

# 13

## Anthropogenic Interactions with Rock Varnish

Ronald I. Dorn

### ABSTRACT

This chapter focuses on the ubiquitous biogeochemical coating known as rock varnish (or sometimes desert varnish in an arid climate) that forms naturally as a result of interaction between budding bacteria and clay minerals. This chapter interfaces with this book through exploring natural processes that generate this coating and the sensitivity of rock varnish to both natural climatic changes and anthropogenic forcings. High-resolution electron microscopy reveals that budding bacteria concentrate both manganese (Mn) and iron (Fe) on cell surfaces. Postdeposition processes mobilize nanoscale Mn and Fe that cements clay minerals to the underlying rock or preexisting varnish. Although other hypotheses exist to explain varnish formation, this model is the only proposed formation process that has a rate-limiting step and does not fall prey to the “varnish rate paradox.” Despite rates of varnish accretion of microns per millennia in warm deserts and microns per century in more mesic settings, anthropogenic processes have altered its biogeochemistry in a variety of ways. Globally, lead fallout has contaminated the surface-most micrometer. Regionally, acid fog and anthropogenic dust generation alters varnish textures. Locally, ash from wildfire combines with graffiti such as chalk to coat varnishes. Humans have also applied “artificial varnish” to minimize the aesthetic impact of road construction in wealthier communities.

### 13.1. INTRODUCTION

Prior to the mid-19th century, western thought focused on positive aspects, both religiously and culturally, of the impacts of human activity on Earth’s surfaces (Glacken, 1967). Thought began to change with the writings of geographer George Perkins Marsh and naturalist Count Buffon (comte de Buffon, 1749–1804; Marsh, 1864). These approaches to the study of the destructive effects of human activities initiated the modern sustainability movement (Lowenthal, 2000). In envisioning this book, Dontsova et al. (2020) present a level of detail and evidence for the pervasiveness of human impact unthinkable in the time of George Perkins Marsh—teasing out anthropogenic from natural drivers of biogeochemical change.

The chapters of this book analyze biogeochemical changes from three broad perspectives: (a) natural forcings such as mineral and rock decay; (b) climate change that potentially mixes anthropogenic and natural impacts on; and (c) anthropogenic forcings. This chapter interfaces with all three perspectives by reviewing natural forcings that lead to the accretion of the ubiquitous biogeographical rock coating known as rock varnish (and sometimes also termed desert varnish), and then how rock varnish responds to both natural climatic changes and anthropogenic processes.

The dark ferromanganese-rich and clay accretion of rock varnish is often termed desert varnish because it is most noticeable in warm arid regions. However, Krumbein and Jens (1981) and Dorn and Oberlander (1982) emphasized that rock varnish is a better term because of the presence of this same coating in all terrestrial environments. Recent examples of varnish studies in nondeserts include settings in SE Asia (Casanova-Municchia et al.,

---

*School of Geographical Sciences and Urban Planning,  
Arizona State University, Tempe, Arizona, USA*

---

*Biogeochemical Cycles: Ecological Drivers and Environmental Impact, Geophysical Monograph 251, First Edition.*  
Edited by Katerina Dontsova, Zsuzsanna Balogh-Brunstad and Gaël Le Roux.  
© 2020 American Geophysical Union. Published 2020 by John Wiley & Sons, Inc.

2016), southern Belgium (Goossens et al., 2015), caves in Spain (Lozano & Rossi, 2012), a German Gothic cathedral (Macholdt et al., 2017), and different settings in China (Xu et al., 2018).

Rock varnish greatly alters the appearance of rock surfaces at all different scales, even though it is typically less than 100  $\mu\text{m}$  thick (Figure 13.1). Its constituents do not derive from the underlying rock (Dorn, 1998; Krumbein & Jens, 1981; Potter & Rossman, 1977), but instead derive from external sources such as dust deposited on rock surfaces. Rock varnish typically grows at rates of microns per thousand years in arid environments (Liu & Broecker, 2000), although faster growth rates do occur in more mesic settings (Dorn & Meek, 1995; Krinsley et al., 2017). These very slow rates of accretion deposit millennial-scale microlaminations that are recognized as a paleoclimatic indicator and dating technique (Liu, 2017; Liu & Broecker, 2013; Liu et al., 2013). With such slow rates of accretion, however, rock varnish is not generally recognized as an indicator of anthropogenic activity.

This chapter presents evidence that rock varnish that forms in both warm desert and wetter settings should receive more recognition as a biogeochemical indicator of anthropogenic interactions. This chapter starts with a summary of current knowledge on the processes by which rock varnish accretes on rock surfaces. The next section then explores how, prehistorically, humans used varnished surfaces as natural blackboards on which to engrave rock art—sometimes leaving behind iron-rich paint and quartz mechanically driven into engraved surfaces. Historically, humanity's imprint on rock varnish processes rest at global scales where the accretion of lead and other heavy metals contaminate the surface—most layer of rock varnish, even in such distant locations as Greenland. Regional impacts include anthropogenic acid fog dissolving varnish and increases in atmospheric dust loading inundating varnishes with particle fragments. More local impacts include ash from wildfires accreting onto nearby rock surfaces and the creation of “artificial varnish” to try to disguise the impact of development in deserts.

### 13.2. LANDSCAPE GEOCHEMISTRY OF ROCK VARNISH

Clay minerals dominate the composition of rock varnish (Dorn & Oberlander, 1982; Krinsley et al., 1995; Potter & Rossman, 1977), comprising up to two-thirds of a typical rock varnish found in warm deserts. Although over 40 other minor and trace elements also occur in rock varnish (Bard et al., 1978; Dorn, 1998; Dorn et al., 1990; Engel & Sharp, 1958; Fleisher et al., 1999; Macholdt et al., 2015; Nowinski et al., 2010), the key to varnish formation rests in the oxyhydroxides of manganese and

iron (Hooke et al., 1969; McKeown & Post, 2001; Potter & Rossman, 1979) that typically range from 15 to 40% by weight and are the agents that cementing clay minerals together and to the underlying rock surface (Dorn & Oberlander, 1982; Krinsley, 1998; Krinsley et al., 2013; Potter, 1979). Table 13.1 presents variations in the elemental chemistry of bulk samples of scraped rock varnish from different global settings.

Landscape geochemistry (Fortescue, 1980; Perel'man, 1966) is an environmental geochemistry paradigm focused on explaining spatial geochemical patterns found in low-temperature weathering environments. From a landscape geochemistry perspective, the different constituents of rock varnish accrete because specific physical, biological, and geochemical barriers exist on rock surfaces (Perel'man, 1986).

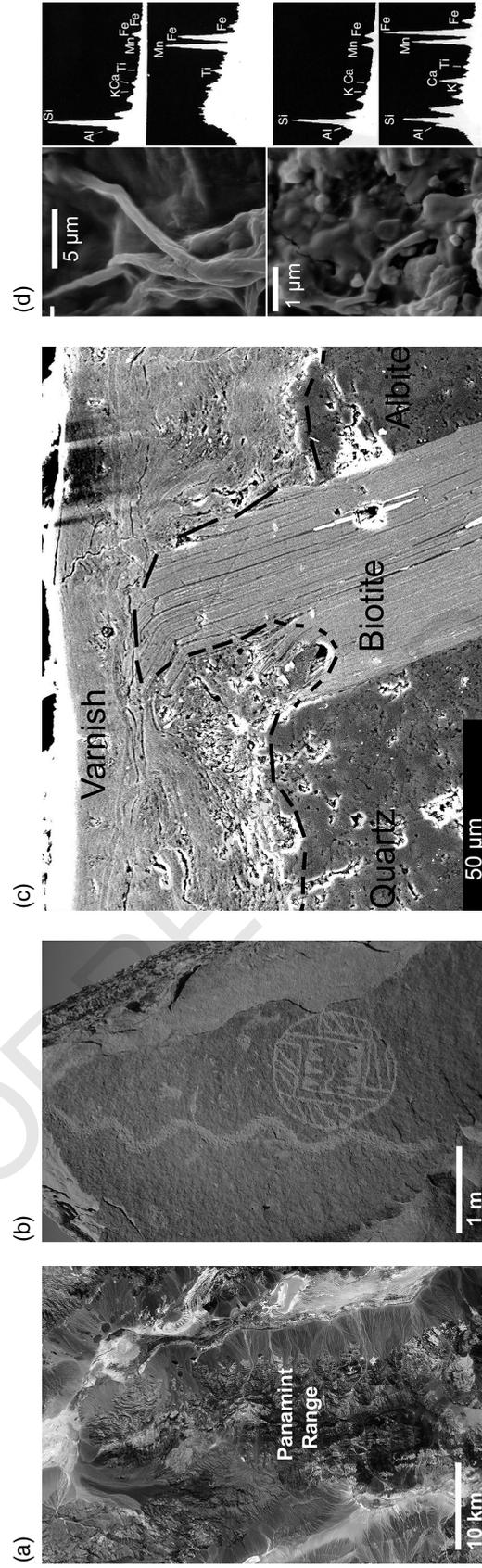
The clay minerals and other small bits of eolian particles initially attach to varnish (Aulinas et al., 2015; Dorn et al., 2013) through van der Waals forces (Figure 13.2); these particles are loosely cemented by nanoscale deposits of silica (Langworthy et al., 2010), carbonate, Mn, and Fe (Dorn et al., 2013; Krinsley et al., 2009). Clay minerals are then fixed to the underlying rock (Dorn, 1998; Dorn, Krinsley, et al., 2012) and to other rock varnish (Krinsley et al., 2013) by Mn–Fe oxyhydroxides.

Budding bacteria are the key agents that concentrate both Mn and Fe (Dorn & Oberlander, 1982; Krinsley et al., 2017). Budding bacteria, for example the genera *Pedomicrobium* (Dorn & Oberlander, 1982), encrust Mn and Fe oxides around their cells and hyphae (Figures 13.2 and 13.3). The budding process enables these bacteria to be buried underneath the accumulation of varnish and still reproduce by hyphae extension. After cells are encrusted with Mn and Fe, ongoing diagenesis breaks apart these cell encrustations into nanoscale granules (Dorn, 1998; Krinsley, 1998) that are then remobilized and reprecipitated as nanoscale Mn–Fe (Krinsley et al., 2017) amongst the mixed-layer clays (Figure 13.2) in a process first explained by Potter (1979, 174–175):

Deposition of the manganese and iron oxides within the clay matrix might then cement the clay layer...the hexagonal arrangement of the oxygen in either the tetrahedral or octahedral layers of the clay minerals could form a suitable template for crystallization of the layered structures of birnessite.

However, varnish is not stable at the nanoscale; McKeown and Post (2001, 712) explained that ongoing disequilibria exists even after the varnish formed:

[e]ven if analysis methods are improved, the situation will remain complicated by the flexibility and great variety of Mn oxide structures. The common elements of these structures enable them to easily intergrow with and transform with one another.



**Figure 13.1** Rock varnish viewed at different scales. (a) Alluvial fans debouching from the Panamint Range into Death Valley on the east and the Panamint Valley on the west are visibly darkened with varying amounts of rock varnish. (b) Petroglyph carved into a joint face partly coated with rock varnish from Petrified Forest National Park. (c) Secondary electron image of rock varnish coating rocks of the Orinoco River, the first site for the scholarly study of rock varnish. (d) Bacteria sheaths concentrating Mn–Fe rich material in rock varnish from Tibet, as indicated by energy dispersive spectra of bacteria hyphae as compared with spectra of the adjacent varnish. [(a) [www.earthobservatory.nasa.gov/images/6470/death-valley-national-park](http://www.earthobservatory.nasa.gov/images/6470/death-valley-national-park) (Public Domain); (b) von Humboldt (1812) (Public Domain); (c) Krinsley et al. (2009). Reproduced with permission of Mary Ann Liebert.]

