Chapter 21

Rock Varnish and its Use to Study Climatic Change in Geomorphic Settings

Ronald I. Dorn

Introduction

The dusky brown to black coating of rock varnish dominates bare rock surfaces of many desert landforms (Oberlander, 1994). Thicknesses less than even 0.020 mm (or 20 micrometres, μm) are enough to darken light-colored rock types (Fig. 21.1). The gradual pace of change on many desert landforms permits the slow accretion of rock varnish at rates of a few micrometres per thousand years (Dorn, 1998; Liu and Broecker, 2000). Just about any rock type will accumulate varnish, in so long as rock-surface erosion is slow enough to permit varnish accretion.

Rock varnish formation starts when bacteria oxidize and concentrate manganese (Mn) and iron (Fe) (Dorn and Oberlander, 1981; Krumbein and Jens, 1981; Palmer et al., 1985; Hungate et al., 1987; Jones, 1991; Drake et al., 1993; Dorn, 1998; Krinsley, 1998). Although random collection of rock varnish reveals an impressive array of dozens of different types of microorganisms and their molecular by-products (Nagy et al., 1991; Dragovich, 1993; Perry et al., 2002; Kuhlman et al., 2005; Kuhlman et al., 2006), the bacteria that actually initiate varnish grow very infrequently (Dorn, 1998). Hence, rock varnish accumulates very slowly. If all of the organisms purported to cause varnish formation (Taylor-George et al., 1983; Eppard et al., 1996; Perry et al., 2003) actually contributed, rates of formation would reach millimetres per thousand years.

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Simple mathematics helps to visualize constraints on varnish formation. With both sides of an oxide-encrusted sheath of bacteria being ca. 0.3 μm thick and with clay minerals making up about 70% of varnish (Potter and Rossman, 1977; Potter and Rossman, 1979c; Krinsley et al., 1995; Dorn, 1998), only a few varnish-producing bacteria need to grow every thousand years to produce varnish. Five Mn-enhancing bacteria per hundred years is enough to generate a very fast-accumulating varnish in deserts. This means that the budding bacteria (Hirsch, 1974) making varnish (Dorn and Oberlander, 1982) can wait in a dormant state until a gentle wetting event takes place, and clear visual *in situ* evidence reveals they then enhance the Mn-Fe that glues clay minerals to rock surfaces (Dorn, 1998; Krinsley, 1998).

The details of varnish accumulation are important to understand in utilizing varnish as a desert geomorphic tool able to decipher climatic change. During wetter conditions, Mn enhancement is favored over Fe (Dorn, 1990; Jones, 1991; Cremaschi, 1996; Broecker and Liu, 2001). Mn fits into the crystalline structure of interstratified clay minerals that come to rest as dust on rock surfaces. The hexagonal arrangement of oxygen in clay acts as a template (Potter, 1979: 174–175) for the nanometre-scale bits of Mn that derive from bacterial sheaths (Fig. 21.2). The net effect is to form the type of Mn-mineral found in rock varnish, typically birnessite (Potter and Rossman, 1979a,b; McKeown and Post, 2001). This process of nanometre-scale varnish accretion is summarized in Fig. 21.2.

The slow and steady accumulation of rock varnish forms the basis of its use as a powerful tool to understand desert geomorphology. Mn-rich microlaminations (Fig. 21.3) result from wetter times in a

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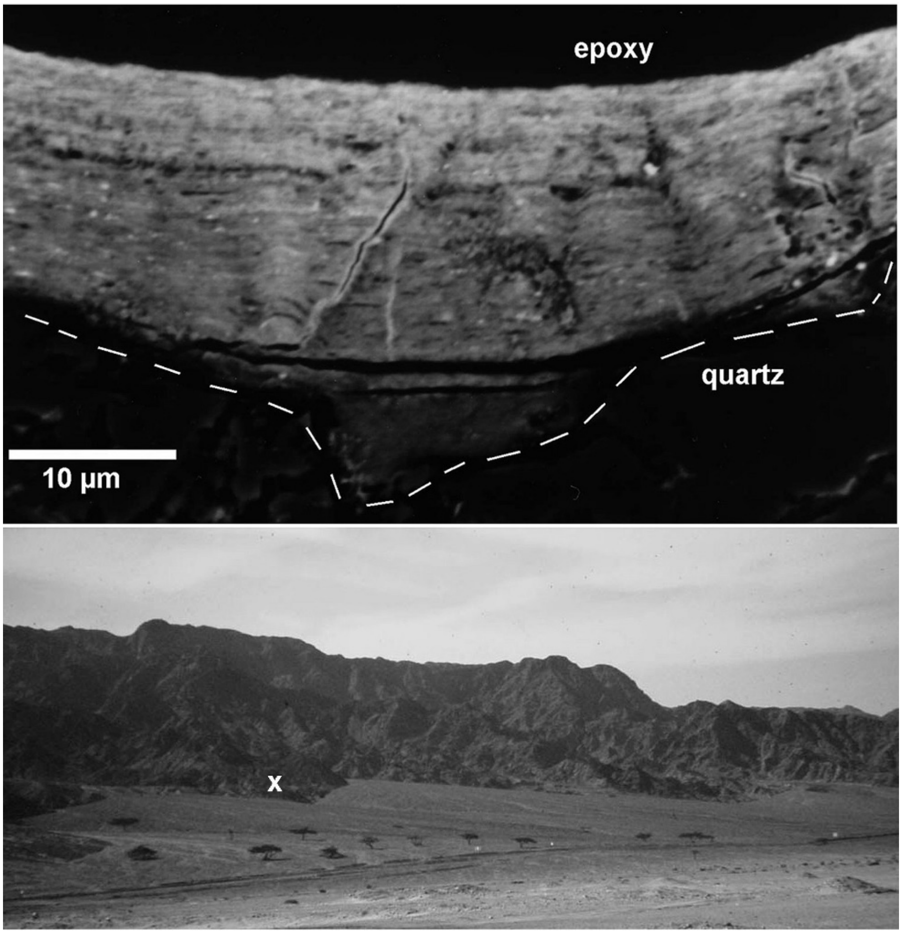

Fig. 21.1 Rock varnish dramatically darkens the appearance of desert landforms. This backscattered (BSE) electron microscope image derives from the "x" on the corresponding ground photograph of varnished slopes, Sinai Peninsula. The greater brightness of rock varnish in the BSE image reflects the higher atomic number of the manganese and iron in rock varnish

desert, because these conditions are more favorable for the growth of the Mn-enhancing bacteria. When the climate dries with fewer gentle winter-season wetting events, varnish does not stop growing. Clay minerals still deposit in dust. Mn-enhancing bacteria still grow. However, the ratio of Mn to Fe drops with the greater aridity, due to more alkaline materials deposited on desert surfaces (Dorn, 1990; Jones, 1991; Cremaschi, 1996; Broecker and Liu, 2001; Lee and Bland, 2003). The net effect is that drier periods generate varnish microlaminations with a higher percentage of clays and lower abundance of Mn (Fig. 21.3).

The next section of this chapter presents a revolution in varnish palaeoclimatic research brought about in just the past few years.

