AIRBORNE HYPERSPECTRAL IMAGERY FOR THE PETROLEUM INDUSTRY

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ABSTRACT

Petroleum companies can use high performance, airborne hyperspectral technology as a cost-effective tool to improve evaluation of downstream assets, environmentally impacted areas, and terrain characterized by hydrocarbon-seepage. VNIR-SWIR data cubes acquired during Geosat's Hyperspectral Group Shoot 1998 contain new information about manmade facilities and oil-productive geologic structures that is not readily available from other sources. For exploration, a Southern California area with significant historic oil production was evaluated. Here Sulphur Mt. has oil seeps documented on a published geologic map. A spectrally unique airborne signature was spatially associated these published oil seeps. A very similar spectral signature was found 20 km east within clearings on a heavily vegetated flank of an anticline and at the anticline's plunging nose. In late 1999 the nose of the anticline was visited and many active seeps and ponding of oil were documented. A new Geosat project (HGS2000) has been initiated to characterize oil seep sites with handheld spectrometer measurements and field observations. The Sulphur Mt. seeps were confirmed as active during a field visit and handheld spectrometer measurements are planned during the summer of 2000.

A primary goal of HGS2000 is to support construction of a spectral library for oil seeps and impacted soil and to link airborne spectra with ground spectra for the same feature of interest. Perhaps oil seeps, stains, and soil mixed with oil residue foster development of a more open landscape, gives rise to a unique vegetation assemblage, alters the soil characteristics (color, amount and type of iron, etc.), and/or are easier to detect with hyperspectral sensors when in more open areas. This spectral library will be applicable for downstream applications and the detection of contaminated soil. Within industrial sites evaluated during HGS98, unique spectral signatures were found in settling ponds, "natural" seasonal vegetation stress was clearly mapped, and no significant indication of vegetation stress was found around wharfs, abandoned oil wells, and pipelines – this type of information can be used to help manage downstream assets.

1.0 INTRODUCTION

Geosat's cooperative R&D hyperspectral group shoot (HGS98) evaluated several areas in the western USA with a high performance, airborne hyperspectral sensor. The MapFactory analyzed airborne data over two sites – Pacheco Creek in central California and mountainous terrain in southern California west of Santa Barbara. The surveys were acquired with 5-meter ground sampling distance. Each flight strip covered an area about 2.5 km across. The flight strip length was ~3 km in Pacheco Creek and ~25 km in the Santa Barbara area. The hyperspectral sensor acquired VNIR-SWIR wavelengths across 128 bands.

We found that our typical multi-step process for extracting hydrothermal mineral alteration (see Kruse and others, 1996) from hyperspectral data was not fully appropriate for the HGS98 industrial and mountainous test sites. These sites included a wide range of vegetation (including irrigated agriculture) and man-made facilities, the features of interest were subtle, and we had no field data. Our previous work on using hyperspectral imagery for mineral mapping (Goodwin and others, 1999) had to be modified. For HGS98 had much more success extracting new patterns and robust signatures when we manually evaluated individual pixels within their spatial context and used *a priori* knowledge about geology, facilities, and vegetation to help guide the evaluation. Image processing

*Presented at the Fourteenth International Conference on Applied Geologic Remote Sensing, Las Vegas, Nevada, 6-8 November 2000. *Affiliations updated in 2005*

tactics had to be developed by the analyst to promote detection of subtle spectral signatures.

We used ENVI software for the analysis (see Kruse and others, 1996 for software details). We combined and segregated the VNIR from the SWIR to extract more useful endmembers. We applied the minimum noise fraction (MNF) transformation and established the purest pixels via the pixel purity index (PPI). We then identified endmembers from the purest pixels (n-dimensional visualization) and mapped the abundance of these endmembers (mixture tuned matched filtering or MTMF). The flight strips were difficult to georeference due to distortions associated with line-scanner technology. Features of interest seen on aerial photographs and USGS maps were visually correlated to the hyperspectral imagery. We have found that line-scanner sensors are excellent for detection, but are not satisfactory for generating maps that are acceptable to our clients. Operator intervention is required to accurately locate individual hyperspectral pixels on basemaps and image maps.

