Temperature Dependent Minerals as a Tool to Prove High Temperature of a Blind Geothermal System. Case Study: Well “X” at Java Island of Indonesia

Darren A. Utomo1, Rizal Abiyudo2, Isto J. Saputra1, Riki Irfan1 and Dalmathias Archady3

1PT Medco Cahaya Geothermal, Jakarta, Indonesia
2PT Medco Power Indonesia, Jakarta, Indonesia
3PT Ormat Geothermal Indonesia, Jakarta, Indonesia
The Energy Building, 7th Floor, SCBD Lot 11A

Email: darren.adrinanto17@gmail.com
https://orcid.org/0000-0002-7071-3749

Abstract. Geology and mineral alteration are studied to review the equilibrium of blind geothermal system in Java Island, Indonesia. The “X” well is a slim hole well that has been drilled to 2000 mMD. Indication of high-temperature geothermal system is observed by pressure-temperature survey and mineral alteration recovered by full core from surface to bottom (2000 mMD). Geologically, this geothermal prospect is situated on a caldera system with the volcanism started since the Lower Pleistocene related to the early stages of magmatic activity of the modern Sunda arc. Multiple eruptions associated with the pre-caldera, syn-caldera, and post-caldera volcanism deployed rock formation which are consisted of andesitic lava series, volcanic breccia, and pyroclastic. Based on the study of mineral alteration, three hydrothermal alteration zones are defined from temperature-dependent minerals to predict reservoir temperatures, smectite zone (T<180°C) from the surface down to 1200 mMD, transition zone (T = 180-220°C) down to 1383 mMD, and illite zone (T>220°C) down to 2000 mMD. Moreover, the hydrothermal alteration zone is mainly used to estimate the depth of clay cap, transition, and reservoir zone for a future appraisal well. Correlating the temperatures and hydrothermal alteration zones could help in proving a high-temperature geothermal system especially in a blind geothermal system.

1. Introduction

The “X” well is located in caldera complex, geographically located in Java Island in Indonesia. The area is really challenging due to the absence of surface manifestations in the prospect area. One of the challenges in this field is that it is a blind geothermal system which means there is no thermal manifestation in the system [1]. The only surface manifestation is indicated by acidic fumarole located in a crater, about 9 km east from “X” well and neutral spring in the north, about 9 km north from “X”. The crater itself is possibly the upflow of the system whilst the outflow is located in the northern part of the caldera [2]. However, it is very risky to explore, drill, and to produce geothermal steam due to high corrosion issues and volcanic hazards. On the other hand, there is a possibility that there are two hydrothermal systems [2] in the area based on the MT data, the eastern crater which has an acidic
system and the center part of the caldera which is possible to have a neutral system. The use of slim hole for exploration is to get sufficient data such as geology and geochemical data.

Based on the location itself, the caldera is associated with caldera which used to be a massive stratovolcano that exploded around hundred thousand years ago [3]. From the collapsed stratovolcano, the fault created from the collapse creates another eruption around the caldera. It is shown that most of the younger eruptions are located in the southern part of the caldera, from there, it can be referred that the southern [4] part of the caldera has a crustal weakness zone.

The decision to drill the “X” well is also based on the structures which are seen by the lineaments seen through remote sensing. The lineaments in the caldera show that there is a high intensity of lineaments in the southern part of the caldera. The structure shows that the high intensity of lineaments has a range from west to east. From the lineaments, it can be referred that the fault zone interpreted from regional setting has the same pattern to the lineaments itself, in which both regional setting and lineament analysis have west to the east fault zone.

2. Geology

2.1. Stratigraphy

Based on Figure. 1, The research area is a caldera that consists of pre-caldera, syn-caldera and post-caldera groups [4]. The pre-caldera group consists of The Old Volcano (OV) and the syn-caldera group consists of the Old Volcano (OV) Ignimbrites. The Old Volcano (OV) was a massive stratovolcano consist of lava flows with altitude approximately 3500 meters about sea level. The Old Volcano (OV) collapsed and formed a caldera with ignimbrites above the formation.

