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Rapid Characterization of Drill Core and Cutting Mineralogy using Infrared Spectroscopy

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Keywords

Alteration mineralogy, spectroscopy, well logs

ABSTRACT

Infrared spectroscopy is particularly good at identifying a wide variety of hydrothermally altered minerals with no sample preparation, and is especially helpful in discrimination among clay minerals. We have performed several promising pilot studies on geothermal drill core and cuttings that suggest the efficiency of the technique to sample continuously and provide alteration logs similar to geophysical logs. We have successfully identified layered silicates, zeolites, opal, calcite, and iron oxides and hydroxides in drill cuttings from geothermal wells. In high vertical resolution measurements (every 10') we note depth-associated changes in alteration minerals, patterns or zones. This paper describes our results to date, noting distinct mineral assemblages related to system temperature.

Introduction

Water geochemistry can vary with depth and location within a geothermal reservoir, owing to natural factors such as changing rock type, gas content, fluid source and temperature. The interaction of these variable fluids with the host rock will cause changes in alteration minerals. These alteration products can suggest regions of current or past fluid flow in the subsurface and early studies also explored the use of both silica and chlorites as geothermometers.

We have surveyed a variety of samples, including drill chip boards, boxed core, and drill cuttings from envelopes and chip trays. This work has demonstrated that core and drill chips can be rapidly surveyed, acquiring spectra every few to tens of cm of section, or the vertical resolution of the chip tray (typically 10 feet). Depending on the sample type we can acquire spectral data over thousands of feet depth at high vertical resolution in a fraction of the time that is needed for traditional analytical methods such as XRD or TEM.

These spectroscopic mineralogy traces can be stacked and analyzed similar to hyperspectral image data sets characterizing changes in degree and type of alteration with depth in a geothermal well. This technique is useful for rapid assessment to identify (a) hydrothermal alteration zones and silicification, (b) presence of swelling clays (smectites, bentonite, i.e. montmorillonite and illite) at depth, (c) specific alteration minerals that may be used as rough geothermometers, and to correlate individual stratigraphic units separated by faults in different wells at a common site.

Methods

Optical and infrared spectroscopy has long been used to identify specific rocks and minerals (e.g. Hunt, 1977). The technique hinges on the interaction of light with geologic materials that absorb specific wavelengths creating a fingerprint signature. The resulting spectrum contains information on both the primary elemental composition as well as crystallographic coordination. At shorter wavelengths, the optical and infrared (0.4 to ~2.5 μm), the resulting spectrum is most sensitive to iron (oxides, oxyhydroxides) and alteration cations (water, hydroxyl, carbonate) (e.g. Clark, 1990; Gaffey, 1997).

Drill core, chip trays and envelope samples were measured using an Analytical Spectral Devices (ASD) spectrometer using



Figure 1. ASD Spectrometer in the core shack at the Blue Mountain DB2 drill site, near Winnemucca, NV. Light source illuminates the cut surface and is sensed by the lens/fiber optic "gun". On the right, the equipment in the Navy's China Lake facility with the wand attachment for measuring chips in envelopes. Chips are emptied onto a sample tray or plate for measurement.

a small halogen source and a white halon calibration panel for correction to absolute reflectance. Core and chip board samples were measured using a small lens objective on the fiber optic while other chip samples used a wand attachment with a light source adjacent to the fiber optic input (Figure 1). The latter set up allows for direct measurement of chip trays or core surface with limited artifacts from uneven illumination.

Geothermal Wells Surveyed

The table below notes the preliminary studies we have conducted to date, including surveys of Desert Peak, Blue Mountain, Humboldt House/Rye Patch and Hawthorne cuttings and core. The regions studied range in type of sample (core, chips), host lithology, and system temperature. The type of sample affects our ability to identify diagnostic mineral species. The host lithology and system temperature result in different alteration minerals. We have also used these pilot studies to establish systematic protocols for future measurements.

Table 1. Geothermal wells surveyed.

Site	Type	Lithology	Well Type	Depth (m)	Max T (C)
Desert Peak	Cuttings glued on board	Tuffs, sediments, phyllite, granodiorite	Exploration	2938	204
Blue Mountain DB2	Core	Phyllite, dacite	Monitoring	1128	unpublished
Humboldt House HHP3	Core	Conglomerate –silicified or mud/sand supported	Exploration	198-306	110
Hawthorne HWAAD-2	Cuttings	Alluvium, sandstone, and granite	Exploration	~surface-1437	49
Hawthorne HWAAD-3	Cuttings	Alluvium, sandstone, and granite	Exploration	~surface to 1175	43
Imperial Valley	Core	Sandstone, siltstone, granite	Exploration	Spot samples	unpublished

Analysis

Several commercial software packages were used to display and analyze the data. The Spectral Geologist (TSG) developed for mineral identification in economic geology drill core was used for rapid display of spectra and automated mineral typing. The automated routines were helpful in characterizing geothermal samples, but were also often inaccurate. The user interface allowed for rapid survey of many hundreds of spectra to visually note unique outliers or transitions within the collected data. In order to obtain more accurate mineral identifications we also applied analysis approaches that have been successful with remote sensing data and we compared individual spectra with libraries derived from pure minerals. In this approach, point spectra were “expanded” to provide a visual sense of width and stacked into a “image cubes” representing depth. An example of this relationship is shown in Figure 2.

