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Clay Alteration Study from Wells of Tompaso Geothermal Field, North Sulawesi, Indonesia

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ABSTRACT

Tompaso geothermal field is situated on the northern arm of Sulawesi Island, Indonesia. It is one of PT. Pertamina Geothermal Energy (PGE) project in the eastern part of Indonesia archipelago. Petrology analysis from cuttings (general lithology description, XRD & petrography data) and borehole data (rate of penetration, circulation losses, and PT measurements) of wells LHD-27 and LHD-30 from Tompaso Geothermal field have been used for this study. It is mainly a detailed study of clay mineralogy. Clay minerals are known to be sensitive to temperature and chemical changes. Therefore clays are very useful for geothermal exploration as a geothermometer as well as assessing the subsurface fluid pH.

The clay mineralogy occurring in the Tompaso geothermal system consists of: kaolinite, smectite, chlorite-smectite (corrensite) from shallow to intermediate level (T: 50-130^{o}C); illite at intermediate level as a transition zone (T: 180-250^{o}C); chlorite is predominant in deeper levels and acts as a clay marker for high temperature (>250^{o}C) and permeability zone when it is associated with epidote and secondary quartz. Most clay minerals forming temperatures are in agreement with the current stable borehole temperatures. The degree of crystallinity of these clays increases with depth as shown by their decreases in Kubler indices. It also shows that the crystallinity of clay is temperature dependent.

1. INTRODUCTION

Tompaso geothermal field is situated on the northern arm of Sulawesi Island, Indonesia. It can be reached by land transportation from Manado, the capital city of North Sulawesi Province, about 60 km south from the city (figure 1). The field is a part of the Lahendong Working Area, owned and operated by PT. Pertamina Geothermal Energy (PGE) that has been producing 80 MW of electricity from 4 Units (4 x 20 MW) in the Lahendong sector. The Tompaso field is believed to have a different reservoir from the Lahendong field. It is separated from the Lahendong field by the Lengkoan mountain range.

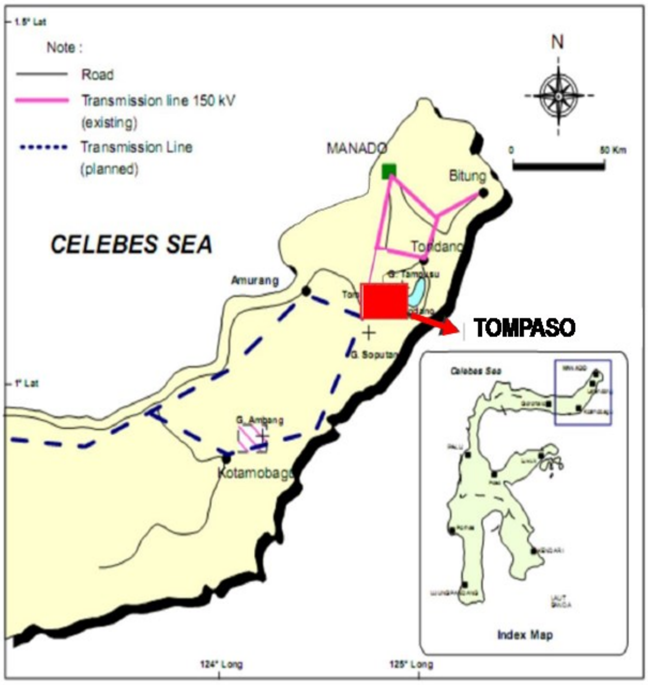

Figure 1. Location map of the Tompaso Geothermal Field.

Borehole data from 2 wells (LHD-27 and LHD-30) were used for this study. They consist of analyzed cutting samples with general lithology description; petrography and XRD data; temperature measurement of wells; drilling parameter data such as rate of penetration and circulation losses. This data is used to study the subsurface geology and hydrothermal alteration in Tompaso field.

Clay minerals are known to be sensitive to temperature and chemical changes. Therefore clays are very useful for geothermal exploration as a geothermometer as well as assessing the subsurface fluid pH. Detail study of clay mineralogy is mainly discussed here.

2. GEOLOGY OF THE FIELD

A series of geoscientific studies (geology, geochemistry and geophysics) were made by PT. Pertamina Geothermal Energy (PGE) from 1982. Geology of the area was first mapped by Ganda and Sunaryo in 1982 and followed by a geochemistry survey. A geophysical survey was added later on by having gravity, DC resistivity and MT resistivity surveys within the prospect area. PGE updated the resistivity model by conducting another detail MT-TDEM survey in 2006 due to pre-drilling requirements.

The Tompaso field is located in the northern arm of the K-shaped Sulawesi Island, Indonesia. This region is dominated by Quaternary volcanic on top of Tertiary sediments (Siahaan 2005, after Hamilton, 1990). The regional geology of Northern-arm of Sulawesi is divided into 3 compartments which are the NE-SW trending compartment (Minahasa compartment), the central E-W trending segment (Gorontalo compartments) and the N-S trending compartment or neck (Siahaan et.al, 2005). The field is a part of the Minahasa compartment that was influenced by the double sided subduction of Molucca plate beneath Sangihe ridge.

