HYDROTHERMAL CLAY MINERALS IN THE ULEBELU GEOTHERMAL FIELD, LAMPUNG, INDONESIA

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SUMMARY - Hydrothermal reservoir minerals, such as clays, wairakite and epidote, occur in samples from wells UBL-01, UBL-02 and UBL-03 drilled in the Ulubelu geothermal field. Well UBL-01 encountered andesite lavas at depths from 680 to 1200 m and lithic tuff at 520 m. The hydrothermal clays consist of chlorite, illite, kaolinite, and interlayered clay chlorite/smectite and illite/vermiculite. These are mostly present in andesite now intensely altered. Moderately porous rocks (5 - 15%) in well UBL-02 consist of lithic tuffs, from 80 to 400 m, above andesite lavas at 420 to 609 m and lithic tuff at 520 m depth. The rocks have been strongly altered with alteration intensities in the range 70 to 90%. The hydrothermal minerals here are dominated by interlayered clays consisting of kaolinite/smectite, chlorite/smectite, illite/vermiculite, plus discrete chlorite, illite, kaolinite and possibly talc. Well UBL-03, at depths from 320 to 607 m, mostly encountered tuff breccias with an intensity of alteration of about 75% and porosities around 15%. The deeper parts consist of dacite lava that is intensely altered, about 90%, with a porosity of about 20%. The hydrothermal minerals in rocks of this well are mostly the same as those in the two other wells but also present are illite/smectite, wairakite and epidote. The hydrothermal minerals delineate fluid flow that is strongly controlled by formation permeability. The interlayered clay minerals record this process. Specific temperature ranges and fluid compositions are interpreted from the presence of the hydrothermal minerals.

1. INTRODUCTION

Clay minerals are hydrous alumino-silicates sensitive to both temperature and the prevailing chemical environment. Their distribution is useful to help model the hydrology of a geothermal field.

Study of the clay alteration mineralogy of the Ulubelu geothermal field was first undertaken by Kemah and Yunis (1997) as part of their work on evaluating the geology-geochemistry of Ulubelu Lampung. They reported illite, chlorite and kaolinite.

The objectives of our study were to (1) determine the distribution of the clay minerals in the subsurface, (2) evaluate their specific temperature ranges, and (3) deduce the chemical environment of fluid/rock interactions.

2. GEOLOGICAL SETTING

The Ulubelu geothermal field is located in the Pulaupanggung sub-district, Tanggamus District, Lampung Province Indonesia, about 50 km northwest of Bandar Lampung. It occurs at the southern end of the chain of the Bukit Barisan volcanos along western Sumatra that are associated with the Semangka Fault and the Great Sumatra Fault (Santoso et al., 1995). The field, situated in high terrain mainly about 700 to 800 m above sea level, is surrounded by higher volcanic terrain including Mt. Tanggamus, Mt. Kabawok, Mt. Korupan, Mt. Rindingan, Mt. Sula and Mt. Kukusan (Figure 1).

Masdjuk (1990) classified the local lithology into many stratigraphic units mainly produced by volcanic activity. A complex of granodiorite, older andesite and the Mt. Kabawok pyroclastics are located in the southeastern part of the field. The Mt. Korupan pyroclastics are in northeast. The Mt.Rindingan pyroclastic and andesite lava complex lie in the north and northwest. The Mt. Sula complex occurs in the west and southwest and the Mt. Kukusan basaltic andesite lava complex is positioned to the south. 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; Kemah and Yunis, 1997). The local stratigraphy is shown in Table 1, and the geological features delineated on Figure 1.

The Ulubelu geothermal field is associated with low residual gravity anomalies. Figure 2 shows two geological profiles constructed from a gravity interpretation across the field in the NW and NNE directions. These results suggest that the Ulubelu field occurs over a graben or small caldera.

