Identification of Fluvially Redistributed Mill Tailings Using High Spectral Resolution Aircraft Data

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Abstract

High spectral resolution data have been successfully used to separate hydrothermally altered rocks from other rock assemblages on the basis of unique clay mineral absorption features at infrared wavelengths. Geoscan Mk II data were therefore acquired to delineate mercury-contaminated mill tailings located within an EPA Superfund site in north central Nevada. These mill tailing sediments are composed of hydrothermally altered material and should be distinguishable in the Geoscan data. This paper discusses the identification of redistributed mill tailings on the alluvial fan located at the terminus of Sixmile Canyon near Virginia City, Nevada; a site where detailed field and geochemical studies have been conducted. Data analysis included georectification, accurate location of mill tailings in the field, utilization of a similarity index mapping algorithm to identify potential mill tailings in the data, and generation of maps. The similarities between surficial geology and Geoscan generated maps indicate that contaminated mill tailing materials located on the surface are generally distinguishable from other fluvially deposited sediments. The Geoscan map does incorrectly define some non-contaminated regions. Nevertheless, the Geoscan map provides guidance for the design of field sampling programs and significantly reduces the size of the area requiring intensive field investigation.

Introduction

During the mid-to-late 1800s, the Carson River Basin was significantly impacted by mining of the Comstock Lode (Cooper *et al.*, 1985), one of the richest silver producing ore bodies in mining history. During the approximate 40 years of mining (1859 to 1900), precious metals were extracted from hydrothermally altered parent rock at more than 100 mills established along the Carson River and its tributary canyons (Figure 1). The milling facilities utilized a crude mercury amalgamation process that resulted in mercury-laden waste. These wastes, referred to as "mill tailings" in this paper, consisted primarily of pulverized hydrothermally altered rock fragments. It has been estimated that 7,500 tons of mercury were released with the tailings during the milling process (Bailey and Phoenix, 1944; Smith, 1943).

During the past 130 years, runoff from rainfall and snow- melt has transported and redeposited portions of the mercury contaminated tailings. Presently, the full extent of downstream contamination is not known. However, mercury concentrations exceeding 100 ppm have been measured along the Carson River, more than 60 km downstream of mining and milling sites (Lechler, unpublished data). Mercury concentrations exceeding background levels (10 to 20 ppb in soils) have been detected in the Stillwater National Wildlife Refuge and the Carson Sink (Figure 1) more than 80 km downstream from the major mill sites (Cooper *et al.*, 1985). In addition, preliminary studies by the Nevada Department of Conservation and Natural Resources found elevated mercury levels in biota, primarily fish and waterfowl, throughout the Carson River valley. It is clear from these investigations that the spatial extent of contamination is enormous and the size of the area requiring detailed field investigation and geochemical analysis must be reduced.

The development of high spectral resolution sensors have made it feasible to map mineral components of the Earth's surface (Goetz *et al.*, 1985). For example, Goetz *et al.* (1983) found that clays associated with hydrothermal alteration zones have an identifiable decrease in reflectance in the 2.1- to 2.4-μm region of the spectrum relative to the 1.6 μm region, a characteristic that is used for mapping purposes. The numerous narrow bands (typical bandwidths range between 10 and 50 nm) of high spectral resolution sensors permit detection of minerals that have distinctive absorption minima at specific wavelengths. These absorption minima are not resolved by broad band sensors such as Landsat multispectral scanner (MSS) that has bandwidths between 100 and 200 nm (Goetz *et al.*, 1985).

In a study of the Cuprite, Nevada area, an alteration map was derived from AVIRIS data (Airborne Visible/Infrared Imaging Spectrometer) based on the absorption characteristics of the hydrothermally altered rock in the 2.0 to 2.4 μm region of the spectrum (Hook and Rast, 1990). The AVIRIS sensor acquires 224 bands of spectral data at bandwidths of 10 nm. Swayze *et al.* (1992) verified a Cuprite, Nevada, mineral map derived from analyzing AVIRIS spectra. Using x-ray diffraction, the presence of 12 out of 18 minerals mapped employing AVIRIS analysis was confirmed. They concluded that, overall, the AVIRIS derived map was accurate and that the only difficulties were the subtle wavelength shifts in spectral features (i.e., absorption minimums and reflectance maximums) for solid solution series minerals such as alunite and montmorillonite.

