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Geobotanical Remote Sensing Applied to Targeting New Geothermal Resource Locations in the U.S. Basin and Range with a Focus on Dixie Meadows, Nevada

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ABSTRACT

This paper presents an overview of the work our collaboration is doing to increase the detailed mapped resource base for geothermal exploration in the Western US. We are imaging several large areas in the western US with high resolution airborne hyperspectral and satellite multispectral sensors. We have now entered the phase where the remote sensing techniques and tools we are developing are mature enough to be combined with other geothermal exploration techniques such as aeromagnetic, seismic, well logging and coring data. The imaging sensors and analysis techniques we have developed give us the ability to map visible faults, surface effluents, altered minerals, and subtle hidden faults. Large regions are being imaged at reasonable costs. The technique of geobotanical remote sensing for geothermal signatures is based on recent successes in mapping hidden faults, high temperature altered mineralization, clays, hot and cold springs and CO₂ effluents the Long Valley Caldera and Mammoth Mountain in California. The areas that have been imaged include Mammoth Mountain and the Long Valley Caldera, Dixie Meadows NV, Fish Lake Valley NV, and Brady Hot Springs. Areas that are being imaged in the summer of 2003 are the south moat of the Long Valley Caldera,

Mammoth Mountain western flanks, Mono Inyo chain north of Mammoth Mountain in CA, and the Humboldt Block in NV. This paper focuses on presenting the overview of the high-resolution airborne hyperspectral image acquisition that was done at Dixie Meadows NV in August 2002. This new imagery is currently being analyzed and combined with other field data by all of the authors on this paper. Results of their work up until June 23, 2003 are presented in other papers in the this volume, and their results up until the time of the conference will be presented in the remote sensing session on Tuesday morning.

Introduction

The authors on this paper are the participants in a growing multi-university, national laboratory, and industry collaboration of remote sensing researchers and geothermal industry exploration experts. The goal of our group is to combine the suite of newly developed remote sensing geothermal exploration techniques with surface and subsurface field data to targeting new geothermal resource locations in the western US Basin and Range, and magmatic areas. We are imaging several large areas in the western US with high-resolution airborne hyperspectral and satellite multispectral sensors. One of the first areas was Dixie Meadows NV. Other areas are Mammoth Mountain and the Long Valley Caldera, Fish Lake Valley NV, and the Brady Hot Springs region. Areas that will have been imaged in the summer of 2003 are the south moat of the Long Valley Caldera, Mammoth Mountain western flanks, Mono Inyo chain north of Mammoth Mountain in CA, and the Humboldt Block in NV. This paper focuses on presenting the overview of the high-resolution airborne hyperspectral image acquisition that was done at Dixie Meadows NV in August 2002.

Dixie Meadows NV was chosen because it is a currently undeveloped possible new geothermal resource that is relatively close to the producing geothermal power plant that is at Dixie Valley NV a few kilometers to the north. The region has classical Basin and Range structure and has been studied by many researchers for many years. An important DOE conference reviewing what has been learned at Dixie Valley over the years was held at Reno two years ago. Please see <http://www.unr.edu/geothermal/>

meetingsandpresentations/meetings_dixie_pres.htm At that meeting there was evidence presented by several authors that the locations of the producing formations coincided with faulting systems that cross cut the primary Stillwater range front fault. (Ref Richard Smith). This is an interesting hypothesis that has guided our selection of Dixie Meadows as test site. The types of remote sensing techniques that we develop are particularly well suited to discovering subtle hidden fault systems, altered mineral, and clays. (Ref Brigitte Martini Thesis). In addition several members of our collaboration have observed visually what seemed might be fault systems, trending north west, cross cutting the Stillwater range front fault at the location called the Dixie Meadows. Based on these ideas, high-resolution airborne hyperspectral imagery was acquired at Dixie Meadows NV in August 2002.

Recently one of us, Dr. Brigitte A. Martini, was awarded her Ph. D. from UC Santa Cruz. Part of her thesis was the creation of methodologies that use high resolution hyperspectral imagery to discover and map hidden faults, altered minerals, clays, and hot and cold springs at Mammoth Mountain and the Long valley Caldera. Her work at Mammoth is particularly instructive and forms the basis of our encouragement to try them at new sites in the western US. There is a website where her results can be viewed. It is at <http://emerald.ucsc.edu/~hyperwww/> The publications of her work are found at <http://emerald.ucsc.edu/~hyperwww/pubs.html> and her complete thesis can be read at <http://en-env.llnl.gov/>

Our collaboration is using SAR radar satellite imagery, very high-resolution Digital Globe satellite imagery, NASA AMES MASTER imagery, and NASA JPL AVIRIS imagery in addition to the airborne high-resolution hyperspectral imagery we acquired. The descriptions of many of the remote sensing systems we are using can be viewed on the website at <http://emerald.ucsc.edu/~hyperwww/instruments.html>

In August 2002 the US DOE program at LLNL funded the acquisition of hyperspectral imagery at Dixie Meadows NV. 18 flight lines were flown by HyVista Corp. using their HyMap in-



Figure 1. Radar reflectance image of the Dixie Meadows area including the Stillwater Range and the dry Lake Dixie. The area imaged by our hyperspectral acquisition is approximately in the center of the figure.

