CHARACTERISTICS OF MINERAL ALTERATION ZONES IN KADIDIA GEOTHERMAL FIELD, SIGI DISTRICT, CENTRAL SULAWESI PROVINCE

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ABSTRACT

Kadidia geothermal area is located in Sigi Regency, Central Sulawesi Province. The survey area is about 57.1 km from the city of Palu and about 41.9 km from the capital city of Sigi Regency, Sigi Biromaru. The purpose of this research is to determine the characteristics of hydrothermal alteration in the research well. The method used is petrological analysis on KDD-1 well core data starting from the depth of 44,3 m – 703,85 m, petrographic analysis on 17 rock samples and Specterra analysis based on secondary data. The alteration minerals that appeared in research wells include chlorite, calcite, sericite, secondary quartz, iron oxide, opaque minerals and clay minerals with alteration types in the form of replacement and direct depositional. Based on the presence of minerals and determination of alteration zones, obtained Chlorite-Calcite-Illite-Smectite zone, which is characterized by the presence of chlorite, calcite, smectite, sericite alteration minerals at a depth of ± 12.7 m to ± 599 m. At depth of ± 599 to ± 703 m, alteration minerals that appear include chlorite, calcite, illite-smectite which are more dominant. Furthermore, it also found the presence of secondary quartz minerals that fill vugs, sericite and iron oxides with a rare intensity. This zone includes in the argillic zone with a temperature of 140°C - 220°C. It was concluded that the alteration rocks in KDD-1 wells are estimated as caprock zones of the Geothermal Kadidia system, which are formed because of the interaction between rocks and acidic fluid to low acid.

Keywords: Alteration mineral, Argillic, Geothermal, Kadidia.

INTRODUCTION

Analysis and study of hydrothermal alteration are one of the important stages in geothermal exploration. One of the features that can characterize the prospect of geothermal energy is hydrothermal alteration. Hydrothermal alteration is a very complex process that involves changes in minerals, chemistry, and texture as a result of the interaction between geothermal fluids and rocks. Hydrothermal alteration can provide direct information about geothermal reservoirs because of geothermal fluids, by interaction, can change the composition and properties of rocks. Alteration minerals, some of which are known to form at specific and stable temperature regimes. By identifying the existence of alteration minerals, it can determine the approximate location of the prospect zone, especially in the plan to determine the location of the exploration and exploitation wells in the next stage. Besides, alteration minerals can also reflect subsurface temperatures.

Kadidia Area, Sigi Regency, Central Sulawesi Province is one of the areas that have geothermal potential. The existence of geothermal potential in the Kadidia area is characterized by the presence of surface manifestations in the form of hot springs with a temperature of 45,5° - 81,4° C and hydrothermal alteration. Kadidia area was chosen as the location of the investigation because based on the results of previous investigations it was known to have a wide area of prospects of 16 km^2, with an estimated potential reserve of 66 Mwe (PSDMBP, 2015). Further investigation into the availability of geothermal potential is carried out by examining one of the existing manifestations, hydrothermal alteration.

This research was conducted for Geothermal Studies in the research area to determine the characteristics of hydrothermal alteration minerals in research wells which included lithology, mineralogical composition, alteration mineral types and alteration zones based on the presence of alteration minerals.

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LITERATURE REVIEW

Physiographically, Kadidia is located in the Takolekaju Mountains zone. This zone is located in the Northwest Geological Map of the Poso which borders the Palu Koro fault zone in the Southwest and with the fault zone in Poso in the East. The Palu Koro fault extends approximately 240 km from the north (Palu City) to the south (Malili) to Bone Bay. This fault is an active sinistral fault with shifting speed of around 25-30 mm/year (Kaharuddin drr., 2011). Poso fault is a structural contact zone between the metamorphic belt of Central Sulawesi and the magmatic belt of West Sulawesi (Bemelen, 1949; Hamilton, 1979; Simandjuntak et el, 1991; Simandjuntak et al, 1992). Seismicity suggests that at the present this fault is no longer active (Kertapati et al, 1992). However, the recent earthquake on the west coast of Tomini Bay indicates that at least the northern portion of the thrust being reactivated.

The observed area (Figure 1) is set within the Poso Regional Geology Map (T.O. Simandjuntak et al., 1997) which was compiled by rock units consist of Lake Deposits, Napu Formation, Kambuno Granite and Tineba Volcanics. Kadidia Area is set around the Tineba Volcanics. This formation consists of hornblende andesite lava, basaltic lava, quartz latite lava, and breccia. Andesite lava is grey to greenish-grey, porphyritic with phenocrysts composed of plagioclase and hornblende, the plagioclase is partly altered to sericite, stilbite, glass, and clay. Latite-quartz lava is grey, porphyritic, with alteration minerals consisting of clay, sericite, and chlorite. The breccia has andesite to basalt components and moderately consolidated. This unit has resulted from submarine volcano eruptions.