Lyon and Honey (1990) were able to map alteration

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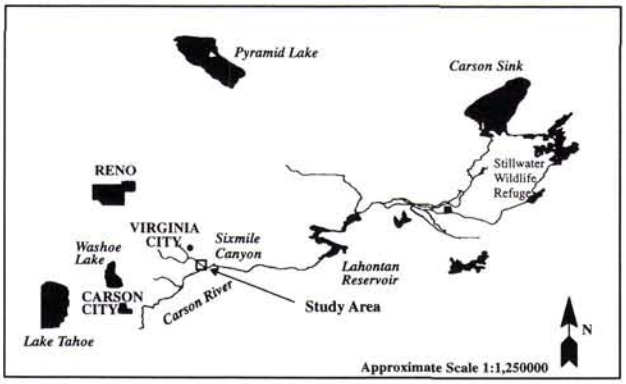

Figure 1. Map of the Carson River Valley, Nevada. The Sixmile Canyon alluvial fan study site is indicated by the small box.

zones and mineral deposits using the Geoscan Mk II scanner for one area in Australia and three areas in Nevada. They reported that the eight 53-nm-wide shortwave infrared bands acquired by the Geoscan sensor were narrow enough to enable mapping of alteration minerals. Because the Sixmile Canyon mill tailings are composed of hydrothermally altered rock, it was hypothesized that the tailings could be successfully identified from high spectral resolution data.

Thus, the objective of this study was to identify mill tailing sediments that had been fluvially redistributed within the Sixmile Canyon alluvial fan (Figure 1) by analyzing data acquired with the 24-channel, Geoscan Mk II sensor. The resulting spectral maps, delineating regions consisting of contaminated tailings materials, would reduce the area requiring intensive field investigation and geochemical sampling. Currently, the best surficial geologic maps of tailings-contaminated areas are of the alluvial fan located at the terminus of Sixmile Canyon. These maps were constructed using both field and geochemical data, and can be utilized to assess the accuracy and success of the image processing procedures.

Analysis of Geoscan Spectral Data

Data analysis occurred in five phases: (1) data acquisition, (2) georectification of the Geoscan data, (3) accurately locating mill tailings in the field, (4) identification of mill tailings using a similarity index mapping algorithm, and (5) final product generation. Analyses were performed in the order listed above and required the use of three different hardware and software systems. The ERDAS version 7.5 image processing system and the Environmental Protection Agency's (EPA) inhouse algorithms running on SUN SPARC 1+ workstations were used for georectification and final product generation. PCI, Inc. PACE version 5.0 software on a Silicon Graphics Personal Iris was used for data preprocessing, and WTJ Software Services GenIsis version 3.0 software running on an MS-DOS personal computer was used to identify spectrally similar areas.

The procedures utilized for this research were selected for their relative ease of use and quick results. Most research employing high spectral resolution data entail the use of atmospheric correction and radiometric calibration algorithms, acquisition of field and/or laboratory spectra, and sophisticated spectra comparative algorithms (Kruse *et al.*, 1990). Because this technique did not compare field or laboratory spectra to the Geoscan data, atmospheric correction and normalization procedures were not employed. The techniques used for this project included GPS (Global Positioning System) measurement of known mill tailings location in the field; using those coordinates to extract and average spectra from the same locations in the georeferenced Geoscan data; and using the average spectrum to identify other areas with similar spectra. The only requirement for this technique was that the Geoscan data had to be georeferenced prior to average spectrum extraction and similarity mapping.

Data Acquisition

The data used for this project were acquired at 11:50 AM Pacific daylight savings time on 10 August 1991. The spatial resolution of the data was three metres. The Geoscan Mk II scanner acquires 24 channels of spectral information. The sensor has roll, pitch, and yaw stabilization and drift compensation. The field of view is ±45 degrees from nadir with an instantaneous field of view (IFOV) of 2.1 by 3.0 milliradians. The central wavelength and band width for each of the 24 channels are presented in Table 1.

