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Updated Tulehu Conceptual Model Due to Exploratory Drilling: An Example Of Geothermal Field with Tertiary Volcanic Activity

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ABSTRACT

The Tulehu geothermal field is located in Maluku province, Ambon Island. Following several surface surveys, six thermal gradient holes (40-150m deep) had been drilled in total in 2008 and in 2009. The highest borehole bottom temperature (122.6 ºC) was recorded in the well W2.1. The first exploratory well TLU-01, located near by the well W2.1, was drilled to total depth 932 m in 2011. Following this exploratory drilling, another drilling campaign was conducted in June 2017 to April 2018, where four wells (TLU B-1, TLU B-2, TLU C-1, TLU D-1) were successfully drilled to 1800 – 1900 m depth and two of which were tested.

Drilling campaign in 2011 brings a hypothetical conceptual model that became the basis for the development plan and the drilling campaign in 2017. It was found that the drilling result in 2017 gave indication of prospect area shifting and new hypothesis of the heat source. The prospect is shifted to the southeast direction toward the expected system heat source and the area shrinks currently from 7-10 km^2 to 0.7-1.9 km^2 , thus, need to have additional surveys. Part of the previous prospect area, which is mainly delineated by MT survey, was confirmed to be inferred as paleo-geothermal reservoir and the up-doming resistivity structure delineated by MT survey corresponds to the paleo resistivity structure. The temperature log from the well TLU C-1 which was directed to the area is relatively low, I.E. 182 ^{0}C. Whereas, the fluid inclusion analysis from the cutting sample shows a very high homogenization temperature of fluid inclusion (387 ^{0}C) which corresponds to high resistivity value of approximately 160 – 200 Ωm based on the MT model. On the other hand, the most successful well having around 1.5 MWe capacity, shows very close temperature value resulted from PTS flowing survey and fluid inclusion analysis from the cutting sample, i.e. 209 ^{0}C and 223 ^{0}C, respectively. The well is located in the southeastern side of the prospect area. It seems that the geothermal system in Tulehu field might experience an evolution, with a direction from the northwest to the southeast, which inferred to be controlled by the volcanism activity evolution in the area.

1. INTRODUCTION

After several geoscientific surface surveys, six thermal gradient holes (40-150m deep); three holes (40-120m deep) in 2008 and another three holes (150m deep) had been drilled in 2009. The highest borehole bottom temperature (122.6°C) was recorded in the well W2.1. The first exploratory well TLU-01, located near by the well W2.1, was then drilled from December 2010 to July 2011 (drilled depth = 932.65 m). The well TLU-01 (later on called TLU A-1) succeeded in discharge of geothermal fluids. However, the fluid discharge did not last sustainably long, some scaling indication was observed and the pressure and temperature logging data was merely obtained just after the drilling, providing temperature data with the maximum temperature of 115.42°C that does not indicate the natural formation temperature at the reservoir due to the interference by water injection during the drilling.

Following this exploratory drilling, another drilling campaign was conducted in June 2017 to April 2018, where four wells (TLU B-1, TLU B-2, TLU C-1, TLU D-1) were successfully drilled to 1800 – 1900 m depth and two of which were tested (TLU D-1 and TLU B-2). TLU D-1 succesfully tapped high permeability zone, but having low temperature instead. The well was firstly tested, resulting relatively low wellhead pressure (WHP) and the massive scales deposited inside of the flow lines, that require replacement of the discharge pipe and remove the scale frequently. The scales are hard and white to light yellow solids. Some scale samples were collected and prepared for X-ray analysis. The result of analysis indicates that the scales are calcium carbonate (aragonite and minor calcite).

2. CONCEPTUAL MODEL OF TULEHU BEFORE DRILLING CAMPAIGN IN 2017

In Maluku Province, there are nine (9) geothermal fields distributed on five (5) different islands have been nominated by MEMR (2007). No Quaternary volcano is identified in these islands (the nearest Quaternary volcano is Banda Api volcano situated about 85 km southeast of Nusalaut Island).

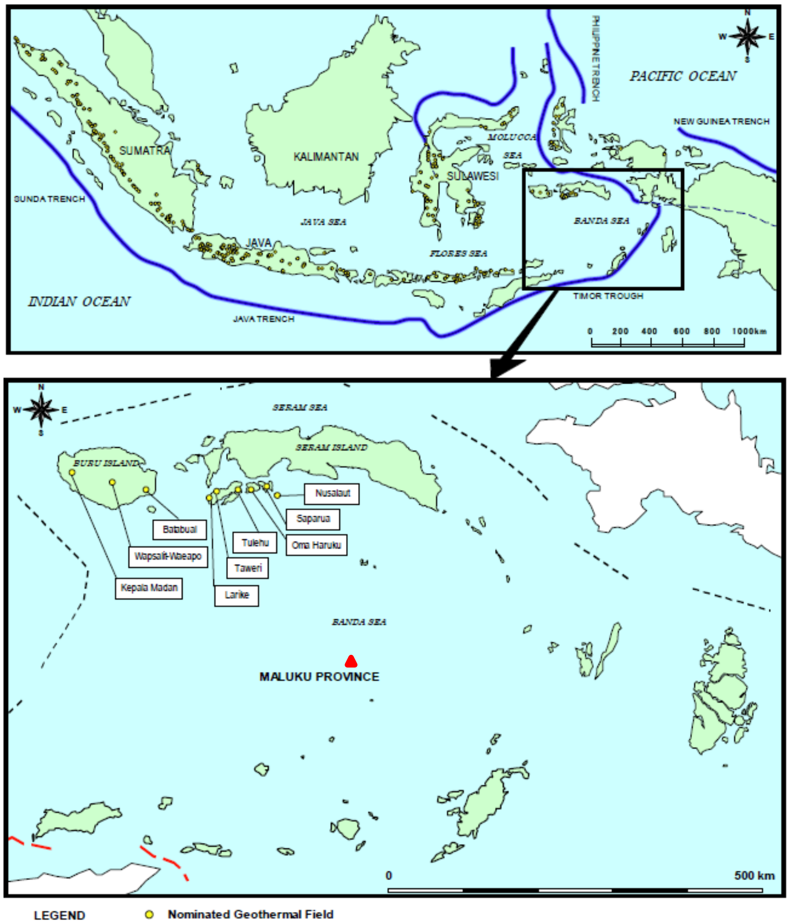

Figure 1 : List of Geothermal Field Nominated by MEMR (2007)

The geology of Ambon Island is mainly characterized by Permian ultrabasic rocks, Triassic sedimentary rocks, Pliocene volcanic rocks (composed of andesite, dacite, tuff breccia, tuff and so on), Pliocene intrusive rocks (granite and diabase), Pleistocene to Holocene coral limestone, and alluvium deposits. The Pliocene volcanic rocks are dominant and cover about 90 % of Ambon Island.

The surface geology in the Tulehu geothermal field consists of the thirteen (13) units (from older to younger) : the Sandstone unit, the Tanjung basalt lava unit, the Salahutu-1 dacitic lava unit, the Salahutu-2 dacitic lava, the Bukitbakar andesite lava unit, the Bukitbakar pyroclastic unit, the Huwe pyroclastic unit, the Mt. Simalopu pyroclastic unit, the Mt. Salahutu pyroclastic unit, the Mt. Kadera pyroclastic unit, the Mt. Eriwakang pyroclastic unit, the Limestone unit and alluvium deposits, (see Figure 2).

