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Hyperspectral Mineral Mapping in Support of Geothermal Exploration: Examples from Long Valley Caldera, CA and Dixie Valley, NV, USA

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Introduction

Growing interest and exploration dollars within the geothermal sector have paved the way for increasingly sophisticated suites of geophysical and geochemical tools and methodologies. The efforts to characterize and assess known geothermal fields and find new, previously unknown resources has been aided by the advent of higher spatial resolution airborne geophysics (e.g. aeromagnetics), development of new seismic processing techniques, and the genesis of modern multi-dimensional fluid flow and structural modeling algorithms, just to name a few. One of the newest techniques on the scene, is hyperspectral imaging. Really an optical analytical geochemical tool, hyperspectral imagers (or imaging spectrometers as they are also called), are generally flown at medium to high altitudes aboard mid-sized aircraft and much in the same way more familiar geophysics are flown. The hyperspectral data records a continuous spatial record of the earth's surface, as well as measuring a continuous spectral record of reflected sunlight or emitted thermal radiation. This high fidelity, uninterrupted spatial and spectral record allows for accurate material distribution mapping and quantitative identification at the pixel to sub-pixel level. In volcanic/geothermal regions, this capability translates to synoptic, high spatial resolution, large-area mineral maps generated at time scales conducive to both the faster pace of the exploration and drilling managers, as well as to the slower pace of geologists and other researchers trying to understand the geothermal system over the long run.

Two sites in the western U.S. are used to demonstrate the utility of hyperspectral surveys for geothermal site characterization and exploration. Extensive hyperspectral studies in Long Valley Caldera in central-eastern California has provided a template for subsequent hyperspectrally-driven geothermal system assessments (Figure 1B). Fault mapping, discharge zone delineation, gross hydrothermal circulation patterns, general hydrothermal system geochemical character and temperatures are gleaned from the hyperspectral data. The combination of hyperspectral data with other geophysical and geochemical datasets serves to both test hyperspectral's capabilities for geothermal system characteriza-

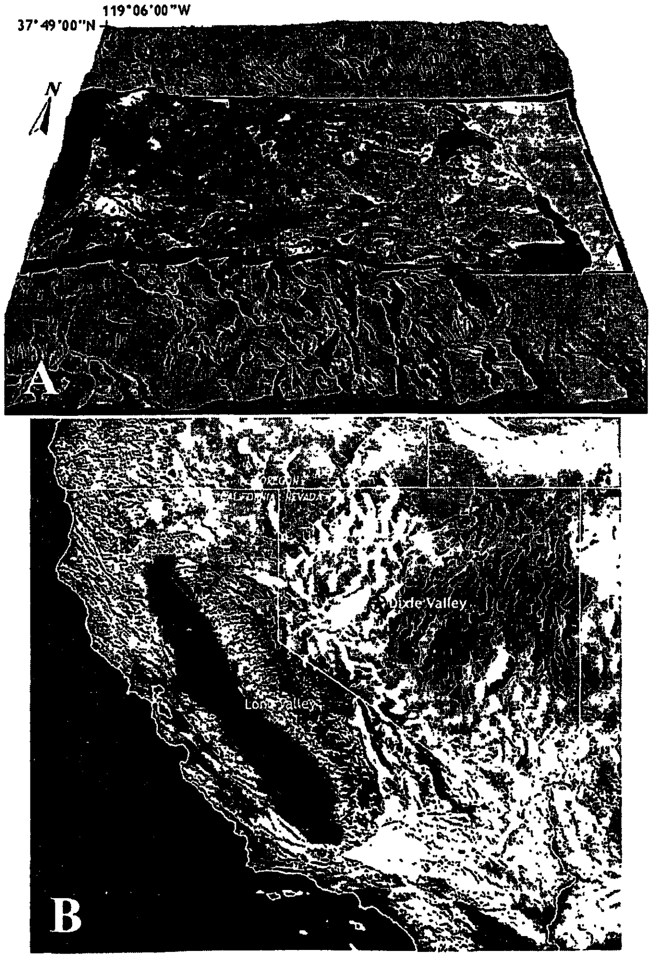


Figure 1a. Spatial extent of 1999 HyMap acquisition over Long Valley Caldera draped over a USGS 10-meter DEM. B. Geographical location of Long Valley Caldera, CA and Dixie Meadows, NV.

tion and to combine with and build on the information and models gleaned from other datasets. The goal is to extend hyperspectral data and techniques into other geothermal regions both at the production and prospect level. Such an incursion has begun in central Nevada, just to the south of the Dixie Valley geothermal field, in a locale referred to as Dixie Meadows (Figure 1B). It is hoped that the level of mapping and characterization success reached in Long Valley, is possible at Dixie Meadows.

