MAPPING AND CORRELATING DESERT SOILS AND SURFACES WITH IMAGING SPECTROSCOPY

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Abstract. The soils and geomorphic surfaces of large regions of semi-arid and arid land in North America (Basin and Range, Mojave and Sonoran Deserts) are unmapped and uncorrelated. AVIRIS provides a vehicle to test the special capabilities and potential limitations of imaging spectrometers to monitor and detect continuous broad spectral changes, characteristic of soil spectral evolution, as well as narrow absorption features associated with variations in clay concentration and mineralogy in developing soils. It has been demonstrated that the relative ages of stable geomorphic surfaces and certain developmental properties of the "soil chronosequences" associated with these surfaces, are "spectrally" correlated and can be assessed by remote sensing. Regional mapping of contemporaneous geomorphic surfaces, by fully exploiting soil spectral evolution with imaging spectroscopy, would provide valuable new interpretive base maps linking soils and geomorphology, their temporal relationships, and potentially paleoclimates. Studies based on these maps would guide researchers to concentrate their efforts on either focused or regional spatial scales and would facilitate investigations into geomorphic thresholds, paleoclimatic boundaries and impacts, and soil developmental relationships (genesis and morphology).

Introduction

Soils developed on granitic alluvial fans of the broad Sierran piedmont of Owens Valley, California, over the past 0.5 Million years have been differentiated by their reflectance spectra, as measured by the six-channel Landsat Thematic Mapper (TM) [Gillespie et. al., 1986, Smith et. al., 1990a,b], the seven-channel airborne Thematic Mapper Simulator (TMS) [Gillespie et. al., 1986, Fischer, 1991], and most recently by the the 224-channel Airborne Visible / Infrared Imaging Spectrometer (AVIRIS) [Gillespie et. al., 1990b, Fox et. al.,1990, Fischer, 1990]. The soils range from undeveloped or very weakly developed Torriorthents on recent (Holocene age) inset and distal fans, to well developed Haplargids on older (late Pleistocene age) proximal and medial fans. These soils have developed without significant eolian carbonate enrichment or organic carbon accumulation in 'A' horizons but, display distinct morphologic development in: Horizonation, structure, consistence, clay formation, and oxidation with a consistent increase in color rubification; reddening (hue) and brightening (chroma), with increasing age.

Reflectance spectra of the fans differ in proportion to the concentrations of iron oxides and hydrous clay minerals coating sand grains exposed or deposited at the surface through "bioturbation"(accelerated soil mixing caused by burrowing fauna).

Soil-geomorphic field studies at Oak Creek and Birch Creek, on the Sierran piedmont, have demonstrated that surface spectral differences (spectral signatures) are associated with real differences in soil development through time [Burke et. al., 1986, Gillespie et. al., 1986]. Thus it appears that remote sensing can be used to differentiate relative soil ages and correlate contemporaneous geomorphic surfaces in arid and semi-arid deserts, possibly over vast regions. The spectral resolution of imaging systems like TM are too coarse (low-dimensional) to resolve the sharp hydroxyl absorption bands of clays near 2.2 µm. Thus multispectral systems like TM are insensitive to variations in clay mineralogy, which are important in characterizing soils and are diagnostic of climatic and paleoclimatic regimes. Furthermore, the band positions and the limited number of TM channels are such that dry grass and certain mixtures of soil and shrubs appear spectrally similar. This ambiguity increases the uncertainty of soil spectra estimated from TM data.

Pine Creek offers a geological setting where alluvial fans are correlated to an established "sequence" of glacial moraines with regional expression. The age limits placed on these moraines also constrain the ages of adjacent, geomorphically related alluvial fans. Pulses of fan deposition were roughly synchronous with Pleistocene glacial-interglacial cycles driven by paleoclimatic change. Lateral breaches of specific moraine crests resulted in a sequence of discrete lateral debris flow fans. The breaches were apparently induced by supraglacial streams during periods of maximum glacial advance. Distal fans associated with the same glacial stages, however, were deposited dominantly during deglaciations. This temporal control provides an advantageous environment in which to test the capabilities and limitations of AVIRIS to differentiate broad spectral signatures associated with the subtle spectral evolution of surfaces only slightly different in age. In addition, AVIRIS sensitivity to narrow clay absorbtion features, potentially diagnostic of soil genesis and ancient climatic regimes, was also evaluated.

