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SUBSURFACE HYDROTHERMAL ALTERATION AT THE ULUBELU GEOTHERMAL FIELD, LAMPUNG, SOUTHERN SUMATRA, INDONESIA

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ABSTRACT

The liquid dominated Ulubelu geothermal field is situated in Lampung, southern Sumatra, Indonesia. The field lies in steep terrain between 300 and 1600 m above sea level (a.s.l.) but mostly from 700 to 800 m. The host rocks are mainly Quaternary andesitic pyroclastics and lavas. The field is at the southern end of the Great Sumatra Fault. The basement comprises pre-Tertiary volcanic rocks. Samples from 3 wells, namely UBL-01, UBL-02 and UBL-03, were studied and geophysical data, made available by Pertamina including gravity and resistivity results, were used.

Hydrothermal minerals display a distinct zonation of both clay and non-clay minerals. They show that the rock-altering fluid was produced from a liquid dominated reservoir. There are four hydrothermal mineral zones, namely: smectite, mixed-layer clays, chlorite and chlorite-epidote. The smectite zone is present at shallow levels (from near surface to 650 m a.s.l.). The mixed-layer clay zone occurs at 500 to 650 m (a.s.l.). The chlorite zone occurs at 100 to 500 m (a.s.l.). The chlorite-epidote zone occurs deeper than 100 m (a.s.l.).

The measured formation temperatures are generally lower than those indicated by the mineral geothermometers (chlorite, epidote, wairakite and others) by about 20^o to 60^{o}C and the fluid inclusion geothermometers by 10^o to 100^{o}C. Cooling may have occurred although the measured well temperatures may be too low, as wells were not thermally stable when the measurements were made.

The permeability of the reservoir is indicated by the presence of albite and adularia. These minerals mostly indicate higher permeable zone and coincide with the location of the production zones.

INTRODUCTION

The Ulubelu geothermal field is located in Sumatra Island, of the western part of the Indonesia Archipelago. The field occurs at the southern end of the Great Sumatra Fault System. This system trends along the long axis of the western part of the island. The Semangka fault extends to the Sunda Strait, along the Semangka River into Semangka Bay and beyond. This field is situated in the Pulaupanggung sub-district, Tanggamus district, Lampung Province about 50 km northwest of Bandar Lampung.

A survey of the field started only in 1990. Since 1993, three exploration holes have been drilled and the Geothermal Division of Pertamina has conducted geophysical surveys. Kemah and Yunis (1997) first undertook study of the clay alteration mineralogy of the Ulubelu geothermal field as part of their work on evaluating the geology-geochemistry of Ulubelu Lampung. They reported illite, chlorite and kaolinite. Hydrothermal studies in wells UBL-01 and UBL-03 respectively were conducted by Siahaan (1997) and Silaban (1998).

The Ulubelu geothermal field is associated with low residual gravity anomalies. This suggests that the Ulubelu field occur over a graben or small caldera that coincide with low apparent resistivity. Well temperatures are from 50 to 210^{o}C (figure 2).

Samples were selected and collected as cores and cuttings from wells UBL-01, UBL-02, and UBL-03 (figure 1). Well UBL-01 is located southwestern of Datarajan village on the surface elevation 750m (a.s.l.) in an area of low apparent resistivity and gravity low anomalies as results of resistivity and gravity examination. Well UBL-01 penetrates Mt. Rindingan pyroclastics, Mt. Kukusan basaltic lavas and Mt. Sula andesite lavas. Well UBL-02 is on the surface elevation 850m (a.s.l.) situated 4 km west of UBL-01 (figure 1), it lies within the surficial Mt. Rindingan pyroclastics. The hole penetrated altered tuff from about 50 to 400 m depth, but with altered breccia tuffs at about 150 to170 m and from 400 to 430 m. Other altered rocks are andesite breccia, andesite lava and tuffs at 430 to 460 m, 460 to 535 m and 535 to 600 m depths respectively. Breccia and tuff occur from 600 to 640 m depths. Well UBL-

03 was drilled in the center of the field on the surface elevation 700 m (a.s.l.), it encountered andesite, tuff, dacite, breccia-andesite and altered tuff-breccia (Kemah and Yunis, 1997).

LOCAL GEOLOGY

The Ulubelu geothermal field is located in high terrain. The highest part of the field is in its northern part at approximately 1300 m, but the summit of Mt. Rindingan is close to 1700 m. The lowest place, around 300 to 400 m, is located in the southern part of the field, and southeast of Mt. Kukusan. Most elevations in its central part are about 700 to 800 m (a.s.l.), the higher volcanic terrains of Mts. Tanggamus, Kabawok, Kurupan, Rindingan, Sula and Kukusan (figure 1) surround it.