Long Valley Caldera

Our geological knowledge of Long Valley caldera is quite advanced as its restless demeanor over the past 25 years has encouraged abundant monitoring and study. Much is known about the dynamics and chemistry of this system due to the vigorous drilling program in the caldera that began in 1960, subsequent long-term monitoring and sampling programs of the liquid and gas discharge zones along with various fault and fracture mapping efforts. However, questions still remain concerning the location of fundamental heat sources, the patterns and conduits of hydrothermal fluid transport as well as subsequent up-flow and discharge zones.

Long Valley is a massive, east-west elongate (32 km x 17 km), 760,000 year old caldera that formed along the eastern edge of the Sierra Nevada escarpment [*Bailey et al.*, 1976]. Subsequent intra and extra-caldera volcanism has maintained the high heat flows of the caldera and nursed several aerially extensive, deep hydrothermal systems. The most recent system peaked at 40ka [*Sorey*, 1985; *Sorey et al.*, 1978], and likely sources from thermal input in the western caldera beneath the north-trending Mono-Inyo volcanic chain [*McConnell*, 1995; *Sorey*, 1985; *Sorey et al.*, 1991]. Though the hydrothermal system appears to have been silica-saturated at one time, present day chemistry embodies carbonate saturation. Only alkaline to neutral, slightly saline, sodiumbicarbonate hydrothermal waters discharge surficially in the central and eastern caldera and temperatures from hotsprings range from 79-93°C [*Sorey et al.*, 1991]. The only acidic waters known to occur in the caldera issue as steam from fumaroles on the northern and southern flanks of the parasitic rim-cone, Mammoth Mt., as well as a few places within the western and central caldera including Basalt Fumarole and Fumarole Valley. The 40 MW Casa Diablo geothermal plant is nested between sets of large northwest-trending normal faults in the western-central caldera and feeds off ~170°C reservoirs at a depth of 600 meters. Aggressive exploration programs in the region intend to expand the current production fields, most likely to regions farther west. Thus, any additional information regarding the dynamics of the hydrothermal system and its discharge geometry is crucial in planning a drilling program and developing a successful production extension in the Long Valley region.

Hyperspectral Mineral Mapping

Alteration Mineral Distribution as Proxy for Discharge Zones

Discovering profuse quantities of hydrothermally altered minerals is usually the first indication geologists have of anomalously high geothermal gradients in a particular region. The maximum densities of alteration occur along the zones of highest permeability which normally include faults, fractures and unit contacts. These permeable areas serve as up-flow, discharge and recharge zones. Continuous discharge of gas and hot water over many years eventually alters the soil and rock along contacts, fractures and faults which tend to be linear. Thus linear distributions of kaolinite and other hydrothermal alteration minerals discussed above, may be used as a proxy for fault and fracture distribution mapping within hyperspectral imagery. Locating these distributions, their orientation and determining their identity is key knowledge both for geothermal explorationists and for volcanologists studying the chemistry and dynamics of active volcanic hydrothermal systems. Unfortunately, alteration minerals tend to look very similar and can be challenging to map in the field (especially if diffusively distributed, as many are).

Traditional point surveys in the form of wells, surface water and rock sampling provide sparse surface coverage of rock and alteration types and detailed depth coverage of stratigraphy, petrology, alteration identification and temperature. This approach provides much information about single points and little information about the rocks and the system between each point. However, airborne hyperspectral imaging provides hydrothermal mineral distribution maps over large areas at a realtively fine sampling interval (~3-5 meters). The spectroscopy of most important alteration minerals is well known and algorithms used in identifying and mapping their distributions have been in place for over a decade now. Mapping suites of alteration minerals with confidence and good geo-precision is thus easily done with advanced well-calibrated hyperspectral imagers (eg. AVIRIS, HyMap).