Pre-Processing Procedures

Prior to data analysis, the data were checked to determine data quality and that the data were acquired on line; that is, the areas depicted in the data are the same as the areas on the flightline map. The scan mirror on the Geoscan sensor acquires scanlines from right to left instead of the commonly utilized left to right orientation. In addition, the data were acquired from south to north. Therefore, when viewing the original data on the computer monitor, the resulting image

Table 1. Wavelength Intervals for the 24-Channel Geoscan Mk II Sensor

Channel#	Central Wavelength (μm)	Bandwidth
Visible Channels		
1	0.522	0.042
2	0.583	0.067
3	0.645	0.071
4	0.693	0.024
5	0.717	0.024
6	0.740	0.023
7	0.830	0.022
8	0.873	0.022
9	0.915	0.021
10	0.955	0.020
Near Infrared Channels		
11	2.044	0.044
12	2.088	0.044
13	2.136	0.044
14	2.176	0.044
15	2.220	0.044
16	2.264	0.044
17	2.308	0.044
18	2.352	0.044
Thermal Infrared Channels		
19	8.640	0.530
20	9.170	0.530
21	9.700	0.530
22	10.220	0.533
23	10.750	0.533
24	11.280	0.533

was upside-down and transposed. PCI Easi-Pace software was used to mirror and rotate the data into a proper orientation. This procedure did not resample or alter the raw response values in any way other than to move each pixel value into a new orientation. Because the techniques planned for data analysis did not require comparison of the Geoscan data to field or laboratory reflectance spectra, no other pre-processing procedures were employed.

Geometric Correction

The final product of this study was a map that could be used for field sampling purposes. Therefore, it was critical to accurately georectify the Geoscan data into geographic coordinates (Universal Transverse Mercator (UTM) projection). Typically, spectral analysis is conducted prior to georectification because the rectification algorithms cause some spectral smoothing. However, this effect is relatively small due to the high spatial resolution of the data and the large number of relatively uniform pixels in the area of interest.

The georectification process was the most time intensive part of this study as it required several iterations. A sufficient number and spatial distribution of control points had to be identified during the several iterations to attain a reliable georectification. The reason for the difficulty was due to the limited number of identifiable control points and the large amount of topographic variability. The flight line covers significant topographic change. Considering that the aircraft flew at a constant altitude, the changes in topography resulted in corresponding changes in pixel size, although these changes were less than one metre. It is also possible that the sensor stabilization and drift compensation did not completely remove all effects of aircraft movement on the scanner data as it was recorded, especially if turbulence was encountered.

The georectification utilized in-house EPA Environmental Monitoring Systems Laboratory algorithms (developed by Ridgeway Weerackoon of the Desert Research Institute, unpublished). The first step required selection of identifiable points, i.e., ground control points or GCP, common to the Geoscan data and USGS 7.5-minute quadrangle maps. These coordinates (control point easting/northing and image row/column) were used to develop coefficients to determine the row and column positions within the rectified image file. The coefficients were calculated by an overall cubic equation. (Linear and weighted linear equations did not perform as well as the overall cubic.)

Prior to calculation of the coefficients, the algorithm used the GCPs gathered by the analyst to produce an output grid in UTM coordinate space. If any of the GCPs did not fall within a user-specified threshold (five pixels for this study), they were not used in the calculation of the coefficients. The total number of GCPs defined was 22, 18 of these GCPs were retained to calculate coefficients, and the final RMSE (root-mean-square error) values for rows and columns were 2.468 and 1.377, respectively. The RMSE is an indication of how well the GCPs were mapped into UTM grid space. For example, a row RMSE of 2.468 means that the cell position within the UTM grid may be incorrect by ± 2.468 cells or pixels of easting. Transposed into metres, these RMS values indicate that the GCPs were mapped to correct northing/easting coordinates within ± 9 metres of the USGS map position. However, USGS quadrangle maps contain inherent error (discounting paper stretch, USGS states that 90 percent of all identifiable points are within 1/50 of an inch of their true position on the map, i.e., ± 12 metres) and that there will be areas (non-GCP pixels) within the data where the errors may be larger.