Microlamination Revolution

Orange and black varnish microlaminations (VML) were first reported three decades ago (Perry and Adams, 1978), although Charles B. Hunt showed me thin section images with these microlaminations dated to 1958. Others then started to explore the potential for VML to serve as a palaeoclimatic indicator with Mn-rich layers indicating wetter conditions (Dorn, 1984; Dorn, 1990; Cremaschi, 1992, 1996; Diaz et al., 2002; Lee and Bland, 2003; Thiagarajan and Lee, 2004). This prior research, however, represented only a tiny fraction of the work needed to connect VML to specific palaeoclimatic events.

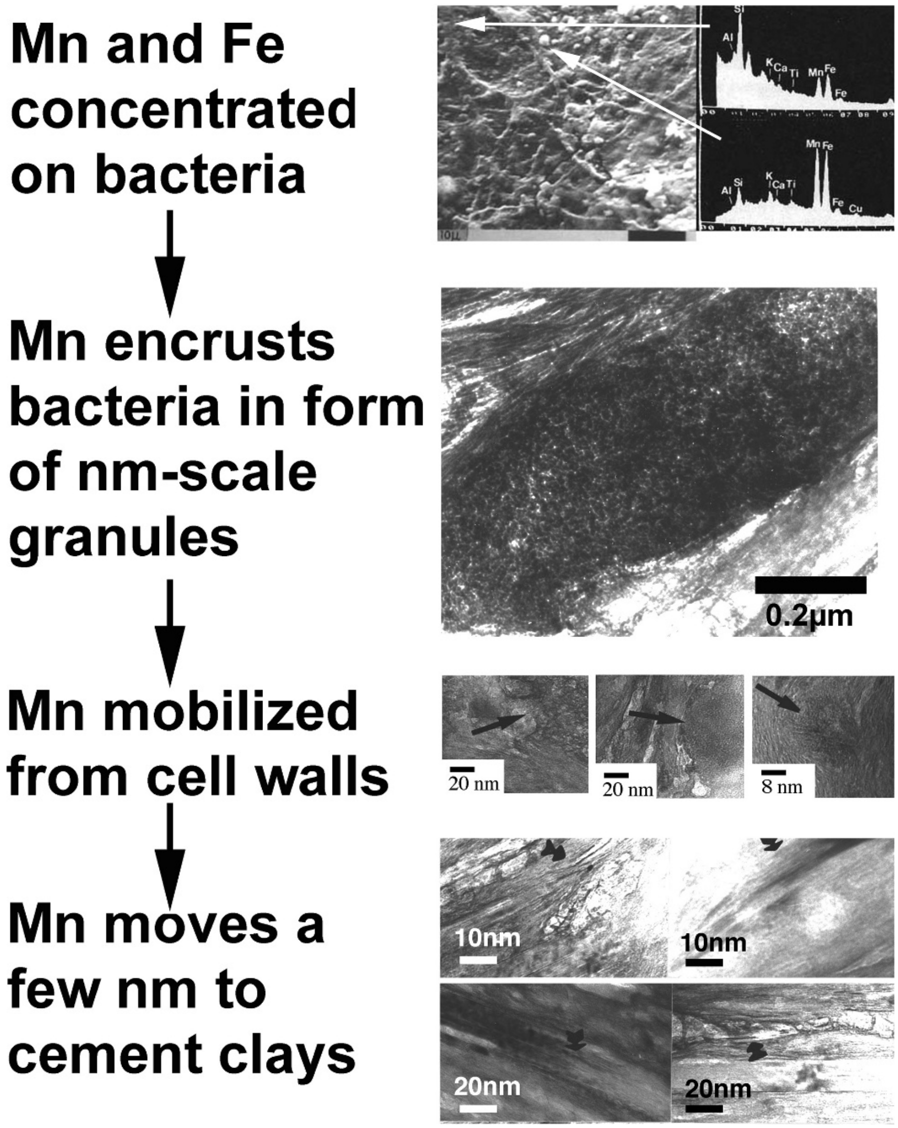

Fig. 21.2 Varnish formation starts with the oxidation and concentration of Mn (and Fe) by bacteria. Gentle wetting events provide enough carbonic acid to dissolve nanometre-scale fragments of Mn. Ubiquitous desert dust supplies interstratified clay minerals. The Mn-bacterial fragments fit into the weathered edges of clays, cementing clays much like mortar cements brick. The upper image is from secondary electrons, and the others are high resolution transmission electron microscopy (HRTEM). A more detailed discussion of alternative hypotheses of varnish formation can be found elsewhere (Dorn, 2007)

Tanzhuo Liu started to unravel the puzzle of VML in the early-1990s as a part of his dissertation applied to desert geomorphology (Liu, 1994; Liu and Dorn, 1996). "TL" to his colleagues then took a post-doctoral position at Lamont-Doherty Earth Observatory and continued to analyze VML from rock varnishes around the world (Liu and Broecker, 2000; Liu et al., 2000; Zhou et al., 2000; Broecker and Liu, 2001; Liu, 2003; Liu and Broecker, 2007, 2008a, 2008b).

Focusing on geomorphic surfaces of known age, Liu analyzed ultrathin cross sections of tens of thousands of rock-surface microbasins filled with rock varnish. These sedimentary deposits were then evaluated through light microscopy, backscattered-electron microscopy, and microchemical mapping methods.

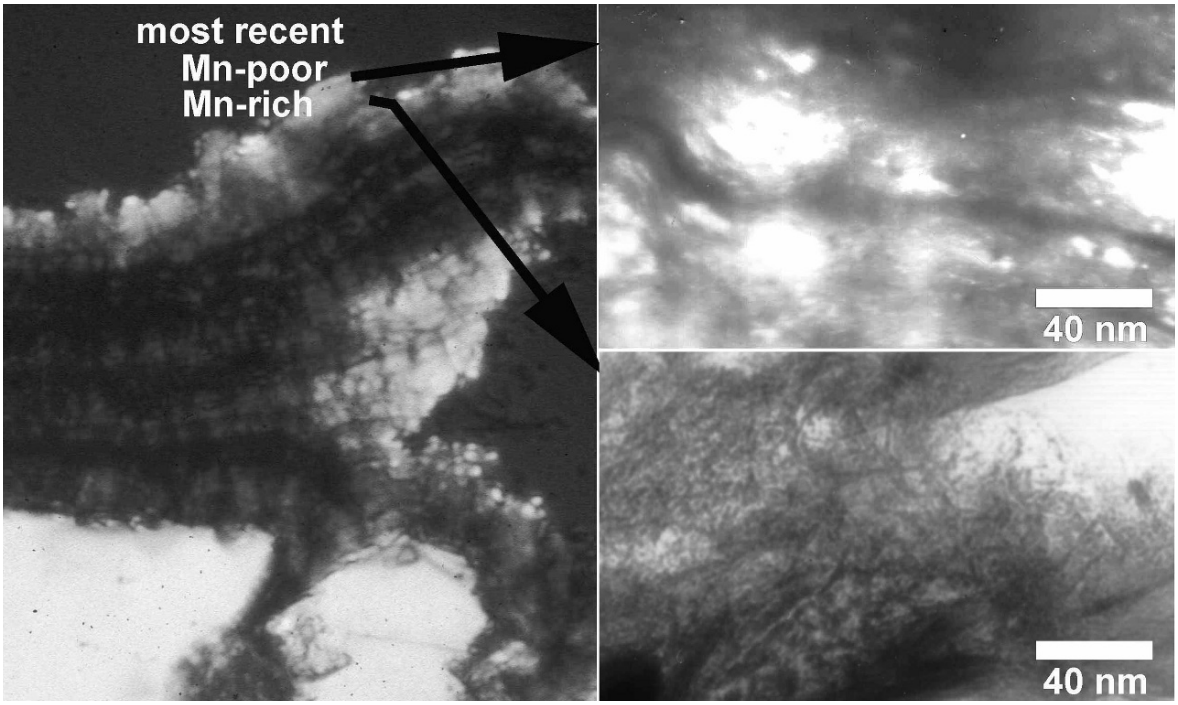

Fig. 21.3 Mn-rich and Fe-rich microlaminae of rock varnish from the Coso Range of eastern California. The left image is a light microscope image of alternating Mn-rich and Fe-rich layers. The upper right image is a HRTEM view of the most recent Mn-poor layer dominated by laminated clay minerals. In contrast, the most recent Mn-rich layer directly underneath still displays the granular texture of bacterial casts that are remobilizing into adjacent clay minerals while in nanoscale disequilibria

