Fluid evolution of Umbul-Telomoyo Geothermal system

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Abstract. Umbul-Telomoyo is located in the Quarter of Telomoyo Mount, Central Java. The geothermal system in this region is formed by the residual heat coming from the magma chamber with associated with recent activity of Telomoyo Mount complex. The estimation of geothermal reserve is approximately 92 MWe which was feasible to further development. The surface manifestations consisting of the Candi Umbul hot spring (APCU), Pakis Dadu hot spring (APPD) and Candi Dukuh hot spring (APPD). Based on Cl-SO₄-HCO₃ diagram, it shows that APCD belongs to chloride-bicarbonate water, while APCU and APPD belongs to chloride water. All hot springs included to the immature water zone according to the Na-K-Mg diagram. The Cl-Li-B diagram described that this geothermal system consists of two different reservoirs in which this data was also supported by Magnetotellurik survey (MT). Temperature estimation of reservoir of Candi Dukuh is around 215-230°C and reservoir of Candi Umbul is around 235-250°C. Litology in CTL-1 and CTL-2 wells were generally dominated by products of Telomoyo volcanic, lava and pyroclastic rocks. Litology found in CTL-1 and CTL-2 wells has changed to range of intensity low and high. Minerals formed in CTL-1 and CTL-2 wells were generally clay minerals (smectite, kaolinite, chlorite, and illite), calcite, secondary quartz, anhydrite, and epidote, gypsum, siderite, hematite, zeolite and alunite, that altered primary minerals. This alteration rocks turned into a caprock in the Umbul-Telomoyo geothermal system.

1. Introduction
The geothermal field of Umbul-Telomoyo is located in Telomoyo Mount, one of Kuarter volcanoes in Central Java. In 1988, Pertamina conducted initial research toward this area by some studies such as geology, geochemistry and geophysics. Furthermore, in 1993, Pertamina drilled TSH-01 well with 502 meters in depth. The temperature gradient of well is 10 °C/100 meters. The lithology consists of tuff breccia, andesite breccia, andesite and tuff which had been experienced hydrothermal altered.

In 2010, Centre of Mineral, Coal and Geothermal Resources (PSDMBP) also carried out geology, geochemical and geophysical survey. The research provided an estimation of the Candi potential geothermal reserve in the Umbul-Telomoyo area around ± 92 MWe which was included in the potential of geothermal energy in an unexpected reserve class. On the other side, in 2016, PSMBP drilled the CTL-1 and CTL-2 well at 702.6 and 703.4 meters depth respectively. The lithologies of CTL-1 and CTL-2 were product of Telomoyo volcanic activity in which formed lava and pyroclastic rocks. It altered from weak to very strong intensity.
2. Regional Setting
This area was controlled by Quaternary volcano morphology which was divided into plains, volcanic cones and undulating hills. The stratigraphy of the research area consists of volcanic rocks such as lava and pyroclastic from Ungaran, Telomoyo, Andong and Merbabu products. There is a basement in the research area which consists of sedimentary rocks having tertiary age which underlie all volcanic products was deposited at Quaternary [2] (see Figure 1).

Western-southeast and southwest-northeast faults were the most common geology structure controlling this area. They lead to occur hot springs. These faults included:
- Three rims of the caldera impacted to subsidence that created the depression zone.
- Volcanic structure such SW-NE normal fault was formed by the activity of Telomoyo Mount. This structure also caused the discharge of manifestations of Candi Umbul and Pakis Dadu.
- The tectonic structures such as strike-slip faults were relatively N-S and NW-SE which was the regional structure and partly covered by younger rocks. Some of these structures were reactivated and influenced the occurrence of manifestations of Candi Dukuh [2].

3. Surface Manifestation
Manifestation of Umbul-Telomoyo occurred in this field as hot springs and altered rocks separated in different locations. The four manifestations included Candi Dukuh 1, Candi Dukuh 2, Candi Umbul and Pakis Dadu [2].

3.1. Hot Spring of Candi Dukuh 1 (APCD-1)
The temperature measured in this spring is at 34.9°C, while the air temperature is 24.9°C with 7.2 of pH, electrical conductivity around 621 umhos, and a debit of water 2 l/sec. The hot spring was relatively clear and fresh. Also, there were a boiled gas, sediment deposition that was collected in a pool and used by local people for bathing.

3.2. Hot Spring of Candi Dukuh 2 (APCD-2)
This manifestation is located about 100 meters from Candi Dukuh-1. The measurement of pH is about 7.2 with water temperature at 35.7°C, while air temperature 24.6°C, electrical conductivity 843 umhos and debit 2 l/sec. The hot spring was relatively clear, fresh. It was also found a gas bubble. Around this springs there were several parts of the sediment material.