2.0 EXPLORATION

The mountainous area west of Santa Barbara is characterized by 1) coastal bluffs with a pumping station (?), pipeline, and abandoned oil wells, 2) oil seeps that are documented on a geologic map, and 3) a large anticline with numerous well pads and reported seeps. The area is characterized by prolific historic oil production. Outstanding geologic maps (scale 1:24,000) are available from the Dibblee Geological Foundation of Santa Barbara, California. For this study we used the geologic map of the Santa Paula Peak Quadrangle (Dibble, 1990).

Within coastal outcrops we were *unable* to spectrally differentiate between Tertiary and Quaternary geology formations using the hyperspectral data (see The MapFactory, unpublished). These formations have very similar mineralogy – they are characterized by white-weathering siliceous units of varying grain size. Further inland, the Sulphur Mt. subarea was used to evaluate whether mapped oil seeps caused a unique hyperspectral signature (Figure 1). Oil well and “tar seep” symbols are displayed on the USGS topographic map across this mountainous area. In addition, the State of California maintains an excellent inventory of seeps (Hodgson, 1987). We processed and interpreted two flight lines across the area.

Geographically correlating the mapped seep symbols with the hyperspectral imagery was difficult. We analyzed the imagery in detail on a pixel-by-pixel basis. The spectral signature of each pixel was analyzed and differences noted. On Landsat TM color composites, there were some clusters of pixels in the area with mapped seeps that had colors different from dried grass and healthy oak tree canopies (Figure 2). We found that a unique spectral signature could be spatially associated with clusters of pixels that visually correlated well with the oil seep symbols on the published map (Figure 3). At the onset of HGS2000 (July 2000), fieldwork verified that the published seeps (see Figure 1) were active (Figure 4) and in the same general location as the hyperspectral pixels characterized by the “oil seeps and stains” spectral signature (Figure 3). In August 2000 the area will be visited with a handheld VNIR-SWIR spectrometer to confirm the correlation between these active oil seeps and our unique spectral signature.

After the encouraging results at Sulphur Mt., we analyzed imagery 20 km east at Steckle Park east below the crest of a productive anticline (Figure 5). On the geologic map there are no documented seeps. Our goal was to find pixels at Steckle Park that matched the unique spectral signature associated with known oil seeps 20 km west. We discovered several openings in the thick canopy on the NE flank of the plunging anticline – these may be abandoned well sites. Within these openings we found pixels with a hyperspectral signature that was very similar to the one associated with mapped oil seeps at Sulphur Mt. These openings are difficult to access. However, one of our team members (Pat Caldwell) remembered seeing oil seeps while mapping for Chevron USA ~20 years ago in the valley along the NE flank of this plunging anticline. In August 1999, he went to Steckle Mt. and documented many active oil seeps and ponding of oil in a ditch along the highway at the plunging nose of the anticline. After his return, we reprocessed the hyperspectral data cube over his field area (Figure 5). Again, we found spectral signatures for individual pixels that were very similar to the unique spectral signature previously associated with oil seeps in Sulphur Mt. The striking similarity between the hyperspectral signature of pixels located 20 km apart (compare

Figures 3 and 5) suggests a similar composition or origin (see Oliveria and Crosta, 1996). No red-edge shift is detected (Oliveria and others, 1997). No coincidental occurrence of ferric oxides was noted (Vincent, 1997).

