HYDROTHERMAL ALTERATION AND FLUID CHARACTERISTICS STUDY OF PANTI GEOTHERMAL FIELD, PASAMAN REGENCY, WEST SUMATRA, INDONESIA

Philbertha Aurelia Wibisono[1] and Niniek Rina Herdianita[2]

[1]Department of Geological Engineering, Faculty of Earth Science and Technology, Bandung Institute of Technology, Jl. Ganeca 10, 40132, Indonesia.
[2]Research Group of Petrology, Volcanology and Geochemistry, Faculty of Earth Science and Technology, Bandung Institute of Technology, Jl. Ganeca 10, 40132, Indonesia.
philly.wibi@gmail.com

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ABSTRACT

Panti Geothermal Field is being associated with pull-apart basin at Sumatran Fault System and Tertiary volcanic activities. This field has seven hot and warm springs with temperatures up to 99°C. A more detailed analysis is needed to get a better understanding of subsurface alteration and fluid characteristics in Panti geothermal field. This research's goal is to understand the alteration process and fluid characteristic by determining lithologies, subsurface alteration, and manifestation fluid characteristics.

Primary data of a geothermal gradient well core (PNT-1) with 534 meters depth and manifestation fluid geochemistry data were used in this research. Secondary data of geological and geophysical reports of the observation field were used to support the research. Megascopic and microscopic observation, X-Ray Diffraction, fluid inclusion, and water geochemistry analysis were conducted in this research.

The lithologies of PNT-1 were grouped into Granodiorite, Old Talu Volcanic Product, Young Talu Volcanic Product, and Alluvial Unit of Eocene-Holocene age. The intensities of alteration from samples are weak to intense. Alteration zones consist of [1] Smectite-Chlorite-Quartz Zone at 0-85 meters depth, [2] Smectite-Chlorite-Quartz-Calcite Zone at 85-481 meters depth, and [3] Illite-Chlorite-Calcite-Quartz-Epidote Zone at 481-534 meters depth. Dissolution and open-space filling also occurred. Hydrothermal alteration paragenesis of open-space filling minerals shows that ancient fluid was neutral with 140-160°C then cooled down to 120-130°C. Currently, Panti Hot Springs are neutral, partially equilibrated, sulphate water type, while Ujung Padang and Lundar hot and warm spring are neutral bicarbonate water. Lundar Warm Spring is partially equilibrated while Ujung Padang Hot Springs are immature. There are 3 hydrothermal systems named Panti, Ujung Padang, and Lundar. The systems sourced from meteoric water that charged through tectonic fractures, heated up by unrevealed intrusion rock, and discharged as thermal springs towards faults. Panti, Ujung Padang, and Lundar system have permeable zones with temperatures less than 150°C on Granodiorite, Granite-Granodiorite, and Slate unit respectively.

1. INTRODUCTION

Panti Geothermal Field is located on Pasaman Regency, West Sumatra, at 200km north of Padang City, and 15km northeast of Talu. At Panti Geothermal Field, active manifestations can be found at Panti, Ujung Padang, and Lundar such as hot and warm springs. The drilling of well PNT-1 was done by Centre of Mineral, Coal, and Geothermal Resource in 2017 to collect subsurface information i.e. hydrothermal alteration and subsurface lithologies. Hydrothermal alteration can be assessed by analysing the secondary mineral replacement, open-space filling, and dissolution which gives much information to the geothermal activity history of Panti Geothermal Field itself. Hydrothermal manifestation fluid geochemistry study was conducted to understand the origin and characteristics of the Panti geothermal system nowadays.

2. GEOLOGICAL CONDITION

Physiographically, the research area is located on the Barisan Mountain Range zone (Darman & Sidi, 2000). This zone has Quaternary volcanic activities such as active volcanoes and intrusions. The string of active volcanoes is close to the Sumatra Fault Zone and crustal thinning due to transtensional regime (Barber *et al*., 2005). Some Quaternary intrusions can seep through fractures and consolidate while still maintaining enough heat to generate a geothermal system (Tamanyu & Sakaguchi, 2003).

Tectonically, the research area is controlled by pull-apart basin with NW-SE trend and influenced by Sumatran Fault Zone (Muraoka *et al.,* 2010) which forms a depressed region in the centre of the research area. The river-flow pattern, especially inside the depressed area shows rectangular pattern with lineaments of N-S. Rectangular river-flow pattern hints that tectonic structures influence the morphology of the research area. There are at least 6 faults that can be observed in this area i.e. Batuampar, Aekpantau, Berohmekete, Petok, Lubuksikaping, and Sumatran fault (Fig. 1).

The Batuampar and Petok faults are relatively NE-SW sinistral strike-slip faults (Lumbantobing & Herdianita, 2019). The Aekpantau, Berohmekete, and Sumatran Faults are NW-SE dextral faults (Lumbantobing & Herdianita, 2019; Barber *et al*., 2005). The Lubuksikaping is NNE-SSW normal fault (Barber *et al*., 2005).

