Laboratory Spectrometry of Rock Coatings: Implications for Land Management Activities In the Arid Southwest

J. David Lashlee
U.S. Army Yuma Proving Ground
Engineering Division
CSTE-DTC-YP-MT-ED
Yuma, Arizona 85365-9110

Dr. Charles Rosenfeld
Oregon State University
Department of Geosciences
104 Wilkinson Hall
Corvallis Oregon, 97331-5506

Abstract

Accurate knowledge of landforms, natural processes that form and modify them, and engineering characteristics of surface materials is a fundamental knowledge for landscape managers. This is particularly true where military testing and training activities accelerate natural geomorphic processes or modify landforms that are associated with natural and cultural resources. Arid environments are often assumed by remote sensing specialists to be less complicated to analyze for earth science applications than humid, tropic, and arctic environments, since there is minimal vegetation to obscure surface features. While this may indeed be the case for many aerial photograph and image interpretation applications, the results of more quantitative multispectral and hyperspectral digital image processing techniques are complicated by a variety of environmental factors that are not always fully appreciated by the remote sensing community. Rock coatings, including rock varnish, weathering rinds, and carbonate deposits, have pronounced effects on hyperspectral reflectance in the reflected solar spectrum (400 to 2500 nanometer wavelengths). It is important for those who study arid environments remotely to understand geomorphic controls on spectral reflectance and the potential problems they may introduce to classification accuracy, landscape modeling, and target recognition algorithms.

INTRODUCTION

Yuma Proving Ground

Yuma Proving Ground (YPG) is a general-purpose testing facility within the U.S. Army Test and Evaluation Command. YPG's mission includes testing artillery, tank and automotive systems, aircraft armament and air delivery systems, mines, and munitions. It also supports training operations and visiting military units. YPG is located adjacent to the confluence of the Colorado and Gila Rivers in the Sonoran Desert Section of the Basin and Range Physiographic Province (Figure 1). Larger in size than the state of Rhode Island, YPG encompasses more than 3,367 km^2 (1,300 mi^2) of the hottest and driest area in the United States. Extreme temperatures and low annual precipitation best characterize climatic conditions at YPG. The highest recorded temperature since 1954 was 51 C (124 F) in June 1990 (Yuma Meteorological Team, 1998). Precipitation at YPG usually occurs in late summer months as brief, but intense thunderstorms and in winter as less intense, longer duration rain showers. The area has been arid for the last 13,000 years with the present climatic regime and plant species established approximately 4,000 years ago (Betancourt et al., 1990). Perennial plant cover averages from 1 to 5 percent across this region.

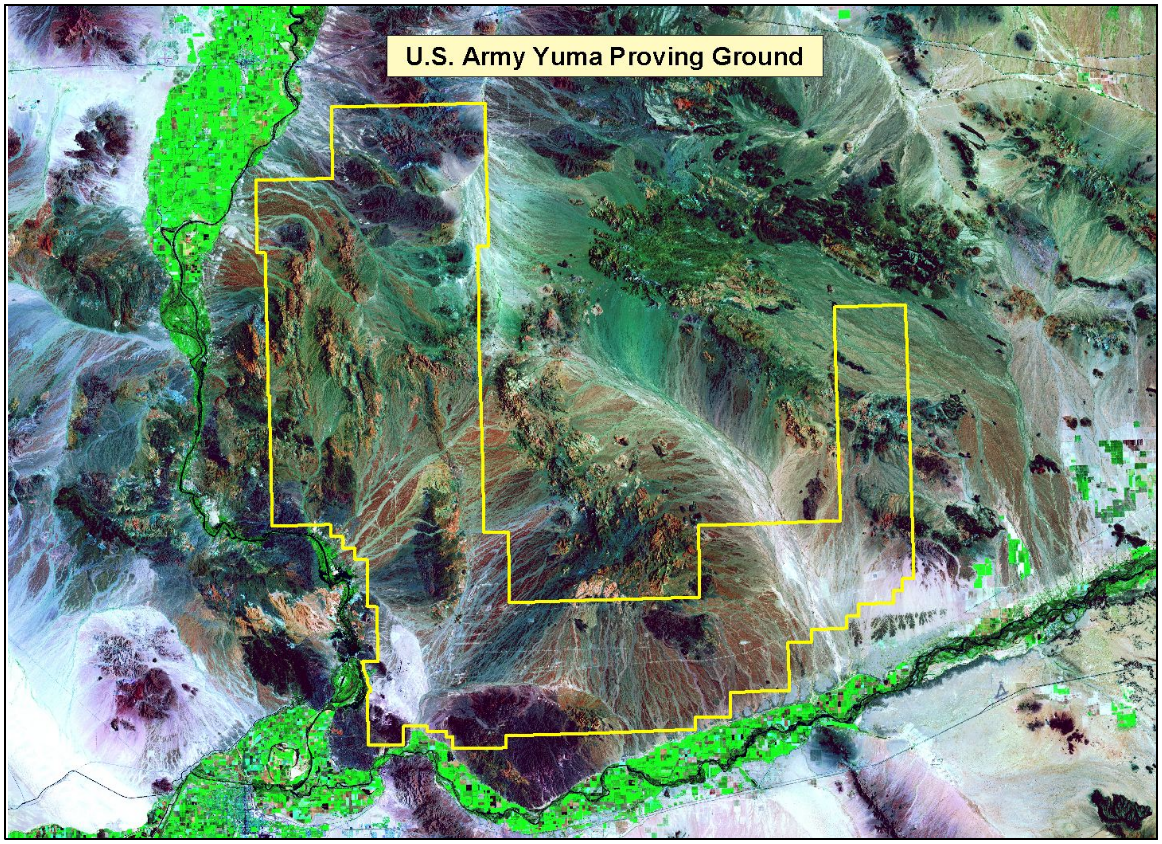

Figure 1. Landsat Thematic Mapper 7, 4, 2, color composite image of the Yuma Proving Ground.

