# Geothermal Prospecting using Hyperspectral Imaging and Field Observations, Dixie Meadows, NV

**T. Kennedy-Bowdoin[1], E. A. Silver[1], B. A. Martini[2], W. L. Pickles[3]**

**[1]University of California at Santa Cruz**
**[2]HyVista Corporation, Sydney, Australia**
**[3]Lawrence Livermore National Labs**

***Keywords***

*Hydrothermal alteration minerals, hyperspectral, Dixie Valley, remote sensing, geothermal prospecting, hot springs*

## ABSTRACT

In an ongoing project to relate surface hydrothermal alteration to structurally controlled geothermal aquifers, we mapped a 16 km swath of the eastern front of the Stillwater Range using Hyperspectral fault and mineral mapping techniques. The Dixie Valley Fault system produces a large fractured aquifer heating Pleistocene aged groundwater to a temperature of 285°C at 5-6 km. Periodically over the last several thousand years, seismic events have pushed these heated fluids to the surface, leaving a rich history of hydrothermal alteration in the Stillwater Mountains. At Dixie Hot Springs, the potentiometric surface of the aquifer intersects the surface, and 75°C waters flow into the valley. We find a high concentration of alunite, kaolinite, and dickite on the exposed fault surface directly adjacent to a series of active fumaroles on the range front fault. This assemblage of minerals implies interaction with water in excess of 200°C. Field spectra support the location of the high temperature mineralization. Fault mapping using a Digital Elevation Model in combination with mineral lineation and field studies shows that complex fault interactions in this region are improving permeability in the region leading to unconfined fluid flow to the surface. Seismic studies conducted 10 km to the south of Dixie Meadows show that the range front fault dips 25-30° to the southeast (Abbott et al., 2001). At Dixie Meadows, the fault dips 35° to the southeast, demonstrating that this region is part of the low angle normal fault system that produced the Dixie Valley Earthquake in 1954 (M=6.8). We conclude that this unusually low angle faulting may have been accommodated by the presence of heated fluids, increasing pore pressure within the fault zone. We also find that younger synthetic faulting is occurring at more typical high angles. In an effort to present these findings visually, we created a cross-section, illustrating our interpretation of the subsurface structure and the hypothesized locations of increased permeability. The success of these methods at Dixie Meadows will greatly improve our understanding of other Basin and Range geothermal systems.

## Introduction

As oil prices continue to skyrocket, development of alternative energy sources becomes increasingly important. Geothermal power is a cost effective alternative to fossil fuel that could power much of the western United States. Extensional tectonics in the Basin and Range province provide elevated heat flow and increased fractured rock permeability. Pleistocene lake waters trapped within these fractured zones provide a vast region of potentially productive geothermal aquifers. Most of the clearly productive geothermal systems in this region have been developed, and advanced methods for locating previously hidden resources need to be created.

Hydrothermal alteration mineralogy can tell us a lot about the history of a geothermal system and help us evaluate its economic potential. Periodically seismic events push heated fluids to the surface causing hydrothermal alteration (Sibson, 2000). Surface mineralogy can determine the temperature, pressure, and chemistry of subsurface fluids, as well as their distribution. Traditional field mapping of hydrothermal mineral alteration can be tedious and costly. Hyperspectral imaging has proven to be a very effective method in mapping these minerals. Martini (2002) used this technique with HyMap and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) hyperspectral data to gain an understanding of the local tectonic, hydrothermal, biological, and volcanic systems in Long Valley Caldera, and Crowley and Zimbelman (1997) used AVIRIS to map alteration on Mt. Rainier.