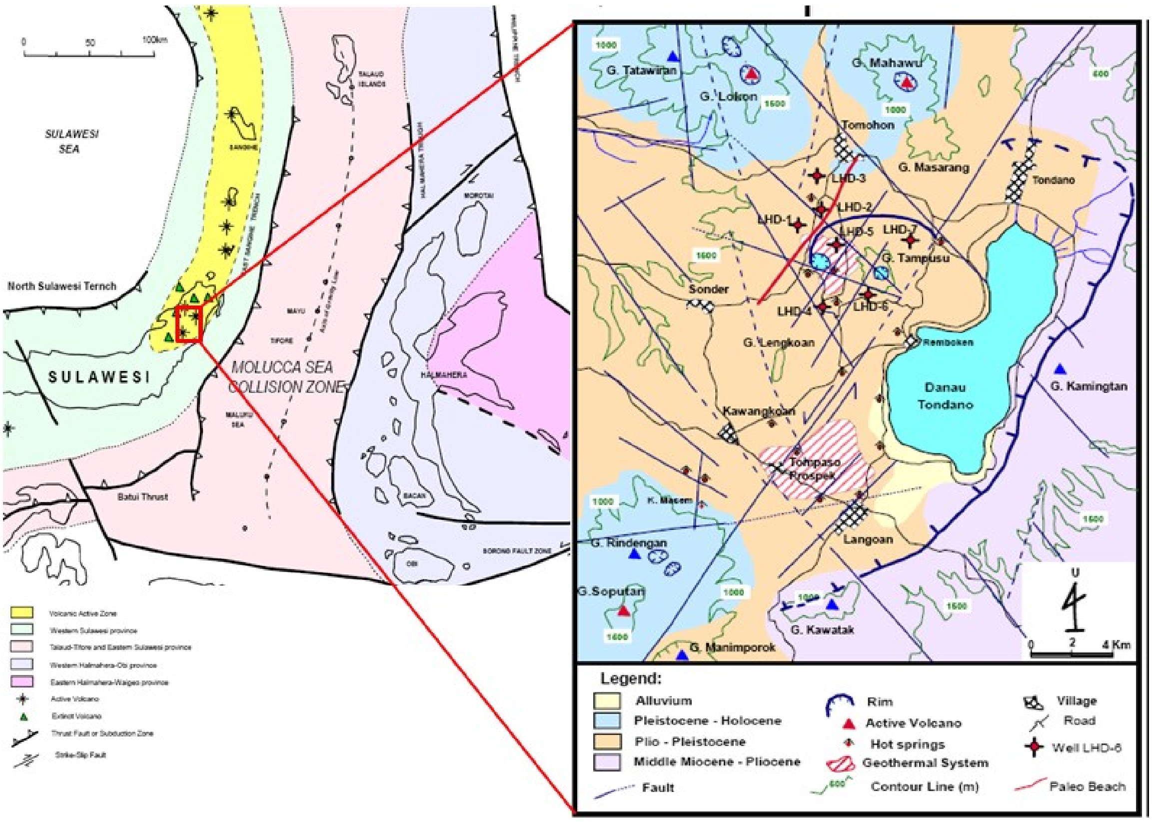

Figure 2. Tectonic setting of Sulawesi Island and regional geology of Minahasa compartment (modified from Siahaan et.al., 2005).

The Minahasa compartment is characterized by a series of active volcanoes that formed the volcanic inner-arc of Minahasa, consists of Mt. Soputan, Mt. Lokon-Empung, Mt. Mahawu and Mt. Klabat and Mt. Dua Saudara that trend south west - north east (Siahaan et.al, 2005). The closest and youngest volcano near the prospect (8 km South West) is Soputan volcano which is still active. All of these young Quaternary volcanoes are part of The Great Tondano Caldera which erupted during the Plio-Pleistocene. The remnants of this caldera are still visible on the eastern part of the beautiful Tondano Lake bounded by highland which is the rim of the caldera (figure 2).

The area is composed of volcanic rocks and characterized by classic strato-volcano interbedded layers of pyroclastic rock, andesite and basaltic andesite lava. An early geological map was made by Ganda and Sunaryo (1982) and further detailed study of the structure was added by Siahaan (2000). The geological studies divided the lithology into 7 different formations; according to the oldest to youngest rocks they consist of:

- Tondano Formation (Tt): Interlayers of pyroclastic breccias, andesite lava, and tuff. These rocks carved the morphology on the south eastern part of the field. This lithology is the oldest unit in the field.
- Tondano Tuff (Tf): This unit comprise mainly tuff and pumice formed during the formation of the Tondano caldera. It can be compared to ignimbrite that formed during the erratic explosion of Tondano volcano.
- Lengkoan Lava (Qlk): Lengkoan mountain range is located on the northern side of the prospect and consist mainly of andesite lava. This lava body is thought to form the boundary between the Lahendong and Tompaso prospects.
- Rindengan 1 (Qrd1): A series of interbedded layers of pyroclastic breccia, lapilli, tuff. This unit forms the flat morphology and covers the most part of the prospect area.
- Rindengan 2 (Qrd2): Interlayers of andesite lava and breccia; volcanic bomb and lapilli from proximals to the Rindengan mountain.

- Sempu (Qsp): Interbedded layers of pyroclastic breccias and andesite lava from Sempu volcanic centre located in the south part of the field.
- Tondano Lake deposit (Qal): alluvium and lake deposit that consists of fine grain sandstone with thin layer of tuff. These sediments occur in the vicinity of Lake Tondano on the eastern side of the field.

