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Mapping alteration in geothermal drill core using a field portable spectroradiometer

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ABSTRACT

Hydrothermal alteration mineralogy in geothermal systems is commonly used to infer system temperature and past fluid flow patterns. Infrared spectroscopy is particularly good at identifying a wide variety of hydrothermal alteration minerals. The technique requires little sample preparation, and is especially helpful in discrimination among a wide range of phyllosilicate minerals that may be difficult to distinguish in hand sample or require lengthy preparation for XRD analysis. We have performed several pilot studies of geothermal drill core and chips to prototype rapid alteration characterization over large depths. These preliminary studies have established reliable methods for core/chip surveys that can quickly measure samples with high depth resolution and show the efficiency of the technique to sample frequently and provide alteration logs similar to geophysical logs. We have successfully identified a wide variety of phyllosilicates, zeolites, opal, calcite, iron oxides, and hydroxides, and note depth-associated changes in alteration minerals, patterns, or zones. Alteration mineralogy identified using these techniques shows good correlation with traditional petrographic microscope and XRD methods.

1. Introduction

Late phase geothermal exploration includes test drilling whereby a few deep wells are bored to validate temperature and permeability related to geologic and geophysical properties of the prospect. Size and depth of the borehole, and drilling methods (continuous core or rotary drilling) are elements of the exploration program that are influenced by cost as much as by the information to be gained. Continuous core provides the most geologic data possible from a drill hole, specifically information about reservoir fractures and hydrothermal alteration. However, rotary drilling is less expensive and more commonly used by the geothermal industry. Some drill holes include a combination of rotary and core operations. Rotary rigs recover geologic cuttings via the drilling fluid. Cuttings provide less geologic information regarding matrix and vein associations but are still geologically useful. We have surveyed both geothermal drill core and cuttings using infrared spectroscopy to identify alteration at depth as a means of enhancing understanding of the geothermal system, and this paper focuses on three locations for which continuous core samples were available to us.

Shortwave infrared spectral data are commonly used to identify many hydrothermal alteration minerals and precipitates that are of interest in geothermal exploration (e.g., Yang et al., 2001; Kratt et al., 2006; Calvin et al., 2015). Our group has been using this type of data since 2002 to successfully identify and map hydrothermal alteration minerals and geothermal deposits in remote sensing and field-based exploration studies (as recently summarized by Calvin et al., 2015). For these core and cuttings surveys we used our field ASD spectroradiometer with a contact probe containing an internal halogen light source.

This paper describes pilot studies we completed in an effort to define optimal data collection and processing methods, and demonstrates the effectiveness of spectral analysis of drill core for geothermal exploration. The cores used in these studies are from slimholes drilled at the Humboldt House and Blue Mountain geothermal areas in Nevada, and the Akutan geothermal area in Alaska. In the Humboldt House and Akutan examples prior detailed geochemical studies had already been performed, and their results are compared to our spectral data findings. We recommend that future studies of geothermal drill core use spectral logging as an initial survey method to refine sample locations for subsequent detailed or high-resolution geochemical analyses. In a manner similar to its use in aerial remote sensing, spectroscopy should be used as a reconnaissance tool to rapidly glean mineralogical information from downhole samples and help direct focus of later detailed studies.

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2. Background

2.1. Previous work

Detailed mineralogical studies of geothermal fields have revealed a wide array of alteration minerals that are linked to the temperature, pressure, and rock type of the system (e.g., Browne, 1978; Henley and Ellis, 1983). Temperature zonation of alteration assemblages is also used in exploring for economic minerals in hydrothermal systems (e.g., Silberman and Berger, 1985). The use of these alteration facies in geothermal systems has been less well studied, particularly as it relates to borehole geology and system temperature, though several early studies explored the use of both silica and chlorites as geothermometers (e.g., Browne, 1978; Reyes, 1990). Several studies have noted alteration zonation, and that types of clay minerals (illite, montmorillonite, beidellite) can characterize temperature of alteration in geothermal systems (Guisseau et al., 2007; Inoue et al., 2004). In low-temperature systems Mas et al. (2003) found kaolinite as an indicator of current fluid pathways and kaolinite crystallinity was a tracer of fluid temperature. Specifically related to EGS stimulation, Ledésert et al. (2009) found that the presence and amount of calcite may suggest models for the chemistry of injecting fluids and the higher the calcite content the lower the natural circulation in the system. These past studies rely on time consuming sample preparation and analysis through the use of X-ray diffraction (XRD), transmission electron microscopy (TEM), and often require clay mineral separation. These studies typically survey isolated locations within the well rather than continuous measurements that could be integrated with other logging techniques.

