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# Heat Source Movements in Lahendong Geothermal Field and Its Affect to The Reservoir Characteristics

Jatmiko P. Atmojo[1], Djedi S. Widarto[1], Yustin Kamah[1], Eko A. Bramantyo[2]

[1] Upstream Technology Center, PT. Pertamina (Persero)

[2] PT. Pertamina Geothermal Energy

jatmiko.atmojo@pertamina.com

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## ABSTRACT

Active plates tectonic zone in northern Indonesia has formed series of active volcanoes on the northern island of Sulawesi and Maluku archipelago. Lahendong geothermal system is located in the center of G. Lengkoan, G. Tampusu and G. Kasuratan and was formed around 2.2 million to 0.5 million years ago.

Lahendong geothermal field is located at elevation of 750 to 1000 masl. Until 2013 there are 29 wells drilled from 10 clusters with depth of well varying between 1200 to 2500 m. Currently, the Lahendong field has intalled power plants with total capacity of 80 MWe. The reservoir produces two phase fluid, but southern part of the reservoir is less water saturated than northern. Specially, reservoir beneath Linau Lake produces the biggest producer steam (up to 20 MWe), but unfortunately the fluid is highly acidic.

Research of heat source activities by using Geothermometer mineral marker such as chlorite, actinolite, epidote, wairakite and smectite from rocks cutting and cores taken from the wells indicated that there occurred three heat sources shifting, which started moving from Kasuratan to Pangolombian, then moving toward Linau Lake and finally back again to Kasuratan. The evolution of heat sources is possibly related to the tectonic activities in the regional area, and it greatly affect characteristics of the reservoir of Lahendong field. Heat dispersal patterns showed the highest temperature is in the southern part (area of Linau and Kasuratan) and towards eastern part (Pangolombian) temperature decreases. Based on data of water levels and pressures in the reservoir, it is indicated that a structural barrier separates into two areas between Linau and Kasuratan.

## 1. INTRODUCTION

Lahendong Geothermal Field is one of PT. Pertamina Geothermal Energy's fields in Sulawesi Island. The field is located in Tomohon City about 40 km south of Manado, North Sulawesi. Until the year 2013, the field has been drilled twenty-nine wells, and generated 4 units of geothermal power plant with 20 MWe capacity each. Geothermal system formed by volcanic activity due to the presence of the collision dynamics of the movement of 2 plates tectonics. Lahendong Field is located in active volcanic areas of the path that are part of a very large caldera complexs, which Tondano and Pengolombian calderas. There are some still active volcanics around the Lahendong field consisting of Mt. Soputan, Mt. Lokon-Empung, Mt. Mahawu and Mt. Klabat, and Mt. Dua Saudara, trending southwest to northeast. Map of wells location are shown in Figure 1.

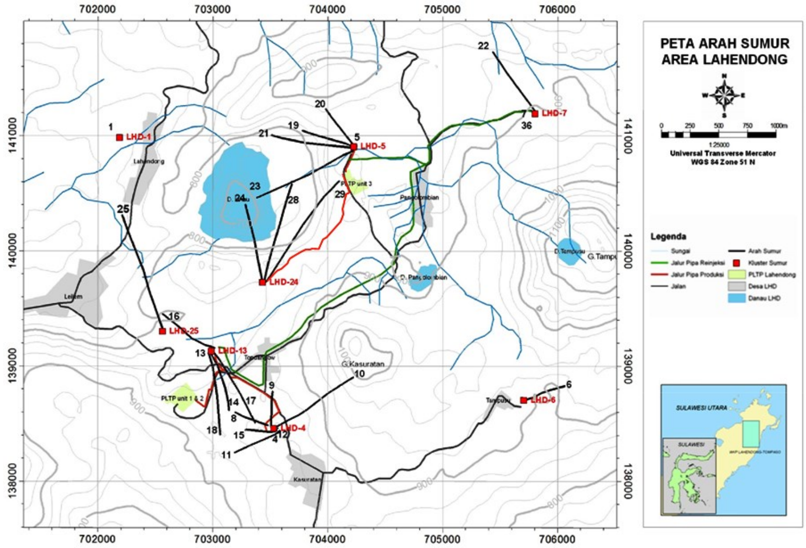


**Figure 1: Maps of wells location in Lahedong geothermal field**

This study discusses historical of heat sources that formed geothermal systems in Lahendong area and its affect to the reservoir characteristics. Subsurface hydrothermal alterations were observed from core and cutting samples of selected wells LHD-23, 24, 28, 36, and 37 using binocular microscope, polarization microscope and XRD.