After the collapse, the post-caldera group was formed which consist of older and younger formations. The older post-caldera group mostly located in the southern and western parts of the caldera. The older post-caldera groups consist of A1, A2, B1, B2, C1, C2, D, and E formations, with rock formations mostly consist of andesitic lava flows and pyroclastics [3]. The younger post-caldera group is mostly located in the center part of the caldera. The younger post-caldera groups consist of CC, LS, F1, F2, QVC, G, and H formations, with rock formations mostly consist of young andesitic lava flows and pyroclastics with lake sediments in the northern part of the caldera.

The pre-caldera, syn-caldera, and post-caldera have an unconformity relation, meanwhile, in the post-caldera groups, each of the older post-caldera group or younger post-caldera group are interfingering between formations [5]
2.2. Structures

The structures and permeability in the research area were interpreted from remote sensing studies, tectonic studies, and field mapping. Based on the tectonic studies of Java, the volcanic mountains in Java were formed due to the subduction between Indo-Australian and Eurasian Plate [6], which could lead to a NW-SE or NE-SW strike-slip faults with W-E magmatic axis.

Remote sensing studies of the area shows that the distribution of the lineaments has various direction but mostly extends from N-S, NNW-SSE, and W-E. These faults range in the center part and the southern part of the caldera, cutting through the post-caldera formations in the center and the southern part of it.

The hypothesis is that the sequence of the structure and volcanic formation starts from the tectonic activities which created the NW-SE or NE-SW fractures and created the major volcanoes from B1 mountain to C2 mountain. The NW-SE or NE-SW structures created minor structures that extend from [7]. The recent formation of the structures and volcanic activities is the cinder cones formation and NNW-SSE fault in the north of caldera.
3. Methodology

3.1. Slim Hole (Full Core)

The slim hole drilling Figure 2 is a small diameter hole drilling with diameter 9-5/8”, 7”, 4.5”, 3.5”, and 2-3/4” casing which is used to obtain certain data such as full core, pressure and temperature data. The slim hole drilling costs lower than the conventional big hole drilling. The use of slim hole drilling in this area is used to obtain the lithology of the rock formation, to determine the alteration minerals, the temperature, the pressure and the losses within the well [8]. Due to the blind system geothermal in the area, the use of slim hole drilling is very useful to determine the subsurface temperature and key minerals in geothermal exploration. The full core data obtained from the slim hole drilling is a key data for the next exploration phase. In this well, the total depth of the drilling reaches 2000 mMD.

Core data indicates that the lithology of the well consists of volcanic breccias on depth 2000 – 1475 mMD, volcaniclastic on depth 1475 – 1000 mMD and series of lava flow on depth 1000 mMD - surface. From the core data, the alteration minerals are analyzed with megascopic, petrographic, and X-Ray Diffraction analysis. X-Ray Diffraction (XRD) analysis is a non-destructive test method used to analyze the structure of crystalline materials. XRD analysis, by way of the study of the crystal structure, is used to identify the crystalline phases present in a material and thereby reveal chemical composition information. Petrographic and XRD analysis are used for detailed analysis to determine the temperature using temperature dependent minerals [9, 10]

![Figure 2. Slim Hole Casing Configuration.](image-url)
3.2. **Temperature Dependent Minerals**

Temperature dependent minerals are commonly associated minerals (Figure 3) which indicates the temperature of the minerals when it is formed in the hydrothermal system [9, 10]. In this well, temperature dependent minerals are used as an estimation temperature of the geothermal system due to the absence of thermal manifestation in the surface. The commonly associated minerals have a formation temperature range, this range is combined from several minerals in each depth to determine the overlapping temperature. The overlapping temperature of different minerals indicates the temperature range of the depth.

![Figure 3. Temperature Dependent Minerals [9].](image)

### Table 1. Commonly Associated Minerals

| Alteration Zones | Sub-Zones | Commonly Associated Minerals |
|------------------|-----------|-----------------------------|
| S.G.             | Smectite  |
|                 | Illite    |
|                 | Biotite   |
|                 | Epidote   |
|                 | Amorphite |

4. **Methodology**

4.1. **Laboratory Analysis and Alteration Zone**

The laboratory analysis was used to determine the details of the minerals are petrography and XRD. These samples were taken from the interesting depths of the core which shows key minerals based on the megascopical analysis [10]. The use of petrography is to determine the clay and other non-clay minerals. On the other hand, the use of XRD is to determine the details of the clay minerals such as smectite, illite, chlorite or interlayered clay.
Table 1. Depth of the Samples Used for Lab. Analysis.