Laboratory spectroscopic methods for mineralogy have been established for many decades. Spectroscopic methods using portable field instruments for core sample mineralogy were developed in the late 1990s (e.g., Kruse, 1996; Taylor, 2000). Studies by Taylor (2000), Sun et al. (2001), and Harraden et al. (2013) demonstrated the effectiveness of spectral measurements on a relatively small number of core samples for mineral exploration. These initial studies also noted consistency between results from spectral analysis and other geochemical methods, including XRD and X-ray fluorescence (XRF). In an early spectral analysis of geothermal samples, Yang et al. (2000) and Yang et al. (2001) measured 96 samples from Te Mihi and 285 samples from the Broadlands–Ohaaki geothermal systems in New Zealand and compared spectral results with prior studies. Most recently, automated systems have been developed to collect data at more frequent or near-continuous depth intervals and the technique is often used to better understand ore deposits (e.g., CSIRO, 2012; Tappert et al., 2011; Ross et al., 2013; see Section 5.2).

Our preliminary efforts in surveying geothermal drill core and cuttings concentrated on systematic collection of spectral data with depth at intervals of tens of centimeters to tens of meters (Kratt et al., 2004; Calvin and Solum, 2005; Calvin et al., 2010; Table 1). These pilot studies were conducted to demonstrate the value of the technique for geothermal exploration, and to establish methods that optimize speed, effort, and effectiveness. We also surveyed cuttings from the San Andreas Fault Observatory at Depth (SAFOD), and though this is not a geothermal drill hole it is included in Table 1 for completeness. As noted in Table 1, these studies surveyed from a few hundred to several thousand meters depth in data collection periods from a few hours to at most three days. We collected from 99 to 2350 individual spectra, that were then collated into depth associated databases. We analyzed these core spectra using standard methods we apply to remote sensing data sets (see Section 3.2). These initial studies helped refine the data collection and analysis methods described below. Although we collected data on cuttings for Desert Peak and Hawthorne, Nevada, the Desert Peak survey had strong interference from glue holding the chips on the board (Kratt et al., 2004). For the cuttings from the two holes at Hawthorne, Nevada these lower temperature systems did not show either the mineralogical diversity or depth-dependent changes seen in the core. Therefore, this paper focuses on the core surveys, two of which also had independent mineralogical analysis using petrographic and XRD techniques, allowing us to compare and contrast results.

2.2. Drill core locations and geology

These initial studies were conducted as unfunded demonstration projects when geothermal borehole samples were available; our surveys were not part of a planned exploration program at any of the well sites. As such, we were able to access core and chips from several locations in Nevada, as well as core from Alaska that was housed at Western Washington University. In most cases, traditional methods were used to log the lithology of the well and analyze selected cut sections, allowing us to compare our spectral data with previously published results. This paper presents detailed mineral identifications for the three well locations where core was available, Blue Mountain and Humboldt House in Nevada and Akutan in Alaska (see also Table 1).

2.2.1. Humboldt House-Rye Patch, Nevada

The Humboldt House-Rye Patch (HH-RP) geothermal area in Pershing County, is approximately 120 miles northeast of Reno, Nevada along the I-80 corridor. The site was identified in early drilling by Phillips Petroleum and has subsequently had a number of seismic and geophysical exploration activities to refine the conceptual model (Ellis, 2011). In 2003, a collaboration between the University of Nevada, Reno (UNR) and Presco Energy drilled 5 wells with core recovered from P32-2, P10-1, and P3-1. Detailed geochemistry and mineralogy of these three wells was the subject of two UNR Masters theses (Johnson, 2005; Otahal, 2006). The core was housed at UNR storage facilities where we conducted a spectral survey of P3-1 in Fall 2009, collecting 789 spectra at roughly 15 cm (~6 in) intervals over 105 m (350 ft) depth. Rock samples have since been skeletonized and are housed at the Great Basin Sample repository of the Nevada Bureau of Mines and Geology.

The general geology of the site is primarily Quaternary basin fill alluvial fan conglomerates with Pleistocene lake sediments. In P3-1, continuous core was collected below the alluvial conglomerate, from 651 to 1000 ft (198–306 m) depth. The core lithology was a sand and silt matrix-supported gravel conglomerate, with a few thin beds (<0.5 ft) of coarse sand. Otahal (2006) logged the lithology and alteration present in the core, and used petrography, SEM, XRD, and ICP-MS to characterize the geochemistry of approximately 40 samples. The area has extensive surface sinter deposits and silicification of the conglomerate was the dominant alteration noted in the core.

2.2.2. Blue Mountain, Nevada

Blue Mountain was a geothermal prospect development supported by the Department of Energy's Geothermal Technology program. The site is situated west of Winnemucca in north-central Nevada. Deep Blue No. 2 well (DB2) was an exploration slimhole well to test the commercial potential of the site. The core was the subject of a physical properties study by Ponce et al. (2009) who also presented generalized stratigraphic columns and other data synthesized from the engineering and drilling report (Fairbank Engineering, 2004). Approximately 300 reflectance spectra of core from the DB2 hole were acquired at irregular intervals in the field in May 2005. These spectra span the depth interval from 660 to 3700 ft (201–1128 m) with spot samples acquired over the course