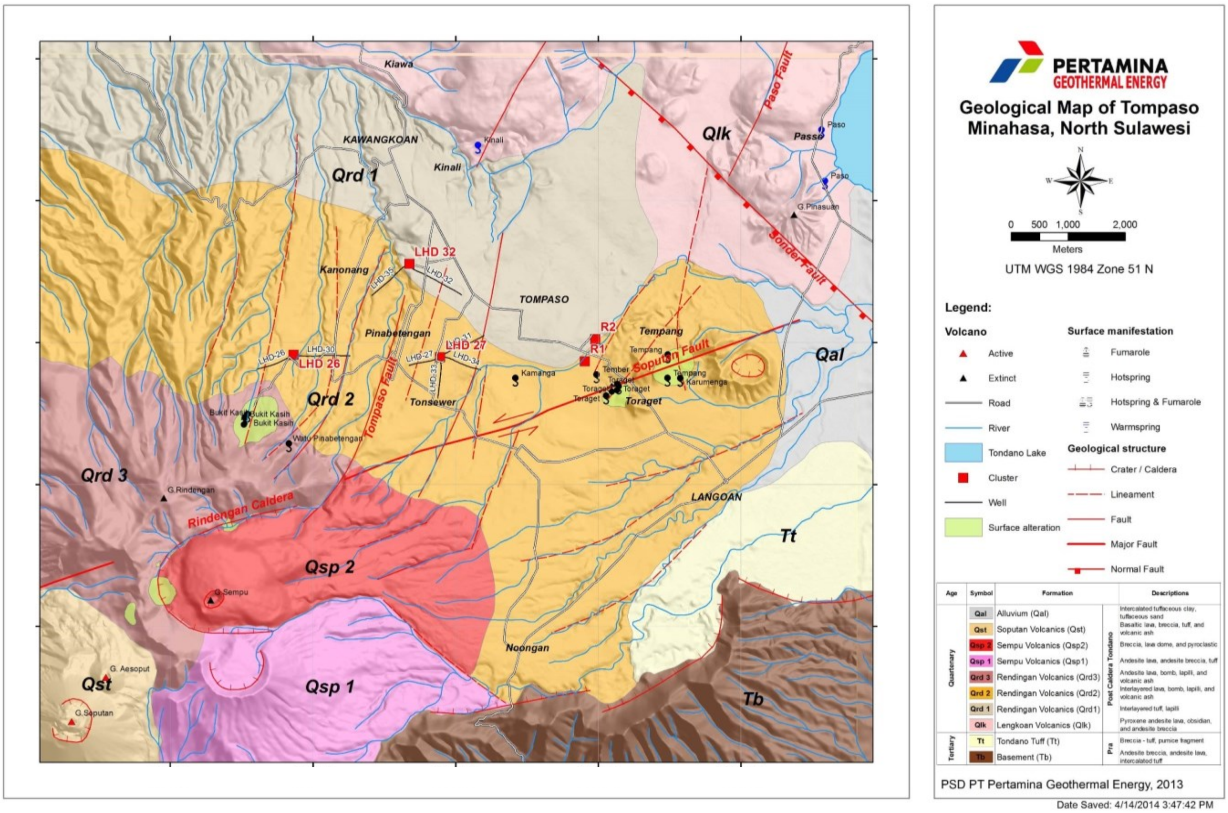

Figure 3. Geological map of Tompaso area (modified from Siahaan,2000, after Ganda & Sunaryo, 1982).

Several geological structures were interpreted from aerial photographs and suggest a predominant trend. NE-SW and ENE-WSW lineaments are the major trends in the Tompaso field. These structures could be major factors that influence the hydrology and emergence of the geothermal manifestations inside the prospect area (figure 3).

Based on geological evidence, it appears that the magmatic evolution expected as a heat source moved from the northeast to the southwest, from Mount Lengkoan to Mount Sempu, Mount Rindengan-Maniporok-Aesoput and finally to Mount Soputan. Therefore, the heat source(s) that currently exist are relatively shallow and derived from Mount Soputan. The regional faults produce a high permeability zone trending NE-SW through the area (Tri Handoko, 2009; Siahaan, 2000).

3. SUBSURFACE GEOLOGY

Rocks penetrated by the drilling were composed of loose volcanic materials and tephra on near surface; tuff, pumice, lapilli, andesite breccia and a thick layer of andesite lava on the deeper part (fugure 4). This sequence of rocks can be compared with the field stratigraphy as follows: From the surface down to 200 mMD the hole penetrated the Riendengan 1 (Qrd1) Formation consisting of interbedded tuff and pyroclastic breccia; from between 200-400 mMD, it penetrated layers of tuff breccia and tuff with lithic and pumice fragments that compare with the Tondano Tuff Formation (Tt); below 400 mMD until TD, it is suggested that the rocks come from the Tondano Formation (Tt) with thick layer of Andesite pyroxene lava on top of intensely altered pyroclastic breccia. The Tondano Formation plays a major role on the geothermal system as a deep aquifer for the Tompaso field. The deepest well drilled in Topmaso reached 2000 mVD and it didn’t reach the sedimentary basement. Thus, it suggests that the basement in this area is deeper than 2000 meter (figure 4).

Borehole image from well LHD-27 captured the evidence of faults and fractures intersected. It suggests that the major contributing factor to the well’s production is secondary permeability. No direct evidence indicates the role of primary permeability or the inherent rock porosity. NE-SW trending open fractures with dips towards the south east directions at 80-90^o angle is the predominant.

