OVERVIEW OF THE LAHENDONG GEOTHERMAL FIELD, NORTH SULAWESI, INDONESIA: A PROGRESS REPORT

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SUMMARY –Lahendong is a geothermal field located in the northern part of the North Arm of Sulawesi. It forms part of the Sangihe volcanic arc. Re-examination of cores and cuttings recovered from some of the 17 drillholes to depths of 2500m, as well as re-interpretation of air photographs and field checking has enhanced our understanding of the geology and hydrothermal alteration of the field. The thermal manifestations are of steam-heated-type, and their distribution is mainly controlled by the NE – SW trending faults. However the hydrothermal alteration of cores and cuttings shows that the thermal fluid is water of near neutral pH. The deep reservoir is hosted by volcanic rocks of Pleistocene age and volcanic-sedimentary rocks of Pliocene age which are intruded by diorite dykes. The hydrothermal fluid-rock interactions have produced clays, calcite, anhydrite, pyrite, iron oxide, quartz, epidote, prehnite, pumpellyite, adularia, secondary albite, and possibly tourmaline. The hydrothermal mineral paragenesis suggests that at least 3 stages of alteration have taken place. The earliest stage formed mono-mineral veins and cavities and the second and the third stages yielded veins and cavities with more diverse mineralogy and texture. However, the hydrothermal mineral geothermometers suggest that the productive reservoir has not undergone significant temperature change since the minerals formed. This paper is a progress report of research aiming to determine the subsurface geology and to reveal the evolution of the Lahendong hydrothermal system.

1. INTRODUCTION

The Lahendong geothermal field is located about 30 km south of Manado, the Capital of North Sulawesi Province, at an elevation of about 750 m above sea level. It is the first developed field in the eastern part of Indonesia.

Lahendong is a water-dominated field with reservoir temperature > 300^{o}C. The proven productive area is 4 km^2. Currently it has 20 MWe installed capacity, but is being projected to produce 60 MWe by 2010. The field is managed by Pertamina Geothermal Energy (PGE), and the power generation by PLN (State Electricity Company). Up to September 2004, 17 wells have been drilled (i.e., LHD-1 to LHD-17) to depths ranging from 1500 – 2500 m.

This paper describes the geology and the variation and styles of subsurface hydrothermal alteration of the field, and forms a progress report of a research project on the subsurface geology and the evolution of the Lahendong geothermal system by the first author.

2. TECTONIC AND VOLCANISM OF MINAHASA AREA

Lahendong is situated at the North Arm of Sulawesi, in a part of the volcanic arc extending from Sangihe Island to the Minahasa area. The North Sulawesi Trench occurs as the result of the subduction of the Celebes Sea Plate to the south beneath the North Arm of Sulawesi, while the volcanic arc extending from Sangihe Island to Minahasa area formed due to subduction of the Molucca Sea Plate to the west (Hamilton, 1979; Hamilton, 1988; Simandjuntak & Barber, 1996; Lumbanbatu *et al*, 2003). The tectonic elements of the Minahasa are presented in Figure 1.

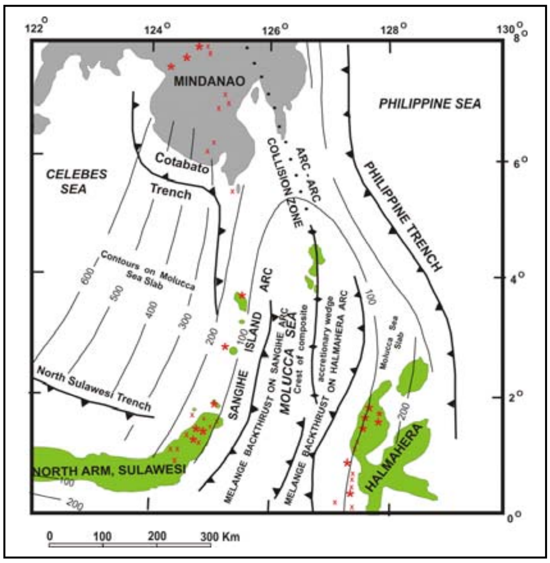

Figure 1. Tectonic elements of the Minahasa area (re-drawn from Hamilton, 1988). Contours show depth of subducting slabs in km; * active volcano; x inactive volcano.