The movement of geological structures in the research area is estimated to be influenced by a fault with the Northwest to Southeast direction and fault with the Southwest to Northeast direction. A large fault with the Northwest – Southeast direction is expected to be a fault that controls the appearance of two groups of hot springs in Ampera Village, Palolo Sub-district while the Northeast - Northeast fault structure is expected to be the fault that controls the appearance of a hot spring group in Berdikari Village, Palolo Sub-district.

The tectonic activity that is still active today, namely the Palu Koro Fault segment with the Northeast – Southeast East direction, is expected to control the formation of a geothermal system in the Kadidia area. Besides, there also magmatic activities that occur during the Pliocene which form plutonic rocks. At Pliocene, tectonic activity occurred which formed a horizontal fault with the Southwest West – Northeast East direction. Tectonic activity continues along with the activity of young magmatism in the form of uplifting and strain. This event was marked by the disclosure of plutonic rocks to the surface and the formation of a pull-apart basin in the central part of the study area.

The Kadidia geothermal area is in the depression zone which is thought to be a collapse of the synistral fault following the direction of the Palu Koro fault movement. Formed as a result of a pull-apart mechanism from the sinistral fault in which there are normal faults. This depression is thought to be the boundary of the Kadidia geothermal system.

Kadidia area is dominated by plutonic rock with a granitic-dacitic composition that spreads around the depression zone of Kadidia and sedimentary materials from the collapse of older rocks, namely lake deposits, colluvium, alluvium fan and alluvium deposits that fill the central part of depression zone. Besides, there is metagranite located in the southern part of the research area.

Based on the previous survey (PSDMBP, 2012), the stratigraphy unit of rocks in Kadidia geothermal area consists of several rock units sorted from the oldest to the youngest, as follows:

1. Metagranite (Tmg).
2. Granite 1 (Tg 1).
3. Granite 2 (Tg 2).
4. Granite 3 (Tg 3).
5. Granite 4 (Tg 4).
6. Granite 5 (Tg 5).
7. Granite 6 (Tg 6).
8. Granite 7 (Qg 7).
9. Granite 8 (Qg 8).
10. Lake deposits (Qed).
11. Colluvium (Qkl).
12. Alluvium fan deposits (Qka).
13. Alluvium (Qal).

METHODS

The objects observed in this study were rock core samples (core) and *Specterra Mineral Analyzer* analysis data. Core samples were analyzed using petrological analysis (megascopic observation) from the depth of 44.3 m to 655.8 m and petrographic analysis (microscopic observations) of 17 rock and

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mineral samples from underneath the surface of the research well. Besides, secondary data from the analysis of *Specterra Mineral Analyze*r with petrology and petrographic analysis will be combined to obtain the alteration mineral characterization of the research wells, KDD-1 well.

Petrology analysis is an analysis carried out with a description of megascopic in the rock core (core) from drilling well of KDD-1 with a loupe, so it can be identified as physical characteristics and lithology types.

Petrography analysis aims to identify the types of primary minerals, alteration minerals and types of lithology in thin sections with a polarizing microscope (Olympus CX31), so it can be identified microscopically, types of rocks and minerals that can be seen microscopically. However, with petrography analysis, it was not possible to find out the composition of clay minerals composing of rocks.

Specterra analysis aims to determine the types of alteration minerals, especially clay minerals using *Specterra Mineral Analyzer*. This analysis was done out of secondary data obtained from the Center for Mineral, Coal and Geothermal Resources (PSDMBP).

RESULTS AND DISCUSSION

Well Lithology

Based on the petrology and petrography analysis of the research area in the KDD-1 well, it can be divided into four lithologies, namely conglomerate, sandstone, claystone, and monomic breccia, as displayed in Figure 2.

1. Conglomerate

Conglomerate was found at a depth of 13 – 90 m, 111 – 165 m and 213 – 278 m. Based on megascopic analysis, the fresh color of this conglomerate was light grey to green whereas the weathered color was brownish, component grain size coarse sand to pebble, angular component, matrix-supported, medium sorted to poorly sorted, the component consisted of sandstones, andesitic and basaltic igneous rocks whereas the matrix was composed of fine sand to clay. This rock had been slightly altered.
The fresh color of the sandstone component was light grey whereas the weathered color was brownish grey, grain size medium sand to pebble, angular component, medium sorted. The fresh color of the granite component was light grey whereas the weathered color was brownish, hypocrystalline texture, phaneritic granularity, inequigranular, subhedral. The fresh color of the andesitic component was light grey whereas the weathered color was brownish, hypocrystalline texture, aphanitic granularity, in equigranular, subhedral, with identified mineral composition as quartz, plagioclase, biotite. Matrix was composed of fine sand to clay with light grey color and well sorted. The mineral composition consisted of quartz, plagioclase, biotite, calcite, iron oxide and clay mineral.
Based on microscopic analysis, the thin section had already been altered with a coarse grain texture, in equigranular, hypocystalline, subhedral, hypidiomorph. Composed of primary minerals (quartz, plagioclase, k-feldspar, and biotite) and secondary minerals (calcite, chlorite, clay minerals and opaque minerals) by 81%. Ground mass was composed of clay minerals by 23%. In general, this rock had been slightly altered, i.e. by 23% percent. Based on the Streckeisen classification (1976), the component of this rock was identified as *Granite*.

