Chapter Two: Hyperspectral Imaging in Long Valley Caldera: Present and Paleo Hydrothermal Systems

1.0 Introduction

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. In areas known to be volcanically active, the sources of alteration seen at these zones are predominately fluids and gas heated at depth by magma. Determining the location, spatial distribution, orientation, and identity of these hydrothermal alteration mineral suites is key knowledge both for geothermal explorationists and for volcanologists studying the chemistry and dynamics of active volcanic hydrothermal systems. For example, hydrothermal mineral maps of geothermal fields in Honshu, Japan (Nakamura et al., 1981) and Steamboat Springs, USA (White et al., 1978), found and characterized many of the of the most important discharge zones within these hydrothermal systems.

Alteration minerals reveal much about present and paleo flow dynamics and chemistry. 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, an efficient synoptic method for mapping alteration minerals exists which provides the elusive, continuous x-y distribution of surface mineralization that serves to refine current working hydrothermal models: airborne hyperspectral imaging. Every spatial element (pixel) of a hyperspectral dataset contains unique spectral information that allows us to identify most geological materials, analogous to a fingerprint. This type of remote sensing easily produces synoptic mineral maps.

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.

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 (Figure 2-1). 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 refinements of discharge zone geography. I also address the abilities of hyperspectral imaging for geothermal prospecting efforts, as this technology may prove key in future exploration and assessment of remote volcanic regions.

2.0 Background

2.1 Hydrothermal system

The hydrothermal system of Long Valley Caldera has waxed and waned over the millennia with two distinct high discharge periods that scarred the volcanic tablelands of this region and one period of apparent hydrothermal quiescence. Sorey (1985) described a system that reached peak flow and aerial extent at approximately 300ka by dating hydrothermal deposits and analyzing stratigraphic relationships of lake sediments and hot spring sinters (Bailey et al., 1976). Flow and deposition waned post-300ka, but again peaked at 40ka. The hydrothermal system seen today is likely the tail end of this second hydrothermal regime. Oxygen isotope analysis, age dating, and stratigraphic relationships reveal that the initial hydrothermal system source was from the central caldera, probably driven by thermal input from the Long Valley Caldera magma chamber (McConnel, et al., 1997). The thermal source driving the present day hydrothermal system appears to have shifted to the western caldera beneath the Mono-Inyo volcanic chain (Lachenbruch et al., 1976; Sorey, 1985; Sorey et al., 1991; McConnel et al., 1995). Two models for flow dynamics in the caldera have been suggested. Both Sorey, 1985 and Blackwell, 1985 invoke cold meteoric waters flowing from the Sierran front in the western caldera through or just above the Bishop tuff, drawing heat from a magmatic source beneath the Mono-Inyo volcanic chain, and finally, partially discharging along the fault zones of the resurgent dome in the central caldera (Figure 2-2). The presence of a high temperature (>200°C) reservoir has been confirmed through drilling, fluid sampling, and other geological investigations (Smith and Suemnicht, 1991; Sorey et al., 1991, 1993). Sorey described a shallow flow of thermal waters east from these discharge points in the central caldera, creating a landscape of small creeks, springs, and shallow, predominately ephemeral lakes. Blackwell also saw this pattern, but included an east-west return of cold water from the eastern rim and caldera ring fractures through volcanic fill at depth. Both models appear grossly viable as explanations of source of heat, general flow direction, and locations of recharge/discharge zones, but some model components are consistent when compared with surface and well-log mineralogy and/or temperature data. Understanding zones of upflow, transport, and discharge has been especially problematic.

The geochemistry of the hydrothermal system has been resolved by several studies including lithological mapping, geochemical fluid sampling studies, isotopic studies, and alteration mapping and quantification in drill logs. Though the hydrothermal system appears to have been silica-saturated at one time, present day chemistry embodies carbonate saturation. This results in recent, localized deposition of travertine (Lipshie, 1976), whereas sinter deposition appears to have been much more important in the past. Only alkaline to neutral, slightly saline, sodium-bicarbonate hydrothermal waters discharge surficially in the central and eastern caldera, though slightly thermal waters (45°C) discharge from a small spring on Mammoth Mountain's western flank at Red's Meadow. Temperatures from hot springs in the caldera 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 Mammoth as well as a few places within the western and central caldera including Basalt Fumarole and Fumarole Valley. The lack of surface water discharge in the western caldera is probably due to higher topography in this region relative to the caldera floor to the east.

The hydrothermal alteration assemblages studied by Flexser (1991) are dominated at depth by illite, smectite and illite/smectite interlayered clays. McConnel et al. (1997) also noted calcite, pyrite, quartz, kspar, albite, chlorite, and epidote in the Long Valley Exploratory Well (LVEW) core from the resurgent dome. Such assemblages are typical of intermediate temperature hypogene alteration environments described in ore deposit literature. In general, young volcanic systems such as Long Valley are thought to be proto-epithermal mineral deposits, and study of epithermal-hosted alteration aids prediction of mineralization in Long Valley. Various authors have reported small, localized mapping endeavors of surficial hydrothermal alteration, including Cleveland, 1962; Rinehart and Ross, 1964; Bailey, 1976, 1989; Suemnicht and Varga, 1988; Sorey, 1985; Sorey et al., 1991, 1993. Their mapping revealed the presence of kaolinite, alunite, montmorillinite, calcite, and sinter, all of which are found in the opalized, argillized, and advanced argillized zones of epithermal mineral deposits. However, field identification of alteration can be quite difficult. Alteration minerals tend to be very fine grained and of similar colors and grain size; they are often diffusively distributed and hence difficult to map spatially or to see with the naked eye; and even laboratory XRD analysis can prove difficult for many clays. Hence, current knowledge of the distribution and identification of alteration assemblages caldera-wide is poor.

2.2 Structural system

The dominant structural trend is northwest-southeast. The large Sierran frontal faults, such as Hilton Creek and Hartley Springs, trend in this direction. Northwest-trending faults also cut the resurgent dome in the west-central caldera and are thought to be extensions of the Hilton Creek system (Bailey, 1976). A series of north-south trending faults populates the western moat of the caldera, and the southernmost cuts the north flank of Mammoth Mt. Such faults likely aided the focusing of magma that extruded to form the Mono-Inyo volcanic chain (Bailey, 1976; Sampson and Cameron, 1987; Pollard and Aydin, 1988; Miller, 1989). In close geographical relation, is the northeast-trending Discovery Fault zone of Suemnicht and Varga (1988). This fault zone cuts through crust in the western caldera and is associated with domes and flows of the Mono-Inyo volcanic trend. Finally, ring fracture faults have been mapped in the western and northern caldera. Recent work by Prejean (2001) delineates several WNW-trending structures in the south moat that are likely southern ring fractures, while aerial photo interpretation also reveals weakly displayed ring fractures in the eastern moat (Bailey, 1989).