**Table 13.1** Examples of elemental variation exhibited in bulk chemical analyses of rock varnishes found in desert regions. Samples were analyzed by particle induced X-ray excitation

| Element | Site and sample details                       |   |   |  |  |                                       |   |
|---------|---|---|---|--|--|---------------------------------------|---|
|         | Trail Fan, Death Valley/ Former rock fracture | Manix Lake, Mojave Desert/ > 1 m above soil | Makanaka Till, Hawaii/ With silica skin | Sinai Peninsula, Egypt/ > 1 m above soil | Petroglyph South Australia/ > 1 m above soil | Ingenio, Peru Desert/ At soil surface | Ayers Rock, Australia/ From rock fracture |
| Na      | BLD   | 1.1   | 0.62                                    | 0.28                                     | 0.17   | NA                                    | NA  |
| Mg      | 0.14  | 3.44  | 1.98                                    | 1.5                                      | 1.21   | 2.11                                  | 1.58                                      |
| Al      | 23.74   | 25.77                                       | 21.13                                   | 22.94                                    | 22.81  | 20.45                                 | 28.77                                     |
| Si      | 39.09   | 32.35                                       | 29.77                                   | 32.81                                    | 33.34  | 45.88                                 | 35.69                                     |
| P       | 0.49  | 1.15  | 0.69                                    | BLD                                      | 0.53   | 0.53                                  | BLD                                       |
| S       | 0.7   | 0.3   | 0.2                                     | BLD                                      | BLD  | 1.13                                  | BLD                                       |
| K       | 3.45  | 2.11  | 3.3                                     | 2.42                                     | 2.79   | 2.91                                  | 2.11                                      |
| Ca      | 4.87  | 1.35  | 4.89                                    | 2.91                                     | 2.18   | 6.22                                  | 1.45                                      |
| Ti      | 1.52  | 0.84  | 0.73                                    | 0.68                                     | 0.65   | 0.85                                  | 1.19                                      |
| Mn      | 10.87   | 12.47                                       | 13.6                                    | 11.97                                    | 21.7   | 4.94                                  | 11.91                                     |
| Fe      | 13.47   | 18.09                                       | 21.13                                   | 22.94                                    | 13.26  | 12.03                                 | 16.57                                     |
| Ni      | 0.13  | BLD   | BLD                                     | BLD                                      | BLD  | BLD                                   | BLD                                       |
| Cu      | 0.12  | 0.22  | 0.33                                    | 0.25                                     | 0.44   | 0.04                                  | BLD                                       |
| Zn      | 0.27  | 0.3   | 0.49                                    | 0.42                                     | 0.44   | 0.16                                  | BLD                                       |
| Rb      | BLD   | 0.25  | BLD                                     | BLD                                      | BLD  | BLD                                   | BLD                                       |
| Sr      | BLD   | 0.21  | BLD                                     | 0.42                                     | BLD  | 0.11                                  | BLD                                       |
| Zr      | 0.29  | 0.22  | BLD                                     | BLD                                      | BLD  | BLD                                   | BLD                                       |
| Ba      | 0.85  | 0.19  | 0.16                                    | 0.18                                     | 0.14   | 2.42                                  | 0.73                                      |
| Pb      | BLD   | 0.74  | 0.98                                    | 0.27                                     | 0.34   | 0.22                                  | BLD                                       |

Note: From Dorn et al. (1990).

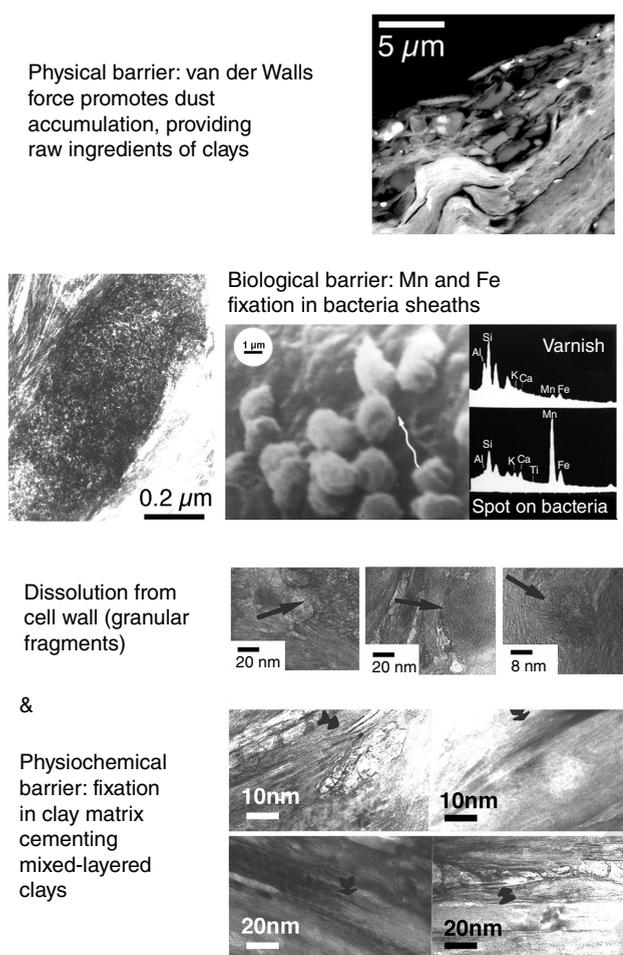
BLD, below limit of detection; NA, not analyzed.

Thus, while budding bacteria originally concentrate the Mn–Fe, it is the geochemical dissolution at the nanoscale and subsequent reprecipitation of oxyhydroxides in clays that results in varnish formation. It is important to stress, however, that shifts at the nanoscale do not create instability in the laminations seen at the micron scale that are stable for tens of millennia (Liu, 2017; Liu & Broecker, 2013; Liu et al., 2013)—much like cars moving around inside a parking lot do not change the lot itself.

Budding bacteria comprise only a small component of the microbial community that has been found associated with rock varnish through culturing techniques (Dorn & Oberlander, 1982; Krumbein & Jens, 1981; Northup et al., 2010; Palmer et al., 1985; Perry et al., 2004; Taylor-George et al., 1983) and phylogenetic insight (Benzerara et al., 2006; Eppard et al., 1996; Esposito et al., 2015; Irit et al., 2019; Kuhlman et al., 2005, 2008; Kuhlman, Fusco, et al., 2006; Kuhlman, McKay, et al., 2006). In general, these studies find a broad diversity of eukaryotic and bacterial taxa, most of which do not actively participate in manganese or iron concentration through oxidation. However, the authors of these studies admit that sampling thus far has been analyzing varnish materials from just a few sampling sites. In addition, other sorts of organic analyses reveal that the nature of the organic

matter in analyzed varnish samples is consistent with a bacterial origin (Malherbe et al., 2017) and that the microbial community of varnish is similar to adjacent soils in that prokaryotic and fungal communities exist, with gram-positive bacteria found more often (Schelble et al., 2005). In brief, varnish is home to a diverse microbial community, most of which is not directly involved in Mn–Fe concentration or varnish formation.

The budding bacteria (Figure 13.3) hypothesis (Dorn & Oberlander, 1982; Krinsley et al., 2017) to explain the great enrichment of Mn and also Fe in rock varnish has a number of competing explanations that can be grouped into several broad categories. Some favor enrichment through purely abiotic processes that involve alternating reducing and oxidizing environments (Engel & Sharp, 1958; Goldsmith et al., 2014; Soleilhavoup, 2011), or a role of fluids moving upwards from the underlying soil (Lebedeva et al., 2019). Another group of hypotheses favors organisms different than budding bacteria that can concentrate Mn and Fe (Krumbein & Jens, 1981; Northup et al., 2010; Palmer et al., 1985; Taylor-George et al., 1983). Recent research points to a role for photooxidation perhaps related to electroactive bacterial communities that produce the Mn-mineral birnessite (Lu et al., 2019; Ren et al., 2019; Xu et al., 2019).



**Figure 13.2** Rock varnish accretion requires a series of different types of barriers to transport of the various constituents. [Dorn (1998). Reproduced with permission of Elsevier.]

Still others potentially draw connections to growing phylogenetic insight about the organisms growing on and in varnish (Benzerara et al., 2006; Eppard et al., 1996; Esposito et al., 2015; Kuhlman et al., 2005, 2008; Kuhlman, Fusco, et al., 2006; Kuhlman, McKay, et al., 2006). The problem with these competing explanations is that they all lack a rate-limiting step and fall prey to the “varnish rate paradox.”

The varnish rate paradox, presented previously (Dorn, 2007; Dorn & Krinsley, 2011; Krinsley et al., 2017), is that there are so many different ways proposed to explain Mn (and Fe) enrichment in varnish—yet warm desert locations studied by the various researchers display rates of varnishing of microns per millennia (Dorn, 1998; Liu & Broecker, 2000). Nondesert sites display much faster rates of varnishing and often contain in situ evidence of budding bacteria (e.g. Dorn & Meek, 2005; Krinsley et al., 2017). Although the process of bacterial adsorption and oxidation can be quite fast (Namgung et al.,

2018; Vázquez-Ortega & Fein, 2017), budding bacteria are only rarely observed in situ in warm desert varnishes. Still, Dorn & Krinsley (2011) emphasized that only budding bacteria have been observed in situ concentrating Mn and Fe, while other organisms have never been seen actively enhancing Mn or Fe in varnish samples.

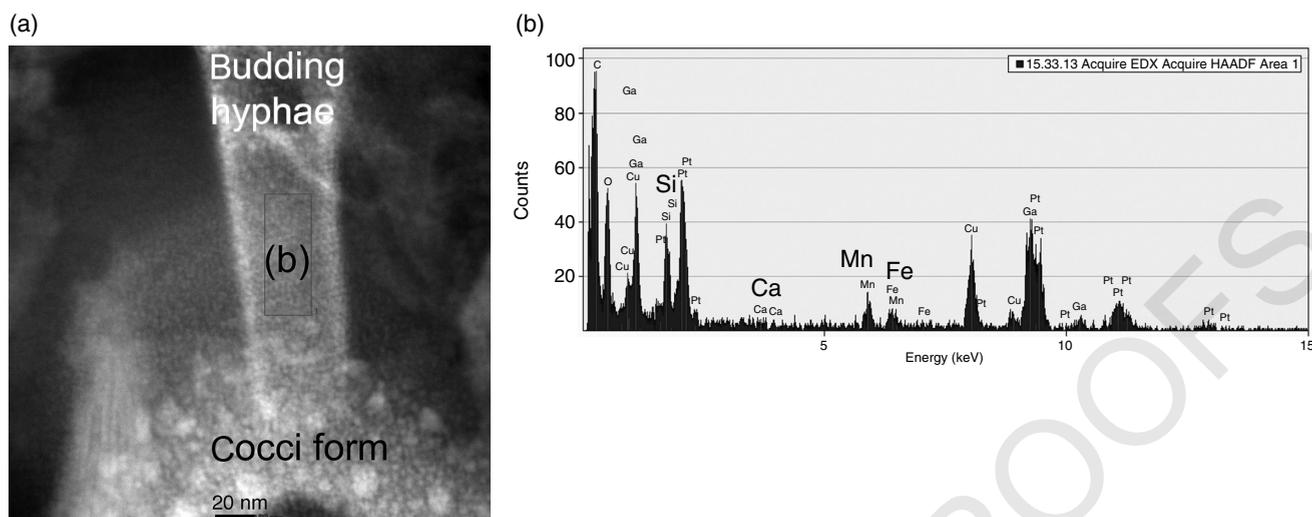
In contrast to the occasional growth of budding bacteria, abiotic processes would generate varnishes 100–10,000 times faster than observed (Dorn & Krinsley, 2011; Krinsley et al., 2017). The reason for faster formation through abiotic enrichment is that there is no rate-limiting step. Theoretically, Mn and Fe concentration relies on leaching of the divalent cations from dust sources during acidic wetting events, followed by increases in pH to oxidize the Mn and Fe. Given that dust deposition and wetting events occur tens of thousands of times over a millennia, if small pH–Eh shifts actually generated varnish as proposed (Engel & Sharp, 1958; Goldsmith et al., 2014; Soleilhavoup, 2011), varnishes should be meters thick and not microns thick as found naturally.