3.3. Hot Spring of Candi Umbul (APCU)
This manifestation appeared from rock fracture and was accommodated in a pool for bathing. The physical characteristic of hot spring were clear, fresh, and colorless. There was also found boiled gas, but no sediment was found. The measurement of the hot spring parameters including water temperature of 35.6°C, air temperature 28.6°C, with pH 7.55, electrical conductivity 1842 umhos and discharge 4 l/sec.

3.4. Hot Spring of Pakis Dadu (APPD)
This hot spring was 500 m to the north of the Candi Umbul. The measurements showed that a hot spring temperature is 34.7°C at air temperature 25.9°C, with pH 6.47, electrical conductivity 1688 umhos and debit 1 l/sec. The physical characteristic of hot spring were clear, steamy, tasteless, and no sediment.
4. Data and Methodology

4.1 Data

All data used in this study were obtained from Centre of Mineral, Coal and Geothermal Resources (PSDMBP), including data on water chemistry data, geophysical data (magnetotelluric map), geological map, cores lithology and well temperature. There are two wells used in this research, namely CTL-1 well and CTL-2 well, with a depth of 700 meters.
4.2 Methodology
The method used in this research are description of megascopics and laboratory analysis. Laboratory analysis that has been conducted petrographic, and XRD analysis on several samples of rock samples at certain depths.

Megascopics analysis of rock core is used to identify the type of rock contained in CTL-1 and CTL-2 wells. In addition, to determine the intensity of alteration and identify the mineral alteration and mineral vein that appears and abundance. Parameters such as rock color, structure, texture, and mineral composition and the relationship between alteration minerals in surrounding rocks are also observed.

Petrographic analysis was performed to confirm the rock types, alteration minerals and their abundance, and paragenesis. In addition, this analysis was used to know intensity of hidrothermal alteration. This analysis used 40 core samples at certain depth.

XRD analysis has been conducted to determine clay mineral composition through polarization microscope. This analysis used eight sample. Samples are selected from all the lithologic units and analysed for clays.

5. Result
5.1 Geothermal System (Recent Condition)
5.1.1 Geochemistry.
Based on the diagram of Cl-HCO₃-SO₄ (see Figure 2), It showed that the hot spring of Candi Umbul and hot spring Pakis Dadu belonged to water chloride type, whereas for hot spring of Candi Dukuh-1 and Candi Dukuh-2 were chloride-bicarbonate water. The type of chloride water at the hot springs Candi Umbul and Pakis Dadu indicated that the water derived directly from the depths and carried dissolved chemical compounds as a result of the interaction of hot fluids with rocks at depth (PSDMBP, 2010). Candi Dukuh-1 and Candi Dukuh-2 hot springs belonged to a type of bicarbonate water with neutral pH, indicating that the fluid was formed on the lower slopes of the geothermal system. The fluid flowed away laterally from the geothermal reservoir zone and appeared in areas with lower elevations [1].

Na-K-Mg diagram (see Figure 3) represented that the hot springs of Candi Dukuh, Candi Umbul and Pakis Dadu were located in immature water zone. This phenomena marked that the balance reaction between the fluid and the rock was unreachable or the hot spring may mixed with surface water or dilution [2]. The diagram of Cl-Li-B (see Figure 4), the research area had two different reservoirs. It was supported by the value of the Cl/B and Li/B ratios which showed different grade between the Candi Umbul group and Candi Dukuh group. Determination of reservoir temperature using Na/K geothermometer described that the temperature of Candi Dukuh reservoir is 215-230°C and Candi Umbul reservoir is 235-250°C, respectively.

Isotope analysis used two different hot springs from nine cold waters and a lake water. The water sample was analyzed by isotope to determine the equation of local meteoric water line. The following step, it resulted the equation of local meteoric water line: δD = 8 δ¹⁸O + 16.77, (R² = 0.32). Candi Umbul was to the left of the meteoric water line, indicating that the water was likely coming directly from the depth and the dilution with meteoric water which may had less probability (see Figure 5).
5.1.2 Geophysics.
According to magnetotellurik (MT) survey around Telomoyo Mount, there was a continuous distribution of low resistance (<10 Ohm-m) through the hot springs of Candi Umbul and Pakis Dadu. The distribution of low-type resistance was interpreted as the response of the caprock located in the southwest of the peak of Telomoyo Mount and spread from the surface to a depth of 1500 – 2000 meters. However, the geothermal reservoir was estimated to be beneath the caprock with its peak at a depth of about 1500 meters. The peak of this reservoir drove to deepen towards the northwest and reached a depth of 2000 meters below ground level [2].