The hot spring waters in this field were classified into Cl-type or Cl-HCO_3-type (Figure 3). It is thought that in some springs, the high contents of Cl ions in the waters might be caused by admixture of seawater with meteoric water. The isotope data of D vs O-18 plot for Batulompa, Oma, and Panta Tulehu springs clearly supports this hypothesis, although, there are other hot spring waters (Sila, Hatuasa, Tulehu, T. Biru) with a different trending line and relatively large oxygen-18 shift indicating interaction of hot water with reservoir rocks under high-temperature conditions. It should be noted, an oxygen-18 shift might also occur in carbonates rock such as limestone even when the temperature is low, therefore the presence of high-temperature geothermal water cannot be judged only from these data.

It is observed that almost all springs derived from same reservoir and not all springs affected by seawater (Figure 4). Sila (green triangle), Hatuasa (red circle) and Hatuing (blue circle) clearly indicates different seawater trending line (Cl vs SO_4 plot). This inference is supported by the Na-K-Mg trilinear plot that some hot-spring water probably underwent deep fluid-rock interaction and were derived from a geothermal reservoir with a temperature higher than 200°C. Therefore, it is concluded that the geothermal fluid originates from meteoric water, manifested in Sila and Hatuasa, whereas some springs (Batulompa, Oma, Pantai Tulehu) are resulted from the mixing with seawater, including fluid from TLU-01 (orange diamond) which is also diluted by either seawater or (most likely) groundwater (see Figure 5).

Figure 2 : Geological Map of the Tulehu Geothermal Field

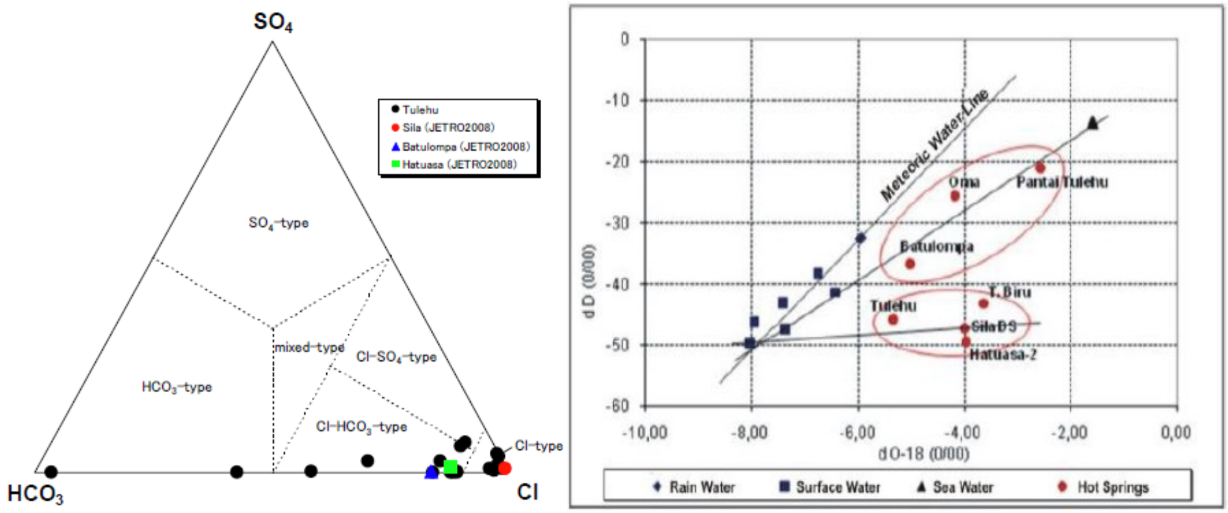

Figure 3 : Cl-SO4-HCO3 plot (left) and Isotope data of O18 vs D plot (right)

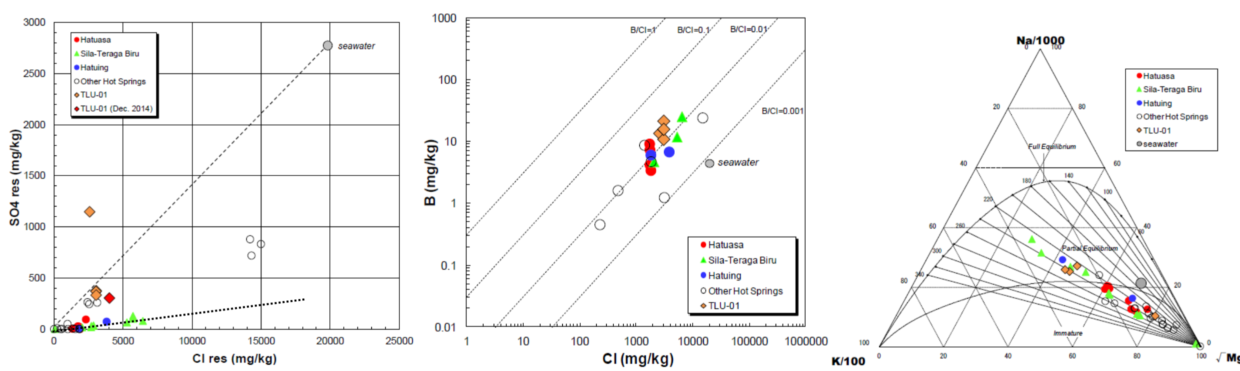

Figure 4 : Cl vs SO4 plot (left), Cl vs B plot (middle), and Na-K-Mg plot (right)

MT survey revealed a low resistivity zone (< 10 ohm-m) extends on the northwestern side of Mt. Eriwakang. The most active geothermal manifestations and altered ground are situated in this low resistivity zone: the Sila hot springs, the Telaga Biru hot springs, the Hatuasa hot spa and the Banda alteration zone. The most prospective geothermal resource likely extends under this low resistivity zone. Judging from the resistivity map at a depth of 1,000 m (see Figure 6), a relatively high resistivity zone (resistivity higher than 40 ohm-m) extends under the low resistivity zone. The Hatuasa hot spa and the Banda alteration zone are also situated in this high resistivity zone.

A tentative model for the geothermal system in the Tulehu geothermal field based on the obtained data and information is presented in Figure 7 and 8. The prospective area for a geothermal development extends on the northwestern side of Mt. Eriwakang. It is considered that the centers of geothermal activity is found along the Banda Hatuasa fault between the Hatuasa hot spa and the Banda alteration zone. Although hot waters from the Hatuasa hot spa do not show any features in their chemistry indicating the existence of prospective geothermal resources, this can be explained by the presence of the impermeable zone, corresponding to the low resistivity zone. This impermeable zone prevents the up-flow of deep geothermal fluid around the bottom of the detected low resistivity zone. Therefore, the Banda Hatuasa fault can be regarded as a main target for drilling.