Methods

Field soil investigations were conducted on the geomorphic surfaces of the Pleistocene and Holocene distal fan sequence (Figure 4a, letters 'D' & 'H') and the Pleistocene lateral fan sequence (Figure 4b, letter 'L') to obtain surface and soil-specific data. Soil profiles were described, samples were collected and analyzed for particle size distribution (sand, silt, clay), and clay characterization (X-Ray Diffraction). Profile Development Index (PDI) [Harden, 1982, Harden and Taylor, 1983] was used to quantify selected properties of each soil, providing an independent semi-quantitative age estimate for each fan surface. About 1 centimeter thick surface soil samples were collected and sieved to retain the 250 µm - 2 mm sand fraction. Beckman laboratory spectral analysis (0.4 - 2.45 µm region) was performed on these sands to determined the "spectral signature" of each surface and to provide the ' reference' spectrum of both soil endmember components used in modelling. These field and laboratory data, evaluated with respect to the age constraints established for each surface, became the independent variables or standards against which AVIRIS capabilities, limitations, and sensitivity were measured.

High-dimensional (224 channel; 0.4 - 2.45 μm) AVIRIS images of the Pine Creek area were acquired by NASA on July 29, 1989. 171 channels of meaningful data were obtained. Spectral Mixture Analysis (SMA) was used to process the data. In essence, SMA provides a strategy for analyzing images to extract compositional information based on the principles of field mapping. Signals from each pixel, as expressed by radiance or reflectance values in each channel, are separated into components (endmembers) representing spectrally distinct surface materials and instrumental or atmospheric effects. Endmember components are selectively edited and recombined to form image units interpretable within the framework of field map units [Adams et. al., 1989, Adams et. al., 1990]. This approach calibrates the image data and models them as linear mixtures of laboratory reference spectra (Beckman spectra of field surface samples used for soil endmembers). Four reference endmembers, present in various proportions, at the pixel 20 meter scale, were selected: RED SOIL (moderately developed, well oxidized and argillic), WHITE SOIL (undeveloped and sandy), vegetation (alfalfa field), and shade/shadow. The final result of SMA is a "fraction" image of proportions of each spectral endmember. The remaining unmodelled data, are concentrated in residual images for each band [Gillespie et. al., 1990]. The spectral effects of vegetation (~15% cover on distal fans, mainly *Coleogyne* ; and ~15 -20% cover on medial fans, largely *Ephedra, Artemisia*, and *Purshia*) and topography (shade and shadow) present in various additive proportions of each pixel and modelled as scaled fractions in DN s of brightness may be suppressed or removed from the data at this point, leaving information on soil alone. In such a display, soil development proceeds along a spectral evolutionary path or trajectory (soil spectral evolution) between the undeveloped WHITE SOIL and the moderately developed RED SOIL reference endmembers. Any given soil unit in the image will plot along this trajectory, at a position that corresponds to its degree of development (Figure 2). In this manner, statistical testing of differences and similarities, and thus quantitative relative dating, is possible.

The "soil-surface-spectral" relationships that support the strategy for regional chronocorrelation and mapping of geomorphic surfaces are summarized in Figure 1. This flow chart depicts the general processes and procedures required to effect results. Initially a climatic change, either gradual or abrupt, must trigger local or regional geomorphic thresholds to be exceeded. In the case of regions with similar geologic settings, lithologies, and climatic influence, the triggered geomorphic response may in fact be regional, producing depositional or erosional surfaces that are contemporaneous across large or even vast areas. Localized chronosequences in such cases could be chronocorrelated to others within the region. Where settings, lithologies, and climatic influences are highly variable or complex within or across regional or threshold boundaries, synchroneity of events on broad spatial scales is unlikely and local chronosequences may be out of phase with others within the region (Figure 5) [Fischer and Booker, 1989]. When a new surface is abandoned following an event it becomes geomorphically stable and time zero for soil development begins. Soil horizonation begins to concentrate soil properties within shallow layers that thicken and deepen with time. Bioturbation by burrowing insects and rodents then excavates sand grains from these horizons (primarily the 'B' horizons where clay minerals accumulate and iron oxides form) and deposits representative samples at the surface. The concentration of iron oxides and hydrous clays coating these exposed sand grains become the surface expression of soil development at depth.