2. Sandstone

Sandstone was found at a depth of 91 – 110 m, 166 – 185 m, 201 – 212 m, 279 – 419 m, 441 – 503 m and 513 – 525 m. Based on the megascopic analysis, the fresh color of this sandstone was light grey whereas weathered color was brownish grey, grain size very fine sand to medium sand, grain shape angular to subangular and medium sorted. This rock had been slight to moderately altered. The mineral composition consisted of quartz, biotite, plagioclase, calcite, and clay minerals.
Based on microscopic analysis, the thin section had clastic texture, medium sorted and grain shape angular to subangular. Composed of primary minerals (quartz, plagioclase, k-feldspar, biotite and pyroxene) and secondary minerals (calcite, chlorite, clay minerals and opaque minerals) by 70%. Matrix was composed of calcite and clay minerals by 30%. In general, this rock had been moderately altered by 36%. Based on the Pettijohn classification (1975), this rock was identified as *Feldsphatic graywacke*.

3. Claystone

Claystone was found at depth of 186 – 200 m, 420 – 440 m and 504 – 512 m. Based on the megascopic analysis, the fresh color of this claystone was dark grey with weathered color was brownish-black. This rock had been slightly altered.

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Microscopically, had matrix was composed of clay minerals by 77%, primary minerals (k-feldspar, and quartz) and secondary minerals (iron oxide, clay minerals and opaque minerals) by 23%. In general, this rock had been slightly altered by 16%. Based on the Pettijohn classification (1975) this rock was identified as *Mudstone*.

4. Monomic Breccia

Monomic breccia was found at a depth of 524 – 703 m. Based on the megascopic analysis, the fresh color of this monomic breccia was light grey – greenish-grey whereas the weathered color was brownish grey, component grain size medium sand to cobble, angular to subangular component and medium sorted to poorly sorted. The component consisted of sandstone, andesitic and basaltic igneous rocks whereas the matrix was composed of fine sand to clay. This rock had been slight to moderately altered.

The fresh color of the granite component was light grey whereas the weathered color was brownish, hypocrystalline texture, phaneritic granularity, inequigranular, subhedral. The fresh color of the andesitic component was light grey whereas the weathered color was brownish, hypocrystalline texture, aphanitic to porphyritic granularity, in equigranular, subhedral. Matrix was composed of fine sand to clay with light grey color and well sorted. The mineral composition consisted of quartz, plagioclase, biotite, calcite and clay minerals. Based on microscopic analysis, the thin section had already been altered with a coarse grain texture, hypidiomorph, hypocystalline, in equigranular and subhedral. Composed of primary minerals (plagioclase, k-feldspar, biotite, pyroxene, and quartz) and secondary minerals (calcite, chlorite, secondary quartz. clay minerals and opaque minerals) by 65%. Ground mass was composed of clay minerals by 25%. In general, this rock had been slightly altered by 20%. Based on the Travis classification (1955), the component of this rock was identified as *Granite*.

Alteration Minerals of Research Area

Analysis of alteration minerals in the research area was divided into two methods, namely petrography analysis and secondary data analysis using *Specterra Mineral Analyzer*.

Identified minerals based on petrography analysis, namely :

a. Calcite

Calcite was present in almost throughout of the KDD-1 well, replacing some to completely of the plagioclase, k-feldspar, matrix and also present to fill the vugs. Calcite was colorless (PPL), low relief, no pleochroism, refractive index $n_{min} > n_{med}$, interference color was pale yellow orde 1. Calcite was taking some of the matrix (Figure 3) while some were also filling the vugs.

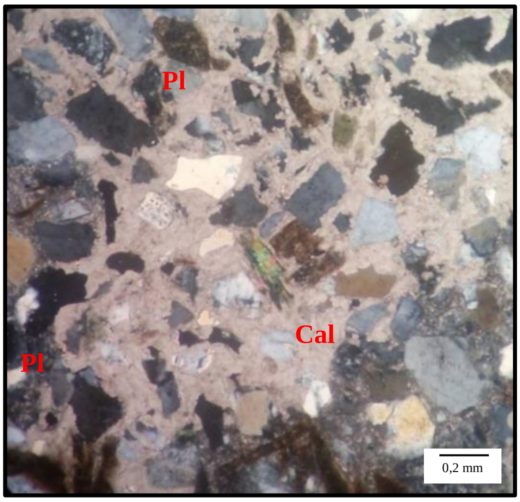

Figure 3. Thin section photomicrograph at a depth of 441.6 m, showing calcite (Cal) fill the vugs and replaced some of the matrix.

b. Sericite

Sericite was present at the depth of 244.3 m. Sericite had a characteristic of a brownish color, low relief, no pleochroism, refractive index $n_{min} < n_{med}$, interference color was greenish-grey orde 2, sericite replaced some to completely of plagioclase and (Figure 4). Sericite is formed under acid-neutral conditions with a pH of 4 – 6 and can replace kaolin group minerals at pH 4 – 5. Sericite is formed with fine grain size at temperature conditions >200 – 250° C and coarse grain size at temperature > 250 –300° C.