In an effort to apply these techniques to the realm of geothermal prospecting, the consortium of the University of California at Santa Cruz (UCSC), Lawrence Livermore National Labs (LLNL), the University of Nevada at Reno (UNR), and the University of Utah (UU) collected a HyMap hyperspectral dataset at Dixie Meadows, in August of 2002

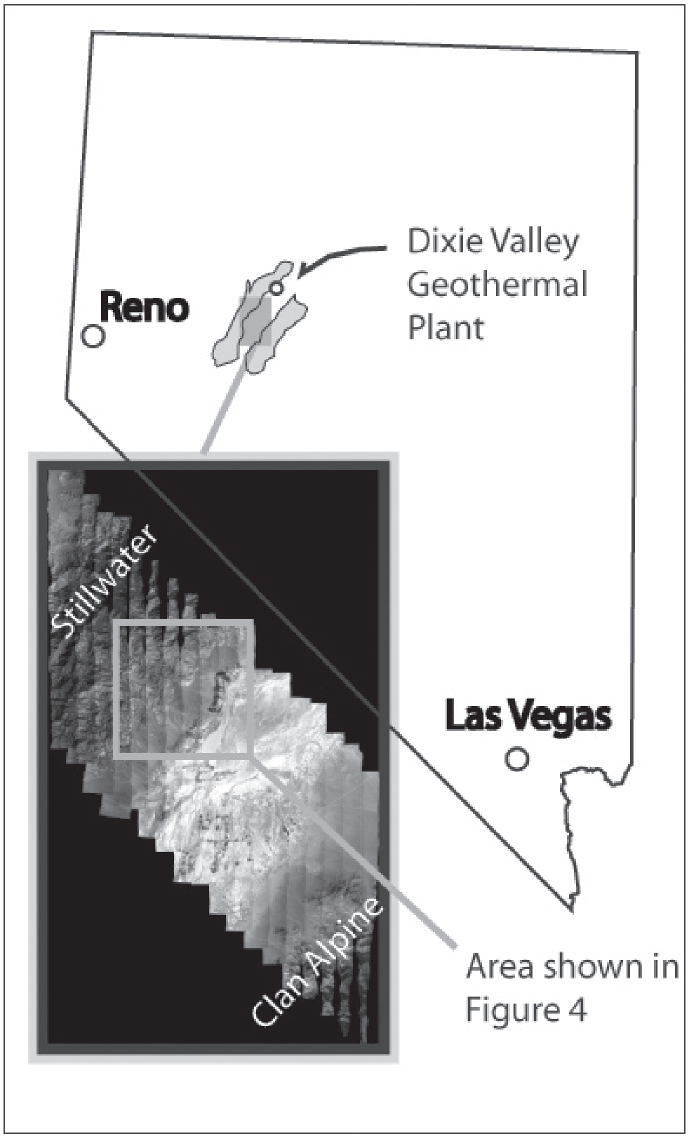


**Figure 1.** Location of Dixie Meadows HyMap Data acquired in 2002.

these events and determine what properties of the system might enable this type of faulting. Understanding the effects of low-angle normal faulting on fluid pathways is crucial to understanding the geothermal system at Dixie Meadows.

## Methods

The Dixie Meadows dataset consists of eighteen North-South trending flight lines. HyVista Corporation delivered both radiance-at-sensor and apparent reflectance data to Lawrence Livermore National Laboratories in November of 2002. Simultaneously, UCSC began its analysis of the data using Research Systems Incorporated (RSI) Environment for Visualizing Images (ENVI™) software.

Initially the large data set was subset into smaller areas of interest along the range front. Two ENVI algorithms were used to identify and extract spectrally pure endmembers within the image subsets, Minimum Noise Fraction (MNF) and Pixel Purity Index (PPI). MNF is an algorithm designed to suppress noise, enhance signal and ultimately determine what part of the dataset is spectrally useful. PPI is an algorithm used to highlight spectrally extreme pixels. Endmembers were selected from these remaining extreme pixels and mapped using one of the ENVI mapping algorithms, Mixture Tuned Matched Filtering (MTMF). Portions of these maps were field-checked