(Masdjuk, 1990) has classified the local lithologies into stratigraphic units, mainly produced by volcanic activity consist of a complex of granodiorite, the older andesites and the Mt. Kabawok pyroclastics are located in the southeastern part of the field. The Mt. Korupan pyroclastics are in the northeast. The Mt. Rindingan complex occurs in the west and southwest and the Mt. Kukusan basaltic lava complex is in the south (figure 1). Between the Mt. Kukusan basaltic andesite lavas and the Mt. Sula andesite lavas are pumice tuffs. The Lake Ulubelu and the Mt. Duduk dacite lava complexes are seated in the middle of the area (Masdjuk, 1990) and (Kemah and Yunis, 1997). A stratigraphic column is shown in table 1.

Table 1. Stratigraphy of the Ulubelu geothermal field

	AGE (My)	LITHOLOGY
Holocene	0.0023-0.006	Alluvium and surficial alteration
Pleistocene	1.40 1.41 1.41 1.75	Mt. Korupan pyroclastics Mt. Rindingan pyroclastics Mt. Rendingan andesite lavas Mt. Kabawok pyroclastics
Pleistocene /Pliocene	1.41-3.94	Lake Ulubelu complex
Pliocene	3.39 3.94 4.50 ?	Mt. Duduk dacite lavas Mt. Kukusan basaltic lavas Mt. Sula andesite lavas Pumice-tuff
Miocene	14.67	Granodiorite and older andesites

Modified from (Masdjuk, 1990 and Kemah and Yunis, 1997)

THERMAL MANIFESTATIONS

The Ulubelu geothermal field lies within a degassing volcano of volcanism system occurs along the axis of the fault system (Hochstein and Sudarman, 1993). The field is liquid dominated and comprises mainly andesitic pyroclastics and lavas.

Thermal surface manifestations in the Ulubelu geothermal field consist of fumaroles, hot springs, mud and hot pools.

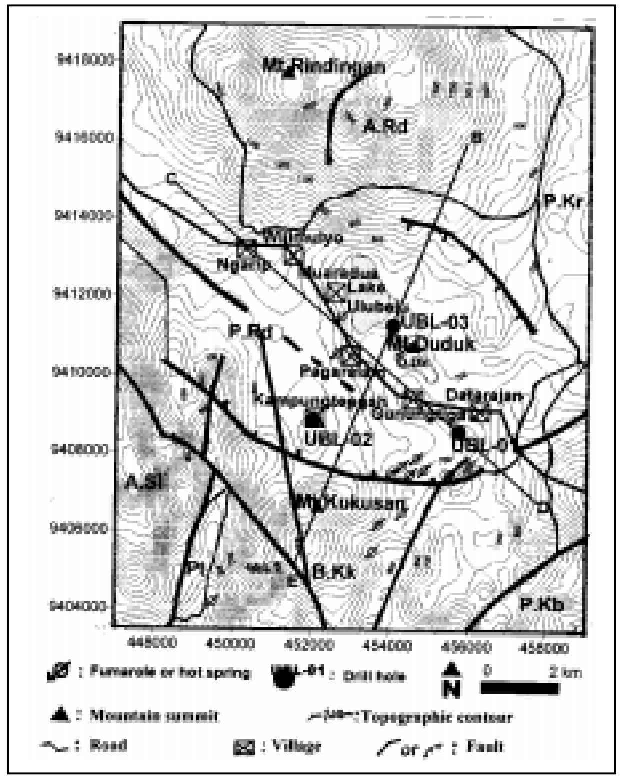

Figure 1. Simplified geological map of the Ulubelu geothermal. P.Kr = Mt. Korupan pyroclastics (1.40 My), A.Rd = Mt. Rindingan andesite lavas (1.41 My), P.Rd = Mt. Rindingan pyroclastics (1.41 My), P.Kb = Mt. Kabawok pyroclastics ((1.75 My), D.Dk = Mt Duduk dacite lavas (3.39 My), Bk.k = Mt. Kukusan basaltic lavas (3.39 My), A.Sl = Mt. Sula andesite lavas (4.50 My), Pt = Pumice-tuff. The thin contour represents topography (m a.s.l.)

The fumaroles are present at higher elevations in the central part of the area. They are situated close to Mt. Duduk and the villages of Muaradua and Pagaralam (figure 1).

