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Geothermal Model of the Lahendong Geothermal Field, Indonesia

Hary Koestono[1], Eben Ezer Siahaan[1], Marihot Silaban[1], Hjalti Franzson[2]

[1]Pertamina Geothermal Energy, Jakarta, Indonesia

[2]Iceland GeoSurvey, Reykjavik, Iceland

hary_ka@pertamina.com, eesiahaan@pgeindonesia.com, marihots@plasa.com, hf@isor.is

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ABSTRACT

Lahendong Geothermal Field is tectonically located in the northern neck arm of Sulawesi Island. The field is part of the depression of the Pangolombian caldera with clear structures in the eastern part but relatively open to the west. The depression of the Pangolombian caldera is being one of the most important with respect to the geothermal system in Lahendong. Thermal structures on surface are mostly fault controlled with a dominant NW-SE and NE-SW directions, and are believed to control the permeability of the Lahendong system. The Lahendong geothermal field is hot water dominated system divided into two reservoirs, the Southern and Northern one. A total of twenty three wells have been drilled into these reservoirs. The Southern one has temperatures of 300 to 350^{o}C with dryness about 80%, and the northern one has lower temperatures between 250 to 280^{o}C with dryness around 30%. Three main alteration zones are encountered in this field namely smectite zone, smectite-chlorite and illite-prehnite-epidote zones. The smectite zone is mainly characterized by the appearance of low temperature clay and a layer with resistivity <10 ohmm. The smectite-illite-chlorite zone is characterized by the appearance of an acid layer and illite-prehnite-epidote zone is characterized by the appearance of chlorite, epidote, prehnite, and secondary quartz. The temperature distribution shows that the interesting site for geothermal resource utilization in the field is located in the NW, W, and SW direction of well pad LHD-4 and W and SW direction of well pad LHD-5.

1. INTRODUCTION

Lahendong geothermal field is located at about 30 km south of Manado, in the northern arm of Sulawesi Island (Figure 1). The Sulawesi Island is formed due to an active subduction in the south eastern part (Mollusca sea) and northern part (Celebes sea).

Regionally, this field is located in the west margin of the Tondano Depression which extends about 20 km in north-south direction and opens to the west. Within this depression is the Pangolombian rim circular in shape and is an important structure in Lahendong geothermal system.

This geothermal field was discovered in 1982 and geological, geochemical and geophysical works has been conducted since that time. Three shallow wells were drilled around Linau Lake in the same year. From 1982 to 1987, Pertamina drilled 7 exploration wells LHD-1 and LHD-5 in the northern reservoir system, LHD-4 in the southern reservoir system and LHD-3, LHD-6 and LHD-7 in the boundary margin of the prospect area (Robert, 1987; Siahaan, 2005).

The development wells LHD-8 to LHD-16 at Lahendong Geothermal Field were drilled from 1991 to 1998 and the first 20MW power plant was commenced in 2001. The development stage continued from 2005 to 2007 in which 7 production wells were drilled which generated electricity 2 X 20 MW for power plant Unit II and III and was commenced in 20087 and 2008.

The paper will explain about the tectonic structure, hydrothermal alteration, reservoir, temperature, and the geothermal model of the system based on data from 23 wells. The geological data is mostly based on the cutting analysis of samples taken at 3 m interval. There are 7 production wells in well pad LHD-4 and 13 are located in the southern block and 5 wells in pad LHD-5 in the northern block, whereas well pad LHD-7 in eastern part is reinjection wells.

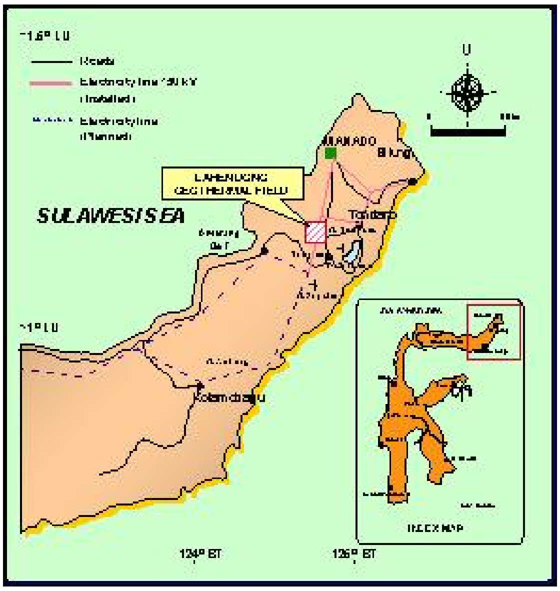

Figure 1. Location map of Lahendong Geothermal Field

2. GEOLOGICAL OUTLINE

2.1. Regional Geology

The geology of Lahendong consists of hyaloclastites and lava flows intercalated with the sediment formation formed during the Miocene time. Tondano depression is the important structure in the area and is formed due to the big eruption which occured on the Late Miocene or Early Pliocene time.