Just as detailed analysis of varves led to a revolution in understanding of deglaciation chronology (De Geer, 1930), and painstaking analysis of grains in sediment cores in the North Atlantic led to a revolution in understanding of iceberg armadas related to global cold snaps (Heinrich, 1988), Liu's work over the past decade has led to a similar revolution in rock varnish palaeoclimatic research.

Liu subjected his VML method to a blind test administered by Richard Marston, editor of *Geomorphology* (Liu, 2003; Marston, 2003; Phillips, 2003). Liu and Fred Phillips analyzed samples from the Mojave Desert for VML and ^{36}Cl ages, respectively. They then sent their results separately to Marston, who published a summary of the blind test:

> "This issue contains two articles that together constitute a blind test of the utility of rock varnish microstratigraphy as an indicator of the age of a Quaternary basalt flow in the Mohave Desert. This test should be of special interest to those who have followed the debate over whether varnish microstratigraphy provides a reliable dating tool, a debate that has reached disturbing levels of acrimony in the literature. Fred Phillips (New Mexico Tech) utilized cosmogenic ^{36}Cl dating, and Liu (Lamont-Doherty Earth Observatory, Columbia University) utilized rock varnish microstratigraphy to obtain the ages of five different flows, two of which had been dated in previous work and three of which had never been dated. The manuscripts were submitted and reviewed with neither author aware of the results of the other. Once the manuscripts were revised and accepted, the results were shared so each author could compare and contrast results obtained by the two methods. In four of the five cases, dates obtained by the two methods were in close agreement. Independent dates obtained by Phillips and Liu on the Cima "I" flow did not agree as well, but this may be attributed to the two authors having sampled at slightly different sites, which may have in fact been from flows of contrasting age. Results of the blind test provide convincing evidence that varnish microstratigraphy is a valid dating tool to estimate surface exposure ages." (Marston, 2003: p. 197)

The analysis of VML at sites of known age led to development of calibrations. The best-developed cali-

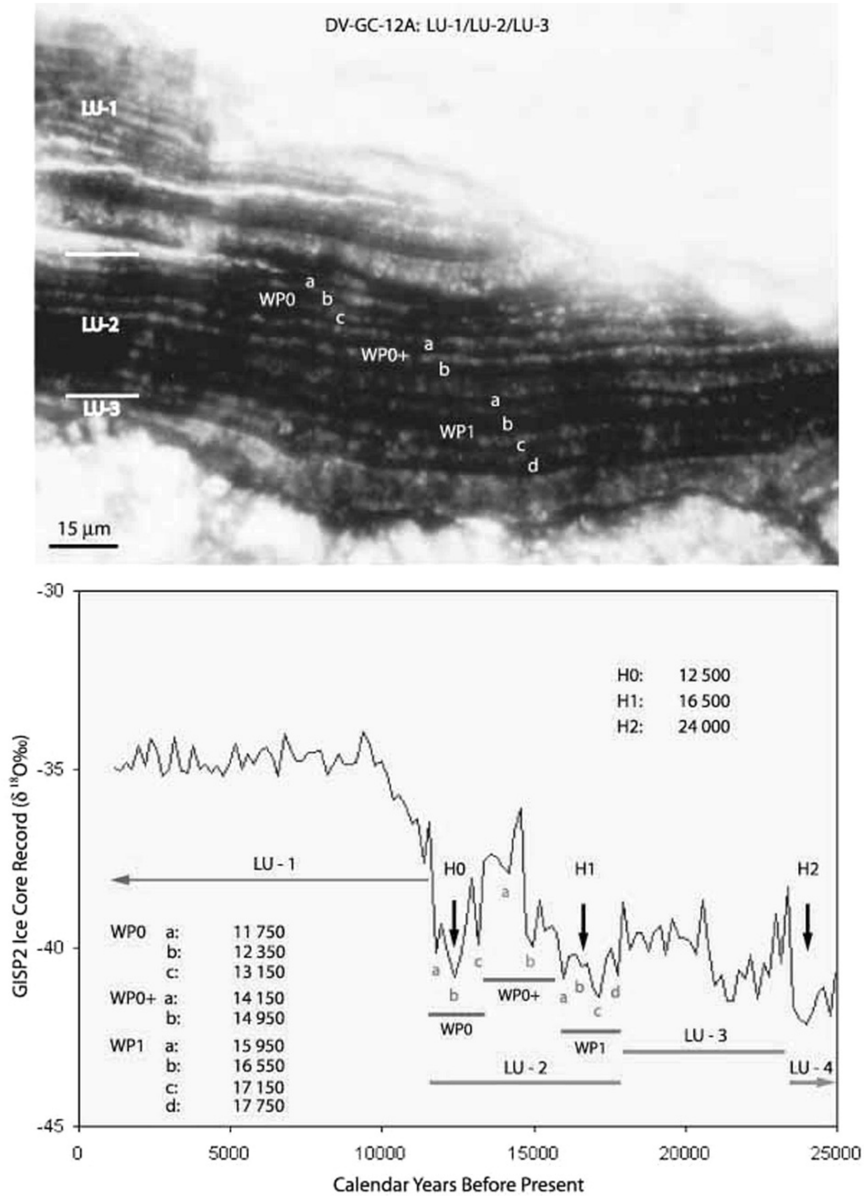

Fig. 21.4 Example of the rock varnish record of the latest Pleistocene wet events in Death Valley, California, and its possible correlation with the GISP2 ice core record in Greenland (Bond et al., 1999). WP = wet event in Pleistocene. LU = Layering Unit; H = Heinrich event. WP0 corresponds with the Younger Dryas (courtesy of Tanzhuo Liu from http://www.vmldatinglab.com/)

brations are for arid regions of the western USA, although Liu's research includes the deserts of Patagonia, China, Australia and elsewhere (Liu, 2008). The late Pleistocene (Figs. 21.4 and 21.5) and Holocene (Figs. 21.6 and 21.7) calibrations for the interior western USA form the basis of exemplars presented in the next section.