5.1.3 Hydrogeochemistry.
The geothermal system of Candi Umbul-Telomoyo was thought to be related to the youngest volcanic activity of the Telomoyo complex that still retains heat from the magma chamber. The system was also controlled by a large rim structure that restricted two different reservoirs in the study area. The structure of this rim was likely to be impermeable material (sealing fault). Strike-slip fault had N-S direction located in the east of the research area that caused the emergence of Candi Dukuh hot spring, while the normal fault that trails SW-NE caused in Candi Umbul and Pakis Dadu springs (see Figure 6)

All springs manifestations in the research area included in the outflow zone. Candi Umbul and Pakis Dadu springs that have a type of water chloride was expected to come from the reservoir, Whereas, the hot springs of Candi Dukuh has a water chloride-bicarbonate type indicating that the fluid was formed on the lower slope of the geothermal system. The fluid flows laterally away from the geothermal reservoir zone and appears in areas with lower elevations [1].
There are two reservoirs in the research area, namely Candi Dukuh reservoir and Candi Umbul reservoir. Candi Dukuh reservoir has temperature 215-230°C while Candi Umbul reservoir has temperature 235-250°C.

5.2 Subsurface Lithology

CTL-1 and CTL-2 wells showed the lithologies in research area were Quaternary volcanic rock consisting of lava, tuff and pyroclastic breccia. Pyroclastic breccia was generally gray, fragments composed of andesite, black, afanitic, less than 5 cm in size, with angular shape embedded in tuff base mass and gray glass masses, open packing, poor sorting, green and moderate porosity. While black andesite lava, afanitic, consists of plagioclase, mineral mafic, glass volcanic and compact. Tuff had physical characteristic such as grayish black, grain size gray ash, good sorting, closed pack, medium porosity and brittle. The rocks came through the intensity of mineral changes from weak to very strong.

5.3 Hydrothermal Alteration

Identification of hydrothermal alteration minerals in CTL-1 and CTL-2 wells was based on megaskopis descriptions, petrographic analysis and X-Ray Diffraction (XRD) analysis. The results of the analysis can be seen on the figure 7 and figure 8. Alteration minerals consisted of clay minerals, quartz, carbonate minerals (calcite and siderite), sulfate minerals (anhydrite and gypsum), calc-silicate (epidote and zeolite) and other minerals.

Clay minerals presented on various depth on sample of CTL-1 and CTL-2 wells. Clay minerals commonly altered plagioclase phenocryst and groundmass of volcanic glass. Based on XRD analysis, clay minerals identified included smectite, kaolinite, illite and chlorite.

Quartz was generally present associated with calcite and anhydrite. It was formed as a change of plagioclase. It also changed the groundmass as a result of silicification. Quartz that fill the veins and cavities were commonly found through direct precipitation or through replacement processes.

Carbonate minerals consisted of calcite and siderite. Calcite was found in almost every depth. Calcite was present altered the groundmass of the glass and replaced plagioclase phenocryst. Calcite that filled the veins and cavities, after quartz or anhydrite. While, siderite was found in shallow depths (0 - 450 m) and is more common in CTL-1 well. Siderite altered hornblende.

Sulfate minerals consisted of anhydrite and gypsum. As with quartz and calcite, anhydrite was also found in almost every depth. Anhydrite was present altered of plagioclase, groundmass, and filled the veins and cavities. Meanwhile, gypsum was found in shallow depths and filled cavities. It was present
as a vein that replaces calcite. The presence of calcite and anhydrite minerals indicated that fluids contained considerable CO₂ and SO₄.

Calc-silicate minerals consisted of epidote and zeolite. Epidote was formed at high temperatures and in environmental conditions with a neutral pH [5]. Epidote was found in relatively deep depths, with little abundance. It was always appeared with calcite. Early epidote occurred at >490 m, which was used to identified as top of reservoir. While, zeolite was found in CTL-1 wells, with little abundance (<5%). Zeolites present altered glass minerals.

There were various minerals may also appear e.g. pyrite, hematite, and alunite. Pyrite appeared as an opaque mineral formed in shallow up to the deepest depths. Pyrite replaced pyroxene, anhydrite and vein fill. Hematite was formed due to the oxidation process. This mineral existed as a basic mass with considerable abundance. Hematite altered plagioclase and volcanic glass. Alunite present filled the veins and cavities associated with quartz. In the study area, alunite formed in shallow depths.

