with a transparent ruler placed perpendicular to the outer varnish surface on the color prints; then true varnish thickness was obtained in micrometers by multiplying the apparent thickness with a conversion factor of 1/477. Measurements when converted to absolute varnish thickness are accurate to ±1 μm. On each thin section, thickness was measured at the maximum depth of the individual varnish microbasins that display the most complete and consistent microstratigraphy (Fig. 1) and thus most closely represent the entire exposure history of the sampled geomorphic feature (Fig. 2; also see Liu and Dorn, 1996). When crack(s) appeared in a varnish microbasin (cf. Fig. 2D), the thickness was deducted from the overall thickness measurement.

The layering patterns provide supplementary information. Measuring thicknesses of the oldest layering, however, does not alter the fact that each data point fails to include the lag time between surface exposure and the initiation of varnish growth; no study has yet quantified this lag time in a systematic fashion. Postdepositional modifications such as spalling, chemical leaching, compaction, and diagenesis (cf. Krinsley, 1998) may reduce the original varnish thickness. The influences of those factors imply that the varnish growth rates obtained in this study are only minimum values. Furthermore, although some workers (cf. Reneau et al., 1992) do not think that layering patterns offer insight into varnish age, the data presented here represent the results of the first systematic study on rates of varnish growth on samples selected from a specific, replicable environmental context: varnish growing in 1–3-mm-wide microbasins on rock surfaces.

RESULTS

Table 1 lists only the greatest thickness measured on each sample, and Figure 2 presents the color images of the corresponding varnish microbasins; however, the full data set of the thickness measurements is available.[2] The greatest varnish thickness observed in this study is 244 μm (Fig. 2K), from the 14.0 ka (^{14}C) highstand of Searles Lake in the Mojave Desert (Benson et al., 1990). The thinnest varnish is 10 μm thick (see footnote 2) and was collected from an 11.5 ka (^{14}C) alluvial-fan surface in Las Vegas Valley of southern Nevada (Bell et al., 1998). The calculated mean thickness of these varnishes is 100 μm, with a standard deviation of 55 μm. This result is in good agreement with our field and laboratory knowledge that, regardless of their ages, rock varnishes in the drylands of the western United States rarely reach a thickness >200 μm.

We found that there is no correlation between varnish thickness and age of the underlying geomorphic surface. Rather, varnish samples of similar apparent age can be quite different in thickness. (The adjective "apparent" is used herein to indicate that the geomorphic age is not the age of the varnish; there is an unknown lag time between the ages in Table 1 and the onset of varnishing.) On a regional scale, for example, varnish samples from the ca. 14 ka (^{14}C) shorelines of Searles Lake and Bonneville Lake have thicknesses of 244 and 121 μm, respectively (Fig. 2, K and L). On a local scale, varnish samples from the 10.5 ka (^{14}C) highstand of Silver Lake and 11.5 ka (^{14}C) highstand of Coyote Lake in the Mojave Desert display comparable microstratigraphies that are, however, extremely different in thickness, being 212 μm for the former and 68 μm for the latter (Fig. 2, E and F). Even on a submillimeter scale, different parts of a varnish microbasin may have different thicknesses owing to topographic variations within the microbasin (Fig. 2, A, E, G, P, and Q). However, varnish samples with similar thicknesses may not be similar in age. A ca. 120 ka varnish sample from the Blackwelder shoreline of Lake Manly in Death Valley (Hooke and Dorn, 1992) is 150 μm thick (Fig. 2W); varnish samples with thicknesses close to this value could be either younger, like the one from the 81 ka Lathrop Wells lava flow (Fig. 2U; Zreda et al., 1993), or much older, like the one from the 250 ka alluvial-fan surface in Death Valley (Fig. 2X).

Apparent varnish-accumulation rates were calculated from the full data set of varnish thicknesses and ages (see footnote 2). Figure 3 presents a plot of apparent varnish-accumulation rate vs. varnish age. We found that varnish-accumulation rates vary widely, from as high as 40 μm/k.y. on a 1.5 ka varnish in Grand Canyon (Fig. 2A) to as low as 0.6 μm/k.y. on a 250 ka varnish in Death Valley (Fig. 2X), with a mean apparent accumulation rate of 6.4 μm/k.y. These rates vary laterally over a single rock surface, being higher in

[2] GSA Data Repository item 200020, Varnish-thickness measurements, ages, and apparent accumulation rates, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

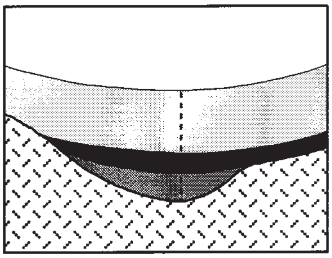

Figure 1. Idealized rock-varnish microbasin showing most complete microstratigraphy from 14 ^{14}C ka geomorphic surface. Dashed line identifies position where maximum varnish thickness was measured.

