Short-Wave Infrared (SWIR) Spectroscopy as Geothermal Well Logging Tool in the Maibarara Geothermal Field, Batangas

Hannah Yvette Bumanglag,[1] Marie April Djohanne Celiz[2], Jim Paulo Bautista[1], Jim Jopro Codia[3]

[1]Maibarara Geothermal Inc., Ortigas Business Center, Pasig City, Manila, Philippines

[2]Belton Place, Yakal St., San Antonio, Makati City, Philippines

[3]PetroGreen Energy Resources Corporation, Ortigas Business Center, Pasig City, Manila, Philippines

hpbumanglag@maibarara.com.ph, jmbautista@maibarara.com.ph, djohanne.celiz@gmail.com, jacodia@petrogreen.com.ph

ABSTRACT

Hydrothermal mineral identification and characterization during the drilling of geothermal wells typically involves the use of microscopic, petrographic, fluid inclusion, and X-ray diffraction (XRD) techniques. While useful, these methods can be time-consuming and expensive, considering the high volume of samples retrieved during geothermal drilling. Reflectance spectroscopy is presented as a fast, cost-effective, and reproducible analytical technique for identifying hydrothermal minerals and, consequently, assessing formation competency and estimating reservoir temperature while drilling. Short-Wave Infrared (SWIR) spectra were generated from drill cutting samples of a geothermal well in the Maibarara Geothermal Field, Batangas. Spectral identification was conducted through comparison of generated mineral spectra with published data within the spectral range of 1000-2500nm. Montmorillonite, illite, kaolinite, chlorite, and goethite were identified and verified against results from microscopic analysis. Information derived from SWIR Spectroscopy was successfully used to interpret subsurface hydrothermal alteration and infer the location of the borehole with respect to the geothermal system.

KEYWORDS: SHORT-WAVE INFRARED SPECTROSCOPY, REFLECTANCE SPECTROSCOPY, HYDROTHERMAL MINERAL CHARACTERIZATION, GEOTHERMAL WELL DRILLING, MAIBARARA GEOTHERMAL FIELD

1. INTRODUCTION

The Maibarara Geothermal System is a productive geothermal reservoir situated 70 km southeast of Metro Manila (**Figure 1**). The production field sits on the NW flanks of Mt. Makiling, an inactive andesitic stratovolcano at the NE-SW trending rifted system of Macolod Corridor in the southeastern Philippines (Defant et al., 1990; Forster et al., 1990; Aurelio et al., 2020). The area's geology can be briefly described by the sequence of Pre-Makiling Volcanics (PMV) consisting of andesitic lava flows with intercalated tuff and breccia, overlain by the pyroclastic deposits and andesitic lavas of the Makiling Volcanics (MV), and succeeded by more recent tuff deposits of the Taal Formation (TF) (Abrigo et al., 1994; Buban et al., 1994). The PMV is intruded by a hornblende quartz diorite pluton (Abrigo et al., 1994; Olivar et al., 2010). The geochemical signatures of the reservoir fluids are generally neutral in pH, with a high-temperature reservoir ranging from 300 to 320°C (Buban et al., 1994; Olivar et al., 2011).

The reservoir sustains the 32-MW power plant of the Maibarara Geothermal Inc. (MGI) comprised of 20-MW

Maibarara-1 plant and 12-MW Maibarara-2 plant. Initially, three (3) production wells (PW-1, PW-2, and PW-4) provide two-phase fluid to power the geothermal plant, while two (2) reinjection wells (IRI-1 and IRI-2) return the fluid to the reservoir. In 2024, MGI developed its outfield reinjection system that led to the drilling of the ORI-1 vertical well. This reinjection well can be found in a well pad located north of the existing power plant (**Figure 1**) and has a total depth of 1400 mMD. The drilling of Well ORI-1 enabled the application of emerging technologies such as reflectance spectroscopy in analyzing hydrothermal clay alterations in the Maibarara Geothermal Field.