| No | Depth       | Lab. Analysis | Petrography | XRD |
|----|-------------|---------------|-------------|-----|
| 1  | 250.84 mMD  | V             | V           | -   |
| 2  | 1002 mMD    | V             | V           |     |
| 3  | 1419 mMD    | V             | V           |     |
| 4  | 1788.44 mMD | V             | V           |     |
| 5  | 1995 mMD    | V             | -           |     |

4.1.1. Smectite Zone. Smectite alteration zone is defined by smectite as a key mineral. Based megascopic analysis on core data in this well, the presence of smectite ranged from 60 – 1383 mMD and the presence of chlorite ranged from 63 – 2000 mMD, but there is a presence of illite starts from 1200 mMD which indicates different alteration zone. From petrographic analysis on depth 250.84 and 1002 mMD (Figure 4), as well as the XRD analysis on depth 1002 mMD shows the presence of Clay mineral. To determine the details of the clay minerals, XRD analysis is used to analyze the details of clay minerals whether it is smectite, illite, chlorite, or mixed clay. XRD analysis in depth 1002 mMD in Figure 5 shows a curve that indicates a mixed layer between chlorite and smectite. Therefore, from the megascopic, petrographic and XRD analysis, the presence of smectite indicates in depth range from 60 – 1200 mMD is smectite alteration zone.

![Figure 4. Petrographic Analysis on Depth 250.84 mMD.](image)

![Figure 5. XRD Analysis on Depth 1002 mMD.](image)
4.1.2. Transition Zone. Transition alteration zone is defined by interlayered clay between illite and smectite as a key mineral. Based on megascopscopic analysis on core data in this well, the presence of smectite ranged from 60 – 1383 mMD and the presence of illite ranged from 1200 – 1613 mMD. The interlayered depth between smectite and illite is from 1200 – 1383 mMD. The megascopscopic analysis used in depth 1419 (Figure 7) to determine the clay minerals, the results are that on depth 1419 is only indicated by illite but there is no presence of smectite. Therefore, from the megascopscopic, petrographic and XRD analysis, the presence of interlayered clay between illite and smectite without illite only alteration minerals indicate in depth range from 1200 – 1383 mMD is a transition alteration zone.

4.1.3. Illite Zone. Illite alteration zone is defined by illite and as a key minerals and epidote as associated minerals. Based on megascopscopic analysis on core data in this well, the presence of illite ranged from 1200 – 1613 mMD but there is an interlayered with smectite from 1200 – 1383 mMD and the presence of. From petrographic analysis (Figure 6) and XRD analysis on depth 1419 mMD clay mineral. To determine the details of the clay minerals, XRD analysis is used to analyze the details of clay minerals whether it is smectite, illite, chlorite, or mixed clay. XRD analysis in depth 1419 mMD (Figure 7) shows a curve that indicates illite. Therefore, from the megascopscopic, petrographic and XRD analysis, the presence of illite without interlayered clay between illite and smectite indicates in depth range from 1383 – 2000 mMD is an illite alteration zone.

![Figure 6. Petrographic Analysis on Depth 1419 mMD.](image)
4.1.4. Epidote Sub-Zone. Epidote alteration sub-zone is defined by epidote as a key mineral and chlorite as an associated mineral. Based on megascopic analysis on core data in this well, the presence of epidote ranged from 1785 – 2000 mMD and chlorite ranged from 63 – 2000 mMD. From petrographic analysis on depth 1788.44 (Figure 8) and 1995 mMD (Figure 9) shows the presence of epidote and chlorite. Therefore, from the megascopic and petrographic, the presence of epidote and chlorite in depth range from 1788 – 2000 mMD is an epidote alteration sub-zone.

**Figure 7.** XRD Analysis on Depth 1419 mMD.

![Figure 7. XRD Analysis on Depth 1419 mMD.](image)

**Figure 8.** Petrographic Analysis on Depth 1995 mMD.

![Figure 8. Petrographic Analysis on Depth 1995 mMD.](image)

**Figure 9.** Petrographic Analysis on Depth 1788.44 mMD.

![Figure 9. Petrographic Analysis on Depth 1788.44 mMD.](image)
4.2. Temperature

After the laboratory analysis, the presence of the key minerals in each depth is used to determine the temperature of the depth itself by using the temperature dependent minerals method.