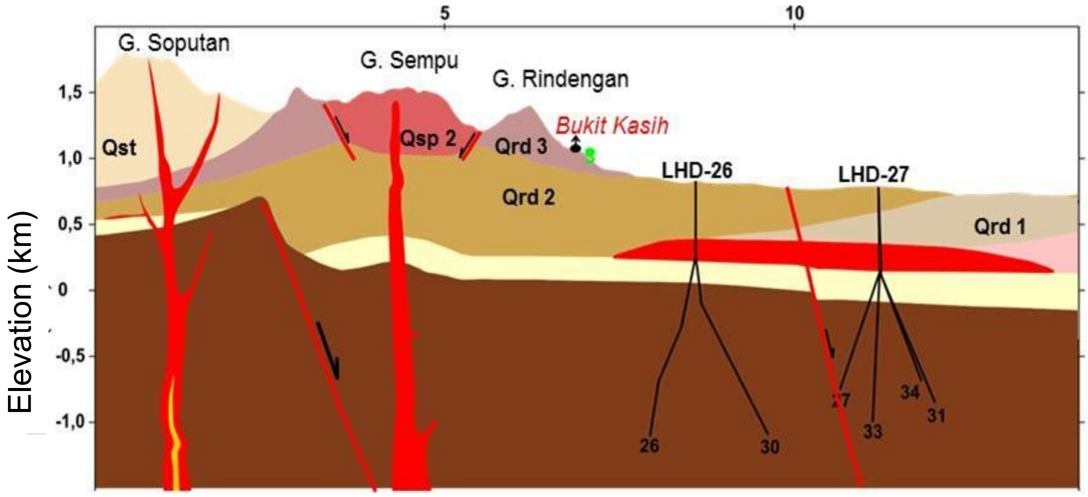

Figure 4. E-W Cross Section of the Tompaso Field showing the vertical and horizontal deposition of rocks.

4. CLAY MINERALOGY

The importance of clay mineralogy in geothermal exploration has been well known for many years. Clays are mainly useful as mineral geothermometers in addition to calc-silicate minerals. There are three ways in which clays are typically useful (Harvey & Browne, 1991):

1. The presence or absence of a clay mineral may coincide with a specific temperature range.
2. Changes in crystallinity or degree of organization of the structures of some mixed-layer clays takes place at a specific temperature.
3. The transition between two end-member clays involves changes in chemical composition that may be temperature dependent.

Therefore, information about clay minerals help defines the hydrology of a geothermal reservoir.

4.1. Identification and Distribution of Clays

22 samples from both wells have been analyzed to identify clays. It was carried out by scanning all the cuttings sample in to Rigaku XRD machine using CuKα radiation at the Geology laboratory facilities of University of Gadjah Mada, Jogjakarta. Samples were undergone preparation for air dried and ethylene glycol to differentiate specific clay minerals. The clay minerals were identified according to Grim (1968) and Reynolds & Moore (1997).

The clay minerals formed in LHD-27 and LHD-30 consists of: Kaolinite, Smectite, Interlayered Chlorite-Smectite (Corrensite), Chlorite, Illite.

Kaolinite and Halloysite is common in near surface alteration and is only presents down to 240 metres. It has a strong 001 peak at 7.2 Å basal spacing. In sample LHD-27 (132-135 m depth), it has a broad peak (0.6 Å). Whereas in well LHD-30, kaolinite is present as a better crystalline clay with a thinner gap (0.4 Å) in the 001 peak and has distinct 7.2 and 3.59 Å peaks.

Smectite is common at shallow depths and sometimes interlayered with chlorite to form chlorite-smectite (corrensite) sheets. The clay has a typical 001 peak at 15-17 Å basal spacing that broadens significantly when treated with ethylene glycol. It is present solely between 132-816 mMD in well LHD-27. In well LHD-30, smectite occurs at depths from 211 to 625 mMD and occurs in association with chlorite below 625 mMD to form corrensite.

Illite is a higher temperature clay and is present at deeper levels in both wells. It is characterized by its 001 peak at 10.1 Å basal spacing. It occurs at 849 to 938 mMD in LHD-27. While in LHD-30, it exists at 1621-1624 mMD and both are associated with chlorite.

Corrensite is a trioctahedral chlorite-smectite clay. It is characterized by its 001 reflection at 31 Å basal spacing and followed by 15 Å and 7.5 Å for its 002 and 003 reflections. This interlayered clay is present only in well LHD-30 from interval of 421 to 1324 mMD.

Chlorite is ubiquitous and can be easily recognized macroscopically by its flaky texture and moss-like green color. In XRD charts, it is identified by its regular peaks at 001, 002, 003, 004 of 14.2, 7.1, 4.7, 3.5 Å respectively. Chlorite is present below 849 mMD in well LHD-27 and at 724 mMD in LHD-30. Chlorite is predominant clay from below these depths to TD in both wells. Nearly all samples that contain chlorite have weak 001 and 003 peaks compared to their 002. This shows that the chlorites are mostly richer in iron than magnesium

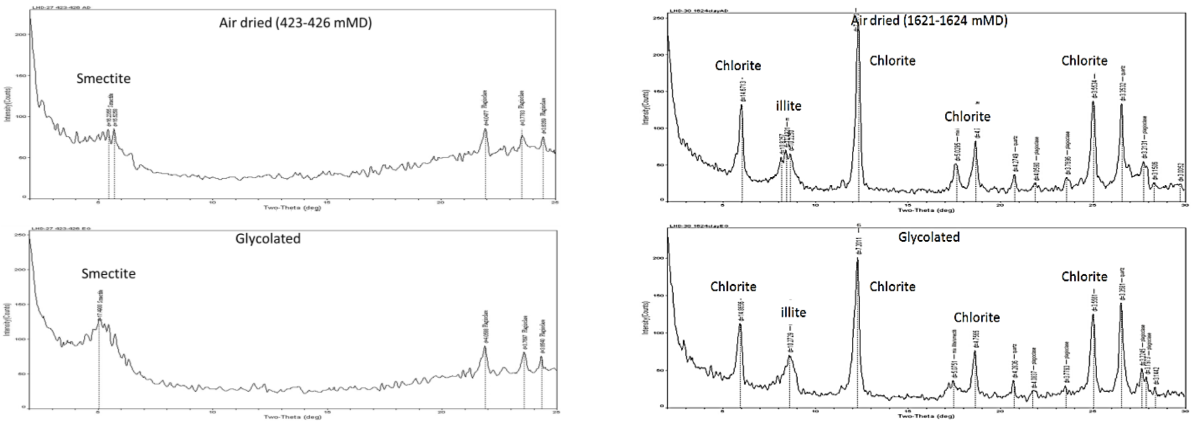

Figure 5. Identification of clays using XRD charts. Examples taken from well LHD-27 at depth of 423-426 mMD and from LHD-30 at depth of 1621-1624 mMD.