The research area has 7 unofficial lithostratigraphic units i.e. Slate, Basalt, Limestone, Granite-Granodiorite which formed during Pre-Tertiary, Granite Intrusion that formed during Eocene, Breccia Tuff during Miocene, and Holocene Alluvial Unit (Lumbantobing & Herdianita, 2019; Centre of Mineral, Coal, and Geothermal Resources, 2017).

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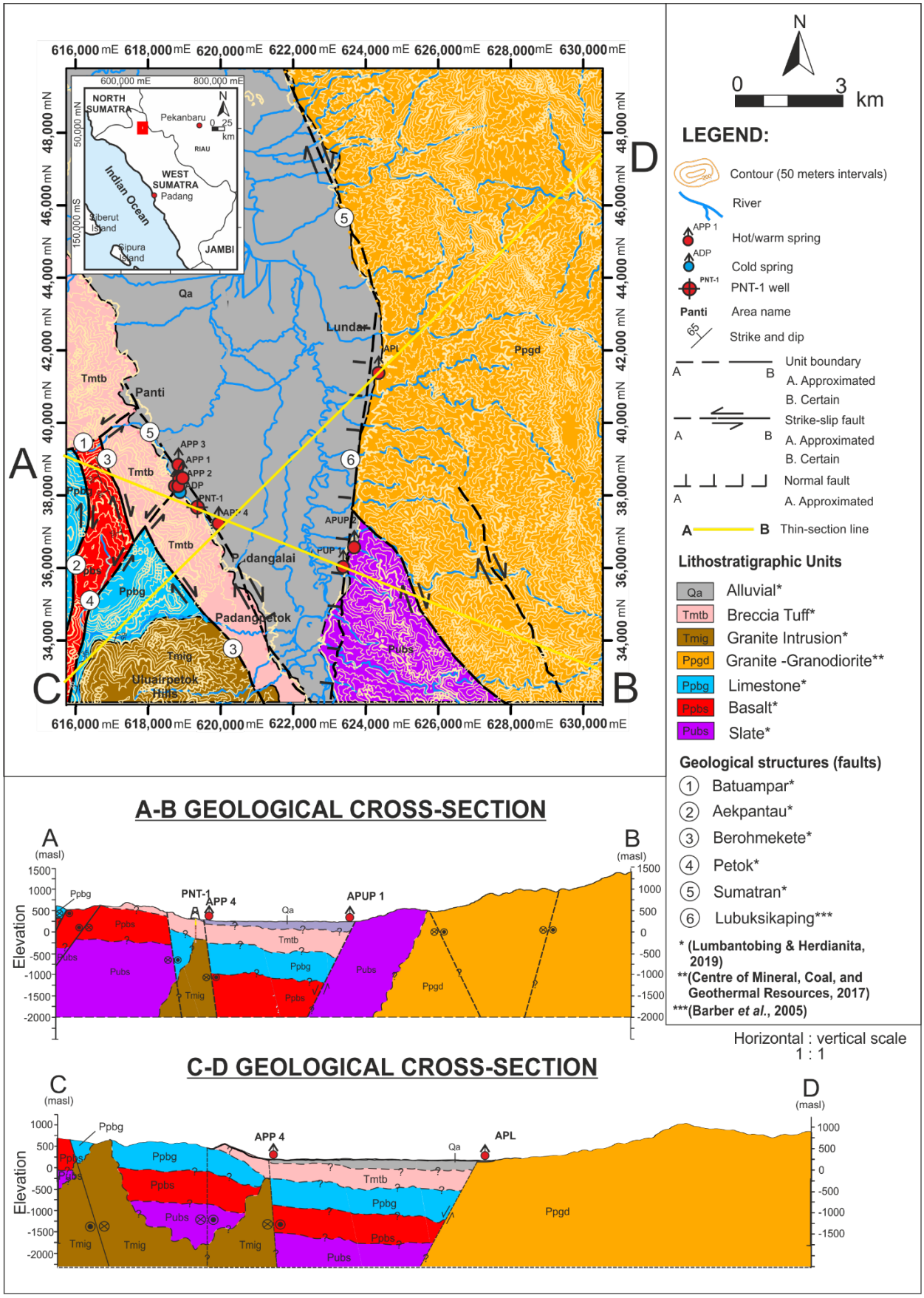

Figure 1: Geological map of Panti Geothermal Field (compiled from Barber *et al.*, 2005; Centre of Mineral, Coal, and Geothermal Resources, 2017; Lumbantobing & Herdianita, 2019).

