Rock varnish as an indicator of aeolian environmental change

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Abstract

Micromorphological changes in rock varnishes indicate long-term fluctuations in the abundance of aeolian dust. Varnishes on K-Ar dated volcanics from the Coso Range, eastern California, record three lengthy dusty periods alternating with two lengthy periods of less-abundant dust over the last ca. 200,000 years BP. This sequence corresponds with the paleo-lake levels of nearby Searles Lake. The presence or absence of micromorphological changes may be used to map the distribution of dusty aeolian conditions in the late-Pleistocene.

Cation-ratio dating of rock varnishes formed on ventifacts provides a minimum age for the cessation of aeolian abrasion. Varnish on ventifacts started to form about 5300 years BP in the Cronise area of the Mojave Desert in eastern California. Varnish on gravel float on a fossil dune in the same area started to form ca. 5100 years BP. These chronometric ages suggest that a major period of aeolian activity abated by the mid-Holocene in the Cronise area of the central Mojave Desert.

Although problems in accurate interpretation of rock varnish still exist, these case studies illustrate the promise of rock varnish as an indicator of aeolian environmental change.

Introduction

There are few terrestrial records of change in aeolian conditions and fewer still that are amenable to dating. In this paper, two new methods of assessing the spatial and temporal variations in aeolian conditions are presented, both using rock varnish. Although still experimental, these methods have the potential to enhance our
understanding of aeolian environmental change during the Holocene and late-Pleistocene.

Rock varnish is a paper thin accretion of clay minerals, manganese and iron oxides and trace elements that form dark coatings on rocks (Potter & Rossman 1977). Ubiquitous in the terrestrial weathering environment, varnish occurs from hyper-arid to humid areas (Dorn & Oberlander 1982). While varnishes develop in soils, regolith, riverine, lacustrine, crenitic, cave and other near surface environments, this paper will focus on those varnishes exposed only to subaerial conditions. This is to assure that the constituents of varnish are derived exclusively from airborne fallout.

The nature of airborne fallout affects several characteristics of subaerial varnishes. The manganese:iron ratio in varnish layers may be used to record changes in the alkalinity of the aeolian environment (Dorn 1984). Variations in the stable carbon isotope composition of organic matter in varnish may indicate paleobotanical fluctuations (Dorn & DeNiro 1985).

This paper proposes that the micromorphology of rock varnish is controlled largely by the abundance of aeolian dust, and that superposition of dissimilar micromorphologies reflects fluctuations in the aeolian environment. In addition, cation-ratio dating of varnish (Dorn 1983, Dorn et al. 1986) on ventifacted surfaces provides the opportunity to determine a minimum age for the cessation of aeolian abrasion.

Environment and varnish micromorphology

Interest in the micron-scale structure of rock varnish started with scanning electron microscope (SEM) observations by Krumbein (1969), Potter and Rossman (1977), Perry (1979), Dorn and Oberlander (1982) and Whalley (1983) followed suit, but a systematic set of observations on the factors influencing varnish micromorphology has been lacking until now.

Method

Varnishes were sampled for this study from over 100 arid, semi-arid and humid sites and along over a dozen climatic-altitude transects in western North America. Unless stated otherwise, samples were collected from outcrops at least one meter above the surrounding soil, cleaned with compressed air and light agitation in deionized water to remove loose airborne fallout, and coated with gold-palladium, gold, or carbon for viewing by scanning electron microscopy (SEM) and by energy-dispersive analysis of X-rays (EDAX). Samples were not scrubbed clean, as some investigators have done, because harsh mechanical action alters some varnish structures. Before coating, selected samples were also prepared by critical point drying to examine micro-organisms.
Classification of varnish micromorphologies

While only a selected data set can be presented here, over 1000 hours of SEM observations indicate varnish micromorphologies fall into a continuum of forms that vary between botryoidal and lamellate (Fig. 1). Virtually all botryoidal sites have a vegetation cover of over 50%; lamellate and intermediate varnishes tend to occur where the vegetation cover ranges from <5% to ca. 35%.

Subaerial varnishes were also sampled from over a dozen altitude-climatic gradients in western North America. A representative result, from Kitt Peak in southern Arizona, is presented in Figures 2A-2C. The environmental transition between intermediate and botryoidal in these transects is a plant cover of about 40%. No statistically significant relationship was found at these transects between varnish micromorphology and surficial soil texture, lithology, plant height or plant species.