Table 1. Clay mineral identification from cuttings of well LHD-27 and LHD-30. List of Abbreviations: Sm (smectite); Kao (Kaolinite); ill (illite); Corr (Corrensite); Chl (Chlorite)

Well	Depth	Basal spasing (d)		Minerals	00ℓ	Δ°2θ		Well	Depth	Basal spasing (d)		Minerals	00ℓ	Δ°2θ	
	mMD	AD	EG			AD	EG		mMD	AD	EG			AD	EG
LHD-27	132-135	15.658	17.383	Smectite	001	0.721	0.704	LHD-30	121-124	7.237	7.273	Kaolinite	001	0.417	0.393
		7.249	7.262	Kaolinite	001	0.597	0.681		211-214	15.769	17.660	Smectite	001	0.651	0.577
	150-153	16.977	17.113	Smectite	001	0.682	0.635		316-319	16.085	18.093	Smectite	001	0.608	0.551
		9.995	10.747	Halloysite	001	0.648	0.717		421-424	15.330	17.658	Corrensite	002	0.596	0.795
	237-240	17.936	17.659	Smectite	001	0.423	0.100			7.284	7.284		003	0.477	0.833
	390-393	16.742	17.587	Smectite	001	0.844	0.507		523-526	15.278	17.046	Smectite	001	0.490	0.495
	423-426	16.236	17.490	Smectite	001	0.492	0.874		622-625	15.601	17.315	Smectite	001	0.408	0.428
	528-531	16.598	17.792	Smectite	001	0.760	0.680		724-727	15.018	15.119	Chlorite	001	0.362	0.535
	813-816	15.228	16.916	Smectite	001	0.798	0.590			7.249	7.214		002	0.390	0.470
	849-852	14.817	15.171	Chlorite	001	0.544	0.539		820-823	15.655	17.451	Corrensite	002	0.477	0.492
		7.097	7.121		002	0.294	0.336			7.394	7.824		003	0.500	0.351
		9.994	10.043	Illite	001	0.237	0.317		922-925	15.224	15.996	Corrensite	002	0.392	0.493
	885-888	14.243	14.474	Chlorite	001	0.435	0.432			7.406	7.811		003	0.393	0.402
		7.099	7.155		002	0.353	0.357		1021-1024	15.226	16.171	Corrensite	002	0.417	0.548
		11.233	11.119	Illite	001	1.434	0.774			7.369	7.852		003	0.500	0.472
	935-938	14.377	14.575	Chlorite	001	0.304	0.255		1120-1123	15.226	16.113	Corrensite	002	0.385	0.421
		7.099	7.178		002	0.269	0.294			7.382	7.838		003	0.377	0.363
		9.996	10.132	Illite	001	0.534	0.479		1219-1222	14.816	15.547	Corrensite	002	0.368	0.416
	999-1002	14.153	14.245	Chlorite	001	0.305	0.310			7.308	7.702		003	0.386	0.381
		7.086	7.109		002	0.262	0.251		1321-1324	15.070	15.994	Corrensite	002	0.422	0.507
	1164-1167	14.250	14.067	Chlorite	001	0.261	0.234			7.284	7.810		003	0.447	0.418
		7.121	7.087		002	0.244	0.230		1420-1423	14.725	14.669	Chlorite	001	0.372	0.355
	1236-1239	14.196	14.665	Chlorite	001	0.286	0.295			7.225	7.178		002	0.369	0.429
		7.087	7.168		002	0.270	0.312		1522-1525	14.817	14.865	Chlorite	001	0.335	0.421
										7.213	7.190		002	0.311	0.442
									1621-1624	14.671	14.866	Chlorite	001	0.288	0.319
										7.167	7.201		002	0.280	0.329
										10.493	10.273	Illite	001	0.654	0.533
									1720-1723	14.865	14.768	Chlorite	001	0.355	0.405
										7.201	7.202		002	0.323	0.305
									1822-1825	15.017	14.919	Chlorite	001	0.352	0.423
										7.237	7.190		002	0.307	0.396
									1921-1924	14.818	14.818	Chlorite	001	0.320	0.360
										7.202	7.201		002	0.285	0.342
									2020-2023	14.571	14.622	Chlorite	001	0.338	0.323
										7.155	7.167		002	0.319	0.407
									2122-2125	15.278	14.864	Chlorite	001	0.632	0.283
										7.225	7.225		002	0.355	0.347
									2202-2205	14.719	14.868	Chlorite	001	0.684	0.427
										7.179	7.213		002	0.283	0.323
										15.601	17.517	Smectite	001	0.841	0.697

4.2. Degree of Crytallinity

The degree of crystallinity is defined as the half height peak width of the 001 reflection (figure 6). This value is also known as the Kubler Index. It is usually expressed in $\Delta^o 2\theta$ values. The Kubler Indices decrease with increasing of the clay mineral as a function of increasing temperature (Ma et.al, 1992). The relationship between crystallinity as expressed by Kubler Indices with downhole temperature is described in this study.