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PNT-1 well has 4 unofficial lithostratigraphic units. Alluvial unit can be found at 0 to 8 meters depth. It made of brownish soil. This unit belongs to the Alluvial Unit by Lumbantobing & Herdianita (2019). Talu Volcanic Product can be found at 8 to 481 meters depth. The volcanic product consists of volcanic ash, lapilli tuff, tuff breccia, welded lapilli tuff and tuff breccia, and pyroxene andesite lava. These volcanic products are divided into two units i.e. Young Talu Volcanic Product Unit and Old Talu Volcanic Product Units. Both units were divided by oxidation and loss core at 237 to 240 meters in depth. Both also belong to the Breccia Tuff Unit that deposited during Miocene (Lumbantobing & Herdianita, 2019). Tuffs are greenish grey to dark grey, fine to coarse, poorly to well-sorted, consist crystal (i.e. quartz, K-feldspars, biotite, plagioclase, epidote) and accidental slate, quartzite, andesite, and granodiorite fragments. Fragments are embedded in devitrified glass matrix. Perlitic texture can be found at 234 to 237 meters in depth. Meanwhile, eutaxitic and fiamme texture can be observed at 300 to 481 meters in depth. Epidotes in lapilli tuff, and tuff breccia appear to be either singular crystal embedded in glassy matrix, or in basalt and granodiorite fragments. These occurrences of epidote suggest that epidote in the pyroclastic products are product of eroded Basalt and Granodiorite unit. Pyroxene andesite lava presents at 260 to 295 meters and 330 to 350 meters depth. Andesite has a dark grey colour, and contains phenocryst of plagioclase, hornblende, and pyroxene and groundmass of devitrified glass with plagioclase microlites. In this lithology, cockade calcite and quartz veins can be found. At 481 to 534 meters depth, granodiorite is present which is grouped into Granodiorite Unit. Granodiorite unit belongs to Granite Intrusion Unit that formed during Eocene (Lumbantobing & Herdianita, 2019). Granodiorite has faint greenish-grey colour, composed by plagioclase, quartz, muscovite, and K-feldspars.

Some active geothermal manifestations can be found in the research area such as warm and hot springs. In Panti area, four hot springs named APP1, APP2, APP3, and APP4, occur with temperatures between 60.8 to 99.1°C, the acidity of 7.5 to 7.8, and flow rates between 0,5 to 2 L/s (Lumbantobing & Herdianita, 2019). Warm springs are also found in Ujung Padang area (APUP1 and APUP2) with temperatures between 42.1 to 70.8°C, acidity between 7.7 to 9, and flow rate of 0.1 L/s (Lumbantobing & Herdianita, 2019). Another warm spring is located at Lundar area (APL) with a temperature of 37.9°C, the acidity of 8.9, and a flow rate of 0.1 L/s (Centre of Mineral, Coal, and Geothermal Resources, 2017). Thin travertine formed at the mouth of APP1, APP2, and APP3 hot springs (Lumbantobing & Herdianita, 2019). A cold-water sample (ADP) also taken from a river south of APP2 with a temperature of 26.1°C, an acidity of 7.93, and a flow rate up to 0.5 L/s (Centre of Mineral, Coal, and Geothermal Resources, 2017).

Centre of Mineral, Coal, and Geothermal Resources (2017) points out that there are several high-density materials beneath the hot and warm springs and distributed to the fault trend (Fig.2). This high-density material may be the responses of unrevealed intrusion rock (Centre of Mineral, Coal, and Geothermal Resources, 2017). Based on youngest intrusion rock—Granite in well North Sumatra Basin—found in Sumatra (Hehuwat, 1976 in Barber *et al.*, 2005), these intrusive rocks could be formed during Pleistocene. Pleistocene-old granite intrusion is capable to store enough heat for generating a hydrothermal system that still active until now (Tamanyu & Sakaguchi, 2003).

3. HYDROTHERMAL ALTERATION

On the surface, the research area shows indications that it has undergone alteration processes. According to Lumbantobing & Herdianita (2019), some alteration zone can be observed. Based on Corbett & Leach classification (1997), Lumbantobing & Herdianita (2019) grouped three alteration zones on the surface. The argillic alteration zone can be found around Panti hot springs with secondary minerals of smectite and chlorite. Propylitic alteration zone occurs on Basalt and Granodiorite unit with the occurrence of chlorite, epidote, calcite, illite, and pyrite as replacing minerals (Lumbantobing & Herdianita, 2019). On the Limestone unit, the Calcite Vein zone can be observed with the emersion of intensive cross-cutting calcite veins (Lumbantobing & Herdianita, 2019).