5.4 Well Characteristics

CTL-1 and CTL-2 wells are located on the northern slopes of Telomoyo Mount. Both wells were drilled passing a relatively north-south trending fault and a rim structure nearby.

5.4.1. CTL-1 well

The CTL-1 well has elevation of 696 meters above sea level. The characteristic of reservoir permeability were able to be determined by using data of loss circulation. At the CTL-1, Partial Loss Circulation (PLC) and Total Loss Circulation (TLC) were found at depth of 37.90 meters to the final depth. This indicated that the CTL-1 well was located in an intensive fracture zone. These fractures were generally filled by calcite, quartz, anhydrite, partial pyrite and chlorite. The presence of these filling minerals will reduce the reservoir permeability.

Based on the results of alteration minerals present in the CTL-1 well, the caprock zone was at a depth of 0-500 meter, characterized by mineral kaolinite and smectite, associated with siderite, gypsum, quartz, calcite, alunite and anhydrite. In this zone, meteoric water enters through a fault or fracture then the fluid interacts with the surrounding rock and become Ca, Mg and Fe saturated. This is indicated by the presence of smectite, siderite, pyrite, and anhydrite. This fluid has a low CO₂ and neutral pH. The matrix of rocks altered and veins were filled by quartz in association with calcite and anhydrite. Temperature in caprock zone were estimated approximately 120-180°C

5.4.2. CTL-2 well

The CTL-2 well has elevation 780 meters above sea level. The CTL-2 well did not mark the presence of loss circulation (TLC and PLC). The absence of this circulatory loss zone indicated that the well reservoir permeability of CTL-2 is not in good condition.

Based on the results of alteration minerals present in CTL-2 wells, the caprock zone was at a depth of 0-500 meters with a temperature of 120-200°C. This caprock zone is characterized by the presence of impermeable minerals such as smectite and kaolinite. The CTL-2 well temperature referred to the temperature at the present. The measurement of logging temperature was obtained the number of 151, 494 and 700 meters of depth formation at 37.25°C, 70.43°C and 91.23°C respectively. The CTL-2 well thermal gradient is 9.6°C/100 meters until 700 meters depth or about three times the average gradient geothermal (±3°C/100 meters) [3]

5.5 Fluid Evolution

The fluid evolution based on CTL-1 and CTL-2 wells in the Umbul-Telomoyo area is divided into two zones according to the its alteration minerals, the caprock zone and the reservoir zone.

5.5.1. Caprock Zone

The caprock zone was in depth 0-490 meter, characterized by mineral kaolinite and smectite, associated with siderite, gypsum, quartz, calcite, alunite and anhydrite. In this zone, meteoric water enters through a fault or fracture then the fluid interacts with the surrounding rock and become Ca, Mg and Fe saturated. This is indicated by the presence of smectite, siderite, pyrite, and anhydrite. This fluid has a low CO₂ and neutral pH. The matrix of rocks altered and veins were filled by quartz in association with calcite and anhydrite. Temperature in caprock zone were estimated approximately 120-180°C
Hydrothermal fluid mixing with condensate water through fractures. Condensate water has an acid pH and contained SO₄ and CO₂. That is indicated by formation of kaolinite and alunite. This fluid also dissolves (leaching) primary minerals and forms secondary cavity.

The mixing of meteoric water and condensate water which characterized by smectite, anhidrite, calcite, chlorite and hematite (due to the oxidation process).

5.5.2. Reservoir Zone

The reservoir zone was located >490 meters at the depth, indicated by the presence of epidote. Temperature in this reservoir zone were estimated approximately 240-330ºC. Epidote was formed from a hydrothermal solution composed of alkali chloride with a neutral pH. The fluid interaction with andesite rocks will make the hydrothermal fluid rich in Ca and Fe. This is indicated by the presence of epidotes associated with chlorite, illite and calcite vein.

Hydrothermal fluid also mixing with meteoric water characterized by the presence of smectite and chlorite which rich Mg. The fluid has low CO₂ and neutral pH.

The mixing and cooling of the condensate fluid made e fluid descending from the caprock zone to the reservoir zone. Condensate fluid to become heating (retrograde solubility). The heating process resulted anhydrite and calcite formed after quartz.

Subsequently, the condensate fluid descending and mixing with meteoric water causes the reservoir zone to be no longer at a depth of about 490 meters, and the reservoir zone turns into a transition zone. In this zone was indidicated by anhydrite and calcite that still filled veins and cavities.