Similarly, if all the various organisms growing in and on varnish (Benzerara et al., 2006; Brewer & Fierer, 2018; Dragovich, 1993; Eppard et al., 1996; Esposito, 2015; Gleeson et al., 2018; Kuhlman, Fusco, et al., 2006; Kuhlman, McKay, et al., 2006; Kuhlman et al., 2008; Kutovaya et al., 2015; Lang-Yona et al., 2018; Lozano & Rossi, 2012; Malherbe et al., 2017; Northup et al., 2010; Palmer et al., 1985; Paulino-Lima et al., 2016) contributed to varnish formation, rates of accretion would be orders of magnitude higher than observed for the warm desert sites studied (Dorn, 2007; Krinsley et al., 2017). The only hypothesis that explains Mn and Fe concentration, as well as the slow rate of varnish growth in warm deserts, and also some faster growth rates in nondesert environments (e.g. Dorn & Meek, 1995; Spilde et al., 2013), involves the rare event of the growth of budding bacteria (Figure 13.3) and associated concentration of Mn and Fe (Krinsley et al., 2017).

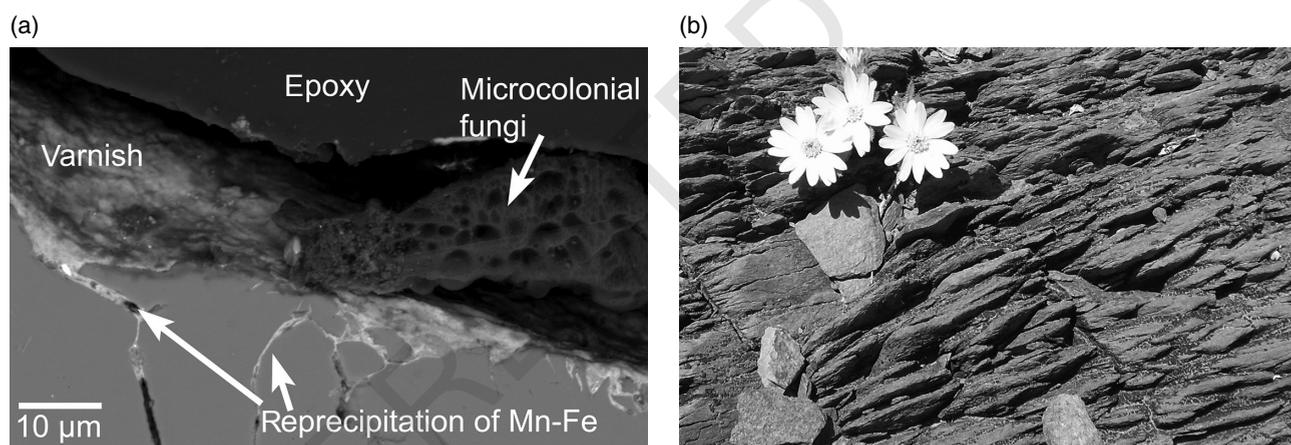
The landscape geochemistry of rock varnish is not only one of accretionary processes that fix constituents on rock surfaces. Rock varnish is also dissolved naturally by acid-secreting organisms such as lichens (Dragovich, 1987) and microcolonial fungi (Dragovich, 1993). The organic acids dissolve the Mn–Fe, thus destroying the cement that binds the varnish together (Figure 13.4). In summary, the landscape geochemistry of rock varnish is a complex dance among processes that fix constituents to rock surfaces and those that release coating components.

### 13.3. PREHISTORIC ANTHROPOGENIC INTERACTIONS

Rock engravings (or petroglyphs) represent the rare circumstance where this biogeochemical deposit has actually received widespread attention for its anthropogenic



**Figure 13.3** High-resolution perspective on fixation of Mn and Fe. (a) Electron microscope image of budding bacteria concentrating Mn and Fe where a budding hyphae emerges from a cocci bacterial form. (b) Location in image (a) matching the energy dispersive spectra showing the concentration of Mn and Fe with Si and small amounts of Ca. The other peaks are artifacts associated with sample preparation. [Krinsley et al. (2017).]



**Figure 13.4** Biofilms grow on rock surfaces where sufficient moisture exists (Viles, 2011). Such biofilms in the Sonoran Desert of central Arizona typically consist of fungi and lichens. (a) Microcolonial fungi secrete organic acids that then dissolve the Mn and Fe in varnish. In the case of this cross-section view using backscattered electrons some of the Mn and Fe have been reprecipitated in rock fractures. (b) Field site near Black Canyon City, where flower widths of 2 cm provide scale. [Dragovich (1993). Reproduced with permission of Taylor & Francis.]

interactions. The act of engraving art into a rock face coated by dark Mn–Fe-rich varnish is commonly discussed in scholarship (Black et al., 2017; Whitley, 2001), in teaching materials about archaeology (Whitley & Loendorf, 1994), and in popular culture describing various rock art sites (<https://www.nps.gov/pefo/learn/historyculture/newspaper-rock.htm>) where ancient peoples have carved motifs (Figure 13.5).

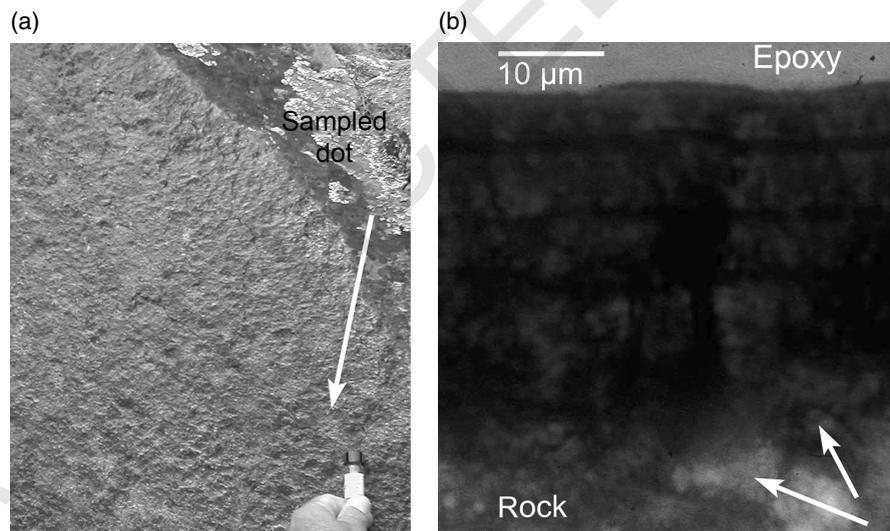
The prehistoric artists did not only engrave motifs into rock varnish, but also applied painting materials. Figure 13.6 presents an example from Buffalo Eddy, Washington, where ocher—identified as a strong iron

energy dispersive X-ray signal—was applied to a pattern of dots. The varnish microlamination pattern that formed on top of the paint material has a pattern consistent with varnish layering unit Wet Holocene Unit 4 that has a calibrated calendar age of about 2800 year BP (Liu & Broecker, 2007).

Luminescence occurs when quartz minerals are mechanically fractured. Quartz also exhibits luminescence when it is rubbed. Dr. David Whitley and colleagues have compiled evidence that quartz was used in the making of many petroglyphs. In particular, basalt flows that generally lack free quartz provide an



**Figure 13.5** Newspaper Rock at Petrified Forest National Park exemplifies how rock varnish provides a ‘black-board’ for prehistoric rock engravings that range in age from terminal Pleistocene to the 20th century (Dorn, 2006).

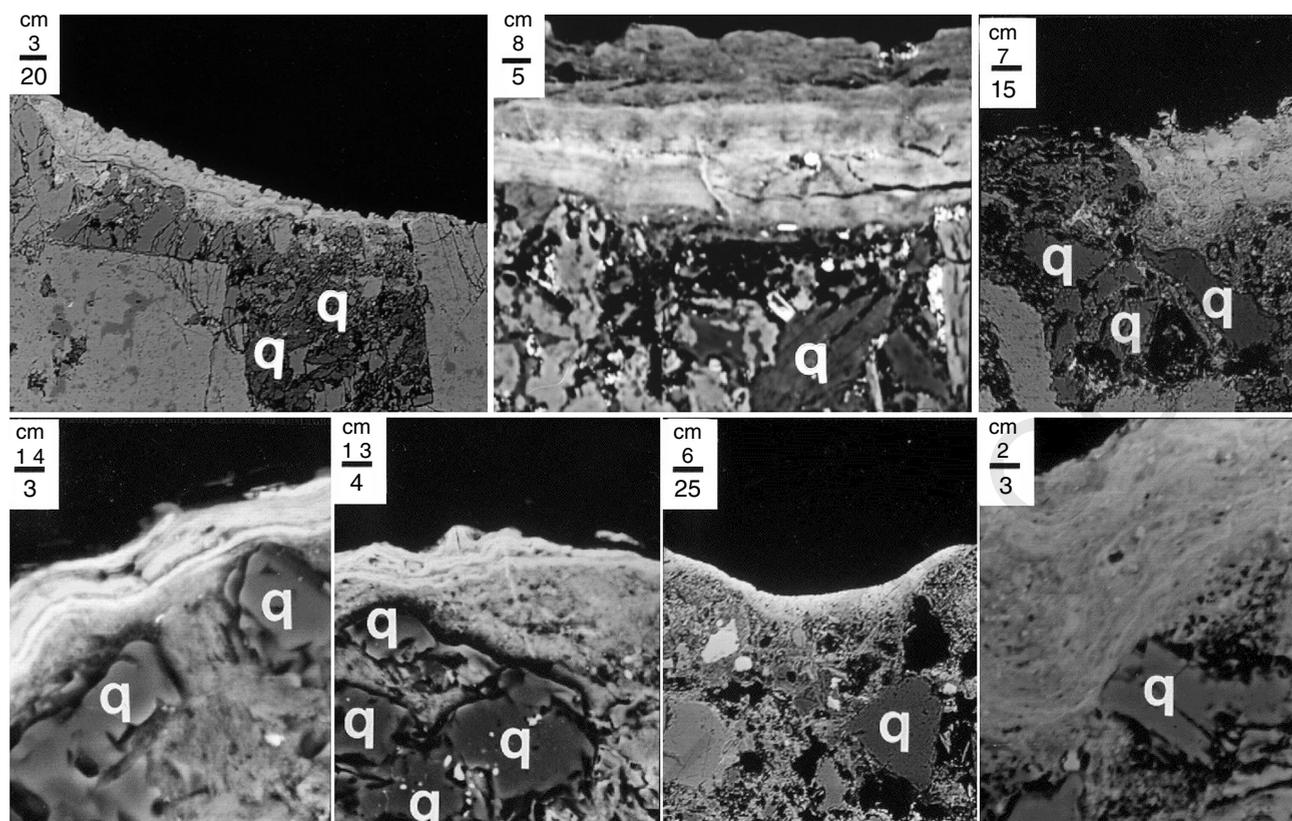


**Figure 13.6** An engraving consisting of a pattern of dots (image a), at Buffalo Eddy, Washington, USA, was subjected to painting (Merrell & Dorn, 2009). Iron-rich material, perhaps goethite, was painted into the dots. (b) Then, rock varnish formed on top of the paint material, as seen in a light microscope ultrathin cross-section of varnish. Arrows in (b) identify the iron-rich materials as confirmed by energy dispersive X-ray analyses.

appropriate way to study whether quartz was used in engraving rock art. The basalt flows of the Coso Range and basalt flows in the Mojave Desert, both in eastern California, reveal shards of quartz embedded into engravings (Whitley, 2000, 2001; Whitley et al., 1999). The flows hosting the Conejo Mine petroglyphs (e.g. Figure 13.7) do not contain free quartz. The archaeological

interpretation is that the shamans making the art likely knew of the luminescence and perhaps engraved the art at night (Whitley et al., 1999).