The alkali chloride hot springs are present at lower elevations, from about 700 to 400 m above sea level (a.s.l.), in the southern part. They are widespread on the southern side of the Ulubelu River and extend to the southwest on the southern slope of Mt. Kukusan (figure 1). Ulubelu Lake is located in the central part of the prospect area, at mean elevations of about 700 m (a.s.l.), It is outlined by Mt. Duduk and the villages of Muaradua and Pagaralam.

HYDROTHERMAL MINERALS

Petrographic description of available cores and cuttings from wells UBL-01, UBL-02 and UBL-03 and combining them with the descriptions by other workers (Siahaan, 1997) and (Silaban, 1998) were studied.

Primary minerals present in the Ulubelu subsurface are mainly feldspars (labradorite, plagioclase), pyroxene (augite), oligoclase and quartz. Tentatively, the most intensely altered are dacite minerals and some of andesite, rhyolite is still intensely altered but lower than others.

The hydrothermal minerals are produced from liquid dominated reservoir, they are clay and non clay minerals that petrography examined.
Adularia. Adularia is replacement of plagioclase common to abundant in well UBL-01. It is common in well UBL-2 and also occurs in the vein. In well UBL-03, it is found from 320 to 840 m depth but rare.
Albite. Albite is replacement plagioclase and pyroxene common in three wells.
Calcite. Calcite is common replacement of plagioclase. In wells UBL-02 and UBL-03, it occurs in the vein.
Chlorite. Chlorite is abundant replacement of plagioclase directly, pyroxene and glass, it is also present in the vugs, cavities and vein. Chlorite is start commonly present at 350 m and below in well UBL-01, below 280 m in well UBL-02 and below 320 m in well UBL-03.
Epidote. Epidote is common replacement of plagioclase, it also occurs in the vugs and vein. Epidote occurs in well UBL-01 below 680 m depth and in well UBL-03 below 609 m depth.
Hematite. Hematite is tentatively only found in well UBL-02 common.
Illite. Illite is common replacement of plagioclase and it is also present in the vein.
Laumontite. Laumontite is common and also occurs in the vein.
Prehnite. Prehnite is rare replacement of plagioclase and occurs in the vugs and vein.
Pyrite. Pyrite is common almost disseminated.
Quartz. Quartz is predominant replacement of plagioclase disseminated. It is also present in the vugs, cavities and vein.
Titanite. Titanite is disseminated abundant and also occurs in the vein.
Wairakite. Wairakite is common replacement of plagioclase, it also occurs in the fracture, cavities and vein.

Clay minerals such as chlorite, smectite illite and mixe-layer clay are identified by X-ray diffraction analysis.
Chlorite. In well UBL-01, chlorite occurs at depths between 500 and 1200 m and associated with present well temperatures between 200 and 230^o C. In well UBL-03, chlorite is present at 440 and 870 m depth.
Smectite. Smectite is present in well UBL-03 until 600 m. The present well temperatures are lower than 170^{o}C.
Illite. Illite is present in three wells mostly distributed below 400 m.
Mixe-layer clays. Mixe-layer clays are present in wells UBL-02 and UBL-03 mostly distributed from 300 to 650 m depths.