5.6 Present Condition

By comparing the past and present conditions, in the study area has changed the temperature and elevation both in the capcrock zone and reservoir zone (Table 1).

Paleotemperature values based on the alteration mineral temperature range and the temperature values under the present conditions obtained from the thermal gradient data wells. The temperature values under present conditions are very different from those of paleotemperatures (see Table 2). In general, present condition have cooling processes. It is caused by the mixing process with cold water MDGW and MDLS which is located about 1 km from the well (see Figure 8). The influence of meteoric water is also seen in hot spring chemistry manifestations that have considerable Mg content.

In addition to temperature, another significant difference in current and past conditions is the difference in reservoir elevation. The reservoir elevation is currently obtained from the geophysical resistivity survey data (Magnetotelluric), while the reservoir elevation in the past was obtained from the initial epidote appearance. Based on table 2, the caprock zone was currently experiencing thickening whereas the top of reservoir has decreased. This is likely due to the presence of condensate fluid in caprock that has high density mixed with meteoric fluid so that the condensate fluid became down to the reservoir and caused the depth the top of reservoir also decreased and resulted in the caprock zone became thicker.
Figure 7. Identification of Alteration Mineral in CTL-1
| DEPTH (m) | ELEVATION (m) | LITHOLOGY | Petrography Mineralogy | XRD Mineralogy | Vein Mineralogy | Cavity Mineralogy |
|-----------|---------------|-----------|------------------------|----------------|----------------|------------------|
| 0         | 700           | Tuff      | Quartz, calcite, hematite, pyrite | Quartz, anhydrite, calcite | Quartz, calcite, anhydrite | Quartz, clay |
|           | 600           | Andesite Lava | Quartz, anhydrite, siderite, pyrite, clay | Calcite, anhydrite | Calcite, anhydrite | Quartz, calcite |
|           | 500           | Pyrite, clay | Calcite, hematite, clay | Quartz, calcite, pyrite, anhydrite, gypsum | Quartz, calcite, anhydrite | Quartz, calcite, anhydrite |
|           | 400           | Anhydrite, calcite, hematite | Anhydrite, kaolinite, pyrite | Anhydrite, pyrite | Anhydrite, pyrite | Clay |
|           | 300           | Calcite, pyrite, clay | Anhydrite, calcite | Anhydrite, calcite | Anhydrite, calcite | Anhydrite |
|           | 200           | Chlorite, hematite | Anhydrite, chlorite, amesite | Anhydrite, calcite | Anhydrite, calcite, chlorite | Anhydrite, chlorite |
|           | 100           | Calcite, siderite, pyrite | Quartz, anhydrite, chlorite, pyrite | Quartz, calcite | Quartz, calcite, anhydrite | Quartz, calcite |
|           | -77           | Quartz, anhydrite, chlorite | Quartz, anhydrite, clay | Quartz, calcite, pyrite | Quartz, calcite, pyrite, gypsum | Quartz, calcite, pyrite |

**Lithology:**
- **Tuff**
- **Andesite Lava**
- **Pyroclastic Breccia**

**Figure 8.** Identification of Alteration Mineral in CTL-2
Figure 9. Model in CTL-1 and CTL-2 Well.

Table 1. Temperature changes in the past and present

| ZONE    | TEMPERATURE | Past         | Now         |
|---------|-------------|--------------|-------------|
| Caprock | 120 – 180°C | 36 – 193°C   |             |
| Reservoir | 260 – 330°C | 215 – 250°C  |             |

Table 2. Elevation changes in the past and present

| ZONE     | ELEVATION | Past      | Now       |
|----------|-----------|-----------|-----------|
| Caprock  | 700 – 200 m | 700 – 1000 m |           |
| Top Reservoir | 200 m   | -1000 m    |           |

6. Conclusions

- The geothermal system of Umbul-Telomoyo belongs to a volcanic complex system that is heavily associated with Telemoyo complex activities. The geological structure of the study area is dominated by some relatively NE-SW and NW-SE trending fault structures that are predicted to facilitate the release of warm springs in the study area. In this system there are two reservoirs located in NE and SW of the research area. The reservoir layer is estimated at depths > 1500 meters.
- Alteration minerals in CTL-1 and CTL-2 wells were dominated by clay minerals, quartz, calcite and anhydrite. There were also mineral gypsum, epidote, siderite, hematite and pyrite.
- Fluid evolution occurs in the caprock zone and reservoir zone. While the process that occurs in the research area was cooling process, water rock interaction, heating and mixing that produces different mineral alteration.
- In the study area has changed the temperature and elevation in the caprock zone and reservoir zone.
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