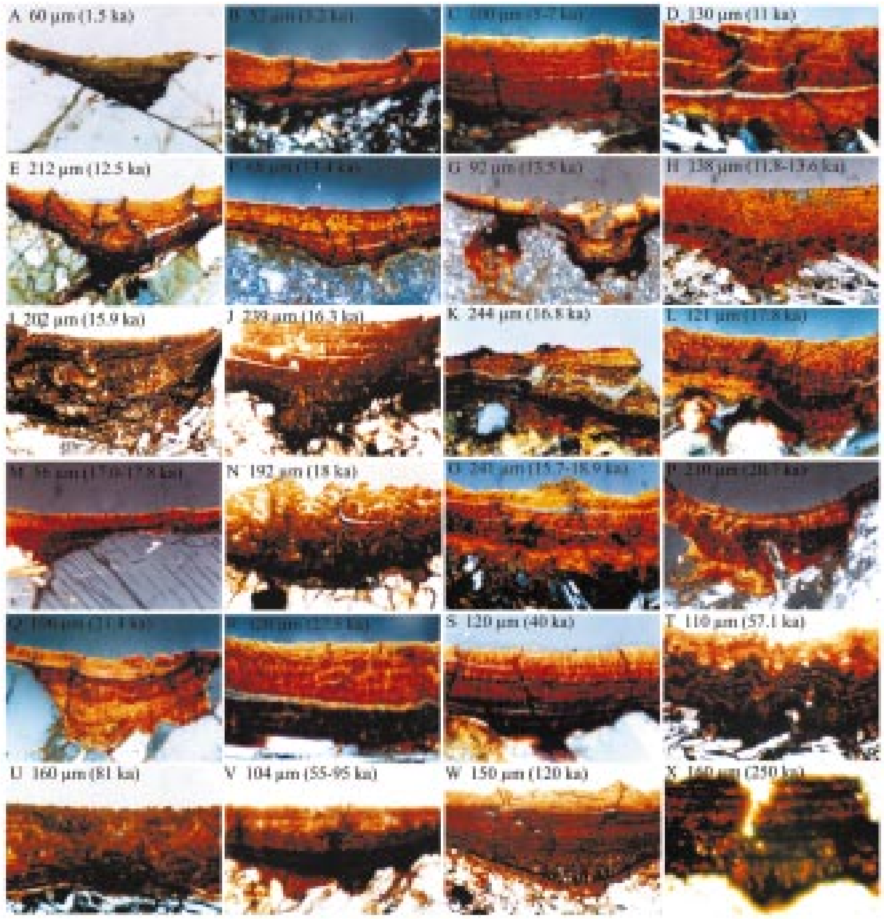

Figure 2. Optical photographs of rock varnish displaying largest thickness and most complete microstratigraphy in 1–3-mm-wide microbasins measured for this study. Numbers at upper left corner of each image provide maximum varnish thickness and ages.

deep varnish microbasins and lower in shallow microbasins (Fig. 2G; see footnote 2). Within a given microbasin, varnish-accumulation rates also vary; the highest rate is in the center and the lowest is on the edge (Fig. 2, A and E). In addition, we observed that younger varnish samples (<30 ka) appear to have higher apparent accumulation rates (3–15 µm/k.y.), whereas older varnish samples (>50 ka) have lower apparent accumulation rates (<3 µm/k.y.) (Fig. 3).