Considering the chemistry of the hot spring waters, it must be noted that the hot water from the Sila hot springs is derived from a geothermal reservoir with the highest temperature in this field. Therefore, there might be a permeable structure connecting the geothemal reservoir that is inferred under the low resistivity zone to the Sila hot spring on the eastern side, or other possibility is another center of geothermal activity around the Sila hot springs may exist. The Sila hot springs occur around the point where the R2 fault branches off from the Banda fault. Therefore, it will be expected that the geothermal reservoir also extends along the Banda fault and the R2 fault.

The underground temperatures measured from wells W2.2 and W2.3 (where temperature increase with depth is scarcely identified) suggest that there are recharge areas around Mt. Terang Alam and around Mt. Salahutu. It should be noted that the high carbonate ion content of most of the hot spring waters in this field suggests the possibility that the hot spring waters were influenced by limestone as indicated by surface geological data and confirmed by the shallow well TG-2 and W2.3. However, such rocks are identified only near the ground surface in this field (55 m thick in TG-2 and W2.3).

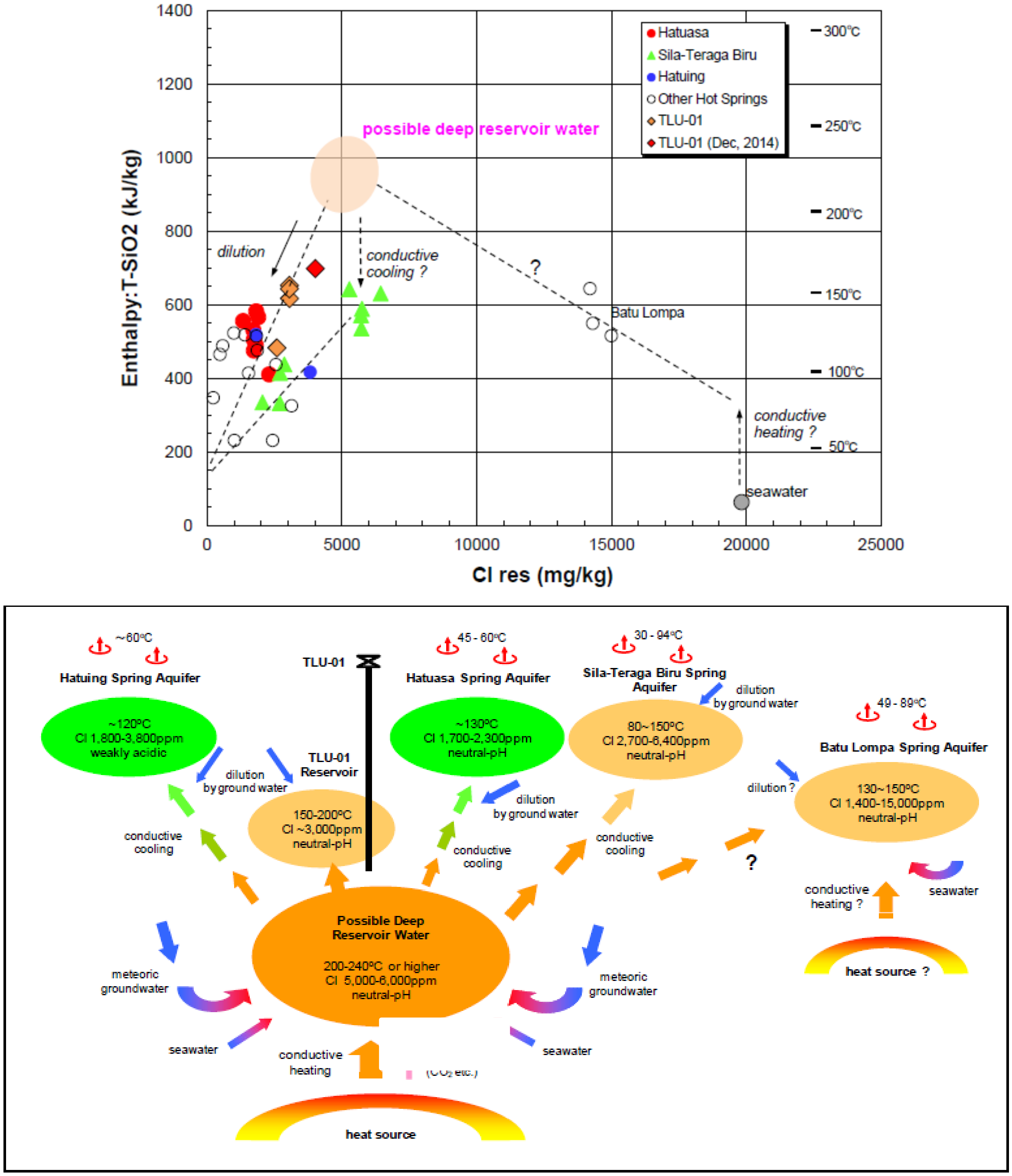

Figure 5 Enthalpy-Cl Mixing Model (above) and Geochemical Model (bottom)