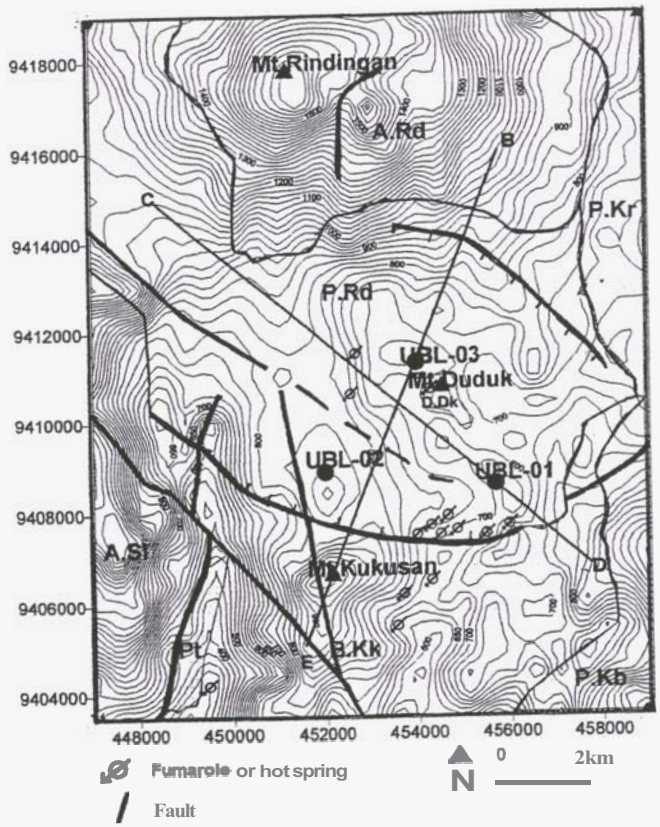


Figure 1. Simplified geological map of the Ulubelu geothermal field showing the locations of wells UBL-01, UBL-02 and UBL-03. P.Kr = Mt. Korupan pyroclastics (1.40 My), A.Rd = Mt. Rindingan Andesite lavas (1.41 My), P.Rd = Mt. Rindingan pyroclastics (1.41 My), P.Kb = Mt. Kabawok pyroclastics (1.75 My), D.Dk = Mt. Duduk dacite lavas (3.39 My), B.Kk = Mt. Kukusan basaltic lavas (3.94 My), A.Sl = Mt. Sula andesite lavas (4.50 My), Pt = Pumice-tuff (4.50 My). The thin contour lines represent topography (m a.s.l.).

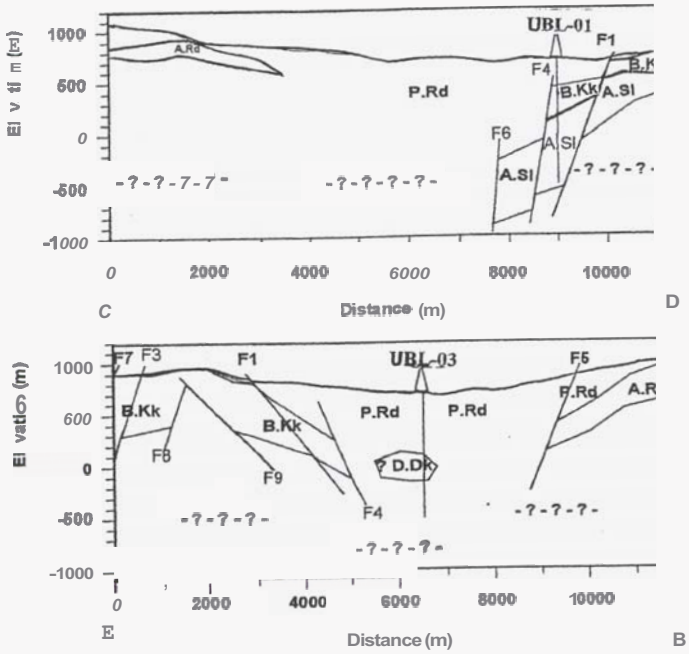


Figure 2. Geological profiles along lines CD and AB (Figure 1) constructed from 2-D interpretation of residual gravity anomalies. The densities (kg/m^3) used for the gravity modelling are: P.Rd = 2100, A.Rd = 2600, D.Dk = 2500, B.Kk = 2800, A.Sl = 2600. See the caption of Figure 1 for the names of rock units.

3. METHODS

Sample selection

Samples were selected and collected as cores and cuttings from wells **UBL-01, UBL-02,** and **UBL-03** (Figure **1).** Twenty-four samples were analyzed by X-ray diffraction and the results are listed in Table 2. Twenty-two samples were examined by *thin* section petrography.