Prehistoric humans undertook considerable effort to modify stones on Earth’s surface. Such modifications are sometimes called earthen art (Frink & Dorn, 2001; von Werlhof, 1989). Earthen art such as the Nasca geoglyphs of



**Figure 13.7** The Conejo Mine petroglyph site in the Coso Range, eastern California, consists of a basalt flow that lacks free quartz. Backscattered electron micrographs of cross-sections of rock varnish formed on top of engravings regularly reveal the presence of quartz—identified by the letter q. The numbers CM3, CM8, CM7, CM14, CM13, CM 6 and CM2 refer to specific engravings sampled. [Whitley et al. (1999).]

Peru and SW North America are some of the most well-studied (Clarkson, 1994; Dorn et al., 2001). However, earthen art can be found all over the deserts of the world in the form of rock cairns (Figure 13.8a). The rocks that were assembled to make a cairn in the Panamint Valley of eastern California had an original arrangement of rock coatings (Figure 13.8b), most typically dark rock varnish on top of a boulder, a thin shiny black ground-line band, iron film underneath the boulder, and perhaps laminar calcrete if the boulder was originally embedded into the Bk (carbonate) soil horizon. When the boulder was moved to build a cairn, sometimes, the orientation of the rock coatings changed (Figure 13.8c). This change provides the opportunity to utilize dating techniques, for example, radiocarbon dating carbonate formed over rock varnish. This carbonate only started to form after the rock was flipped and embedded into the ground (Cervený et al., 2006).

In summary, prehistoric humans interacted with and altered rock coatings such as rock varnish in a variety of different ways. Although the most common example involves carving motifs into heavily varnished rock surfaces, a careful inspection of both rock art and earthen

art reveals that people painted art, mechanically abraded art with quartz that exhibits luminescence, and moved boulders and rocks to create earthen art.

### 13.4. HISTORIC BIOGEOCHEMICAL INTERACTIONS WITH ROCK VARNISH

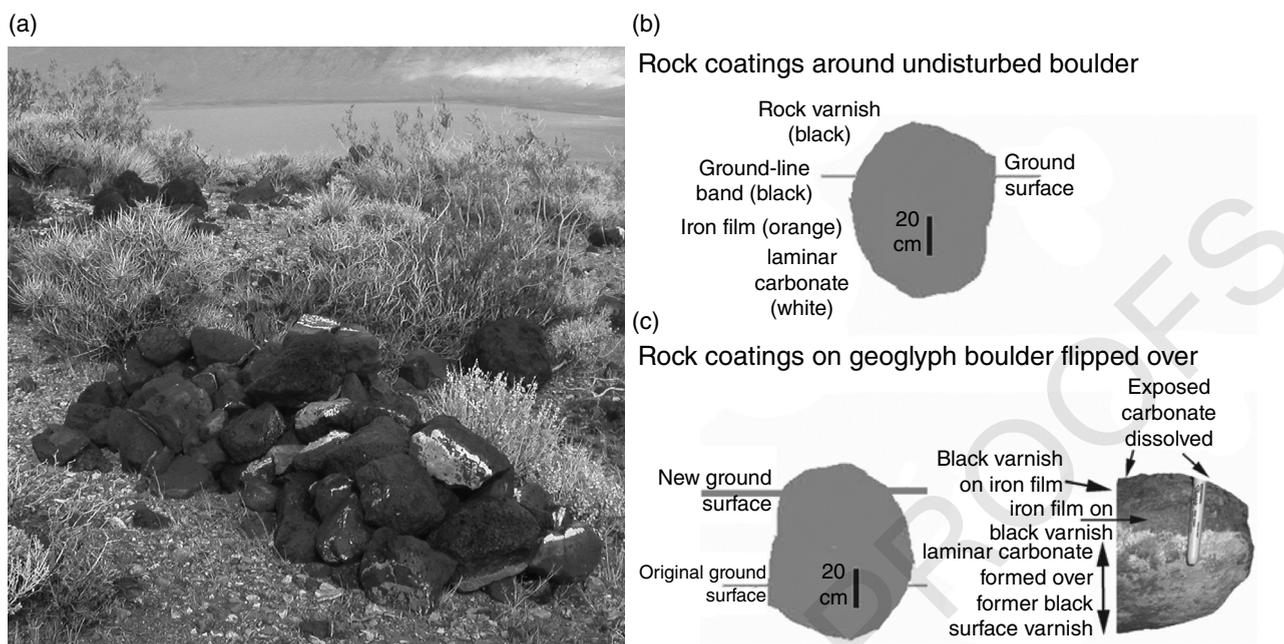
#### 13.4.1. Artificial Varnish

*Imitation is the sincerest form of flattery that mediocrity can pay to greatness.*

Oscar Wilde

Urban development in deserts leaves behind visual scars when bedrock is disturbed to create features such as road cuts. The aesthetic problem rests in the contrast between naturally dark varnish and the much brighter hues of freshly exposed rock. Figure 13.9a illustrates colluvium coated with rock varnish and where freshly broken rock surfaces stand out prominently.

Wealthy subdivisions in the Phoenix metropolitan area have experimented with the application of “artificial



**Figure 13.8** Rock cairn from the Panamint Valley, eastern California. The boulders used to build this cairn came from a desert pavement with considerable antiquity. Some of the boulders were flipped on their side and embedded deeply in the ground. These boulders formed laminar carbonate on top of rock varnish. Thus, the original sequence of rock coatings in (b) was altered to (c). The laminar carbonate only started to form after the cairn was constructed, thus a radiocarbon age for the laminar carbonate provides a minimum age for the cairn. [(a) Seong et al. (2016). Reproduced with permission of Elsevier. (b,c) Cervený et al. (2006). Reproduced with permission of John Wiley & Sons.]

varnish”—a process whereby sodium hydroxide is first sprayed onto places like exposed road cuts, followed by the application of a mixture of divalent Mn and Fe in solution. Upon contact with the alkaline sodium hydroxide, the Mn and Fe oxidizes and the rock surfaces are thus coated with an artificial varnish (Elvidge & Moore, 1980). Figure 13.9c displays a road cut covered with artificial varnish, where only the uppermost bit of soil is light in color. A key difference between true rock varnish (e.g., Figure 13.9b) and artificial varnish (e.g. Fig. 13.9d) is the lack of clays. The result is that the artificial varnish applied over two decades ago is undergoing disaggregation into granules that detach and degrade the artificial varnish (Figure 13.9d).

#### 13.4.2. Lead Contamination of Varnish

The first study of lead in relation to rock varnish occurred with respect to the earthen figure (or geoglyph) called the Bouse Fisherman, a human holding a spear with a quartz tip. The spear is aimed at a wavy line with fish symbols below the wavy line. A field trip lead by the Arizona Geological Survey visited this motif (Spencer & Pearthree, 2015).

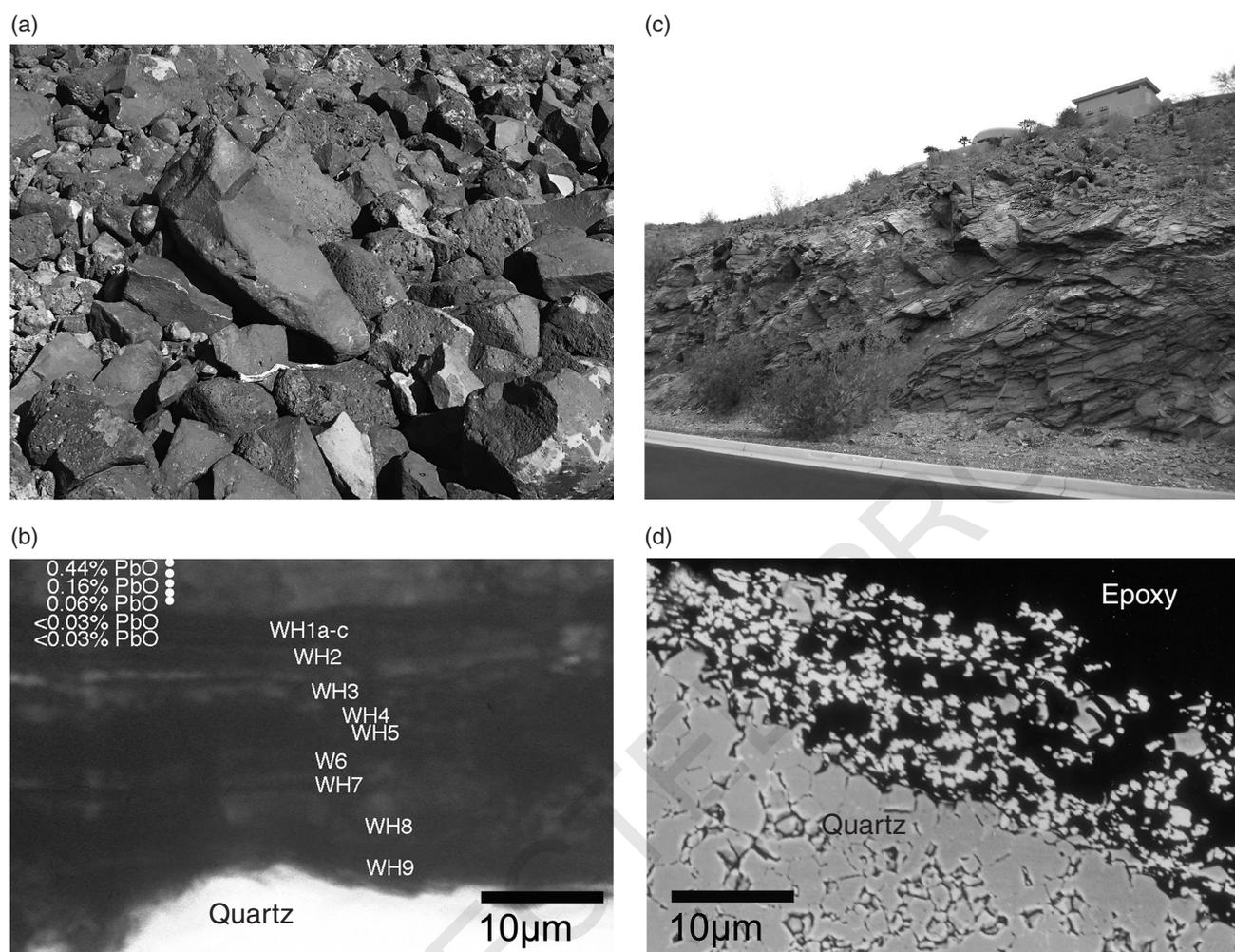
Working with the Bureau of Land Management, lead concentrations were measured in the micron-thick

varnish that had accreted on the stones that were exposed to make the Bouse Fisherman. This varnish was greatly enriched in lead, analyzed with a 300 s counting time with a wavelength dispersive electron microprobe yielding limits of detection at about 0.03% PbO (Dorn, 1998). In contrast, the natural varnish had a very different situation explained as follows:

Lead accumulates in rock varnishes and dust films on desert surfaces. Electron microprobe profiles reveal that lead is a contaminant in the uppermost surfaces of rock varnishes, but these concentrations drop to background levels below the very surface of natural rock coatings that have formed since lead additives were introduced into gasoline in 1922. (Dorn, 1998, 139)

Figure 13.9b exemplifies what is normally encountered when rock varnishes are analyzed. In this figure, lead measurements are superimposed on a color thin-section showing varnish microlaminations; note that the lead contamination occurs only after the Wet Holocene Unit 1, which is a microlamination pattern that formed during the Little Ice Age.