The stratigraphy of Lahendong geothermal field can be divided into 3 lithological units i.e. Pre-Tondano, Tondano and Post Tondano Units.

Post Tondano Unit is commonly found covering the upper part of the stratigraphy and comprises pumice, tuff and volcanic breccia in the upper part and basaltic andesite in the lower part.

The Post-Tondano unit consists of 2 sub-units, the Pra-Pangalombian and Post-Pangalombian Sub-units. The Pra-Pangalombian sub-unit mainly consists of basaltic andesite lava deposited in the northern and southern part of Pangalombian depression. The second sub-unit, the Post-Pangalombian, is composed of eruptions located in the central and peripheral of the depression. The chronological sequence from early to late deposition is described as basaltic andesite lava of Kasuratan, Linau breccia consisting of volcanic breccia and pyroclastic rock, Tampusu basaltic andesite lava and pyroclastic rock, product of Mt. Lengkoan andesitic lava, obsidian and tuff breccia, an altered ground located in the northern side of Kasuratan village extending to Pangalombian rim, in Leilem creek and in the eastern side of Lahendong village (Figure 2). Lake Linau and its crater rim was formed due to the hydrothermal eruption activities and is believed to be the centre of surface thermal manifestations in the field. (Siahaan, 1999).

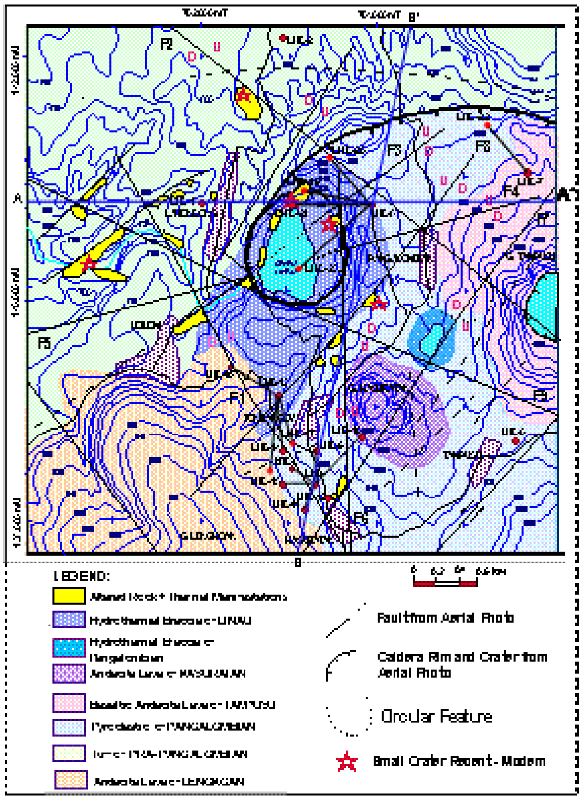

Figure 2. Geological and structural map of Lahendong geothermal field (Siahaan, 1999).

Tondano unit is a rhyo-dacitic pumice rich ignimbrites in the upper part, whereas the influence of micro dioritic intrusion in the lower part makes it difficult to determined its true lithological character.

The last unit, the Pre-Tondano, consists of series of basaltic andesite, andesites, volcanic breccia, hyaloclastites and pyroclastic products.

The sedimentary formation includes limestone and silty marl with foraminifera identified on wells LHD-1, LHD-2 and LHD-3 (Robert, 1987).

2.2. Geochemistry

The surface manifestations that indicate a geothermal system in this field are such as hot springs, mud pools, fumaroles, and altered rock (Figure 3).

The Lahendong geothermal area can be divided into two groups of hot water based on their chemical characteristics of the Cl-B ratio as Lokon-Mahawu group and Lahendong-Tompaso group.