Examples of VML Use in Desert Geomorphology

Desert geomorphic research requiring an understanding of both chronology and climatic change can benefit from the VML method. The potential is limited only by

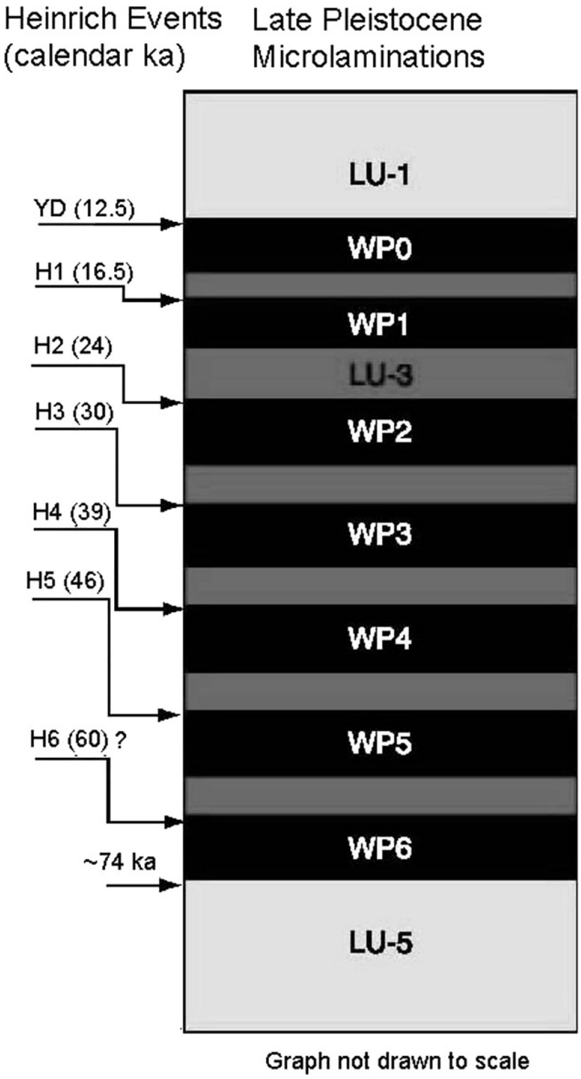

Fig. 21.5 Late Pleistocene calibration of varnish (adapted from Liu, 2003)

Fig. 21.6 Example of a Holocene rock varnish microstratigraphy from Searles Lake in the Mojave Desert, western USA (maximum varnish thickness is 220 microns). The *dark layers* in this image represent wet events that are correlated in time with Holocene millennial-scale cooling events in the North Atlantic region. Preliminary radiometric age calibration indicates that the topmost *dark layer* was deposited during the Little Ice Age around 300–650 calendar years, and the basal *dark layers* formed during a wet/cold period of early Holocene around 10,300 calendar years. Since the climate events recorded in the varnish are contemporaneous on a regional scale, these *dark layers* can be used as a tephrachronology-like dating tool to yield age estimates for varnished features (courtesy of Tanzhuo Liu from http://www.vmldatinglab.com/)

the creativity of the researcher. This section illustrates only a few possibilities.

VML in Desert Weathering Processes

Because rock varnish formation starts after the subaerial exposure of a rock surface, VML can yield unique insights into weathering that results in spalling—exposing new rock faces. One example comes from lightning as a weathering process.

Lightning strikes act as agents of rock weathering and erosion (Karfunkel et al., 2001). In a personal observation of the process, I observed a strike opening preexisting fractures in the host ignimbrite of the Superstition Mountains, Arizona. The strike also made a thin fulgurite film from desert dust—fusing dust to the newly opened fracture. Fulgurite crusts are noted elsewhere (Julien, 1901; Libby, 1986). The net result was a crust that formed on top of pre-existing fissuresol (Villa et al., 1995) (Fig. 21.8).

A preliminary study then ensued to examine the feasiblity of using VML to study the role of lightning strikes in desert weathering. The crest of the Superstition Mountains, Sonoran Desert, Arizona served as

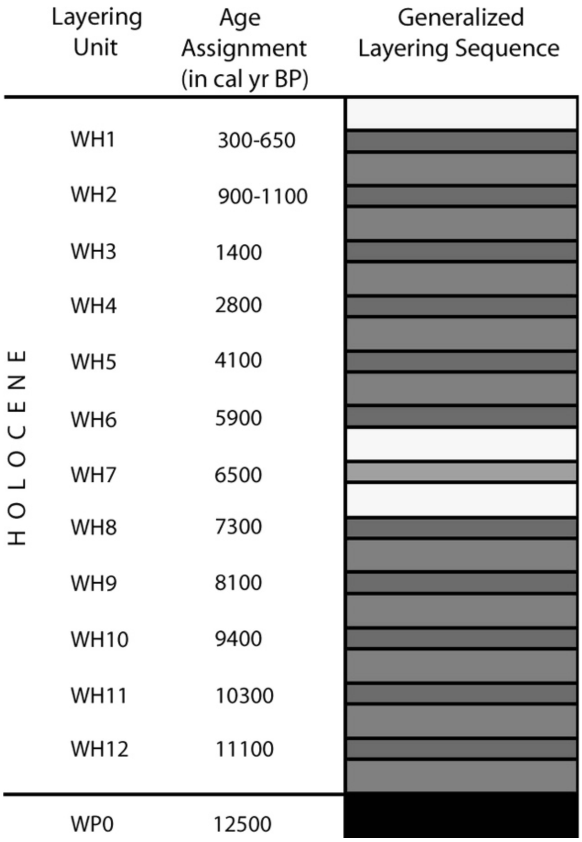

Fig. 21.7 Holocene calibration of varnish microlaminations (adapted from Liu, 2008)

the pilot study area. This rhyolite caldera experiences summer thunderstorms each July through September. Of the 912 spalled fissuresols examined along a 0.45 km transect, 14 displayed evidence of micro-fulgurites. The climatic geomorphology question is whether the frequency of lightning-induced erosion may have been different in the early Holocene, a period of more summer precipitation (Van Devender et al., 1987).

Only Holocene VML sequences (cf. Fig. 21.8) formed on top of these micro-fulgurites. A simple histogram of different VML events failed to reveal any clear indication of temporal clustering (Fig. 21.8). Certainly, a larger number of fused-dust fulgurites will be needed to further test the palaeo-weathering of lightning. However, having the ability to group weathering events in temporal clusters opens the door to new sets of questions related to desert processes that result in detachment.

Another type of desert weathering problem relates to quantifying rates of *in situ* weathering. Consider the classic phenomenon of weathering rinds. Dryland researchers often measure rind thicknesses, having to assume that rind erosion has a minimal effect (Colman, 1982; Pinter et al., 1994)—an assumption untenable in periglacial settings (Etienne, 2002). The formation of VML on desert surfaces permits the study of rind spalling as a collaborative process in weathering-rind development in deserts.

The keys to solving the conundrum of sorting the effects of spalling from weathering rests in knowing both the age of the desert landform and knowing the last spalling event. Both conditions were met for the Tioga-3 glacial moraine of Bishop creek in the semi-arid Owens Valley of eastern California (Gordon and Dorn, 2005). The age of the landform was established by ^{36}Cl measurements of morainal boulders (Phillips et al., 1996). Boulder spalling ages were determined by VML. The amount of *in situ* weathering was measured directly underneath the varnish VML by counting pores in backscattered electron microscope imagery (Dorn, 1995b).