HyMap Data Acquisition

Long Valley caldera was flown on September 7, 1999 with the Australian HyMap sensor (Integrated Spectronics, Ltd.). The acquisition covered approximately 540km^2 between latitude of 37° 30" to 37° 36" and longtitudes of 118° 42" to 119° 04" W (Figure 1a). It consists of seven east-west flightlines (2.3 km x 32 km) with a spatial resolution that varies from 3 to 5m depending on local topography (elevation ranges from 2070m on the caldera floor to about 3300m in the Sierra Nevada range and at Mammoth Mountain). HyMap samples the electromagnetic spectrum of reflected sunlight from 450 to 2500 nm wavelength in 126 separate but contiguous wavelength bands from 13 to 17 nm wide. Signal-to-noise ratio (SNR) is well over 1000:1 for most wavelength regions[*Cocks*, 1999] . The instrument was flown aboard a twin-engine Cessna with complete radiometric and spectral calibration and simultaneous DGPS data acquisition. Data cubes were radiometrically corrected to apparent reflectance using the ATREM algorithm [*Gao*, 1993], and spectrally smoothed using the EFFORT algorithm [*Boardman*, 1998].

Geospatially corrected maps of alteration mineralization were created on a caldera-wide scale; something rarely done in such large volcanic areas. Zones of discharge were easily mapped and their dominant mineralization identified. Coupling this information with previously mapped faults, well-data (including temperatures and alteration) and surface sampling data allowed identification and refinements of discharge zone geography.

Results—Kaolinite Mapping at Fumarole Valley and Hot Creek

Sets of synoptic mineral maps have been produced for all of Long Valley Caldera, however discussion here is limited to the Fumarole Valley/Hot Creek (FV/HC) region. In total, 28 minerals were detected within the entire Long Valley hyperspectral dataset. Though different minerals dominate different regions of the caldera, a few minerals are more or less ubiquitous throughout the entire caldera. One of these minerals is kaolinite, a potassium-rich clay. Kaolinite can form deutirically, however when found in association with higher temperature sulfates or other clays, it may be hydrothermal in origin (forming at temperatures of 100-200°C; never exceeding 220°C). The FV/HC region has around 10 major identifiable and mappable minerals, including an abundance of kaolinite. Much of this kaolinite is found in association with the sulfate alunite which forms at temperatures of 100 -230°C; generally exceeding 200°C. This advanced argillic phase alteration suite is found in several other sites around the caldera, though distribution densities found in the FV/HC region are second only to that found on the flanks of Mammoth Mt. The presence of kaolinite-alunite assemblages in volcanic environments indicates a high temperature, vapor-phase, acid sulfate hydrothermal input.

Figure 2 shows kaolinite mineral mapping results from one line of HyMap data that cuts across the FV/HC region. Figure 2A shows the HyMap data in a greyscale format. Fumarole Valley and Hot Creek are both identified. Figure 2B shows the kaolinite distribution as measured with the HyMap data. The brighter the population, the closer the match to known pure kaolinite spectral response. Previous faults are shown as the lighter colored square-box lines [*Bailey*, 1989] while hyperspectral-based faults are shown by the darker rounded-box lines [*Martini*, 2002]. The interpretation of the faults is solely from locating and vectorizing linear distributions of hydrothermal alteration minerals (in this case, montmorillinite, kaolinite, alunite, and nacrite of which kaolinite is the only mineral distribution shown in Figure 2).

Discussion

Mineral mapping in the FV/HC region was very successful. The major hydrothermal alteration mineral assemblages were located and identified. The fact that linear distributions of alteration were found to coincide with previously known fault paths, allows us to bootstrap the technique towards the detection and mapping of other linear distributions of alteration as proxy for zones of high permeability (be they faults, fractures, etc.). Subsequent field checking has revealed that the linear zones identified with hyperspectral data analysis are likely faults/fractures of some kind. In particular, the largest east-west trending structure in the center of Figure 2B was found to have both topographic expression along its length and slip indicators at its western extent. This previously unidentified structure, though only a couple of kilometers long, is decidedly important to hydrothermal fluid-flow model construction. In general, large east-west structures would aid in transfering hydrothermal waters from west to east across the caldera. Before this study, very little evidence existed for such structures. Hyperspectral-based fault mapping, along with other seismic work [*Prejean*, 2001], confirms past speculation that the Long Valley hydrothermal system is structurally controlled in addition to being unit-controlled [*Sorey et al.*, 1991; *Suemnicht and Varga*, 1988]. Such information is invaluable to those trying to constrain the location of flow paths in the caldera.

