ASSESSING HYDROTHERMAL SYSTEM DYNAMICS AND CHARACTER BY COUPLING HYPERSPECTRAL IMAGING WITH HISTORICAL DRILLING DATA: LONG VALLEY CALDERA, CA, USA

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SUMMARY – Synoptic maps of hydrothermal alteration have previously been constructed for Long Valley Caldera located in central-eastern California, however the purpose of this work is to determine what continuous surface alteration information can or cannot reveal about alteration at depth and thus hydrothermal system dynamics and character. Mineral maps produced from hyperspectral imaging are compared with known geology including historical drilling data. A good correlation is obtained between the types of alteration found at the surface and that found at depth. Generally, the temperatures and alteration measured at depth echo the alteration (and implied temperatures) that is subsequently mapped at the surface. However some specific comparisons at individual well sites still remain inconclusive due to external variables that are difficult to control and measure such as intense vegetation coverage, secondary weathering and transport, and instrument limitations. An attempt to rise above some of these issues is made by exploring trends of alteration and thus hydrothermal system character by using alteration density plots. Such plots confirm current working models of hydrothermal system dynamics and geometry and support new geothermal prospecting in the region.

1. INTRODUCTION

Alteration minerals reveal much about present and paleo flow dynamics and chemistry of 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 and temperature. In other words, the point survey approach provides much information about single points and modest information about the rocks and the system between each point.

However, an efficient synoptic method for mapping alteration minerals exists which provides the elusive, continuous x-y distribution of surface mineralization that serves to refine hydrothermal system models: airborne hyperspectral imaging. Every spatial element (pixel) of a hyperspectral dataset contains unique spectral information that allows us to identify most geological materials including primary geothermal mineralization and secondary hydrothermal alteration minerals. This type of remote sensing easily produces synoptic mineral maps of large areas in short amounts of time (weeks instead of the years usually required by traditional field surveys).

Hyperspectral imaging was applied to the long-lived, intermediate temperature, hydrothermal system occupying the Long Valley caldera in central-eastern California. 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, and 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, and subsequent up-flow and discharge zones.

2. METHODS

The HyMap hyperspectral imager was flown over Long Valley in September 1999, acquiring continuous spectral data of all surface materials including rocks, alteration minerals, soil, water, vegetation, and man-made structures (see Figure 1 for survey boundary).

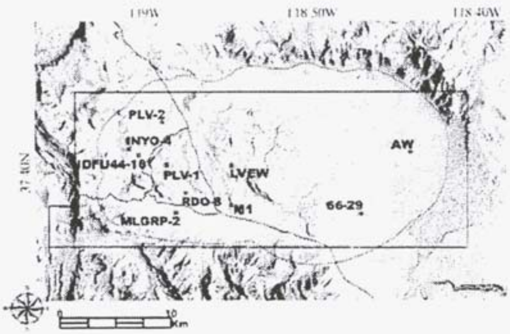

Figure 1. Long Valley Caldera shown in shaded-relief. Caldera boundary is dashed. Well locations discussed in text are shown by squares. Polygon is the boundary of the 1999 HyMap survey.

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 mapped and their dominant mineralization identified. This information was then coupled with previously mapped faults, well-data (including temperatures and alteration) and surface sampling data allowing refinement of discharge zone geography and assessment of the correlation between continuous surface alteration and alteration measured at depth from drill core.

2.1 Hyperspectral Imaging

Hyperspectral imagers sample the electromagnetic spectrum tens to hundreds of times in narrow contiguous wavelength partitions. A complete spectral signature is thus measured for any earth material. The interaction of light and/or heat with crystalline mineral structures produces a set of absorptions and reflectances unique to that crystalline structure. Hyperspectral technology is an important advance over the more limited material identification abilities provided by multispectral instruments such as the Landsat or ASTER satellites. Full identification of earth materials, not simply discrimination, is possible.