Faults still experiencing seismic activity include these northwest-normal faults in the south central portion of the caldera, including the Hilton Creek Fault; the northwest trending normal faults that cut the resurgent dome; and the approximate east-west trending right slip faults, also in the southern moat (Vetter and Ryall , 1983; Prejean, 2001). The north-south and northeast trending faults in the western moat do not appear to host seismic activity. Linear northeast trends of seismicity occur south of the caldera within the Sierran block. However, they are not associated with any known surface rupture, and the trends appear to coincide with oblique left-lateral slip faults at depth (Prejean, 2001).

2.3 Hyperspectral Imaging

In 1985, Goetz et al. introduced the world to hyperspectral imaging, ushering in a new age of remote sensing. By sampling the electromagnetic spectrum tens to hundreds of times in narrow contiguous wavelength partitions, a complete spectral signature can be measured for any earth material (Figure 1-3). For example, the reflectance or emittance of radiation from any material often produces unique spectral signatures. The interaction of light and/or heat with crystalline mineral structures produces a set of absorptions and reflectances unique to that crystalline structure. Absorptions may be due to charge transfers and molecular bond bending, stretching, and vibrations. However, significant absorption of light and heat energy occurs within the Earth's atmosphere, predominately by H_2O, CO_2, NO_2, 0_2, and O_3 molecules. Hyperspectral technology is an important advance over the more limited material identification abilities provided by multispectral instruments such as the Landsat satellites. Full identification of earth materials, not simply discrimination, is now possible.

Measurement and quantification of the interaction of radiance with the Earth's surface is done with hyperspectral imagers, also known as imaging spectrometers. Spectrometers can be used in the field in the form of handheld spectroradiometers, in the laboratory under controlled lighting conditions, and as imaging spectrometers on air and space-based platforms. At this time, only NASA's experimental Hyperion imaging spectrometer is space-based; all other hyperspectral imaging is done from aircraft. Several hyperspectral imagers are operated around the world. 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 can produce data with spatial resolutions (pixel sizes) on the order of 3-5 meters and swath widths that average 2.5 kilometers. Perhaps most importantly, its Signal-to-Noise Ratio (SNR) is well over 1000:1 for most wavelengths.

2.4 Previous Remote Sensing Studies

Long Valley caldera has received little study via standard remote sensing techniques. Landsat TM (Thematic Mapper)-based volcanic lithological mapping was completed by Levine in 1985. He used various spectral band-ratioing techniques to discriminate various volcanic flows in the greater Long Valley region. Del Grande, 1985 utilized dual channel, air-based TIR (thermal infrared) data to map heat flow anomalies in the caldera. She coupled the airborne temperature surveys with field temperature surveys from core and drill holes and shallow thermistors to produce three-dimensional heat flow anomaly maps. However, shallow convective systems are hard to characterize, and extrapolating surface measurements several hundreds of meters into the crust is uncertain. Fialko, et al., 2001 completed an InSAR (Interferometric Synthetic Aperture Radar) study of Long Valley, which delineated the focus of current re-inflation in the central caldera as an inclined prolate spheroid at a depth of 7-9 km. De Jong, 1997; Hausback and Chrien, 1997 and Sorey et al., 1998 performed initial hyperspectral imaging studies on Mammoth Mt. that mapped the locations of CO_2-induced tree-kills on the volcano's flanks, while

DeJong and Chrien, 1995 attempted to map the CO_2 emissions directly, but with limited success.

To date, several studies have addressed mapping of hydrothermal alteration minerals in Long Valley caldera (Martini et al., 1999; 2000; 2001). However, there has been limited interpretation and synthesis of the hyperspectral data with other geophysical and geological data for the hydrothermal system. Hyperspectral work at various Tertiary hydrothermal systems indicates that important information regarding the geochemistry, temperature, and discharge patterns can be determined (Livo et al., 2000; Crowley et al., 1999; Rockwell et al., 2002; Kruse, 2000; 2002). Livo et al. (2000) mapped patterns of hydrothermal alteration in the Yellowstone Basin, and linked these maps with other hydrological and geochemical studies in the region. Crowley et al. (1999) mapped summit and flank hydrothermal alteration at Mt. Rainier, and combined these data with DEMs to produce flank stability maps, that may indicate future loci for debris flows and/or lahars. Rockwell et al. (2002) produced alteration mineral maps of the Marysvale Volcanic Field, and combined these data with XRD analysis. Kruse (2000) mapped hydrothermal deposits in Steamboat Springs, Nevada, and studied the temporal evolution of these sinter-rich, alkaline hot springs.

3.0 Methods

3.1 Data Acquisition and Processing: HyMap Hyperspectral Imagery

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° 36” N and longitudes 118° 42” to 119° 04” W (Figure 1-4). 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 Sierras and at Mammoth Mt.) The instrument was flown aboard a twin-engine Cessna with complete radiometric and spectral calibration and simultaneous DGPS data acquisition. The dataset was acquired as part of a group-shoot that included several other U.S. governmental, educational, and commercial entities and was organized by Analytical Imaging and Geophysics (AIG) in Boulder, CO, USA and the HyVista Corporation in Sydney, Australia. Primary processing and analysis presented in this paper was done within the ENVI software environment. The analysis techniques and processing flow were presented previously in Chapter 1, Section 3.2.

4.0 Results: Caldera-wide Alteration Mineral Maps

4.1 Site-specific alteration maps

4.1.1 Western Caldera – Mammoth Mt.

The overlapping rhyodacitic domes and flows of the small stratovolcano Mammoth Mt. have been intensely altered into assemblages of vapor phase sulfates and clays. Alteration occurs primarily on the southwestern, northern, and eastern flanks, but localized zones of alteration exist on the southern flank (Figure 2-3A). The northern flank is dominated by acid sulfate alteration associated with the Mammoth Mt. fumarole. The northwestern flank is dominated by extensive hematite deposition, while the southwestern flank is covered in extensive kaolinite and alunite, and is probably the site of a paleo-fumarolic field. The southern flank is dominantly stained with hematite and minor kaolinite, kaosmectite, and montmorillinite at the Horseshoe Lake Fumarole. The entire mountain is pervasively altered, though the summit region is far more altered than the surrounding, lower elevation flanks (see Figure 2-3B). Most of the acid sulfate alteration appears localized along faults that have either currently active fumaroles or paleo-fumaroles. Kaosmectite and montmorillinite are more widely distributed around the mountain, typifying lower temperatures on the borders of hotter fumarolic zones. The profuse hematite on the southern and northwestern flanks may be gossan-like in origin - iron-oxide alteration above sulfide deposits.