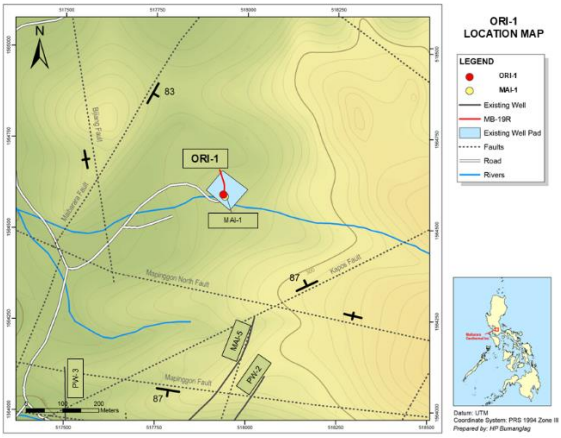


Figure 1: Plan view of Maibarara Geothermal Field, showing the location of ORI-1 in Pad C

Understanding hydrothermal mineral alteration assemblage is important as it provides a wealth of information on the subsurface characteristics of a geothermal system. The alteration minerals represent a footprint of the temperature, pressure, and permeability conditions, as well as the composition of the geothermal fluid and the nearby rock system (Reyes, 1990; Savitri, 2024). Common industry approaches rely on microscopic, petrographic, fluid inclusion, and X-ray diffraction techniques to gain mineralogical insights on the alteration, which, however, require a longer time and costly analysis. The infrared reflectance spectroscopy, an extensively applied mineral exploration methodology, presents a novel opportunity in fast-tracking the detection of alteration minerals as applied in the geothermal industry (e.g., Kamau et al., 2020; Savitri, 2021), especially during well drilling campaigns.

Infrared reflectance spectroscopy is a non-destructive tool capable of zooming in on the reflectance spectra within the Visible and Near-Infrared (VNIR) (400-1000 nm) to Short Wave Infrared (SWIR) (1000-2500 nm) of the electromagnetic spectrum (Kamau et al., 2020). At certain wavelengths, the atoms and molecules exhibit absorption features due to energy level transitions and compositional differences (Kamau et al., 2020). Within the realm of SWIR, hydroxylated minerals such as clay, mica, smectite, chlorite, sulfate, zeolite, hydroxide, carbonates, tourmaline, and ammonium-associated groups register spectral absorption features (Savitri, 2024) and can be detected using spectroscopy analysis.

This study aims to explore the emerging technique of VNIR-SWIR reflectance spectroscopy in Maibarara Geothermal System and assess its performance in characterizing and analyzing the geothermal alteration minerals present on the drill cuttings of ORI-1.

2. METHODOLOGY/APPROACH

Samples were sourced from the drill cuttings of ORI-1. A total of ninety-three (93) drilled well cutting samples from ORI-1 were processed and subjected to Reflectance Spectroscopy Analysis. Cuttings were collected in a 23 cm x 15 cm canvas bag for each sampling interval (5 meters) from 1 m down to 446 m, to observe the changes in mineralogy throughout the wellbore. No cuttings

were analyzed beyond measured depths of 449 m due to circulation losses. Representative samples measuring approximately 100 grams each were placed in a small ceramic plate or aluminum bowl (**Figure 2A**). To prevent the interference of water when looking at the target minerals (**Figure 4A**), the ORI-1 samples were continuously dried for about 24-48 hours inside a room with T = 39°C. Samples that were not sufficiently dried even after 24 hours were sun-dried for a few hours at Pad C (**Figure 2B**).

VNIR-SWIR reflectance spectroscopy analysis was employed on two setups: coarse (Sample 1) and fine (Sample 2), to determine which size would be more suitable in future analyses. Coarse cuttings were immediately subjected to spectroscopy analysis using a compact and portable Terraspec® (350-2500 nm) spectrometer created by Analytical Spectral Devices, Inc (a Malvern PANalytical company) (Figure 2C). Using coarse samples is said to be advantageous in terms of sample preparation but may be influenced by the variability of the composition of the sample, inconsistent sizes of the sample gains, and the inadequate window size of the instrument probe. To address this, a minimum of three scans from different spots of the sample were taken. For the fine-size setup, drill cuttings were further pulverized using a mortar and pestle and sieved using a 0.075 mm-aperture sieve (Figure 2D). Despite requiring a longer turnaround time (approximately 36 to 60 hours) for sample preparation, this setup can be advantageous due to the homogeneity and equal grain sizes of the samples. The remaining cuttings were stored for future analyses. The output files were processed using the ViewSpecPro 6.2 software and viewed and manually interpreted using the SpecWin 2.0 software.

Comparison of the resulting spectra of the coarse and fine samples showed that both sample types were able to identify the same minerals; however, the resulting spectra from fine samples had higher reflectance and were significantly less noisy. Consequently, only fine samples were prepared and used at depths greater than 136 m.