Geomorphology

YPG lies at the southern end of the Basin and Range physiographic province, a vast area extending as far north as Oregon, characterized by over 400 relatively regularly spaced, north-northwest trending subparallel mountain ranges, with intervening, broad and gently sloping alluviated basins formed by high angle extensional faulting (Dohrenwend, 1987). The most notable features of the YPG landscape are the relief and bareness of these mountains and extensive desert pavements developed in broad intermontaine alluvial basins. Other major landforms on the installation include alluvial fans and bajadas, which often transition to broad alluvial plains drained by ephemeral stream washes, and sand dunes. These Quaternary valley fill deposits make up almost 70 percent of the YPG landscape (Figure 1).

Geologic maps are a primary source of information for a variety of applied earth science applications, including land use evaluation and planning, siting critical facilities, and the design and construction of infrastructure requirements like utilities, transportation corridors, and surface-water impoundments (National Geologic Mapping Act of 1992, 2000). Unfortunately, geologic materials at YPG are relatively poorly understood. The only geologic maps covering the entire YPG area are State of Arizona maps at 1:1,000,000 (Reynolds, 1988) and 1:500,000 (Wilson et al., 1969) map scales. Few large or medium scale maps needed for improved installation management have been published. This problem is compounded when those areas that are mapped at 1:24,000 scale have all alluvial deposits, an estimated 900 mi^2 of YPG, generalized into a single map category called “Quaternary Alluvium”. It would be advantageous if these areas could be accurately mapped and quantitative information about them extracted using remote sensing techniques. Significant funding has, in fact, been directed towards development of knowledge on remote sensing characteristics of geomorphic surfaces and their correlation with climatic change. However, limitations in the spectral and spatial resolutions of airborne and space-borne multispectral scanners have restricted the usefulness of these data for detailed, large-scale mapping (Lashlee, et al., 1993). As a result, soils and geomorphic surfaces of large regions of semi-arid and arid land in North America remain unmapped and uncorrelated (Fischer, 1991).

Geomorphic Mapping for Installation Management

Installation management methodologies at YPG based on a geomorphic framework provide managers with a scientific basis for making decisions related to planning, design, construction, implementation, operation, and maintenance of engineering projects, as well as a variety of resource management and compliance issues. These data are also critical for mitigating the effects of erosion and waste dispersal for environmental protection. An understanding of the landscape as an integrated process-response system, rather than a set of discrete and independent landforms, facilitates prediction of impacts of the geomorphic system on testing operations, and likewise, impacts of military testing and training on landscape stability.

Natural and cultural resource management at DoD installations is an increasingly important component of military planning and operations support. For example, Lashlee et al. (1999) mapped geomorphic surfaces in a 64-km^2 area of YPG using 1:24,000 scale stereoscopic color aerial photography and Landsat Thematic Mapper color composite images. Geomorphic surfaces were then compare to Native American cultural resources mapped in the field with differentially corrected Global Positioning System coordinates using Geographic Information System spatial overlays. A vast majority of cultural sites, including those eligible for the National Register of Historic Places, were located on Pleistocene age (10,000 to 2 million years old) geomorphic surfaces. Very few sites occur on Holocene age (< 10,000 year old) surfaces. Spatial patterns demonstrated between archaeology and geomorphology were supported by a chi square statistical test rejecting the hypothesis that sites are evenly distributed across the landscape as a function of the size of geomorphic surfaces. This research suggests that both differential preservation of geomorphic surfaces and human behavior act in concert to explain the spatial distribution of cultural resources at YPG. Landform and geomorphic process maps such as these allow managers to develop predictive models concerning how resources are most likely distributed across landscape elements and how operations can be managed to minimize impacts and maintain landscapes for sustained mission use.

Geomorphic Controls on Hyperspectral Reflectance

Geomorphic Surfaces and Desert Pavements

The criteria most often used for field identification and mapping of alluvial geomorphic surfaces are: (1) degree of desert pavement development, (2) amount and character of rock varnish, (3) soil type, (4) topographic position, and (5) drainage characteristics (Bull, 1991). With the exception of subsurface soil profile development, each of these mapping criteria can, with varying degrees of success, be assessed remotely in the reflected solar spectrum. It is also important to note that other recent studies that have demonstrated the application of thermal (Gillespie et al., 1984) and RADAR data (Kierein-Young, 1995; Farr and Chadwick, 1996) for mapping geomorphic surfaces.

Desert pavements are common landscape features in arid regions of the world and are known as hamada or reg in Arabic regions, sai in Asia, and gibber in Australia (Cooke, Warren, and Goudie, 1993). While formational geomorphic processes are generally understood, the magnitude and duration of processes responsible for formation of pavements vary with location. Desert pavements consist of a surface layer of closely packed gravel, usually one particle thick, that overlies a thin, gravel-poor vesicular A (Av) soil horizon. Pavements are important features in the Southwestern U.S. where they have been used in subdividing and correlating Quaternary alluvial fans for studying neotectonics and Quaternary climatic change (Christenson and Purcell, 1985; Bull, 1991). Desert pavements are a fundamental part of soil and landscape evolution of volcanic landforms (Wells et al., 1985; McFadden et al., 1986) and are found on a variety of landforms ranging from Holocene to Tertiary in age (Cooke and Warren, 1973; Bull, 1991). Well-developed pavements are common features of YPG and the Lower Colorado Sonoran Desert.

Rock Coatings

Rock Varnish

One of the most striking features of arid landscapes is the nearly ubiquitous presence of rock varnish; a thin, dark, shiny film or coating, found on the surfaces of pebbles, boulders, and rock outcrops (Allen, 1978). A typical rock varnish layer is less than half a millimeter deep on a rock's surface and is generally composed of about 60 percent clay minerals, 20 to 30 percent oxides of manganese and iron, and trace amounts of more than 30 other minor compounds (White, 1990). The source of these materials is eolian (wind-blown) dust. The rarity of well-developed rock varnish on Holocene aged geomorphic surfaces suggests that the formation of continuous black varnish coatings requires at least 10,000 years and develops slowly, at a rate of a few micrometers per thousand years. Rock varnish developed on surfaces of pavement clasts has been used to provide calibrated age estimates of Quaternary landforms (Christenson and Purcell, 1985; Bull, 1991).