The primary instrument used in this study is HyMap, an instrument built by Integrated Spectronics Ltd. and operated by HyVista Corp., Sydney, Australia. This hyperspectral imager measures light from 0.45-2.5 microns in 126 contiguous spectral bands with widths ranging from 13-17nm. Typically mounted on small, low-flying aircraft, HyMap regularly produces data with spatial resolutions (pixel sizes) on the order of 3-5 meters and swath widths that average 2.5 kilometres. Perhaps most importantly, its Signal-to-Noise Ratio (SNR) is well over 1000:1 for most wavelengths.

2.2 Long Valley hyperspectral survey

HyMap data was flown on September 7, 1999 at roughly noon, Pacific Standard Time. The acquisition covered approximately 540km^2 between latitudes 37" 30" to 37" 46" N and longitudes 118° 42" to 119° 04" W (Figure 1). Seven parallel, overlapping, east-west flightlines were taken at a spatial resolution that varies from 3 to 5m, depending on local topography (elevation in this region ranges from 2070m at the caldera floor to about 3300m in the Sierra). The instrument was flown aboard a twin-engine Cessna with complete radiometric and spectral calibration and simultaneous DGPS data acquisition.

2.3 Hyperspectral data pre-processing

Primary processing and analysis were done within the ENVI software environment. The data were received as radiance (mW/cm^2/sr/nm) and were then calibrated to apparent reflectance via a radiance transfer model called ATREM (Atmospheric Removal) (Gao, 1993). We attempted to address any path radiance correction limitations with a smoothing algorithm called EFFORT (Empirical Flat Field Optimal Reflectance Transformation). This is a statistically driven algorithm that removes artefacts by spectrally smoothing the data (Boardman, 1998). As the images were acquired opportunistically with no ground measurements possible on the day of overflight, only EFFORT-corrected apparent reflectance data were used in this study.

Once calibrated, the data were subjected to classification and mapping algorithms within ENVI. Generally speaking, ENVI analyses use statistically based algorithms for spatial and spectral subsetting of data to isolate unique spectral populations, or pure endmembers, within an image. The search for pure image endmembers is facilitated by a set of algorithms aimed at reducing the data both spatially and spectrally. First, the complex spectral variability inherent in a hyperspectral dataset was manipulated with a principle components-like algorithm called the Minimum Noise Fraction (MNF) transform, which essentially suppresses noise and enhances signal. Bands with the most signal are extracted from the original dataset and subjected to a spatial reduction algorithm called the Pixel Purity Index (PPI), which isolates pixels with the purest spectral signatures most likely to represent a single material of interest. These signatures are collected into libraries and used in various material mapping algorithms that ultimately produce system-wide mineral distribution maps.

2.4 Mineral maps

Matched Filter was the primary algorithm used in classification efforts. This algorithm determines the abundances of endmembers using partial pixel unmixing routines. Classification results consist of separate abundance images for each spectral endmember fed into the Matched Filter(MF) algorithm. Mineral classes from the MF results are spatially corrected via DGPS data taken during the time of overflight and converted to vectors capable of being overlaid on a myriad of different geospatial products including digital topographic maps, DEMs, aerial photo, the original HyMap data and/or any other spatially corrected geological dataset within remote sensing software or appropriate GIS atmosphere.

In addition to simple geospatial mineral distribution plotting, a mineral assemblage density/probability plot is also produced. This plot is created with a single mineral group distribution that is contoured based on density of said mineralization. These contours are simply a measure of the average spatial density, i.e. the percentage of surface area of a particular mineral group that has been detected and mapped with the hyperspectral data.

2.5 Subsurface data

The rich surface alteration data provided by hyperspectral imaging was coupled with temperature and lithological data gleaned from a select ten wells drilled over the past forty years. Note that this list is not comprehensive and merely represents a small sample of available drill core information in the caldera. Table 1 lists ten separate wells, their bottom depth, bottom hole temperature, surface rock or soil unit, identity of hyperspectrally measured mineralization in a 200 m radius around the well head, and a catalogue of mineralization found at depth in the drill core (where available). All well site locations are shown in Figure 1.