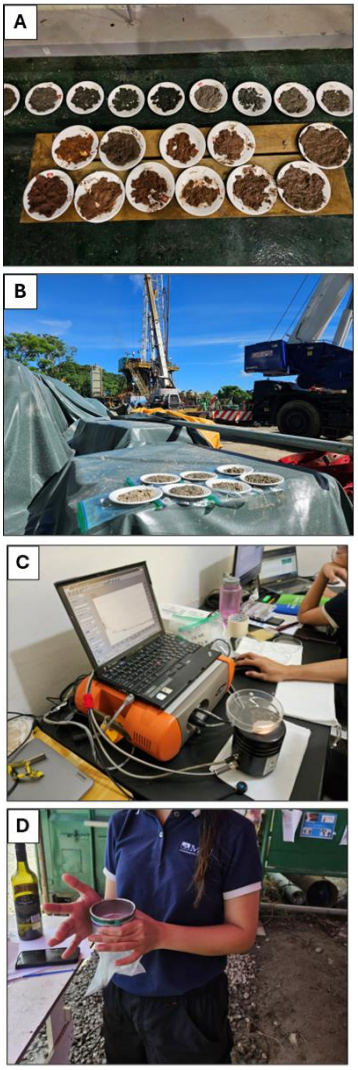


Figure 2: A. Cuttings were transferred into ceramic plates for spectroscopy analysis. B. The samples were sun-dried to remove moisture before the analysis. C. Pulverized samples were sieved for the fine-size setup. D. Drill cuttings were characterized using TerraSpec TSP field spectroscopy.

To supplement the synthesis of mineral data from reflectance spectroscopy, petrographic analysis was

conducted for eleven (11) drill cutting samples collected from the different hole sections of the well. Samples located at the hole section of the total depth (TD) and at remarkable lithologic horizons were selected for microscopic identification. Additional information from this analysis was correlated with the results of the clay analysis using reflectance spectroscopy (**Figure 3**).

3. RESULTS AND DISCUSSIONS

The reflectance spectroscopy analysis was able to distinguish between different clay alterations throughout the well. At depths of 0 to 446 m, montmorillonite ($(Na, Ca)_{0.33}(Al, Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$), a type of smectite, was identified in reflectance spectroscopy by broad absorption features at ~1400, ~1920, and ~2200 nm features, and lack of features from 2280 – 2500 nm (**Figure 4B**). The tool was also able to describe the relative abundance of this expanding clay. At the 26" and 17-1/2" hole section (from 1-201 m), varying degrees of smectitic alteration were encountered. The highly argillized paleosol layer at 201-256 m showed intense smectitic alteration, while the abundance and intensity of the alteration waned with depth at the 12-1/4" and 8-1/2" hole sections (259 to 415 m). Looking at the petrographic analysis, the montmorillonite appeared as off-white to dull gray, thick slurry material, which was apparent even after washing the cuttings. This clay was also observed as an alteration of the tuffaceous matrix of basaltic and andesitic tuff breccia and found associated with indurated hematized volcaniclastics. This mineral is associated with low temperature alteration and signifies a formation temperature of less than 220°C. If present without illite, estimated temperature drops to less than 180°C (Reyes, 1990).

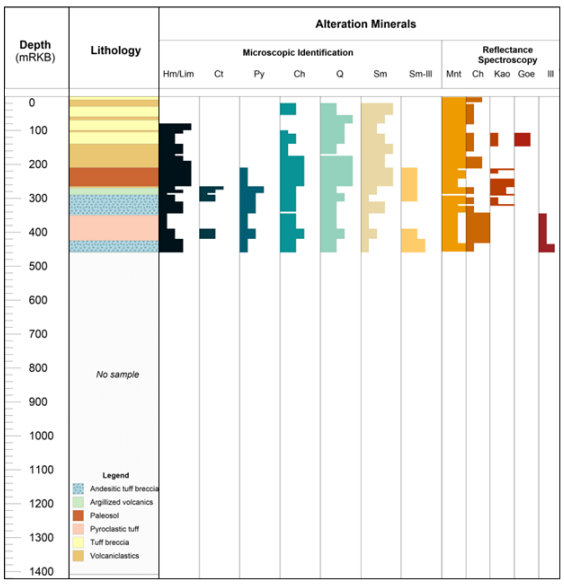


Figure 3: Composite log illustrating clay mineral abundance as analyzed, alongside lithologies identified microscopically and depth log

Similarly, chlorite ($(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot (Mg,Fe)_3(OH)_6$) was identified in reflectance spectroscopy by its absorption features at ~2250 nm and ~2340 nm (**Figure 4C**). An "Fe-slope", shown as increasing reflectance from 1120-2100 nm may be present for Fe-rich chlorite. In terms of abundance detected in this analysis, chlorite was generally abundant for the entire section, but with a stark increase at 336-421 m depth, where it was more dominant than montmorillonite (**Figure 3**). It was noticeably absent in the paleosol or highly altered reddish brown clay section (201-256 m), which was dominated by montmorillonite and kaolinite. Chlorite chips were present in trace amounts but were noted to be overprinted by clay. Conversely, chlorite was dominant from 336-421 m at the dark gray pyroclastic tuff unit, seen as alteration of the groundmass of the grains. Chlorite is formed as an alteration product of Mg- and Fe-silicates in igneous rocks, at temperatures of 120-320°C. Due to its relatively wide range of temperature

formation, mineral association was used as a basis for estimating the general temperature.