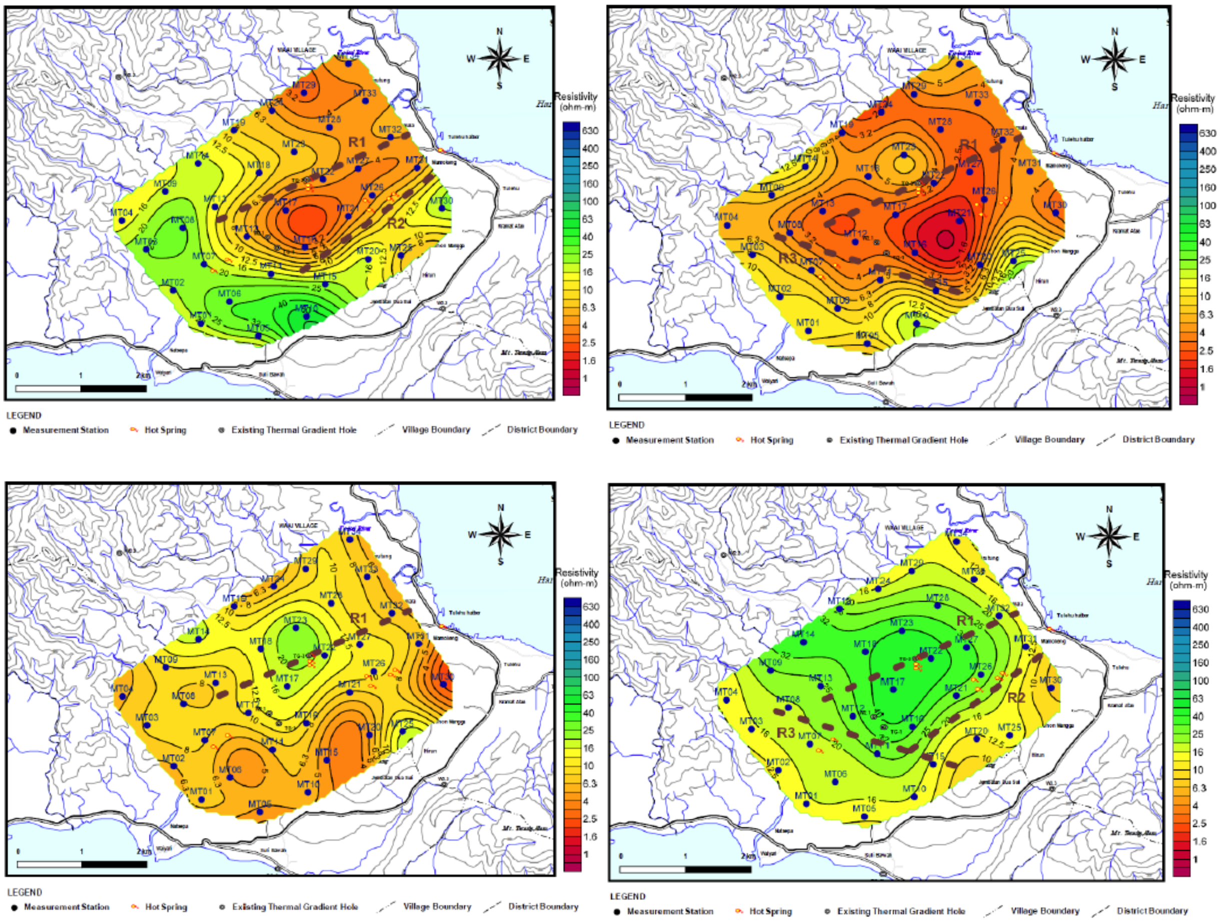

Figure 6 : Resistivity Map at depth : 100 m, 250 m, 500 m, 1000 m, (clockwise direction from top left)