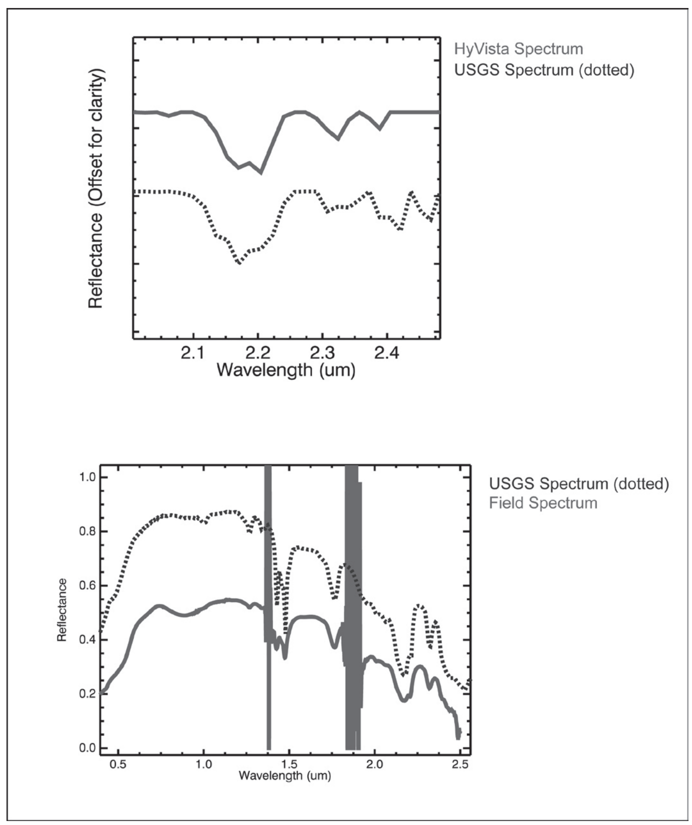


**Figure 2.** The first plot compares the spectrum of a pixel extracted from the HyMap data to the USGS lab spectrum for alunite. The differences are the result of mixing of materials within the pixel. The second plot compares the USGS spectrum to an averaged field spectrum taken at the location of the pixel shown in the first plot. Note that the first plot and the second plot cover a different range of the spectrum.

(see Figure 1). This area is an ideal location for this study because of its close proximity to the largest geothermal field in Nevada (the Dixie Valley geothermal field). HyMap uses 126 spectral bands to collect data in the visible and the short-wave infrared wavelengths at variable spectral sampling bandwidths (17 nm between 2.0 and 2.5 μm). The airborne high-resolution hyperspectral imagery has a spatial resolution of about 3 meters depending on local topography.

The unique exposure of the geothermally altered footwall at Dixie Meadows is related to the unusual fault system. The Dixie Valley Fault produced one of the only recorded large earthquakes on a low angle normal fault (Abbott et al., 2001). Activity on faults with a dip of less than 45 degrees is a highly debated subject. Andersonian theory of faulting would not predict such a fault mechanism (Anderson, 1942), however, several researchers (Abers et. al., 1997, Abbott et al., 2001, Johnson and Loy, 1992) have shown that a significant portion of shallow crustal extension is accommodated in this manner. The Dixie Fault system is an interesting field area to study using an Analytical Spectral Devices (ASD) Field Spec Pro field spectrometer (see Figure 2).

Detailed fault maps were created using three-dimensional views of the region generated by projecting the geocorrected HyMap data over publically available Digital Elevations Models (DEM). Correlation between mineral alteration lineations and changes in slope were assumed to be fault related. Traditional field methods were used to check the locations of mapped faults and determine strike and dip and relative motion between blocks. Linear trends in vegetation were also used in conjunction with other evidence to locate faults. This method works well in arid regions where surface water must come up along faults from deep aquifers to allow vigorous plant growth.

## Results

Mineral mapping over 16 km of the imaged range-front, revealed one area with elevated concentrations of high-temperature alteration minerals (Kennedy-Bowdoin et al. 2003). The majority of subsequent research is focused on this region (see Figure 4). At least three zones of alteration can be distinguished: acidic alteration (high temperature) of Tertiary tuffs, alkaline alteration of Tertiary tuffs, and intermediate alteration of Triassic meta-sedimentary rocks (see Figure 3).