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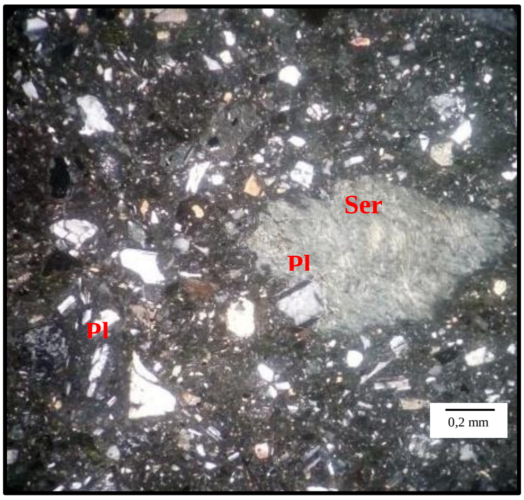

Figure 4. Thin section photomicrograph at a depth of 244.3 m, showing sericite (Ser) replaced some to completely plagioclase (Pl).

c. Chlorite

Chlorite was present at the depth of 109.2 m, 184.1 m, 237 m, 360.8 m, 372 m, 441.6 520 m, 598.1 m, 607.8 m, 655.8 m. Chlorite has a green color, moderate relief, no pleochroism, refractive index $n_{min} < n_{med}$, interference color was reddish-yellow orde 1, replacing some to completely plagioclase and biotite. Chlorite was formed at a neutral pH over a wide temperature range, >120ºC (Reyes,1990). Chlorite was taking some of the plagioclase (Figure 5).

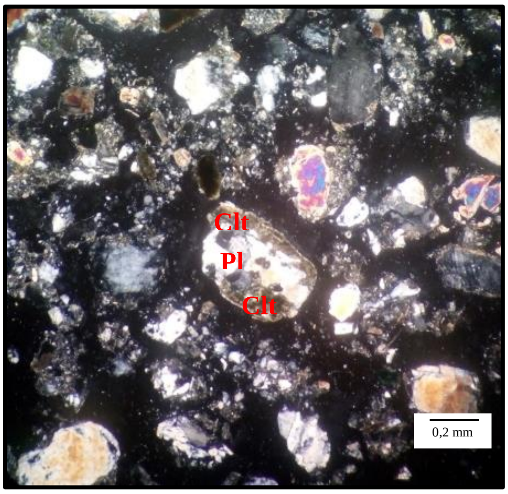

Figure 5. Thin section photomicrograph at a depth of 372 m showing chlorite (Clt) replaced some of the plagioclase (Pl).

d. Secondary Quartz

Secondary quartz was present at a depth of 44.3 m, 162 m, 184.1 m, 372 m, 598.1 dan 607.8 m. Secondary quartz was colorless, low relief, no pleochroism, *mosaic texture*. Secondary quartz was present to fill in the vugs (Figure 6). Secondary quartz was present at temperature >100˚C with neutral pH (Reyes, 1992).

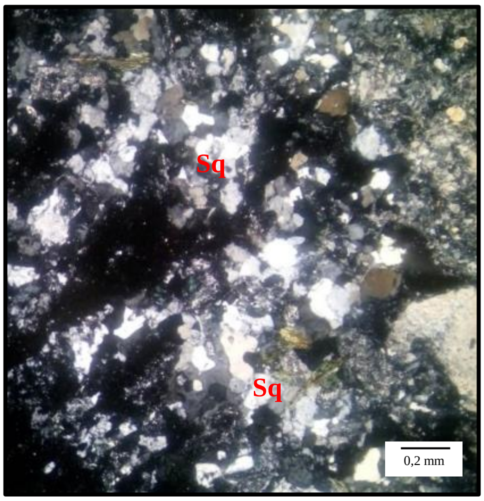

Figure 6. Thin section photomicrograph at a depth 607.8 m, showing quartz was present (Qtz) filling the vugs.

e. Opaque Mineral

Opaque mineral was almost present in all depth of the well. Opaque mineral had a characteristic of isotropic characteristics, some were symmetrical like cubic which was estimated to be pyrite, as inclusion minerals in plagioclase, k-feldspar, and matrix (Figure 7).