3. RESULTS

3.1 Hyperspectral mineral maps

Figure 2 shows an example of mineral mapping results for a small section of the HyMap data centered around the INYO-4 well. The centre of the image subset is occupied by a small lake within the 600-yr old Inyo phreatic crater.

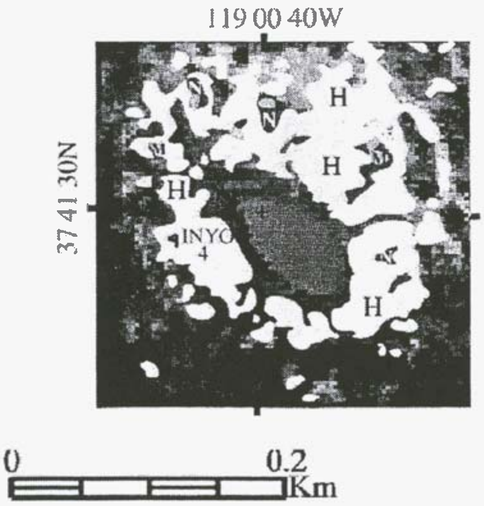

Figure 2. Alteration mapped in the vicinity of well INYO-4 (well indicated by small black flag). H=Hematite M=Montmorillinite N=Nacrite

Initial alteration plots have been enhanced from the simple "pixelated" distributions to denser polygons of alteration. These grey-scale blocks labelled with letters to indicate their identity better emphasize alteration location. Notice most of the alteration in this scene is hematite (H) with smaller pockets of the smectite montmorillinite (M) and the high temperature kaolinite polymorph, nacrite (N). Mineral maps such as that shown in Figure 2 exist for the entire caldera.

3.2 Drill core mineralogy comparison

Table 1 explores the relationship between surface alteration and alteration mapped at depth. In many cases the surface alteration echoed the temperatures and chemistries found at depth. In a few cases however, surface alteration (or lack thereof) was not well correlated.

The highest temperature reached in the caldera is in the reservoir tapped by well IDFU44-16. This well was drilled to 1799 m and sampled waters at 218°C and a pH of 9.3. Alteration of surface basalts near this well produced nacrite, montmorillinite and hematite. Nacrite is consistent with high temperatures at depth as it usually forms at temperatures around 285°C, while kaolinite forms at around 250°C. Montmorillinite generally forms at lower temperatures (~150°C) and occurs around regions of higher temperatures. The presence of hematite is not surprising considering the surface unit is basalt, however little can be gleaned about temperature or chemistry from this mineral.

RDO-8 was drilled just north of Mammoth Lakes through tills to a depth of 715m and a bottom hole temperature of 202°C. This temperature predicts a hot hydrothermal system at depth. Mapped surface alteration from HyMap consists of alunite, amorphous silica, kaolinite and montmorillinite; a classic acid sulfate, advanced argillic alteration assemblage. Alteration at depth is reportedly kaolinite, smectite, opal, lesser quartz and Kspar and at great depth, illite and calcite. Alteration at depth and on the surface match reasonably well with the exception that no sulfates are found at depth and no silicates are detected on the surface. The latter part of this discrepancy is due to the inability of HyMap to identify most silicates.

M1 (Mammoth-1) was drilled at Casa Diablo (site of current geothermal power production) through rhyolites and tuffs to a depth of 1605 m and a bottom hole temperature of 172°C. No alteration data at depth was available. Surface alteration consisted of buddingtonite, kaolinite, kaosmectite, hematite and amorphous silica. The kaolinite, kaosmectite and amorphous silica are acid sulfate alteration and match with the reported temperature at this well. The extensive hematite may be gossan-like and support high temperature acid sulfate deposition at depth and subsequent oxidation at the surface. Finally buddingtonite, a late-stage vapor phase ammonium feldspar, suggests a high temperature hydrothermal source at depth.