In the pixels evaluated to date, our "oil seep and stain" feature has had some vegetation associated with it (see the visible portion of signature in Figures 3 and 5). There is preliminary evidence that the feature is associated with more sparsely vegetated terrain (including clearings, roads, well sites, etc.). The signature can be associated with some road shoulders and unpaved access-road surfaces on the anticline that may be built with materials that have been mixed with oil residue and/or have been subjected to sheetwash from upslope areas of oil seeps. Perhaps oil seeps, stains, and soil mixed with oil residue fosters development of a more open landscape, gives rise to a unique vegetation assemblage, alters the soil characteristics (color, amount and type of iron, etc.), and/or is easier to detect when in more open areas. Geosat's HGS2000 project will evaluate possible causes for the spectral response.

3.0 DOWNSTREAM ASSETS

The Pacheco Creek area is impacted by industry, landfills, and urban sprawl. It is flanked on each side by refineries and tank farms, offloading piers downstream, and railroad/waste management activities upstream. In the vicinity of Pacheco Creek and the adjacent city of Martinez, there were over 25 spills from 1988 to 1994. The one that may have had the most impact on the study area was a petroleum spill in May 1992 from the Avon wharf. However, the California Office of Emergency Services only records oil spill data in tabular form, so it is not possible to correlate spill locations with the hyperspectral flight strip. Nevertheless, we evaluated the hyperspectral data for vegetation stress near the Avon wharf but found no indication of stress (e.g., a "red-edge shift" or decreasing depth and width of the chlorophyll absorption band at 0.67 micrometers – both features are summarized in Singhroy and Kruse, 1991). In fact, examining individual pixels downslope of facilities, along the banks of the creek, and in the extensive wetlands revealed little evidence of vegetation stress across the Pacheco Creek estuary. In the southern California site, we also found little evidence of vegetation stress in the vicinity of abandoned drilling sites or about a pumping station at Punta Gorda (see The MapFactory, unpublished; Chen and others, 1996).

We are now reevaluating the Pacheco Creek area using our Geosat HGS98 and HGS2000 oil spill/oil stain spectral library. The results are encouraging – we are detecting discrete areas across impacted areas that have spectral signatures suggesting"oil-contaminated soil." This work has broad application for evaluating downstream petroleum assets, brownfields, industrial properties that are being considered for alternative land use, and potentially for prioritizing clean-up operations. These contaminated soil signatures are very subtle and require extensive operator interaction and experience, field observations correlated to specific pixels, and excellent hyperspectral data cubes that include VNIR and SWIR wavelengths.

The hyperspectral data differentiates and reveals unique spectral signatures for four industrial ponds that are within the industrialized landscape of Pacheco Creek (Figure 6). . The spectral response of two ponds is similar and shows the 0.67 chlorophyll absorption feature. However, the spectral response of other two ponds does not display this chlorophyll absorption feature, indicating a markedly different solution is contained within these two ponds (see Figure 6). This type of information could be key to a baseline or monitoring effort. A specialist and field sampling is required to place these signatures into an operational and regulatory context

4.0 SUMMARY

Sophisticated, high performance, airborne VNIR-SWIR hyperspectral sensors, such as those built by Integrated Spectronics (including the Probe-1 and HyMap Systems), can be effectively used in both the upstream and downstream sectors of the petroleum industry. Using these sensors, we were able to extract *new* information that is *not* readily available from other sources. To detect and characterize subtle oil seep, oil stain, and soil contamination features, our studies indicate a high performance VNIR-SWIR sensor such as Probe-1 and HyMap is required. In addition, image-processing tactics had to be developed by our analysts to enable detection of these subtle spectral signatures. We manually evaluated individual pixels within their spatial context and used *a priori* knowledge about geology, facilities, and vegetation to help guide our interpretation and classification. Flight planning, ground sampling, and processing of the cubes (from raw to radiance to reflectance) need to be coordinated to optimize the quality of the data and interpretation. Good planning and experience analyzing hyperspectral and field data from oil-impacted environments facilitate detection of subtle features. Geosat's HGS2000 will directly link oil seeps with field spectral measurements and observations. Our goal is to build a robust family of spectral signatures that can be used for evaluating upstream and downstream assets.