The upper surfaces of late Holocene and Pleistocene desert pavement clasts at YPG and elsewhere in the Sonoran Desert are covered with manganese-rich (Mn-rich) rock varnish (Figure 2). The undersides of many clasts, particularly those on older, well-developed pavements, are covered with iron-rich (Fe-rich) rock varnish (Figure 3). In Arizona's Lower Colorado Sonoran Desert, (Elvidge and Collet, 1981) estimated that 75 percent of rock outcrops are coated or show significant traces of rock varnish, that alluvial and colluvial materials may or may not be varnished, and that the environmental conditions for varnish formation still likely exist. As is shown in Figure 4, the presence of well-developed Mn-rich rock varnish completely obscures host rock lithology in the visible wavelengths from 400 to 700 nm. Laboratory spectrometry was performed for this study to quantify the spectral effects of rock coatings in the reflected solar spectrum (400 to 2500 nm wavelengths).

Figure 2. Manganese-rich (Mn-rich) rock varnish on desert pavement clast sample.

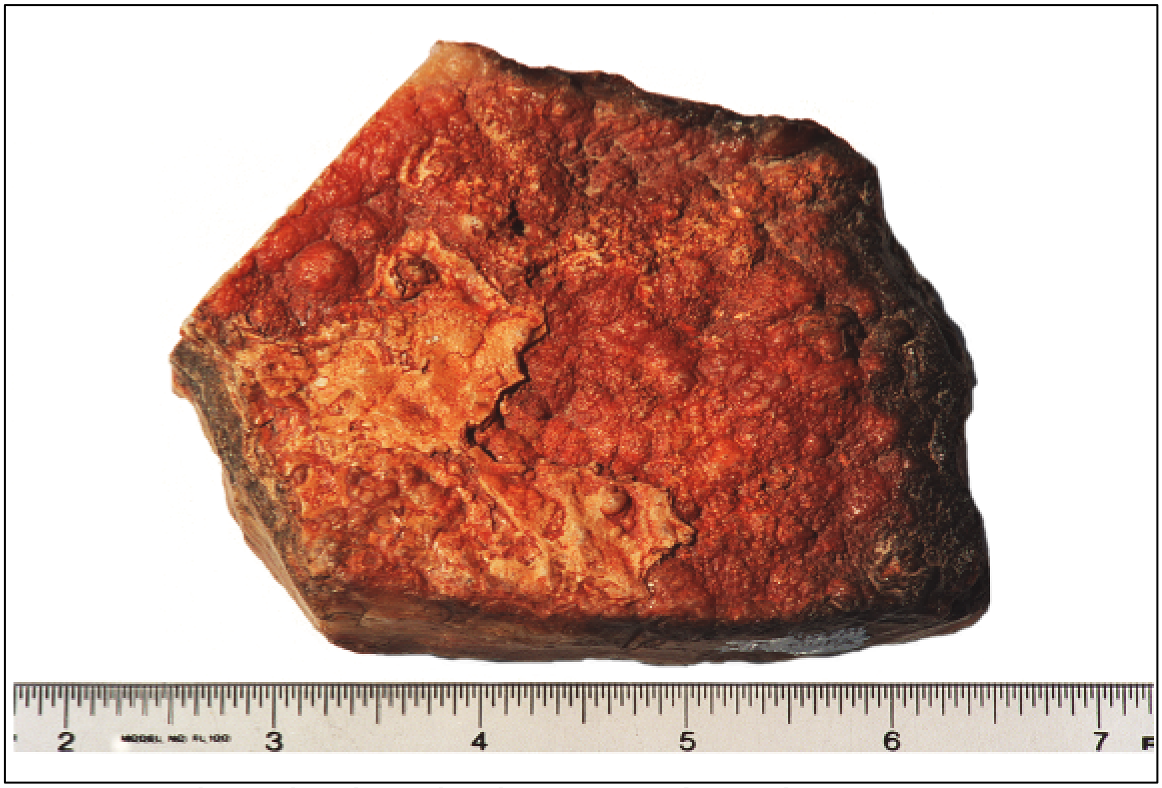

Figure 3. Iron-rich (Fe-rich) rock varnish on desert pavement clast sample.

Figure 4. Host rock lithology of desert pavement clast sample.

Spectral Effects of Rock Varnish

Laboratory spectrometry reported herein was performed with a FieldSpec FR Spectroradiometer (Analytical Spectral Devices, 1995) and a tripod mounted, 14.5 Volt, 50-Watt Lowel Pro-lamp light source. Data were acquired by positioning the spectrometer optical probe 3 to 5 mm above each sample and collecting ten different measurements across the surface of each clast. A spectralon panel was used as an ideal diffuse reference surface to calibrate clast measurements from raw digital numbers to spectral reflectance. Spectra were then compiled in a spectral library and individual measurements of each clast were averaged using Environment for Visualizing Images (ENVI) software (Research Systems Incorporated, 1999).

Figure 5 shows average hyperspectral reflectance signatures of the desert pavement clast shown in Figures 2 (sample top), 3 (sample bottom), and 4 (host rock interior). Three general observations are shown in these data. First, Mn and Fe-rich rock varnish have very different spectral reflectance characteristics. The second observation is that Mn-rich varnish has a much more pervasive effect on host rock reflectance than does Fe-rich varnish. Finally, the presence of either type rock varnish has serious implications for remote sensing studies in arid lands, particularly geologic mapping that attempts to delineate the spatial distributions of rock type and condition, and geomorphic mapping, concerned primarily with landform delineation and identification of geomorphic processes.