PLV-1 is located in the western caldera on the Rhyolite Plateau (RP). It was drilled through rhyolites and reached a total depth of 715 m and a bottom temperature of 124°C. Amorphous silica, montmorillinite and chlorite was detected

Table 1 – Comparison of surface alteration with alteration at depth

Drill Site	Total Depth (m)	Surface Unit	Max T °C	Surface Alteration	Alteration at depth*
PLV-1	715	Qmr	124	<<kaolinite, amorphous silica, montmorillinite, chlorite	smectite (lesser kaol.), cristobalite, abundant alunite and illite at depth
PLV-2	640	Qmb	50	none	smectite
M1	1605	Qer,Qet	172	buddingtonite, kaolinite, kaosmectite, hematite	
IDFU44-16	1799	Qmb	220	nacrite, montmorillinite, hematite	
MLGRP-2	491	Qmb, till	74	amorphous silica (kaolinite at depth)	smectite, opal
INYO-4	1500	Qmb	83	nacrite, montmorillinite, hematite	smectite, kaolinite, some halloysite, opal at great depth, hematite on surface
RDO-8	715	till	202	alunite, kaolinite, amorphous silica, montmorillinite	kaolinite, smectite, opal, lesser quartz and kspar, very deep: illite and calcite
LVEW	2300	Qer, tuff	100	<<<amorphous silica	calcite, pyrite, quartz, kspar, albite, chlorite, epidote
66-29	2125	sediments	–73	<<calcite, amorphous silica	
AW		Qaf	10	calcite, chlorite, hematite	

Qmr=moat rhyolite Qmb=moat basalt Qer=early rhyolite Qet=early tuff Qaf=alluvium
* alteration data from Flexser, 1991

surficially. There were also minor amounts of kaolinite. Smectite, lesser kaolinite and cristobalite were found at depth and abundant alunite and illite at great depth. The surface and depth alteration match fairly well with the exception of the lack of detected sulfate alteration on the surface.

LVEW was drilled 2300m into the central resurgent dome through rhyolites and tuffs reaching 2300 m and a final bottom hole temperature of –100°C. Mapped surface alteration was limited to a few pixels of amorphous silica and nothing else for a significant radius around the well-head. This might be a function of the great depth of the hole which suggests that the deeper the system, the less likely it is to be expressed on the surface. Alteration at depth is dominated by calcite, pyrite, quartz, Kspar, albite, chlorite and epidote. Though seemingly located in a zone of discharge, this well never reached known reservoir temperatures (–230°C). Structurally it appears to be a good place to drill to the hottest parts of the system, but the lack of alteration there and on nearby faults suggests that these structures are not discharge conduits. 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 (McConnel et al., 1997). This system has since waned and moved to the west beneath the RP.

INYO-4 was drilled just west of the Inyo phreatic craters through basalts to 1500 m and reached a bottom hole temperature of **83°C.** Surface alteration is nacrite, montmorillinite and hematite. Kaolinite did not exist within the 200 m radius of the wellhead but was abundant within 300 m Alteration at depth is smectite, kaolinite, some halloysite, opal at depth and surface hematite. The high temperatures at INYO-4 predict a high temperature assemblage of surface alteration. The presence of nacrite, a high temperature polymorph of kaolinite (~285°C), partially fulfills this prediction. Montmorillinite surrounds the surface nacrite. This argillic alteration assemblage suggests higher temperatures at depth.

MLGRP-2 is located in the south-westem region of the caldera and was drilled through basalt and till to 491 m, reaching a bottom temperature of **74°C.** Surface alteration was entirely amorphous silica with evidence of kaolinite at depth (due to anthropogenic excavation at this site). Alteration at depth is reportedly smectite and opal. The surface alteration and at depth roughly correlate (though smectite is a broad category of clays that includes many species). Amorphous silica on the surface and opal at depth implies a region of sustained hydrothermal fluid flow, probably more alkaline in nature. The kaolinite at depth and not on the surface suggests this to be an older zone of flow over other areas that host more abundant surface argillic phase alteration.