4.1.2 Western Caldera – Mono-Inyo Chain

The Mono-Inyo volcanic chain is comprised of several tens of domes and flow complexes. Earthquake Dome is primarily made up of quartz latites, contemporaneous with the latites of Mammoth Mt. to the southwest (~200ka-50ka). Locally, there are tuff outcrops, as well as mafic basalt flows and cinder on the northern and southwestern flanks. Alteration on the dome is primarily hematite with lesser kaolinite and alunite (Figure 2-4). Most of the alteration is centered on the southern flank in a rough NNW-trend. The other domes and flows to the northwest (including Dry Creek Dome and Mammoth Knolls) are primarily porphyritic rhyolites (~100 ka). Pervasive alunite, dickite, and kaolinite lie on the rhyolite plateau region which is sliced up by the Discovery Fault Zone. There are lesser amounts of amorphous silica, with the densest deposits on the southern flank of Drycreek Dome and Mammoth Knolls. The Inyo Craters proper are covered in kaolinite, alunite, and hematite. This alteration is highly localized to the craters, with very little alteration along the north to northwest trending faults that cut the craters region. However, just to the west of the craters, there is a significant zone of alteration mapped in the flats. A large area is covered by high temperature dickite and alunite, and surrounded by lower temperature kaolinite and montmorillinite. This zone of alteration is not currently associated with any known faults.

4.1.3 Western Caldera – Mineral Hill

Mineral Hill lies in the south-western caldera and is a historic mining district dating from the late 1870's. Though mined aggressively for only about three years, active claims still exist in and around the initial Alpha Claim on the southwestern flank of the hill. Miners were searching for gold and silver in the Tertiary aged basalts, and though they did find these precious metals, it was not enough to be economic in the late 19th century. The mining that did occur back then, and subsequent mining through the years, has generated a scarred landscape on Mineral Hill. Mineral-mapping results from the HyMap data show abundant oxidation of the basalts in the form of hematite (Figure 2-5). There are large amounts of the sulfate, jarosite high on Mineral Hill, streaming down-slope on three sides (to the west, north, and east). Small, localized patches of kaolinite/halloysite exist, as well as small amounts of feldspar (possibly albite). There are several areas of calcite, including an area where a small WNW-trending fault juxtaposes the Tertiary basalts with Paleozoic metasediments, and also contains kaolinite and some hematite

4.1.4 West-central Caldera – Casa Diablo, Basalt Fumarole

The region between the dome and lava flows of the western caldera and the flows of the central resurgent dome are shown in Figure 2-6. The central portion of the image in Figure 2-6 is occupied by Highway 395: primarily high temperature alteration (kaolinite and alunite) lies along normal faults that form a small graben. The Casa Diablo geothermal plant is located between the main eastern Casa graben fault and a smaller northwest trending normal fault. All of the above faults cut through a combination of early resurgent dome rhyolites, Quaternary basalts and andesites, and Quaternary alluvium and tills. Both these faults and the western graben fault of Fumarole Valley (to the east), have characteristic patterns of alteration seen all over the caldera. The highest temperature alteration (alunite and some kaolinite) is right along the fault traces, while lower temperature alteration (kaosmectite, hematite, montmorillinite) is more diffusively distributed around the hotter zones and more regionally. Amorphous silica is found predominantly on the flats surrounding the fault-bounded hills, although there is some silica along faults at higher elevations. The unusual mineral buddingtonite has a limited distribution, just northwest of Basalt fumarole and just northwest of Casa Diablo. Buddingtonite is an ammonium feldspar, formed during later periods of vapor phase activity.

From alteration distributions, I can detect many of the faults previously mapped by Bailey. However, alteration within the southern part of the image and various other locations doesn't match his map. Prejean's faults (Prejean, 2001) are relatively new additions to the pantheon of known fault trends and distributions: her precise re-locations with the seismic catalogue from 1997-98 reveals a more linearized set of faults. Alteration distributions from this study coincide with various segments of Prejean's faults, that she referred to as the South Moat Fault Zone (SMFZ).

4.1.5 Central Caldera – South Moat Fault Zone

The SMFZ of Prejean (2001) is located in the southern moat of Long Valley, and parallels Highways 203 and 395. Figure 2-7 shows Prejean's faults in green, while Bailey's faults are shown in dark green (Bailey, 1989). The relocated seismicity that defines this fault zone is shown by small red dots. The faults of this zone would cut through Quaternary tills and basalts, but it should be stressed that the faults from Prejean (2001) were determined purely from seismicity; these structures have no known surface trace to date. Mineralization along this fault zone is primarily amorphous silica, hematite, and minor surface kaolinite, some of which appears to have been unearthed by human excavation. The relatively sparse distribution elsewhere, and dense distribution within the excavated area, implies that kaolinitization may be more pervasive than surface alteration distributions suggest. A similar site is just north of the airport, where road-building uncovered a dense deposit of kaolinite in a pit dug for pavement-making material. Other mineralization in this figure is associated predominantly with the big graben-defining, northwest trending normal faults of the central caldera (especially the dickite-kaolinite assemblage).

4.1.6 Central Caldera – Fumarole Valley

Fumarole Valley is a large, northwest-trending graben that cuts the central resurgent dome. The faults defining this graben cut through the early Pleistocene rhyolites of the resurgent dome. These post-caldera, aphyric to sparsely porphyritic domes, flows and tuffs are altered primarily to localized zones of alunite-dickite-kaolinite mineralization along the major northwest-trending faults (Figure 2-8). Some of the alteration is clearly float from the original deposition point, which is most likely on the faults themselves. Only one highly altered zone still has an active fumarolic field. This consists of 4-5 vents on the western graben fault of Fumarole Valley. The lower elevation areas at the mouth of the valley (further south) are altered primarily to amorphous silica, hematite, montmorillinite, and chlorite, with localized deposits of kaolinite-alunite-amorphous silica at Hot Bubbling Pool. The head of Fumarole Valley has a fairly large deposit of amorphous silica, which appears to have originally been a kaolinite deposit.

4.1.7 East-central Caldera – Little Hot Creek

Little Hot Creek occupies a roughly east-west trending gorge on the northeastern flank of the central resurgent dome in Long Valley. Hydrothermal water doesn’t reach the surface until half-way between the beginning of the gorge (in the west) and the valley-flats that it empties into (in the east). Figure 2-9 shows the distribution of mineralization is this area. The faults cut post-caldera rhyolites and other Quaternary sedimentary deposits, and it is thought that the central, north-northwest trending faults that bound the Clay Pit mine serve as zones of upflow for the hydrothermal waters discharging in Little Hot Creek (Sorey, 1985). The alteration in this area is ascribed to the earlier peak period of hydrothermal flux (300 ka), and the local heat source for this area probably stems from ~500ka volcanism just to the north. Some of the highest densities of alteration in the caldera are found in this locale, though this perception may be biased by the large amounts of alteration exposed by mining activities at Clay Pit. Abundant acid-sulfate type alteration is found along the northwest-trending fault just to the south of Clay Pit, while alteration to the west of this zone is representative of cooler formation temperatures (or removal of original alteration). Amorphous silica and montmorillinite lie in the flats and hills of the resurgent dome to the west.