Well **UBL-01** is located southwest of Datarajan village (Figure 1), in an area of low apparent resistivity and gravity low anomalies. Well **UBL-01** penetrates Mt. Rindingan pyroclastics, Mt. Kukusan basaltic lavas and Mt. Sula andesite lavas. Well temperatures are between **50** and **230° C,** which covers the most sensitive range for clay minerals (Harvey, **1998).**

Well **UBL-02** is 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 to **170** 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

Table 1. Stratigraphy of the Ulubelu geothermal field

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

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

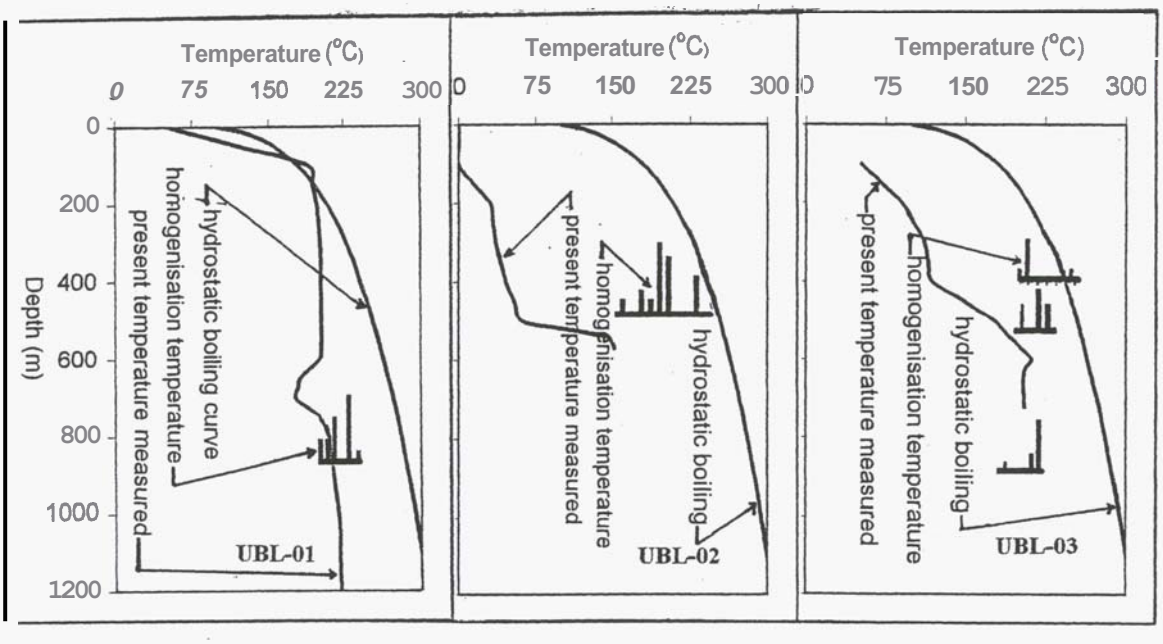


Figure 3. Plots of hydrostatic boiling points, homogenization temperatures and measured temperatures, against depths of the geothemal wells **UBL-0** 1, **UBL-02** and **UBL-03.**

535 to 600 m depths respectively. Breccia and tuff occur from 600 to 640 m (Kemah and Yunis, 1997).

Well UBL-03 was drilled in the center of the field (Figure 1). It encountered andesite, tuff, dacite, andesite-breccia and altered tuff-breccia (Kemah and Yunis, 1997). The measured temperature is from 50 to 210°C (Figure 3).

X-ray diffraction analysis

Clay samples were air-dried, glycolated and heated. The samples were fust crushed into a fine homogeneous powder using a mortar and pestle. The clay minerals were dispersed in distilled water with the $\leq$ 2.0 μm fraction collected by gravitational settling and mounted onto glass slides and allowed to dry below 40°C, ethylene glycol solvated and heated (550°C for 1 hour). A Philips PW 1050/25 diffractometer utilizing CuKα radiation analyzed all samples. Interpretation of the X-ray diffraction profile data is based on Brindley and Brown (1980) and Moore and Reynolds (1989).

4. RESULTS

Well UBL-01

Chlorite. Chlorite is relatively common below 220 m depth and is abundant below 520 m; the present measured temperature here is about 200°C. Chlorite is a common replacement of plagioclase and pyroxene. It is also exposed in the matrix. vugs and veins intergrown with fine-grained quartz.

The chlorite is characterized by reflections at 14.2, 7.1, 4.74 and 3.55 Å and kaolinite by reflections at 7.16 and 3.58 Å. The 7.1 and 3.55 Å peaks of chlorite and 7.16 and 3.58 Å peaks of kaolinite are superimposed. They were distinguished by heating to 550° C for 1 hour whereupon the 7.16 peak of kaolinite collapsed (Table 2).