Verbeek (1908) and Kamerling (1925) *vide* Ganda & Sunaryo (1982) mention that the oldest volcano in Minahasa is the Lembeyan volcanic complex. It was active during the Miocene, producing andesitic to basaltic breccia, lava and tuff. The remnants of its caldera wall form hills in the east of Lake Tondano (Effendi, 1976).

During the Late Pliocene or Early Pleistocene a major volcanic eruption took place, outpouring several hundred cubic kilometres of tuff and ignimbrites, and forming the large Tondano volcano-tectonic depression (part of which is now occupied by Lake Tondano). This 20 km-long structure trends NNE-SSW, parallel to the Sangihe Arc. A smaller eruption centre then emerged inside the Tondano depression, and is known as the Pangolombian depression, in which the Lahendong geothermal field occurs.

At present 3 most active volcanic centers at the Minahasa area, i.e., Klabat, Lokon - Mahawu, and Soputan - Riendengan. Lahendong are located between Lokon-Mahawu and Soputan–Riendengan. The last eruption of Mts. Lokon and Soputan took place in 2002 and 2000, respectively (Volcanological Survey of Indonesia web page, last updated March 2004).

3. GEOLOGY OF THE LAHENDONG AREA

The geology of the Lahendong area summarised here is mainly based on re-evaluation of the results from previous workers, combined with the re-examination of the subsurface rocks and field checking. The studied wells discussed in this progress report are LHD-1, 3, 4, 5 & 7. A geological map and a cross-section are presented in Figures 2 and 3, respectively.

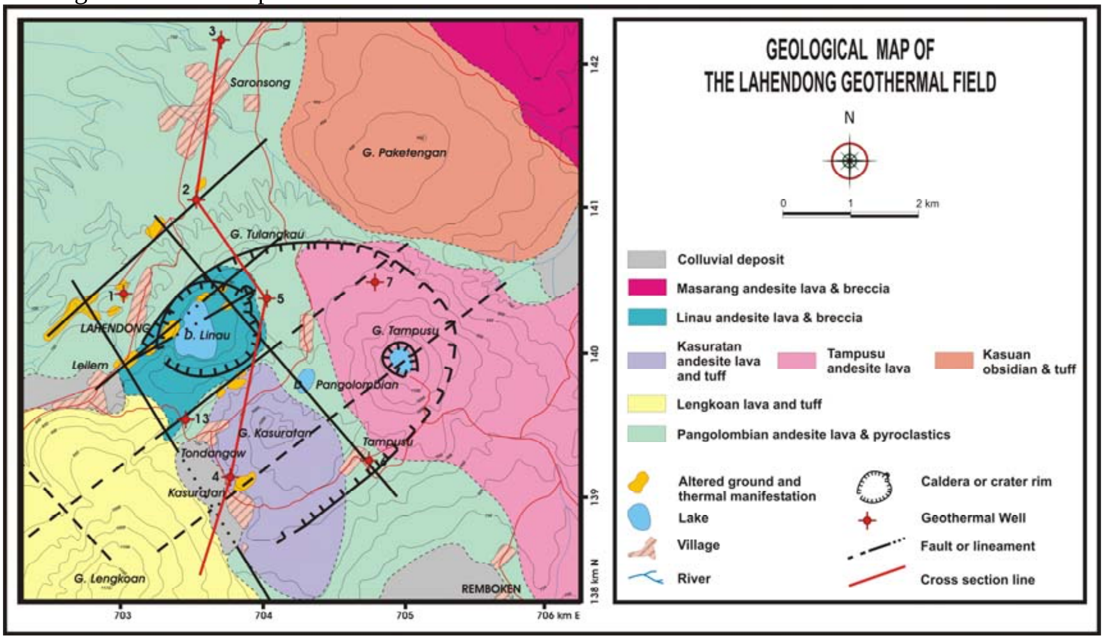

Figure 2. Geological map of the Lahendong geothermal field, North Sulawesi (revised from Robert, 1987, and Siahaan, 2003).