To the east, along Little Hot Creek Gorge, a good deal of alteration occurs along the northern cliff faces and tops. This alteration is dominantly hallyosite, kaolinite, alunite, dickite, and white mica. The first four minerals indicate a classic advanced-argillic assemblage, though the white mica suggests an even higher temperature threshold than normally observed in alteration assemblages in the caldera. Ore deposit terminology would refer to this alteration assemblage as sericitic-argillic. In contrast, there is very little alteration on the southern cliffs, with only sparse kaosmectite and amorphous silica detected. The zone where water finally reaches the surface is characterized by halloysite-alunite, but also has small calcite deposits. This is probably hydrothermally deposited calcite or travertine, with abundant halloysite and minor calcite and kaolinite lying downstream. Much of this alteration is probably fluvially deposited, and not primary.

4.1.8 Central Caldera – Hot Creek, Alkali Flats

The solitary Hot Creek lava flow and the Alkaline Flats lie to the east of the resurgent dome. The eastern flank of the resurgent dome rhyolites is cut by several north-trending normal faults, which are the site of intense, advanced argillic alteration (primarily alunite and kaolinite) (Figure 2-10). East of the resurgent dome, Hot Creek cuts into coarsely porphyritic, low silica rhyolites of the 300ka Hot Creek flow. Hydrothermal waters flow up along a northwest-trending normal fault and discharge hot water into the glacially-fed, northeast flowing Hot Creek. Beginning with the point of thermal discharge, the walls of Hot Creek gorge are significantly altered to kaolinite and lesser alunite. The floors of the gorge are littered with small travertine terraces (hydrothermal calcite). Towards the downstream termination of dense alteration deposits, a previously unmapped linear structure cuts across Hot Creek in a nearly east-west trend, through both the Hot Creek rhyolites (Qmr) and the sandstone/conglomerate deposits of Pleistocene Lake Long Valley (Qsc). This linear feature was detected by mapping primarily kaolinite and amorphous silica distributions, and it may also serve as a conduit for fluid-flow. Alteration of the Hot Creek lava flow itself is minimal, though dispersed kaolinite and alunite was detected.

East of the Hot Creek flow and Hot Creek proper, lies the Alkaline Flats region of Long Valley. Rhyolite Hot Spring at the eastern flank of Hot Creek lava flow is a low flow hot spring with small deposits of travertine nearby. Just to the south of this spring, there is a much larger deposit of hydrothermal calcite that was probably once the site of extensive active travertine terraces. To the north and east of Rhyolite Hot Spring, the Alkaline Flats has few high temperature mineralization assemblages on the primarily Quaternary alluvial deposits (Qal). The mineralization is dominated by amorphous silica with minor kaolinite. Other evaporite minerals were detected in the analysis, but are not shown for clarity reasons.

4.1.9 Eastern Caldera – Eastern Ring Fracture Zone

The Eastern Ring Fracture Zone lies in the far northeastern corner of the caldera, where it lies almost entirely within Quaternary alluvial fan and lacusterine deposits. Hydrothermal waters in this region are thought to derive from local eastern caldera heat sources and circulation patterns (Figure 2-2). The dominant mineralization along the fracture zone is amorphous silica (Figure 2-11), but there is a smaller localized zone of hydrothermal calcite deposition within the fracture zone, and several small areas of high temperature alteration (kaolinite-dickite) lie west of the fracture zone. To the east of the fracture zone, there is more amorphous silica and travertine, which may correspond to a previously un-mapped set of ring fractures. Considerable amounts of dickite on the western flanks of the Glass Mountains (east of the caldera boundary), appears to be from some older system, or perhaps float from higher units in the Glass Mountains.

5.0 Discussion

5.1 Mineralization in Long Valley Caldera and implications for gross hydrothermal system and chemistry

The character and distribution of hyperspectrally-detected mineralization in Long Valley Caldera both confirms and provides new information regarding the geochemistry and hypothesized circulation patterns of hot waters. The spatial distribution of hydrothermal mineral assemblages speaks to zones of discharge, while the identity of the mineralization speaks to gross temperature and pH of formation, and hints at initial rock lithology.

Alteration patterns in the western caldera

The western caldera is dominated by advanced argillic to argillic mineral assemblages. Hyperspectral mineral mapping at Mammoth Mt. revealed profuse summit alteration similar to the vapor phase, acid-sulfate assemblages of other large regional volcanoes such as Mt. Rainier in Washington State or Mt. Shasta in northern California. The lack of surface water discharge on this mountain coupled with the presence of several active fumaroles, suggests that most of the alteration on Mammoth Mt. is indeed vapor phase. Small springs discharge around Mammoth, but at far lower elevations than where most of the alteration is mapped. The abundant hematite alteration on Mammoth Mt. may be due to several things. At the simplest level, the volcanic rocks of Mammoth are coarsely porphyritic quartz latites. These more mafic flows contain abundant phenocrysts of pyroxenes and hornblende, which have a higher propensity for iron oxidation. However, the sheer abundance and density of alteration seems to suggest a more complicated genesis. Vapor phase zones within ore deposits sometimes have mineralization referred to as a gossan, which are iron oxides (e.g. hematite) that form directly above a sulfide deposit of some kind (e.g. crust rich in pyrite). A long history of alteration at Mammoth might allow for such a deposit to form. In addition, the rhyolites and latites of this region are known to be underlain with various flows of basalt and andesite, and it has been theorized that prolific basalt injection is currently occurring in the western moat (Eichelberger et al., 1988). Thermal fluids devolitalizing off these magmas beneath Mammoth may be aiding surface iron oxidation. Regardless of the hematite source, the dense and ubiquitous alteration on the summit of Mammoth indicates a long-lived alteration system.

Just to the northeast, the DFZ alteration assemblages are also indicative of advanced argillic to argillic alteration, deposited via a vapor phase. The alunite and kaolinite found on the western flank of Dry Creek Dome along the main structure of the DFZ coincides with previously mapped distributions of alunite (Suemnicht and Varga, 1988). Suemnicht and Varga argued that the presence of such a mineral suggests deep-seated faults and circulation patterns. On the basis of this and other structural observations, they also argued that the DFZ structures were Mesozoic faults that have recently reactivated. The hyperspectral-based mapping of alunite and kaolinite on the main DFZ structure, along with distributions of previously unrecognized alunite and kaolinite to the east on the Rhyolite Plateau, suggest that this fault zone is both real and a zone of hydrothermal upflow. Very little hydrothermal alteration is mapped just to the east of the DFZ, (with two exceptions) which suggests that the DFZ is the major zone of hydrothermal upflow in the western caldera.