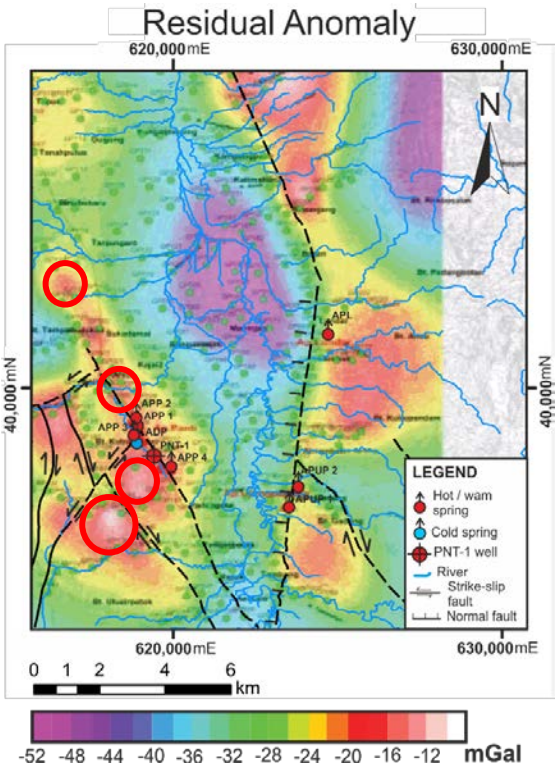

Figure 2: Residual anomaly map from the gravity survey (Centre of Mineral, Coal, and Geothermal Resources, 2017). Red circles indicate anomalous high-density materials.

Several alteration processes such as replacement, open-space filling, and dissolution are present on PNT-1 (Fig. 3). Based on replacing secondary minerals occurrence, three alteration zones can be determined. From 0 to 85 meters depth, the Smectite-Chlorite-Quartz alteration zone appears. This zone has its primary minerals were replaced by smectite, chlorite, and quartz. According to alteration intensity classification by Browne (1995) (Herdianita, 2012), the intensity of alteration in this zone varies between weak to moderate. Further deep with 85 to 481 meters depth, Smectite-Chlorite-Quartz-Calcite alteration zone shows up with smectite, chlorite,