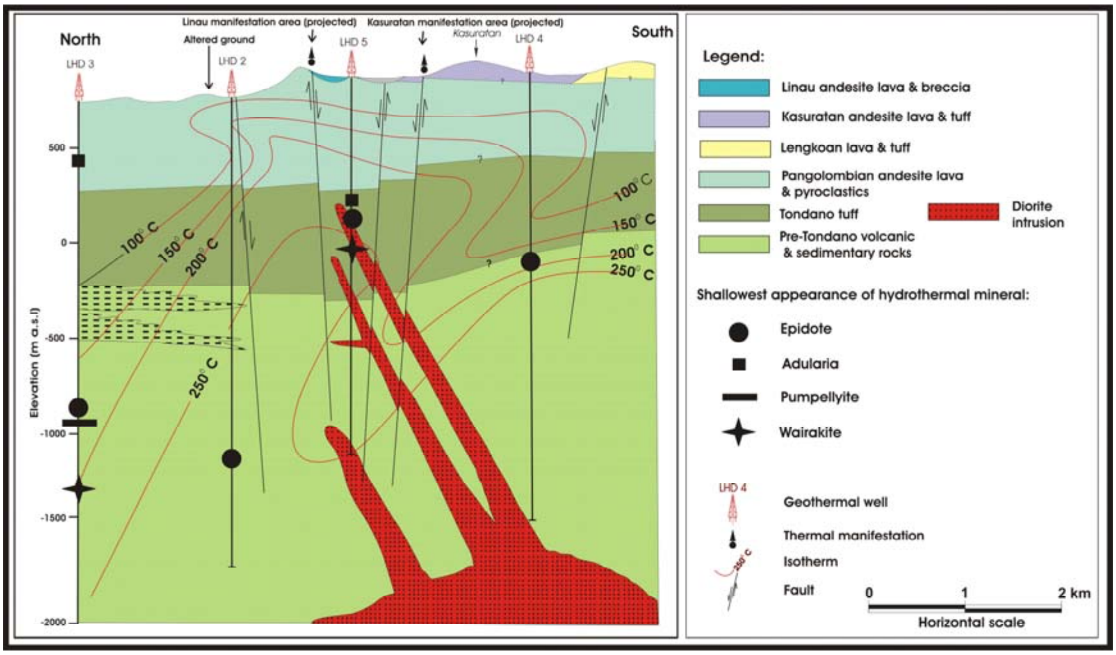

Figure 2. North – South cross-section from LHD-3, 2, 5, and 4 showing the distribution of lithologic units, the shallowest occurrence of some important hydrothermal minerals, as well as the present-day isotherms.

3.1. Stratigraphy

The rock units in surface and subsurface are described in the following paragraphs. Their stratigraphic relationship is illustrated in Figure 4.

Colluvium		
Masarang andesite lava & breccia		
Linau andesite lava & breccia (0.458 ± 0.042 Ma)		
Kasuratan andesite lava & tuff	Tampusu andesite lava	Kasuan obsidian & tuff
Lengkoan lava and tuff (0.586 ± 0.051 Ma)		
Pangolombian andesite lava & pyroclastics		
Tondano	Diorite intrusion	tuff (0.871 ± 0.097 Ma)
Pre-Tondano		volcanic & sedimentary rocks (2.19 ± 0.03 Ma)

Figure 4. Schematic diagram of the stratigraphy of the Lahendong area. Ages determined from K/Ar dating are indicated.