The two densely altered locales to the west of the DFZ at the Inyo Phreatic Craters, and high on San Joaquin ridge to the west of the caldera boundary. The extreme youth of the craters and their mode of formation explains the high degree of advanced argillic to argillic alteration seen both in the craters and to the west. This mineralization was likely a vapor phase deposition. The lack of any similar alteration north or south along the Mono-Inyo volcanic chain faults and flows, suggests that this alteration is quite young and not indicative of long-term circulation patterns. Farther west, the advanced argillic to argillic alteration on and around San Joaquin ridge appears to be associated with small Pleistocene volcanic centers (~83-108ka) that are separate from Long Valley. Much of the alteration also coincides with several of Bailey's mapped faults, but it is unclear whether this alteration stems from Long Valley hydrothermal fluid flux or from another system. The age of the volcanics in this area suggests that even if the alteration is related to Long Valley, it probably dates to the older (300ka) hydrothermal system.

The one place in the caldera where advanced argillic to argillic phase alteration may not dominate is at Mineral Hill in the far southwestern corner of the caldera. The presence of kaolinite and its polymorph, halloysite, indicate some argillic-phase alteration, but the presence of calcite and feldspar may suggest higher temperatures and an alteration system more closely resembling potassic. Much of this type of alteration may stem from significantly older periods of thermal fluid flow, since the rocks of Mineral Hill are Pliocene. However, the age can't be determined from spectral alteration data alone, and the initial patterns of surface alteration on Mineral Hill have been lost due to mining and subsequent sulfate (jarosite) and oxide (hematite) alteration.

Alteration patterns in the central caldera

Alteration in the central caldera is centered primarily on the resurgent dome (see Figure 2-12). The advanced argillic to argillic mineral assemblages at both Casa Diablo and Fumarole Valley exemplify the type of alteration seen elsewhere on the resurgent dome. Both of these sites host active fumaroles that are currently altering the ground to kaolinite, alunite, and various polymorphs of these minerals. Sites with such alteration, but no currently active fumaroles, very likely hosted fumarolic activity in the near past. Indeed, renewed activity induced by seismicity or eruptive activity could probably reactivate "dead" fumaroles, in much the same way that hydrothermal discharge can increase in a region due to similar stimuli. Both the Casa Diablo region and Fumarole Valley have substantial amounts of amorphous silica. Amorphous silica is seen along both the previously known faults from Bailey (1989), as well as the faults newly defined by Prejean (2001) and Martini (this study). In the Casa Diablo area, it is generally found in association with the low temperature clay montmorillinite, and less frequently with the higher temperature clay kaolinite. The patterns are similar to the Fumarole Valley area, which has an additional association with chlorite. Though amorphous silica can be deposited from fairly hot waters, the silica found in these two scenes appears to be associated primarily with lower temperature mineralization (~150°C). The exceptions are areas of amorphous silica found in conjunction with the zones of advanced argillic alteration along major faults. One example of this is the large white deposit of volcanic ash at the head of Fumarole Valley (Figure 2-8). This deposit was very likely pure kaolinite at one time, but has since been opalized. The dominant signature from this deposit is thus amorphous silica with only a few pixels of kaolinite detected.

The fairly dense concentrations of amorphous silica and hematite within the SMFZ of Prejean (2001) were probably deposited from lower temperature, alkaline to neutral waters. Their importance is their spatial distribution, rather than their chemistry, since the alteration in this area coincides with the projected surface trace of several seismically mapped faults. Prejean's study included a multi-temporal analysis of seismicity in the south moat which documented an upward migration of seismicity along discrete west-northwest trending structures that she attributed to upward hydrothermal fluid flow. Though there are no surface traces of these faults, her theory suggests a scenario where hydrothermal fluids would eventually reach the surface, allowing for hydrothermal alteration of the rocks and soil. A candidate east-west trending alteration zone is clearly visible in both Figures 2-7 and 2-12.

The mineralization assemblages at and around Hot Creek are a combination of assemblages described in the previous three locales. The Hot Creek scene is home to extensive advanced argillic to argillic alteration along both the eastern resurgent dome faults and the northeast trending Hot Creek. The previously unmapped east-west trending structure that cuts Hot Creek is also defined by higher temperature advanced argillic to argillic phase minerals, including kaolinite, alunite, and minor amorphous silica. There is much more amorphous silica in the lower elevations of the Hot Creek scene, where it is generally associated with the lower temperature clay, montmorillinite. When not associated with the vapor phase of fumarolic regions along faults, amorphous silica is probably indicative of lower temperature, alkaline waters. The farther east one goes in the caldera, the less advanced is the argillic phase alteration. The region around Alkali Flats has only minor occurrences of argillic phase kaolinite and montmorillinite, and the Rhyolite Hot Spring area has none. Both of these areas are dominated by amorphous silica and calcite deposition and the mineralization is probably sinter and travertine, both of which are deposited out of hot spring waters with varying chemistries. The presence of abundant sinter and travertine in the low-lying flats suggests a high surficial fluid flow of hot, alkaline to neutral waters in the past,. Current chemistry data from hot springs in the region agree with this assessment. Lipshie (1976) suggested that travertine deposition is more important now than sinter deposition, which dominated in the past. Ages of travertine terraces at Hot Creek are approximately 10ka, which appears to support Lipshie's argument, however sinter ages at Casa Diablo are ~30ka. In general, the pervasive amorphous silica deposition throughout the caldera with obviously reduced source flows and the limited deposition of travertine at currently, active hot springs, argues for an older sinter system and a newer travertine system.

Alteration patterns in the eastern caldera

Most of the mineralization in the eastern caldera is more sparsely distributed than in the central and western caldera, and is dominated by amorphous silica and argillic phase kaolinite and montmorillinite. Mineralization west of Little Hot Creek resembles this set of minerals, with dominantly amorphous silica and minor montmorillinite. Mineralization to the northeast, at the Eastern Ring Fracture Zone, is also dominated by amorphous silica with minor calcite, and advanced argillic to argillic phase clays including dickite, kaolinite, and montmorillinite. The amorphous silica and calcite is associated specifically with the ring fractures, both those mapped by Bailey (1989) and those presented here, and they are probably due to upflow of thermal waters along the ERFZ, as suggested by both Sorey (1985) and Blackwell (1985). The localized distributions of kaolinite-dickite-montmorillinite west of the ERFZ, are a bit mysterious, while montmorillinite and kaolinite can be deuteric, dickite is usually the result of hydrothermal fluid alteration, so these are probably fluid and not vapor phase deposits. It is also possible that these advanced argillic assemblages aren't primary, and that the minerals were carried to their present locations via non-thermal creeks and springs. None of these features have been field-checked.