The major effect of Fe-rich varnish is to increase the overall brightness of the clast signature in the 500 to 2500 nm wavelengths without significantly changing the shape of the original host rock signature. This suggests that clast lithology could be mapped using hyperspectral remote sensing techniques in areas where Fe-rich varnish dominates the landscape. Alternatively, spectral attenuation by the well-developed Mn-rich varnish typical of the Sonoran Desert is twofold. First, Mn varnish both decreases spectral reflectance and significantly modifies signature shape in the visible and infrared wavelengths from 400 to 1800 nm. Since incident radiation is completely absorbed by the Mn varnish, spectral information in the 400 to 1800 nm wavelengths is limited to the varnish. However, spectral information the mid-infrared 2000 to 2500 nm wavelengths are brighter than, but similar to host rock reflectance. Fortunately, this wavelength region is where many diagnostic spectral absorption features for geologic materials are located, which also shows potential for lithologic discrimination. For example, although both the shape and depth are modified, neither Mn nor Fe-rich rock varnish significantly obstructed the host rock absorption feature centered on 2250 nm. Spectral absorption features exhibited by all 3 signatures at 1.4 and 1.9 nm are due to water absorption bands.

Weathering Rinds

Weathering rinds are uniformly thick zones of chemical alteration that occur around the periphery of clasts when they are exposed to environmental conditions at or near the earth’s surface (Birkeland, 1984). Rinds are common features in arid and semi-arid regions of the U.S., where they are typically several millimeters thick. However, weathering rinds are not limited to arid or even terrestrial environments, having also been observed on Mid-Ocean Ridge basalts (Seifert and Brunotte, 1995) and basaltic flows on surface of Mars (Burns and Fischer, 1993). Rates of chemical weathering vary with mineral composition and grain size of clasts as well as climatic regimes. For example, Birkeland (1984) notes that in the time it takes to completely weather granitic boulders to grus in a soil, dense volcanic rocks may show only thin weathering rinds. Data from an extensive study by Coleman and Pierce (1981) in which over 7,000 weathering rinds were sampled at 150 sites in the Western U.S. suggests that at least 4,000 years are needed to form incipient weathering rinds.

Fine-grained volcanic rocks like basalts often exhibit distinct rinds because the sharp coloration differences produce a clear boundary (Figure 6) compared to coarser grained volcanics and sedimentary rocks. A typical effect of chemical weathering on basalt is for feldspar and mica to be converted to clay and magnetite. Basalt weathering rind thicknesses increase at rates that are functions of the kinetics of chemical reactions at the inner edge of the advancing rind (Bull, 1991). As such, the green colored rind records an inward progression of chemical weathering, whose thickness corresponds to the duration of exposure of the sample. As is the case in Figure 6, weathering rinds may exhibit variable thicknesses because rinds are more friable than the underlying host rock and may separate from the clast surface due to spalling, exfoliation, biologic activity, or other physical weathering processes. Generally however, the arid, hyperthermic Sonoran climate and ubiquitous occurrence of rock varnish favor oxidizing conditions that promote rind growth as well as conditions of minimal rates of erosion of weathering rinds (Bull, 1991).

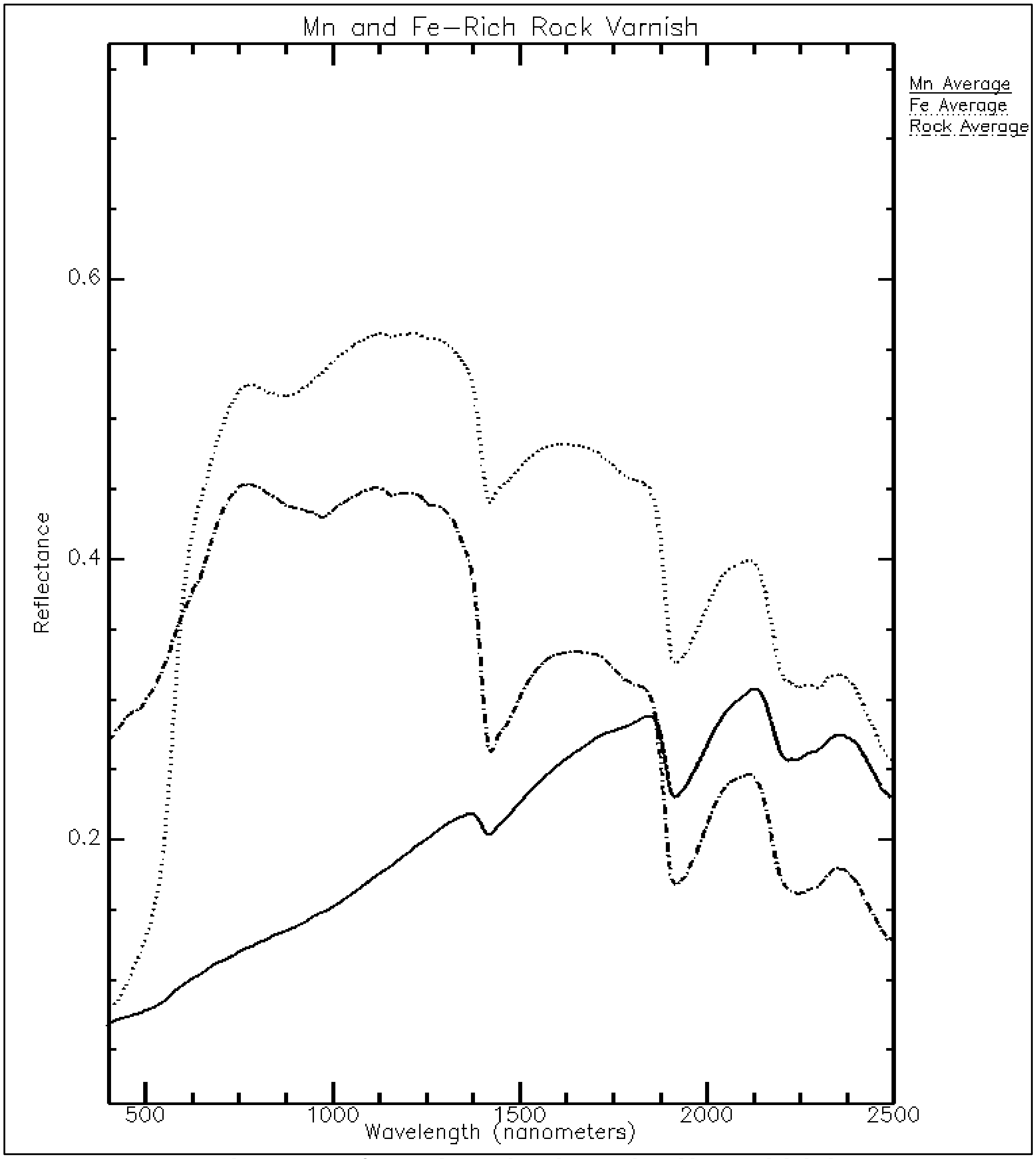

Figure 5. Hyperspectral signatures of Mn and Fe-rich rock varnish and host rock lithology.