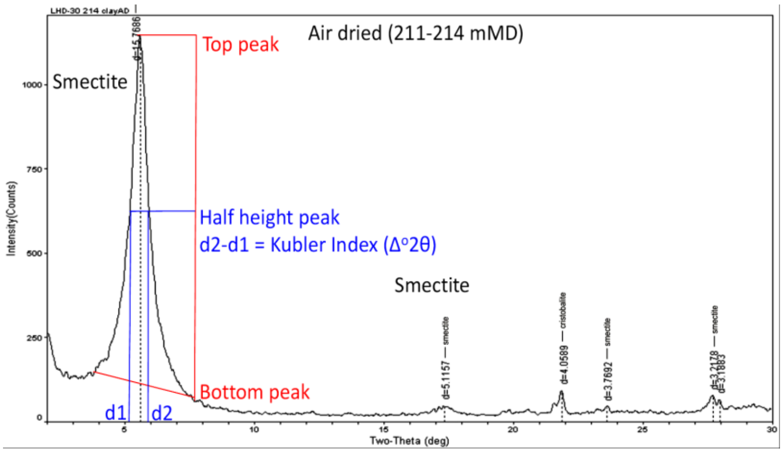

Figure 6. Determination of Kubler Index (Δ°2θ) to measure the degree of clay minerals crystallinity.

A detailed study on Kubler Index indicates a good relationship between clay crystalline with temperature and depth. The Kubler Indices from LHD-27 and LHD-30 show decreases with an increase in depth and temperature. However, LHD-30 seems to have a lower decrease in Kubler Index compared to LHD-27. This is probably due to LHD-30 which has a deeper and smoother temperature gradient profile. This allows the formation of mix layer clay (eg. Corrensite) that is not appear in LHD-27. Composite logs represent the relations are available in figures 7 and 8.

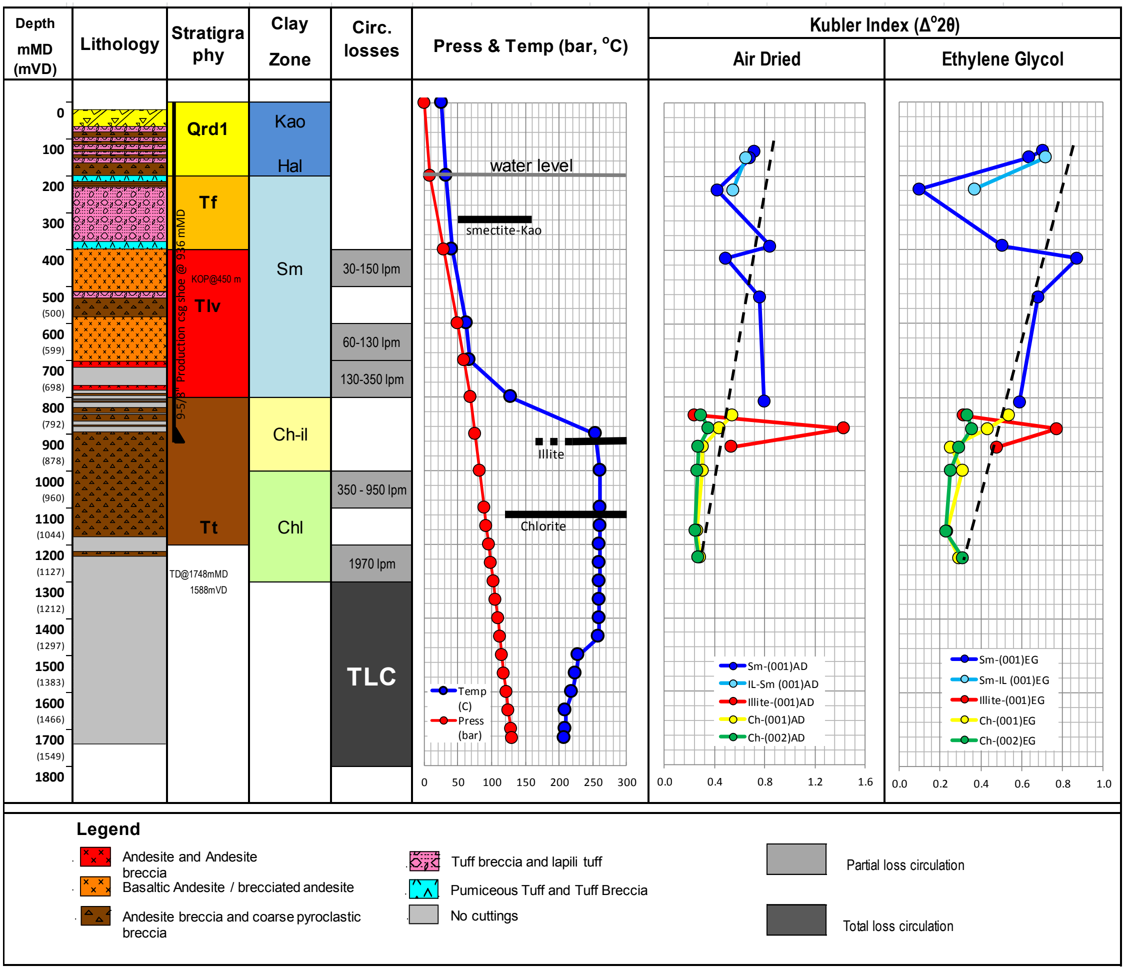

Figure 7. Composite log showing clay distribution and the Kubler Index graphs from well LHD-27.