Alteration assemblages at Little Hot Creek are different from those discussed above. The alteration along the north-south trending fault bounding the western edge of Little Hot Creek Gorge is covered in the classic zonation pattern of advanced argillic phase mineralization: dickite and alunite surrounded by kaolinite and halloysite with minor, more pervasive montmorillinite. This zone was probably a fumarolic area at one time, with extensive vapor phase alteration. This assessment probably applies to that alteration seen in the Clay Pit Mine as well, where most of the alteration is very high temperature alunite and dickite, accompanied by kaolinite. Kaolinite, halloysite, alunite, dickite, and white mica occur along the northern cliffs of Little Hot Creek Gorge itself. Although no fault is currently known along Little Hot

Creek Gorge (only cross-cutting faults), the linear distribution of alteration in Figure 2-10 and its high temperature nature, suggests an east-west zone of structural weakness. The presence of paleo-fumarolic vents on the southern cliffs suggests that paleo-vents could also exist on the northern cliffs, which would explain the dense, linear, high temperature alteration there. Such vents would be aligned along the theoretical east-west fault/fracture. While the age of this alteration is not known, the original thermal source is thought to have been the 500ka lava flow just to the north. The waters currently discharging halfway down Little Hot Creek gorge are the second hottest and have the second highest flow rate in the caldera behind Hot Creek. These essentially neutral waters appear to be depositing some calcite as travertine at the Little Hot Creek Pools proper.

5.2 Caldera-wide implications

5.2.1 Gross patterns of alteration systems

The overall distribution of alteration shown in Figure 2-12 essentially corresponds to patterns of fluid flow in the caldera proposed by Sorey (1985), Blackwell (1985), Sorey et al., (1991) (Figure 2-2). However, in addition to the spatial distribution of highly altered rock and soil, the identity of the alteration is now also known. When Figure 2-12 is divided into gross alteration groups, a compelling pattern emerges that begins to frame out a better understanding of the geochemical nature of the hydrothermal system, and of where it is discharging (or has discharged in the past). Figure 2-13 shows caldera alteration divided into three groups based on hyperspectral analysis: Acid Sulfate, Alkaline, and Other. These groupings imply a relative pH, source chemistry, timing, and environment of deposition. Acid sulfate alteration occurs when sulfur rich gases rise towards the surface, and condense and oxidize to create acidic fluids capable of altering rock to clays and sulfates. Acid sulfate systems often form in areas with little surface water flow. Clay and sulfate deposition is common in such areas, while amorphous silica is not. Alkaline systems (also referred to as adularia-sericite alteration) come from hot, alkali-chloride rich waters that are neutral to alkaline in pH. These systems tend to have high fluid flow rates and deposit substantial amorphous silica. A third system not specifically demarcated on Figure 2-13 is travertine, that forms from carbonate rich waters and generally requires a carbonate source at depth. The travertine systems in Long Valley are lumped together with the alkaline systems. The "other" category groups several areas of what appears to be acid sulfate alteration, but with unique or questionable genesis. This includes the very recent acid-sulfate alteration on the Inyo craters and the acid-sulfate alteration on both the western Pleistocene volcanic centers and Mineral Hill that have only tenuous connections to the Long Valley hydrothermal system. As discussed previously, the age of Mineral Hill alteration may be quite old, and hence not representative of present day flow regimes. And though younger, the western Pleistocene volcanic centers were probably altered during an early stage of the hydrothermal system, if their alteration stems from the Long Valley system at all. Finally, the direct lack of surface alteration in the general vicinity of the Inyo Craters suggests that this manifestation is a relatively new phenomenon. Most of the long-lived, deep-seated hydrothermal circulation appears to be occurring to the east.

5.2.2 General geochemical patterns

In general, much of the higher temperature, advanced argillic to argillic alteration assemblages can be grossly characterized as vapor phase, acid-sulfate mineralization. The area of acid sulfate alteration in the caldera is slightly larger than the area of alkaline alteration, but these alteration systems are also zoned differently. The western half of the caldera is dominated by acid sulfate alteration while the eastern half is dominated by alkaline alteration. There are of course exceptions to this rule. The resurgent dome primarily hosts acid sulfate alteration, but the northern one third of the dome is mixed between acid sulfate and alkaline. Several large areas of alkaline alteration cover the north-northwest flank, with one acid sulfate zone cutting through. This acid sulfate is almost certainly related to the large northwest trending resurgent dome fault that runs along the same trend as the alteration. The east-northeastern flank hosts primarily acid sulfate alteration with zones of alkaline-type alteration towards the east.

The eastern half of the caldera appears to host an almost exclusively alkaline alteration system with the one exception of the advanced argillic assemblages due east of Hot Creek in the Alkaline Flats region. Though small in area, these regions have very high temperature sulfates. Advanced argillic clays occur in alkaline alteration systems, but the presence of high temperature sulfates tends to imply a more acid sulfate origin. In addition, these acid sulfate distributions are directly in line with a theorized east-west fault further west that cuts Hot Creek and has certainly hosted vapor phase acid sulfate alteration.

Laterally, there appears to be a zoned distribution of alteration systems, but this is probably explained more fully by examining the alteration systems vertically. Figure 2-14A shows the same alteration system zones overlaid on the HyMap imagery, but in addition, this data is overlaid on a 2x vertically exaggerated DEM. Again, the lateral variation across the caldera is striking, but Figure 2-14B reveals a compelling vertical variation. It appears that the alkaline alteration system lies in the lower elevations of the caldera, while the acid sulfate alteration system lies at higher elevations on the resurgent dome and western moat volcanics. This is consistent with acid-sulfate formation mechanisms, which entail low rates of surface water flow. The zones of higher elevation on and around the resurgent dome lack substantial, enduring fluid flow. This is doubly so for the western caldera where no hot springs or creeks are known west of Highway 395. In contrast, the lower elevations are home to abundant springs and creeks, especially in the Alkaline Flats region. High fluid flow is conducive to alkaline alteration and especially deposition of extensive amorphous silica (sinter), which is abundant in the eastern caldera and other low-lying regions with semi-permanent surface water flow. Paradoxically, many regions in the caldera that have abundant sinter and alkaline alteration products do not currently have any associated flow. It is likely that these regions were at one time sites of extensive fluid flow and home to an active alkaline alteration system. Also, given the right stimulus (earthquakes, eruptive activity, etc.) these regions could spring back into life. Although not currently discharging and depositing on the surface, it is highly likely that thermal waters still exist below the surface in these locations, and such areas, combined with fault information, are still candidates for geothermal exploration.