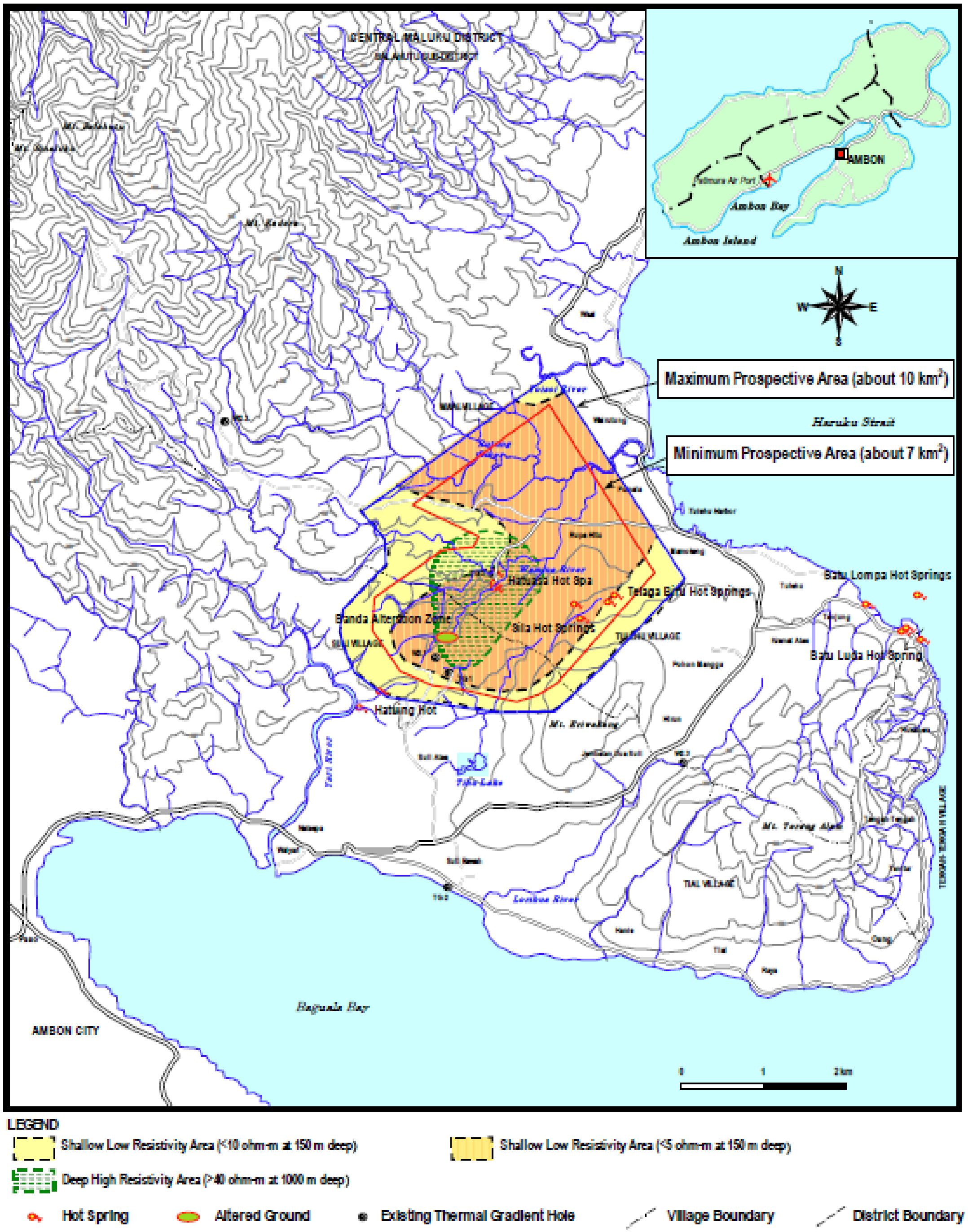

Figure 7 : The Geothermal Prospective Area of Tulehu as delineated by MT Survey

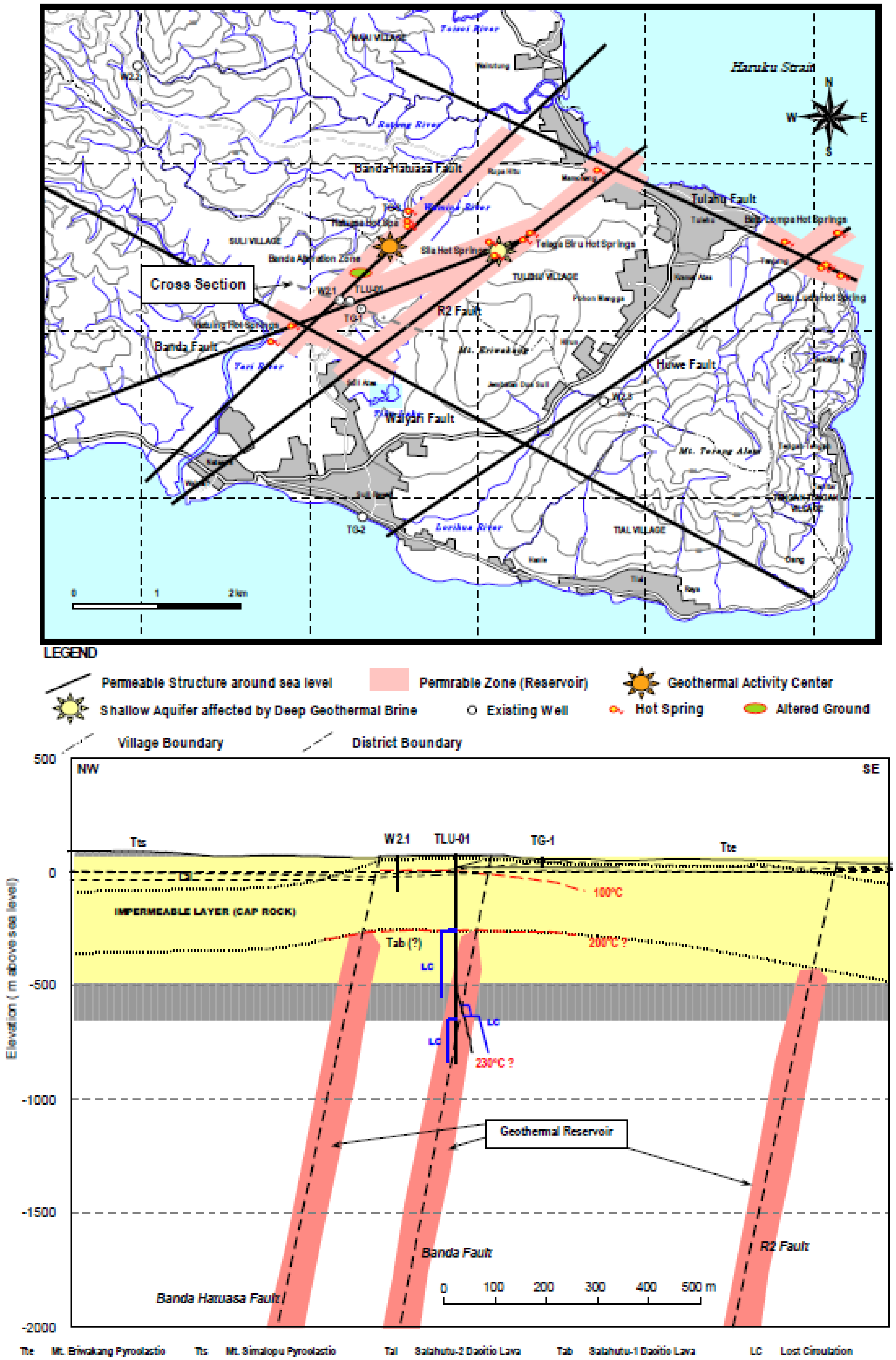

Figure 8 : Geothermal Conceptual Model of Tulehu Field

3. RESULT OF DRILLING CAMPAIGN IN 2017

Drilling plan of four exploratory wells, consisting of three (3) exploratory production wells and one (1) exploratory reinjection well, had formulated in 2016 (Figure 9). The objectives of these four (4) well drillings are to confirm :

i. Presence of geothermal reservoir (test permeability, temperature, and fluid characteristics). at deeper levels along Banda Fault (and Banda Hatuasa Fault) at the western area (around A and D Pads)
ii. Presence of geothermal reservoir (test permeability, temperature, and fluid characteristics). at deeper levels along Banda Fault at the central area (around B and C Pads)
iii. Capacity for reinjection at the eastern area along Banda Fault (around E pad)
iv. Subsurface data related with geothermal structures to formulate drilling plan of rest of the wells required for the power plant project

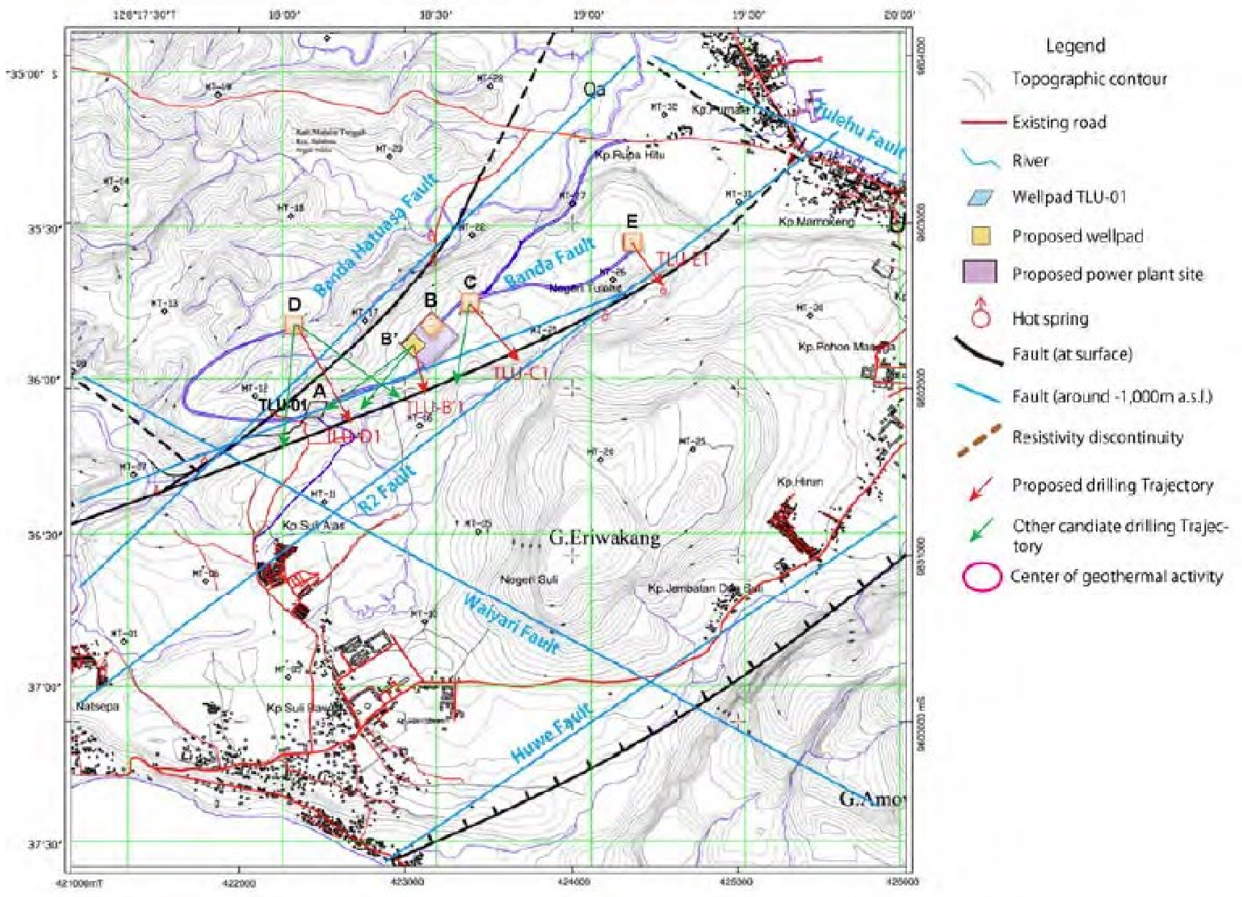

Figure 9 : Drilling Plan of Four Exploratoray Well

The drilling result summarizes in the Table 1.

The first exploratory well TLU-D1 successfully tapped multiple and very high permeable zone, although measured temperature is relatively low. The fluids were successfully discharged but massive calcite scaling on the well testing facilities was observed. The second exploratory well TLU-B1 was drilled resulted on very low permeability, but measured temperature exceeds 200°C. The well was unable to discharge fluid, however the measured temperature is invaluable to refine the next drilling target since it showed convective temperature profile (Figure) indicating nearby convective (possibly reservoir) zone is exist. Unfortunately, due to underestimation of its permeability, it was decided to reduce steps on the heat-up survey and conducting PT logging only on day 1 and 49, thus the convective temperature profile was revealed when drilling of the third exploratory well TLU C-1 was in progress.