Meanwhile, kaolinite ($Al_2Si_2O_5(OH)_4$), a clay mineral associated with acidic fluids, was identified by microscopic analysis and reflectance spectroscopy at shallow depths of 206-316 m (**Figure 3**). This was observed in the cuttings as "bleached" and whiter in color. The formation of kaolinite is caused by the fluids that alter tuff breccia and other volcanics containing aluminum-rich silicates like feldspars. Reyes (1990) identifies a formation temperature of ambient to 120°C for kaolinite.

Goethite, an Fe-oxide (α-FeO(OH)), was identified at 101-136 m with an absorption feature at ~920 nm (**Figure 3**). Goethite commonly forms as a weathering product of Fe-bearing minerals such as pyrite. The presence of goethite possibly signifies cold water incursion originating from relatively shallower depth.

Lastly, illite ($(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2(H_2O)]$) was identified in reflectance spectroscopy with absorption features at ~1400 and ~2200 nm (**Figure 4D**). Compared to montmorillonite, the ~1920 nm water feature was not as deep, and there were absorption features at ~2340 and ~2440 nm. Its presence was marked in reflectance spectroscopy from 336 m depth downwards and occurred with montmorillonite, albeit at a relatively low abundance (**Figure 3**). This signifies the onset of the interlayered illite-smectite transition zone, with an estimated formation temperature of 180-230°C (Reyes, 1990). The transition zone became more dominant at the 12-1/4" and 8-1/2" hole sections from 261-301 m and reappearing at 381-451 m. Illite increased in abundance with depths deeper than 426 m, which was expected as smectite presence dwindled and temperature profiles increased with depth.

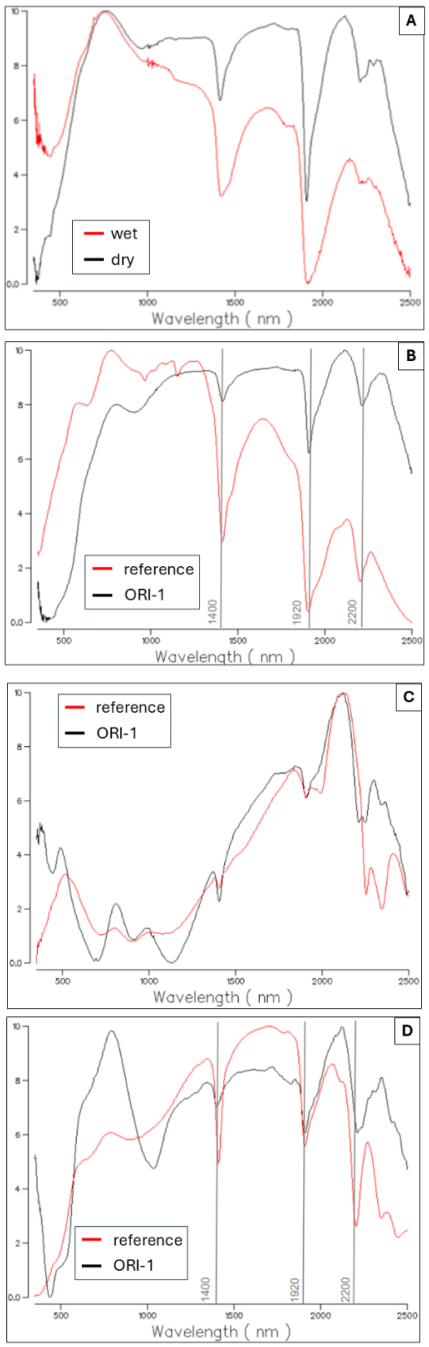


Figure 4: A. Comparison of the wet and dry spectra of sample ORI-1 (136 m). B. Spectra of the ORI-1 (81 m) sample and montmorillonite reference. C. Spectra of the ORI-1 (361 m) sample and Fe-chlorite reference (red). Note the presence of other minerals in this sample, hence the difference in absorption features. D. Spectra of the

ORI-1 (436 m) sample and illite. Note that montmorillonite and weak chlorite are also present in the sample.