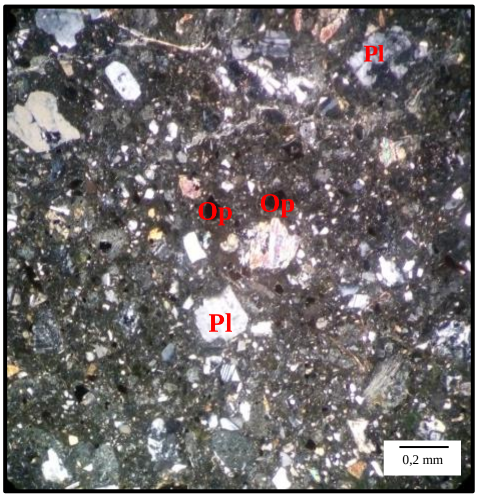

Figure 7. Thin section photomicrograph at a depth of 244.3 m, showing opaque mineral (Op) was present.

f. Iron oxide

Iron oxide was present in depth of 199.8 m, 244.3 m dan 598.1 m Microscopically (Figure 8) iron oxide had a characteristic reddish dark brown color, low relief, fine texture, iron oxide replaced some of plagioclase and matrix.

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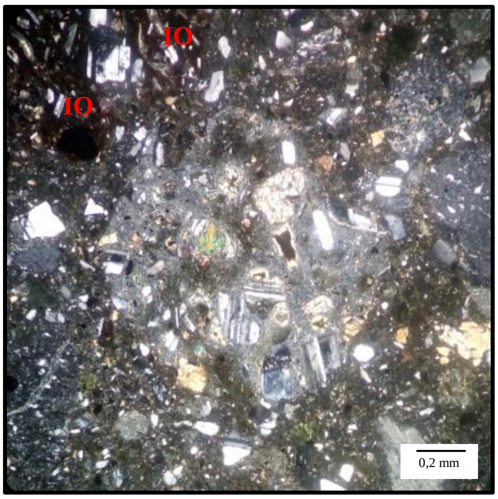

Figure 8. Thin section photomicrograph at a depth of 244.3 m, showing the iron oxide (IO) replaced some of the matrix.

g. Clay Mineral

The type of clay minerals based on petrographic analysis can not be accurately identified without the support of XRD data. Clay mineral a had characteristic of brown, low relief, replaced some of the plagioclase, quartz, and k-feldspar (Figure 9). Clay mineral was present almost throughout the well, starting from a depth of 12.7 m to 703.7 m. Clay minerals formed where air and water interact with silicate minerals, breaking them into clays and other products (Sapiie, 2006).

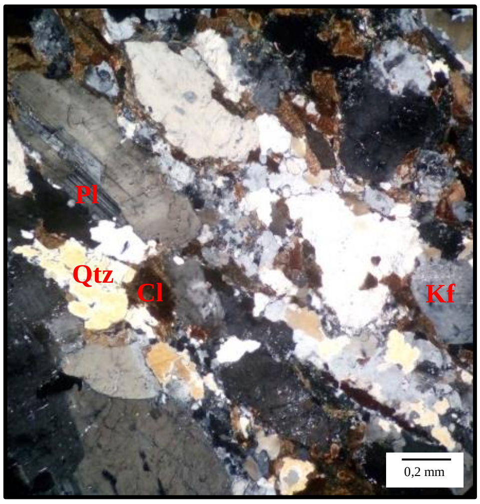

Figure 9. Thin section photomicrograph at a depth of 237 m, showing clay mineral (Cl) replaced some of the plagioclase (Pl), quartz (Qtz) and k-feldspar (Kf).

Alteration Mineral of Research Well Based on Specterra Mineral Analyzer Analysis

Alteration minerals can also be analyzed through *Specterra Mineral Analyzer*. The *Specterra* analysis was carried out to determine the type of alteration minerals, especially clay minerals that appeared in the research area using *SpecTerra*.
This analysis showed which mineral was the most dominant and the mineral groups within the depth of 12.7 m to 703.7 m (Appendix I).

Alteration Zone of Research Well

Based on the abundance of alteration mineral associations formed in KDD-1 wells, there are dominant alteration minerals, namely chlorite, calcite, smectite and the presence of secondary quartz minerals that fill the vugs, sericite and iron oxide with the intensity that is rarely or not too dominating to ± 599 m. From a depth of ± 599 to ± 703 m, it was found that chlorite, calcite, illite-smectite alterations were more dominant than other alteration minerals, namely secondary quartz and iron oxides with a rare intensity, so these minerals are included in the chlorite-calcite-illite-smectite zone. The presence of alteration minerals with slightly to moderately altered in KDD-1 wells, dominated by clay minerals such as smectite, illite and chlorite support the previous magnetotelluric survey data, which shows that at a depth of 500-1250 m, rock layers have low resistivity anomalies, <10Ωm which forms the contour (PSDMBP, 2015).
This zone was included in the argillic zone (Corbett and Leach, 1997) with approximate temperatures of 140°C – 220°C. This zone had higher clay mineral intensity than other zones and was estimated as a caprock zone at Kadidia geothermal system.