The final part of the georectification process was the actual calculation of pixel or cell response values for the UTM grid. Rectified pixels were assigned an appropriate response value based on the corresponding pixel from the original data by bi-linear interpolation. Interpolation was required because there was not a direct relationship between the original raw pixel position and the rectified pixel. The interpolation process examined the four pixel values surrounding the raw pixel to calculate the rectified pixel value.

A post-rectification analysis was performed to validate the accuracy of the georectification results. Typically, new (non-GCP) points common to the map source and imagery are selected for validation. However, because all identifiable points common to the imagery and map were used for the georectification process, another method had to be developed. The validation was performed by comparing differentially corrected Global Positioning System (GPS) measurements made in the field (discussed in the next section) and the location of the same point within the georectified data. For field sites that were easily identified in the data (six points), it was determined that the average differences between GPS coordinates and imagery georectified coordinates were 4.43 (± 1.99) metres Easting and 22.7 (± 13.99) metres Northing. Errors of this magnitude are considered minimal, given aircraft instability during data acquisition, the significant topographic relief of the area, and errors in the USGS quadrangle maps used to geometrically correct the data. Another important consideration is that GPS uses NAD-83 (North American Datum) while all USGS quadrangle maps are based on NAD-27. Because there is approximately an 80-metre shift between NAD-27 and NAD-83 in Nevada, it was therefore necessary to convert all NAD-83 based GPS coordinates to NAD-27. This conversion process may have caused systematic errors because all GPS points were consistently west and south of the same points in the Geoscan data.

Field Investigation

Field locations were identified in the canyon by personnel from the Nevada Department of Conservation and Natural Resources and the Nevada Bureau of Mines and Geology who were familiar with the area and its mining history. GPS measurements were made at each location using a Trimble Pathfinder. These measurements were differentially corrected to accurately record the latitude and longitude. Each site was photographed using a 35-mm camera, and information on the site was recorded in a field notebook.

Spectral Analysis

Spectral analysis of the Geoscan data consisted of producing similarity index maps that identified locations of potential mill tailing sediments. The field coordinates were used to locate mill tailings in the georectified Geoscan data. The Geoscan spectra of those locations were collected and averaged. The GenIsis Similarity Index (SI) algorithm was employed to compare individual pixel spectra to the average spectrum calculated from the known tailings. The SI equation (taken from Jansen (1993)) is

$$\mathrm{SI} = \frac{\sum_{i=m}^{n} (\mathbf{W}(i) - \mathbf{G}(i))^2}{n-m+1}$$

where the range of channels being compared is *m* through *n*, as defined by the analyst; for this study the range was channels 2 through 18 (0.583 to 2.352μm); **W** = the spectrum for each image pixel, this spectrum is displayed in **W**hite on the computer screen; and **G** = the average spectrum, this spectrum is displayed in **G**reen on the computer screen.

This comparison was performed for each pixel within the data. The result of this algorithm was a map highlighting all spectrally similar areas within the data, as shown in Plate 1

Surficial Geologic Mapping of the Sixmile Canyon Fan

In 1993, a detailed investigation of the movement of mercury- contaminated mill tailings through Sixmile Canyon and into the Carson River (Figure 1) was conducted by researchers at the Desert Research Institute and the Nevada Bureau of Mines and Geology (Miller *et al.*, 1993; Miller *et al.*, in review). The primary product of this investigation was a detailed understanding of the distribution and geochemical nature of mercury-contaminated sediments on the Sixmile Canyon Alluvial Fan located between the mouth of the Canyon and the Carson River system (Plate 2). This fan is a region of current and future development. The areas consisting of mill tailings, and therefore contaminated by mercury, are shown on the map in Plate 2. This detailed, field generated, and geochemically verified map provides an excellent cartographic data set to validate the success of the image processing procedures used herein at identifying the contaminated areas. It is, therefore, essential to understand the processes used to generate the field map portrayed in Plate 2. The steps involved in map development included

(1) *Delineation of the stratigraphic units that comprise the fan complex and the establishment of their relative age.* Units were defined in this case on the basis of stratigraphic and topographic position, sediment color and grain-size distribution, surface morphology and micro-relief, and the presence or absence of parent material weathering. Five stratigraphic units have been defined on the Sixmile Canyon Fan, three of which pre-date mining activity and, therefore, have not been impacted by mill tailing materials. All of the pre-mining deposits exhibit weathering zones (soils) near their upper surface, allowing them to be easily distinguished from the post-mining, mill tailing sediments. In addition to these five fan units, Plate 2 also depicts three valley fill stratigraphic units.
(2) *The characterization and mapping of defined stratigraphic units on 1:12,000-scale color aerial photographs.* The units exhibited significant variations in photographic color, tone, and texture, allowing unit contacts to be readily defined and mapped.
(3) *Field verification, using geologic criteria, of the created maps.* Locally, minor modifications were required, primarily in areas impacted by human activity.