Lokon-Mahawu group is located in the Northern part and is characterized by low silica content and low temperature while the concentration of Ca, Mg and SO_4^{2-} is relatively high. The ratio of Cl/B in this group is higher than the second group. The second group is Lahendong-Tompaso group. This group is located in the Middle and Southern part of the field. The temperature estimation based on the gas geothermometry is around 322°C.

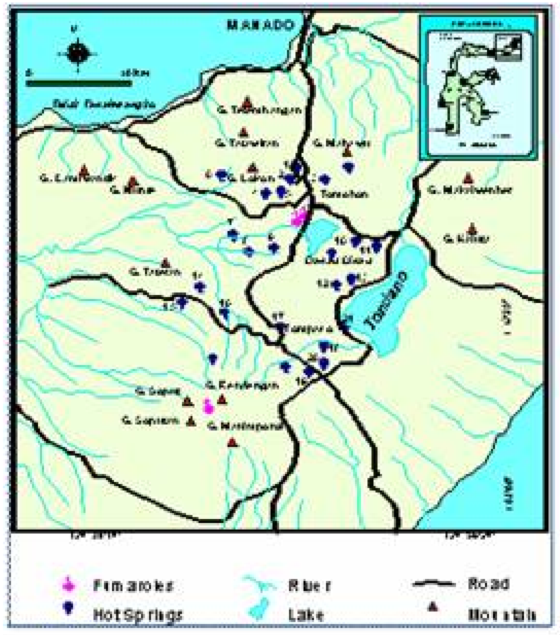

Figure 3. Map showing the distribution of surface manifestation in the field (Siahaan, 1999).

2.3. Geophysics

The geophysical methods used to assess the geothermal system are resistivity, MT and gravity and were conducted in this field since its discovery 1982.

The results of Schlumberger resistivity (AB/2=1000 m) and magnetotelluric (MT-5 EX) showed that the width of the geothermal prospect area identified by low resistivity anomaly (<10 ohmm) is around 15 to 25 km^2. This prospect area has centred in around of Linau Lake (Figure 5).

Detailed MT survey was done in 2008 by modelling of 3D MT inversion and showed an updome resistivity structure at around Linau Lake. The updome resistivity structure is characterized by the resistivity value of 20-60 ohmm which is interpreted as the propilitic zone. This zone is covered by the conductor resistivity structure with value <10 ohmm as the clay cap and part of the argillic zone (Raharjo, et.al, 2008).

3. TECTONIC STRUCTURE

The study on the distribution of the geological structure of the Lahendong Geothermal Field has been carried out by

Pertamina since 1982. Ganda and Sunaryo (1982) mapped the geology of the area. Later in 1987, Geoservice studied the geology and structure of the field based on aerial photographs. Robert (1987) compiled the data of Geoservice together with the well data. Head on resistivity Survey was carried out by Pertamina in 1988. Aerial photograph, landsat interpretation and surface manifestation evaluation was done by Siahaan (1999).

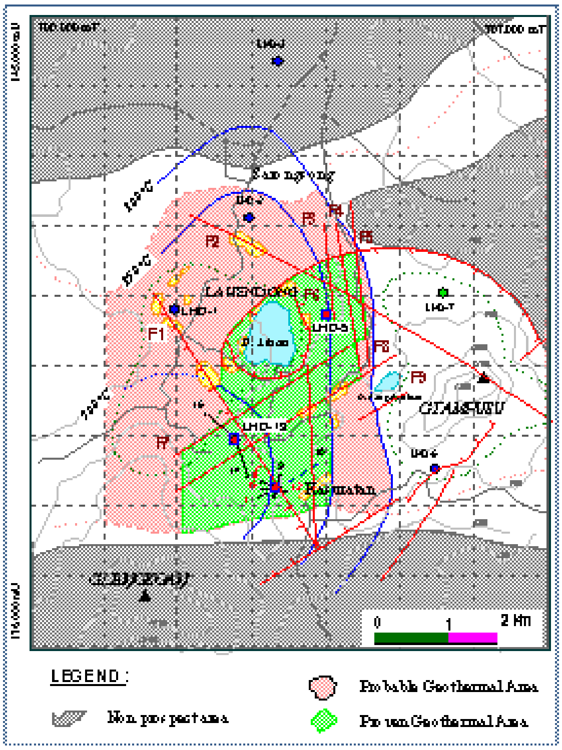

Figure 5. Geophysical map of the Lahendong prospect area (Siahaan, 1999)

Tectonically, five main structures were encountered in the Lahendong geothermal field. The structures are rim Pangolombian, faults striking NE-SW, E-W, NW-SE and N-S.