Pre-Tondano volcanic and sedimentary rocks.
The Pre-Tondano rocks comprise volcanic rocks (tuff, water-laid tuff, andesite lava, andesite breccia) intercalated with volcanic derived sedimentary rocks (fossiliferous siltstone). This unit is the lowermost encountered by drilling, with its top located from +5 m a.s.l to -594 m b.s.l. K/Ar dating of lava from this unit suggests an age of 2.19 ± 0.03 Ma or Late Pliocene (P.T. Gondwana, 1988). The fossiliferous siltstone may correlate with that described by Effendi (1976), of Pliocene age.

Tondano tuff
Tondano tuff outcrops outside the Lahendong geothermal area, and is dominated by lapilli tuff. K/Ar dating of a surface sample suggests its age is 0.871 ± 0.097 Ma, or Early Pleistocene (P.T. Gondwana, 1988). The top of this unit is encountered by drilling from 455 to 6 m a.s.l, with thicknesses ranging from 460 to 600 m. It is characterized by lapilli tuff and tuff breccia with intercalations of pumiceous rhyolitic lava.

Diorite intrusion
Diorite intrusions were encountered by well LHD-5 at several depth intervals (i.e. ~130 m a.s.l, -20 m, -220 m, -420 m, -520 m, and -1015 m b.s.l). They are interpreted as dykes intruding the Tondano and Pre-Tondano rock units, and forming the parts of a larger intrusive body.

Pangolombian andesite lava and pyroclastics
The Pangolombian andesite lava & pyroclastics occupy the largest part of the field. At the surface they comprise interbedded welded ignimbrite, andesite breccia, and tuff. At the subsurface the top of this unit is encountered in the studied wells from +6 to 878 m a.s.l. The subsurface sequence comprises andesite lava, andesite breccia, ignimbrite and tuff, ranging in thickness from 360 to 864 m.

Lengkoan lava and tuff
The Lengkoan lava and pyroclastics occupy the southern part of the field (Mt. Lengkoan), and are composed of andesitic and rhyolitic lavas, intercalated with tuffs and breccias. K/Ar dating indicates their age is 0.586 ± 0.051Ma or Middle Pleistocene (P.T. Gondwana, 1988).

Tampusu basaltic andesite lava
Tampusu basaltic lava occupies the eastern part of the field, and is dominated by basaltic andesite lava flows. The main direction of these flows is to the east, covering the eastern rim of the Pangolombian caldera.

Kasuratan andesite lava and tuff
The Kasuratan andesite lava and tuff comprises Kasuratan Hill. The andesite lava dominates the dome-shaped peak area, while the tuff dominates the flank and the foot, as is observed in field. It was encountered by well LHD-4 from the surface down to 40 m.

Linau andesite lava and breccia
Linau lava and breccia occupy the Linau Lake and its vicinity, in the central part of the field. The lava has a sheeting joint structure dipping outwards from Linau crater. The fragments of the breccia are mainly tuff and andesite. K/Ar dating suggests an age of 0.458 ± 0.042 Ma, or Middle Pleistocene (P.T. Gondwanda, 1988). Many altered bread crust bombs of andesitic composition occur in the alteration zones on the north-western shore of the Lake, and may suggest that a volcanic eruption once took place in the central part of the field.

Kasuan obsidian & tuff
The Kasuan obsidian occupies Paketengan Hill. It is composed mainly of obsidian flows intercalated with tuff. The direction of the flow was mainly NW-SE as is reflected by the elongation of the hill, and field observations.

Masarang andesite lava
The Masarang andesite lava which occupies the NE corner of the field is dominantly composed of vesicular andesite lavas and andesite breccias.

Colluvium deposit
Colluvium is common on the lower flanks down to the feet of the hills.

3.2. Structure

The main geologic structures in the Lahendong area can bee seen on the air photograph, and have been ground-checked. The presence of some of them has been confirmed by drilling.

Pangolombian caldera.
A remnant of the Pangolombian caldera is evident on the air photograph as an elliptical rim opening to the southwest. Reinjection well LHD-7 sited in the south of the northern rim encountered permeable zones from about 1500 m to well bottom at 2200 m.