## 2. SUBSURFACE HYDROTHERMAL ALTERATION IN LAHENDONG FIELD

There are 2 types of alteration by hydrothermal process that reflect the physical and chemical processes into rocks and formations in the Lahendong geothermal system:

1. Leaching, reflects the results of the interaction between rock and acid fluid. The primary rock components are leached by fluid and not replaced by new hydrothermal minerals.
2. Replacement of primary minerals by hydrothermal minerals, which reflects the result of the interaction between the geothermal fluid and the rock wall. This alteration type is formed widespread, at least in all parts of the field penetrated by drilling wells. This alteration type is characterized by the presence of clay minerals, silica, calc-silicate, secondary feldspar, sulfates, sulfides, phosphates, and oxides.
3. Direct deposition, which reflects boiling, cooling, or a mixture process of fluid from fluid reservoir to the surface. This alteration type occurs locally, especially in the parts by type of fracture permeability and the open cavities in the reservoir rock. This type of alteration can be recognized by the presence of quartz, calcite, Fe-Mg carbonate, anhydrite, adularia, epidote, zeolites, clays (illite and chlorite), hematite, and opaque minerals.

Alteration mineral assemblages on the inside of the wells LHD-23, 24, 28, 36, and 37 are composed of minerals formed by hydrothermal fluids that are near neutral, ie ± epidote ± chlorite clay/ sericite ± quartz ± calcite ± hematite (± anhydrite). The mineral assemblages of minerals are formed as a replacement or as gap filler minerals.

### 2.1 Clay Minerals

Types of clay minerals in the Lahendong geothermal field are kaolinite, smectite, chlorite, and illite. Distribution of clay minerals in Lahendong field is shown in Figure 2.

#### 2.1.1 Kaolinite - $Al_2Si_2O_5(OH)_4$

Kaolinites are present on the surface as well alteration rocks in the hot area of active manifestation or heat is off manifestations. In subsurface samples, kaolinites are found in wells LHD-24 (depth 1848 m and 2173 m) and LHD-28 (depth 1662 m).

#### 2.1.2 Smectite - $(_{1/5}Ca, Na)_{0.7}$ $(Al, Mg, Fe)_4$ $[(Si, Al)_8\ O_{20}](OH)_4{\cdot}nH_2O$

Observation of subsurface rock samples by Utami (2011) showed smectite minerals are present as replacement minerals. Petrography indicates smectite are present replacing volcanic glass and plagioclase. In general, smectite in wells LHD-1, LHD-4, LHD-8, and LHD-10 are present at relatively shallow depths (~500 m). In the old hot area, smectite are present at deeper depths ~900 m on the LHD-7 and ~700 m in the LHD-3. Smectite minerals has stable temperature at around 150 °C (Steiner, 1977), whereas in Lahendong, smectite is also present at higher temperatures (up to 250 °C). Smectite is also present at a temperature of 250 °C in Nesjavellir geothermal field, Iceland (Kristmansdóttir and Tomasson, 1976; within Utami, 2011).

#### 2.1.3 Chlorite - $(Mg, Fe^{2+}, Fe^{3+}, Mn, Al)_{12}$ $[(Si, Al)_8\ O_{20}](OH)_{16}$

Chlorite minerals are commonly found in hydrothermal systems. At present active thermal area Lahendong geothermal field, chlorite minerals are present either as substitute or filler cavity. In general, chlorites are present as replacing plagioclase and pyroxene. In well LHD-23, chlorites are present as filler minerals cavity and as replacement of plagioclase and volcanic glass at depth of ~175 to 1400 m, where measured temperatures are between 40 and 160 °C. In LHD-24, chlorites are present as filler minerals cavity and as replacement of plagioclase and pyroxene in the depths of ~600 to 2167 m with measured temperatures between 50 and 230 °C. Chlorite filler minerals cavity as well as replacement of plagioclase and pyroxene are present in wells LHD-28 at depth of 606 to 2085 with measured temperature from 150 to 270 °C. In well LHD-36, chlorites are present as filler minerals cavity and as replacement of plagioclase and pyroxene at depth of ~800 to 1900 m, where measured temperature are between 190 and 290 °C. In LHD-37, chlorites are present as filler minerals cavity and as replacement of plagioclase and pyroxene in the depths of ~900 to 2200 m with measured temperatures ranging from 250 to 290 °C.

Chlorite is stable within a quite large temperature range, for example; ~140 to > 300 °C in the geothermal system at the Philippines (Reyes, 1990), ~100 to ~300 °C in Los Azufres, Mexico (Cathelineau and Nieva, 1985), ~150 to ~290 °C in Broadlands-Ohaaki, New Zealand (Browne and Ellis, 1970). The application of mineral chlorites as geotermometer did not give maximum results in Tongonan system (Scott, 1988) and Broadlands-Ohaaki (Lonker et al., 1990).

#### 2.1.4 Interlayered clays

Interlayered clays are rarely found in the Lahendong geothermal field. Interlayered chlorite/ smectite with 60 % chlorite component (refer to the classification of Moore and Reynolds, 1977) are present in wells LHD-24 (2145m) and LHD-28 (1662 m). In wells LHD-23 (1667-1670 m), LHD-24 (1848 m), LHD-28 (1902 m), LHD-36 (1893-1896 m and 1515-1518 m) and LHD-3 (904-907 m) interlayered chlorite/ smectite with 10 % chlorite are present as replacement component of volcanic glass. This interlayered clays minerals in Lahendong field are not used as a geothermometer.