Thus, Dorn (1998) found that the Bouse Fisherman is not prehistoric. It was made in the 20th century, perhaps for fun or perhaps to become a tourist attraction, consistent

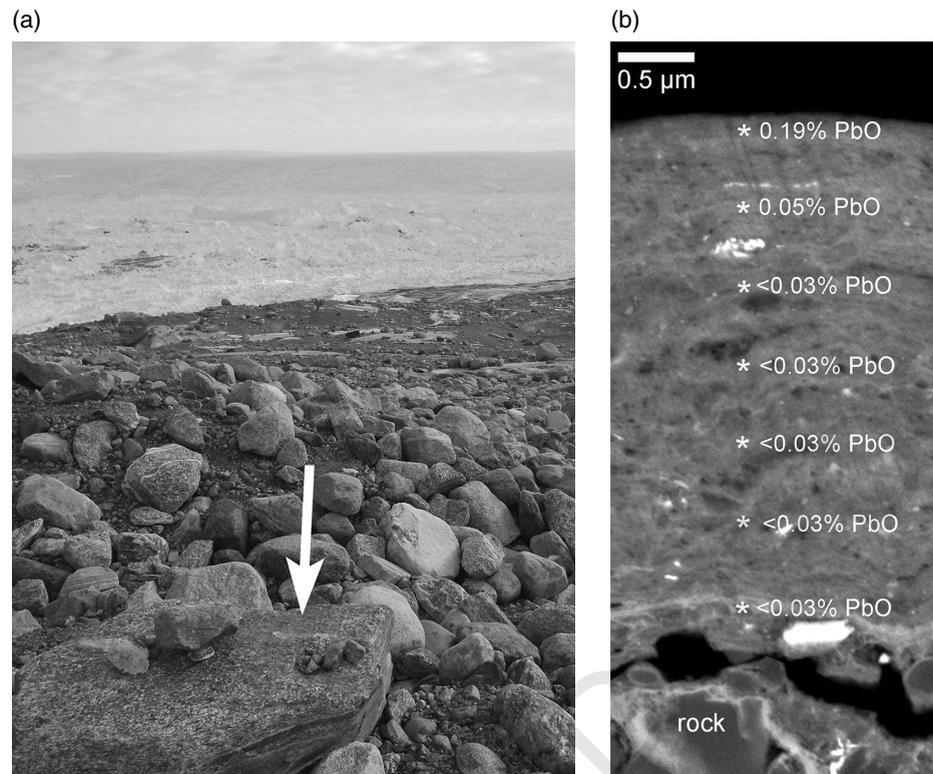


**Figure 13.9** Rock varnish as the dominant natural rock coating in metropolitan Phoenix. (a) Colluvial boulder field at Shaw Butte darkened by rock varnish. The occasional orange iron film indicates rocks spalled by the dirt cracking physical weathering process. (b) Microlaminations form discrete black, orange, and yellow layers in rock varnish thin sections. Electron microprobe analyses reveal a spike in lead in the uppermost micron of this rock varnish from the Phoenix area. Background levels occur once the layer of the varnish is beneath the 20th century. The layer Wet Holocene Unit 1 (WH1) ceased forming about 1850, and its lead concentrations are below the limit of detection at  $< 0.03\%$  PbO. (c) Urbanization tends to create scars across rock faces, but developers in an affluent Phoenix neighborhood applied “artificial varnish” to minimize the aesthetic impact of this road cut. (d) Back-scattered electron microscope image of artificial varnish from image (c) that is experiencing ongoing dissolution, generating a granule-like appearance. [(c) Elvidge & Moore (1980). Reproduced with permission of Taylor & Francis.]

with the use of 20th century symbols for water and fish. Since then, lead profiles have been used to authenticate prehistoric petroglyphs (Dorn, 2006; Merrell & Dorn, 2009) as well as to indicate that a regionally famous Marcos de Niza engraving is not real, but 20th century in origin (Dorn, Gordon, et al., 2012).

The basic observation that lead and other anthropogenic pollutants are enriched in the surface-most layer of varnish now has extensive replication (Fleisher et al., 1999; Goldsmith et al., 2014; Hoar et al., 2011; Hodge et al., 2005; Nowinski, 2009; Nowinski et al., 2013; Sims et al., 2017; Spilde et al., 2013). The iron or manganese in

varnish scavenges lead from the surrounding environment (Adams et al., 2009; Dong et al., 2002; Grangeon et al., 2017; Hassellöv & von der Kammer, 2006; van Genuchten & Peña, 2016). Twentieth-century industrial activities spread lead and other elemental pollutant around the globe, even in areas distant from major lead-pollution sources (Andersen, 1994; Getty et al., 1999). Figure 13.10a is an epiglacial deposit of boulders near the margin of the Greenland Ice Cap. Figure 13.10b superimposes electron microprobe measurements of lead on a back-scattered electron microscope image of rock varnish on the identified boulder in Figure 13.10a. Even



**Figure 13.10** Epiglacial till of the Greenland glacier contaminated by lead. (a) Greenland outlet glacier study site on a medial moraine, identifying the boulder where rock varnish accreted and has been contaminated by lead. (b) Back-scattered electron images of a cross-section of rock varnishes where the surface-most layer is contaminated with lead. Each electron microprobe measurement point is about  $0.5\ \mu\text{m}$  apart, and this means that there exists spatial overlap in the focused beam analyses. Less than 0.03% lead is background, below the limit of detection. [(b) Dorn (1998). Reproduced with permission of Elsevier.]

in such remote locations as Greenland, rock varnish can record an anthropogenic lead signal.

#### 13.4.3. Effects of Acidification on Varnish

Industrial activity near rock art in the Burrup Peninsula of Western Australia has increased the acidity of atmospheric fallout, exposing rock surfaces to pH values just above 4. Prior to industrialization, the pH value of rock surfaces was near neutral (Black et al., 2017). The substantial decrease in pH leads to reduction of Fe(III) and Mn(IV) to mobile divalent forms. This changes the color of rock and petroglyph surfaces and hence endangers the priceless rock engravings.

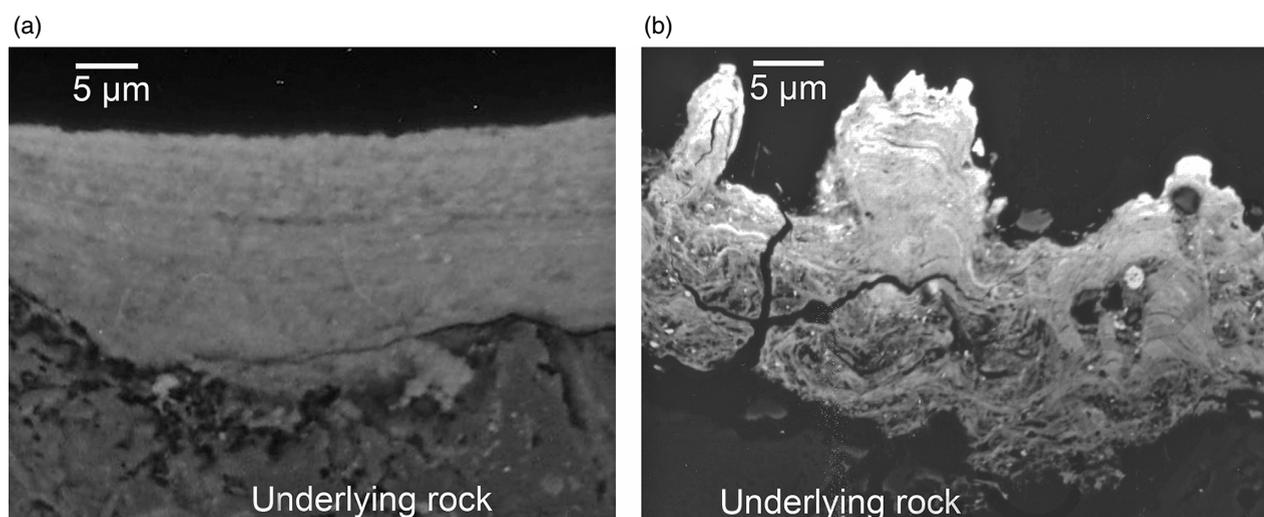
Acidity from urban activities in the Los Angeles area led to the development of acid fog in the region (Brewer et al., 1983; Waldman et al., 1982). Figure 13.11 compares a sample of varnish-coated sandstone in the Santa Monica Mountains in 1941 in what is now Tuna Canyon Park less than 1 km from the Pacific Ocean (Fig. 13.11a) and sample collected from the same site in 1983 (Figure 13.11b). The 1941 sample shows the typical

laminar appearance of rock varnish. In 1983, however, no laminar varnish was found. Instead, the texture of varnish shows evidence of considerable leaching (Dorn & Krinsley, 1991) in the form of increased porous zones and redistribution of Mn–Fe in the form of stringers deposited along the walls of fractures. One explanation for the substantial change in texture in just four decades could be acid fog increasing the mobility of Mn–Fe.

#### 13.4.4. Dust Loading onto Varnish

Rock varnish naturally shows considerable variation in its texture as a result of the abundance of eolian dust. Some varnishes show a finely layered texture without the incorporation of angular pieces of dust (e.g. Figure 13.11a), but rock varnishes collected from particularly dusty locations do show considerable evidence of angular particles of dust being incorporated into varnish (Aulinas et al., 2015; Dorn et al., 2013).