The Pangolombian structure is a caldera rim that is interpreted to provide the good permeability in the field. The NE-SW fault structure is normal and lateral fault, acting as the major volcanic axis. The E-W fault structure is lateral and a transcurrent fault. The NW-SE fault and N-S faults are normal faults which are interpreted to be provide a good permeability to the geothermal system (Robert, 1987). The important faults structure controlling the geothermal systems in the field are F-1 in the well pad LHD-4 and 13 and F-2 and Pangolombian rim for the well pad LHD-5. These three well pads are production site, whereas well pad LHD-7 in the western part has the reinjection wells.

The geological structure and the cross section are shown in the Figure 2 and 6. Well LHD-1 and 2 intersects NW-SE fault and dipping SW at depths of 350 m and 650 m, respectively, but does not intersect the main structure at depth. No productive structure was intersected by well LHD-3. Well LHD-4 intersects the main F-1 structure at depth 2200-2250 m and Well LHD-5 intersects the F-2 structure at 1170-1220 m (Figure 6). LHD-6 intersects a NW-SE F-9 fault at depth of 780 m but failed to intersect a permeable structure in the production part. Well LHD-7 intersects the Pangolombian Rim at depth 1950 m. No open fault structure is intersected by wells LHD-8, 11 and 12. These are show low to no permeability due to silicification in the well fractures. Well LHD-10 intersects the F-6 fault and Well LHD-13 intersect F-1 fault (Azimudin and Hartanto, 1997). Well LHD-14 intersects F-1 fault at 1470 m. Well LHD-17 intersect F-8 fault at close to the surface. Well LHD-18 intersect F-1 fault at 1468 m. No circulation loss is found in well LHD-19. Well LHD-20 and 21 intersects F-2 fault at 1048 and 1355 m, respectively. Well LHD-22 intersects Pangolombian Rim at 2107. Well LHD-23 intersects the Pangolombian Rim at 1703-2000 m as indicated by total loss circulation and is an interesting target structure for northern part of the reservoir system in this field (Figure-6).

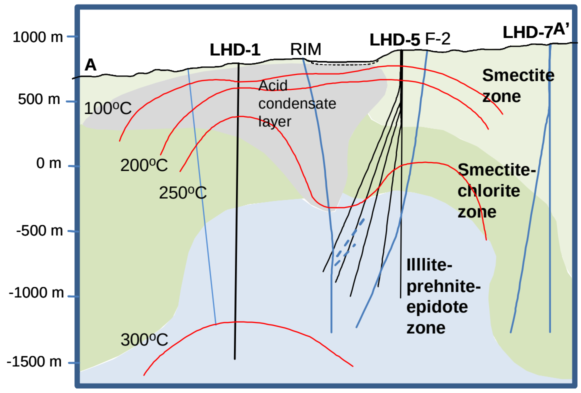

Figure 6. Cross section A-A' showing the wells, geological structures, temperature and alteration zones.

4. ALTERATIONS MINERALOGY

Hydrothermal minerals in Lahendong occur as replacements of primary minerals, replacement and deposition in vein and cavities. The replacement hydrothermal records the interactions between the wall rocks and the hydrothermal fluids, while space-filled minerals reflect the processes that affected the circulating fluid (Browne, 1988).

The subsurface lithology of the Lahendong Geothermal field is dominated by andesitic rocks except on the Tondano Unit that mostly comprises of rhyolitic type (Utami, et al, 2005).

The alteration minerals at shallow depth are dominated by calcite, quartz, hematite and iron oxide. Anhydrite is formed by the partial replacement of plagioclase and pyroxene. Clay minerals commonly found are smectite and interlayered smectite-chlorite at shallow level. Chlorite relatively more common found than illite (Utami, et. al, 2005).