Many more micromorphological structures were observed than can be presented in this paper (Dorn 1985). However, approximately 75% of all subaerial varnishes fall into the botryoidal-lamellate continuum.

Aeolian control on varnish micromorphology

Vegetation cover provides the best correlation between a characteristic of the environment and varnish micromorphology. In presenting a working model of the development of varnish micromorphology, I will endeavor to show that lamellate varnish reflects the abundance of dust in a sparsely vegetated environment, and botryoidal varnish reflects the relative paucity of dust in a well-vegetated area.

Varnish accretion is a two-step process. Initially, micro-organisms oxidize ambient manganese and iron (Krumbein & Jens 1981, Dorn & Oberlander 1982, Taylor-George et al. 1983). Manganese and iron are then incorporated into mixed-layer illite-montmorillonite clay minerals that settle onto varnish surfaces (Potter & Rossman 1977, Fig. 2D). The limiting factors on varnish growth are the abundance of airborne clay minerals and the rate of microbial oxidation.

In the model proposed first by Dorn and Oberlander (1982) and supported here, when clay minerals are abundant in the aeolian environment, the deposition of clay platelets in a parallel orientation dominates the varnish structure and a lamellate varnish is produced. When aerosol clay minerals are less common, oxides accumulate around discrete microbial nuclei and a botryoidal micromorphology is favored.

A test of this model would be a study on the rates of airborne fallout at varnish sites. Airborne collectors were placed for this purpose, and available data indicate that lamellate varnishes occur where dust fallout is greatest. The literature supports these preliminary results; for example, Orgill and Sehmel (1976) and Cahill...
Figure 1 Micromorphology Continuum. Scale bars and scale lengths are in the lower right corner for all scanning electron micrographs in this paper. A Botryoidal micromorphology agglomerations of growths of different sizes, collected about 8 km east of Superior, in Devil’s Canyon, Arizona. B Semi-botryoidal micromorphology, from Superstition Mountains, Arizona. C Lamellate varnish created by the parallel deposition of clays and oxides, collected from South Mountain Park, Phoenix, Arizona.
Figure 2 Kitt Peak transect and incipient varnish. Micromorphologies of varnishes sampled along an altitude-climatic gradient from the base to just below the top of Kitt Peak, southern Arizona. A Semi-lamellate from 914m. B Between botryoidal and lamellate from 1219m. C Compound botryoidal from 1890m. D Incipient varnish on a young surface of Badwater alluvial fan, Death Valley California.
et al. (1981) indicate that suspended aerosols are more abundant in desert areas of sparse vegetation. Gillette and Walker (1977) and Post and Buseck (1984) found that the aerosol clays in desert areas are often composed of mixed-layer clays, similar to those in rock varnish. Marshall (1971) presented a likely mechanism for the relative lack of dust in well vegetated areas. Where the vegetation cover is dense, it shields the ground surface and increases the threshold velocity required to deflake particles, and Gillette et al. (1980) demonstrated that the characteristics of desert surfaces and desert meteorology make arid regions particularly sensitive to the suspension of dust. However, with the very slow rates of varnish formation in arid environments (e.g. Elvidge 1979, Whalley 1983, Dorn et al. 1986), contemporary measurements of human-affected airborne fallout may not reflect the aeolian environment that influenced the development of varnish structures.

There are more specific lines of evidence that support this model. First, SEM/EDAX observations indicate that botryoidal varnishes are deposited at discrete loci. Second, in laboratory replications of varnishes (e.g. Dorn & Oberlander 1982), a botryoidal form of development is favored where the media contains a lower concentration of bentonite and illite clay; importantly, the mineralogy of the manganese deposit in the laboratory varnish is birnessite (G. Rossman, personal communication 1983), the same manganese mineral found in the true desert varnish (Potter & Rossman 1977). Lastly, electron microprobe, particle induced X-ray emission (PIXE) and EDAX measurements of the surface layer of varnishes from over 50 sites in the western U.S. indicate that botryoidal varnishes often have significantly greater concentrations of Mn and Fe oxides than intermediate and lamellate varnishes, on the order of 1.2x to over 2x more. This is what would be expected if lamellate varnish represents the overwhelming of botryoids by the deposition of clay minerals.