DISCUSSION AND IMPLICATIONS

Observations and speculations on rates (or time) of varnish formation are scattered throughout the rock-varnish literature. The most rapid varnish initiation time so far reported in the literature is 25 yr on rocks disturbed during road construction in the Mojave Desert (Engel and Sharp, 1958). In southern California, near Fontana, rock varnish has been reported on 35-yr-old slag deposits (Dorn and Meek, 1995). In this study, we observed that the 1.5 ka basaltic debris flow deposits in Grand Canyon, Arizona, are coated with 60-µm-thick patchy varnish (Fig. 2A) and the 3.0 ka (^{14}C) McCartys lava flows in the Zuni-Bandera volcanic field, New Mexico, are coated with 52-µm-thick patchy varnish (Fig. 2B). In the western United States drylands, many observations of rock varnish on artifacts (Hunt, 1975; Hayden, 1976), alluvial-fan surfaces (Denny, 1965), and abandoned lake shorelines (Bard et al., 1978) support the conclusion that it generally takes about 3000 to 5000 yr to form a visually discernible patchy varnish and about 10 000 yr for a heavily coated varnish (Elvidge and Iverson, 1983). Our quantitative data from this study indicate that varnishes accumulate at rates of <1 to 40 µm/k.y. Given an average thickness of 50 and 100 µm for visually discernible patchy varnish and heavily coated varnish, respectively, our varnish-accumulation rates are comparable to these earlier anecdotal observations.

Once initiated, rock varnishes appear to accrete semicontinuously on rock surfaces (cf. Liu, 1994; Cremaschi, 1996; Krinsley, 1998). During the course of rock varnish development, only those having the highest accumulation rates will have the greatest potential of being able to first develop as visually discernible patchy varnishes; in contrast, only the slowest-forming varnishes have the potential of achieving very great age (without being eroded). The greater long-term preservation of slower growing varnishes is not a new concept in varnish research (cf. Dorn and Oberlander, 1982), and it probably explains why the apparent accumulation rates of latest Pleistocene and Holocene visually discernible varnishes in our study areas are significantly higher than those of the late Pleistocene varnishes (Fig. 3).

For decades, geologists and archaeologists have used the slow growth of varnish on rock surfaces as a means of estimating ages for ancient landforms, petroglyphs, and artifacts (Carter, 1980; Espizua, 1993; Grote and Krumbein, 1993). The underlying hypothesis of this dating technique is that rock varnish accumulates at a comparable rate in a given region. The results from this study provide the first quantitative evidence that varnish-accumulation rates change greatly on both local and regional scales, and that even in a single varnish section there are large variations in accumulation rates (Figs. 2 and 3). Relative or absolute varnish thickness cannot be used to provide a reliable estimate for the age of varnished landforms.

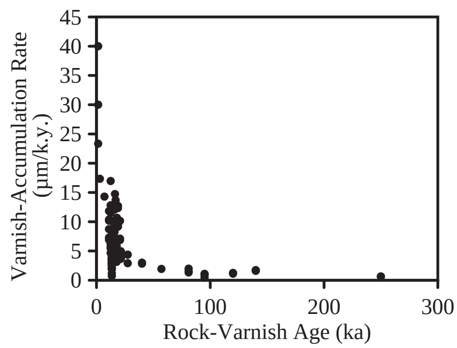

Figure 3. Variations of apparent varnish-accumulation rate over varnish age.

Given the apparent accumulation rates of a few micrometers per millennium (or a few nanometers per year) obtained in this study, rock varnish is probably the slowest known accumulating terrestrial sedimentary deposit. Such finding has a significant implication for the potential use of rock varnish as a climate recorder. Despite wide differences in growth rate, chemical microstratigraphy in rock varnish has been demonstrated to be regionally consistent and comparable (Liu and Dorn, 1996; Liu et al., 1998); it carries valuable information about past environmental fluctuations (Perry and Adams, 1978; Dorn, 1984; Liu and Dorn, 1996; Liu et al., 1998). As seen in Figure 2, varnishes from the drylands of the western United States contain alternative black layers that are rich in Mn and orange layers that are poor in Mn (Fleisher et al., 1999); the alternations probably correspond to the fluctuations of moisture conditions in deserts (Cremaschi, 1996; Liu et al., 1998). Similar types of microlaminations are also observed in rock varnish from the Judean Desert in Israel, Gurbantünggut Desert in western China, and Patagonian Desert in Argentina. The slowly accumulating rock varnish offers a long-term (at least 0–250 k.y.) climate recorder in deserts where other climate proxies are either not available or difficult to read.

CONCLUSIONS

This study provides an answer to Alexander von Humboldt's 200-yr-old question on the rate of varnish growth, by presenting the first quantitative database from well-dated sites in semiarid to arid environments of the western United States. Rock varnish is the slowest accumulating terrestrial sedimentary deposit; it has growth rates of <1–40 nm/yr. The tremendous variability in growth rates, observed here for varnishes at spatial scales from micrometers to kilometers, invalidates varnish thickness as a reliable age indicator in geomorphology and archaeology.

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