At this semi-arid locale, less than 10% sampled granodiorite boulder surfaces remain uneroded (the WP1 samples in Fig. 21.9). These uneroded spots hosted the thickest weathering rinds. In contrast, about half of the boulder surfaces experienced weathering-rind detachment during Holocene, and these have the thinnest rinds (the LU-1 samples in Fig. 21.9). While the conclusion of this study (Gordon and Dorn, 2005) is certainly not surprising, VML analyses now permit research strategies promoting dialogue between *in situ* weathering and weathering-limited detachment.

VML in Desert Soil Processes

Desert pavements are living entities, constantly interacting with adjacent biophysical processes. With each successive pavement-altering process, there is potential for some original clast surface to erode and reset the VML signal. For example, particle alteration might be from spalling (Amit et al., 1993), biodisturbance (McAullife, 1994), water flow (Wainwright et al., 1999), dust interaction (Mabbutt, 1979; Gossens, 2005), and other processes (Dixon, 1994). An important part of pavement studies, therefore, rests in quantifying clast disturbance rates—a problem that has made harder by an inability to gather basic data.

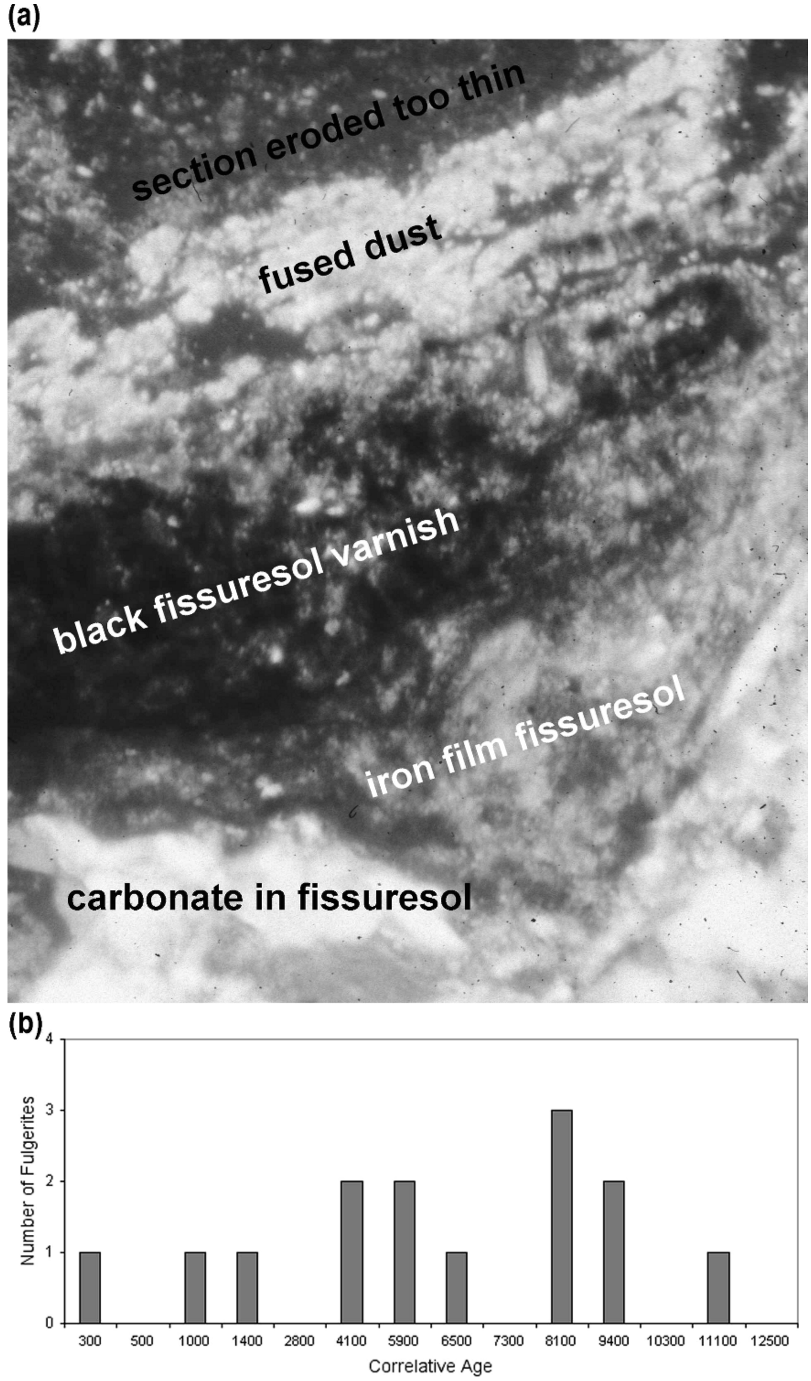

Fig. 21.8 VML formation on fulgurites from the Superstition Mountains crest, central Arizona. (**a**) An observed lightning strike created a sequence of fused dust on Mn-rich fissuresol varnish, on iron film fissuresol, then on laminar calcrete. (**b**) VML patterns on top of fourteen fused-dust fulgurites from the Superstition Mountains crest do not reveal a clear temporal pattern

It has certainly been possible to obtain reasonable ages for the onset of a pavement through cosmogenic nuclide dating of large boulders carried by debris flow (Nishiizumi et al., 1993), as well as finding datable materials in the sediment hosting the pavement (Reheis et al., 1996). VML analysis now provides an opportunity to obtain detailed information about pavement disturbance over timescales of thousands of years.

A conventional radiocarbon age on woody material at Hanaupah Canyon alluvial fan in Death Valley starts the clock of pavement modification at one site on the fan's late Pleistocene surface. The 24 ka conventional

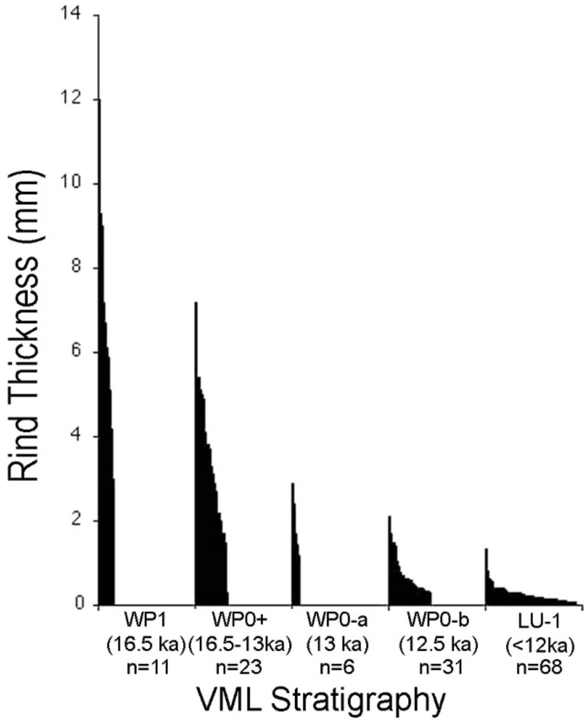

Fig. 21.9 Distribution of rind thickness under rock varnish thin sections collected from the Tioga-3 glacial moraine of Bishop Creek, Owens Valley, eastern California. Rind thickness was measured by the microporosity in BSE thin sections. VML assignments are based on the late Pleistocene calibration curve, with the goal of providing only broad time ranges. These data show that rinds are constantly eroding, "resetting" the VML clock, even as they thicken over time