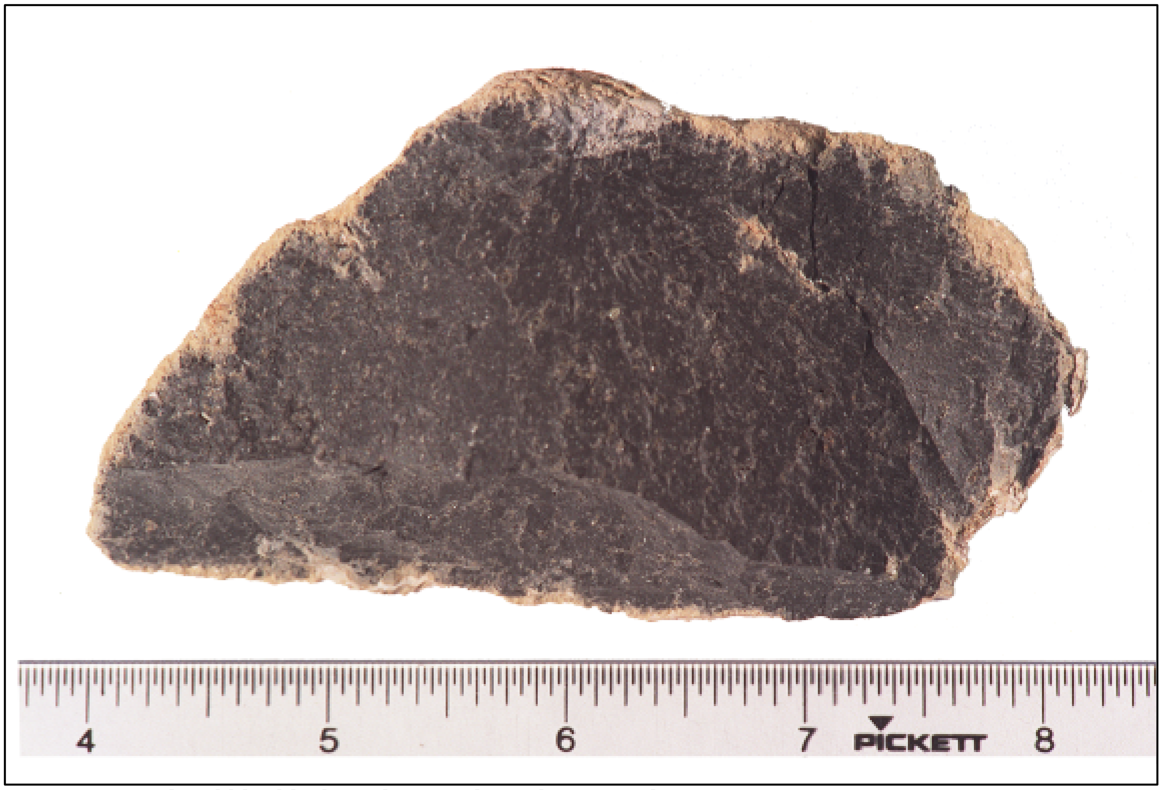

Figure 6. Basalt cobble (black) and external weathering rind (green).

Spectral Effects of Weathering Rinds

Figure 7 shows spectral reflectance of the basalt sample shown in Figure 6. Basalt has a dark, flat, and featureless spectral signature. The weathering rind is both brighter, particularly in the green and red portions of the visible spectrum responsible for its light greenish-yellow color, and also exhibits a strong, wide absorption feature centered at 1000 nm, as well as the water absorption features at 1400 and 1900 nm. Differences in the reflectance of fresh and weathered surfaces are highly significant in the reflected solar spectrum. Only the outermost layer of rocks, a depth between 5,000 to 10,000 nm actually contributes to spectral reflectance (Amos and Greenbaum, 1989). Since weathering rinds in the Sonoran Desert can form to a depth several millimeters, spectral signatures are derived completely from the weathered clast surface. In addition, because the products of chemical weathering are often chemically different than the original rock surface, classification and mapping errors can result due to misleading mineral constituent composition interpretations.