In the depth of reservoir, epidote appears at depth around 133 mabsl in well LHD-1, 115 to 200 mbsl in the pad LHD-4, 120 to 240 mbsl at pad LHD-5 and deeper towards the pad of LHD-13 where epidote is found at depth of about 400 to 500 mbsl (Figure 7), indicating an underlying hot propylitic zone. Epidote is found at temperature more than 240°C-250°C (Browne, 1978). Deeper down in the wells LHD-4, 10, 12 and 13, silicification occurs that probably results in sealing the permeability marked by the low permeability in these wells.

5. RESERVOIR

The important factor in the reservoir of the geothermal system is that the permeability and this is controlled by the faults system. The reservoir rock is found in the Lahendong geothermal system are mostly andesite as a part of the unit of Pra-Tondano.

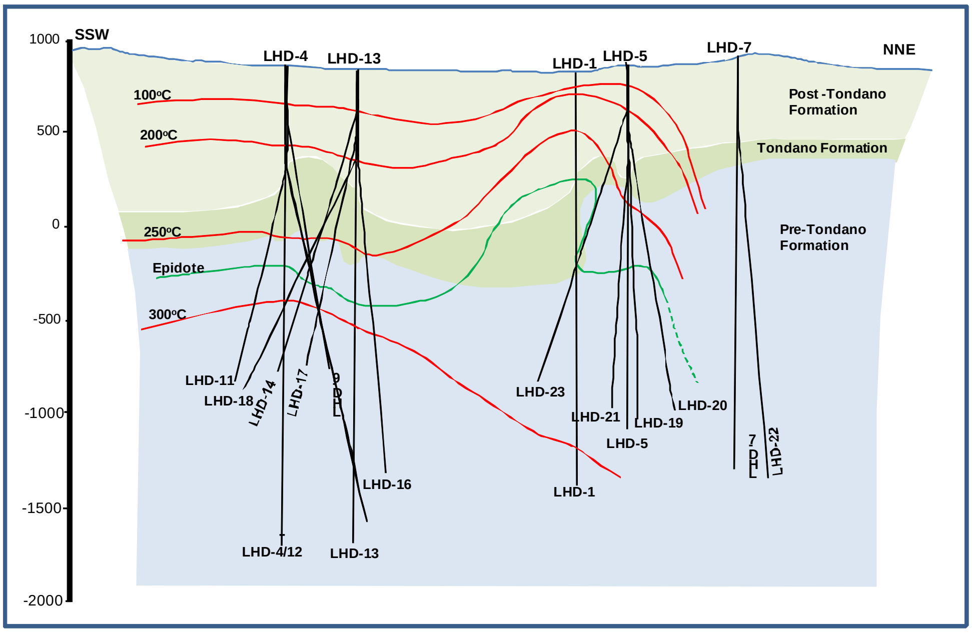

Figure 7. Cross section along B-B' showing the different formation, temperature distribution and depth of the the first appearance of epidote.

The reservoir system of the Lahendong geothermal field is divided into two systems, the Southern and Northern one. The Southern one has temperatures of 300 to 350°C with dryness about 80%, and the northern one has lower temperatures between 250 to 280°C with dryness around 30%. These two blocks are separated by a structure trending N-S and interpreted to be acting as the pressure barrier.

Some of the well data shows the existence of a shallow reservoir. The shallow reservoir in this field is encountered at a depth about 400 to 700 m. Shallow reservoir is found at a depth of about 650 m in well LHD-1, LHD-2, pad LHD-4 and 5 indicating lateral outflow from a shallow aquifer (Robert, 1987, Siahaan, 2003; Siahaan, 2005).

The deep reservoirs are located at depths below 1000 meter characterized by the appearance of epidote and usually correspond to circulation losses during drilling. Total circulation loss occurs at different depth in several wells especially in LHD-5, LHD-7 and LHD-23. The depth of circulation loss in the different wells is shown in Figure 8.

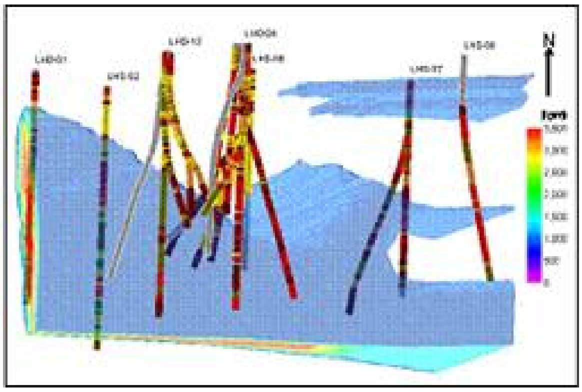

Figure 8. Section E-W showing the depth of circulation loss during drilling in the each well

6. TEMPERATURE DISTRIBUTION

The formation temperature in the Lahendong geothermal field was measured during the heating-up period. Most of the wells in the Lahendong geothermal field have temperature ranging from 250°C to 350°C except wells LHD-3, 6 and well pad LHD-7 having temperatures below 150°C (Figure 9). These wells are located at the boundary of the geothermal system.