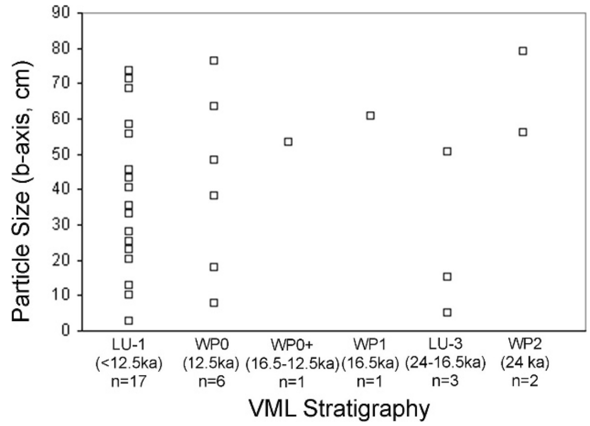

Fig. 21.10 Clast exposure on a 26 ka-old desert pavement in Death Valley, as measured by the late Pleistocene VML calibration (Fig. 21.6)

^{14}C measurement (Hooke and Dorn, 1992) has a calendar calibration of ca 26,800 years. Thus, undiminished particles should have a VML stratigraphy of WP2 in Fig. 21.5.

In a 64 m^2 plot, randomly selected pavement clasts were examined to assess suitability for VML analysis. A sample size of 30 was reached after evaluating 242 samples. This relatively high ratio of suitable-to-unsuitable samples was possible because the Death Valley alluvial fans are an optimal area for VML dating (Liu and Dorn, 1996). No constraints were placed on particle sizes. The only discriminating issue in clast selection was whether the varnish was appropriate for VML, using criteria established by Liu (1994, 2008).

Only two clasts had a VML sequence as old as the conventional radiocarbon age for the deposit (Fig. 21.10). More than half of the pavement clasts hosted varnishes developed within the past 12.5 ka, as revealed by the presence of only the LU-1 VML Holocene unit (Fig. 21.10). Eleven clasts experienced enough disturbance to expose surfaces anew in the latest Pleistocene. There does appear to be a slight particle-size effect in surface disturbance, where the most stable pavement surfaces tend to be on the largest clasts (Fig. 21.10). However, VML analysis reveals that it is possible for small pavement clasts to remain stable for long periods.

A different issue related to pavement stability concerns the occurrence of old plant scars. Desert pavements can host perennial plants for a time; and then when those plants die, the reworked fan and aeolian deposits undergo a series of changes that eventually generates a new pavement (Peterson, 1981; Peterson et al., 1995; McAuliffe and McDonald, 2006). Reformation of pavement within ancient plant scars might record ancient droughts (McAuliffe and McDonald, 2006).

To assess the potential of VML to detect old drought periods, thirty old plant scars were sampled on the Shadow Mountain Fan, McDowell Mountains, Scottsdale. These fossil plant scars are noticeable from their circular to oval shape, from the smaller clast sizes inside subtle depressions, and from the VML signal itself. Away from these plant scars, the oldest VML sequence on the fan yields a WP2 or last glacial maxima minimum age. Inside the plant scars, however, the VML sequence is always Holocene. Although the sample size and single site location of this pilot study is limited, pavement clast VML ages do appear to reveal two distinct age clusters (Fig. 21.11). One cluster is in the mid-Holocene, and a second is at the transition

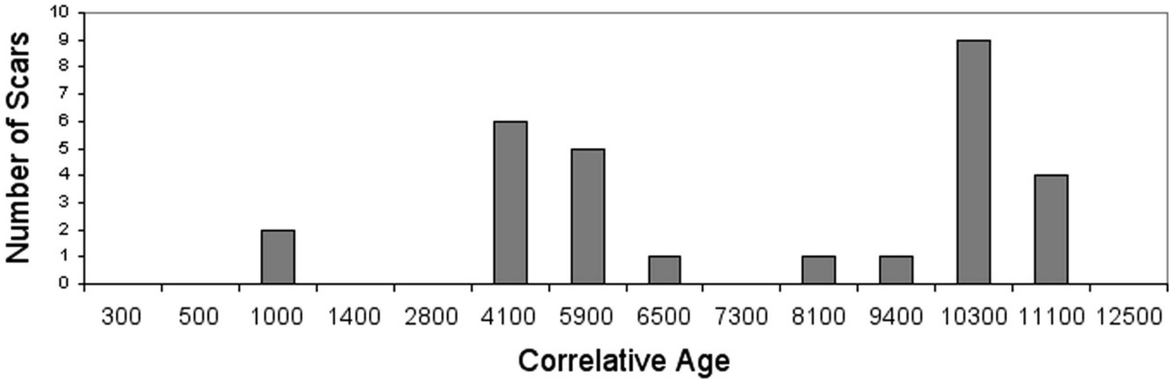

Fig. 21.11 Clast exposure in fossil plant scars from desert pavements, southern McDowell Mountains, Sonoran Desert, Arizona

between the Pleistocene and Holocene. Because the VML signal would reflect an unknown amount of time between plant death and pavement reformation in the scar, the VML signal would necessarily have to be a minimum age for the loss of vegetative cover.

Researchers no longer have to settle for indirect deduction about the ages of pavement-altering events. The following sort of intuitive guess work at inter-site correlations is all too common: "the light to moderate coatings of rock varnish on surfaces of pavement clasts within depressions are very similar to the degree of varnish formation on clasts of gravelly alluvial fans deposited 8,000–12,000 yr ago at a site in the Mojave Desert" (McAuliffe and McDonald, 2006: 213). These and many other researchers have been forced to utilize the appearance of varnish because of the lack of a better tool. Now, the VML revolution means that studies of pavement evolution can be grounded in clast-specific, site-specific data.

VML in Hillslope Processes

Desert slopes can be areas of historic activity or they can host varnishes indicative of thousands of years of stone stability. Liu exemplifies VML's potential to study hillslopes through case studies of colluvial boulder stripes at Yucca Mountain, Nevada, fault escarpments in the western Great Basin, and of a debris-flow cone in Death Valley (Liu, 2008).

Desert landslides represent another fertile area for VML research, especially as urban expansion continues to abut steep mountains. Larger landslides are better dated with cosmogenic nuclides, because previously unexposed rocks are brought to the surface (Hermanns et al., 2001; Ballantyne and Stone, 2004). However, smaller landslides on the order of 100 m^2 are more difficult to study, because many of the clasts have a prior exposure history on the slope prior to mass wasting.

An example of the potential of VML to study desert landslides comes from metropolitan Phoenix, Arizona. Smaller landslides pepper the urban area and pose a hazard to development that continues to move up against steep mountains. A key hazard question is whether these smaller deposits are fossil artifacts of a wetter Pleistocene, as is the case for the larger events in the region (Douglass et al., 2005).

South Mountain, central Arizona, offers an opportunity to study the problem. The largest urban park, this metamorphic core complex (Reynolds, 1985) presents steep flanks on many margins. For most of the Sonoran Desert, the boundary between grussified and relatively fresh granite rests deep underneath the surface. The granitic portions of this range, however, pose a landslide hazard because the subsurface weathering front is within a few metres of the surface. This permeability contrast generated a sturzstrom in the region (Douglass et al., 2005) and is associated with smaller granitic landslides in the area.