TLU C-1 was targeted by relying on the resistivity structures that there was a possibility a relatively higher temperature geothermal reservoir might be presented below the Hatuasa hot spring area at depth. PLC and some drilling breaks inferring the presence of permeability has been observed during TLU C-1 well drilling, but the well does not have enough permeability and/or temperature for fluid production. By referring currently obtained subsurface temperature (Figure 10), there was a possibility that the subsurface temperature in an area around TLU-B1 is higher than in around TLU C-1. Therefore, southern area was selected for drilling target zone to secure fluid.

Although its injectivity is relatively low (6.2 t/h / bar), TLU-B2 well successfully discharged fluid. Base on PTS logging data during production test, presence of multiple permeable zone has confirmed in TLU-B2. The maximum observed temperature during flowing was about 213°C at around 1,653 m (which shall be higher at shut-in condition). This result confirms that subsurface temperature at the southern area in the development area is higher than northern and western area.

Although epidote found within the prophylitic alteration zone, its scarcity confirms the geothermometry study that the reservoir temperature shall not be higher than 220-230°C. In addition, considering the youngest volcanism age (Mt. Eriwekang) within the area that is submarine volcano in the last Pliocene – early Quarternary age.

Considering the TLC and PLC occurred in the five exploratory wells corresponding to the location of Banda Fault and Banda Hatuasa Fault (Figure 10-right) as well as the presence of abundant calcite and quartz, it is able to conclude that the permeable structure correlated with the two fault has been filled with the secondary minerals. The presence of Euhedral columnar-shape calcite crystal indicating possible relic permeability reinforces this hypothesis.

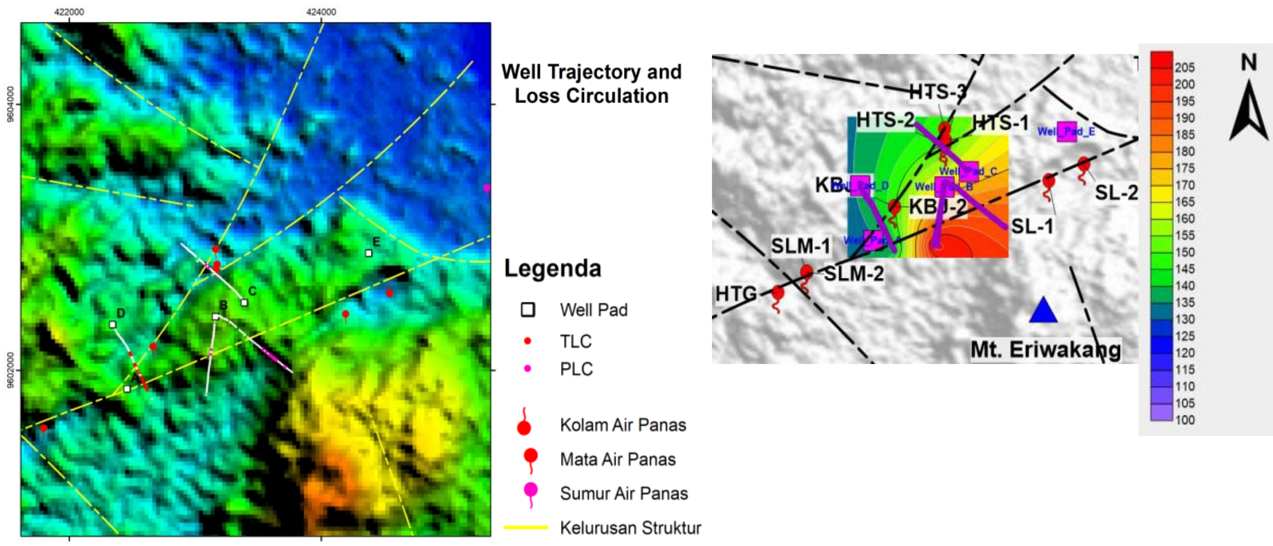

Figure 10 : Well Trajectory, Loss Circulation and Estimation of Sub-surface Temperature Profile

Table 1 : Summary Drilling Result

Wells	Depth	Alteration	Permeability	Temperature	Targets Result	Other Notes
TLUD-1	1712m	Argilic type at 0-385m, dominantly Silicified at 385-507m (transition), and prophylitic afterward Epidote found (rare) at 700-1070m and intermittently at 1170-1700m Calcite was abundant almost in entire hole while calcite veinlet was observed from depth 780m.	Very high TLC : 984m followed by intermittent return all the way to bottom hole Spinner : 930-970m, 970m below and 1410m Injectivity : 776 t/h / bar	140.5°C at 1561m Fluid inclusion : 208-242°C at 1154-1157m	970m : Banda Hatuasa Fault 1410m : Banda Fault	Successfully discharge the fluid Massive Calcium carbonate scale deposition observed
TLUB-1	1800m	Silicified & Argilic type at 0-355 m, and Prophylitic afterward, interspersed by Silicified at certain interval (705-820 m, 1030-1135 m) Euhedral columnar-shape calcite crystal found (possibly sign of relic permeability) Epidote found (rare) at 700-810m and intermittently at 1050-1800m	Good permeability not encountered. PLC: 1002 to 1016 m (0.30 bpm) and 1101 – 1103 m (8 bpm)	205°C at 1782m Fluid inclusion : 208-295°C at 1187m, 204-312°C at 1484m	PLC in the possible zone of Banda fault. The fractures related with Banda fault have been filled by mineral precipitation, such as the calcite and silica veinlet.	Linear/conductive temperature profile up to depth m, following by vertical/convective temperature profile to total depth
TLUC-1	1900m	Silicified & Argilic type alternately at 0-235 m and Prophylitic afterward Epidote found continuously at 800-1500m, although rare Abundant calcite, especially at 800-1200m and 1450-1700m	Good permeability not encountered. PLC: 1388.7 to 1491.2 m (0.2 to 4 bpm)	181.2°C at 1882 m (PT day-10) Fluid inclusion : 244-384°C at 1520m, 254-286°C at 1871m	PLC in the possible zone of Banda Hatuasa fault, but it has been filled by the calcite, silica veinlet	Conductive profile all along the depth
TLUB-2	1800m	Silicified & Argilic type alternately at 0-380 m and prophylitic afterward Epidote found (rare) at 950-1250m and intermittently at 1350-1800m Abundant calcite, at 1050-1800m	Low to moderate Spinner : 1100m, 1173-1180m, 1450-1456m, 1655-1660m Injectivity : 6.21 t/h / bar	213°C at 1653m (PTS flow test) Fluid inclusion : 199-209°C at 1655m, 193-223°C at 1757m	Presence of multiple permeable zone between Banda Fault and resistivity discontinuity R2	Successfully discharge the fluid No calcite scaling Total flow rate : 93 t/h at WHP 3 bara