#### 2.1.5 Illite $[K_{1.5\text{-}1.0}Al_4\ [Si_{6.5\text{-}7.0}\ Al_{1.5\text{-}1.0}O_{20}](OH)_4]$

Illites are present in both the hot area of active and inactive at Lahendong field. Illites are present as replacement of volcanic glass in wells LHD-23 (1667-1670 m) and LHD-37 (1515-1518 m). Measured temperature at depths are of ~ 240 °C. Utami (2011) reported the presence of illites are as replacement of plagioclase, quartz, and klinozoisit and as cavity filler minerals. In well LHD-5(~650-1331 m), measured temperatures are at between 235-255 °C. In LHD-24, illites are present at a depth of 1848 m and 2145 m with measured temperatures of ~210 °C, whereas in LHD-28, illites are present at a depth of 1662 m and 1902 m with measured temperatures of ~250 °C.

In hot areas that are not currently active, illites are present in well LHD-36 (1893-1896 m), measured temperature are at ~290 °C as replacement of volcanic glass. Utami ( 2011) reported the presence of illites in the LHD-3, 6, and 7. Illites is present in wells LHD-7 depth of 1568 m (~660 masl) replace the matrix and at a depth of 1754 m (~ 850 m asl) as a cavity filler side by side with epidote. Measured temperatures are at the current depth of < 100 °C.

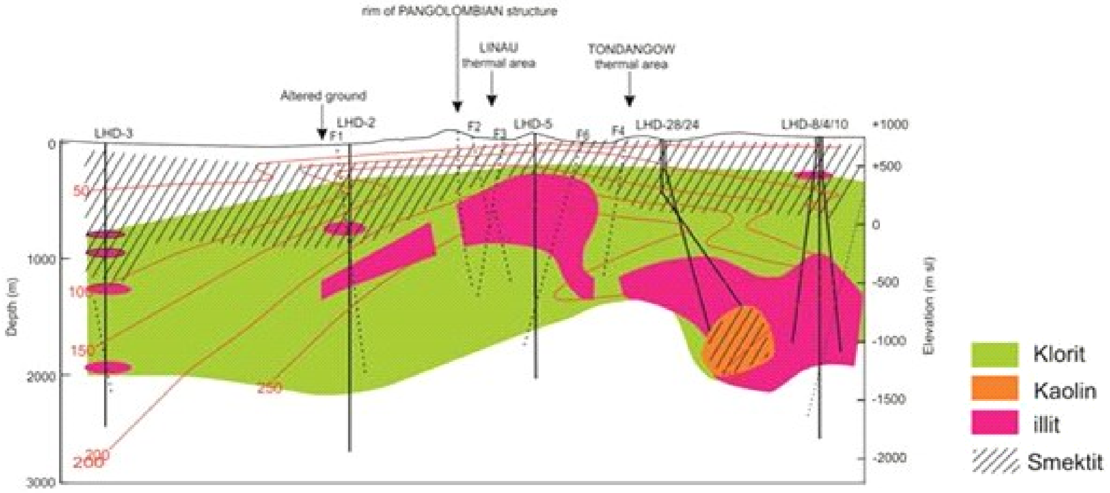


**Figure 2: Clay minerals of Chlorite, Kaolinite, Illite and Smectite distribution in Lahedong geothermal field**

## 2.2 Sulfate Minerals (Anhydrite - $CaSO_4$)

Anhydrites are present either as replacement mineral or as filler minerals in the deeper part of the Lahendong system. These minerals commonly replace primary minerals of plagioclase and pyroxene, and usually are spatially associated with the mineral calcite and opaque minerals. Mineral anhydrites are encountered as filler mineral at depth of 1223-1226 m in wells LHD-23, formed together with calcite after epidote. In well LHD-24, anhydrite are found as replacement mineral at depth of 1848 and 2147-2173.7 m, and as filler mineral at depths of 810 and 2173.7 m. In well LHD-28, anhydrites are encountered as filler mineral at a depth of 606 m. In well LHD-37, anhydrites are encountered as filler mineral at depth of 2228.6, 2229, and 2229.5 m.

Anhydrite solubility in water decreases with increasing temperature but increases with increasing total pressure (Holland and Malinin, 1979 in Utami, 2011). Boiling water and an increase in pH may lead to an increased saturation of anhydrite. Thus, anhydrite can be formed from sulfate-rich vapor condensate experiencing downward percolation, become neutral by reaction with a side of rock or fluid mixed with more neutral pH. Or, anhydrite is formed from acidic fluids where $SO_2$ is derived from magmatic volatiles.