5.0 ACKNOWLEDGMENTS

The sponsors of Geosat's R&D cooperative projects HGS98 and HGS2000 provided the vision and feedback to implement this basic evaluation of hyperspectral imaging for the petroleum industry. Dr. Rebecca Dodge, Education and Research Director of The Geosat Committee (go to *www.geosatcom.com*) and Associate Professor at West Georgia University, provided the leadership to enable funding and completion. Dr. Tod Rubin of Chevron, Mr. Jerry Helfand of Exxon/Mobil, and Dr. Mark Little of Royal Dutch Shell provided timely feedback and guidance. The critical fieldwork has been coordinated and carried out by Patrick Caldwell of The MapFactory for the past two years. James Sokolowski of RMS, and Timothy Leery of ImageLinks efforts are greatly appreciated.

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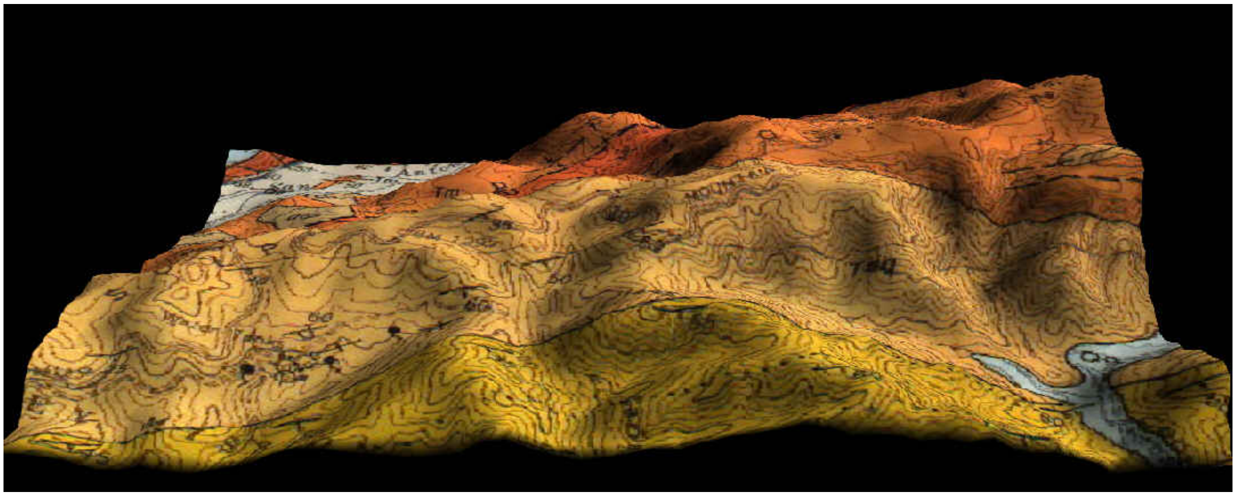


Figure 1. The 1:24,000 scale geologic map of Sulphur Mt (available from The Dibble Foundation) showing oil seeps. This map is draped over the USGS DEM and displayed in a perspective view looking north. The mapped oil seeps can be seen as dots with small tails in the left foreground.