CONCLUSIONS

Based on petrology and petrography analyzes of the observed area in KDD-1 wells. KDD-1 well was composed of several lithologies, i.e.:

1. Conglomerate
2. Sandstone
3. Claystone
4. Monomic breccia

The alteration minerals that appear in KDD-1 wells include chlorite, calcite, sericite,

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secondary quartz, iron oxide, opaque minerals, and clay minerals.

Based on the presence of minerals and determination of alteration zones, it was obtained chlorite-calcite-illite-smectite zone, which is characterized by the presence of chlorite, calcite, smectite at a depth of ± 12.7 to ± 599 m. Besides, it was also found the presence of secondary quartz minerals that fill vugs, sericite and iron oxides which are rarely or not too dominating. At a depth of ± 599 to ± 703 m, it was found that alteration minerals namely chlorite, calcite, illite-smectite are more dominant than other alteration minerals and there also secondary quartz and iron oxide with a rare intensity. This zone was set within the argillic zone with approximate temperatures of 140°C – 220°C. It could be concluded that alteration rocks in KDD-1 wells were estimated to serve as caprock zones of the Kadidia geothermal system which estimated to be formed due to the interaction between rocks and acidic fluid to low acid at temperatures less than 220°C.

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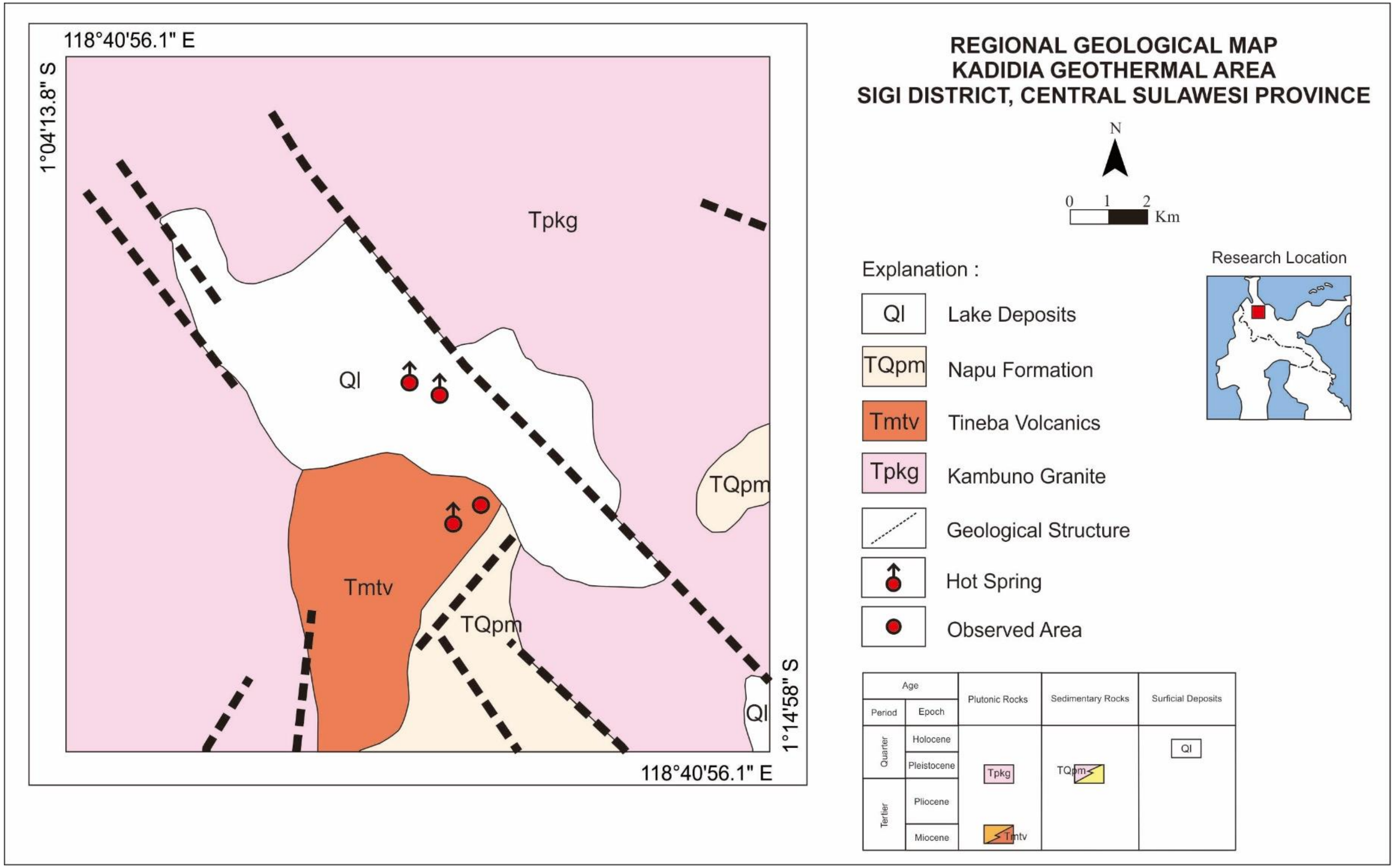