Acidic alteration is common in regions with fluid temperatures in the range of 100-350°C. Typical acidic alteration assemblages include halloysite, kaolinite, alunite, quartz, and dickite (among others). Parent rock has little effect on result-

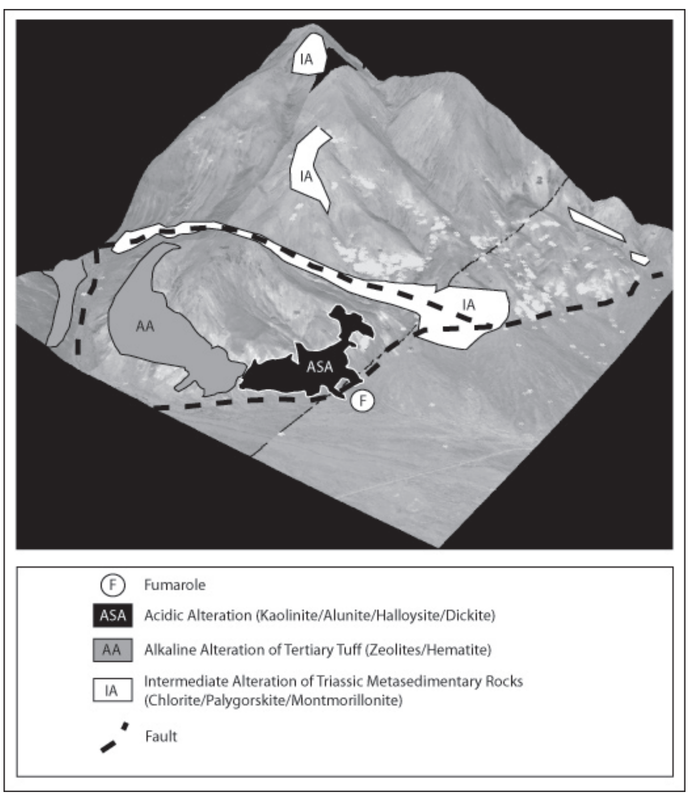


**Figure 3.** The three zones of alteration described in the text are superimposed upon the 3D surface view. This view is looking to the northwest.

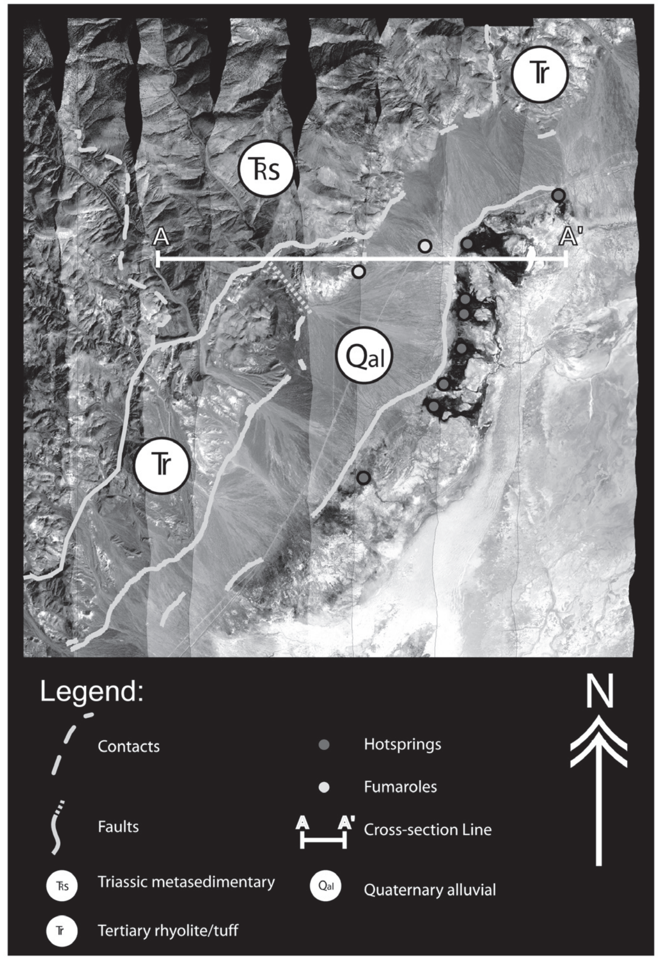


**Figure 4.** Important faults and contacts mapped using the HyMap data and field methods. Note that the cross-section line (Figure 5) is shown in map view.