Generally, temperature distribution correlation between well pad LHD-5 in the northern part and LHD-4 and 13 in the southern part shows a temperature increase (Figure 9).

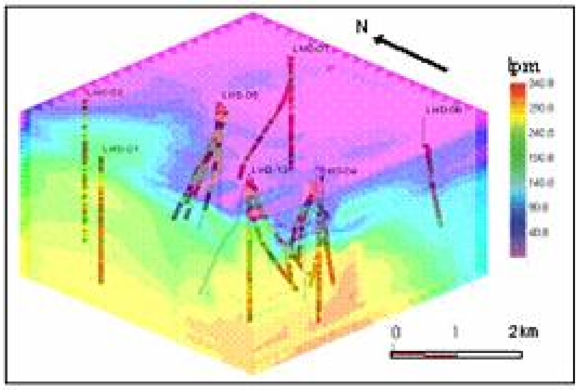

Figure 9. 3D view of temperature distribution in Lahendong geothermal field

In well pad LHD-4 higher temperature distribution is observed in the W, NW and SW part of the well pad towards Mt. Lengkoan as compared to the eastern part. Well pad LHD-5 also shows the same trend in W and SW direction of the well pad. This increase in temperature distribution is evidenced by an increase in maximum temperature from 250°C in well LHD-5 to 280°C in well LHD-23. This site which shows an increase in temperature distribution occurs below Linau Lake which is believed be the center of the upflow zone having temperature >300°C. These higher temperature distributions in both well pads make it an interesting site for geothermal resource utilization in the future.

High temperature minerals such as epidote, albite, wairakite and prehnite are especially found in wells LHD-4 and 5 and corresponds to the measured temperature from the near neutral pH alkali chloride water at temperature around 250 to 350°C. Fluid inclusions study at well LHD-5 shows that the homogenization temperature is around 227 to 269°C (Utami et al, 2005).

7. GEOTHERMAL MODEL OF LAHENDONG

The Lahendong geothermal model was first prepared in 1987. Barnet (1987) did the reservoir assessment, and then the geological model based on 7 exploration wells giving emphasis to structure and the lateral and vertical formation temperature distribution by Robert (1987). The combination of the geological data, geophysics and wells data was modeled by Pertamina Geothermal. The model of Azimudin and Hartanto (1997) emphasized the well data after completion of 14 wells, conceptual model by Siahaan (1999), and the 3D inversion Magnetotelluric model by Raharjo, et al, (2008).

Based on the geological analysis the subsurface condition of the Lahendong Geothermal Field can be divided into three main layers namely: smectite zone, smectite-chlorite zone and illite-prehnite-epidote zone (Figure 10).

The smectite zone is mainly characterized by the appearance of the low temperature clay mineral formed at temperatures between 100 to 150°C. This zone is dominated by basaltic andesite and tuff ignimbrite from the Post Tondano and Tondano Units respectively. In the Lahendong field, this zone behaves as the caprock and especially found throughout the wells LHD-3, LHD-6 and LHD-7 (Siahaan, 2005). This layer is characterized by a conductive layer having resistivity <10 ohmm (Raharjo, et. al., 2008).

The smectite-illite-chlorite zone is characterized by the appearance of chlorite in general and an acid layer with the presence of kaolinite in particular in wells LHD-1 and 5. This acid layer observed in wells LHD-1 and 5 occurs from the surface to 1000 m depth in the former and at shallow depth in the latter. This zone is located in the Tondano and Pra-Tondano Units.

The illite-prehnite-epidote zone is characterized by the appearance of prehnite, epidote, and secondary quartz at depths of about 700 m in well LHD-1 and 2 and at around 1000 to 1300 m in the well pad LHD-4, 5, and 13. This zone is dominated by the Pra-Tondano Unit and marked by resistivity value of 20 to 60 ohm m (Siahaan, 2005; Raharjo, et. al., 2008).