4.2.1. Depth Interval 250 – 300 mMD. In this depth interval (Figure 10), the existing minerals based on megascopic and petrographic analysis are smectite with temperature ranged from 20 – 180°C, pyrite with temperature ranged from 20 – 340°C, chlorite with temperature ranged from 120 – 340°C, and calcite with temperature ranged from 20 – 330°C. Therefore, the overlapping temperature means that the temperature in this depth interval based on the temperature dependent minerals is 120 – 180°C. Pressure-temperature survey on this depth interval shows the temperature ranged from 28 – 70°C. The in-equilibrium result is caused by the presence of chlorite with temperature ranged from 120 – 340°C.

![Figure 10. Temperature Dependent Minerals on Depth Interval 250 – 300 mMD (Brown-Coloured Table) and Mineral Formation Temperature (Blue-Coloured Table, Green-Coloured Table as Maximum Temperature Range).](image)

4.2.2. Depth Interval 975 – 1025 mMD. In this depth interval (Figure 11), the existing minerals based on megascopic, petrographic and XRD analysis are Smectite with temperature ranged from 20 – 180°C, Pyrite with temperature ranged from 20 – 340°C, Chlorite with temperature ranged from 120 – 340°C, and Calcite with temperature ranged from 20 – 330°C. Therefore, the overlapping temperature means that the temperature in this depth interval based on the temperature dependent minerals is 120 – 180°C. Pressure-temperature survey on this depth interval shows the temperature ranged from 138 – 170°C. On this depth interval, the result of temperature dependent minerals and pressure-temperature survey (P-T Survey) shows the equilibrium between temperatures.

![Figure 11. Temperature Dependent Minerals Depth Interval 975 – 1025 mMD (Brown-Coloured Table) and Mineral Formation Temperature (Blue-Coloured Table, Green-Coloured Table as Maximum Temperature Range).](image)

4.2.3. Depth Interval 1200 – 1250 mMD. In this depth interval (Figure 12), the existing minerals based on megascopic, petrographic and XRD analysis are Smectite-Illite with temperature ranged from 180 – 220°C, Pyrite with temperature ranged from 20 – 340°C, Chlorite with temperature ranged from 120 – 340°C, and Calcite with temperature ranged from 20 – 330°C. Therefore, the overlapping temperature means that the temperature in this depth interval based on the temperature dependent minerals is 180 – 220°C. Pressure-temperature survey on this depth interval shows the temperature
ranged from 188 – 211°C. On this depth interval, the result of temperature dependent minerals and pressure-temperature survey temperature shows the equilibrium between temperatures.

4.2.4. Depth Interval 1400 – 1450 mMD. In this depth interval (Figure 13), the existing minerals based on megascopic, petrographic and XRD analysis are Illite with temperature ranged from 220 – 330°C, Pyrite with temperature ranged from 20 – 340°C, Chlorite with temperature ranged from 120 – 340°C, Calcite with temperature ranged from 20 – 330°C and Epidote with temperature ranged from 220 – 340°C. Therefore, the overlapping temperature means that the temperature in this depth interval based on the temperature dependent minerals is 220 – 330°C. Pressure-temperature survey on this depth interval shows the temperature ranged from 227 – 228°C. On this depth interval, the result of temperature dependent minerals and pressure-temperature survey temperature shows the equilibrium between temperatures.

4.2.5. Depth Interval 1950 – 2000 mMD. In this depth interval (Figure 14), the existing minerals based on megascopic, petrographic and XRD analysis are Chlorite with temperature ranged from 120 – 340°C and Epidote with temperature ranged from 220 – 340°C. Therefore, the overlapping temperature means that the temperature in this depth interval based on the temperature dependent minerals is 220 – 340°C. Pressure-temperature survey on this depth interval shows the temperature ranged from 283 – 267°C. On this depth interval, the result of temperature dependent minerals and pressure-temperature survey temperature shows the equilibrium between temperatures.

| Associated Minerals | Temperature (degC) |
|---------------------|--------------------|
|                     | 0 - 50 | 50 - 100 | 100 - 150 | 150 - 200 | 200 - 250 | 250 - 300 | 300 - 350 |
| Smectite-Illite     |        |         |          |          |          |          |          |
| Pyrite              |        |         |          |          |          |          |          |
| Chlorite            |        |         |          |          |          |          |          |
| Calcite             |        |         |          |          |          |          |          |
| Temp. Dependent     |        |         |          |          |          |          |          |