To further constrain flow paths throughout the caldera, the mineral mapping and fault/discharge zone delineation techniques described above were repeated through the entire caldera. This exercise produced a remotely-derived, whole-caldera discharge map, of which many discharge features are likely faults and frac-

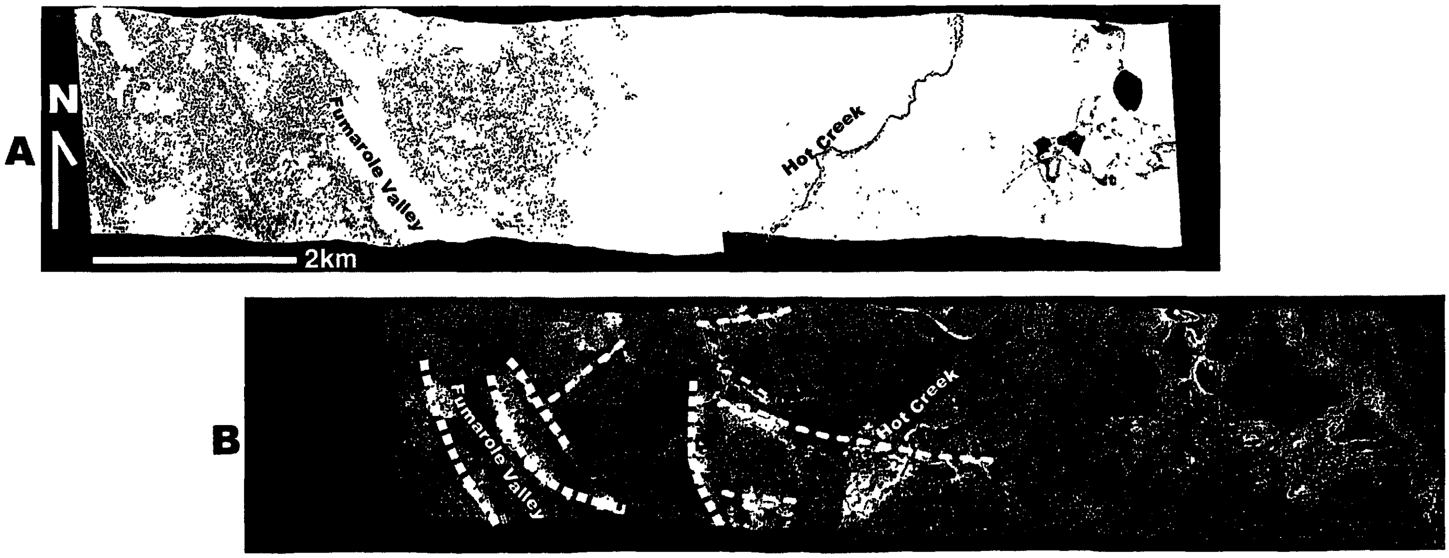
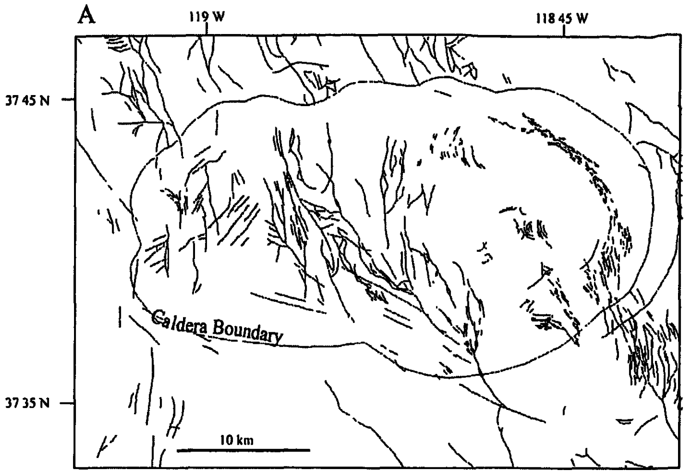


Figure 2A. Geo-corrected, panchromatic HyMap image of the Fumarole Valley/Hot Creek region.