The reservoir fluid of the wells in the Lahendong geothermal fluid is mainly dominated by the Neutral Chloride water except the wells LHD-1, 3 and 7. In the western part, the shallow reservoir is associated with an acid fluid and several wells indicate a vapor dominated zone. The reservoir system is believed to center at around Lahendong-Kasuratan-Linau and is characterized by the distribution of the surface thermal manifestation.

The temperature profile shows different characteristics. Wells LHD-1, 2 and 5 in the northern part have sharp change in temperature gradient at about 350 m depth that stable at 250 to 280°C, whereas, most of the temperature profile of well pad LHD-4 and 13 in the southern part show a change in the temperature gradient at depth 650 m where the gradient is stable at about 320-340°C.

The heat source for the geothermal system in this field is believed to be a magma cooling beneath the Mt. Lengkoan and Mt. Kasuratan (Siahaan, 2005).

One of the important aspects to sustain the geothermal system is the recharge from the surrounding system. The recharge area of the system is from the Mt. Tampusu in the east and Mt. Lengkoan in the SW at an elevation of about 800-900 masl (Batan, 1991).

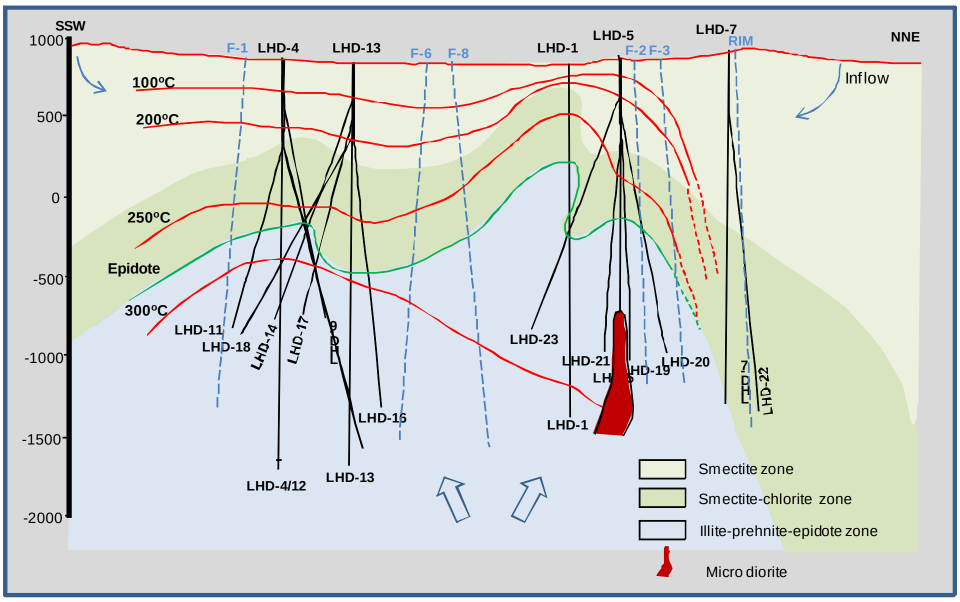

Figure 10. Geothermal model of Lahendong geothermal field (Modified from Siahaan, 2000).

8. CONCLUSION

The stratigraphy of Lahendong geothermal field can be divided into 3 lithological units i.e. Pre-Tondano, Tondano and Post Tondano Units.

Five main structures were encountered in the Lahendong geothermal field. The structures are Pangolombian rim, and faults striking NE-SW, E-W, NW-SE and N-S.

The reservoir system in the Lahendong geothermal field is divided into two reservoirs, the southern part has temperatures of 300 to 350^{o}C with dryness about 80%, and the northern one has lower temperatures between 250 to 280^{o}C with dryness around 30%.

Based on the temperature distribution, the interesting site for geothermal resource utilization is located in the NW, W, and SW direction of well pad LHD-4 and W and SW direction of well pad LHD-5.

Three main alteration zone encountered in this field are smectite, smectite-chlorite and illite-prehnite-epidote zone.

THE RECHARGE AREA OF THE SYSTEM IS FROM THE DRAINAGE SYSTEM OF MT. TAMPUSU AND MT. LENGKOAN.

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