A pilot study of VML on six landslides abutting development at South Mountain reveals that their ages all rest in the Holocene. Using Liu's Holocene chronology (Fig. 21.7), their ages range from more recent than the WH1 layer (less than 300 years) to the early Holocene WH11 layer (ca. 10,300 years). Figure 21.12 illustrates one of the more recent landslide events. The ongoing nature of landslides throughout the arid Holocene, therefore, suggests potential for contemporary mass wasting.

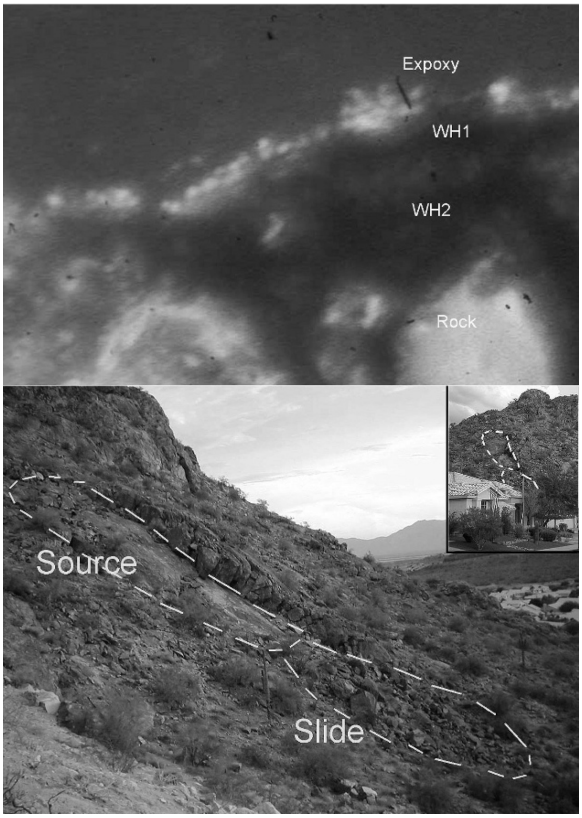

Fig. 21.12 Small landslide in Phoenix, Arizona, on the border margin of South Mountain Park. VML analysis of the source area of the landslide suggests that the landslide is slightly older than 1100 years, the start of the WH2 layer

A major question in desert geomorphology is whether the terminal-Pleistocene to Holocene transition increased rates of hillslope erosion. This "transition to a drier climate" hypothesis is favoured by many investigators who argue that the reduction in vegetation cover accompanied this desiccation, leading to flash floods that transported sediment out onto alluvial fans during the early Holocene (Huntington, 1907; Eckis, 1928; Bull, 1991; Harvey and Wells, 1994; Reheis et al., 1996). One way to test this hypothesis is to analyze VML on debris flow levées that represent discrete erosional events.

The hillslopes of the Panamint Range above Hanaupah Canyon alluvial fan host an extensive number of debris-flow levées. Thirty such levées were sampled sequentially along a south-to-north transect below 1000 m.

The VML patterns on levée boulders do not support the "transition to a drier climate" hypothesis in this field area (Fig. 21.13). Overwhelming erosion in the early Holocene should have produced an overwhelming bias towards Holocene-aged (LU-1) VML. Instead, more than half of the sampled debris-flow levées formed during the late Pleistocene (Fig. 21.13). Still, this is just the first study of its kind. VML analyses of debris-flow levées on other hillslopes may reveal a different pattern.

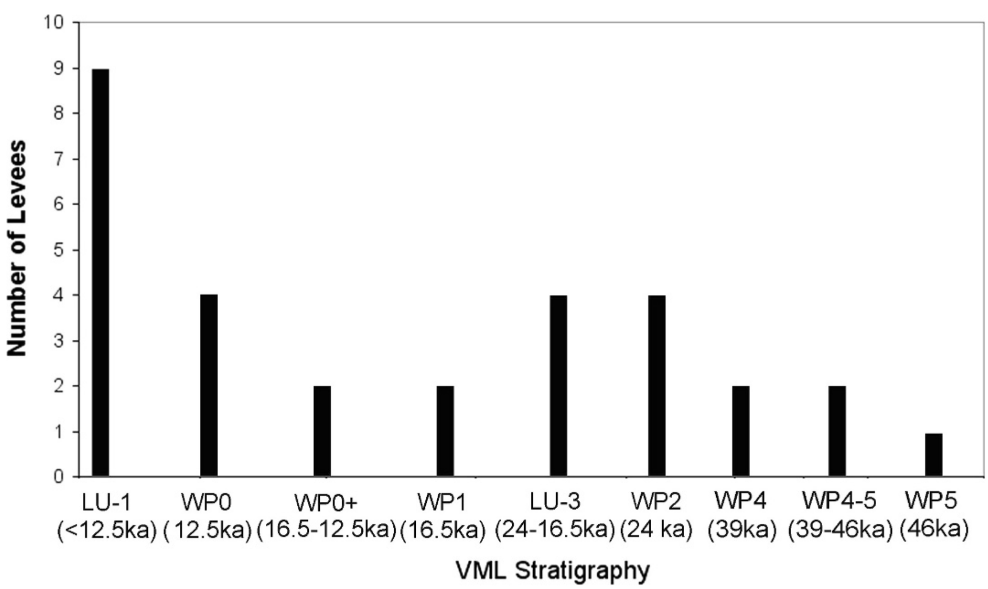

Fig. 21.13 Frequency of debris-flow levées on the lower slopes of the Panamint Range, Death Valley, above Hanaupah Canyon alluvial fan

VML Palaeolake Events

Palaeolake shorelines have served as important calibration sites for the VML method (Liu and Broecker, 2000; Liu et al., 2000; Broecker and Liu, 2001; Liu, 2003, 2008; Liu and Broecker, 2007, 2008a, 2008b). Bonneville, Coyote, Lahontan, Manix, Manly, Panamint, Searles, Silver, and Sumner western USA palaeolakes all yielded VML consistent with prior age control. Considerable potential, therefore, rests in VML providing insight into the chronometry of palaeolakes lacking other age control.

VML in Study of Hydraulic Activity

Large spheroidally-weathered granitic boulders characterize the debris slopes of inselbergs abutting pediments throughout the Mojave and Sonoran Deserts. A climatic-change interpretation holds that these inselberg slopes represent fossil landforms, relicts of subsurface weathering during wetter periods of the Cenozoic (Oberlander, 1972, 1974, 1989; Twidale, 1982). Although the overarching landform might be a by-product of a regional climatic desiccation throughout the Cenzoic, there exists clear field evidence that the fines on these slopes are in adjustment with hydraulic processes (Abrahams et al., 1985; Parsons and Abrahams, 1987). VML analysis offers potential to reconcile these disparate perspectives.

Teutonia Peak inselberg at Cima Dome (Davis, 1905) and the Apple Valley, Mojave Desert (Abrahams et al., 1985; Parsons and Abrahams, 1987), debris slopes offer two venues to analyze the stability of inselberg boulder slopes. The goal rests in understanding the stability of the boulders themselves. There are complexities, however, in working with granitic boulders. One difficulty in boulder sampling rests in the potential for subjectivity, because varnish development varies considerably over a single boulder. Another problem in boulder sampling rests in the processes of boulder erosion; spalling of fissuresols (Villa et al., 1995) is a common erosional process, and these surfaces are not suitable for VML analysis. Thus, sampling had to be random and had to avoid fissuresol surfaces. This was accomplished by running transects from the piedmont junction up these slope. The centre each intersected boulder was sampled, or—if a fissuresol—the closest suitable locale.