Linau crater
Linau crater has a circular rim with steep walls of about 90 – 100 m high. The rocks exposed in this wall are andesite lava with sheeting joints, and breccia, with minor intercalated welded tuff.

NE – SW trending faults
These faults are evident by the alignment of the thermal manifestation areas, i.e. on the west of the Lahendong area, north-western shore of Linau lake, and the Tondangow – Kasuratan areas. At present these faults still function as permeability providers, as the thermal manifestations they control are still active. However, at some depths they may have been sealed, or partly sealed, as is indicated by the petrography of the subsurface rocks.

NW – SE trending faults
The most prominent NW – SE trending faults are those seen on the air photograph crossing the Pangolombian caldera. This fault aligns the thermal manifestation north of Lahendong village, north-eastern part of Linau crater rim, and the Pangolombian Lake. Its existence is supported by the presence of minor faults striking N130E cutting the Pangolombian andesite lava and pyroclastics.

3.3. Thermal manifestations

The main thermal manifestations occur on the western and northern shores of Linau Lake, Leilem, Lahendong, and Kasuratan Villages. They are all of steam-heated type, and mainly controlled by the NE-SW trending faults. No neutral pH water discharges in the Lahendong area. The manifestations usually consist of altered and steaming ground, acid-sulfate hot springs, mud pots, mud pools (with or without mud volcanoes), and hydrogen sulfide gas discharge. The common minerals in the altered ground are kaolin, residual silica, sulphur, very fine-grained pyrite, aluminous salts, and in places iron oxide. The most active thermal activity occurs in the Linau area, where there are some fumaroles as hot as 106 ^oC. The hottest steaming ground (T =60 - 98 ^oC at 45 cm depth), and the hottest acid sulphate springs (T = 80 – 90 ^oC, pH = 2 – 4) occur here.

4. RESERVOIR CONDITION

According to Azimudin (1999) there are 2 reservoir blocks at Lahendong, namely the:

Lahendong – Linau block
This block is located in the northern part of the field, covering the areas northwest, inside, and east of Linau crater. The reservoir northwest of the Linau crater has poor permeability, with acidic dry steam extending from 570 to 370 m a.s.l, and a shallow reservoir extending to -230 m b.s.l, as is confirmed by well LHD-1. The reservoir area inside the Linau crater has an acid dry steam layer extending from 570 to 370 m a.s.l. The presence of this layer is confirmed by shallow drill hole made by VSI. East of Linau crater there are shallow (475 to 275 m a.s.l), and deep (-220 to -1020 m b.s.l) hot water-filled reservoirs with good permeabilties as is confirmed by well LHD-5.

Lengkoan block
The Lengkoan block has medium permeability, and 2 levels of reservoir. The shallow and the deep reservoirs extend from 450 to 250 m a.s.l, and from -150 to -1150 m b.s.l., respectively. The temperature at the deep reservoir is about 350 ^oC. The presence of the Lengkoan block has been confirmed by wells in cluster LHD-4.

5. SUBSURFACE HYDROTHERMAL ALTERATION

5.1. Alteration style & mineralogy

There are 2 alteration styles in the subsurface rocks at Lahendong, i.e., replacement and that formed by direct deposition from circulating fluids. Lavas and intrusive rocks are more resistant to alteration than pyroclastic rocks, except where they are intensely fractured. The phenocrysts in lavas and intrusive rocks are usually more altered than the groundmass. Direct mineral deposition occured in fractures and cavities. The veins dip at 40^o – 70^o and from 100^o - 125^o with respect to core axes. Veins range in width from 0.1 – 10 mm. The hydrothermal minerals encountered in the studied wells include clays, carbonate, sulfate, sulfide, oxides, silica and calc-silicates. The shallowest appearance of some calc-silicate minerals are indicated in Figure 3.