5.2.3 Implications for caldera fluid flow pathways

Several new pieces of information have been added to our understanding of how hydrothermal fluids make their way through Long Valley caldera. Flow of hydrothermal waters in Long Valley caldera is thought to occur primarily along the Bishop Tuff contact at depths averaging around 1 km. The tuff itself can be fairly well fractured and provides an excellent high permeability zone for hydrothermal fluid flow. Others, such as Suemnicht and Varga (1988) and Sorey et al. (1991) have suggested that in addition to being contact controlled, hydrothermal circulation may also be structurally controlled. But until now, viable structures for structurally controlled hydrothermal transport were missing in the caldera structural network. The spatial distribution of alteration systems and individual altered fault zones in this study provides a proxy for examining present and paleo flow patterns and discharge zones.

Figure 2-15 summarizes previously mapped faults and newly proposed faults proposed based on these hyperspectral studies. Major zones of upflow are indicated, plus general directions and paths of flow. While the patterns and directions of flow in Figure 2-15 are not widely different from those shown on Figure 2-2A, it is the recognition of several older structures and the delineation of several previously unmapped or recently mapped fault zones as major transport conduits that sets it apart from previous models (Sorey and others1985 and 1991).

Source waters flow in from the Sierra Nevada in the west, and are heated at depth by magma reservoirs in the western caldera beneath Mammoth Mt. and along the Mono-Inyo volcanic chain to the north. Sorey et al. (1991) indicated that the thermal waters flow upward within the rhyolite plateau region (Figure 2-2A). This study confirms that most of the thermal waters do flow upwards in the vicinity of the Rhyolite Plateau, and that the DFZ structure (shown in dashed green on Figure 2-15), is likely the main zone of upflow. Also, as indicated in Sorey et al. (1991), the thermal waters flow through the Rhyolite Plateau and then down south and around the resurgent dome. Very little alteration on the northwestern flank of the resurgent dome indicates there is little to no hydrothermal upflow in this area. The densely altered SMFZ, coupled with Prejean's (2001) suggestion of upward fluid flow migration during the 1997-98 earthquake swarms, implies that the SMFZ is a major zone of west to east transport of hydrothermal waters. Thermal waters also discharge along the major northwest trending normal faults of the resurgent dome, though on the western side of the resurgent dome, this discharge is confined to the southern half. The normal faults of Casa Diablo and Fumarole Valley are certainly major zones of upflow and are highlighted by small red arrows in Figure 2-15. It appears that thermal waters may flow northward from the southeastern quarter of the resurgent dome region, along the eastern flank of the resurgent dome. This pattern partially explains the source of thermal waters at Little Hot Creek. Two zones of west-northwest trending hydrothermal alteration may delineate major zones of west to east transport of hydrothermal fluids. If these thermal fluids exist, they must come either from farther west, or from the south, because there is little alteration and no likely orientated transport structures to the west. To the south, there is more alteration, mostly localized along a major northwest trending fault that extends north from the eastern Fumarole Valley normal fault. Alteration distributions suggest that hydrothermal fluids make it to the northern parts via this north-northwest fault. Alternatively, thermal waters could flow northward at depth along permeable contact boundaries. In reality, it is probably a combination of both contact and fault controlled flow here, and elsewhere in the caldera. From this point, thermal waters flow to the east along an east-west zone of permeability aligned with the Little Hot Creek Gorge.

The southeastern quarter of the resurgent dome is bounded by several north-trending normal faults that appear to channel discharge of hydrothermal waters. These discharge zones are probably fed by the waters channeled along the southern boundary of the resurgent dome. Hydrothermal discharge at Rhyolite Hot Spring is fed by the same trend of southern moat faults (SMFZ), though some waters may also come from farther north along the east-west trending faults that cut across Hot Creek (far eastern dashed green lines in Figure 2-15). These east-west Hot Creek faults may act as conduits for continued west to east transport of thermal fluids from the eastern flank of the resurgent dome to the eastern Alkali Flats region.

The recharge and discharge zones shown around the Eastern Ring Fracture Zone are similar to those shown in Sorey (1985) and Blackwell (1985). Isotopic data indicates that the waters in this region are not from the western caldera, and are thus part of an isolated east-moat hydrothermal system.

5.3 Is surface alteration a viable guide for estimating subsurface alteration profiles?

The above analysis provides a model of hydrothermal fluid flow paths and discharge points, as well as a gross characterization of alteration systems and chemistries. Loosely, the overall density and identity of alteration zones indicates relative temperatures and geochemistries in the caldera. However, most of these interpretations are based solely on surface alteration data provided by hyperspectral imaging. How much does the surface alteration indicate about hydrothermal fluid flow at depth, including temperatures and chemistries? The rich surface alteration data provided by hyperspectral imaging was coupled with temperature and lithological data gleaned from nineteen wells drilled over the past forty years. Table 1 lists nineteen separate wells, their bottom depth, bottom hole temperature (and pH if available), surface rock or soil unit, identity of hyperspectrally measured mineralization in a 200 m radius around the well head, and a catalog of mineralization found at depth in the drill core (where available). The following sections discuss a sampling of individual well sites and the correlation or lack thereof between surface alteration and temperature and alteration character at depth. All well site locations are shown in Figure 2-16.

5.3.1 Comparison of surface and subsurface data

In many cases, the surface alteration echoed the temperatures and chemistries found at depth. In a few cases however, surface alteration (or the lack thereof), was not well correlated with temperatures and chemistries found at depth.

66-29

Well 66-29 located in the far eastern region of the caldera, was drilled into Quaternary sandstone/conglomerate units (Qsc). The hole is 2125 meters deep, but only reached a bottom hole temperature of only ~73°C. There was no available information regarding alteration at depth, however hyperspectrally mapped surface alteration revealed very sparse calcite and amorphous silica. The paucity of alteration and the relatively low temperature and neutral to alkaline pHs implied by this assemblage, approximately coincide with known, measured temperatures.

MLGRP-2

MLGRP-2 is located in the southwestern region of the caldera and was only drilled to 491 meters, reaching a bottom temperature of 74°C. The hole was drilled through moat basalts (Qmb) and nearby glacial tills (Qti). Hyperspectrally mapped surface alteration was entirely amorphous silica, with evidence for kaolinite at depth (due to anthropogenic excavation at this site). Alteration at depth is reportedly smectite and opal (Flexser, 1991). The alteration on the surface and at depth roughly correlate (though smectite is a broad category of clays that includes many species). The presence of amorphous silica on the surface and of 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, may indicate this is an older zone of flow than other areas that host more abundant surface argillic phase alteration.