Well 66-29 located in the far eastern region of the caldera was drilled 2125m into sediments and reached a bottom hole temperature of **–73°C.** There was no available information regarding alteration at depth however surface alteration revealed sparse calcite and amorphous silica. The paucity of alteration and relatively low temperature and neutral to alkaline pH implied by this assemblage approximately coincides with known temperatures and suggests no major discharge structures in this region.

PLV-2 was drilled north-west of the RP through basalts to a depth of 640m. It had a bottom hole temperature of 50°C and had no detected surface alteration. Only smectite was found at depth. A distinct lack of intense alteration at depth is echoed by these surface measurements.

The coolest temperature well in this study is AW drilled far to the east through alluvium. Temperatures at this site only reach about 10°C. Surface alteration consists of calcite, chlorite and hematite. This suite of minerals could easily be simply weathering products though it also fits a widespread propylitic style alteration assemblage. Either way, the mineralization suggests a good distance from hydrothermal source waters.

4. DISCUSSION: WHAT DOES CONTINUOUS SURFACE MINERALIZATION REVEAL ABOUT SYSTEM-SCALE ALTERATION TRENDS AND SUBSURFACE ALTERATION PROFILES?

Loosely, the overall density and identity of alteration zones indicates relative temperatures and geochemistries in the caldera hydrothermal system. However interpretations based solely on surface alteration data provided by hyperspectral imaging should be weighed carefully. Comparison of surface data with data from depth is an attempt to assess what surface alteration may really be telling us. After all, mapping of alteration over large areas like this is not something commonly done, as the time to find, identify and map alteration is not usually taken.

Surface alteration did provide a fairly good assessment of caldera temperature and chemistry, which was in turn consistent with the well data. High temperature acid sulfate surface alteration generally coincided with high temperatures at depth. Little or no alteration on the surface generally coincided with regions having little to no hydrothermal upflow.

While there is considerable correlation between alteration at the surface and alteration at depth, predicting hydrothermal system temperatures from surface alteration is still risky. Specifically, it appears that surface alteration is not a finely tuned indicator of current temperatures at depth; rather it indicates effects of the longer history. Mineralization at the surface indicates that at one time, there were higher temperatures and acidity, but the timing of mineralization is ambiguous without independent field data including dates of particular units. However plots of alteration in outwardly "dead" hydrothermal zones may serve as points of future discharge given the correct structural or volcanic impetus. For instance, the presence of acid-sulfate alteration in a zone does not require that the zone is still actively discharging steam or fluid water, it only implies that at one time source reservoirs were hot enough to supply waters/steam capable of altering the country rock.

There are other inherent problems to consider when evaluating the distribution of hyperspectrally mapped surface alteration relative to hydrothermal system character and geometry. Surface weathering over short or long time periods can obscure primary hydrothermal alteration by breaking down primary mineralization to weathered forms of clays or oxides. Discrimination between the two thus becomes more difficult. Alteration minerals are inherently easily weathered, eroded and/or transported away from their initial genesis points. This should always be considered when studying alteration patterns in high topographic areas or regions beset by abundant erosional activity such as fluvial or glacial processes. Intense vegetation coverage also makes rock/soil mapping more challenging and it can bias mineral distribution densities to those areas with less vegetation cover. Finally, some alteration minerals within indicator assemblages are visible/near-infrared/shortwave-infrared inactive and cannot be measured uniquely using the wavelengths captured by the HyMap instrument. This includes silicates such as quartz and feldspars.

Some of the problems listed above may explain why surface alteration is not always the best indicator of true hydrothermal character at depth. For instance, both IDFU44-16 and M1 tap hot reservoirs. We might expect to see higher temperature mineralization at the surface around these wells but the mineral with the hottest formation temperature is nacrite at IDFU44-16. Granted nacrite does indicate a high thermal gradient but there is also very little of it found around the well. This is either a true phenomena that reflects the hydrothermal system at depth in this area or the alteration has been obscured in some fashion (such as by historical erosion or vegetation cover). Given that the temperatures at depth are quite high, it seems that surface mapping of alteration does underestimate the thermal potential of this region.