4. SUMMARY AND CONCLUSIONS

In previously drilled Maibarara wells, wellsite geologists have relied solely on macroscopic and microscopic analysis of drill cuttings to identify minerals. The strength of reflectance spectroscopy analysis lies in its reliability and accuracy to verify mineral identification and pinpoint specific clay mineral geothermometers (i.e., differentiating illite from smectite, detecting kaolinite) and their relative abundances.

However, since the samples require preparation, clay analysis results cannot be used as a basis for real-time drilling decisions such as casing setting depth and mud chemistry. To shorten the turnaround time, it is recommended to use a makeshift bulb array dryer or an incubator as a faster alternative for drying the samples. Furthermore, not all minerals identified microscopically can be detected through spectroscopic analysis. Spectral signatures of more dominant minerals, such as montmorillonite, mask less abundant minerals (e.g., hematite and silica). While relative abundance can be estimated, utilizing a paywalled software is necessary to obtain quantified results.

All things considered, reflectance spectroscopy analysis is helpful in drilling as it verifies microscopic identification, provides insight into specific clay geothermometers, and paints a picture of where we are in the geothermal system. It is highly recommended to be employed in future drilling projects in Maibarara, as a supplementary analysis to well sitting.

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REFERENCES

Aurelio, M.A., Rafael, D.J.P., Bermas, A., Escudero, J.A.P., Ybañez, R.L., Ybañez, A.A.B., Baldago, C.B., Balangue-Tarriela, M.I.R.D., Sarmiento, D.M., Trinidad, J.R., Lagmay, A.M.F.A. & Young, A. (2020). Taal 2020 ground fissures: indications of rift volcanism? *In proc. Virtual GEOCON 2020: The 33rd Annual Geological Convention*. Quezon City (Virtual Base), Philippines, 1-3 December 2020. In CD.

Abrigo, F., Buban A., Sussman, D., Sta. Maria, R. & Mogen, P. (1994). *Maibarara Geologic and Reservoir Model as of March, 1994* (pp. 1-155). Philippine Geothermal Incorporated Internal Report.

Buban, A. C. (1994). Geologic and Reservoir Model of the Maibarara Geothermal Field. In *Proceedings, 16th NZ Geothermal Workshop, Auckland, New Zealand*.

Defant, M., Maury, R., Joron, J., Feigenson, M.D., Leterrier, J., Bellon, H., Jacques, D., & Richard, M. (1990). The geochemistry and tectonic setting of northern section of the Luzon arc (the Philippines and Taiwan). *Tectonophysics 183*, 187-205.

Forster, H., Oles, D., Knittel, U., Defant, M.J., & Torres, R.C. (1990). The Macolod Corridor: A rift crossing the Philippine Island arc. *Tectonophysics 183*, 265-271. https://doi.org/10.1016/0040-1951(90)90420-D.

Kamau, M., Hecker, C., & Lievens, C. (2020, February). Use of short-wave infrared reflectance (SWIR) spectroscopy to characterize hydrothermal alteration minerals in Olkaria geothermal system, Kenya. In *45th Workshop on Geothermal Reservoir Engineering 2020*.

Olivar, M.V.M., Fernandez, L.C.D., Cruz, H.D., Isip, H.L., Tilos, R.E., & Rosario del, E.P. (2010). *Resource Characterization, Reserves Estimation and Development Scheme of Maibarara Geothermal Field, Philippines*. PetroGreen Energy Corporation & Maibarara Geothermal Incorporated Internal Report (pp. 1-9).

Reyes, A. G. (1990). Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment. *Journal of Volcanology and geothermal research*, *43*(1-4), 279-309.

Savitri, K. P., Hecker, C., van der Meer, F. D., Sidik, R. P., Baroek, M. C., & Azis, H. (2021, October). Infrared Spectral Mineralogy for Geothermal Exploration: a Preliminary Study Using Cutting Edge Technology Infrared Imaging Spectroscopy (IRIS). In *World Geothermal Congress 2020+ 1*.

Savitri, K. P. (2024). Spectral Analysis for geothermal exploration: A method investigation to bring the technology closer to geothermal community.

Simpson, M. P. (2015, August). Reflectance spectrometry (SWIR) of alteration minerals surrounding the Favona epithermal vein, Waihi vein system, Hauraki Goldfield. In *Proceedings of the AusIMM New Zealand Branch Annual Conference, Dunedin, New Zeeland* (pp. 490-499).

Yang, K., Huntington, J. F., Browne, P. R., & Ma, C. (2000). An infrared spectral reflectance study of hydrothermal alteration minerals from the Te Mihi sector of the Wairakei geothermal system, New Zealand. *Geothermics*, *29*(3), 377-392.