This enables soil spectral evolution to function as a remote measure of soil development and surface age. Detection, modelling, correlation, and mapping of surfaces can then follow. Ground-truthing and age control must be maintained to ensure accurate mapping, keep the model calibrated to surface soil, vegetation, geomorphic, and geologic units or parameters, and to signal the need to reevaluate the model endmembers as thresholds or boundaries are crossed.

Results and Implications

Color slide 3 shows a fully modelled scene at Pine Creek and is provided at the back of this publication. Discussion of results and interpretations, however, will be referred primarily to the scaled fraction images of the WHITE SOIL and RED SOIL reference endmembers (Figure 4a & 4b) respectively. It is quite evident that effective spectral differentiation of the surfaces has been achieved. The differences, while subtle on individual surfaces, are quite diagnostic when comparing the pleistocene lateral and distal fans. PDI age difference between the two is only about 5 - 8 ka (laterals fans are ~28 ka and the distal fans ~20 ka). The lateral debris flow fans show subtle gray scale differences among themselves in Figure 4b, and when viewing the modelled color slide, differences are apparent. It also became evident that areas of dry grass are still being spectrally confused. In this case with the moderately developed RED SOIL endmember (Figure 3). This problem is also prominent in the RED SOIL reference endmember fraction image (Figure 4b) where it can be located by the letter 'G' on Holocene age surfaces in distal fan and ephemeral stream delta positions. While the slide shows RED assigned to the developed RED SOIL component, BLUE to the undeveloped WHITE SOIL component, and GREEN to VEGETATION, the dry grass sites appear quite red. The problem of dry grasses and senescent vegetation (Figure 3) can be reduced or eliminated by a number of strategies and techniques now being studied or tested [see Roberts et. al., 1990, Smith et. al., 1990a,b, Gillespie et. al., 1990a,b]. Spalling granitic clasts mantling a surface and exposed granitic boulders that form debris flow levees have also be confused with undeveloped sandy soil in some areas where they are unrelated to surface age or reflect original surface condition [Gillespie et. al., 1986; Fischer, 1991]. Figures 4a & 4b are essentially reciprocals or compliments of one another which can be conceptually represented by the spectral relationship shown in Figure 2. The advantage provided by high-dimensional imaging spectrometers to monitor continuous broad spectral signatures and detect broad often subtle transitions or changes (soil spectral evolution), that may go unnoticed or undetected in low-dimensional systems like TM, make it possible to resolve these problems through modelling techniques, spatial interpretation, or evaluation of residual images of unmodelled scene constituents or narrow diagnostic absorbtion features. Secondary clay minerals developed in soils and brought to the surface, if detectable, would provide valuable information about soil genesis and paleoclimatic regimes. Particle size determination of the surface soils showed a range of only about 1 - 4% clay. Inspection of the band residual images near 2.2 μm after modelling revealed no residual clays [Gillespie et. al., 1990]. This means that either all the clays present, in low concentration, were effectively modelled by the RED SOIL endmember, or that the instrument was insensitive to small differences in clay concentration or mineralogy. XRD of several surface soil samples indicated that smectites dominate the clay fraction with Montmorillonite most abundant. Traces of Kaolinite were also present.