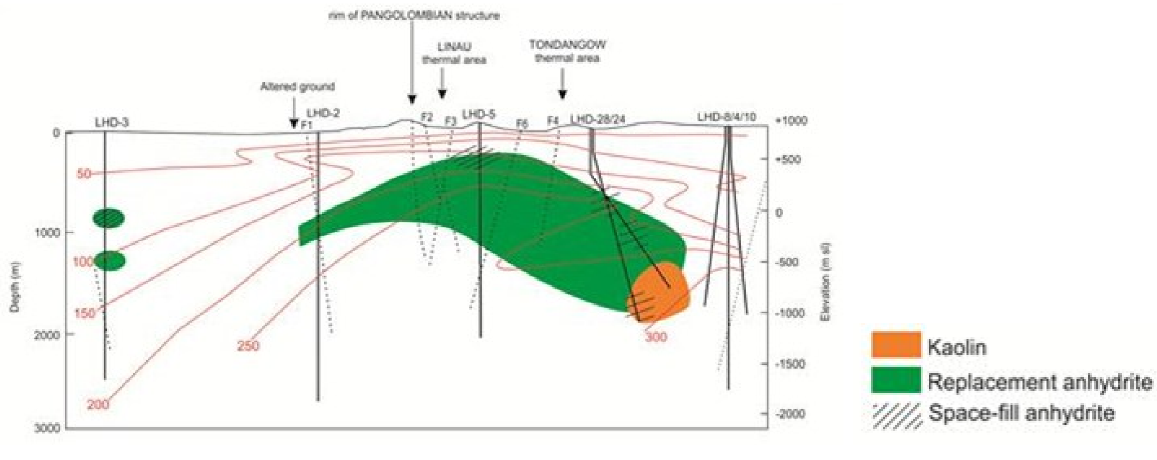


**Figure 3: Clay minerals of Kaolinite and anhydrite distribution in Lahedong geothermal field**

## 2.3 **Carbonate (calcite)**

Calcites are found either as replacement of plagioclase or as filler in all types on the thermal active and inactive areas. In thermal area of Linau Lake in Lahendong field (wells LHD-1, 2, 5, 23, 28, and 37), replacement of calcites occur sporadically beginning from 175 m depth in wells LHD-23 and to depth of 2085 m in well LHD-28.

In the hot area of Kasuratan (cluster LHD-4), replacement of calcites occur sporadically from depth of 150 m to 1450 m, whereas filler minerals are found to be limited at interval depth between 350-1350 m and 2300 m in well LHD-4; ~1010 - 1495 m in well LHD-8 and -1230 - 375 m in well LHD-10. In LHD-4 (850 m) two generations of calcite veins are encountered as mirror to the other carbonate minerals (dolomite, magnesite, siderite; Utami, 2011), chlorite and hematite. Under the hot area of Tondangow (LHD-13) replacement and filling calcite are found from depths of ~ 100 m to 2500 m. Distribution of calcites in Lahendong field are shown in Figure 4.

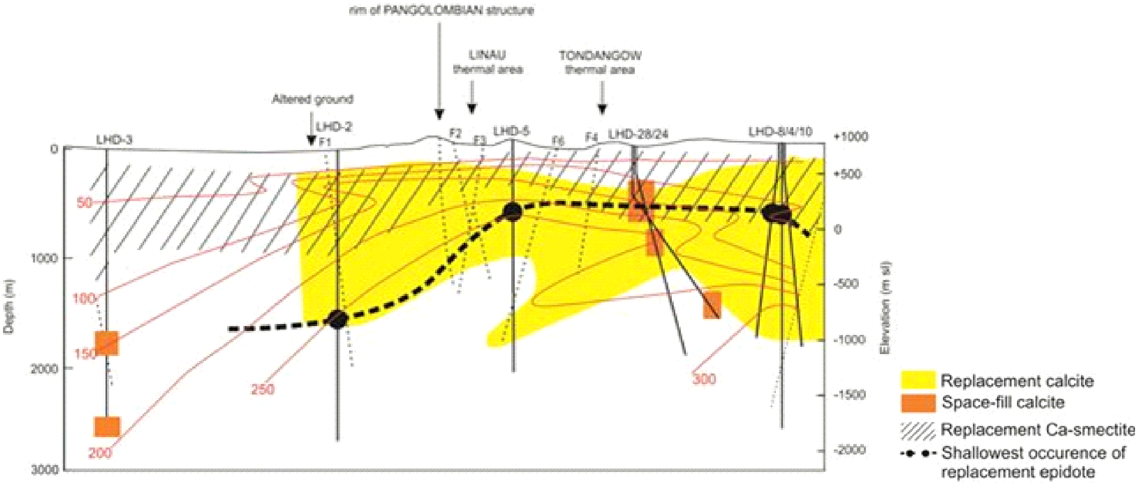


**Figure 4: Calcite distribution in Lahedong geothermal field**

### 2.4 Quartz

Quartz minerals are found very widespread either as replacement or as filler mineral in different proportions both in the hot area of active and non-active. As of replacement minerals, generally replacing plagioclase and quartz glass and a few pyroxene partially. Replaced quartz glass forms a micro-crystalline. Quartz are found in most types of veins and fissures. In Lahendong field, quartz as filler minerals have at least 8 kinds of textures, such as massive, crustiform, colloform, comb, zonal, mosaic, feathery and latice bladed. Five textures are first classified into primary growth textures, while the remaining three are the recrystallization texture. Quartz are also found sporadically in well LHD-1, as a replacement phase. Distribution of quartz in Lahendong field are shown in Figure 5.