Anthropogenic activities are known to increase the abundance of dust in many settings (Baddock et al., 2013; Brazel, 1989; Goudie, 2014), with Owens (Dry) Lake as



**Figure 13.11** Comparison of rock varnish collected near the Pacific Ocean in Los Angeles that was impacted by acid fog. (a) A representative back-scattered electron image of the laminar texture observed from a sample collected by Joseph Spencer in 1941. (b) The author collected samples from the same site in 1982 and did not find any laminar textures. Instead, the irregular surface, evidence of reprecipitation of Mn–Fe on fracture walls, and zones of leaching could reflect the impact of acid fog.

an example. Diversion of water to Los Angeles led to Owens (Dry) Lake becoming the largest single source of particulate matter under  $10\ \mu\text{m}$  in the United States (Gillette, 2013). Severe drought in California exacerbates the dust problem in the region (Borlina & Rennó, 2017).

An example of the impact of anthropogenic dust loading in the region can be found even in the high alpine setting of the nearby Palisades Glacier of the Sierra Nevada, California. Boulders immediately adjacent to the margin of the Palisades Glacier accumulated dust material whose source could be from Owens (Dry) Lake. A reason why anthropogenic dust from Owens (Dry) Lake is the suspected cause is the presence of chlorine (sum spectrum in Figure 13.12b). Chlorine would not be expected if the source of dust was local, but ongoing additions of chlorine, and then removal by leaching from snowmelt, would be consistent if at least some of the dust had a source related to Owens (Dry) Lake.

The dust is cemented by silica glaze rather than manganese-rich rock varnish (Figure 13.12). Silica glaze is a coating composed primarily of amorphous silica, but sometimes mixed with aluminum and iron (Dorn, 1998). Its formation is abiotic and results from nanoscale deposition of silica spheroids (Langworthy et al., 2010). Silica glaze often interdigitates with other rock coatings such as varnish (Dorn, 1998).

#### 13.4.5. Wildfire Interactions with Varnish

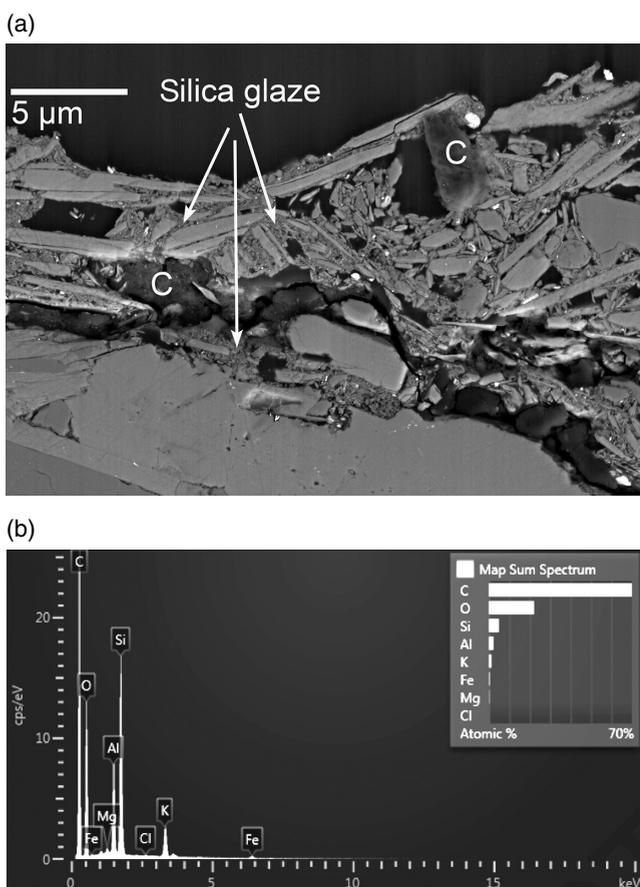
Wildfires, both natural and human caused, result in millimeter and centimeter-scale spalling of rock surfaces, thus removing rock varnish (Dorn, 2003). However,

human activities have accelerated the incidence of wildfires in dryland settings such as the western United States (Abatzoglou & Williams, 2016). A minimally explored arena of research involves the interactions of rock coatings and wildfire ash (Tratebas et al., 2004). Figure 13.13 illustrates how chalking of petroglyphs has combined with ash from wildfire to make a paste that adheres to and coats the underlying natural rock varnish. This one pilot study indicates interactions between human-induced wildfires and rock varnish, however, and there are undoubtedly far more interactions than those observed by Tratebas et al. (2004).

### 13.5. SUMMARY

This chapter concerns the natural, slow growing rock coating known as rock varnish. Rock varnish (sometimes called desert varnish in warm arid settings) is typically  $< 50\ \mu\text{m}$  thick, but it can completely darken rock surfaces changing even the lightest colored rock black. The key to understanding its formation rests in the process by which iron and especially manganese is greatly concentrated in this rock coating—well over 50 times concentrations in the underlying rock, dust, or nearby soil.

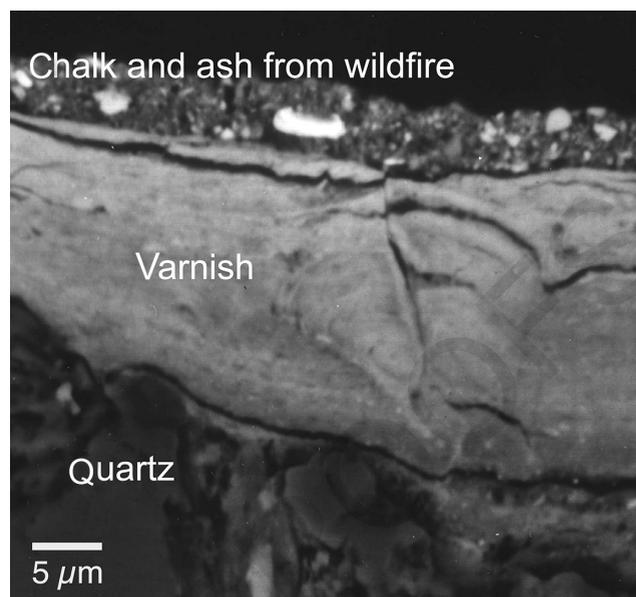
There are a number of competing explanations for how the manganese (and iron) concentration occurs. Abiotic explanations involving small pH–Eh fluctuations and a plethora of different organisms such as bacteria and fungi can explain Mn concentration found in varnish. However, all extant explanations except one do not involve a rate-limiting step. If any of the proposed abiotic explanations actually made varnish, it would form in



**Figure 13.12** Silica glaze is the cement for dust fall on a glacial boulder next to the Palisades Glacier, Sierra Nevada, California. (a) Back-scattered electron image of dust inorganic mineral and organic (C, carbon) particles. (b) Several energy-dispersive X-ray spectroscopy (EDS) analyses of this and similar cross sections were combined and the spectrum represents the sum of all of the EDS data gathered for the coating. The Cl in the sum spectrum is a signal consistent with the source of the dust being from Owens Dry Lake, even though snowmelt would gradually leach Cl over time in this environmental setting. The strong C signal reflects the carbon coating and organic materials; the other elements derive from the dust particles and inorganic minerals that compose much of the dust.

deserts at rates orders of magnitude faster than the observed microns per millennia rates. If all of the various biotic concentration mechanisms were in play, formation rates would be even faster. The only process that explains the Mn (and Fe) concentration and also slow rate of formation involves the occasional growth of budding bacteria. Also, budding bacteria are the only proposed agent of varnish formation with direct observational support of in situ concentration of Mn (and Fe).

The focus of this chapter rests in exploring interactions between natural rock varnish and human modification of the environment. Prehistorically, humans used rock surfaces darkened by varnish as ‘blackboards’ on which to



**Figure 13.13** Back-scattered electron image of petroglyph that was chalked by amateur archaeologists in hopes of improving a photograph of the motif at Whoop-up Canyon, Wyoming. Then, a wildfire influenced the area, and the chalk mixed with soot from a wildfire. The combination of chalk and ash adhered to the underlying rock varnish for a period of at least 1.5 years when the sample was collected. [Tretabas et al. (2004). Reproduced with permission of Taylor & Francis.]

engrave motifs called petroglyphs. Humans also altered stones and boulders to create earthen art, and in the process modified rock varnish in such a way as to change its relative position, and as a consequence allow its dating by radiometric and varnish microlamination methods.

The biogeochemistry and structure of rock varnish have been modified by human activities in a number of different ways. At the global scale, atmospheric lead pollution (as well as other heavy metals) has contaminated the surface-most micrometer of varnish, even in such remote areas as Greenland. At the regional scale, modification of the earth to create dry lakebeds has created massive dust loadings that have altered the structure of rock-coating formation in general in the surrounding region. Also at the regional scale, acidification of the environment in the Los Angeles area of California and the Burrup Peninsula in Australia has dissolved Mn and Fe from the varnish and altered its structure; a ripe area for future biogeochemical research involves the alteration of rock varnish in other settings acidified by anthropogenic activities. More locally, ash from wildfire has combined with anthropogenic graffiti such as chalk on rock surfaces to alter rock coatings. A final example of human activities involves the attempt by wealthier suburban housing developments to mimic natural rock varnish by coating road scars with artificial varnish, still

composed of Mn and Fe, but lacking clay minerals and hence lacking long-term stability.

### ACKNOWLEDGMENTS

I thank two anonymous reviewers and the handling co-editor for their suggestions that improved the chapter. Carolynne Merrell and Jason Lyon provided National Park Service permission and opportunity to analyze priceless samples from Buffalo Eddy. Barbara Murphy supplied the Greenland Ice Cap sample. Joseph Spencer collected the sample from the Santa Monica Mountains in 1941.