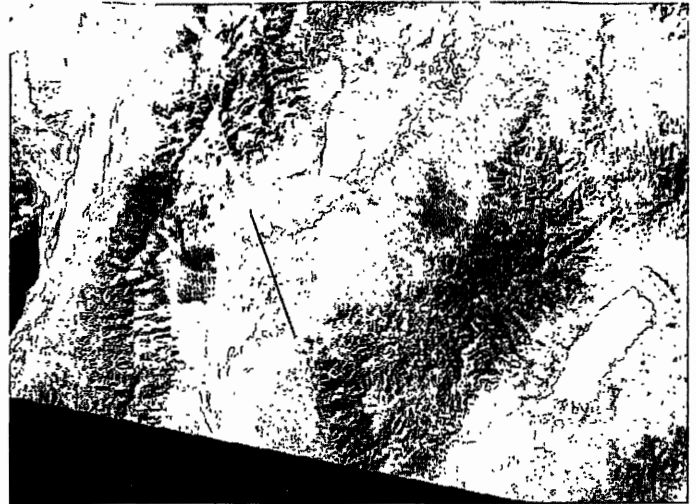


Figure 2. NASA AMES MASTER infrared image of the Dixie Meadows area with a northwest trending line marked on it. The line is the approximate location of suspected fault systems that crosscut the Stillwater Range front fault. The intersection of the faults could have increased permeability possibly resulting in geothermal power production.



Figure 3. Photo taken on the day of the hyperspectral acquisition looking northwest from Dixie Valley road looking at the heavily altered Stillwater range front. This photo is near the center of the area imaged by the hyperspectral acquisition.

strument made by Integrated Spectronics, Ltd. The website that contains the detailed specifications of this sensor and the methods used for acquiring imagery are explained on their web site at <http://www.hyvista.com/main.html>

The Dixie Meadows imagery is solar reflectances from 400 to 2500 nm, in 126 separate but contiguous bands. Each pixel is from 3 meters to 2 meters in dimension and the signal-to-noise is greater than 1000:1. The imagery was acquired from a low flying twin-engine small aircraft, in strips or flightlines that are approximately 1.2 Km wide. The imagery was processed by HyVista to provide radiance, atmospherically corrected reflectance, and georectified reflectance. It was distributed to all members of our

Table 1. The beginning and end points for each of the 18 flight lines in latitude and longitude (NAD 87)

Image-line #	Begin Latitude	Begin Longitude	End Latitude	End Longitude
1	39.76012	-118.19	39.91	-118.19
2	39.74932	-118.1759027	39.89920	-118.1759027
3	39.73852	-118.1618054	39.88840	-118.1618054
4	39.72772	-118.1477082	39.87760	-118.1477082
5	39.71692	-118.1336109	39.86680	-118.1336109
6	39.70612	-118.1195136	39.856	-118.1195136
7	39.69532	-118.1054163	39.84521	-118.1054163
8	39.68452	-118.091319	39.83441	-118.091319
9	39.67372	-118.0772218	39.82361	-118.0772218
10	39.66292	-118.0631245	39.81281	-118.0631245
11	39.65212	-118.0490272	39.80201	-118.0490272
12	39.64132	-118.0349299	39.79121	-118.0349299
13	39.63053	-118.0208326	39.78041	-118.0208326
14	39.61973	-118.0067354	39.76961	-118.0067354
15	39.60893	-117.9926381	39.75881	-117.9926381
16	39.59813	-117.9785408	39.74801	-117.9785408
17	39.58733	-117.9644435	39.73721	-117.9644435
18	39.57653	-117.9503462	39.72641	-117.9503463

collaboration. The exact locations of the actual flight lines that were acquired are shown in the table in Table 1.

Conclusion

We have established a collaboration of remote sensing researchers and are now applying our advanced remote sensing techniques to target new geothermal resources in Dixie Meadows NV. Our work combines the established hyperspectral imagery tools with other field surface and subsurface geothermal exploration and development methods. The high-resolution airborne

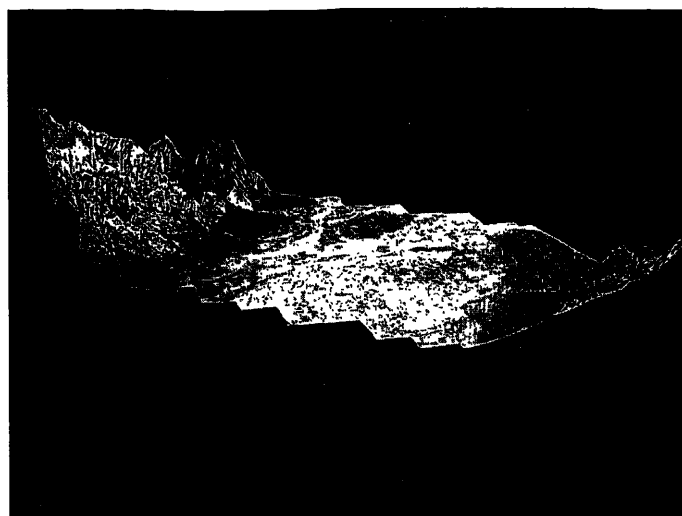


Figure 4. Composite of all the Dixie Meadows hyperspectral image lines draped over a DEM.

hyperspectral image acquisition that was done at Dixie Meadows NV in August 2002 is currently being analyzed and combined with other field data by all of the authors on this paper. Results of their work up until the time of the conference will be presented in papers in the remote sensing session.

References

- Nash, G. D. and G. Johnson, 2002. "Soil Mineralogy Anomaly Detection in Dixie Valley, Nevada Using Hyperspectral Data", *Proceedings: Twenty-Seventh Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 28-30, 2001, SGP-TR-171.
- Martini, B.A., New insights into the structural, hydrothermal, and biological systems of Long Valley Caldera using hyperspectral imaging, PhD thesis, 291 pp., UCSC, Santa Cruz, 2002.
- Smith, R.P., V.J.S. Grauch, and D.D. Blackwell, Preliminary results of a high-resolution aeromagnetic survey to identify buried faults at Dixie Valley, Nevada, submitted to GRC Transactions, 26, 2002.