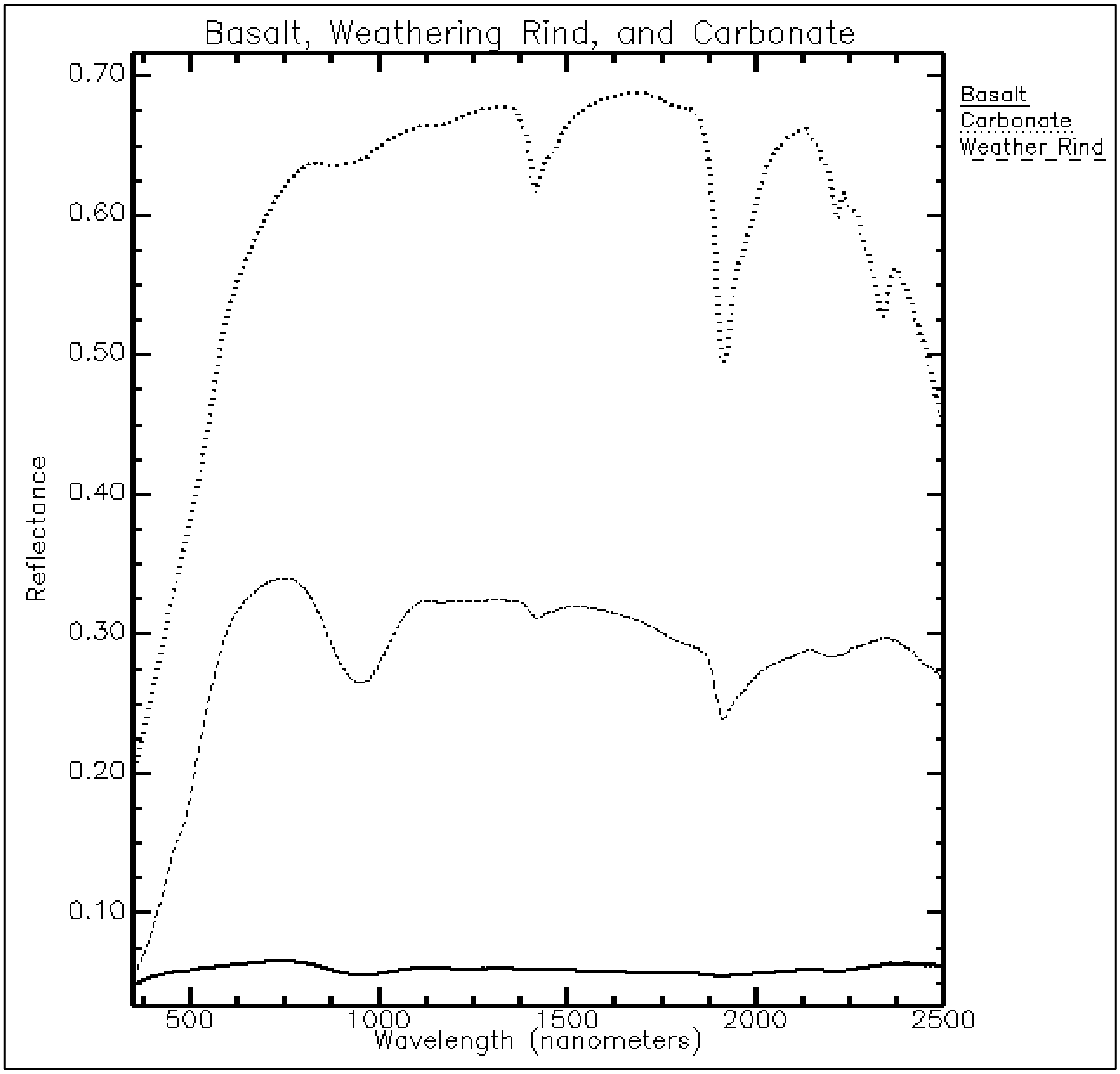

Figure 7. Hyperspectral signatures of basalt rock sample, weathering rind, and carbonate deposit.

Carbonate Deposits

Both Waters (1985) and Lashlee et al. (1999) discussed the geomorphology of different parts of YPG and summarized field observations of calcic horizons, indurated layers formed as calcium carbonate migrates in solution downward from A and B soil horizons and precipitates at depth. Stage II calcic horizon development is characterized by continuous coatings on subsurface pebbles and some inter-pebble filling. Figure 8 shows a thick carbonate deposit overlying the weathering rind of the basalt sample shown previously in Figure 6. Continued carbonate leaching and deposition over time leads to Stage III, characterized by greater inter-pebble filling and plugging of soil pore space.

Figure 8. Carbonate deposit (white) and weathering rind (green) on basalt clast sample from Figure 6.

Because carbonate deposition is a subsurface pedogenic process, coated rocks buried for some time in soil must be exposed at the surface to be a factor in remotely sensed data. The presence of desert pavement clasts containing significant amounts of carbonate are indicative of degraded surfaces that have been substantially reworked by surface erosion in the past, perhaps during less arid climatic conditions. Such geomorphic surfaces are not uncommon at YPG. It is also not unusual to find relatively young desert pavements, with immature soil profiles, that have formed on top of older, formerly degraded, then restabilized geomorphic surfaces, that have mature profiles at depth (Lashlee et al., 1999).

Carbonate can also form spatially extensive deposits of considerable thickness that over time may be exposed at the surface and visible in remotely sensed imagery. Figure 9 shows Stage IV carbonate deposits, the highest degree of development, characterized by an impermeable calcic horizon sometimes capped by pure laminate layers of calcium carbonate. Waters, citing Bull (1991), states that Stage IV calcic horizons like that shown in Figure 9, might require 50,000 years to develop. Therefore, Pleistocene soils typically have a greater accumulated volume of calcic horizons at greater depth and than do Holocene soils.


Figure 9. Calcium carbonate cemented Gila River fluvial gravels at Yuma Proving Ground.

Spectral Reflectance of Carbonate Deposits

Figure 7 shows the average of spectra collected from the carbonate, weathering rind and fresh basalt surface shown in Figures 6 and 8. Three observations can also be made from these data. First, carbonate reflectance is significantly brighter, not only in the visible wavelengths sensed by the human visual system (400 to 700 nm wavelengths), but across the entire reflected solar spectrum. Second, the carbonate signature lacks the strong absorption feature centered at 1000 nm exhibited by the weathering rind data. Finally, the carbonate data contain diagnostic absorption features at 2225 nm and 2350 nm that are absent from both the basalt and weathering rind spectra (Figure 10). It is clear from these data that materials present in and on the basalt clast shown in Figures 6 and 8 are chemically and spectrally very different substances.