Figure 1. Regional Geological Map of Kadidia Geothermal Area (Modification from Poso Regional Geology Map (T.O. Simandjuntak) PSDMBP, 2012))

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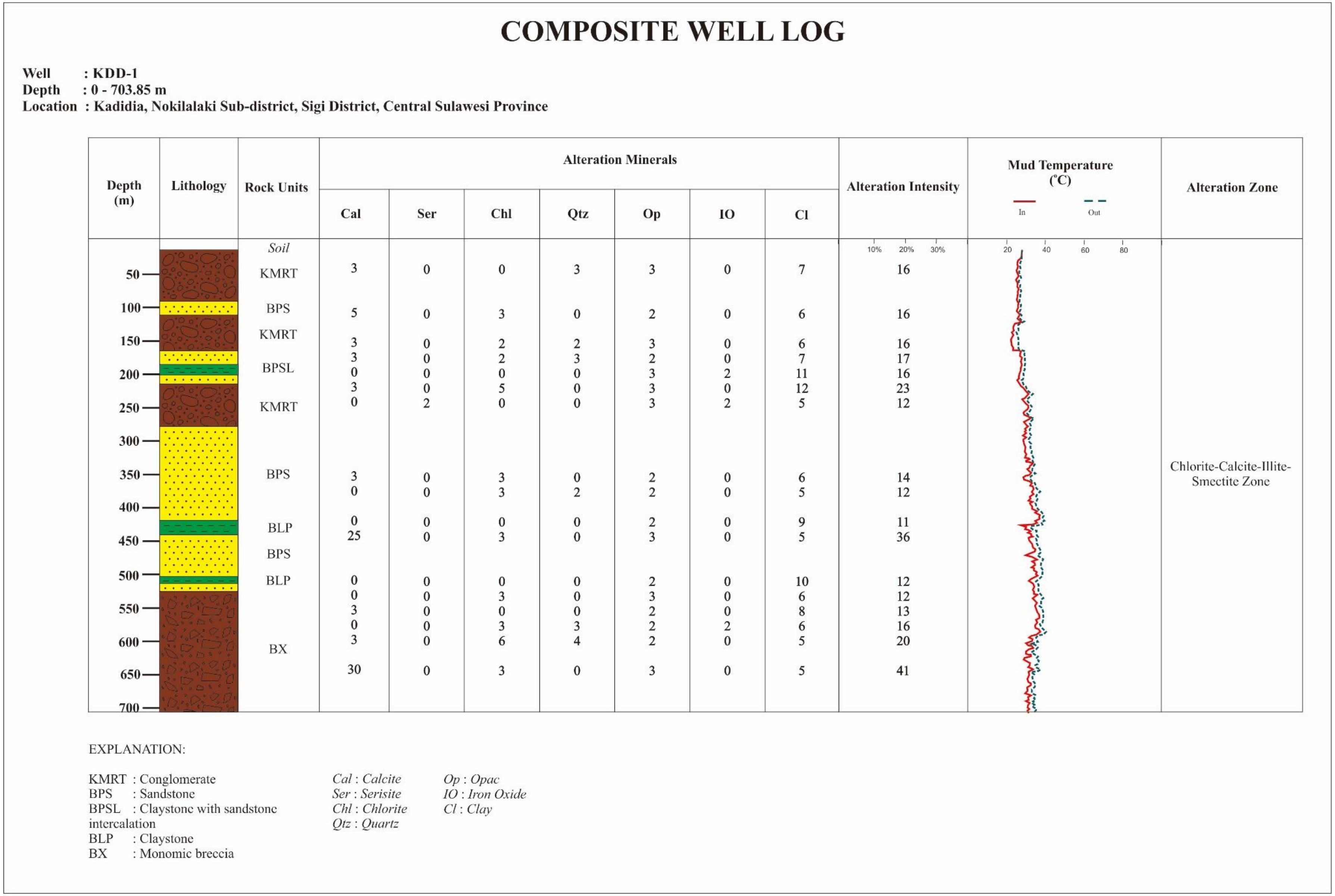

Figure 2. Vertical profile of KDD-1 well.

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Appendix I. List of alteration minerals by *Specterra Mineral Analyzer* in KDD-1 well (PSDMBP, 2015).