Discussion

These observations suggest that the relative amount of aeolian fallout controls the micromorphology of varnish. There are, however, certain local conditions where the empirical correlation between the dustiness of the environment and the micromorphology of varnish is disrupted. These potentially confounding factors will be presented so that other researchers will be able to control for these effects in future sampling.

Aeolian abrasion can either completely remove a varnish or greatly disturb its appearance (Dorn & Oberlander 1982). Similarly, lichens, cyanobacteria (Krumbein & Jens 1981), and microcolonial fungi (Taylor-George et al. 1983) have all been observed in this study as active agents of biochemical erosion, probably through the secretion of organic acids (e.g. Fig. 3A). At other times, these
adventitious organisms simply occur on varnishes, but do not erode them (Fig. 3B). Microcolonial fungi may mimic the appearance of varnish, especially when they are covered with a thin coating of clays. However, no evidence gathered in this study indicates that these organisms play an active role in the concentration of manganese or iron in varnish.

Varnish bacteria can counter the influence of aeolian dust and generate a semi-botryoidal appearance even in arid regions. This occurs in hollows that are microns to millimeters in diameter. These sheltered depressions provide a suitable micro-environment for bacteria to colonize and concentrate Mn-Fe oxides fast enough to generate a micromorphology that trends toward botryoidal.

The structure of a thin, youthful varnish can often be influenced by an irregular shape of the underlying rock. The depositional tendency toward either lamellate or botryoidal is obscured until the varnish thickens to the point where the influence of the substrate is effectively erased.

The correlation between micromorphology and the aeolian environment is invalid where sampling micro-environments are not subaerial and are not well above the surrounding soil. For example, Figure 4A illustrates the boundary of crack varnish and subaerial varnish. The subaerial varnish is botryoidal in tendency, but the clay fallout that has been collecting in the rock crevice probably overwhelmed the subaerial tendency towards botryoidal and generated a lamellate varnish. Figures 4B and 4C contrast varnishes collected over one meter above the soil surface with a varnish collected just above the soil surface. Proximity to the soil surface tends to push the varnish towards the lamellate end of the continuum.

Lastly, there are pseudo-varnishes that may be mistaken for true varnishes and can have a roughly similar micromorphology. For example, Mn-rich hydrothermal deposits often resemble botryoidal varnishes superficially. Also, shiny and smooth accumulations of amorphous silica can occur intermixed with rock varnish (Butzer et al. 1979) or as separate coatings (e.g. Curtiss et al. 1985).

Where varnish is not influenced by these local effects, there appears to be a strong relationship between varnish micromorphology and environment. Part of the frustration in proving this conclusively is the slow rate of varnish growth. Elvidge (1979) and Whalley (1983) stress that varnish takes thousands of years to completely coat a rock. For example, chert artifacts in the Mojave Desert that have been cation-ratio dated by Dorn et al. (1986) to be older than 10 000 years BP still do not have a complete varnish coating. Similarly, cobbles on the 10 500 BP high stand of Searles Lake (Smith 1984) are not completely varnished. This suggests that observations of the contemporary environment over a few years may not necessarily relate to the longer-time required to develop the character of surficial varnish structures.
Figure 3 Effect of microcolonial fungi. A MCF creating hollows probably by the secretion of organic acids. Varnish collected near Jake's Corner in central Arizona. B Macrobotryoidal varnish (upper part of the image) is clearly distinct from the MCF (lower part of image). Varnish collected near dam of Roosevelt Lake, Arizona.
Figure 4 Microenvironmental effects. A Juxtaposition of subaerial varnish (semi-botryoidal) and varnish developed only in a rock crevice (lamellate), collected from a surface of Hanaupah Canyon alluvial fan, Death Valley. B Lamellate varnish collected just above the soil surface, from Ah-shish-la-pah badlands, near Chaco Canyon, New Mexico. C Microbotryoidal varnish collected a little over a meter above the adjacent soil, from the same site as Figure 4B in an area of Pinyon Pine and dense bunch grass.
Paleo-aeolian record in varnish

Micromorphological stratigraphies with age-control

This section presents microstratigraphies of alternating lamellate and botryoidal layers in varnish on dated surfaces. Accepting even on a tentative basis the validity of the correlation between aeolian environment and varnish micromorphology, fossil layers in varnishes are interpreted here as paleoenvironmental signals, where fossil lamellate layers indicate dusty conditions, and fossil botryoids indicate less aeolian fallout.