The XRD analyses of the systematically selected subsurface rock samples have not yet completed, however, it can be reported that the clays common in them include chlorite, smectite, and illite. Chlorite is present at almost all depths. It is common as a replacement of plagioclase, pyroxene, and glass, as well as vein or cavity filling. Illite is found in the deeper parts of the studied wells, i.e., from about 450 m depth. It sometimes occurs as part of vein mineral. Hasibuan (1987) mentions the presence of smectite from 200 – 400 m and at 1100 m depths in LHD-4. According to Pudjianto (1988)

smectite occurs at LHD-5 from 100 – 900 m depth. Kaolinite is reported by Hasibuan (1987) to occur at shallow depth (~200 m) in LHD-1. Pudjianto (1988) reports that kaolinite occurs in LHD-5 from about 300 down to 1000 m depth.
Calcite is common as a replacement of phenocrysts and as fracture and cavity filling, but is absent in rhyolitic lava (e.g. in well LHD-3, at ~72 m a.s.l.). Calcite with bent cleavages, indicating deformation after deposition, is present in LHD-1 at ~ -150 m b.s.l., LHD-5 at ~ 400 m a.s.l, LHD-7 at ~ -700 m and ~ -850 m b.s.l.

Anhydrite first appears at ~ 100 m a.s.l. in LHD-1, as the latest cavity filling mineral after calcite and chlorite. In LHD-3, where there are sedimentary rock intercalations (e.g. at ~ 230 m a.s.l.), anhydrite is common, together with calcite, filling the chambers of globigerinid fossils. Pyrite is very common in the studied wells where it is disseminated in the ground mass or matrix.

Quartz is common as both a replacement and formed from direct deposition. In lavas and intrusive rock it replaces plagioclase phenocrysts, while in pyroclastic rocks microcrystalline quartz replaces the matrix. Quartz was usually the first mineral deposited in veins, patches and vugs, although it is also common after other minerals.

The common calc-silicate minerals are titanite, epidote, wairakite, pumpellyite, and clinozoisite. Adularia and secondary albite also occur. Titanite is common in all studied wells, as both replacement and vug filling; sometimes it is associated with leucoxene. Hematite usually occurs as a replacement mineral, and is more common in pyroclastic rocks than in lavas. It is absent in diorite.

Epidote occurs in all studied wells. It first appears at ~ 350 m a.s.l, in LHD-7, as replacement of plagioclase phenocrysts in andesite lava, and as a fracture filling deposited after calcite. The down-hole temperature here is less than 100 ^oC. The occurrence of epidote in LHD-2 was reported by Hasibuan (1987), i.e., at ~ -920 m b.s.l., where the down hole temperature is > 250 ^oC. In LHD-3 epidote appears at ~ -950 m b.s.l, as replacement of plagioclase phenocrysts in andesite lava. The down hole temperature here is ~175^{o}C. Epidote is common in well LHD-4, from ~ -145 m b.s.l. down to the bottom hole, where it occurs as replacement mineral and / or fracture filling after quartz. The present-day temperature ranges from about 190 – 350 ^oC. Epidote occurs in LHD-5 at most intervals cut by diorite dykes where the present-day temperature is about 250 ^oC. It both replaces plagioclase in diorite, and partly fills vein, some brecciated. Wairakite and prehnite are first present at around sea level in LHD-7, where they replace plagioclase fragments in crystal-rich tuff. Here wairakite also completely fills a fracture. The present-day temperature is < 100 ^oC. Prehnite also occurs at ~ -1450 m b.s.l. as cavity filling in tuff breccia, where the down hole temperature is ~ 125 ^oC. Prehnite was not found in other studied wells.

Pumpellyite is rare, and occurs as a replacement mineral in LHD-1 & 3. In LHD-1 it replaces plagioclase crystal fragments of tuff breccia from ~ -700 m b.s.l. Pumpellyite partially replaces plagioclase phenocrysts in brecciated vesicular lava at ~ -850 m b.s.l. in LHD-3. Clinozoisite together with quartz occurs in veins after illite in LHD-5 at ~ -225 m b.s.l.