Spectral detection and discrimination of 1 - 4% clay concentrations in surface soils may be close to the limit of AVIRIS sensitivity in spectrometer D. With improved SNR this capability will be a powerful diagnostic tool. Spectral sensitivity to subtle differences in surface/soil ages appears to be at least as accurate as would be determined from conventional mapping techniques. However, mapping and chronocorrelation of geomorphic surfaces and their soils on regional scales, in semi-arid and arid environments, using remote sensing, is much more practicable than conventional mapping techniques. The soil-surface-spectral relationships and SMA provide a strategy to effectively study geomorphic patterns, transitions or thresholds on broad regional scales. Regional maps would serve as a guide for more focused research into clues to regional geomorphic and soil developmental response to paleoclimatic change.

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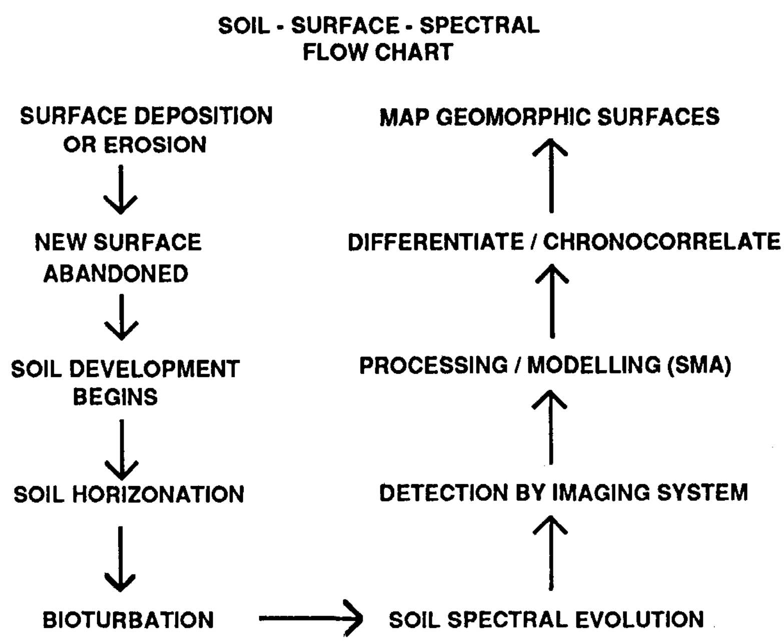


Figure 1. Flow chart depicting the processes, relationships, and gross strategy required for regional mapping of contemporaneous geomorphic surfaces by remote sensing in semi-arid and arid envirnments to be efficient and practicable.