Chlorite is also present as interlayered chlorite/ smectite at 680, 840, 1000 and 1120-m depth (Table 2). This mineral is characterized by reflections at around 14.5 Å on air dried, ethylene glycol treated and mounts heated to 550° C. The chlorite/smectite was tentatively found at a depth of 689 m and below. Harvey and Browne (1991,a) reported, following Kristmansdottir (1976), that the gradual transformation of trioctahedral smectite to discrete chlorite was completed above 270" C.

Illite. Illite is present at 520,1080 and 1200 m depth and is always together with kaolinite and chlorite, but chlorite is not present at 1200 m. The illite (2M1 type) is characterized by reflections at 10.0, 5.02, 4.48 and 3.34 Å. Interstratified illite/vermiculite is also found at 1200 m depth (Table 2). Illite is as abundant here as chlorite.

Kaolinite. Kaolinite is present in most samples from well UBL-01 (Table 2). The major peak at 7.16 Å, which collapses when heated to 550" C for 1 hour, characterizes it.

Well UEL-02

The majority of clay minerals present in samples from this well are mixed layer clays such as kaolinite/smectite, chlorite/smectite, chlorite/illite and illite/vermiculite, but there is also discrete chlorite. illite, kaolinite and possibly talc.

Kaolinite/smectite. Kaolinite/smectite is only present at 80-m depth in well UBL-02. It was identified tentatively by X-ray diffraction. Kaolinite/smectite has a peak at about 7.9 Å (air-dried), 7.7 8, (glycolated), that was destroyed by heating up to 550°C. It is also present together with discrete kaolinite.

Chlorite/smectite. Interstratified chlorite/smectite is present in well UBL-02. It occurs from shallow depths down to the deepest sample analyzed. This mineral exists at 80, 480, 520, 567, and 609 m depth. X-ray diffraction analysis recognized this mineral by the characteristic expansion of the major peak when solvated with ethylene glycol.

Chlorite/illite. Chlorite/illite was discovered only at 609 m depth. It is characterized by peaks in the range 10 to 14 Å, that do not change with ethylene glycol treatment or heating, except for a slight increase in peak intensity when heated.

Illite/vermiculite. Illite/vermiculite is characterized by a reflection at between 10 and 14 8, (air-dried sample) that collapses to 10 Å when heated up to 550° C. It is present at 360,400,480, and 609 m depth.

Chlorite. This clay is not as abundant here as it is in well UBL-01. It exists only at 100 and 609 m. Illite was discovered only at 520 and 567 m depth but interlayered illite/ vermiculite minerals are present above and below, such as from 360 to 609 m. Kaolinite is present also from 80 to 567 m depth. Talc was tentatively identified but its presence needs to be confirmed.

Well UBL-03

Clay minerals in this well are similar to those in the two other wells but here occur interlayered illite/smectite and rectorite (regularly interstratified illite/smectite). In this well also exists wairakite that is not found in well UBL-02.

Illite/smectite. Illite/smectite is characterized by peaks in the range 10 to 14 8, in air-dried samples, that expand with solvated ethylene glycol treatment but collapse to 10 Å when heated to 550° C. It was only tentatively identified at 400 m depth where rectorite also exists. Rectorite (regular stratified illite/smectite) was indicated by its reflection at about 25 Å in an air-

dried mount that expanded when treated with ethylene glycol but collapsed to 20 Å when heated (Table 2). The illite/smectite minerals occur at 320 and 400 m depth.

Wairakite. Wairakite was detected petrographically. It is common to abundant at depths from 725 to 800 m. X-ray diffraction analyses confirmed its presence at 400 m.

Epidote. Epidote is abundant at the Ulubelu geothermal field together with adularia and albite.

5. DISCUSSION.

Clay minerals present at Ulubelu are chlorite, illite and kaolinite, and mixed layered chlorite/smectite, chlorite/illite, illite/ vermiculite, illite/smectite, and kaolinite/smectite.

Present measured temperatures at the Ulubelu geothennal field are from about 40 to 230°C (Figure 3); Table 2 compares the measured well temperature with the identity **of** the clay minerals present in cores and cuttings. Chlorite, illite and kaolinite mostly occur at reservoir temperatures from about 203 to 222°C, illite/vermiculite is present at temperatures up to 222°C, chlorite/smectite from 200 to 220°C, illite/smectite at 103°C. Chlorite/illite and kaolinite/smectite appear to have no thermal significance. The homogenization temperatures of inclusions are between 200 and 250°C (Figure 3).