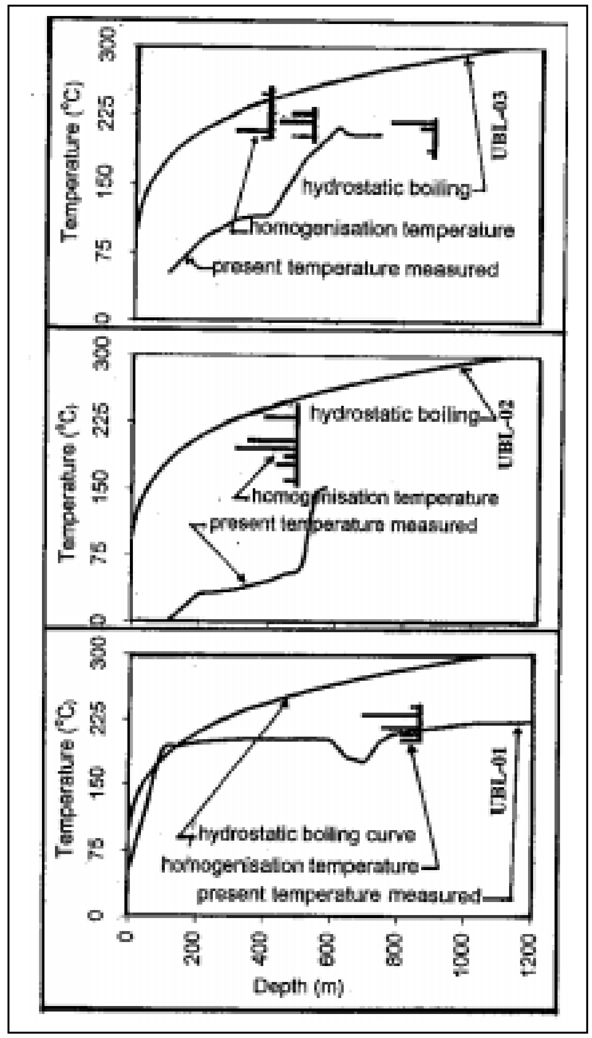

Figure 2. Plots of hydrostatic boiling curve, homogenization temperatures and present temperature measured against depths of geothermal wells UBL-01, UBL-02 and UBL-03.

Studied of hydrothermal mineral results combining with the other researches before, such as, Kemah and Yunis (1997), Siahaan (1997), Silaban (1998) may deduce the distinct zonation of four hydrothermal mineral zones, namely: smectite, mixed-layer clays, chlorite and chlorite-epidote. The smectite zone is present at shallow levels from near surface to 650 m (a.s.l.) and at temperatures of < 200^o C. The mixed-layer clay zone occurs at 500 to 650 m a.s.l. and is associated with temperatures of 200^o to 230^o C. The chlorite zone at between 100 and 500 m (a.s.l.) has a temperatures range of 230^o to 240^{o}C. The chlorite-epidote zone occurs deeper than 100 m at (m.s.l.) and at temperatures ranging from 240^o to 260^{o}C. The range temperature is referred to Browne (1998) and Kemah and Yunis (1997).

FLUID INCLUSION GEOTHERMOMETRY

There are six sets of fluid inclusion data, from the three wells. The homogenization temperatures in samples from well UBL-01 are higher than the measured downwell temperatures but below the hydrostatic boiling temperatures. In well UBL-02, however, the deduced temperatures are higher than the measured temperatures but match the hydrostatic boiling curve. The homogenization temperatures (Th) values well UBL-3 are higher than the well temperatures and also match with hydrostatic boiling curve at 400 and 480 m depth, but are a little lower than the hydrostatic boiling temperature at 860 m depth.

Well UBL-01 (920 m), gave reliable homogenization temperatures ranging from 225 to 245^o C. These are higher by 10 to 30^o C than the temperatures measured after only one day heating which seem unreliable, but they are still lower than the hydrostatic boiling temperature for pure water.

Well UBL-02 (480m), gave homogenization temperatures ranging from 205 to 245^o C. This mode is higher, by about 100^o C, than the recently measured well temperatures. The modes of the Th data mostly match the present boiling temperature at this depth. Two phase fluids were present in this well when the inclusions were formed.

The inclusions in samples from well UBL-03 may have been trapped at boiling temperatures. The homogenization temperatures in samples from 400, 480 and 860 m lie between 200 and 250^o C. These are higher than the recently measured temperatures by about 50 to 80^o C. The homogenization temperatures at 400 and 480 m depth match with hydrostatic boiling curve, but at 860 m, they are below it. The presence of vapor rich was and two phase inclusions in one sample are evidence of boiling here.

The inclusions in all three wells were probably trapped under boiling conditions and are higher than the measured temperatures. This suggests that cooling has occurred although the measured well temperatures may be too low, as the wells were not thermally stable when the measurements were made.

The inclusions trapped while boiling show that this field has been cooling since they are formed. The inclusions are present in calcite, anhydrite and quartz. The inclusions contain very dilute (near pure) water with equivalent wt. % salinities close to 0.0 to 0.9 %. The two-phase inclusions are liquid-rich (water dominated), with an average density of water close to 0.8 g/cm^3 (well UBL-02). The homogenization temperatures (Th) are mostly between about 200^o C to 250^o C.

Some samples contain inclusions with both two-phase and vapor inclusions. These are both primary and secondary inclusion and demonstrate boiling occurred during fluid entrapment.

The measured formation temperatures are generally lower than those indicated by fluid inclusion geothermometry by 10 to 150^o C. Cooling may have occurred although the measured well temperatures may be too low as the wells were probably not thermally stable when the measurements were made. The homogenization temperatures are between 200 to 250^o C compared to 140 to 220^o C measured well temperatures 10 to 100^o C lower (figure 2).