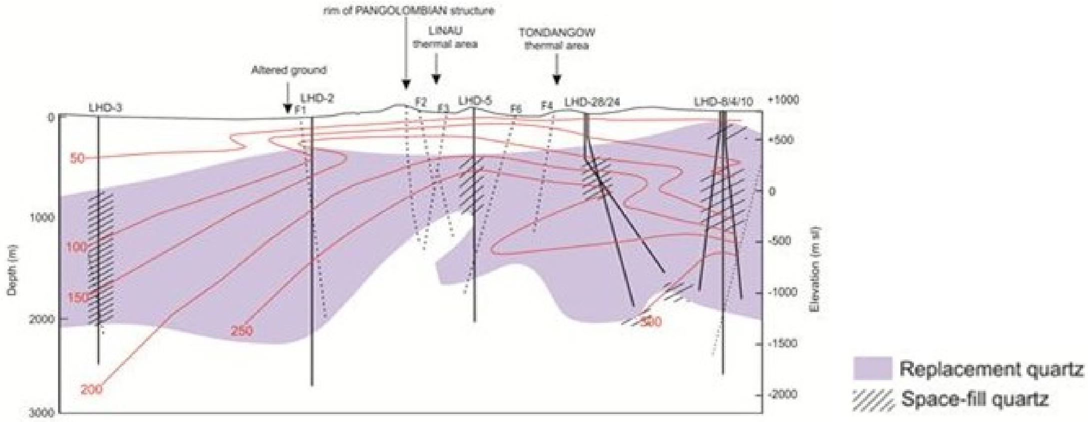


**Figure 5: Quartz distribution in Lahedong geothermal field**

### 2.5 Secondary Feldspar (Alkali feldspar - (K,Na)[$AlSi_3O_8$])

Feldspar hydrothermal minerals in Lahendong field are fine size of adularia and albite. These minerals are sensitive to affect permeability, and abundance of adularia as filler minerals are in touch with the local permeability. At Broadlands (New Zealand), feldspar mineralogical sequence related to increasing well productivity is as follows: primary andesin → albite → albite + adularia → adularia (Browne, 1970 in Utami, 2011). This sequence does not apply in Lahendong field, because there has been several generations of hydrothermal processes in which the final outcome is observed accumulation of the whole process (Utami, 2011).

In Lahendong, adularia and albite found either as replacement or as filler minerals, but more commonly are as replacing feldspars. Both of these minerals replace primary plagioclase. Replacement adularias area are found either on the rocks that have highly permeable matrix (tuffs and breccias) or less permeable rocks (andesite lava and welded tuff). Distribution of adularia and albite cross section is shown in Figure 6.

### 2.6 Calc–silicate

In Lahendong field, Calc-silicate minerals are found as of epidote, wairakite, and actinolite. Calc-silicate minerals are geothermometer sensitive minerals and can be used to estimate the thermal conditions of the past at the time of its formation

(Browne, 1970). In this section we will discuss the presence and distribution of these minerals while the mineral applications for reconstruction of models to interpret the evolution of heat sources in the geothermal system.

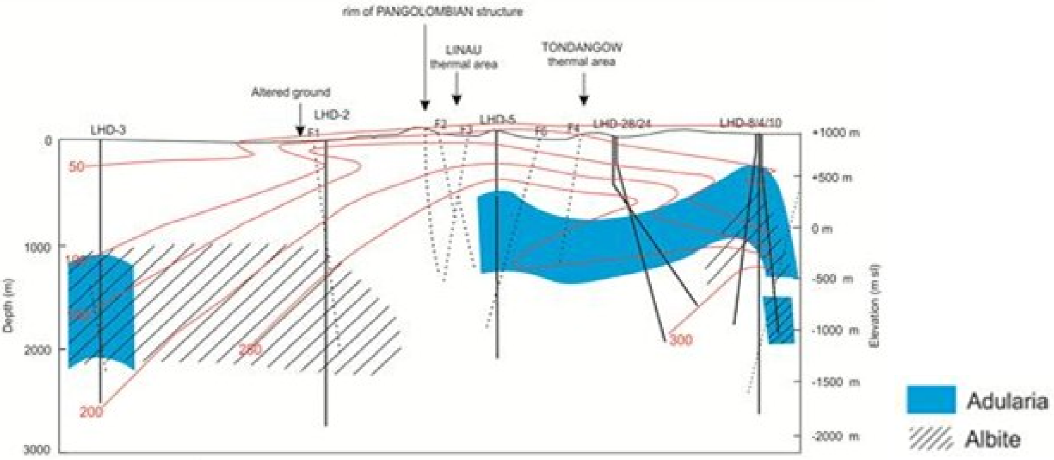


**Figure 6: Adularia and Albite distribution in Lahedong geothermal field**

2.6.1 Epidote - $Ca_2Al_2O. (Al, Fe^{3+})OH[Si_2O_7] [SiO_4]$

In general, epidote mineral assemblages are present in the form of heat in both active and inactive hot area. The presence of epidote replaces plagioclase and pyroxene area usually as filler minerals or cavity. Bird et al. (1984) reported a stable temperature epidote ranging from ~240 to 350 °C.