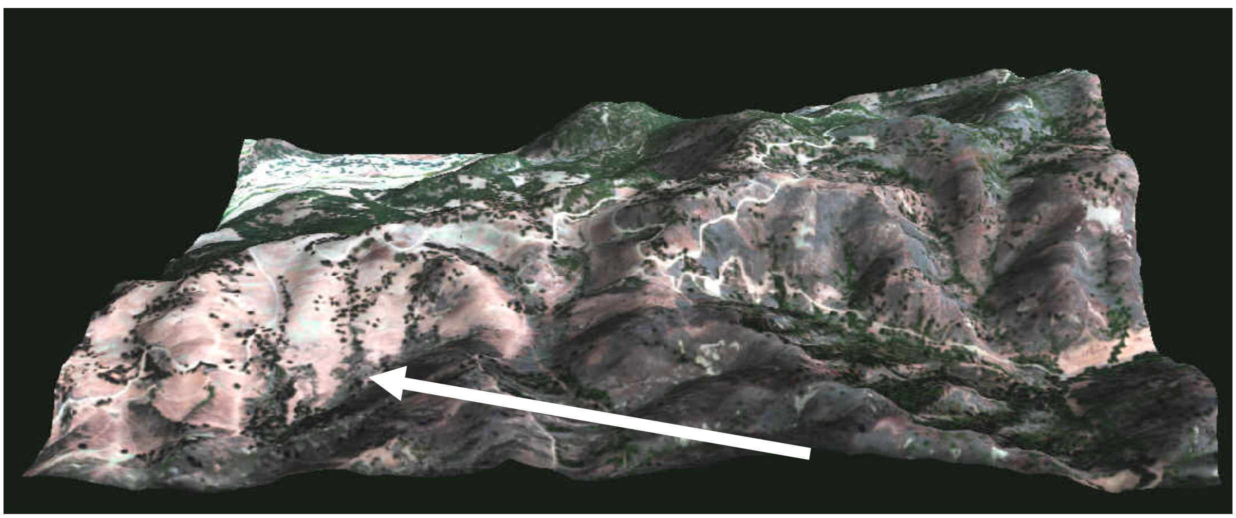
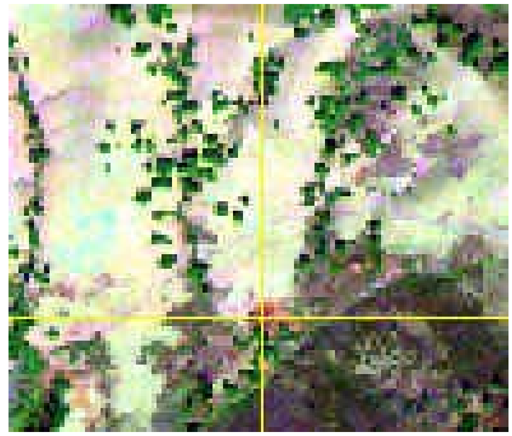


Figure 2. Hyperspectral data rendered as a natural color composite equivalent to TM bands 3,2,1 (as R,G, B). The image has been draped over the USGS DEM. This perspective view is equivalent to that seen in Figure 1. The white arrow shows the locations of the mapped oil seeps. In July 2000 these were visited as part of HGS2000 and confirmed to be live oil seeps.



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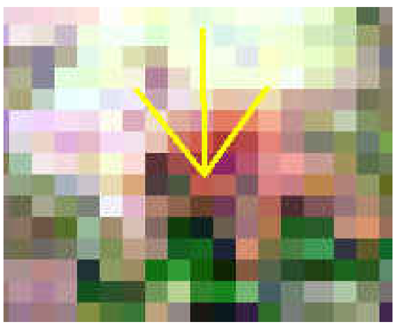