Figure 2B. The kaolinite distribution image. Pixels that match the reference kaolinite spectrum to 95% are shown in white. Previously mapped faults are shown by the square-box lines, while hyperspectrally determined structures are shown with rounded-box lines.



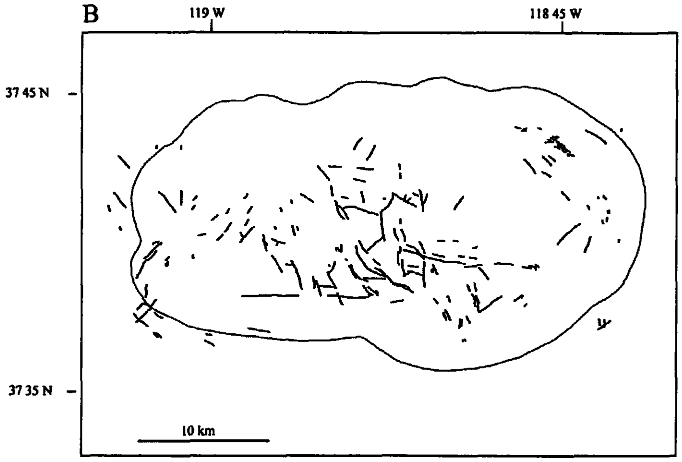


Figure 3A. Map of previously known fault distribution in Long Valley Caldera.

Figure 3B. Hyperspectrally detected faults and fractures.

tures. Figure 3A shows the fault map of the Long Valley region that includes detailed local caldera structure [*Bailey*, 1989], the Discovery Fault Zone in the western caldera [*Suemnicht and Varga*, 1988] and the South Moat Fault Zone [*Prejean*, 2001]. Figure 3B shows faults derived from interpretation of high spatial resolution, HyMap-derived hydrothermal mineral maps, and is an example of the level of detail to expect when using hyperspectral imaging to map structural components. Clearly not all of the faults in Long Valley are detected using this hyperspectral technique. In fact, only ~ 17% of faults are detected (72 km of fault/fracture length compared to a total of 420 km of fault length). This is a fairly low number, however, all the general structural trends are captured in the hyperspectral map (as well as several newly detected populations such as the east-west trending fault in the FV/HC region). It is important to note that the 17% relates to total length of faults and fractures, not individual faults. In other words, a high proportion of individual faults are detected, though their entire length may not be captured. For instance, of the 3284 meter long secondary structure of the Discovery Fault Zone, 1306 meters was actually detected in the form of linear distributions of kaolinite and alunite. Only 39.8 % of the length of the fault was actually mapped, however the location and trend of the structure is discernable, which is most important for the creation of a complete structural network for models, hazard analysis and geothermal exploration strategies.

The implication of the above research for future hyperspectral surveys of poorly known geothermal areas is two-fold. First, linear distributions of hydrothermal alteration minerals can provide workable maps of structural networks in active volcanic regions with a history of hydrothermal discharge. Second, not all structure is mappable using this method, and the lack of alteration in a region does not preclude faulting or hydrothermal activity at depth. In addition, though the lack or profusion of alteration in a region hints at relative ages of faulting, hyperspectral imaging analysis is incapable of producing actual ages of mineralization.

Works in Progress and Future Directions

Surface Mineralization in Combination With Drilling Data

The next step involves tieing the surface data extracted with hyperspectral imaging to other forms of geophysical and geochemical data, in order to start building a more three-dimensional view of geothermal regions. Initial phases of this have begun in Long Valley, where the rich surface mineral maps derived from the HyMap data are coupled with mineral and temperature data taken from core and drill holes around the caldera. The idea is to determine what surface mineralization implies about mineralization at depth and thus chemistry and temperature of the hydrothermal system.