### REFERENCES

- Abatzoglou, J.T., & Williams, A.P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, *113*, 11770–11775.
- Adams, J.P., Kirst, R., Kearns, L.E., & Krekeler, M.P.S. (2009). Mn-oxides and sequestration of heavy metals in a suburban catchment basin of the Chesapeake Bay watershed. *Environmental Geology*, *58*, 1269–1280.
- Andersen, S.T. (1994). History of the terrestrial environment in the Quaternary of Denmark. *Bulletin of the Geological Society of Denmark*, *41*, 219–228.
- Aulinas, M., Garcia-Valles, M., Fernandez-Turiel, J.L., Gimeno, D., Saavedra, J., & Gisbert, G. (2015). Insights into the formation of rock varnish in prevailing dusty regions. *Earth Surface Processes and Landforms*, *40*, 447–458.
- Baddock, M.C., Strong, C.L., Murray, P.S., & McTainsh, G.H. (2013). Aeolian dust as a transport hazard. *Atmospheric Environment*, *71*, 7–14.
- Bard, J.C., Asaro, F., & Heizer, R.F. (1978). Perspectives on the dating of prehistoric Great Basin petroglyphs by neutron activation analysis. *Archaeometry*, *20*, 85–88.
- Benzerara, K., Chapon, V., Moreira, D., Lopez-Garcia, P., Guyot, F., & Heulin, T. (2006). Microbial diversity on the Tatakouine meteorite. *Meteoritics and Planetary Science*, *41*, 1259–1265.
- Black, J.L., MacLeod, I.D., & Smith, B.W. (2017). Theoretical effects of industrial emissions on colour change at rock art sites on Burrup Peninsula, Western Australia. *Journal of Archaeological Science Reports*, *12*, 457–462.
- Borlina, C.S., & Rennó, N.O. (2017). The impact of a severe drought on dust lifting in California's Owens Lake area. *Nature: Scientific Reports*, *7*, 10.1038/s41598-41017-01829-41597.
- Brazel, A.J. (1989). Dust and climate in the American southwest. In M. Leinen, M. Sarnthein (Eds.), *Paleoclimatology and paleometeorology: Modern and past patterns of global atmospheric transport*. Dordrecht, Netherlands: Kluwer Academic Publishers.
- Brewer, R.L., Gordon, R.J., Shepard, L.S., & Ellis, E.C. (1983). Chemistry of mist and fog from the Los Angeles urban area. *Atmospheric Environment*, *17*, 2267–2270.
- Brewer, T.E., & Fierer, N. (2018). Tales from the tomb: the microbial ecology of exposed rock surfaces. *Environmental Microbiology*, *20*, 958–970.
- Casanova-Municchia, A., Bartoli, F., Bernardini, S., Caneva, G., Della Ventura, G., Ricci, M.A., BounSuy, T., & Sodo, A. (2016). Characterization of an unusual black patina on the Neang Khmau temple (archaeological Khmer area, Cambodia): a multidisciplinary approach. *Journal of Raman Spectroscopy*, *47*, 1467–1472.
- Cervený, N.V., Kaldenberg, R., Reed, J., Whitley, D.S., Simon, J., & Dorn, R.I. (2006). A new strategy for analyzing the chronometry of constructed rock features in deserts. *Geoarchaeology*, *21*, 181–203.
- Clarkson, P.B. (1994). The cultural insistence of geoglyphs: the Andean and Southwestern phenomena. In Ezzo, J.A. (Ed.), *Research along the Colorado River* (pp. 149–177). Proceedings from a Symposium Presented at the 59th Annual Meeting of the Society for American Archaeology, Anaheim, California, April. Tucson, AZ: Statistical Research.
- comte de Buffon, G.L.L. (1749–1804). *Histoire Naturelle, générale et particulière, avec la description du Cabinet du Roi*. Paris: Imprimerie Yonale.
- Dong, D., Hua, X., & Zhonghua, L. (2002). Lead adsorption to metal oxides and organic material of freshwater surface coatings determined using a novel selective extraction method. *Environmental Pollution*, *119*, 317–321.
- Dontsova, K., Balogh-Brunstad, Z., & Le Roux, G. (Eds.) (2020). *Biogeochemical cycles: Anthropogenic and ecological drivers*. American Geophysical Union.
- Dorn, R.I. (1998). *Rock coatings*. Amsterdam: Elsevier.
- Dorn, R.I. (2003). Boulder weathering and erosion associated with a wildfire, Sierra Ancha Mountains, Arizona. *Geomorphology*, *55*, 155–171.
- Dorn, R.I. (2006). Petroglyphs in Petrified Forest National Park: Role of rock coatings as agents of sustainability and as indicators of antiquity. *Bulletin of Museum of Northern Arizona*, *63*, 53–64.
- Dorn, R.I. (2007). Rock varnish. In D.J. Nash, S.J. McLaren (Eds.), *Geochemical sediments and landscapes* (pp. 246–297). Oxford, UK: Blackwell Science.
- Dorn, R.I., Cahill, T.A., Eldred, R.A., Gill, T.E., Kusko, B., Bach, A., & Elliott-Fisk, D.L. (1990). Dating rock varnishes by the cation ratio method with PIXE, ICP, and the electron microprobe. *International Journal of PIXE*, *1*, 157–195.
- Dorn, R.I., Gordon, M., Pagán, E.O., Bostwick, T.W., King, M., & Ostapuk, P. (2012). Assessing early Spanish explorer routes through authentication of rock inscriptions. *Professional Geographer*, *64*, 415–429.
- Dorn, R.I., & Krinsley, D.H. (1991). Cation-leaching sites in rock varnish. *Geology*, *19*, 1077–1080.
- Dorn, R.I., & Krinsley, D.H. (2011). Spatial, temporal and geographic considerations of the problem of rock varnish diagenesis. *Geomorphology*, *130*, 91–99.
- Dorn, R.I., Krinsley, D.H., & Ditto, J. (2012). Alexander von Humboldt's initiation of rock coating research. *Journal of Geology*, *120*, 1–12.
- Dorn, R.I., Krinsley, D.H., Langworthy, K.A., Ditto, J., & Thompson, T.J. (2013). The influence of mineral detritus on rock varnish formation. *Aeolian Research*, *10*, 61–76.

- Dorn, R.I., & Meek, N. (1995). Rapid formation of rock varnish and other rock coatings on slag deposits near Fontana. *Earth Surface Processes and Landforms*, 20, 547–560.
- Dorn, R.I., & Oberlander, T.M. (1982). Rock varnish. *Progress in Physical Geography*, 6, 317–367.
- Dorn, R.I., Stasack, E., Stasack, D., & Clarkson, P. (2001). Through the looking glass: Analyzing petroglyphs and geoglyphs with different perspectives. *American Indian Rock Art*, 27, 77–96.
- Dragovich, D. (1987). Weathering of desert varnish by lichens. In: A. Conacher (Ed.), *Readings in Australian Geography* (pp. 407–412). Proceedings of the 21st IAG Conference, Perth.
- Dragovich, D. (1993). Distribution and chemical composition of microcolonial fungi and rock coatings from arid Australia. *Physical Geography*, 14, 323–341.
- Elvidge, C.D., & Moore, C.B. (1980). Restoration of petroglyphs with artificial desert varnish. *Studies in Conservation*, 25, 108–117.
- Engel, C.G., & Sharp, R.S. (1958). Chemical data on desert varnish. *Geological Society of America Bulletin*, 69, 487–518.
- Eppard, M., Krumbein, W.E., Koch, C., Rhiel, E., Staley, J.T., & Stackebrandt, E. (1996). Morphological, physiological, and molecular characterization of actinomycetes isolated from dry soil, rocks, and monument surfaces. *Archives of Microbiology*, 166, 12–22.
- Esposito, A., Ahmed, E., Cizzazzo, S., Skorski, J., Overmann, J., Holmstrom, S.J.M., & Brusetti, L. (2015). Comparison of rock varnish bacterial communities with surrounding non-varnished rock surfaces: Taxon-specific analysis and morphological description. *Microbial Ecology*, 70, 741–750.
- Fleisher, M., Liu, T., Broecker, W., & Moore, W. (1999). A clue regarding the origin of rock varnish. *Geophysical Research Letters*, 26(1), 103–106.
- Fortescue, J.A.C. (1980). *Environmental geochemistry. A holistic approach*. New York: Springer-Verlag.
- Frink, D.S., & Dorn, R.I. (2001). Beyond taphonomy: Pedogenic transformations of the archaeological record in monumental earthworks. *Arizona–Nevada Academy of Sciences Journal*, 34, 24–44.
- Getty, S.R., Gutzler, D.S., Asmerom, Y., Shearer, C.K., & Free, S.J. (1999). Chemical signals of epiphytic lichens in southwestern North America; natural versus man-made sources for airborne particulates. *Atmospheric Environment*, 33, 5095–5104.
- Gillette, D., Ono, D. and Richmond, K. (2004). A combined modeling and measurement technique for estimating wind-blown dust emissions at Owens (dry) Lake, California. *Journal of Geophysical Research: Earth Surface*, 109(F1). doi:10.1029/2003JF000025
- Glacken, C.J. (1967). *Traces on the Rhodian shore. Nature and culture in western thought from ancient times to the end of the Eighteenth Century*. Berkeley, CA: University of California Press.
- Gleeson, D.B., Leopold, M., Smith, B., Black, J.L. (2018). Rock-art microbiome: influences on long term preservation of historic and culturally important engravings. *Microbiology Australia*, 39, 33–36.
- Goldsmith, Y., Stein, M., & Enzel, Y. (2014). From dust to varnish: Geochemical constraints on rock varnish formation in the Negev Desert, Israel. *Geochimica Cosmochimica Acta*, 126, 97–111.
- Goossens, D., Mees, F., Ranst, E.V., Tack, P., Vincze, L., & Poesen, J. (2015). Rock fragments with dark coatings in slope deposits of the Famenne region, southern Belgium. *Belgeo: Revue belge de géographie*, 4, 1–14.
- Goudie, A.S. (2014). Desert dust and human health disorders. *Environment International*, 63, 101–113.
- Grangeon, S., Fernandez-Martinez, A., Claret, F., Marty, N., Tournassat, C., Warmont, F., & Gloter, A. (2017). In-situ determination of the kinetics and mechanisms of nickel adsorption by nanocrystalline vernadite. *Chemical Geology*, 459, 24–31.
- Hassellöv, M., & von der Kammer, F. (2006). Iron oxides as geochemical nanovectors for metal transport in soil–river systems. *Elements*, 4, 401–406.
- Hoar, K., Nowinski, P., Hodge, V.F., & Cizdziel, J.V. (2011). Rock varnish: A passive forensic tool for monitoring recent air pollution and source identification. *Nuclear Technology*, 175, 351–359.
- Hodge, V.F., Farmer, D.E., Diaz, T.A., Orndorff, R.L. (2005). Prompt detection of alpha particles from Po-210: another clue to the origin of rock varnish? *Journal of Environmental Radioactivity*, 78, 331–342.
- Hooke, R.L., Yang, H., & Weiblen, P.W. (1969). Desert varnish: an electron probe study. *Journal of Geology*, 77, 275–288.
- Irit, N., Hana, B., Yifat, B., Esti, K.W., & Ariel, K. (2019). Insights into bacterial communities associated with petroglyph sites from the Negev Desert, Israel. *Journal of Arid Environments*, 166, 79–82.
- Krinsley, D. (1998). Models of rock varnish formation constrained by high resolution transmission electron microscopy. *Sedimentology*, 45, 711–725.
- Krinsley, D., Ditto, J., Langworthy, K., Dorn, R.I., & Thompson, T. (2013). Varnish microlaminations: new insights from focused ion beam preparation. *Physical Geography*, 34, 159–173.
- Krinsley, D., Dorn, R.I., & DiGregorio, B.E. (2009). Astrobiological implications of rock varnish in Tibet. *Astrobiology*, 9, 551–562.
- Krinsley, D.H., Dorn, R.I., DiGregorio, B.E., Razink, J., & Fisher, R. (2017). Mn–Fe enhancing budding bacteria in century-old rock varnish, Erie Canal, New York. *Journal of Geology*, 125, 317–336.
- Krinsley, D.H., Dorn, R.I., & Tovey, N.K. (1995). Nanometer-scale layering in rock varnish: implications for genesis and paleoenvironmental interpretation. *Journal of Geology*, 103, 106–113.
- Krumbein, W.E., & Jens, K. (1981). Biogenic rock varnishes of the Negev Desert (Israel): An ecological study of iron and manganese transformation by cyanobacteria and fungi. *Oecologia*, 50, 25–38.
- Kuhlman, K.R., Allenbach, L.B., Ball, C.L., Fusco, W.G., La Duc, M.T., Kuhlman, G.M., et al. (2005). Enumeration, isolation, and characterization of ultraviolet (UV-C) resistant bacteria from rock varnish in the Whipple Mountains, California. *Icarus*, 174, 585–595.
- Kuhlman, K.R., Fusco, W.G., La Duc, M.T., Allenbach, L.B., Ball, C.L., & Kuhlman, G.M., et al. (2006). Diversity of microorganisms within rock varnish in the Whipple