Once this surficial geologic map showing potentially mercury-impacted areas had been created, geochemical data were used to verify the distribution of contaminated sediments in the surficial geologic map. The geochemical data consisted of more than 40 samples collected from approximately 20 locations on the fan. Samples were collected not only from the surface, but at depth. In addition, multiple samples were collected from all five of the delineated fan stratigraphic units. The samples were subsequently analyzed by the Nevada Bureau of Mines and Geology for mercury and a variety of other trace metals (see Miller *et al.*, in review, for analytical procedures). The geochemical data confirmed that the distribution of mercury-contaminated sediments, deposited by fluvial processes, had been accurately defined on the surficial geologic map. Regions interpreted to consist of non-contaminated, pre-mining materials exhibited concentrations near background, whereas post-mining deposits exhibited total-mercury concentrations ranging from a few to more than 350 ppm; concentrations that are well above mercury background levels in this area (Miller *et al.*, in review).

Plate 2 shows that the contaminated materials were deposited within discrete zones on the fan surface (labeled lobes A, B, and C in the figure) which extend from the mouth of Sixmile Canyon and into the Carson River. The map shows that about 21 percent of the fan area has been significantly impacted to date by mercury-contaminated mill tailings. Field observations, coupled with vertical geochemical sampling, revealed that the contaminated sediments are generally confined to the upper 1.5 m of the fan surface. Locally, however, the easily identifiable mill tailing sediments are buried by contaminated, but less distinctive materials.

Results and Discussion

The spectral analysis shows that it is technically possible to use Geoscan data to identify areas potentially contaminated with mercury-rich mill tailing sediments. To determine the validity of the spectral analysis, the similarity index map of the Sixmile Canyon alluvial fan (derived from the Geoscan data) was compared to the surficial geologic map. Comparison of these maps (Plates 1 and 2) shows that nearly all of the contaminated areas along the western margin of the fan, labeled lobes B and C on Plate 2, have been correctly identified by the Geoscan data analysis. In addition, there are several sites on the fan where mercury-contaminated mill tailings have been "dumped" or where re-processing of mercury-contaminated tailings for gold and silver has or is occurring. These areas are labeled as tailings dumps (Md) on Plate 2. The multispectral data correctly identified both lobes B and C and the dumps.

The Geoscan data were less successful at identifying zones of contamination located near the center of the Sixmile Canyon Fan; a region labeled lobe A on Plate 2. Only modern channel and gully systems, which are cut into mercury-contaminated materials, have been defined as potentially consisting of tailing sediments. It is not understood at this time why more of this contaminated region was not delineated by the Geoscan data. The omission of areas within lobe A may, however, be primarily related to two factors. First, qualitative field observations suggest that sediments in depositional lobe A exhibit less hydrothermally altered clay than is found in lobes B and C. This probably results from the fact that lobe A was the first post-mining stratigraphic unit deposited on the fan, and the hydrothermally altered materials were mixed during transport with significant quantities of pre-mining sediment derived both from the fan surface and the Sixmile Canyon drainage basin. Because the similarity index is dependent, in large part, on the reflectance from hydrothermally altered clay minerals, lower percentages of these clays may have hindered the identification procedure used here.