Integrated Desert Pavement Spectral Reflectance

Mapping Quaternary geomorphic surfaces in arid and semi-arid environments requires an understanding of landforms, geomorphic processes, and the controls they exert on spectral reflectance. Geomorphic processes that dominate reflectance in the Sonoran Desert are desert pavement and rock varnish formation, eolian silt deposition, and fluvial dissection. As recorded at spatial resolutions currently available, desert pavements are spectral mixtures in which each pixel contains an integrated average reflectance of the surface materials present within its bounds. The presence, chemistry, and condition of rock coatings are primary considerations, particularly when applying new and emerging technologies like hyperspectral data analysis. Data presented in this paper clearly show that a single pavement clast sample can have more than one type of rock coating, each with significantly different hyperspectral signatures. The following discussion summarizes some important considerations related to spectral reflectance of desert terrain in order of significance-- rock varnish, lithology, soils, and vegetation.

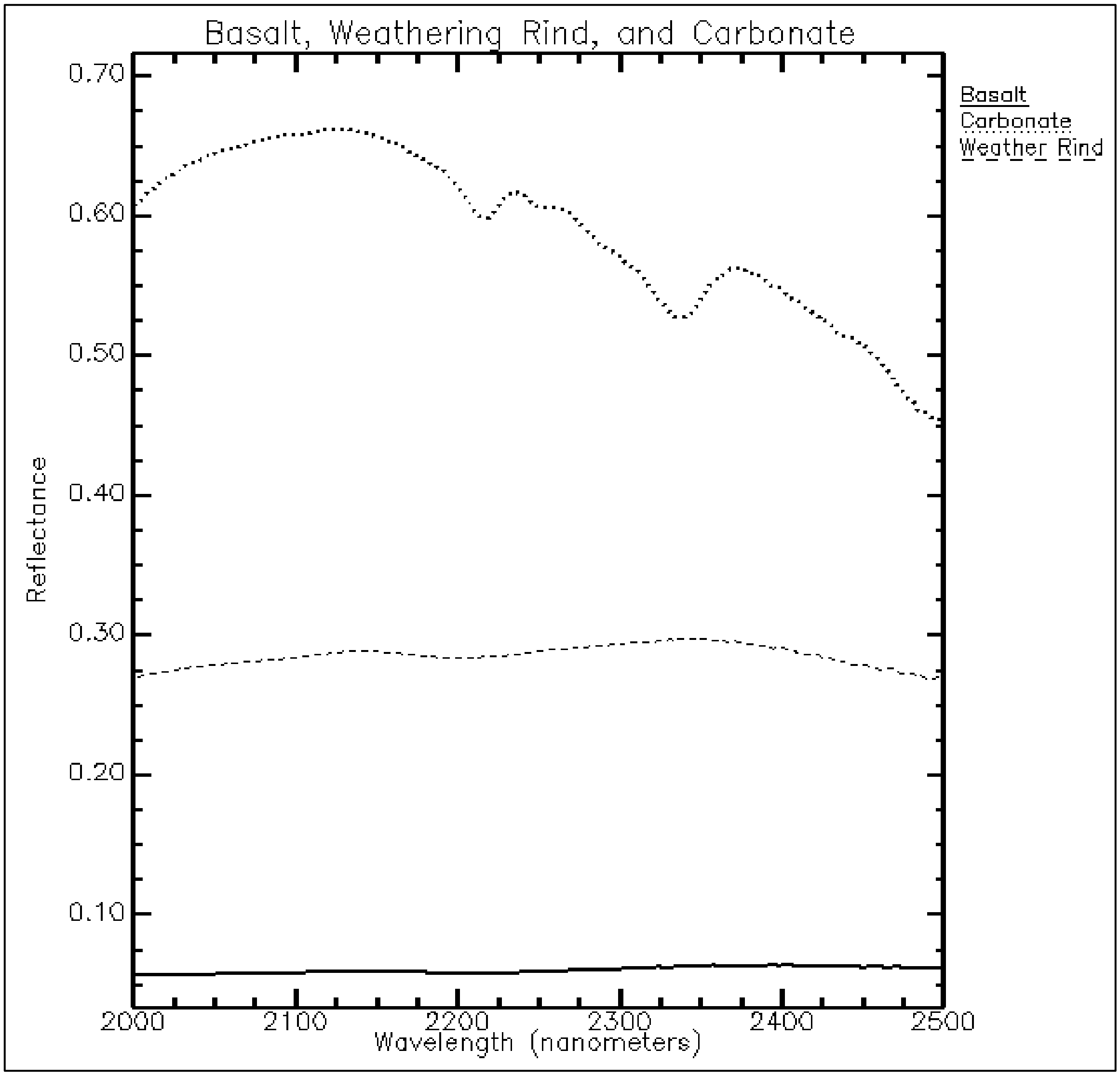

Figure 10. Spectral absorption features of carbonate deposit in the 2000 to 2500 nanometer wavelengths.

Rock Varnish

The degree to which lithologic information is obscured by rock coatings depends on the type of coating formed, its chemistry, morphology, and condition, which is in turn controlled by complex environmental factors (White, 1990). In the Lower Colorado Sonoran Desert, well-developed Mn-rich rock varnish generally precludes lithologic mapping in the 400 – 1800 nm wavelength regions. Only the 2000 to 2500 nm wavelengths are available for lithologic discrimination. Fe-rich coatings clearly have a less significant effect on host rock spectral reflectance characteristics than do Mn-rich varnishes. Pleistocene age desert pavements in the Sonoran Desert typically have Mn-rich on clast tops and Fe-rich on clast bottoms. Most researchers agree that this type varnish significantly decreases overall spectral brightness and that shorter wavelengths are absorbed by rock varnish coatings to a greater extent than longer wavelengths. However, there is disagreement in the literature on whether heavily varnished and sediment-coated surfaces retain reflectance information of underlying rock types. Spatz et al. (1987) and Rivard et al. (1992) found that long wavelength radiation penetrated varnish coatings resulting in lithologic spectral dominance, so bedrock information could be derived. Elvidge and Collet (1981) and White (1990) found that manganese-rich varnishes precluded lithologic recognition by obscuring underlying host rocks.