INYO-4

Inyo-4 was drilled just west of the Inyo phreatic craters in the western caldera through Quaternary western moat basalts (Qmb) to 1500 meters and reached a bottom hole temperature of 83°C. Hyperspectrally mapped alteration at this site was nacrite, montmorillinite, and hematite. Kaolinite did not exist within the 200 m radius of the well head, but was abundant within 300 m of the drill site. Alteration at depth is reportedly smectite, kaolinite, some halloysite, opal at depth, and surface hematite. The higher temperatures at Inyo-4 would predict a higher temperature of surface alteration, and this is observed - Nacrite is a high temperature polymorph of kaolinite (~285°C). Montmorillinite surrounds the surface nacrite. This argillic (to possibly advanced argillic) alteration assemblage suggests a high temperature geothermal source at depth, but would probably over-estimate the temperatures of water at depth.

LVEW

LVEW was drilled into the central resurgent dome through early Quaternary rhyolites (Qer) and tuffs (Qet). It reached 2300 m and a final bottom hole temperature of ~100°C. Though this temperature is quite a bit higher than the previously described wells, hyperspectrally mapped surface alteration was limited to a few pixels of amorphous silica, and nothing else for a significant radius around the well-head. This is probably a function of the great depth of the hole and suggests that the deeper the system, the less likely it is to be expressed on the surface. 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 to sample the hottest parts of the system, there is virtually no surface alteration near the site. The lack of alteration on nearby faults would suggest that these faults do not act as discharge structures, and they were revealed not to be major upflow zones in the caldera hydrothermal system. 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 (Sorey, 1995; McConnel et al., 1997). This system has since waned and moved farther to the west beneath the western caldera.

Mammoth-1

Mammoth-1 (M1 on Figure 2-16) was drilled at Casa Diablo through early Quaternary rhyolites (Qer) and tuffs (Qet) to a depth of 1605 m and a bottom hole temperature of 172°C. No alteration data at depth was available. Hyperspectrally-mapped surface alteration consisted of buddingtonite, kaolinite, kaosmectite, hematite, and amorphous silica.   The kaolinite, kaosmectite, and amorphous silica are indicative of acid sulfate alteration and high associated temperatures, which matches the reported temperature at this well. The extensive hematite may be gossan-like, and provide further evidence for high temperature sulfide deposition at depth and subsequent oxidation at the surface. Finally, the presence of buddingtonite, a late-stage, vapor phase ammonium feldspar, supports a high temperature hydrothermal source at depth.

RDO-8

RDO-8 was drilled just north of Mammoth Lakes through Quaternary tills (Qti) to a depth of 715 m and 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, which is a classic acid sulfate, advanced argillic alteration assemblage that would indicate very hot water at depth. 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 matches 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 the inability of visible-near infrared hyperspectral imaging to discriminate silicates.

IDFU 44-16

The highest temperature reached in the caldera is in the reservoir tapped by well IDFU 44-16. This well was drilled to 1799 meters and sampled waters at 218 °C and a pH of 9.3. Alteration of surface Quaternary moat basalts (Qmb) near this well, produced predominately nacrite, montmorillinite, and hematite. The presence of nacrite is consistent with the high temperatures at depth revealed by drilling. Nacrite usually forms at temperatures around 285°C, while the more common kaolinite forms at around 250°C. The smectite, montmorillinite forms at lower temperatures (~150°C) and usually surrounds 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.

5.3.2 Does surface alteration tell us about conditions at depth?

While there is considerable correlation between alteration at the surface and alteration at depth, predicting temperatures of waters at depth from surface alteration is a risky proposition. In general, 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, if units are older in “dead” hydrothermal zones, they may simply be dormant, retaining the potential to serve as points of future discharge, given the correct structural or volcanic impetus.

The degree, amount, and spatial distribution of hydrothermal mineralization is a better guide to discharge zones. For instance, the surface alteration at Inyo-4 indicates a much hotter source in this region than exists today. 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.

Despite these caveats, surface alteration did provide a fairly good assessment of caldera temperature and chemistry, which was 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. Such regions generally had only minor amounts of amorphous silica and/or calcite, both of which can be formed at fairly low temperatures. Detailed mapping of surface alteration coupled with complete fault maps (both traditional and hyperspectral based) would enhance current geothermal exploration methodologies. The addition of such maps would focus reconnaissance surveys on the most promising targets, and use both time and money more efficiently.

6.0 Conclusions

A refined geography of hydrothermal flow and discharge zones was constructed using hyperspectral-based mineral mapping. Hydrothermal mineral identification and pattern of distribution was used at several sites across the caldera, to determine gross geochemistry, temperature, and main flow conduits. Previously suggested patterns of hydrothermal flow (Sorey, 1985; Blackwell, 1985; Sorey et al., 1991) are supported by the mineral mapping results of this study, with minor departures. Waters flow into the caldera from the Sierra Nevada in the west, and are heated by a magma source at depth. Much of the water appears to utilize the Discovery Fault Zone as a major zone of upflow, and discharges along the main DFZ structure and east across the Rhyolite Plateau. The SMFZ also appears to act as a major hydrothermal flow conduit, channeling fluids from west to east. Significant upflow and discharge occurs along faults that cut the central resurgent dome, though conspicuously, no discharge appears happen on the far western boundary. Highly faulted, perhaps these structures on the resurgent dome are acting as a barrier to flow, rather than as conduits. From the central resurgent dome, hydrothermal waters discharge and flow east along several, previously unknown east-west trending zones of permeability. Both Little Hot Creek and Hot Creek are likely fed by these east-west flowing waters. Finally, the far eastern hydrothermal system appears isolated from that seen to the west.

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 possible structural control of hydrothermal waters. In reality, hydrothermal flow is probably controlled by a combination of both unit contacts and structure.

The general geochemical nature of the hydrothermal system was also determined by classifying mineralization into broad alteration groups dictated mainly by chemistry, temperature, and mode of deposition. Acid-sulfate and alkaline classifications were established for all the major zones of alteration mapped in the caldera. Acid-sulfate alteration areas were found to correlate with high topography, starved of water and dominated by vapor-phase hydrothermal flow, while alkaline areas correlated with water-rich, lower topography regions. As such, the western moat and the resurgent dome are acid-sulfate dominated, while the southern moat and eastern caldera are alkaline dominated.

The comparison of surface alteration with well-hole alteration was compelling. Though not a perfect correlation, alteration at depth roughly corresponded to surface alteration, if not in exact identification, then in general temperature of formation thresholds. In general, high temperature alteration on the surface correlated with high temperatures at depth. However, some locales did have high temperatures at depth, and virtually no surface alteration. This suggests either removal of surface alteration by some process, lack of alteration due to youth of hydrothermal flow, or the lack of any correlation. Regardless, hyperspectral-based mineral mapping in geothermal environments provides a substantial analysis of hydrothermal flow paths, discharge points, and rough chemistry and temperature. In the future, hyperspectral surveys of other volcanic regions, will serve to focus other analyses and field work, and make geothermal characterizations more rapid and efficient.