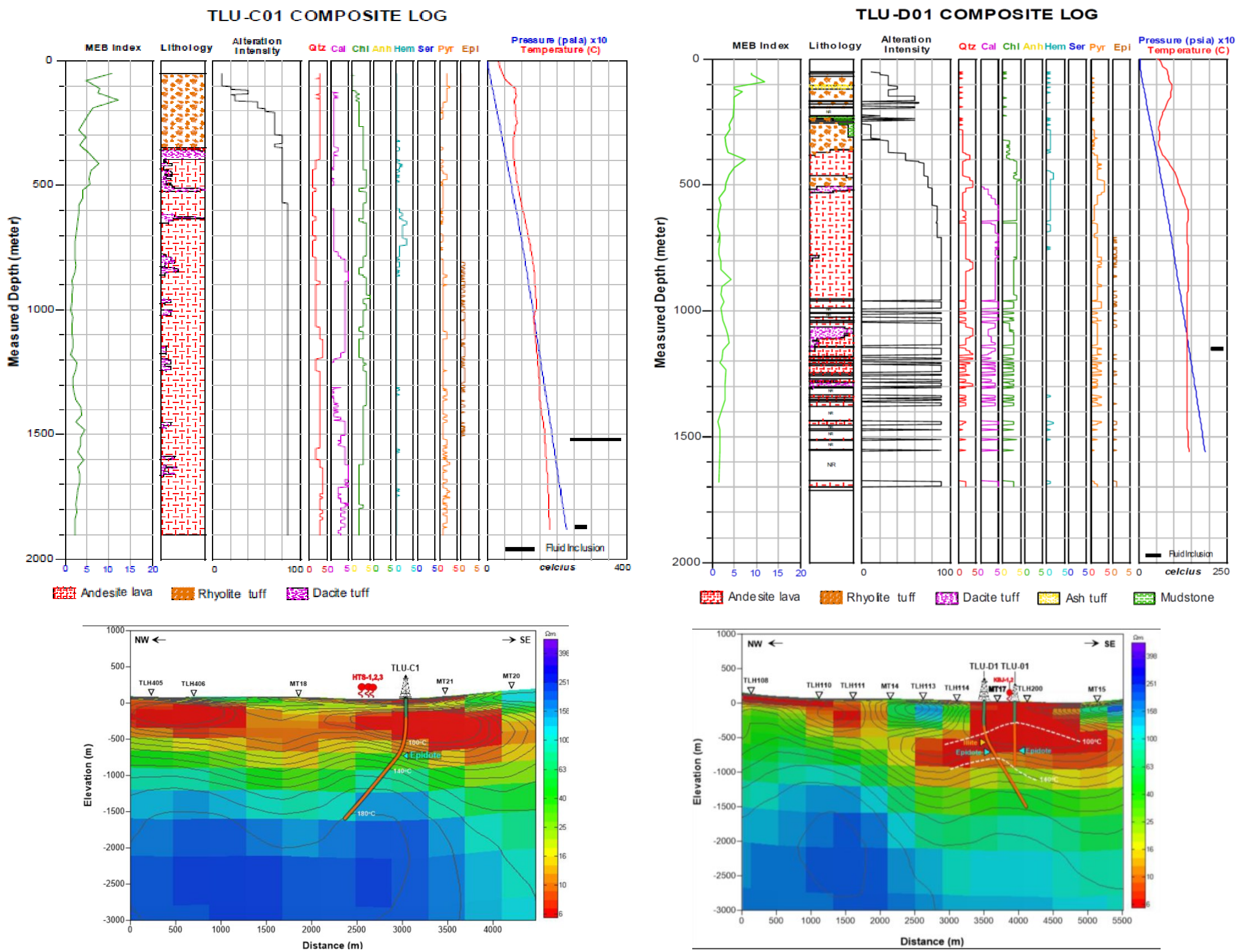

Figure 11 : Composite Log, Alteration Zone and Resistivity Model Cross Section along TLU-C1 (left) and TLU-D1 (right) Trajectories

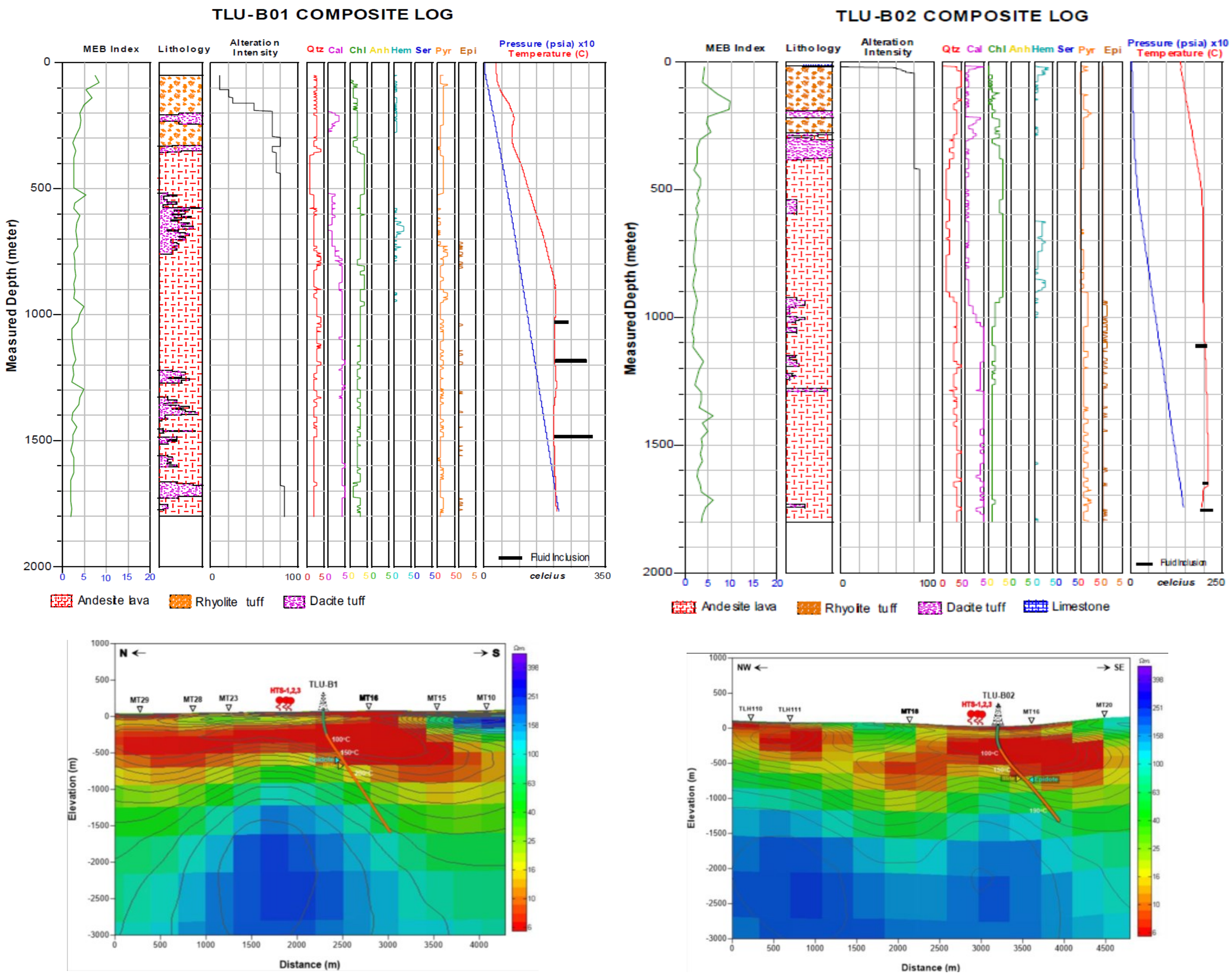

Figure 12 : Composite Log, Alteration Zone and Resistivity Model Cross Section along TLU-B1 (left) and TLU-B2 (right) Trajectories