In LHD-23, epidotes replacing plagioclase are present at depths of 884-1670 m, measured temperature area at range from 100 to 200 °C. As a filler minerals cavity, epidotes are present at a depth of 1200 - 1600 m. In LHD-24, epidote replacing plagioclase and pyroxene are present at depths between 600 and 2173 m with measured temperature at range from about 50 to 200 °C. Epidote as a cavity filler is encountered at a depth of 2173 m. In LHD-28, epidotes replacing plagioclase are present at depths of 600-2085 m with measured temperature between 150 and 280 °C. In LHD-36, epidote replacing pyroxene is present at a depth of 1713 m with measured temperatures of about 290 °C. In LHD-37, epidote replacing plagioclase and pyroxene are present at depths of 900-2200 m with measured temperature between 250 and 280 °C.

2.6.2 Actinolite - $Ca_2(Mg, Fe^{2+})_5 [Si_8O_{22}](OH, F)_2$

Actinolite are generally formed at temperature of at least 300 °C (Bird et al., 1984). The appearance of actinolite in the shallowest wells LHD-24 is at a depth of 2145 m, there is as replacement plagioclase mineral with measured temperature of ~190 °C.

2.6.3 Zeolite - $(Na_2, K_2, Ca, Ba)[(Al, Si)O_2] n.xH_2O$

Zeolites were observed in this study of wairakit, while Utami (2011) reported the presence heulandit and mordenite in wells LHD-10 and LHD-6. Wairakit in wells LHD-23 appeared at a depth of 1466-1469 m as a replacement mineral plagioclase with measured temperature of ~170 °C. In well LHD-37, wairakit present as a replacement mineral plagioclase at a depth of 2230 m with temperature of ~300 °C. Bird et al . (1984) reported the formation wairakit temperature to range from ~200 to 300 °C.

## 3. DISCUSSION

The data obtained from the drilling of all wells in the Lahendong field gives an indication of two reservoirs:

- Shallow reservoir has moderate temperatures (100-200 $^oC$) and there is a depth of about 250-500 meters.
- High temperature reservoir ( T > 225 $^oC$ )is found at a depth of below 1200 meters.

Shallow exploration wells of well LH-1 drilled near Lake Linau give an indication of the presence of a very shallow reservoir which is the dominance of the steam reservoir. Shallow reservoirs are also detected on wells LHD-1, LHD-4, LHD-5, LHD-9, LHD-14, in which one of the following events occur: lost circulation of mud, drilling break, rising temperature and chloride content in the mud, wild bursts of steam.

Deployment of measured temperature based on well data shows there are two prospect areas with high temperatures. Cluster LHD-4 and LHD-12 in the area of Southern area has a temperature of more than 300 °C, whereas Cluster LHD-5 and LHD-24 which are located in the northern part have a temperature of 250 $^oC$. Figure 9 shows the distribution of isothermal of Lahendong field at a depth of 1000 m. Cluster LHD-7 and LHD-6 located in the Eastern and southeastern area have lower temperatures, this area is designated for reinjection. Figure 8 shows distribution of reservoir temperature in Lahendong field.

Occurrences of hydrothermal minerals and its distribution provide clues about the beginning of the geothermal system. Chlorite minerals are present either as a substitute or filler cavity minerals. Chlorite veins are formed at early phase and usually as the first mineral formed in a multi-mineral veins, textural relationships indicate that the mineral chlorite is formed in the interaction between the hot fluid and the primary phase, especially pyroxene.