- Mountains, California. *Applied and Environmental Microbiology*, 72, 1708–1715.
- Kuhlman, K.R., McKay, C.P., Venkat, P., La Duc, M.T., Kulman, G.M., & Principe, E. (2006). Microbial fauna associated with rock varnish at Yungay, Atacama Desert, Chile. *Astrobiology*, 6, 153–154.
- Kuhlman, K.R., Venkat, P., La Duc, M.T., Kulman, G.M., & McKay, C.P. (2008). Evidence of a microbial community associated with rock varnish at Yungay, Atacama Desert, Chile. *Journal of Geophysical Research*, 113, G04022. doi:10.1029/2007JG000677, 002008
- Kutovaya, O.V., Lebedeva, M.P., Tkhakakhova, A.K., Ivanova, E.A., & Andronov, E.E. (2015). Metagenomic characterization of biodiversity in the extremely arid desert soils of Kazakhstan. *Eurasian soil science*, 48, 493–500.
- Lang-Yona, N., Maier, S., Macholdt, D.S., Müller-Germann, I., Yordanova, P., Rodriguez-Caballero, E., et al. (2018). Insights into microbial involvement in desert varnish formation retrieved from metagenomic analysis. *Environmental microbiology reports*, 10, 264–271.
- Langworthy, K., Krinsley, D., & Dorn, R.I. (2010). High resolution transmission electron microscopy evaluation of silica glaze reveals new textures. *Earth Surface Processes and Landforms*, 35, 1615–1620.
- Lebedeva, M.P., Golovanov, D.L., Shishkov, V.A., Ivanov, A.L., & Abrosimov, K.M. (2019). Microscopic and tomographic studies for interpreting the genesis of desert varnish and the vesicular horizon of desert soils in Mongolia and the USA. *Boletín de la Sociedad Geológica Mexicana*, 71, 21–42.
- Liu, T. (2017). VML Dating Lab. <http://www.vmldating.com/> [accessed 1 October 2019].
- Liu, T., & Broecker, W.S. (2000). How fast does rock varnish grow? *Geology*, 28, 183–186.
- Liu, T., & Broecker, W.S. (2007). Holocene rock varnish microstratigraphy and its chronometric application in drylands of western USA. *Geomorphology*, 84, 1–21.
- Liu, T., & Broecker, W.S. (2013). Millennial-scale varnish microlamination dating of late Pleistocene geomorphic features in the drylands of western USA. *Geomorphology*, 187, 38–60.
- Liu, T., Broecker, W., & Stein, M. (2013). Rock varnish evidence for a Younger Dryas wet event in the Dead Sea basin. *Geophysical Research Letters*, 40, 2229–2235.
- Lowenthal, D. (2000). *George Perkins Marsh: Prophet of conservation*. Seattle: University of Washington Press.
- Lozano, R.P., and Rossi, C. (2012). Exceptional preservation of Mn-oxidizing microbes in cave stromatolites (El Soplao, Spain). *Sedimentary Geology*, 255, 42–55.
- Lu, A., Li, Y., Ding, H., Xu, X., Li, Y., Ren, G., et al. (2019). Photoelectric conversion on Earth's surface via widespread Fe- and Mn-mineral coatings. *Proceedings of the National Academy of Sciences*, 116, 9741–9746.
- Macholdt, D.S., Herrmann, S., Jochum, K.P., Kilcoyne, A.D., Laubscher, T., Pfisterer, J.H., et al. (2017). Black manganese-rich crusts on a Gothic cathedral. *Atmospheric Environment*, 171, 205–220.
- Macholdt, D.S., Jochum, K.P., Pöhlker, C., Stoll, B., Weis, U., Weber, B., et al. (2015). Microanalytical methods for in-situ high-resolution analysis of rock varnish at the micrometer to nanometer scale. *Chemical Geology*, 411, 57–68.
- Malherbe, C., Hutchinson, I.B., Ingley, R., Boom, A., Carr, A.S., Edwards, et al. (2017). On the habitability of desert varnish: A combined study by micro-Raman spectroscopy, X-ray diffraction, and methylated pyrolysis–gas chromatography–mass spectrometry. *Astrobiology*, 17, 1123–1137.
- Marsh, G.P. (1864). *Man and Nature; or physical geography as modified by human action*. New York: Charles Scribner.
- McKeown, D.A., & Post, J.E. (2001). Characterization of manganese oxide mineralogy in rock varnish and dendrites using X-ray absorption spectroscopy. *American Mineralogist*, 86, 701–713.
- Merrell, C.L., & Dorn, R.I. (2009). Indian Writing Waterhole and Tom's Spring: Two central Idaho petroglyph sites in the Great Basin tradition. *American Indian Rock Art*, 35, 203–217.
- Nangung, S., Chon, C.M., & Lee, G. (2018). Formation of diverse Mn oxides: a review of bio/geochemical processes of Mn oxidation. *Geosciences Journal*, 22(2), 373–381. <http://dx.doi.org/10.1007/s12303-018-0002-7>, 1–9.
- Northup, D.E., Snider, J.R., Spilde, M.N., Porter, M.L., van de Kamp, J.L., Boston, P.J., Nyberg, A.M., & Bargar, J.R. (2010). Diversity of rock varnish bacterial communities from Black Canyon, New Mexico. *Journal of Geophysical Research*, 115, G02007. doi:10.1029/2009JG001107
- Nowinski, P. (2009). *Desert varnish as an indicator of modern-day air pollution in southern Nevada*, PhD dissertation. Las Vegas: University of Nevada, Environmental Science.
- Nowinski, P., Hodge, F.W., Gerstenberger, S., & Cizdziel, J.V. (2013). Analysis of mercury in rock varnish samples in areas impacted by coal-fired power plants. *Environmental Pollution*, 179, 132–137.
- Nowinski, P., Hodge, V.F., Lindley, K., & Cizdziel, J.V. (2010). Elemental analysis of desert varnish samples in the vicinity of coal-fired power plants and the Nevada Test Site using laser ablation ICP-MS. *The Open Chemical and Biomedical Methods Journal*, 3, 153–168.
- Palmer, F.E., Staley, J.T., Murray, R.G.E., Counsell, T., & Adams, J.B. (1985). Identification of manganese-oxidizing bacteria from desert varnish. *Geomicrobiology Journal*, 4, 343–360.
- Paulino-Lima, I.G., Fujishima, K., Navarrete, J.U., Galante, D., Rodrigues, F., Azua-Bustos, A., & Rothschild, L.J. (2016). Extremely high UV-C radiation resistant microorganisms from desert environments with different manganese concentrations. *Journal of Photochemistry and Photobiology B: Biology*, 163, 327–336.
- Perel'man, A.I. (1966). *Landscape geochemistry* (Translation No. 676, Geological Survey of Canada, 1972). Moscow: Vysshaya Shkola.
- Perel'man, A.I. (1986). Geochemical barriers: theory and practical applications. *Applied Geochemistry*, 1, 669–680.
- Perry, R.S., Dodsworth, J., Staley, J.T., & Engel, M.H. (2004). *Bacterial diversity in desert varnish* (pp. 259–260). Third European Workshop on Exo/Astrobiology, Mars: The search for life. European Space Agency Publications.
- Potter, R.M. (1979). *The tetravalent manganese oxides: clarification of their structural variations and relationships and characterization of their occurrence in the terrestrial weathering environment as desert varnish and other manganese oxides*,

- PhD dissertation (245 pp.). Pasadena, CA: California Institute of Technology.
- Potter, R.M., & Rossman, G.R. (1977). Desert varnish: The importance of clay minerals. *Science*, *196*, 1446–1448.
- Potter, R.M., & Rossman, G.R. (1979). The manganese- and iron-oxide mineralogy of desert varnish. *Chemical Geology*, *25*, 79–94.
- Ren, G., Yan, Y., Nie, Y., Lu, A., Wu, X., Li, Y., Wang, C., & Ding, H. (2019). Natural extracellular electron transfer between semiconducting minerals and electroactive bacterial communities occurred on the rock varnish. *Frontiers in Microbiology*, *10*. doi: 10.3389/fmicb.2019.00293
- Schelble, R.T., McDonald, G.D., Hall, J.A., & Neelson, K.H. (2005). Community structure comparison using FAME analysis of desert varnish and soil, Mojave Desert, California. *Geomicrobiology Journal*, *22*, 353–360.
- Seong, Y.B., Dorn, R.I., & Yu, B.Y. (2016). Evaluating the life expectancy of a desert pavement. *Earth-Science Reviews*, *162*, 129–154.
- Sims, D.B., Hudson, A.C., Keller, J.E., Konstantinos, V.I., & Konstantinos, M.P. (2017). Trace element scavenging in dry wash surficial sediments in an arid region of southern Nevada, USA. *Mine Water and the Environment*, *36*, 124–132.
- Soleilhavoup, F. (2011). Microformes d'accumulation et d'ablation sur les surfaces desertiques du Sahara. *Geomorphologie: relief, processus, environnement*, *2*, 173–186.
- Spencer, J.E., & Pearthree, P.A. (2015). Fall 2015 Arizona Geological Society field-trip guide: Northern Plomosa Mountains and Bouse Formation in Blythe Basin. *Arizona Geological Survey Open File Report, 15-10*, 1–24.
- Spilde, M.N., Melim, L.A., Northrup, D.E., & Boston, P.J. (2013). Anthropogenic lead as a tracer for rock varnish growth: implications for rates of formation. *Geology*, *41*, 263–266.
- Taylor-George, S., Palmer, F.E., Staley, J.T., Borns, D.J., Curtiss, B., & Adams, J.B. (1983). Fungi and bacteria involved in desert varnish formation. *Microbial Ecology*, *9*, 227–245.
- Tratebas, A.M., Cervený, N., & Dorn, R.I. (2004). The effects of fire on rock art: Microscopic evidence reveals the importance of weathering rinds. *Physical Geography*, *25*, 313–333.
- van Genuchten, C.M., & Peña, J. (2016). Sorption selectivity of birnessite particle edges: a d-PDF analysis of Cd(II) and Pb(II) sorption by  $\delta$ -MnO<sub>2</sub> and ferrihydrite. *Environmental Science: Processes and Impacts*, *18*, 1030–1041.
- Vázquez-Ortega, A., Fein, J.B. (2017). Thermodynamic modeling of Mn(II) adsorption onto manganese oxidizing bacteria. *Chemical Geology*, *464*, 147–154.
- Viles, H.A. (2011). Microbial geomorphology: a neglected link between life and landscape. *Geomorphology*, *157*, 6–16.
- von Humboldt, A. (1812). *Personal narrative of travels to the equinoctial regions of America during the years 1799–1804 by Alexander von Humboldt and Aime Bonpland*. Written in French by Alexander von Humboldt V. II (Translated and Edited by T. Ross in 1907). London: George Bell & Sons.
- von Werlhof, J. (1989). *Spirits of the Earth. A study of earthen art in the North American deserts*, Volume 1, *The north deserts*. El Centro, CA: Imperial Valley College Museum.
- Waldman, J.M., Munger, J.W., Jacob, D.J., Flagan, R.C., Morgan, J.J., & Hoffmann, M.R. (1982). Chemical composition of acid fog. *Science*, *218*, 677–680.
- Whitley, D.S. (2000). *The art of the Shaman: Rock art of California*. Salt Lake City: University of Utah Press.
- Whitley, D.S. (Ed.), (2001). *Handbook of rock art research*. Altamira Press.
- Whitley, D.S., & Loendorf, L.L. (1994). Off the cover and into the book. In D.S. Whitley, L.L. Loendorf (Eds.), *New light on old art: Recent advances in hunter-gatherer rock art research* (Monograph 36, pp. xi–xx). Los Angeles, CA: UCLA Institute of Archaeology.

UNCORRECTED PROOFS