No.	Depth (m)	Dominant Mineral Group
1.	12,7	Smectite, Illite
2.	29,3	Wulfenite
3.	35,3-43,75	Smectite, Illite, Zircon
4.	46,1	Mica, Phosphate, Muscovite
5.	56,5	Illite, Silica
6.	68,5	Smectite
7.	76	Calcite
8.	81,7	Dolomite
9.	88,6	Smectite, Illite
10.	99,3	Smectite, Zircon
11.	101,15	Illite, Zircon, Phosphate
12.	104,45	Illite, Silica
13.	106,95	Illite, Phosphate
14.	110,45	Sulfate, Silicate, Phosphate, Kaolinite
15.	113,45	Silica, Phosphate
16.	118,2	Calcite
17.	125,3	Calcite, Pyroxene
18.	136,1	Smectite, Illite, Calcite
19.	149,7-154,3	Smectite
20.	167,3	Sulfate, Calcite, Silica
21.	173,5-189,3	Smectite
22.	207,4	Calcite
23.	214,3	Silica, Phosphate
24.	239,1	Smectite, Illite, Kaolinite
25.	244,8	Kaolin-Smectite
26.	263,4	Calcite
27.	271,25	Silica, Phosphate
28.	293,15	Illite
29.	305,27	Smectite
30.	308	Zircon
31.	309,6	Silicate, Phosphate
32.	326,3	Smectite, Zircon
33.	328,8	Smectite
34.	334,6	Chlorite
35.	337,75	Zircon
36.	347,1	Smectite, Calcite, Zircon
37.	352,5	Smectite
38.	360,3	Silica
39.	361,9	Smectite, Calcite
40.	365,6	Smectite, Chlorite
41.	367	Smectite
42.	368	Smectite, Silica, Calcite
43.	370,3	Smectite
44.	370,6	Smectite, Chlorite
45.	373	Zircon

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46.	373,7	Silica
47.	376,7	Calcite
48.	384,1	Smectite
49.	403,9	Silica, Phosphate
50.	424,45	Silica, Phosphate, Calcite
51.	447,5	Silica
52.	477,15	Calcite
53.	487	Silica
54.	503,3	Amphibole
55.	508,15	Silica, Phosphate, Calcite, Smectite
56.	515,2	Silica, Phosphate
57.	523,15	Pyroxene, Mica, Chlorite, Sulfate
58.	525,65	Calcite
59.	526,15	Calcite, Chlorite, Illite
60.	526,20	Smectite, Illite
61.	527,85	Smectite
62.	528,47	Muscovite
63.	528,8	Pyroxene, Smectite, Zircon, Kaolin-Smectite
64.	535,45	Calcite
65.	536,1	Silica, Smectite
66.	539	Smectite, Phosphate
67.	540	Smectite, Phosphate, Silica, Sulfate, Kaolinite
68.	545,15	Smectite
69.	556,45	Smectite
70.	565,47	Smectite
71.	569,65	Smectite
72.	573,8	Chlorite
73.	580,9	Smectite
74.	586,7	Smectite, Calcite
75.	590,33	Kaolin–Smectite, Muscovite
76.	591,67	Smectite
77.	592,90	Kaolin-Smectite, Smectite, Phosphate, Silica
78.	593,75-595,5	Phosphate, Silica, Calcite
79.	597	Smectite, Silica
80.	597,38	Smectite
81.	597,43	Calcite
82.	597,65	Sulfate, Smectite
83.	598,5	Silica
84.	598,65	Smectite
85.	599,75-604	Kaolinite, Illite, Smectite
86.	604,2	Hematite, Kaolinite-Smectite, Smectite
87.	604,53	Illite
88.	608,15	Illite, Kaolin-Smectite
89.	609,2	Muscovite
90.	618,3	Dolomite
91.	625,5	Smectite
92.	626	Illit, Kaolin-Smectite, Pyroxene, Smectite
93.	627	Kaolinite
94.	631,8	Pyroxene, Smectite, Kaolin-Smectite

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95.	634,4	Smectite, Phosphate
96.	636,23	Smectite, Illite
97.	640	Kaolin-Smectite, Smectite, Illite
98.	642,8	Smectite, Phosphate, Calcite
99.	645	Smectite, Kaolin-Smectite
100.	645,75	Calcite, Sulfate
101.	653,7	Hematite, Kaolin-Smectite
102.	662,15	Calcite, Pyroxene
103.	667	Muscovite, Pyroxene, Hematite, Smectite
104.	672	Illite
105.	675,75	Kaolinite, Smectite, Illite
106.	678,5	Kaolin-Smectite, Smectite, Calcite
107.	679,75	Calcite
108.	679,85	Smectite
109.	682,05	Kaolinite, Smectite, Calcite, Silica
110.	684,6	Silica, Phosphate
111.	689,9	Kaolin-Smectite, Pyroxene
112.	693	Illite, Kaolin-Smectite, Smectite
113.	699	Kaolin-Smectite, Smectite
114.	699,75	Kaolin-Smectite
115.	699,9	Kaolin-Smectite, Smectite, Hematite
116.	703,7	Illite

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