Second, along lobe A, deposits composed primarily of hydrothermally altered mill tailing sediments are locally buried by mercury-contaminated, but less distinctive, post-mining deposits; that is, deposits containing very low percentages of hydrothermally altered clay minerals. In some cases, these less distinctive surface materials represent eolian (wind-blown) sediments that have accumulated around shrubs and other forms of vegetation. In other localities, the

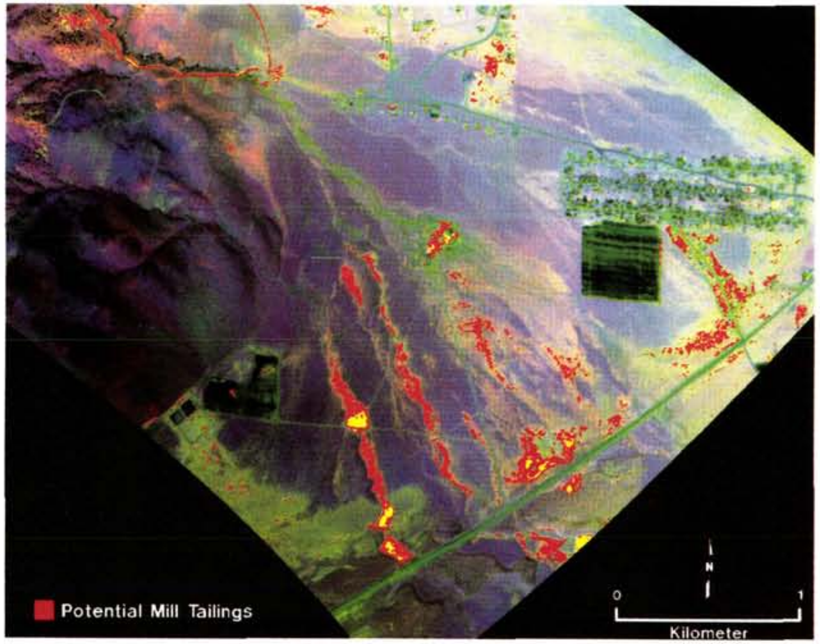

Plate 1. A three-band color composite of the Sixmile Canyon alluvial fan, Nevada; channel 21 (9.700μm) is color-coded red, channel 11 (2.044μm) is green, and channel 7 (0.830μm) is blue. Vegetation appears black in this image and alteration materials appear yellow to light pink. The similarity index map of potential mill tailings is overlaid on the image in bright red.