Preliminary results indicate a good deal of correlation between alteration found at the surface and alteration found at depth. For instance, the well RDO-8 was drilled just north of Mammoth Lakes through Quaternary tills (Qti). It was drilled to a depth of 715 m and reached a bottom hole temperature of 202°C. This temperature would predict a hot hydrothermal system at depth and advanced argillic alteration. Hyperspectrally mapped surface alteration consists of alunite, amorphous silica, kaolinite and montmorillinite. Alteration at depth is reportedly kaolinite, smectite, opal, lesser quartz and kspar, and at great depth, illite and calcite (Flexser, 1991). The surface assemblage is classic acid sulfate, advanced argillic alteration and would indicate very hot water at depth. Alteration at depth matches surface alteration reasonably well with the exception that no sulfates are found at depth and no silicates are found on the surface. The latter part of this discrepancy is due to the inability of visible-near infrared hyperspectral imaging to discriminate silicates.

Further east, the LVEW well was drilled into the central resurgent dome through early Quaternary rhyolites (Qer) and tuffs (Qet). It was drilled to a depth of 2300 m and reached a final bottom hole temperature of ~100°C. Though this temperature is fairly high, the hyperspectrally mapped surface alteration was limited to a few pixels of amorphous silica, and nothing else for a significant radius around the well-head. Alteration at depth is reportedly dominated by calcite, pyrite, quartz, k-feldspar, albite, chlorite and epidote. Though seemingly located directly in a zone of discharge, this well never reached waters at known reservoir temperatures (~230°C). Although structurally it seemed to be the best place to drill in order to sample the hottest parts of the

Long Valley system, there is virtually no surface alteration near the site. In addition, the lack of alteration on nearby faults would suggest that these faults do not act as discharge structures. The presence of high temperature mineralization at depth may reflect the vestiges of the once dominant hydrothermal system centered on the resurgent dome that peaked at approximately 300ka [*McConnell et al.*, 1997; *Sorey et al.*, 1995]. This system has since waned and moved farther to the west beneath the western caldera. So, though hyperspectral data did not capture the mineralization seen at depth, it did appear to capture the current state of local hydrothermal discharge (or lack thereof).

In general, it doesn't appear that surface alteration is a finely tuned indicator of current temperatures at depth, rather it indicates what the longer history has been. The timing of the mineralization is ambiguous without field data including age dates of particular units. However, if units are older and occupy "dead" hydrothermal zones, it may simply mean they are dormant and could serve as future points of discharge given the correct structural or volcanic impetus. The degree, amount and spatial distribution of hydrothermal mineralization appears to be a better guide to discharge zones.

High temperature, acid sulfate surface alteration generally coincided with high temperature source reservoirs at depth. The lack of or sparse alteration on the surface generally coincided with regions hosting little to no hydrothermal upflow. Such regions generally displayed only minor amounts of amorphous silica and/or calcite, both of which can be formed at fairly low temperatures (with respect to hotter acid-sulfate environments). Surface alteration coupled with complete fault maps (both traditional and hyperspectral based), would certainly enhance current geothermal exploration methodologies. The addition of such maps would make reconnaissance surveys far more directed initially and prove more efficient with respect to both time and money.

Dixie Valley – New Insights Into a Classic Geothermal Locale

The Dixie Valley geothermal field (DVGF) is located just east of the Stillwater Range and west of the Clan Alpine Mountains. With an installed capacity of 62 MW, the DVGF is fed by a structurally controlled hydrothermal system. Historical flow models allow for one major conduit of flow which is considered to be the large range-bounding Stillwater fault. More recent thinking based on new and reinterpreted geophysical data (including deep wells, seismics, and aeromagnetics) suggests that hydrothermal fluid flow occurs along several sets of structures, rather than on a single fault plane[*Blackwell*, 2000; *Smith*, 2002]. Smith et al., 2002 have further suggested that producing geothermal reservoirs are located where the major fault sets merge (both in the north at the main Dixie Valley geothermal field and in the south at the Dixie Meadows prospect). It seems clear that our understanding of the geothermal system in the Dixie region hinges on improved knowledge of the local structural system, which includes mapping all faults and fractures capable of hydrothermal fluid focusing and transport.