The occurrence of wairalute and epidote also supports the evidence **of** the subsurface temperatures at Ulubelu. Wairakite has **a** temperature range of about 240 to 310°C (Reyes, 1990) and 200 to 330" C (Harvey, 1998a). Epidote is present at temperature above 200°C; Reyes (1990) and Harvey (1998) recorded temperature for epidote at 240°C and above in the Philippine and Wairakei fields.

Wairakite occurs in wells UBL-01 and **UBL-03** but epidotes are present in all three wells. They mostly appear fi-om 203 to 222°C which is slightly below their usual thermal stability range.

The chlorite/illite, chlorite/smectite and illite/smectite in the illite/chlorite zone present within andesite host rocks may be produced by rocks interacting with neutral pH fluid and the presence of kaolinite **may** result from rocks being altered by steam heating (Suryadarma and Fauji, 1991).

6. CONCLUSIONS

The clay minerals in the Ulubelu geothermal field show a distribution with respect to temperature. These temperatures are consistent with the temperatures indicated by fluid inclusions. The widespread distribution of clay minerals with depth results from interactions between the host rock and neutral pH fluids. Fluid inclusion freezing measurements indicate that **almost** pure water was trapped.

7. ACKNOWLEDGMENTS

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Table 2 Result of X-ray diffraction analysis of clay minerals

Wells and Depth	Rock type	Spacing (A) Air-dried	Glycolated (24 hours)	Heated (550°C)	Tm (+/-)°C	Minerals
520 m	lithictuff	14	14	14	203	Chlorite
		10.8	9.4	9.7		Illite
		7.1	7.1			Kaolinite
680 m	dacite	14.6	14.7	14.7	205	Chlorite/Smectite
	lava	7.2	7.2			Kaolinite
840 m	andesite	14.3	14.4	14.5	214	Chlorite/Smectite
	lava	7.1	7.1			Kaolinite
1000 m	andesite	14.9	14.9	14.9	220	Chlorite/Smectite
	lava	7.1	7.1	7.1		Chlorite
1080 m	andesite	14	14	14	221	Chlorite
	lava	10	10	10		Illite
		7	7			Kaolinite
1120 m	andesite	14.5	14.5	14.5	221	Chlorite/Smectite
	lava	7	7	7		Chlorite
1160 m	andesite	14	14.3	14.1	222	Chlorite
	lava					
1200 m	andesite	14	14		222	illite/Vermiculite
	lava	10	10	10		Illite
		7	7			Kaolinite
UBL-2						
80 m	rhyolite	7.9	7.7			Kaolinite/Smectite
	tuff	7.2	7.1			Kaolinite
120 m	lithic tuff	15	17	17		Chlorite/Smectite
		7.2	7.2	7.2		Chlorite
360 m	lithictuff	10.7	10	10.6	41	Illite/Vermiculite
400 m	breccia tuff	10.7	10	10.1	46	Illite/Vermiculite
480 m	andesite	14.3	17.5	14.5		Chlorite/Smectite
	lava	10.7	9.6	10		Illite/Vermiculite
		7.1	7.1			Kaolinite
520 m	andesite	14	15	14	103	illite/smectite)
	lava	9.9	10	10.3		Illite
		7.2	7.1			Kaolinite
567 m	lithic tuff	15.1	17.3	14.5<	152	Chlorite/Smectite
		9.9	9.9	10.1		Illite
		7.1	7.1			Kaolinite
609 m	andesite	14.9	17	15.2		Chlorite/Smectite
	lava	14	14.3	14.3		Chlorite/Illite
		10.4	10	10.5		Illite/Vermiculite
		7.3	7.1	7.3		Chlonte
UBL-3						
320 m	lithic tuff	24.8	28.4	20.7		Rectonte (*Illite/Smectite*)
		15.4	17.4	9.9		Illite/Vermiculite
		12.8	14.1	14.2		Illite/Chlorite
400 m	breccia	15.2	16.9			Chlorite/Smectite
	tuff	12.6	13.3	10.1		Illite/Smectite
		7.2	7.2			Kaolinite
440 m	breccia	14.9	16.9		147	Chlorite/Smectite
	tuff	12.5	13.5	14.2		Chlorite/Illite
		7.2	7.2	7.2		Chlorite
607 m	rhyolite	14.3	14.4	14.6	212	Chlorite/Smectite
	lava	7.2	7.2			Kaolinite
870 m	dacite	14.3	14	14.6		Chlorite/Smectite
	lava	10	10	10		Illite
		7.1	7.1			Kaolinite
890 m	dacite	10	10	10		Illite
	lava	7.1	7.1			Kaolinite

Tm = measured temperature