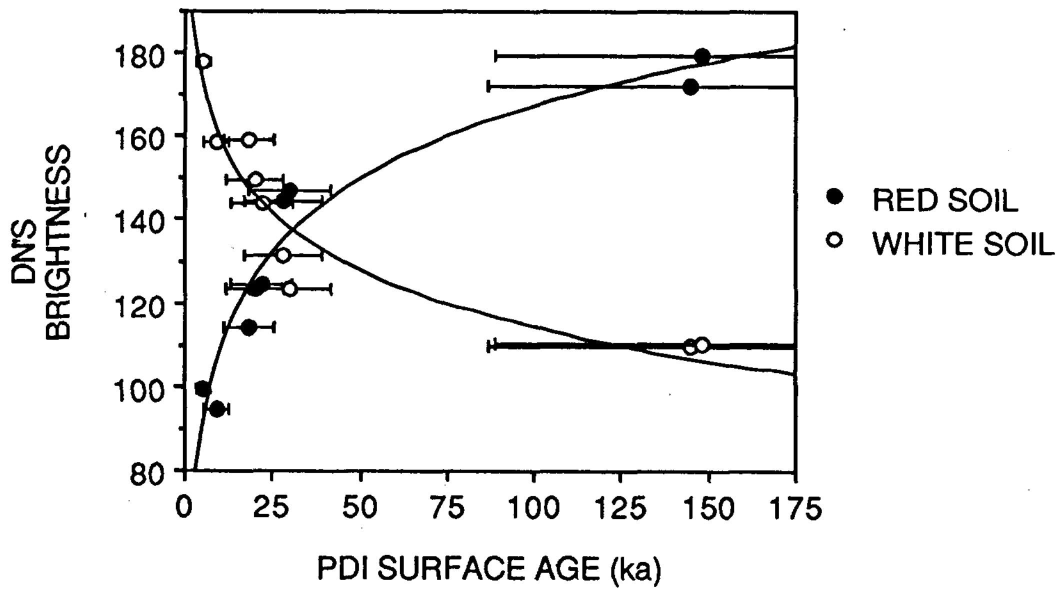


Figure 2. A plot depicting the spectral relationship between RED SOIL and WHITE SOIL reference endmember scaled fractions from surfaces with age control. The moderately developed (well oxidized and argillic) RED SOIL fractional DN's increase, while the undeveloped sandy WHITE SOIL fractional DN's decrease, with increasing surface age. (Error bars show ~40% of PDI derived surface ages as error for Quaternary surfaces in Basin and Range Province).

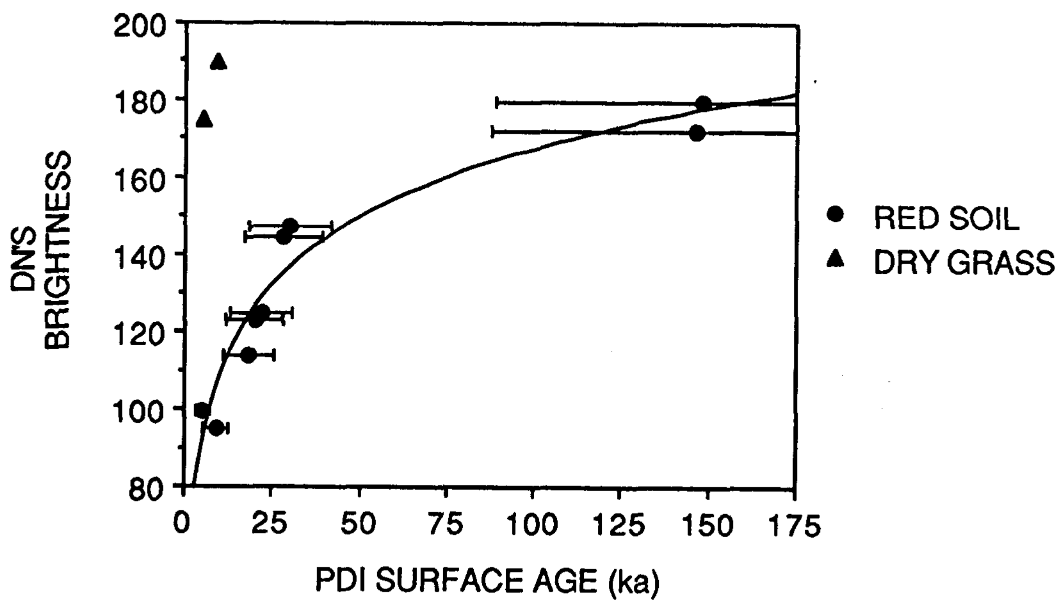
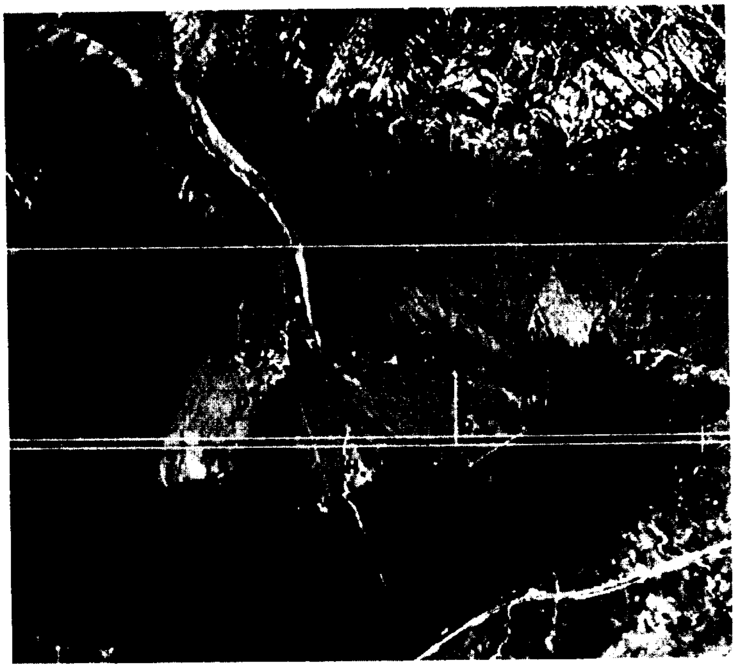