ing acidic alteration minerals. Alkaline alteration forms from Ca- and Na-rich fluids and moderate temperatures generally form zeolites. Intermediate alteration is common where fluids are rich in Ca-Mg, and K, and results in illite/smectite mineralogy at moderate temperatures, and chlorite-epidote mineralogy at higher temperatures (Inoue, 1995). In Figure 3, the distributions of these minerals are used to outline zones of alteration.

Our field observations of structures in this region show that the Dixie Valley Fault dips 35 degrees to the southeast at Dixie Meadows. This extends the region of active low- angle normal faulting on this fault at least 10 km to the north of the Abbott et al. (2001) study.

We measured 75°C waters at Dixie Hot Springs where water reaches the surface along a synthetic fault. At the Dixie Meadows fumaroles, we measured 94°C ground temperatures and observed active precipitation of elemental sulfur.

## Discussion

The zone of acidic alteration is directly adjacent to active fumaroles that are presently precipitating acidic alteration minerals, indicating that geothermally heated water is boiling near the surface (Inoue, 1995). This acidic alteration occurs at the intersection of two faults, indicating enhanced crustal permeability in this region. The occurrence of lower temperature assemblages can be explained in several ways. Perhaps zones of intermediate/alkaline alteration access different fluids. Specific fault conduits may penetrate to different depths within the aquifer and account for the difference in hydrothermal chemistry. Or perhaps the fault conduits are less dilated, allowing slower movement of fluids and greater cooling before reaching the surface. Ultimately, alteration in this system may occur over longer time scales and the assemblages observed today may represent not only present-day hydrothermal chemistry and flow patterns, but also chemistry and flow from the distant past. Only analytical age dating of alteration minerals would resolve this issue as quantitative spectroscopy has yet to convincingly provide mineral age information.

The combination of all of the data acquired in this study and the cross-section constructed by Abbot et al. (2001) allows us to interpret the subsurface geology and structure at Dixie Meadows. Figure 5 illustrates that both the source of the fluids at Dixie Hot Springs and the alteration and fumarolic activity at the range front is a 2 to 3 km deep geothermally heated, fractured rock aquifer.

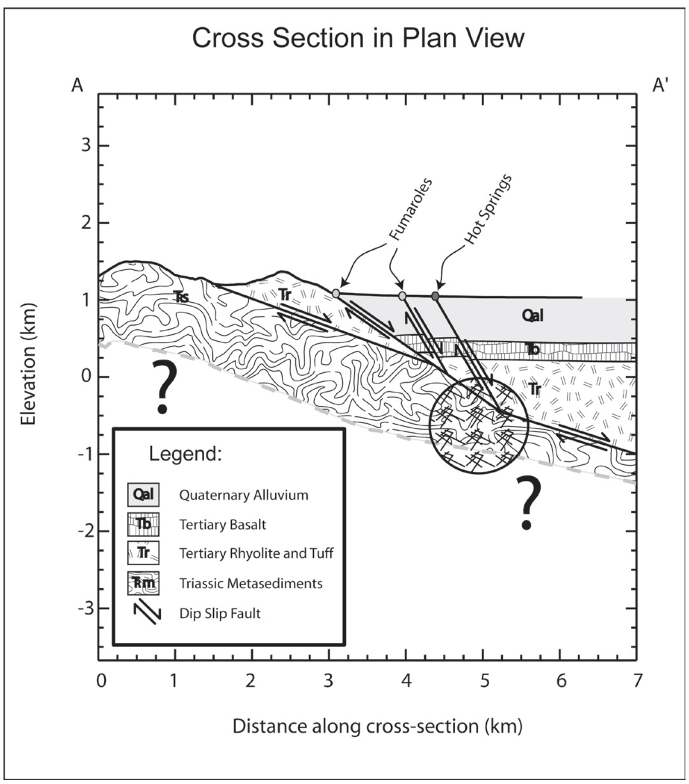


**Figure 5.** Faults grow progressively steeper to the east; modern faulting is forming at typical normal fault angles. The hatched area depicts the proposed location of the high fracture permeability induced by complex fault interactions. The question marks indicate that the location of the Humboldt complex of intrusive rocks is unknown.