These “core spectral cubes” were then analyzed using routines that have been successfully applied to hyperspectral remote sensing data to statistically reduce the data dimensionality and identify unique spectral features. This analysis was performed

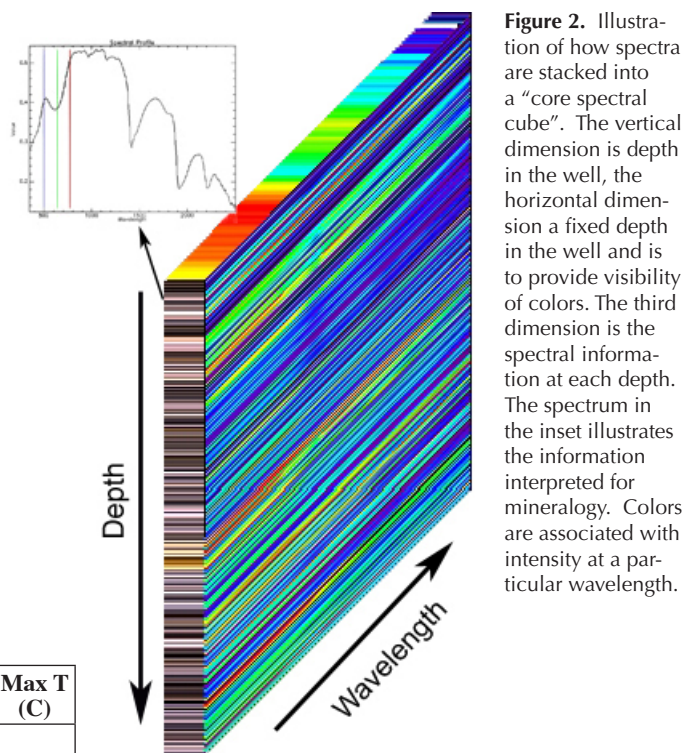


Figure 2. Illustration of how spectra are stacked into a “core spectral cube”. The vertical dimension is depth in the well, the horizontal dimension a fixed depth in the well and is to provide visibility of colors. The third dimension is the spectral information at each depth. The spectrum in the inset illustrates the information interpreted for mineralogy. Colors are associated with intensity at a particular wavelength.

in the software package ENVI (Environment for Visualizing Images). False color and decorrelation stretch image combinations were made of spectral bands around known mineralogical features. We then applied spectral similarity and matching techniques to map similar spectra at different depths. All three methods, survey, color composites and statistical analysis identify spectra that are common or representative of the well.

Interpretation

Many spectra identified were suggestive of individual minerals, yet the majority of spectra in the log are mineral mixtures. All core and cutting spectra that displayed distinct diagnostic features were compared with mineral spectral libraries to identify constituents. Representative spectra from the Humboldt House core are shown in Figure 3 along with a depth representation of where those spectra occur. Unaltered mafic material has a low albedo and lacks any features, this is mapped as a coral color. Hydrated quartz shows large features at 1.4 and 1.9 μm from the water in the structure and is mapped in blue. Relatively pure kaolinite is noted by the diagnostic doublet at 2.2 μm and is mapped in green. A wide range of mixed illite/chlorite in varying concentrations are observed (magenta) and many of these spectra show the very narrow characteristic feature at 0.43 μm associated with jarosite. Mixtures of chlorite and epidote (cyan) indicating propylitic alteration are also seen in this survey.

The mineralogy with depth (right side of Figure 3) shows that unaltered material grades into alteration at depth. The most common alteration in this hole is illite/chlorite with varying abundances of these two minerals (dark green, magenta and purples). Components that are discretely and narrowly distributed include quartz and opal (blue and red) which appear in narrow zones

suggestive of cross cutting veins, kaolinite (bright green) and epidote-mixtures (cyan). The different clay minerals identified suggest differences in local temperature and pH conditions and distinguish between argillic and propylitic alteration zones at depth (Browne, 1978; Henley and Ellis, 1983).