Rock varnish often develops discontinuously on pavement clasts (Figure 11), first filling in low spots in the rock surface. As a result, pits and groves are often more heavily varnished than smoother areas. Varnish may also adhere differently to the various minerals on a single clast. It is not uncommon for banded rocks such as gneiss to be varnished such that lithology is obscured in the visible wavelengths on all but the banded minerals, which show through. Differential rates of erosion on heterogeneous desert pavement gravels also contribute to spectral variation. For example, granular rocks, like sandstone and granite, may disintegrate before a varnish coat can form. Carbonate-based rocks like limestone may be too soluble, even in the desert, to form varnish.

Figure 11. Desert pavement surface with variable clast size and shape, types and amounts of rock varnish, heterogeneous clast lithology, and soil matrix.

Clast Lithology

Desert pavement clast lithology can be homogeneous or heterogeneous and it's common for pavements in close proximity to have very different lithologic and morphologic characteristics. For example, the authors have studied in detail 3 pavements with different stages of development and formed on different landforms in the Yuma Wash watershed at YPG. The youngest is an alluvial fan developed from mudflow and other alluvial deposits from a single canyon whose surface was later covered by volcanic rhyolite deposited during a Holocene igneous extrusion event. This surface has homogeneous lithology, very consistent brownish-red rock varnish development, and exhibits a strong bar and swale topography typically of young desert pavements. The middle age pavement is a truncated pediment whose clasts are composed of a heterogeneous mixture of banded gneisses, foliated schists, quartzites, and other metamorphic rock, each exhibiting different rock varnish characteristics. Directly across the channel is a Pleistocene stream terrace composed of alluvial fanglomerate, a mixture of potentially every rock type present in drainage basin. The clast shown in Figures 2 through 4 was collected on this surface and illustrates the well-developed Mn and Fe-rich rock varnish present. Soils geomorphology suggests the ages of these pavements range from 8 to 12 ka, 12 to 70 ka, and 70 to 200 ka, respectively.

In addition to lithologic differences evident in the 2000 to 2500 nm wavelengths, differences in rock type and relative age also result in surface roughness variations (gravel and cobble size and shape) which may be observable in optical remote sensing data as variable amounts of shadow. One should reasonably expect more shadow on surfaces with bar and swale topography and terrain where boulder and cobble fields exist as compared to the older, flatter well-developed desert pavement surfaces. Since shadow varies with sun angle, the amount of shadow in the reflected solar spectrum changes both seasonally and temporally throughout the day.

Soils

Laboratory and field data collected for this study, including soil texture classification, chemical composition analysis, and extensive field spectrometry data, support the accretionary desert pavement formation model (Wells et al., 1985) that holds that the underlying soil matrix is composed of eolian dust accumulating above a vesicular Av soil horizon. Soil samples from Av horizons at different locations at YPG have similar texture and mineralogy and therefore similar hyperspectral signatures, regardless of the geologic age, or available parent material of individual surfaces. These data not only suggest the dominant pedogenic process for pavement development is dust accumulation, but also that dust at YPG may originate from a single source area in the region. From a remote sensing perspective, this process has a normalizing effect on spectral contributions of soils, since it is likely the same for different aged pavements. This allows remote sensing geomorphologists to concentrate on the more problematic interpretations of integrated rock varnish, clast lithology, and surface roughness. It is however common to have variable amounts of soil matrix exposed in different aged pavements as well as different locations of the same surface. For example, the edges of some pavements at YPG are often lighter colored because runoff in the form of concentrated sheetflow overturns and disperses pavement clasts to a greater extent than at the center of the surfaces. It is not the composition of soil matrix that changes, but rather the amount of soil matrix exposed that is recorded in remotely sensed data.

Vegetation

Vegetation on desert pavement surfaces is generally sparse and typically restricted to washes that drain them. A study of pavement surfaces of Yuma, Arizona (Musick, 1975) found that underlying soils had a higher silt, clay, and salinity content than non-pavement soils in the area. As a result, pavements have slower infiltration rates, with little precipitation entering the soils compared to non-pavement soils, and precipitation that does enter the soil is held near the surface and evaporates quickly. Temperature extremes may also contribute to bareness of these surfaces. While the average maximum daily temperature for July is 41 C (106 F), Cochran (1992) found that temperatures within 1 inch of the black, desert pavement gravels in Yuma often exceed 160 F during July and August. The authors also measured pavement soil temperatures of 150 F in July 1998 at YPG. The restriction of vegetation to drainage networks of desert pavements is a valuable indicator of drainage pattern and density, both in the field and in remotely sensed data.

Summary

Understanding natural environments and geomorphic processes at the nations test centers is essential to installation management and critical to mapping, modeling, and simulation efforts. Desert pavements at YPG and elsewhere in the Lower Colorado Sonoran Desert are dominated by Mn-rich rock varnish and are spectrally featureless in that they contain no diagnostic spectral absorption features. Relative degrees of varnish darkening, or patination, have long been used as a relative age indicator in the fields of archaeology and geomorphology. A research question currently being addressed at YPG is whether hyperspectral remote sensing is an effective tool for determining both relative geologic age (500 to 1800 nm wavelengths) and dominant rock lithology (2000 to 2500 nm wavelengths) for mapping Quaternary geomorphic surfaces in the Lower Colorado Sonoran Desert. Spectral data presented in this paper demonstrate that, even under controlled laboratory conditions, remote sensing of terrains characterized by the presence of a variety rock coatings may be more problematic than is generally acknowledged by the remote sensing community.

Acknowledgements

Personnel of the U.S. Army Yuma Proving Ground, Material Test Command, Engineering Division, and the Oregon State University Department of Geosciences conducted this research. The authors gratefully acknowledge those who contributed significantly to completion of the study. Funding was obtained from the U.S. Army Engineer Waterways Experiment Station Laboratory Discretionary Research Program. The YPG Command Technology Directorate provided technical and logistical support. Zhao Lu of Analytical Spectral Devices, Inc performed laboratory spectrometry. Soils geomorphology was performed by Dr. Eric McDonald of the Desert Research Institute Quaternary Sciences Center. Valerie Morrill, YPG Conservation Manager, assisted with vegetation and study area descriptions. This report has been approved for public release; distribution is unlimited.

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