Cased-hole Gamma Ray Log Assessment and Application to Support Reservoir Characterization at Salak Field in Indonesia

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Abstract. Gamma Ray (GR) logging is a common wireline activity conducted in the oil & gas industry to identify sand and shale bodies. In the geothermal industry, studies have shown that the GR count has a close correlation with the silica content of rocks. Generally, rocks with high silica content (i.e., felsic) will have relatively higher GR count than rocks with low silica content (i.e., mafic). In the reservoir section of geothermal field, very few (to almost none) rocks cuttings are obtained because mud loss normally occurred. Therefore, another dataset is required to identify lithologies/formations and GR log is one of the continuous datasets in the reservoir hole section that may help to solve this problem. At Salak, open-hole GR logs have been obtained during well completion, but these are few compared to the hundreds of wells drilled. In 2017, the GR tool was included in the bottom-hole assembly (BHA) of wireline surveys at Salak, such as Pressure-Temperature (PT) and Pressure-Temperature-Spinner (PTS) and thus, providing an opportunity to collect infill cased-hole GR data. Evaluation of the cased-hole GR logs indicated good quality and correlation with open-hole GR logs and used to support lithology/formation interpretation, especially for the Rhyodacite Marker (RDM) and Marine Sediments and Volcaniclastic (MSV) Formations as both the formations have distinct GR response compared to other formations at Salak.

1. Introduction
The Salak (also known as Awibengkok) Geothermal Field is located 70 km south of Jakarta, the capital of Indonesia (Figure 1). This geothermal field is the largest producing geothermal field in Indonesia with a current total installed capacity of 377 MWe from six power plants: 180 MWe from PLN (Indonesian Electricity Company) Units-1, 2 & 3, and 197 MWe from the Star Energy Geothermal Salak Units 4, 5 & 6 [1]. Typical geothermal fields in Indonesia, the Salak Geothermal Field is located in the mountains that are part of the Taman Nasional Gunung Halimun-Salak with elevations varying between 950-1,500 m above sea level (a.s.l.). The highest peaks are the inactive andesitic volcanoes of Gunung Salak, Gagak, Perbakti, and Endut that lie along with the primary trend of the Sunda Volcanic Arc. These peaks border the geothermal field in the east, northwest, southeast, and south, respectively, and give way to lower hilly country in the north and south (at 600-950 m a.s.l.). The Cianten Caldera, a collapsed andesitic stratocone, lies further to the west with a floor at ~850-950 m a.s.l. The commercial geothermal resource is spatially associated with the andesitic-to-rhyolitic volcanism that has occurred over the past 330 ka,
especially silicic volcanic that were erupted in the last 280 ka along with a major NNE-trending structure [2]. In most geothermal fields, very few (or no) rock cuttings are obtained in the reservoir section. This is a common phenomenon because mud circulation is lost while drilling the reservoir hole section. Cutting conventional or sidewall cores in the reservoir section is time-consuming, expensive, and risky; thus, drillers tend to focus on quickly completing the well to the target depth and forego information gathering. An alternative way to gather reservoir lithology information is through wireline logging, e.g., resistivity imaging and GR logging.

The GR tool/log is one of the more continuous datasets run in the reservoir hole section and may help in the identification of lithology or formation. At Salak, the borehole image and GR logs have been used to identify rock types while calibrating the logs with actual physical core samples. Unfortunately, open-hole GR data (taken during borehole image logging) is very minimal at Salak (<20% of total wells); hence, infill cased-hole GR data was considered to allow interpolation between wells. In 2017, the GR tool was included in the BHA of the PT and PTS surveys at Salak, and this provided the opportunity to collect infill reservoir data. This evaluation was conducted to assess the quality and utilization of cased-hole GR, especially in supporting formation interpretation. As an analog, a similar assessment was conducted in a geothermal field in the Philippines, and the results showed that silica-rich rocks are identifiable in both the open- and cased-hole GR data Guevarra-Segura, pers. comm.