Figure 5 presents a collection of micromorphological stratigraphies of varnishes on various volcanic rocks in the Coso field and vicinity (Duffield & Bacon 1981). Each micrograph in Figure 5 is representative of multiple samples taken from adjacent rocks and adjacent outcrops in the same K-Ar dated volcanic deposit. However, the large age-uncertainties in these youthful K-Ar dates should be kept in mind.

McFadden et al. (1984) and Mayer and Anderson (1984) suggest a mechanism, operating with plant cover, that may explain dust fluctuations in the Coso Range. As the pluvial lakes in eastern California expanded and contracted, the amount of dust generated decreased and increased concomitantly. The Coso Range is surrounded by Owens, China, and Searles lake basins (e.g. Smith 1984). The lake-level history of Searles Lake over the last 250,000 years BP corresponds approximately with the observed micromorphological changes in varnish (Smith 1984). A dry to shallow lake occurred in the Searles basin from ca. 0 to 10,000 years BP, along with xeric vegetation in the northern Mojave Desert (Spaulding et al. 1983, Wells 1983). This may correspond with the top lamellate layer in Coso Range varnishes (e.g. Fig. 5A). The single subsurface botryoidal layer on varnishes younger than ca. 81,000 years BP may correlate with the deep and intermediate lake levels from 10,000 to 90,000 years BP (Figs 5B & C). The second lamellate layer in varnishes older than ca. 81,000 years BP may be from the shallow to intermediate lake phase from about 90,000 to 105,000 years BP (Figs 5D & E). The second botryoidal layer in Figure 5F may have formed during the phase of a deeper lake from about 105,000 to 130,000 years BP. Extensive lamellate deposits occur below the second botryoidal layer in Coso varnishes less than 600,000 years BP; this lamellate varnish may be from the shallow lake from ca. 130,000 to 570,000 years BP. Varnishes on volcanics older than ca. 600,000 to 1 million years BP may have many layers.

There is abundant support for a widespread micromorphological change in areas that have experienced major paleohydrological (Smith 1984, Begin 1984) and paleobotanical fluctuations (Spaulding et al. 1983, Wells 1983) in the late-Wisconsin. A problem in interpretation arises when varnishes older than the late-Wisconsin are examined. The major difficulty revolves around whether these
layers can be correlated with other records of Quaternary environmental change, or whether they represent only local fluctuations. Until the precision of dating varnishes can be improved for times beyond the period accessible to accelerator-radiocarbon dating (Dorn et al. 1986), interpretation of older varnish micromorphological stratigraphies will remain speculative.

_Mapping regions of abundant dust in the late-Wisconsin_
There are rock varnishes that are at least late-Wisconsin in age at
sites that are very arid at present and that lack botryoidal layers in the subsurface. The varnishes in Figures 6A and 6B were collected in the central Mojave Desert well below 1000 m. Spaulding (1983) notes that desert scrub vegetation did occur below 1000 m during the late-Wisconsin in the Mojave Desert. Assuming accuracy in dating, it is possible that these environments were dusty enough even in the late-Wisconsin to maintain a lamellate micromorphology.

It would be possible to use the presence or absence of botryoidal varnishes to provide a means of mapping the distribution of arid areas experiencing significant levels of dust deposition during the late-Wisconsin.

**Dating cessation of aeolian abrasion**

East Cronise basin in the central Mojave Desert of eastern California contains abundant ventifacts. Most of these, however, are fossil forms in that varnish can be found growing on the polished, pitted and grooved surfaces. This varnish was collected and analyzed for cation-ratio dating.

Varnish was sampled from a boulder approximately two meters in diameter on top of a small hill, just southeast of Basin Road exit off I-15, between Barstow and Baker. The varnish formed on the
grooves a few centimeters deep dates to 5500 ± 200 years BP. The varnish formed on grooves a few millimeters deep dates to 5300 ± 300 years BP, essentially identical to the age of the varnish in the deeper grooves. Similarly, ventifacted boulders sampled from the crest of the Cronise Mountains have varnish growing on etched surfaces that cation-ratio dates to 5500 ± 700 years BP.