Ten boulders from each debris slopes suggest that ongoing boulder erosion has been taking place throughout the late Quaternary. No sampled boulder surface had a VML sequence even reaching back even to the Eemian interglacial or the LU-5 VML microstratigraphy. More than half of the sampled boulder surfaces at each site hosted only a LU-1 VML sequence, indicating Holocene erosion (Fig. 21.14). These data reveal that ongoing boulder erosion supplies sediment to hydraulic systems on inselberg debris slopes. Although these preliminary data do not falsify a climatic change origin for pediment-inselberg granitic complexes, they do indicate active late Quaternary erosion of inselberg boulders.

One of the first uses of VML was the study of alluvial-fans in Death Valley (Liu and Dorn, 1996). In addition to providing chronometric insight into specific depositional events on fan surfaces, VML analyses help decipher the connection between climatic events and fan deposition. If dry periods generate fan building through flash floods mobilizing unvegetated sediment, then Mn-poor dry-period VML should initiate the VML sequence. If wet periods generate fan building through fluvial transport, then Mn-rich black layers should rest at the lowest layers of the varnish.

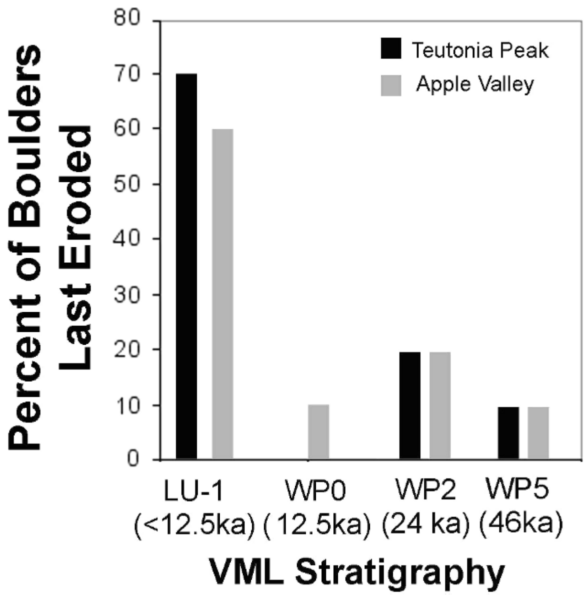

Fig. 21.14 Frequency of boulder erosion on inselberg debris slopes backing pediments in the Apple Valley and Cima Dome, Mojave Desert

Why did it Take so Long?

There are several basic reasons why it took a quarter century to go from the first publication of VML (Perry and Adams, 1978) to Liu's calibration (Figs. 21.5 and 21.7).

First, varnish ultrathin sections are difficult to make. Normal geologic thin sections are too thick, and further thinning to the host glass slide creates a triangular geometry that essentially hides many VML. Section zones too thin result in seeing no VML or in seeing a seemingly random pattern generated by areas of slightly greater resistance. Section zones too thick result in seeing too few VML. Having made a few hundred sections myself, the remainder of this chapter could be spent on anecdotes of how to make mistakes in section preparation and how these mistakes can generate errors in interpretation.

Second, patterns in sedimentary deposits may not necessarily be obvious with analysis of just a few samples. Particularly rapid accretion will form extra layers that combine in varnishes with slower accumulation rates. Variable rates of accretion will, thus, disguise patterns that emerge only after the study of many different sampling locales. It took Liu a decade of careful laboratory work to extract the complete VML pattern from thousands of rock varnish samples. Thus, a general problem comes from researchers who collect a few samples, as Oberlander (1994: 118) correctly emphasized: "researchers should be warned against generalizing too confidently from studies of single localities". Simply put, Liu is the only researcher who was dedicated enough to test the potential of detailed regional patterns of varnish VML accretion.

Third, researchers often select the wrong type of varnish, a problem discussed in detail elsewhere (Dorn, 1998: 214–224). The only type of varnish appropriate for VML analysis forms on subaerial surfaces exposed to only rain and dust deposition.

Fourth, some researchers fail to sample pure rock varnish. Instead, they collect samples that have mixtures of rock varnish with other types of rock coatings, such as heavy metal skin, iron film, oxalate crust, phosphate skin, or silica glaze. Certainly, rock varnish exists in the analyzed samples, as revealed by enhancements of Mn. Yet, published details in many papers reveal clear evidence that these other rock coatings actually interfinger with varnish in the analyzed samples, thus invalidating many conclusions.

Fifth, the occurrence of microcolonial fungi and other acid-producing lithobionts dissolves varnish, erasing microlaminations in the surrounding volume. Even if these organisms are not readily apparent on contemporary surfaces, they may have dissolved VML in the past. The selection of uneroded sequences, then, becomes a vital step analogous to avoiding bioturbation in the study of soils and sediments.

The above difficulties directly imply that the VML method requires that a researcher spend months to years in training. The large number of iterative cycles of field collection, thin section preparation, and laboratory analyses means that this powerful method should be undertaken by someone willing to devote years of constant research to the topic. The development of this expertise is analogous to musicians or surgeons who study for years to master a combination of method and art. Although he was hesitant at first, with the encouragement of colleagues TL has opened a dating laboratory that can accept samples from outside users (Liu, 2008). Hopefully, this VML dating laboratory will serve to encourage a group of future varnish scientists willing to put in the years needed to develop this expertise.

Other Climatic Change Signals

As with any sedimentary deposit, there are a host of ways whereby climatic-change signals might be extracted from rock varnish. The micromorphology of varnish, as seen in secondary electrons, provides a record of palaeodust (Dorn, 1986). Unconformities inside varnish can record aeolian abrasion events (Dorn, 1995a). Interdigitation of other types of rock coatings, such as oxalates, can indicate climatic change favouring a different type of accretion (Dorn, 1998). The occurrence of different types of organic matter might similarly reveal information of past environments (Dorn and DeNiro, 1985; Nagy et al., 1991; Perry and Kolb, 2003). Researchers focused on the search for extraterrestrial life concern themselves with the importance of fossil organisms that might be found entrapped by rock varnish (Probst et al., 2002; Allen et al., 2004; Perry et al., 2006). Even the occurrence of varnish on palaeosurfaces has been used to indicate palaeoaridity (Dorn and Dickinson, 1989; Marchant et al., 1993).

In the past, all varnish palaeoenvironmental methods such as those listed in the previous paragraph ranged from experimental to highly speculative. Some evidence existed to support their use. Yet the detailed and repetitive research needed to move the rock varnish science forward had not been conducted—until now.

The varnish microlaminations method has moved forward into a class of methods that can be considered reliable. VML is based on analyses of thousands sedimentary deposits (varnish microbasins). The VML method has been thoroughly calibrated at sites with numerical age control from multiple methodologies (e.g. radiocarbon, uranium-series, cosmogenic nuclide, and others). Critically, the VML method has been subjected to a rigorous blind test. For desert geomorphologists interested in learning about the chronology and palaeoclimatology of desert landforms, there even exists a commercial laboratory to assist data acquisition. The time is ripe to make dramatic advances at the interface of desert geomorphic processes and climatic change.

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