![Map of West Java showing major cities and volcanic centers, which also shows the location of the Salak geothermal field with other geothermal fields in West Java [3].](image)

2. Subsurface Geology of Salak Geothermal Field
The subsurface rocks at Salak Field are composed of andesitic, basaltic lava, breccia, tuff, and lahar that comprise several long-lived volcanic centers underlying the south-western margin of Gunung Salak [2, 4, 5] divided the subsurface rocks at Salak into four major formations that are thought to represent discrete episodes in the evolution of the western Java segment of the Sunda Volcanic Arc. The “formation” terminology here is used to refer to distinctive time-bounded rock sequences that have not been formally correlated with documented formations on a regional basis. The four major formations,
from oldest to youngest, are the (1) Lower Volcanic Formation that consists of Continuous Sediments, Mixed Volcanics-Sediments (MVS), and Lower Andesite; (2) Rhyodacite Marker or RDM; (3) Middle Volcanic Formation; and (4) Upper Volcanic Formation. Both the Middle and Upper Volcanic Formations consist of a series of dacitic (at their base) and andesitic rocks overlying each other. According to [2], the recent deepest well discerned that MVS is present deep in Salak and no full Continuous Sediments observed. Furthermore, this new interpretation suggests that separating the sedimentary rocks into the Mixed Volcanics-Sediment (MVS) and Continuous Sediments (CS) is impractical. Thus, MVS and the carbonate-rich CS combined and renamed as Marine Sediments and Volcaniclastic or MSV. Besides, multiple intrusions are spread all over Awibengkok geothermal field. (Figure 2) discerns Awibengkok stratigraphy section.

Figure 2. The Awibengkok subsurface stratigraphic section modified from [2].

3. Dataset
The cased-hole GR dataset used in this paper was obtained during 2017-2018. 55 surveys were consisting of shut-in PT and flowing and injecting PTS conducted in 39 wells. Ten (10) of 39 wells have open-hole GR that can be used for comparison.

4. Cased-hole GR Assessment
Prior to using the cased-hole GR data for infill interpretation, an assessment of its quality was conducted. After the field data was obtained, the cased-hole GR data trend or pattern was evaluated as part of the QA/QC process. Two comparisons were made, namely, (1) log up (LU) vs. log down (LD) trend comparison in a particular survey and (2) GR data trend comparison in different surveys (i.e., survey type and/or date). Log down (LD) means that GR-count was recorded during the tool run inside the borehole from the surface to the bottom, while Log up (LU) means that GR-count was recorded during the tool was pulled-up from bottom to the surface. Cased-hole GR data was classified with good quality
if both comparisons show consistent trends, especially if cased-hole GR has a similar pattern with open-hole GR (if available). Only good quality cased-hole GR data were used for further interpretation.

As mentioned earlier, a cased-hole GR assessment was conducted on the 39 wells surveyed during the 2017-2018 logging campaign. The QA/QC process indicated that 36 wells have good quality; three wells had suspicious or anomalous data (Figure 3). From the 36 wells with good quality GR data, 11 had minor inconsistencies, for example:

- similar LD and LU GR patterns but different GR counts;
- different LD and LU GR patterns at shallow depth; and
- LD and LU GR patterns are similar in a survey in the same well, but discrepancy appears when compared with different survey activity/date and wellbore condition (shut-in, injection, or flowing) during the survey.

Multiple surveys could be runs in one wells (in different survey activity/date); hence, the additional data helped in identifying the preferred pattern of cased-hole GR data that was used. Cased-hole GR data is categorized as suspicious or anomalous (and unsuitable to use for interpretation) if the well has either a single cased-hole GR data with inconsistent LU and LD patterns or significant discrepancies appear between the cased- and open-hole GR data. In this case, additional cased-hole GR data is required to confirm the GR trend. The figures below show examples of good quality, inconsistent, and suspicious cased-hole GR data (Figure 4).
5. Cased-hole GR Application to Support Reservoir Characterization

Previous studies indicate that natural GR in geothermal reservoirs have a good correlation with the silica (SiO$_2$) content of the rock. For instance [6] analyzed about 250 rock samples from Iceland and observed that SiO$_2$ concentration is shown to be linearly related to gamma-ray intensity, notably, K, Th, and U contents. In addition, [7] mentioned that the radioactive content (Th, U, and K) is higher in acid/felsic to basic/mafic igneous rock.

In Salak Field, [8] mentioned that the Rhyodacite Marker (RDM) and Marine Sediments and Volcaniclastics (MSV) Formations have high GR response that is discernible in the open-hole GR. The RDM Formation has the highest GR count compared to other formations in the Salak reservoir because it is mainly composed of rhyolitic/rhyodacitic tuff (i.e., high SiO$_2$). Moreover, spectral GR data analysis identified that both U and Th are high in the RDM [9]. Unlike the RDM, GR count in the MSV is relatively high, but it has a wider range because the MSV consists of a mix of volcanic and sediments.
It is believed that the sediment (i.e., shale) content in the MSV is a significant contributor to the high GR content of this formation. Since both RDM and MSV Formations have contacts with relatively low-GR count andesitic rocks (i.e., Lower Andesite and Middle Andesite in Figure 2), the increase in GR count is a good indicator of these formations.