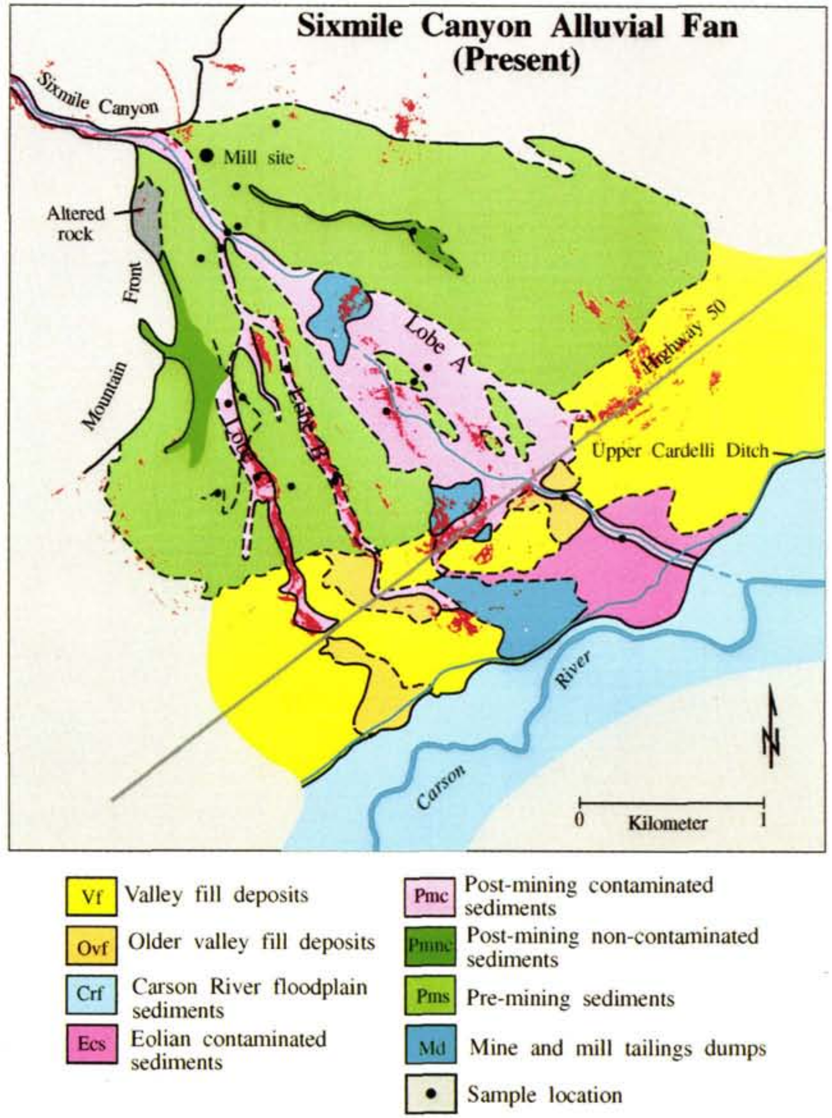

Plate 2. Surficial geologic map of the Sixmile Canyon alluvial fan, Nevada. The mill tailing sediments identified by analysis of the Geoscan data are displayed in red. Mercury contamination has been measured in units Pmc, Ecs, and Md.

surface sediments are pre- mining materials that have been eroded from the older fan units by gully activity and redeposited over the tailings-rich sediments. There is no doubt that burial of the distinctive tailings inhibited identification of contaminated zones using the Geoscan data. Vegetation density may also have affected the Geoscan spectra and, hence, the mapping of contamination in lobe A. Based on qualitative observations, it appears that the depositionally older lobe A is more densely vegetated than either lobes B and C, or the tailings dumps.

Summary and Conclusions

The objective of the work reported in this paper was to identify and map potential mill tailing sediments within the Sixmile Canyon alluvial fan using airborne scanner data. The procedures successfully identified major areas of mill tailings exposed on the alluvial fan surface. Small inclusions from mine dumps were identified as spectrally similar to mill tailings, and several areas of known redeposited mill tailings were not detected by our procedures. The results indicate that airborne scanner data can be effectively used to target key areas of potentially contaminated mill tailings. It is important to note that buried tailings sediments cannot be directly identified from the data; however, they might be inferred from geomorphic features that can be mapped with remotely sensed data.

In spite of some shortcomings associated with using multispectral data to identify mercury-contaminated areas, Geoscan data may provide a first approximation of mill tailings materials distribution within the Carson River valley or other semi-arid regions where contamination associated with precious metal mining is a concern. In fact, because the results show that this technique can be applied to large areas with minimal field work, the procedure may prove to be cost effective for identifying contaminant "hot-spots" when assessing large regions such as the Carson River Superfund Site.

Another principal advantage of the similarity index mapping procedure is that estimates of the areal extent of potentially contaminated areas can be quickly determined from the remote sensing maps. Although these data will contain error, they will provide a first approximation of the location, number, and size of individual sites where trace metal contamination may occur.

Recommendations

The procedures employed for this study were relatively quick and uncomplicated. The results indicate that the GenIsis similarity index mapping routine is an appropriate technique for quickly identifing potential contamination zones for field sampling efforts. Recommendations to improve the methodology documented in this paper are twofold. An aircraft system that records aircraft motion and position simultaneously during scanner data acquisition should be utilized. When combined with digital elevation models, position and motion data will permit a more accurate georectification than was performed herein (Fisher, 1991). In this study, estimates of georectification accuracy suggest that coordinates reported may be at best ± 9 metres from their true position. In reality, coordinates reported may be off by more than 25 metres in some cases, especially in areas where there are abrupt changes in topography.

The second recommendation is to examine results from two other analytical approaches, namely, a spectral unmixing algorithm (Gillespie *et al.*, 1990; Gillespie, 1992) and comparison of field or laboratory spectra to the aircraft data (Kruse *et al.*, 1990). Resources and time available for this project precluded the use of these two approaches. However, both approaches have proven successful in mapping mixtures and may improve the detectability of mill tailings in areas of mixed mineralogy.

Acknowledgments

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References

Bailey, E.H., and D.A. Phoenix, 1944. Quicksilver Deposits in Nevada, *University of Nevada, Bulletin*, 38:12–46.