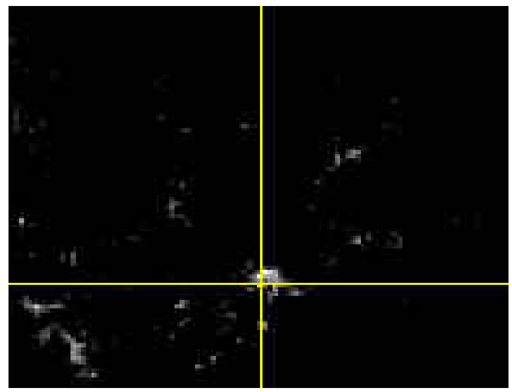

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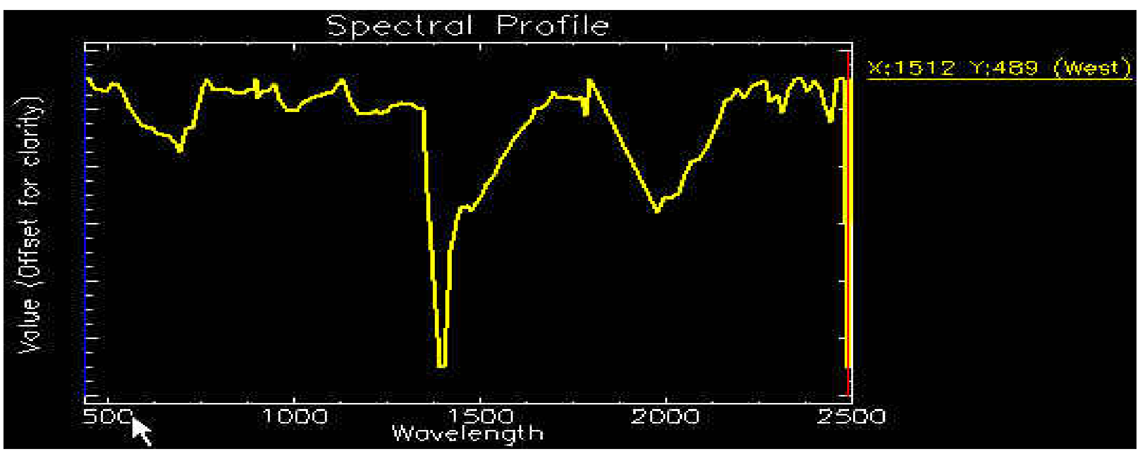

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Figure 3. a and b. Close up of oil seep in Sulphur Mt area (see Figures 1 and 2). c. zoom-in on pixel associated with mapped oil seep. d. 125 of the original 128 bands of reflectance data were processed through ENVI's spectral analysis routine. The bright pixels represent an endmember class correlated with the mapped oil seep – this graphic covers the same geographic area Figure 3b. e. The spectral curve of the pixel associated with the mapped oil seep

Figure 4. The oil seep area mapped by Thomas Dibble (see Figure 1 and 3a). This feature was successfully detected using an airborne VNIR-SWIR hyperspectral sensor with 128 channels and high performance characteristics (the Probe-1 built by Integrated Spectronics). Fieldwork during summer 2000 with a handheld spectrometer will further characterize the site and spectral response.

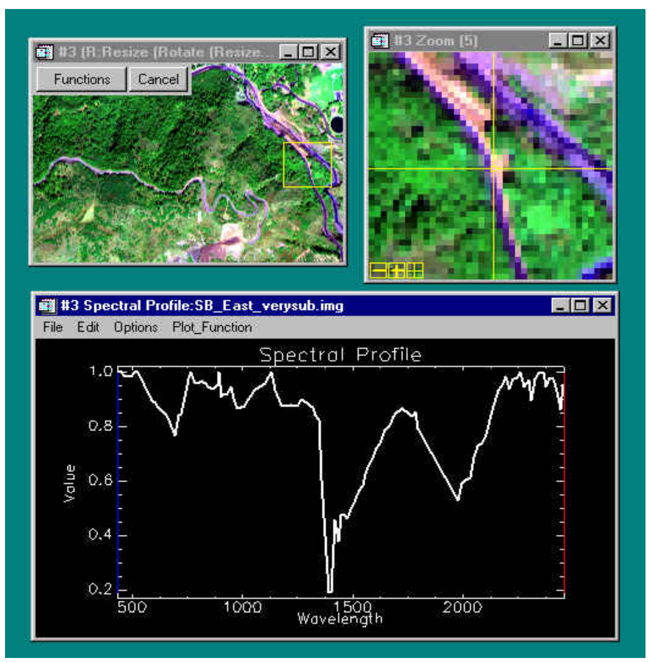

Figure 5. A site 20 km east of the mapped oil seeps and along the NE plunging nose of an anticline where a Probe-1 spectral signature, similar to that documented in Sulphur Mt. (see Figure 3), was associated with oil seeps and ponded oil. Upper left screen capture shows overview of anticline with zoom box. Upper right is the area within zoom box with crosshairs on pixel associated with an oil seep - spectral signature of this pixel shown at bottom.