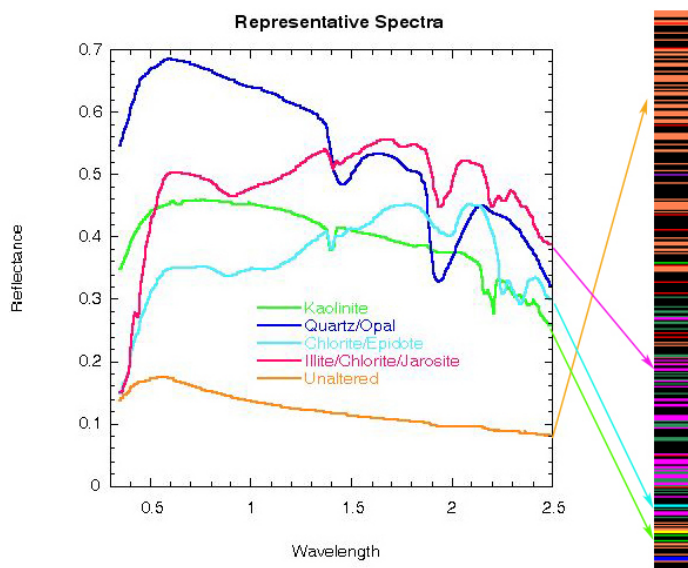


Figure 3. Representative spectral types in the Humboldt House core. Description of spectral features is in the text. On the right is a depth profile of the individual spectral types mapped, colors correspond to the spectral profiles on the left. Black areas are mixtures and are not clearly identified with any single spectral endmember.

Results

Using these techniques we have measured both chips and core from several geothermal wells. Common minerals identified in each of the holes surveyed are shown in Table 2. Varying alteration combinations were noted in each hole and depth dependent or narrow zones of unique alteration were seen in all. Illite/chlorite was seen in most wells, and montmorillonite or kaolinite were also commonly found. The unique signature of prehnite has so far only been identified in the Blue Mountain DB2 core, and hydrated quartz and opal are only seen in wells with the highest temperatures

Table 2. Minerals Identified in Various Geothermal Drill Holes.

Site	Lithology	Depth (m)	Common minerals and accessory materials identified
Desert Peak DP23-1	Tuffs, sediments, phyllite, granodiorite	2938	chlorite, illite, muscovite, unaltered phyllite, hematite, epoxy glue
Blue Mountain DB2	Phyllite, dacite	1128	unalt phyllite, mont./illite, hydr. qrtz/opals, chlorite+montm, serp+prehnite, carbonate, jarosite
Humboldt House HHP3-1	Conglomerate –silicified or mud/sand supported	198-306	weakly altered mafics, illite/chlorite, hydr. qrtz/opals, kaolinite, jarosite
Hawthorne HWAAD-2	Alluvium, sandstone, and granite	~surface-1437	montm., mont+illite+chlor., chlor+epidote, walnut chips, several unique
Hawthorne HWAAD-3	Aluvium, sandstone, and granite	~surface to 1175	montm., mont+illite+chlor., chlor+epidote, carbonate
Imperial Valley	Sandstone, siltstone, granite	Spot samples	Montmorill., hydr qtz/opal, carbonate

(>100C, Tables 1 and 2). Our first survey of the Desert Peak chips glued to a board (Kratt et al. 2004) showed interference from the glue, but still distinguished altered and unaltered zones. Walnut chips, a common additive to drilling mud, is clearly distinguished in chip samples based on the spectral features of organic material that are not found in geologic samples.

Conclusions

We have established reliable methods for core/chip surveys that can rapidly measure samples with high depth resolution. Temperature dependent mineral assemblages are found, both gradational with depth and as narrow zones associated with vein or fracture fill. Silica-opal geothermometer minerals are clearly resolved and seen only in the highest temperature wells.

We can readily identify montmorillonite/illite transitions that may be associated with Na/Ca/K variation and may eventually be used for geothermometry. Many alteration minerals are similar in all wells, yet unique signatures related to lithology and alteration temperature are also seen. Depth surveys up to several kilometers were completed in a few days and can provide an initial assessment and point to sections of interest for more detailed or time consuming analysis such as SEM/TEM/XRD. Some limitations include that pronounced textural changes occurred in the physical character of the core, with no obvious change in mineralogy. Spectroscopy will also not identify if the alteration is recent or ancient, though this is also true of visual and other geophysical logs.

Future Work

We are currently developing automated analysis techniques to convert this detailed spectral logging data into high-vertical-resolution mineral depth profiles that can be linked to lithology, stratigraphy, fracture zones and potential for geothermal production. We should be able to identify depth transition zones or areas of circulation/fracture based on alteration intensity.

Also in development are metrics that would link mapped mineralogy to known geothermometers such as Na-K or Mg depletion, discrimination among illite, montmorillonite, and beidellite, and kaolinite crystallinity. Identification of amorphous and crystalline silica components (chalcedony, cristobalite and quartz) can also constrain silica geothermometry and rapidly identify high temperature systems. The degree of alteration and some mineral types have been shown to be a proxy for host rock permeability, natural circulation, and the potential for reservoir sealing (Guisseau et al. 2007; Inoue et al. 2004; Mas et al. 2003). We hope to correlate these depth resolved alteration patterns with 3-D structural data in order to better understand fluid flow and migration pathways in different systems.

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