From the 2017-2018 cased-hole GR data, nine (9) of 10 cased-hole GR logs have similar trends with open-hole GR logs. Figure 5 (left column) shows the similarity of the cased- and open-hole GR patterns at AWI 15-3RD1. As seen in this figure, both the RDM and MSV Formations have relatively high GR count; the RDM has two GR spikes at its top and near its bottom. The tops of the RDM and MSV interpretation was confirmed by petrographic analysis, where rhyolitic tuff and limestone were identified as markers for the tops of the RDM and MSV, respectively. By using the cased-hole GR data, the bottom of the RDM (or top of the LA) can also be adequately determined in this well.

Another application of the cased-hole GR data is to confirm previous interpretations, such as in AWI 10-4ST1 (right column in Figure 5). Previously, rocks encountered by this well were interpreted using megascopic description and thin section petrography of rock cuttings only. Additionally, this well encountered total loss circulation (TLC) below 3,000 ftMD (measured depth in feet), although mud circulation and rock cuttings were regained at 4,200 ftMD. Consequently, the RDM interval in this well became uncertain. The cased-hole GR data-enabled was accurately identifying the RDM interval at 4,150-4,950 ftMD.
The cased-hole GR data was also utilized to evaluate the contact between the Upper Andesite (UA) and Middle Andesite (MA). The left column in Figure 6 shows that the Middle Dacite (MD) separates the UA and MA. Because MD is not continuously distributed field-wide, the boundary between the UA and MA is difficult to be determined especially in the western portion of the field (right column in Figure 6).

![Figure 6. AWI 1-9OH and 10-1OH composite log consist of depth, open & cased-hole GR, petrography analysis, interpreted lithology, and formation. The left column shows that the MD separates the UA and MA. The boundary between the UA and MA is unknown if MD is not present (right column); this is especially true in west Salak as the MD pinches out in this portion of the field.](image)

A method to identify the contact between the UA and MA was examined by using their cased-hole GR trends (Figure 7). To normalize the comparison, the depth in the y-axis starts from the top of the UA and MA and not necessarily the depths where the UA and MA were encountered. Figure 7 shows that both UA and MA have similar GR trends: the GR count of the bottom of the UA is almost identical to the top of the MA. Thus, it is difficult to separate them by only looking at their GR trends.
Figure 7. GR count chart at AWI 1-9OH and 16-4OH. The GR count and trends of both the UA (light green line) and MA (dark green line) are similar. Using just the average GR count of the UA and MA is also inappropriate because of inconsistency, i.e., the average GR count of the MA is higher than the UA in AWI1-9OH while the GR count in the UA is higher than the MA in AWI16-4OH.

As the use of the GR trend was inconclusive, the next evaluation focused on the GR magnitude (i.e., range and average GR count) of the UA and MA. Unlike open-hole GR that uses API as GR unit, cased-hole GR unit use count per second (cps). The raw data indicates that the GR count (cps) varies widely between wells, and even in the same well with different logging surveys and well conditions. Therefore, this evaluation was conducted in a single well basis and logging survey.

Table 1 shows the range and average GR count (cps) for the UA and MA. Inconsistency was observed in the average GR count with some wells showing higher GR count in the UA than the MA and vice versa. In terms of magnitude, the average GR count is similar between the UA and MA. Interestingly, the range of the GR count is higher in the MA than the UA. This observation may provide hints in distinguishing between the UA and MA in the area where the MD is absent, but it does not assist in determining the contact between the UA and MA.

Table 1. Range and average GR count of the UA and MA units.

| Well Name   | GR Count Range of UA & (average) | GR Count Range of MA & (average) |
|-------------|-----------------------------------|-----------------------------------|
| AWI1-9OH    | 0.00 – 9.53 (3.20)                | 0.00 – 13.28 (3.97)*              |
| AWI21-4OH   | 0.14 – 8.55 (3.72)                | 2.37 – 8.96 (5.21)*              |
| AWI3-3ST1   | 0.00 – 26.00 (8.95)               | 0.00 – 28.50 (10.81)*            |
| AWI7-7OH    | 1.90 – 8.91 (4.20)                | 0.00 – 17.74 (4.37)*             |
| AWI7-8RD1   | 1.00 – 7.00 (3.43)                | 0.00 – 13.00 (5.65)*             |
| AWI16-4OH   | 0.46 – 9.78 (4.56)**              | 0.30 – 13.89 (4.55)              |
| AWI8-1OH    | 1.65 – 10.99 (5.28)**             | 1.01 – 21.86 (4.79)              |
| AWI8-3OH    | 0.00 – 6.59 (2.65)**              | 0.00 – 8.56 (2.18)               |
| AWI8-4OH    | 0.80 – 11.07 (3.61)**             | 0.00 – 10.97 (2.73)              |
| AWI8-6OH    | 0.00 – 9.73 (3.56)**              | 0.00 – 12.68 (2.51)              |