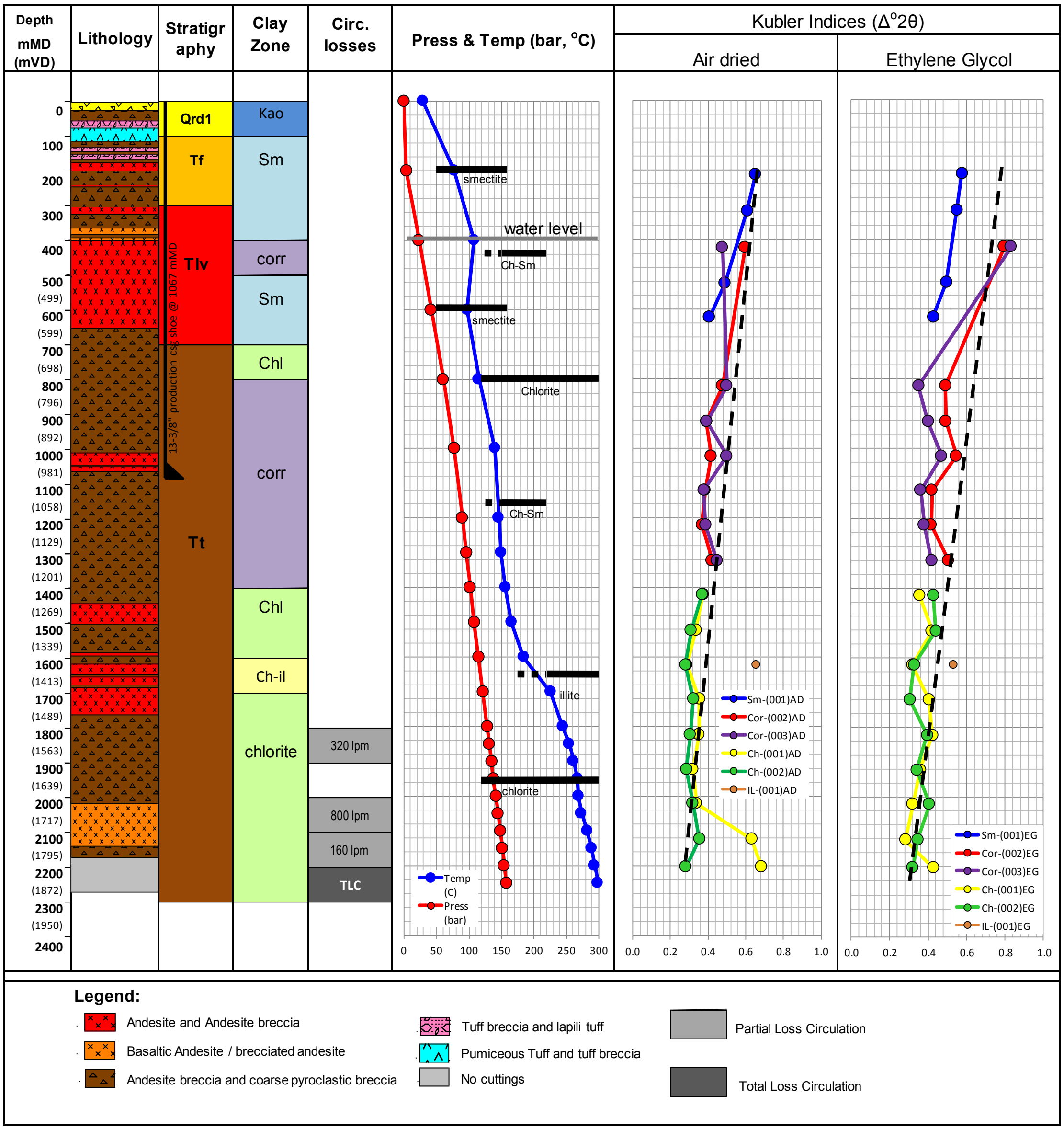

Figure 8. Composite log showing clay distribution and the Kubler Index graphs from well LHD-30.

4.3. Clay Minerals Geothermometry

As mentioned before, the clay variation in two wells corresponds to the progress of depth and temperature. Therefore, it is useful to consider clay mineralogy as a function of geothermometer in the active geothermal system of Tompaso.

In well LHD-27, order the of clay assemblage from the surface down to 1239 mMD is

Kaolinite/Halloysite→Smectite→Illite+Chlorite → Chlorite.

Although near surface kaolinite was not heated to distinguish with Chlorite at 002 peak, the fact that the water level in the well is interpreted at 200 m depth, it is quite possible that kaolinite is present from the condensate steaming the surface and forming acid low temperature clay. Smectite is formed at around 200-800 m depth. At this level, the range of actual downhole temperature is about 50 – 130°C. Illite then formed in association with chlorite at about 850-950 mMD. It has an actual temperature range of 180 to 250°C. The formation of illite after smectite without appearences of interlayer between them is most likely due to sudden jump in temperature from 800 to 900 mMD (ΔT ~ 120°C). Finally, chlorite is predominant in the deeper part below 950 mMD where high temperature (>250°C) and permeability occurs. Chlorite also occurs together with epidote and crystalline quartz. They resemble high temperature and permeability respectively.

The clays from LHD-30 are showing slightly different assemblage than in LHD-27. The difference is the transformation of smectite to chlorite. Corrensite layer occurs in this part. General clay assemblage with respect to temperature is:

Kaolinite → Smectite → Corrensite → Chlorite + Illite → Chlorite.