On the east side of the Cronise Mountains in East Cronise basin, there is a dune known locally as "Cat Dune." The dune is largely fossilized, and the upper layer of sand is indurated. A gravel float has formed a lag on the bottom part of this fossilized sand dune. Cation-ratio dating of varnish on this gravel yields a chronometric age of 5100 ± 200 years BP.

Discussion

The interpretation of paleo-aolian fluctuations from rock varnish has been greatly simplified. In this section, I will briefly illustrate some of the potential complications involved.

The sample preparation and collection procedures are subjective. Multiple samples are, therefore, needed to ensure that enough exposures are present to verify the reproducibility of the results, from place to place on a single rock, from rock to rock on a single outcrop, and from outcrop to outcrop on the same surface.

Crack varnishes can develop micromorphologies different from the adjacent subaerial varnish (Fig. 4A). When crack varnishes are exposed by spalling, they may preserve the micromorphology from the environment of the crevice and generate a stratigraphy unrelated to changes in the aolian environment (Fig. 7A).

The thickness of a given varnish micromorphology layer cannot be related to the length of time under a given paleoenvironmental condition. The varnish is simply recording a sequence of paleo-aolian periods of sufficient intensity to cross a threshold between botryoidal and lamellate micromorphologies. Information on duration is not provided.

It may be possible that a positive feedback process prolongs a given micromorphology, even after an environmental change has occurred. For example, about three quarters of the varnish in a ca. 14 600 year old sample from the Cima volcanic field was found to be botryoidal; however, about two thirds of the time, the varnish has been exposed to a relatively drier Holocene environment (Spaulding et al. 1983, Ore & Warren 1971). Related issues are the variable lag effects between a climatic change and the vegetation and lacustrine changes in an area, and the ca. 100 year lag between the exposure of a surface and the onset of varnishing (Dorn et al. 1986).

A more serious interpretive problem is the preservation of varnish micromorphologies. While many botryoidal micromorphologies are preserved after burial, not all are. Some botryoidal forms undergo a diagenesis to lamellate structures (e.g.
Fig. 7B. Where subsurface botryoidal layers do occur, some may be laterally discontinuous, gradually passing into entirely lamellate cross-sections, and then passing back into the same sequence of micromorphologies. Extensive EDAX analyses indicate the fossil botryoidal layers that are preserved have a much higher concentration of manganese and iron. Unless a fossil botryoidal layer is indurated with high concentrations of Mn- and Fe-oxides, it can undergo diagenesis into lamellate structures.

![Figure 7 Complications in interpretation. A Botryoidal micromorphology on lamellate, collected from a recently spalled surface, Mid-Hills, Mojave Desert. The lamellate varnish found under the botryoidal layer probably formed while in a rock crevice (e.g. Figure 4A). With spalling and exposure to subaerial processes, a surface botryoidal varnish formed. Therefore, superposition of dissimilar micromorphologies can occur without a major environmental change. B Semi-botryoidal surface micromorphology that is lamellate in cross-section. Sample collected from below the "Blackwood" shoreline of Lake Muthy on Shoreline Butte in Death Valley (Hooke, 1972).](image)

Conclusion

Changes in the micromorphology of subaerial varnishes offer an intriguing potential for recording fluctuations in the level of aeolian dust fallout over the last ca. 200 000 years BP. Varnish micromorphology appears to be an accurate indicator of a change from a less-dusty environment during the late-Wisconsin to a dusty environment in the Holocene. Because varnish is ubiquitous and has good internal age-control, it would be possible to map the areas in the southwest that experienced fairly dry, dusty conditions.
even during the late-Wisconsin.

Cation-ratio dating of varnishes formed on fossil ventifacts in the central Mojave Desert indicate that major aeolian abrasion ended by about 5100 years BP. These chronometric dates provide the first ages on the cessation of ventifactation, and they correspond with the cation-ratio ages of varnishes formed on rock float on a fossilized dune in the region. Although only a few ages have been obtained, they provide an indication of the potential of varnish for assessing paleo-aeolian activity.

Acknowledgements

Funded partly by NSF graduate fellowship research stipend, National Geographic Grant 2961-84, and NSF grant SES80-24555 to T.M. Oberlander. Thanks to V. Tchakerian for assistance in the collection and analysis of varnish on ventifacts, D. Quimby for help in field collections, C.R. Berger and A.R. Orme for a critical eye on an earlier draft, and T.M. Oberlander for many conversations on varnish.

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