**Figure 12.** Temperature Dependent Minerals Depth Interval 1200 – 1250 mMD (Brown-Coloured Table) and Mineral Formation Temperature (Blue-Coloured Table, Green-Coloured Table as Maximum Temperature Range).

| Associated Minerals | Temperature (degC) |
|---------------------|--------------------|
|                     | 0 - 50 | 50 - 100 | 100 - 150 | 150 - 200 | 200 - 250 | 250 - 300 | 300 - 350 |
| Illite              |        |         |          |          |          |          |          |
| Pyrite              |        |         |          |          |          |          |          |
| Chlorite            |        |         |          |          |          |          |          |
| Calcite             |        |         |          |          |          |          |          |
| Epidote             |        |         |          |          |          |          |          |
| Temp. Dependent     |        |         |          |          |          |          |          |

**Figure 13.** Temperature Dependent Minerals Depth Interval 1400 – 1450 mMD (Brown-Coloured Table) and Mineral Formation Temperature (Blue-Coloured Table, Green-Coloured Table as Maximum Temperature Range).

| Associated Minerals | Temperature (degC) |
|---------------------|--------------------|
|                     | 0 - 50 | 50 - 100 | 100 - 150 | 150 - 200 | 200 - 250 | 250 - 300 | 300 - 350 |
| Chlorite            |        |         |          |          |          |          |          |
| Calcite             |        |         |          |          |          |          |          |
| Epidote             |        |         |          |          |          |          |          |
| Temp. Dependent     |        |         |          |          |          |          |          |

**Figure 14.** Temperature Dependent Minerals Depth Interval 1950 – 2000 mMD (Brown-Coloured Table) and Mineral Formation Temperature (Blue-Coloured Table, Green-Coloured Table as Maximum Temperature Range).
4.3. Geothermal System

In this blind geothermal system, the absence of manifestation is a challenge to prove the geothermal system, thus the use of slim hole and temperature dependent minerals is a key to determine the geothermal system in the area [8, 11]. Based on the lithologies, alteration minerals, and temperature dependent minerals, the geothermal system in this area consist of clay cap, transitional zone, and reservoir. The clay cap zone ranged from the surface to 1383 mMD and consist of smectite and transition alteration zone. This zone is an impermeable zone due to the presence clay minerals such as smectite and chlorite. The temperature of clay cap ranged from 25 – 180°C based on smectite temperature range. The lithology of this zone mostly consists of andesitic lava series. The transition zone ranged from 1383 – 1600 mMD and consist of illite alteration zone. This zone is determined by illite where the temperature has a medium temperature and the first appearance of epidote which could lead to the top of the reservoir. The temperature of transitional zone ranged from 220 – 330°C based on illite temperature range. The lithology of this zone mostly consists of pyroclastics. The reservoir zone ranged from 1600 – 2000 mMD and possibly deeper, consist of epidote alteration sub-zone. This zone is determined by the presence of epidote as a key mineral of reservoir indication with temperature ranged from 220 – 340°C. The lithology of this zone mostly consists of volcanic breccias. With the presence of relic epidote on depth interval 936 – 998 mMD, this indicates that it was the older top of reservoir.
5. Conclusions
The results of the slim-hole full core can be used to analyze the rock formation by megascopic, petrographic, or XRD with the output to determine the geothermal system. The geothermal system in this area consists of clay cap, transition, and reservoir zone. The clay cap has an indication of smectite and illite mineral alteration presence with temperature ranged from 20 – 220°C with depth down to 1383 mMD. Transition zone has an indication of illite mineral alteration presence with temperature ranged from 220 – 330°C with depth down to 1600 mMD. Reservoir zone has an indication of epidote mineral alteration presence with temperature ranged from 240 – 340°C with depth down to 2000 mMD. The temperature based on temperature dependent minerals has a correlating result to temperature obtained by the pressure-temperature survey. In blind geothermal system, the slim-hole full core could determine the geothermal system and the full core data could be used as a basis for conceptual model and for future interpretation in the next exploration drilling campaign. The temperature dependent minerals method could be used as an estimation temperature of the geothermal system.

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