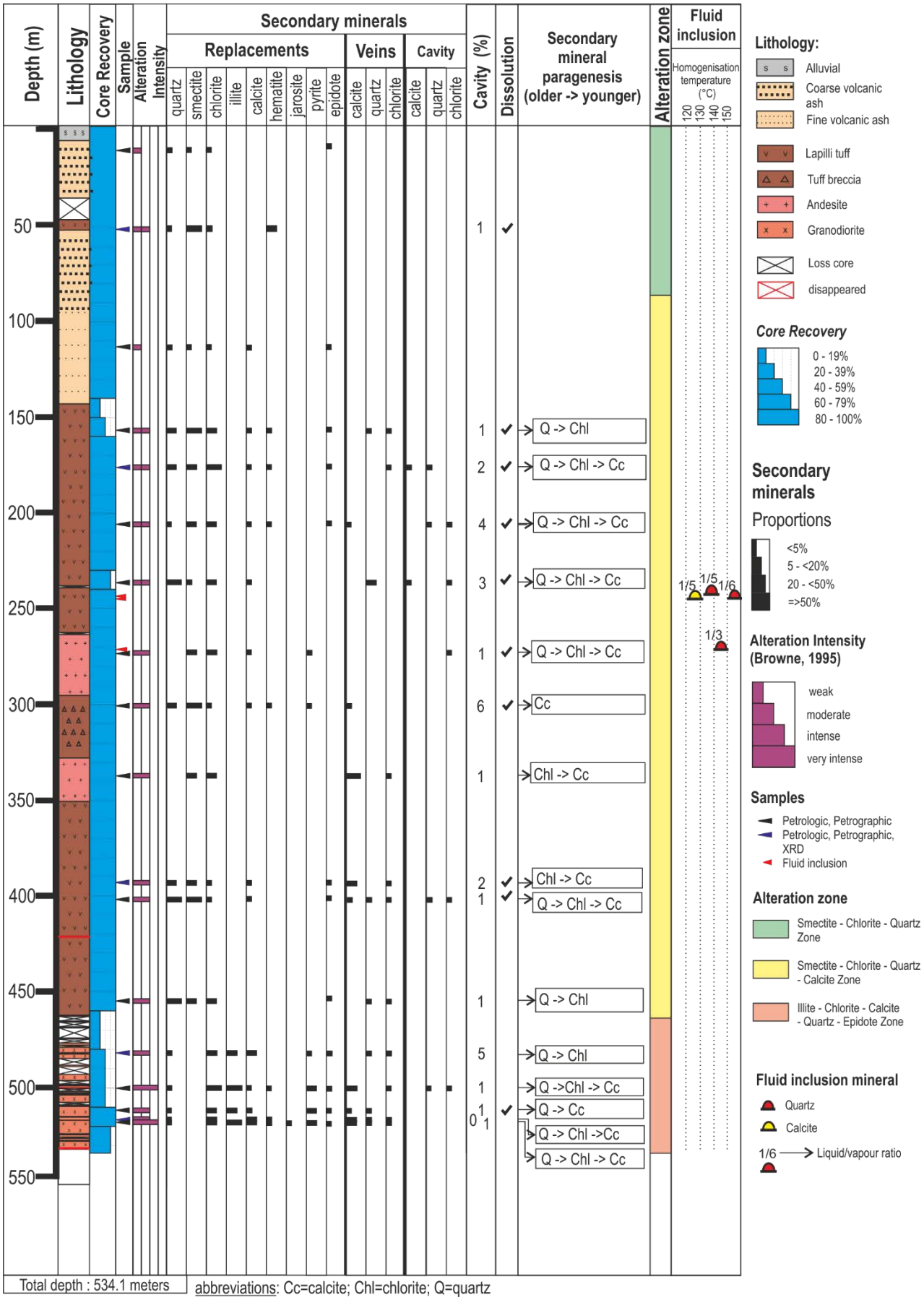

Figure 3: Alterations in PNT-1 well.

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quartz, and calcite altering primary components. The alteration intensity is weak to moderate. At 481 to 534 meters depth, primary minerals of granodiorite are replaced by illite, chlorite, calcite, quartz and, ±epidote. These minerals' appearance also marks the Illite-Chlorite-Calcite-Quartz-Epidote alteration zone. This alteration zone has an intensity of moderate to intense. No interlayered clays were identified in XRD analysis. It concludes that alteration in Granodiorite and Basalt units is old and unrelated to the active system. In this zone, jarosite and hematite can be found at some spots. These minerals indicate that pyrite has undergone interaction with hydrothermal fluid and experienced oxidation. This oxidation process produced sulphate ion that dissolved in hydrothermal water and left jarosite and hematite as the final product. Audio-Magnetotelluric survey (Centre of Mineral, Coal, and Geothermal Resources, 2017) suggests subsurface materials with very low resistivity in the middle of the depressed area up to 1500 meters depth. Clay minerals such as smectite are suspected to produce this response on the AMT survey. Therefore, these clay minerals are expected to form an impermeable barrier that split hydrothermal systems at the west and east side of the depressed area.

Some open fractures have been filled with open-space filling minerals. Based on their paragenesis sequence, quartz precipitated at first, continued by chlorite, and then calcite. Quartz veins can be found between 150 to 534 meters depth with varying textures (i.e. comb, microplumose, and cockade). These textures indicate that quartz precipitated in a neutral environment. Fluid inclusion analysis reveals that the liquid—vapour phase ratio consistently dominated by liquid. Consistent liquid-dominated phase inside voids indicates quartz was formed in a "non-boiling" condition (Moncada *et al*., 2012). The homogenisation temperature lies between 140 to 160°C. Then, chlorite filled open space after quartz and cut quartz vein in certain spots. Chlorite has texture of aggregate granular and fibrous with greenish colour, indicating this mineral is rich with magnesium. After that, calcite filled the open space and cutting quartz and chlorite veins at some point. The textures of calcite are granular, aggregate granular, comb, and cockade. Calcite was formed in a neutral condition (Reyes, 2000). Based on fluid inclusion analysis, calcite has the same characteristic as quartz due to the phase ratio aspect. Thus, calcite was also formed under a "non-boiling" condition. However, the homogenisation temperature of calcite is between 120 to 130°C. The decrease of homogenisation temperature of the fluid in quartz to calcite may be caused by the cooling process.

4. GEOCHEMISTRY STUDY

Water geochemistry study was conducted on hot and warm springs. This study shows that Panti hot springs are partially equilibrated, neutral SO_4 whilst Ujung Padang and Lundar springs are neutral HCO_3 water (Fig. 4a). Ujung Padang springs are immature while other hot/warm springs are partially equilibrated (Fig. 4b). Ratios of Cl/B and Cl/Li shows a wide range of value (Fig. 4c). This wide range of value suggests that hot and warm springs discharge from different reservoirs. Moreover, based on geological condition, Panti hot springs emerge on Sumatran Fault whereas Ujung Padang and Lundar springs discharge on Lubuksikaping fault, separated by the clay-rich depression between both faults. These facts emphasise that Panti springs belong to a different system from Ujung Padang and Lundar springs.

According to the AMT survey, Ujung Padang and Lundar area are divided by low-resistivity clay-rich material. Besides, Ujung Padang springs occur on the Granite-Granodiorite Unit, while Lundar warm spring appears on the Slate unit. In consequence, Ujung Padang springs belong to a different system from Lundar warm spring's system. In total, there are three systems in the research area named the Panti system, the Ujung Padang system, and the Lundar system.