Adularia is first present at ~100 m a.s.l in LHD-1, as a sole vein mineral in bedded crystal tuff. It commonly replaces plagioclase phenocrysts in lavas, or crystal fragments in pyroclastics, as well as becoming part of veins in LHD-3. Adularia is abundant in diorite dykes with brecciated veins in LHD-5, i.e., at ~ -420 m b.s.l. In LHD-7 adularia together with incipient epidote and secondary albite replace primary plagioclase crystal fragments in welded rhyolitic tuff, at ~ -660 m b.s.l. Secondary albite is rare in the studied wells, but occurs in LHD-1, 3, and 7. In LHD-1 albite occurs as cavity filling in andesite breccia at ~ -1100 m b.s.l. In LHD-3 it occurs as vein filling, after quartz but deposited before adularia, at ~420 m b.s.l.

Tourmaline may be present in LHD-1 at ~ 2200 m depth as a replacement of a plagioclase phenocrysts in andesite lava, but not in the other wells studied. Electron microprobe analysis is required to confirm this. Tourmaline is one of mineral indicators for the possible contribution from magmatic gases into the hydrothermal system.

5.2. Sequence of hydrothermal mineral deposition and vein relationships

Petrography shows a mineral paragenesis which is summarised as follows. Five types of veins cut the subsurface rocks at Lahendong, i.e., mono-mineral, mirror, segmental, a combination of mirror and segmental and brecciated veins. There are 4 types of deposition in cavities, i.e., mono-mineral, concentric, non-concentric, and a combination of concentric and non-concentric. The term “cavity” here includes pore, gas bubble, and chambers in fossils.

The minerals commonly deposited in mono-mineral veins or cavities are chlorite, calcite, quartz, titanite, and hematite and, less commonly wairakite, epidote, adularia, and anhydrite. The mirror-type veins or the concentric-type cavities usually consist of 2 or 3 secondary minerals. The first mineral deposited was quartz, chlorite, or calcite. The second and the third mineral deposited was calcite, chlorite, quartz or the calc-silicate minerals. Calcite deposited in the second or third stage but some has bent cleavages, indicating the occurrence of deformation after its deposition. The segmental is the commonest type of vein at Lahendong, and it is not always possible to judge its paragenesis. A brecciated vein occurs in a diorite dyke at ~ -420 m b.s.l in LHD-5. Based on the vein relationship at least 3 stages of alteration can be interpreted. The first stage formed mono-mineral veins cavities. The second and the third stages yielded veins and cavities with more diverse mineralogy and texture, due to maturation of the system.

6. CONCLUDING DISCUSSION

Lahendong geothermal system developed within a Pliocene – Pleistocene volcanic field. The production area is concentrated within the Pangolombian caldera. The shallow reservoir is hosted by Pangolombian andesite lava and pyroclastics, while the deep reservoir is within Tondano tuff and Pre-Tondano volcanic and sedimentary rocks which are intruded by diorite.

Hydrothermal mineralogy suggests that the deep circulating thermal fluid is of near neutral pH. The possibility of the contribution of magmatic gases into some parts of the system still needs to be investigated. Comparison between the hydrothermal mineral geothermometry and the measured well temperatures suggests that the area around well LHD-3 and LHD-7 has cooled. However, in general, the reservoir temperature in the rest of the reservoir has probably been stable since the hydrothermal minerals there formed.

Further study is needed to resolve the relationship between the hydrothermal activity and the volcanic activity at Lahendong. This may involve more detailed petrological studies and more systematic age dating.

The mineralogy of the hydrothermal alteration at Lahendong is relatively simple but the textural relations are quite complex. Further studies on the relationship among the veins, and careful observations on the sequence of mineral replacement may reveal the evolution of hydrothermal system at Lahendong. Systematic fluid inclusion measurements are needed to recognise changes of temperature and fluid composition. Comparison with the present-day reservoir characteristics will also be necessary to understand the temporal behaviour of the system.

7. ACKNOWLEDGEMENTS

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