RESERVOIR CHARACTERISATICS

The field is a liquid dominated system with neutral pH, alkali chloride water. Its manifestations are characterized by fumaroles close to boiling temperature, and boiling springs with neutral pH water (Hochstein and Sudarman, 1993). The main reservoir is actually a two phase heat transfer system. Temperatures and pressures increase with depth. The results of this study in conjunction with the measurements made of present day conditions are here utilized to deduce the characteristics of the Ulubelu reservoir.

The main hydrothermal mineral assemblages were produced by neutral pH waters. The water involved in the fluid/rock interactions was close to pure water with a salinity of 0.0 to 0.9 wt. % NaCl. The presence of kaolinite, however, shows some steam heating has occurred (Suryadarma and Fauzi, 1991). It is product of rocks altered by steam heated waters as the piezometric surface descended after illite formed. Rocks interacting with neutral pH fluids may have produced the widespread illite alteration. Kaolinite was formed next, as result of the descent of acid condensate fluids that transformed illite to kaolinite.

The predicted of deep fluid composition of the Ulubelu field is located at the triple point of the albite - illite - adularia assemblage and close to the triple point of the illite - calcite - wairakite assemblage. Epidote and wairakite occur at Ulubelu together with calcite and illite (figure 3). The positioning the triple point indicates this. The triple points suggest that the deep liquid at Ulubelu has a composition between that at Broadlands and Wairakei.

Some permeable channels at Ulubelu are characterized by veins of adularia occur together with quartz and calcite. Minerals indicating permeable zones at Ulubelu are adularia, albite, quartz, illite, calcite and wairakite. Adularia and albite mostly indicate higher permeability; this may mark production zones. The adularia and albite coincide with quartz at 600, 840, 920, and 1040 m in well UBL-1, 40, 280 and 520 m in well UBL-02, and 320, 470 and 607 m in well UBL-03. Other minerals, such as wairakite, calcite and illite are widespread.

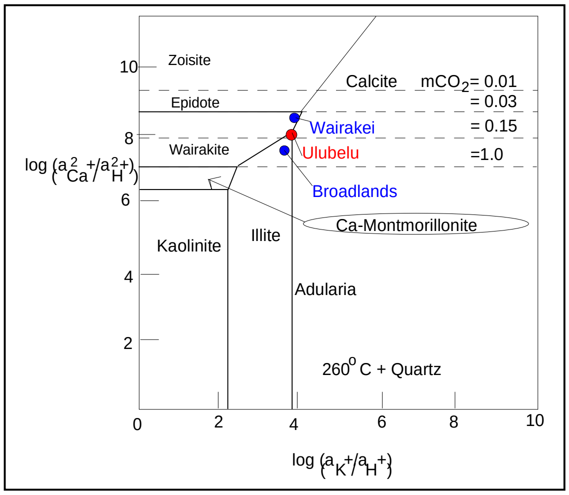

Figure 3. Estimation deep fluid composition in the CaO - Al_2O_3 - SiO_2 - K_2O - H_2O $\pm$ CO_2 system compared with Broadlands and Wairakei fluid compositions (from Browne, 1998)

The widespread interlayered clay minerals are interesting. Harvey and Browne (1991) suggest that mixed-layer clay sequences may predominate where water/rock interactions are too slow to achieve equilibrium, that is, away from fractures, in zones of lower permeability. At Ulubelu the mixed-layer clays are widespread, and probably mark the lower permeability prevailing in this part of the field.

CONCLUSIONS

Liquid dominated system with neutral pH, alkali chloride water of the Ulubelu geothermal field is marked by fumaroles close to boiling temperature, and boiling springs with neutral pH water.

The hydrothermal zonation consists of four hydrothermal mineral zones. The smectite zone is present at shallow levels (from near the surface to 650 m a.s.l.). The mixed-layer clay zone occurs at 500 to 650 m (a.s.l.). The chlorite zone occurs at between 100 and 500 m (a.s.l.). The chlorite-epidote zone occurs at deeper than 100 m (m.s.l.).

The inclusions were probably trapped under boiling conditions and are higher than the measured temperatures. This suggests that cooling has occurred although the measured well temperatures may be too low, as the wells were not thermally stable when the measurements were made. The presence of vapor rich and two phase inclusions in one sample are evidence of boiling there. The homogenization temperatures in samples are between 200 and 250^{o} C and salinity is close to pure water (between 0.0 and 0.9%).

The mixed-layer clays are widespread, and probably mark the lower permeability prevailing in this part of the field.

Minerals indicating permeable zones at Ulubelu are adularia, albite, quartz, illite, calcite and wairakite. Adularia and albite mostly indicate higher permeability; this may mark production zones.

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