Collins, A.H., 1988. *Geological Applications of Remote Sensing in the Virginia Range, Nevada*, Dissertation, University of Nevada, Reno.

Cooper, J.J., R.O. Thomas, and S.M. Reed, 1985. *Total Mercury in Sediment, Water, and Fishes in the Carson River Drainage, West-Central Nevada*, Division of Environmental Protection, Department of Conservation and Natural Resources, Nevada, 96 p.

Elvidge, C.D., and F.P. Portigal, 1990. Change Detection in Vegetation Using 1989 AVIRIS Data, *SPIE*, 1298:178–189.

Fisher, L.T., 1991. Aircraft MultiSpectral Scanning with Accurate Geographic Control, *Geodetical Info*, 5(2):59–62.

Gillespie, A.R., 1992. Spectral Mixture Analysis of Multispectral Thermal Infrared Images, *Remote Sensing of Environment*, 42: 137–145.

Gillespie, A.R., M.O. Smith, J.B. Adams, S.C. Willis, A.F. Fischer III, and D. Sabol, 1990. Interpretation of Residual Images: Spectral Mixture Analysis of AVIRIS Images, Owens Valley, California, *Proceedings of the 2nd Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Workshop*, JPL Publ. 90-54, Jet Propulsion Laboratory, Pasadena, California, pp. 243–270.

Goetz, A.F.H., B.N. Rock, and L.C. Rowan, 1983. Remote Sensing for Exploration: An Overview, *Economic Geology*, 78(4):573–590.

Goetz, A.F.H., G. Vane, J.E. Solomon, and B.N. Rock, 1985. Imaging Spectrometry for Earth Remote Sensing, *Science*, 228(4704): 1147–1153.

Hook, S.J., and M. Rast, 1990. Mineralogic Mapping Using Airborne Visible Infrared Imaging Spectrometer (AVIRIS) Shortwave Infrared (SWIR) Data Acquired Over Cuprite, Nevada, *Proceedings of the Second Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Workshop*, JPL Publication 90-54, pp. 199–207.

Hunt, G.R., and R.P. Ashley, 1979. Spectra of Altered Rocks in the Visible and Near Infrared, *Economic Geology*, 74:1613–1629.

Jansen, W.T., 1993. *GenIsis General Imaging Spectrometry Interpretation Systems, Version 3.00 User's Manual*, WTJ Software Services, San Mateo, California, 74p.

Kahle, A.B., and A.F.H. Goetz, 1983. Mineralogic Information from a New Airborne Thermal Infrared Multispectral Scanner, *Science*, 222:24–27.

Kruse, F.A., K.S. Kierein-Young, and J.W. Boardman, 1990. Mineral

Mapping at Cuprite, Nevada with a 63-Channel Imaging Spectrometer, *Photogrammetric Engineering & Remote Sensing*, 56(1): 83–92.

Miller, J.R., P.J. Lechler, and J. Rowland, 1993. Heavy Metal Transport by Physical Processes in the Carson River Valley, West-Central Nevada, USA: Implications to the Distribution and Storage of Metal Pollutants in Tropical Environments, *Proceedings of the International Symposium on Environmental Geochemistry in Tropical Countries*, 27 Nov.-3 Dec., Niteroi, Brazil, pp. 433–436.

Miller, J.R., P.J. Lechler, J. Rowland, M. Desilets, and L.C. Hsu, in review. Dispersal of Mercury-Contaminated Sediments by Fluvial (River) Geomorphic Processes: A Case Study from Sixmile Canyon, Nevada, USA, submitted to *Water, Air, and Soil Pollution*.

Lyon, R.J., and F.R. Honey, 1990. Direct Mineral Identification with Geoscan Mk II Advanced Multispectral Scanner, *SPIE*, 1298:50–61.

Smith, G.H., 1943. *The History of the Comstock, 1850–1920*, University of Nevada Bulletin No. 37.

Swayze, G., R.N. Clark, F. Kruse, S. Sutley, and A. Gallagher, 1992. Ground-Truthing AVIRIS Mineral Mapping at Cuprite, Nevada, *Summaries of the Third Annual JPL Airborne Geoscience Workshop*, 1–5 June, Volume 1, AVIRIS Workshop, pp. 47–49.

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