Similarly with LHD-27, in near surface, kaolinite occurs and has a temperature range about 50°C. Smectite has a temperature up to 100°C at about 400 mMD. The clay revolves to corrensite at 400 to 800 mMD with a temperature range of 100-110°C. Subsequently illite occurs at 1621 mMD with a temperature about 180-200°C. Chlorite is also corresponds with deeper and higher temperature. However, there is a broad temperature range from 150 to 265°C in this well.

4.4. Clay Zonation

There are four main clay alteration zones which occur in the Tompaso geothermal system. They are smectite, corrensite, illite, and chlorite zones. Those clays are common in geothermal systems worldwide. They are not entirely distinct and allow some overlap between clays.

Kaolinite appears shallow in both wells from near surface down to 200 meters above the water level. Smectite zone exists after Kaolinite in LHD-27 at a about 200 to 800 mMD. In LHD-30, the smectite ends shallower than LHD-27 at about 600 mMD with some interlayer of Corrensite at about 400 mMD. Below the smectite, the alteration progresses to an illite zone. It is associated with chlorite at intervals of 850 to 950 mMD in LHD-27. In LHD-30, corrensite forms after smectite alteration from a depth of 800 to 1300 mMD. Subsequently, Chlorite occurs from about 850 mMD but is predominant from 950 down to 1250 mMD in LHD-27. In LHD-30, chlorite is dominant from 1400 mMD to 2200 mMD with the illite layer at about 1600 mMD.

The subsurface model of vertical and lateral zonation of clays is shown on figure 9. From the model below, the geothermal clay cap is thicker in the western part compare to than that to the east. However, the temperature recorded in well LHD-30 is higher (~300°C) than LHD-27 (~ 260°C). Therefore, the LHD-30 is closer to the upflow zone and the fluid flows to the east as shown by the temperature profile.

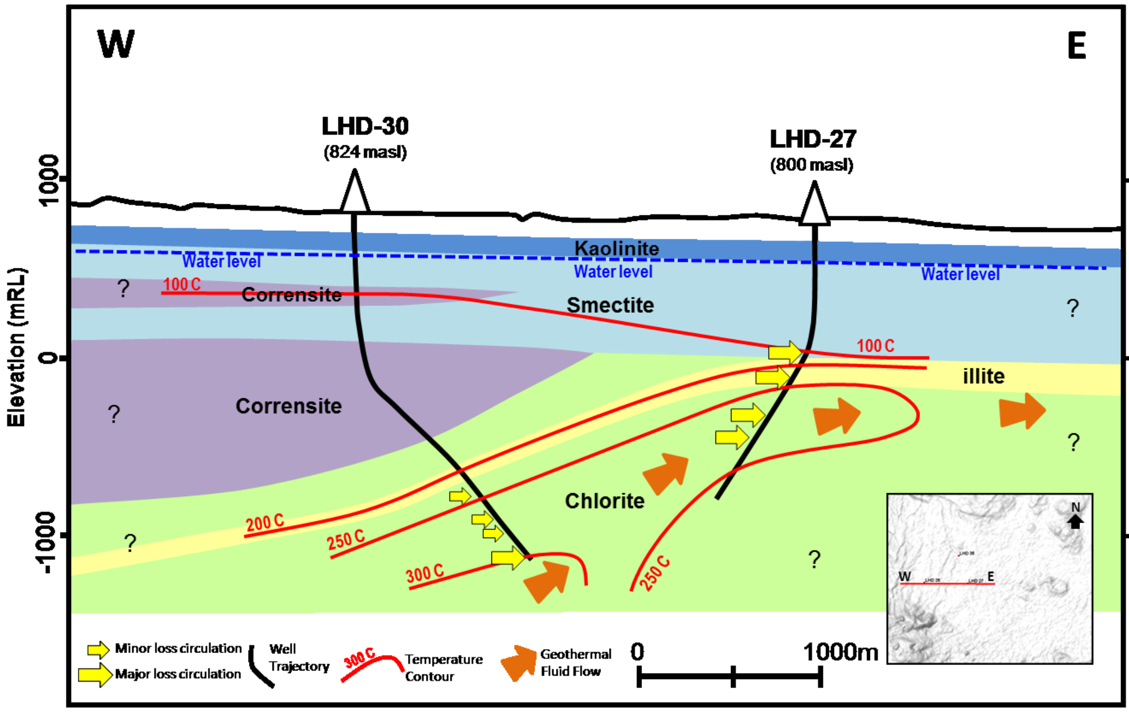

Figure 9. The subsurface model of clay zonation on Tompaso geothermal system deduced from well LHD-27 and LHD-30.

5. CONCLUSIONS

- Clay mineralogy from the Tompaso geothermal system consists of kaolinite, smectite, corrensite, illite, and chlorite.
- The vertical distribution of the clays is mostly in agreement with the current borehole temperature.
- Kaolinite, smectite, and mix layer clay (eg. Corrensite) are present in shallow to intermediate depth. They have low to intermediate forming temperature (50-130°C). All of them act as the impermeable layer (clay cap) of the Tompaso geothermal system.
- Illite is transition clay from intermediate to high temperature (180-250°C) and it is present before the permeable zone in the deeper part.
- Chlorite generally has a wide temperature range (120-300°C). However, chlorite can be a high temperature marker when associated with epidote and quartz. Hence, it is correlates with high temperature and permeability in the geothermal reservoir.
- The degree of crystallinity increases with depth. It is proven by the decrease in Kubler indices with increasing depth and temperature. It also shows that clay crystallinity is temperature dependent.
- With the exception of kaolinite, the clay minerals assemblage was formed under neutral pH fluid.
- The hydrology of the field deduced from the model is the fluid rises near LHD-30 and travels laterally to east towards LHD-27.

6. ACKNOWLEDGEMENT

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