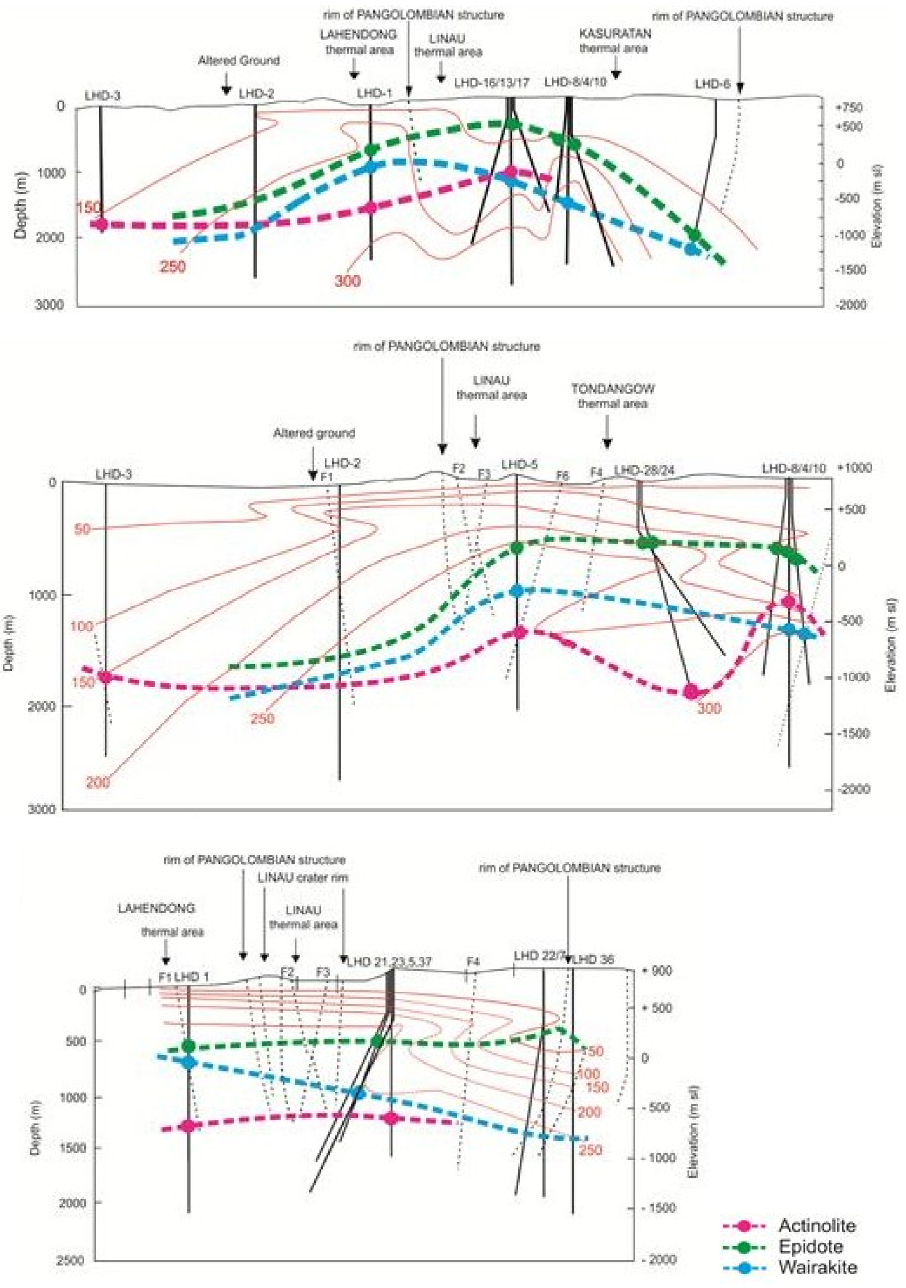


**Figure 7: Distribution of Calc-silicate minerals across the wells in Lahedong geothermal field**

Utami (2011), based data on wells LHD-13 and LHD-4 estimated that the past activity center of heat, called the "old Kasuratan hot center" is located around G. Kasuratan. Early geothermal system probably started after the formation of the structure Pangolombian. The heat source geothermal system is the possibility of magmatic based on its proximity to the centers of gravity of volcanoes and models as well as the emergence of diorite intrusion in wells LHD-5.

The existence of the old central heat Kasuratan (Cluster LHD-4) shallowest identified from the appearance of the mineral chlorite (Figure 9A), that is always formed in the first stages of alteration, and actinolite as an indicator of temperature ≥ 300 °C (Figure 9B), which marks the beginning of high-temperature of hydrothermal regime.

Based on data minerals geothermometer, after the formation of old Kasuratan central heat flow, geothermal systems Lahendong then shifted to the center of heat flow both spatially and temporally with the following sequence:

- Central heat flow shifts to Tondangow and Pangolombian (Cluster LHD-5). This interpretation is based on the shallowest appearance of epidote as an indicator of the temperature of 250 °C (Figure 9C).
- Central heat flow that is shifted back toward Lahendong-Linau and around wells LHD-6. This interpretation is based on the appearance of the shallowest wairakite as an indicator of temperature 220 °C (Figure 9D).
- The appearance of the deepest smectite (temperature ≤ 150 °C) indicates the lower limit or the upper limit of the covering layers of the reservoir during mineralization (Figure 9E).
- Based on the results of measurements of temperature wells at present there are two main centers of heat flow, the heat flow on center of Lahendong and center of Linau Kasuratan heat flow (Figure 9F). There are minor in Pangolombian heat flow (based

on the well LHD-36) which are not reflected in the elevation of > -250 masl. Thus, central heat flow of Pangolombian Kasuratan can be said to reactivation of heat source.