It seems that general alteration trends and thus general characteristics of the hydrothermal system chemistry and geometry are captured with surface alteration mapping. However the specific individual mineral plots such as that shown in Figure 2 are difficult to get a sense of overall trends. To address this difficulty we can highlight patterns and trends of alteration by plotting alteration density rather than straight alteration distribution. Figure **3** is an attempt to represent

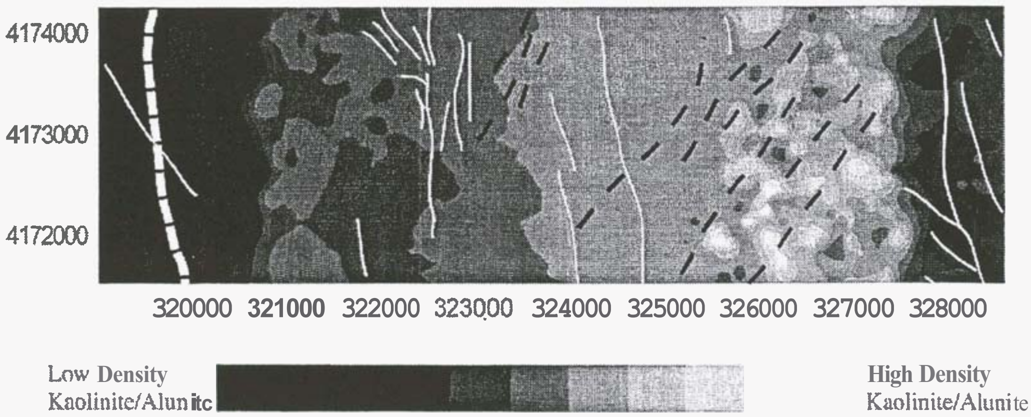

Figure 3. Kaolinite/Alunite alteration density plot over the western caldera and the RP. Dark dashed lines and lighter un-dashed lines are faults. The heavy dashed line to the west is the caldera boundary.

trends in the hydrothermal system geometry and chemistry by plotting the density of the advanced argillic kaolinite-alunite assemblage over a portion of the western caldera and the RP. This is a region of high geothermal prospectivity that is currently being studied and primed for renewed drilling efforts in 2004 by the local geothermal company.

The density patterns produced by this technique confirm current thinking regarding hydrothermal flow models in this portion of the caldera. The densest distributions of alteration are located on the Rhyolite Plateau that has been cut extensively by the northeast trending Discovery Fault Zone (DFZ) of Suemnicht and Varga (1988). Higher than average densities are recorded to the west of the DFZ as well (including the region that hosts IDFU44-16). The advanced argillic phase assemblage then drops off both to the west within the western moat and the Mono-Inyo fault zone and directly to the east of the DFZ. This alteration pattern suggests that the region with the hottest hydrothermal flow (at least at one time) is the Rhyolite Plateau. This pattern is soon to be tested as most of the planned 2004 drill holes are in this area.

5. CONCLUSIONS

Hyperspectral imaging provides a quick, synoptic way of mapping surface alteration over large areas in most terrain. The algorithms for detection and mapping of hydrothermal alteration have become standard however the challenge now becomes how to integrate detailed mineral maps of vast regions of land with traditional geochemical and geophysical models and datasets. The degree to which they are compatible is explored in this paper and the conclusion is that surface alteration does reveal important trends related to gross caldera hydrothermal flow patterns and chemistry (such as that shown in Figure 3). However alteration at the scale of individual drill sites is less conclusively linked to alteration found at depth and more directed studies of surface alteration in the vicinity of high geothermal gradient wells is needed.

6. ACKNOWLEDGMENTS

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