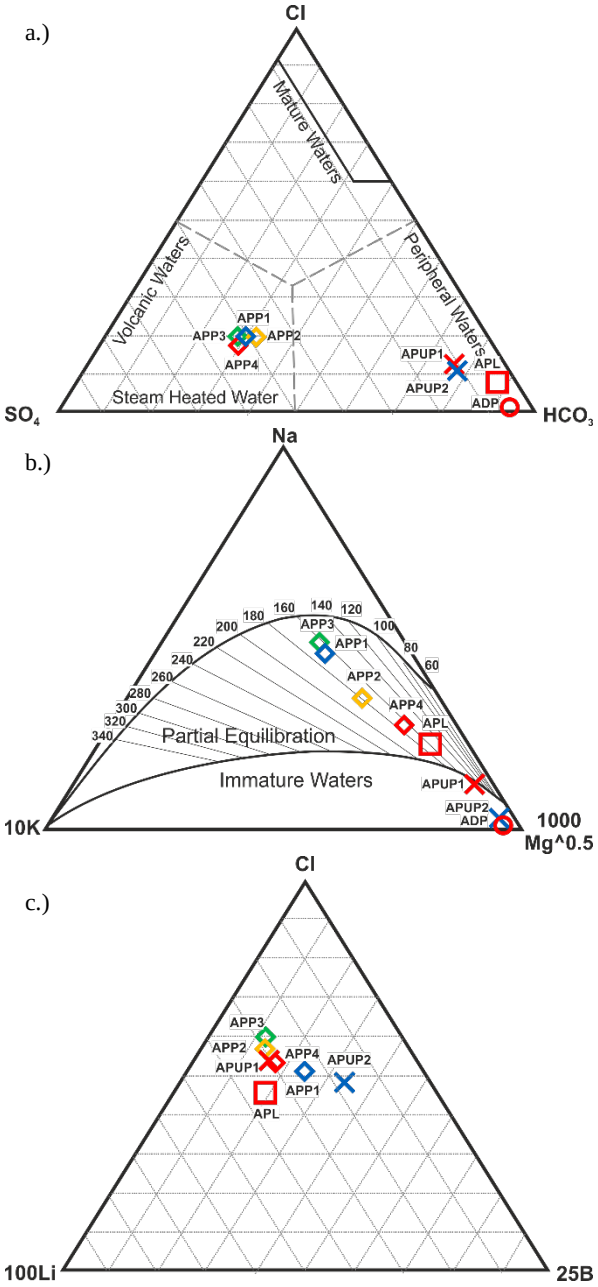

Figure 4: Plotting of a.) Cl, SO4, and HCO3, b.) Na, K, and Mg, c.) Cl, Li, and B.

By the Na-K-Ca geothermometer with Mg correction (Fournier & Truesdell, 1973 in Nicholson, 1993), the reservoir temperature of the Panti system is approximately 130 to 150°C. On the other hand, the Ujung Padang system

has a reservoir temperature of 100 to 120°C. This geothermometer calculation is suitable for both systems because both have high Ca^{2+} content in their manifestation water. But this calculation cannot be implied to the Lundar system due to very low temperature as the result. Hence, the K-Mg geothermometer (Giggenbach, 1988 in Nicholson, 1993) is used for Lundar system because this geothermometer is very responsive to a low-temperature environment (Nicholson, 1993). Based on the K-Mg geothermometer, the Lundar system's reservoir has a temperature of 90 to 110°C.

Analyses of ^{18}O and D stable isotope also conducted to assess the happening process on manifestations (Fig. 5). Panti Local Meteoric Water Line (LMWL) was pulled from the cold-water sample. Figure 5 shows that thermal waters fall around Panti LMWL. This indicates that the origin of thermal water was meteoric water (Nicholson, 1993). The shifting of $\delta^{18}O$ and δD on Panti sample to more positive value suggests enrichment on both stable isotopes. This isotope enrichment is correlated to the form of manifestation which is hot pools. Hot pools make evaporation possible. Evaporation tends to enrich $\delta^{18}O$ and δD (Nicholson, 1993). On the other side, Ujung Padang and Lundar stable isotope values lie near LMWL. This data points out a mixing process with surface water (Nicholson, 1993).

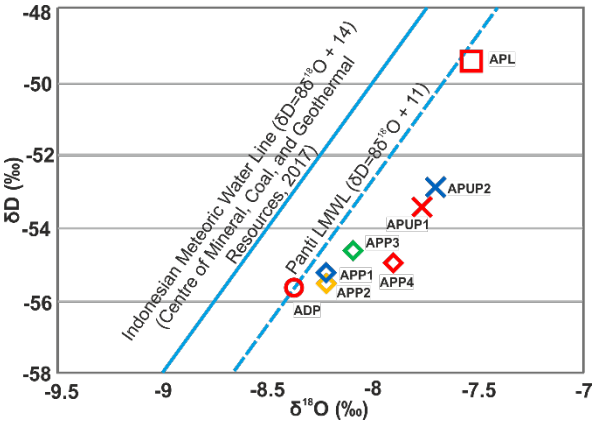

Figure 5: $\delta^{18}O$ and δD stable isotope graph (modified from Centre of Mineral, Coal, and Geothermal Resources, 2017).