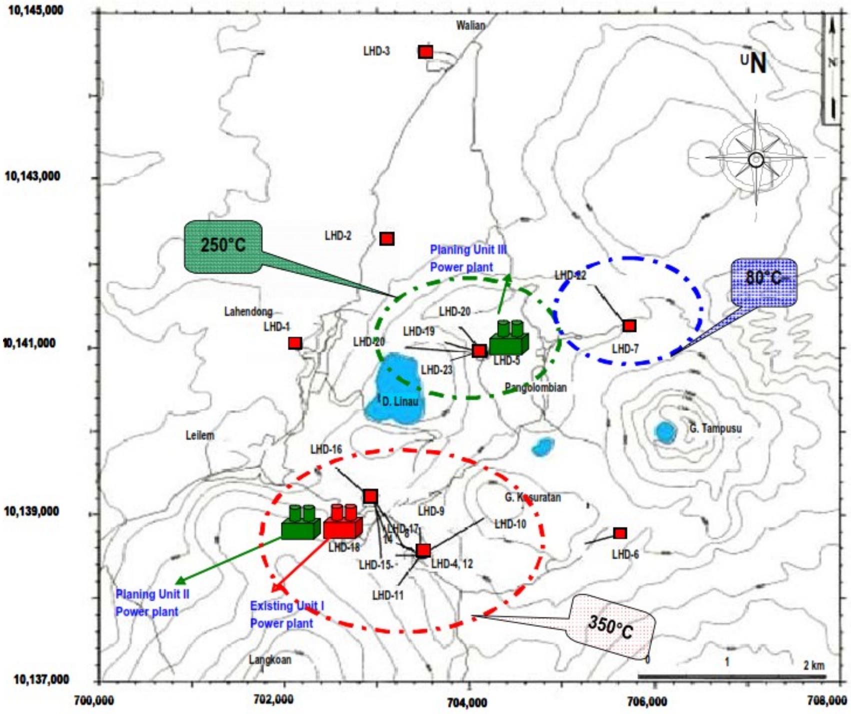


**Figure 8: Map of temperature distribution on Lahedong geothermal field (Yani, A., 2006)**

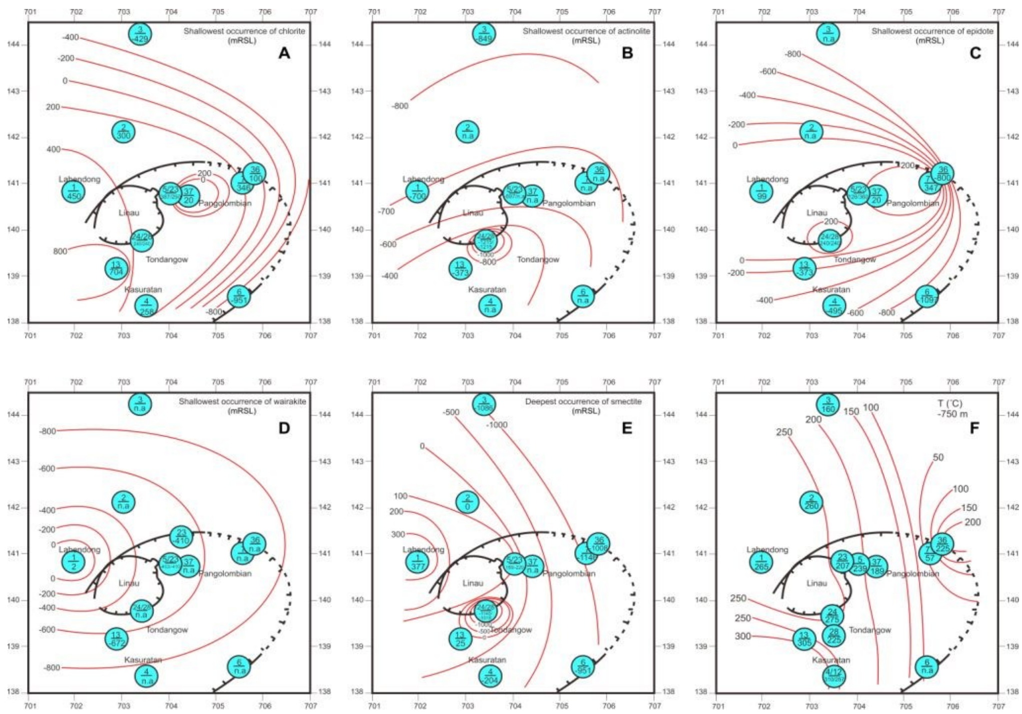


**Figure 9: Maps of the shallowest occurrence of chlorite (A), actinolite (B), epidote (C), wairakite (D), deepest occurrence of smectite (E), and the present-day isotherm at -750 mRSL (F), representing the past and present-day thermal structures of the Lahendong geothermal system (compiled from Pertamina, 2013).**

## 4. CONCLUSION

Based on the analysis of mineralogy and the present condition indicated by the well known data and surface manifestations, the Lahendong geothermal system is a very dynamic system. The most striking dynamics is the centers shift of heat activity. Absolute time of birth of Lahendong geothermal systems cannot be known from this study, however alleged that the hydrothermal system of Lahendong began to develop when there is a circulation of meteoric water is enough to start transferring heat from magmatic heat source into the surrounding environment. The dynamics of geology in the northern arm of Sulawesi allegedly one controller, in addition to the internal events that affect the circulation of the fluid in the system such as self-sealing, mixing and cooling.

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