Figure 3. A plot depicting the increasing scaled fractional component of RED SOIL with increasing surface age, complicated by dry grasses on holocene age surfaces. (young Holocene surfaces appear to be pleistocene age).



A.

B.

Figure 4. Two reference endmember fraction images, Pine Creek. (light = high fraction; dark = low fraction) **A.** (top) undeveloped sandy WHITE SOIL (H = holocene distal fan; D = pleistocene distal fan; W = white soil reference endmember sample site (Beckman lab spectra). **B.** (bottom) moderately developed, well oxidized, argillic RED SOIL (L = pleistocene lateral fans; G = dry grass areas; R = red soil reference endmember sample site. H, D, & L letter placement on images denotes soil pit locations. North is right.

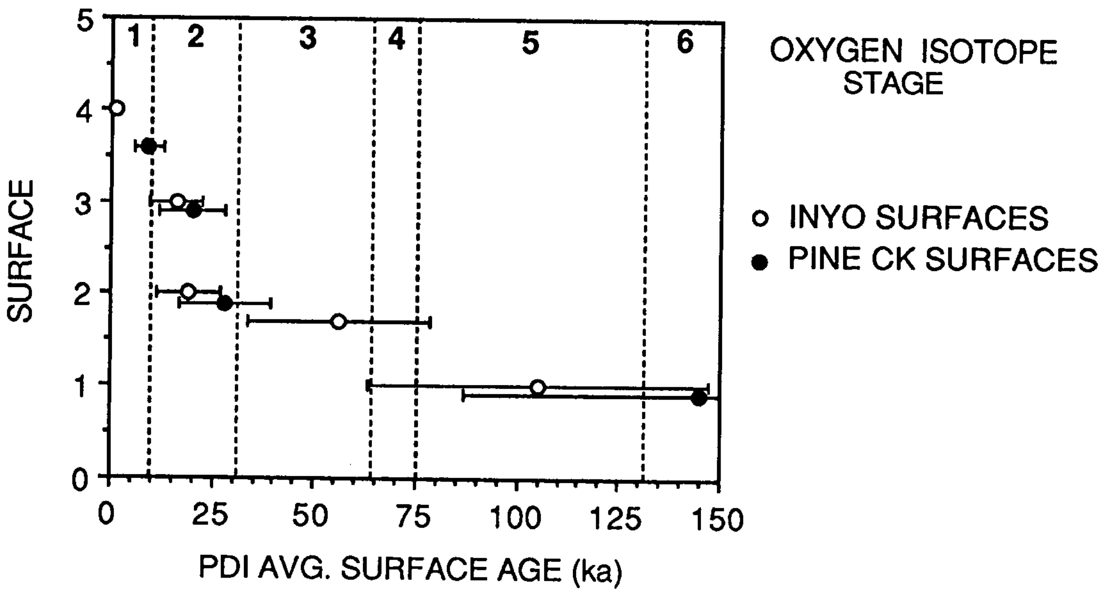


Figure 5. Geomorphic threshold affect on surface deposition and formation. PDI derived average surface ages for Pine Creek, Sierra Neveda and Inyo Mountain fans. Roughly synchronous glaciations of Eastern Sierra produced contemporaneous soils and surfaces. The fans of the unglaciated Inyo Mountains, however, are out of phase with the Sierran Fans, but display their own chronsequences. Rain shadow of Sierra Nevada during glacials and interglacials (Pleistocene).