With this in mind and the success of mapping structure within Long Valley caldera using hyperspectrally-derived mineral maps under our belt, a three-meter HyMap survey was flown over the Dixie region. The eighteen lines were flown north-south and are centered on the Dixie Meadows prospect (Figure 4). Dixie Meadows lies to the south of the main producing DVGF and has peaked the interest of area geothermal companies looking to expand production from the main field. Temperature data from drill holes further south in the Dixie Meadows region are markedly higher than many drill holes in the DVGF proper [*Blackwell*, 2000], and recent structural analysis suggests that the Dixie Meadows region lies within a similar structural framework to that of the DVGF [*Smith*, 2002] further north.

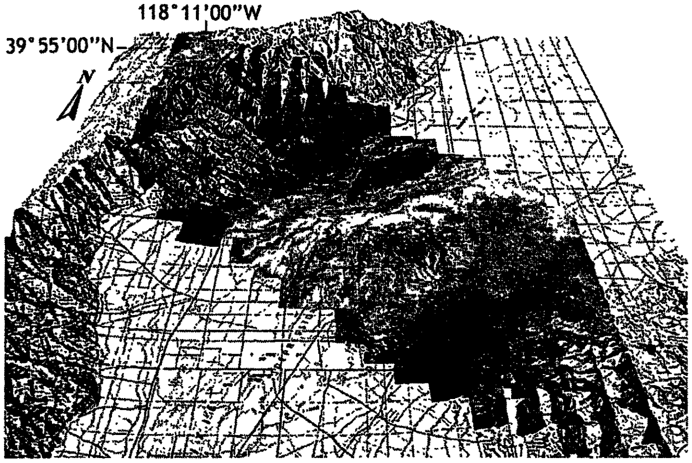


Figure 4. Three-meter HyMap data centered on Dixie Meadows, NV. The 18 lines of hyperspectral data are draped over a USGS 30 meter DEM and accompanying USGS 7.5" topographic quadrangles.

Preliminary results from hyperspectral mineral maps of the Dixie Meadows region are compelling. Four of the six major recognized hydrothermal mineral assemblages (from drillcore) have been identified in the data, including the older epidote-chlorite-calcite assemblage and the younger chalcedony-dolomite-calcite-barite-chlorite/smectite-hematite assemblage[Lutz, 2002]. Previously noted outcrop alteration is also recognized throughout the hyperspectral data, including the gypsum-kaolin-halite fumarole encrustations found at Dixie Meadows proper. Success in mapping these assemblages indicates we should be able to adequately study both the geochemistry and timing of alteration phases at Dixie Meadows.

Initial fault mapping analyses have also been made using the combination of linearized alteration-based fault maps with new aeromagnetic-based fault maps. Many of the faults mapped in the field are detected using the hyperspectral imaging techniques discussed in the previous LongValley sections. In addition, several faults interpreted from the aeromagnetics data are also detected in the hyperspectral data. Finally, several sets of linearized alteration are found throughout the Dixie Meadows imagery that don't correspond to any previously known structures. In particular, a northwest-trending, ~1km long zone of kaolinite and dickite is found on the eastern edge of the valley well within the Clan Alpine mountains range front. The alteration may represent a hitherto unknown major zone of discharge in eastern Dixie Valley.

Conclusions

Hyperspectral-based mineral mapping in geothermal environments provides a substantial analysis of hydrothermal flow paths, discharge points, and rough chemistry and temperature. Much of what we know about the Long Valley system was confirmed, both structurally and geochemically. However, several new fault sets were found within the caldera that aid in elucidating gross hydrothermal fluid flow in the region. Lacking any convincing structures, the hydrothermal system in Long Valley has long been considered unit controlled, but the addition of several convincing east-west trending structures allows for structural control of hydrothermal waters. In reality, hydrothermal flow is probably controlled by a combination of both unit contacts and structure. Comparisons of surface alteration with drillcore alteration data are compelling, though far from being reliable and fully understood. Larger amounts of drillcores and more rigorous statistical comparisons of surface vs. subsurface data are needed in order to clarify the relationship (if any), between mineralization found on the surface and mineralization found at depth. Finally, hyperspectral analysis of the Dixie Meadows region will continue, including more detailed mineral mapping analysis for both hydrothermal alteration and evaporite mineral assemblages and the exploration of the synergy between hyperspectral data and geophysical data such as the aeromagnetics.

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