4. DISCUSSION

The Slate unit was formed during the Carboniferous and metamorphed during Cretaceous (Lumbantobing & Herdianita, 2019). Slate unit topped with Basalt and Limestone unit, then intruded by the Granite-Granodiorite unit during Permian (Lumbantobing & Herdianita, 2019). Then, the Granodiorite unit intruded older units (Lumbantobing & Hedianita, 2019). This unit possibly heated circulating water underneath and produced a high-temperature (220 to 240°C) hydrothermal system, marked by the occurrence of epidote and illite as replacing minerals in basalt and granodiorite. The pull-apart basin formed during Late Eocene which triggered uplift and intensive erosion (Barber *et al.*, 2005). Erosion revealed Slate, Basalt, Limestone, and Granodiorite unit to the surface. During Miocene, there was a massive explosion that formed Talu Caldera (Lumbanbatu, 2009). This caldera-forming explosion indicated by fiamme and eutaxitic texture within welded pyroclastic products (McPhie *et al.*, 1993) in PNT-1. Two eruption cycles were recorded by PNT-1 well which are Old Talu Volcanic Product and Young Talu Volcanic Product unit. These units eroded the existing revealed units during their formation. Therefore, accidental slate, quartzite, granodiorite and epidote fragments exist in these units.

Figure 6 shows the conceptual model of Panti, Ujung Padang, and Lundar system. Recharge areas are estimated from the high elevation areas, named Ujung Padang hills and Kuburanduo hills (Lumbantobing & Herdianita, 2019). Meteoric waters infiltrate through fractures and heated by Pleistocene underlying intrusion rock bodies. This type of heat source emphasises that systems in the research area are non-volcanic (Tamanyu & Sakaguchi, 2003). Based on AMT survey, the depth of three systems vary.

Panti system's reservoir is estimated to appear at -280 masl with a temperature between 130 to 150°C. This estimation also supported by geothermal gradient which as high as 12.4°C/100 meters (Centre of Mineral, Coal, and Geothermal Resources, 2017). Reservoir formed in Granodiorite Unit. The interaction between rock and fluid makes fluid carry SO_4^{2-} ion, leaving jarosite and hematite on granodiorite. The water-rock interaction process also supported by the fact of partially equilibrated neutral sulphate water. The hydrothermal fluid discharged through Sumatran fault. The permeability of Sumatran fault increased when it cross-cuts with Petok fault, resulting in neutral sulphate hot springs emerge with high flow rate.

However, the Ujung Padang reservoir lies at -80 masl with no cap on its top. Reservoir hosted by the fractured Slate unit. The reservoir temperature reached between 100 to 120°C. Hydrothermal fluid escaped through Lubuksikaping fault. Near the surface, hydrothermal water might be mixed with surface water which results in neutral bicarbonate warm springs.

The Lundar system has a reservoir estimated at -250 masl which is fractured Granite-Granodiorite unit. The reservoir has a temperature between 90 to 110°C. The hydrothermal fluid of this system flows upward through Lubuksikaping fault and might also undergo mixing with surface water forming neutral bicarbonate warm spring.

5. CONCLUSION

Alteration of geothermal system at PNT-1 Well has produced smectite in ash, tuff, breccia, and andesite, produced illite and epidote in granodiorite and basalt. Based on epidote and illite presence in Granodiorite and Basalt unit, it indicates that a high-enthalpy geothermal paleo-system has occurred during Miocene. This paleo-system has been involved by Sumatran Fault Zone and uplifted then eroded. The Panti geothermal field contains three separate, small, low temperature, non-volcanic geothermal systems which are Panti, Ujung Padang, and Lundar. These systems are controlled mainly by Sumatran and Lubuksikaping fault and heated by concealed consolidated Pleistocene intrusion rock. According to fluid petrographical and fluid inclusion analysis, the fluid of the Panti system once has neutral acidity with a temperature

between 140 to 160°C then cooled to around 120°C. This geothermal might still exist until now, indicated the occurrence of active hot and warm springs. The reservoirs are quite shallow and separated by geological structures and impermeable clay-rich material. The recent circulating fluid of three systems have temperatures of less than 150°C. These systems circulate through fractures on splays of the Sumatran Fault Zone in Granodiorite, Granite-Granodiorite, and Slate unit respectively. Hydrothermal fluids experienced water-rock interaction and mixing with surface water, discharged through faults, and form neutral sulphate and bicarbonate hot and warm springs.