* The average GR count of the MA is higher than the UA.
** The average GR count of the UA is higher than the MA.
6. Conclusion

The detailed assessment of the 2017-2018 cased-hole GR logs indicates that 92% of the cased-hole GR data has good quality, with 90% of the cased-hole GR having similar patterns with the open-hole GR. Minor GR pattern inconsistency that appears at the shallow depths is apparently due to the weak signal between the formation and the GR tool. Big hole and cemented casing at the shallow depth may cause this weak signal. The cased-hole GR pattern was used to compare between wells and not the GR count because cased-hole GR count or magnitude is not comparable between wells due to large different range of GR count. This difference even appears in the same well with different logging surveys. Lastly, wellbore condition (i.e., flowing, injecting, and after work-over) during the survey appears to influence the GR log signal; thus, this needs to be examined.

Cased-hole GR data can be utilized to interpret subsurface lithology or formation, especially if any distinct differences are present, e.g., rhyolitic (or high-silica content) rocks in a series of andesitic rock, or vice versa. In Salak, cased-hole GR was utilized to determine the RDM and MSV Formations. The tops of the RDM and MSV Formations are important because the RDM has proven to be the best stratigraphic marker at Salak as it extensively covered the greater Salak area [2] and most of the deep feed zones in the south-western Salak are found in the MSV. Furthermore, some feed zones appear to be related to the contact between the MSV and the overlying Lower Andesite [10].

Initial observations suggest that the cased-hole GR may support the difference between the UA and MA in areas where the MD is absent. However, the application of cased-hole GR to determine the boundary of UA and MA is still inconclusive because no distinct GR trends were observed, and both formations have similar average GR count.

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References

[1] Golla G U, Julinawati T, Putri R P, Nordquist G A and Libert F R 2000 The Salak Field Indonesia: On to the next 20 years of production Geothermics 83 Article 101715

[2] Stimac J, Nordquist G, Suminar A and Azwar L S 2008 An Overview of the Awibengkok Geothermal System Indonesia Geothermics 37 300-331.

[3] Aprilina N V, Putra F J, Wicaksono S, Julinawati T, Tanuwidjaja R and Hernawan A 2017 Results of I-I Deep Well: Impact on the Conceptual Model of the Salak Geothermal System. Proc., The 5th Indonesia Int., Geothermal Convention & Exhibition (Cendrawasih Hall - Jakarta Convention Center Indonesia)

[4] Hulen J and Lutz S 1999 Alteration mineralogy and zoning in Corehole AWI 1-2, Awibengkok Geothermal Field, West Java, Indonesia Geothermal Resources Council Transactions 23, 19–23

[5] Stimac J A and Sugiaman F 2000 The AWI 1-2 Core Research Program Part I: Geologic overview of the Awibengkok Geothermal Field, Indonesia Proc., World Geothermal Congress (Kyushu-Tohoku, Japan)

[6] Stefánsson V, Gudlaugsson ST and Gudmundsson A 2000 Silica Content and Gamma Ray Logs in Volcanic Rocks Proc., World Geothermal Congress 2000 (Kyushu-Tohoku, Japan)

[7] Serra O 2008 The Well Logging Handbook. Paris: Edition Technips 569 pages.

[8] Pamurty P N, Satya D Y and Golla G U 2015 Identifying Reservoir Rocks Using Drilling Data. Unpublished Star Energy Report 34 pages.

[9] Satya D Y, Stimac J and Golla G U 2017 Evaluation of AWI 9-9OH Conventional and Spectral Gamma Ray Logs Proc., The 5th Indonesia Int., Geothermal Convention & Exhibition (Cendrawasih Hall - Jakarta Convention Center Indonesia)

[10] Wicaksono S, Aprilina N V, Tanuwidjaja R, Putra F J, Julinawati T, Hernawan A and Mubarok Z 2016 Southwest Salak Evaluation, Unpublished Star Energy Report 46 pages.