## Conclusions and Future Work

In the Dixie Meadows field area, range front faulting is occurring on low angle normal faults. The presence of hydrothermal fluids along the Dixie Valley Fault correlates with active portions of the fault. Hyperspectral mineral mapping resulted in an accurate map of modern high temperature alteration minerals and faulting. Using these techniques, we are able to pinpoint a geothermally heated permeable aquifer that could be developed into a productive geothermal field.

These methods will greatly facilitate the exploration for geothermal resources in the future. We are presently collaborating with Presco Energy LLC at the Humboldt/Rye Patch geothermal system and hope that this type of research will be incorporated into the standard practices of not only Rye Patch explorers, but throughout the geothermal prospecting industry.

## References

Abbott R. E., J. N. Louie, S. J. Caskey, S. Pullammanappallil, March 10, 2001. “Geophysical confirmation of low-angle normal slip on the historically active Dixie Valley fault, Nevada.” *Journal of Geophysical Research*, v. 106, no. B3, p. 4169-4181.

Abers, G. A., C. Z. Mutter, and J. Fang, 1997. “Shallow dips of normal faults during rapid extension: Earthquakes in the Wooklark-D’Entrecasteaux rift system, Papua New Guinea.” *Journal of Geophysical Research*, v. 102, p. 15,301-15,317.

Anderson, E. M., 1942. “The Dynamics of Faulting.” 183 p., Oliver and Boyd, White Plains, N.Y.

Caskey, S. J., S. G. Wesnousky, P. Zhang, and D. B. Slemmons, June 1996. “Surface faulting of the 1954 Fairview Peak ($M_s$ 7.2) and Dixie Valley ($M_s$ 6.8) earthquakes, central Nevada.” Bulletin of the Seismological Society of America, v. 86, n. 3, p. 761-787.

Crowley, James K. and D.R. Zimbelman, June 1997. “Mapping hydrothermally altered rocks on Mount Rainier, Washington, with Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data.” Geology, v. 25, n. 6, p. 559-562.

Inoue, A. 1995. “Formation of Clay Minerals in Hydrothermal Environments.” in Velde, B. (ed.), Origin and Mineralogy of Clays: Clays and the Environment. Springer-Verlag, Berlin, Heidelberg, New York, p. 268-321.

Johnson, R. A., and K. L. Loy, 1992. “Seismic reflection evidence for seismogenic low-angle faulting in southeastern Arizona.” Geology, v. 20, p. 597-600.

Kennedy-Bowdoin, T., B. A. Martini, E. A. Silver, and W. L. Pickles, October 2003. “Hydrothermal alteration mineral mapping using hyperspectral imagery in Dixie Valley, Nevada.” Geothermal Resources Council Transactions, Vol. 27, p. 649-651.

Martini, B.A., 2002. “New insights into the structural, hydrothermal, and biological systems of Long Valley Caldera using hyperspectral imaging.” Ph.D. Thesis, UCSC Earth Sciences Department.

Nash, Gregory D., Glenn W. Johnson, January 2002. “Soil mineralogy anomaly detection in Dixie Valley, Nevada using hyperspectral data.” Proceedings, 27th Workshop on Geothermal Reservoir Engineering, Stanford, California, SGP-TR-171.

Sibson, R. H., June 2000. “Tectonic controls on maximum sustainable overpressure: fluid redistribution from stress transitions.” Journal of Geochemical Exploration, v. 69-70, p. 471-475.