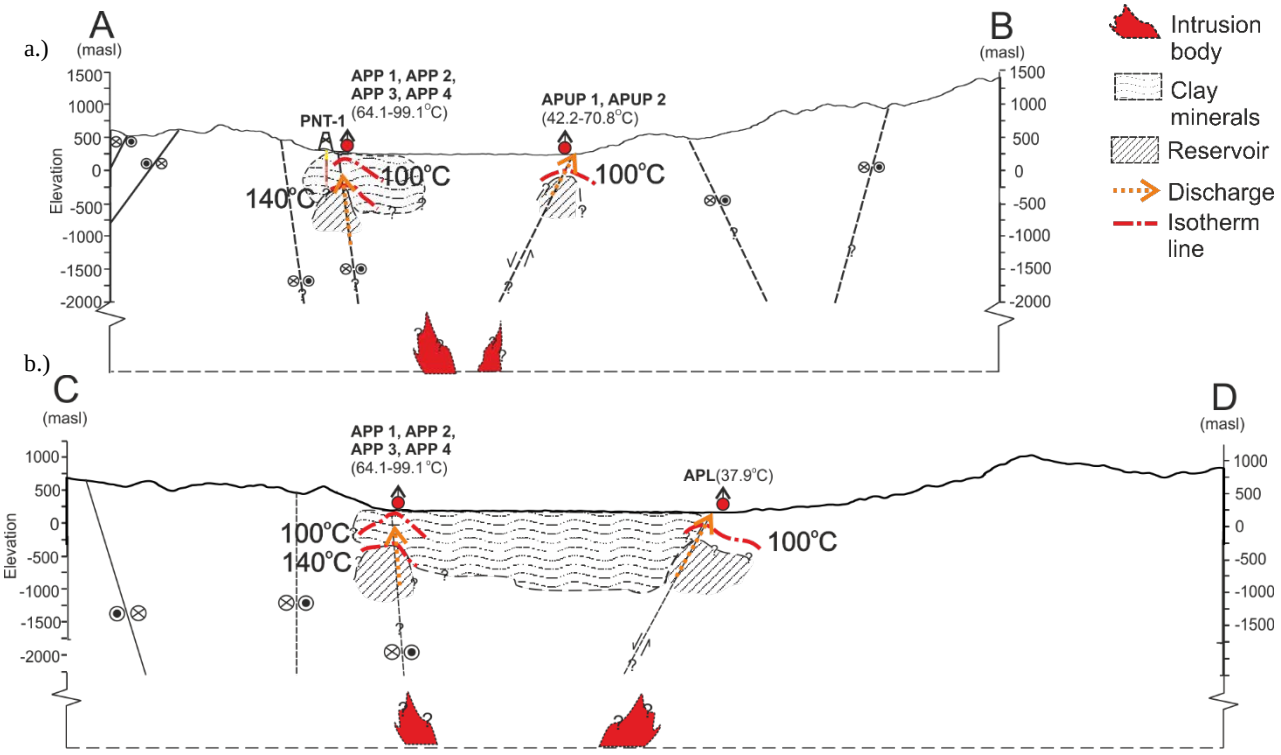

Figure 6: Conceptual model of a.) Panti and Ujung Padang system on A-B cross-section, b.) Panti and Lundar system on C-D cross-section.

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APPENDIX

Geochemistry of Surface Manifestations (Centre of Mineral, Coal, and Geothermal Resources, 2017)

Sample	**Temp**	**pH**	**Li**	**Na**	**K**	**Ca**	**Mg**	**SiO_2**	**B**
	°C		ppm						
APP 1	99.1	7.7	0.44	228.04	8.89	11.5	0.03	140.83	1.75
APP 2	84.6	7.8	0.47	211.24	9.82	14.5	0.09	140.16	0.85
APP 3	84.3	7.8	0.43	214.06	7.78	12.4	0.02	131.79	0.75
APP 4	64.1	7.5	0.42	191.49	7.39	18.6	0.18	122.83	1
APUP 1	70.8	9.0	0.12	71.38	2.18	1.4	0.25	100.99	0.25
APUP 2	42.2	7.7	0.02	19.26	1.71	0.9	0.25	35.65	0.15
APL	37.9	8.9	0.07	56.70	1.99	3.3	0.03	59.69	0.15
ADP	26.1	7.9	0.01	21.76	5.12	12.9	2.13	52.3	1.2

Sample	**Cl**	**F**	**SO_4**	**HCO_3**	**NH_4**	**As**	**Fe**	**Ion Balance**
	ppm							%
APP 1	91.67	7	243.45	139.37	0.5	0.005	0.02	2
APP 2	90.32	7	223.31	145.22	0.5	0.5	0.02	2
APP 3	92.19	7	249.69	135.02	0.5	0.2	0.03	-1
APP 4	76.94	7	237.31	131.04	0.9	0.2	0.005	0
APUP 1	21.50	2	18.36	131.16	0.3	0.005	0.01	1
APUP 2	5.36	1	5.65	39.57	0.5	0.2	0.07	2
APL	9.03	13	4.82	102.29	0.3	0.005	0.02	0
ADP	1.34	0	5.47	103.91	0.4	0.005	0.02	1

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