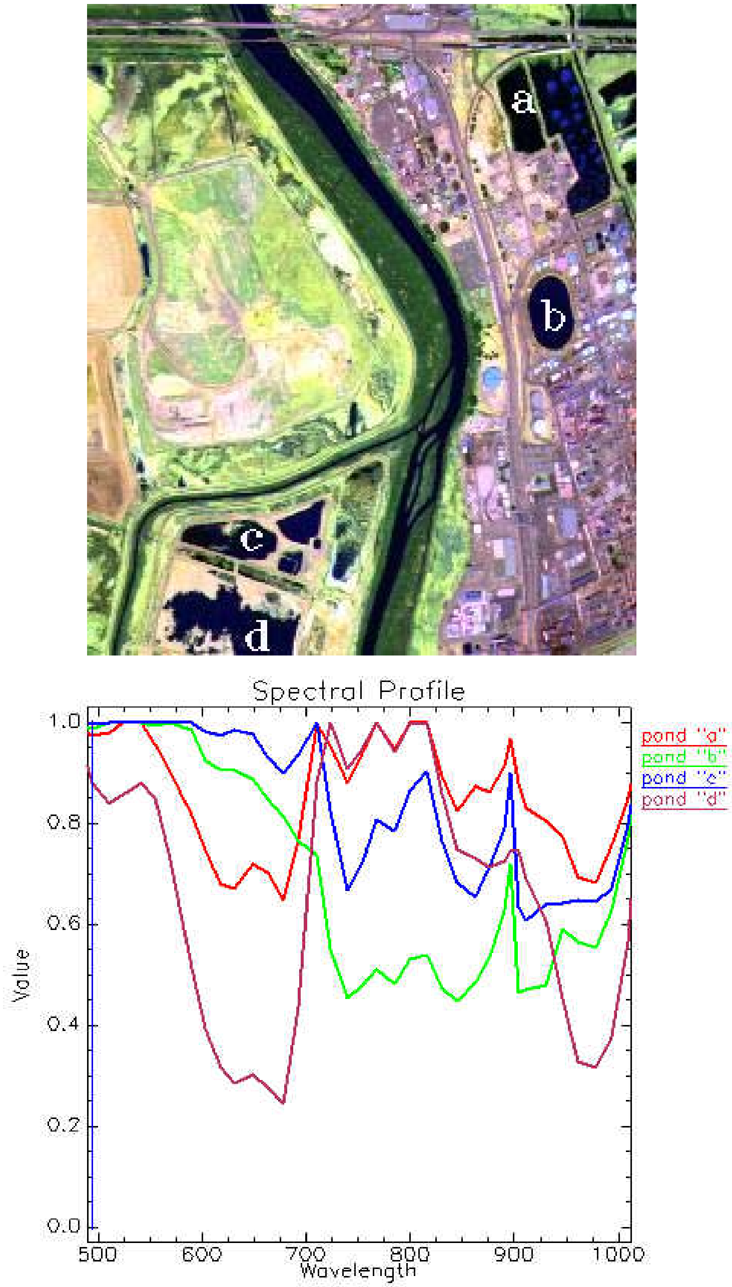

Figure 6. Hyperspectral signatures of 4 different settling ponds (a-d) at Pacheco Creek show unique characteristics. This type of information could be key to a baseline or monitoring effort. A specialist and field sampling is required to place these signatures into an operational and regulatory context. Spectra from four of the ponds is displayed (0.5 to 1.0 um, continuum removed). The spectral response of pond "a" and "d" are similar and show the 0.67 chlorophyll absorption feature (note depth and width of 550-700 nm curves, above). However, this chlorophyll absorption feature is missing within ponds "b" and "c" indicating a different solution compared with the other 2 ponds.