4. THE UPDATED CONCEPTUAL MODEL

4.1. Heat Source and Reservoir Temperature

The geothermal activity center (up-flow area) in Tulehu field is considered to be located at the northern flank of Mt. Eriwakang, judging from subsurface temperature distribution confirmed by exploratory wells (Figure 10 and 15). The volcanic rocks in Mt. Eriwakang are likely to be associated with magma chambers that remain generating heat. Therefore Mt. Eriwakang is a strong candidate of heat source of geothermal system in the Tulehu area. Considering the volcanism age of Mt. Eriwekang, it is expected that the reservoir temperature shall not be higher than 220-230°C

4.2. Reservoir and Permeable Structure

The assumed permeable zone along faults is shown in Figure 13. The Banda fault is considered to be partly permeable, in which high-temperature geothermal fluid up-flows. From the geothermal activity center located around Mt. Eriwakang, geothermal fluid could flow to the north along permeable zones related to Banda fault and fault inferred by resistivity discontinuity R2. Result of well drilling on TLU-D1, TLU-B1 and TLU-B2 shows that permeability along Banda fault is not homogeneous. Some parts of Banda fault are impermeable or used to be permeable but it is filled by hydrothermal alteration minerals. Banda fault and fault inferred by resistivity discontinuity R2 at the central part in the field (between Banda hot spring and Sila hot spring area) is considered to be permeable, which play role for fluid flow passage. Permeability along Banda fault at the shallower level seems to be much permeable than that of deep level considering presence of hot springs and altered ground along Banda fault. In addition, western area part of both Banda Hatuasa fault and Banda fault are considered to be permeable based on TLU-D1

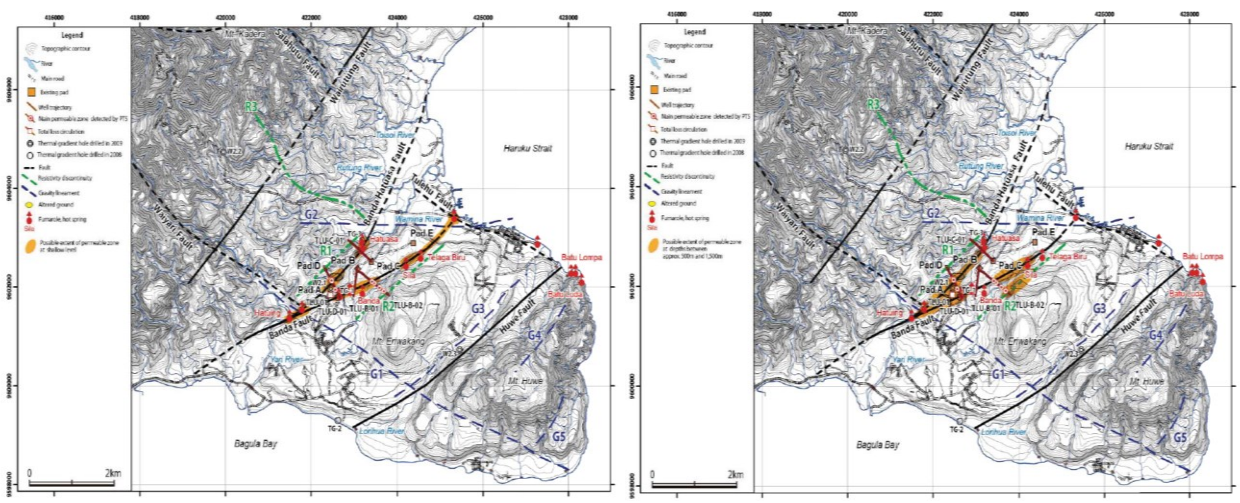

Figure 13 Permeable Zone (orange) at depth shallower than 500 m (left) and at deeper than 500 m (right)

An argillized impermeable layer, recognized in the well geology of exploratory wells corresponding with the low resistivity zone detected in MT survey, will extend at a shallow depth (Figure 11 and 12). This impermeable layer must prevent deep geothermal brine from flowing up to the surface, and the geothermal brine probably flows mainly to the southwest and to the northeast along mainly Banda fault.

It is also observed from the resistivity model that the up-doming resistivity structure intersected by TLU-C1 (Figure 11) does not correlate with a geothermal reservoir. It is inferred as paleo-resistivity structure. The result of fluid inclusion analysis shows high homogenisation temperature of 244-384°C at 1,520m, which is the highest among the samples from the other wells, and the homogenization temperature tends lower (254-286°C) at deeper level (1871 m). Compare to the temperature measured by PT logging at the corresponding depth (177°C), this value is also considerably higher, indicating that the 1520m depth layer on TLU-C1 is used to be hot in the past. This anomaly is contrary with the area tapped by TLU-B1 and TLU-B2. Two of them neither directed to the up-doming resistivity structure nor showing considerable lower measured temperature than the homogenization temperature (Figure 12), but these wells have relatively high temperature instead. In addition, TLU-B2 could discharge fluid with no carbonate scaling observed so far.

4.3. Fluid Flow Pattern and Origin of Fluid

The origin of reservoir water is meteoric and no indication of seawater mixing present (Figure 14). Nicholson (1993) states that seawater mixing can be indicated by very low values of Cl/Mg and Ca/Mg, (10 and 0.3, respectively). Stable isotope data of O18 and D also supports this premise.

The meteoric water is likely penetrating into the deep level in the mountainous area at a relatively higher elevation mainly along Wairutung fault and Huwe fault. The deep water is heated up to 200-230°C by conductive heat. The thermal water at depth is considered to be up-flowing through the permeable zones mainly along Banda fault and resistivity discontinuity R2 between the hot spring areas of Banda and Sila. Up-flowing thermal water is stored in the fractures developed in volcanic rocks, which is tapped by TLU-B2. The hot water, having ascended to the shallow level and flow laterally mainly along Banda fault and Banda Hatuasa fault, is likely diluted and cooled by cold shallow groundwater, and stored in these permeable zones at relatively shallower depth tapped by TLU-01 and TLU-D-01. The diluted and low temperature thermal water discharges to the surface at hot springs such as Hatuasa. Sila and Telaga Biru contain deep geothermal brine and in the same trend line of Cl-SO4 plot with the brine from TLU-B2. This gave other supporting premise that the most prospective area located around Sila. It is believed that Banda Hatuasa fault and Banda fault is locally permeable at the zone of clay cap near the hot springs and allows deep geothermal brine to flow up through the layer to the surface.

Table 2. Chloride, Calcium, and Magnesium Content of TLU-D1 and TLU-B2

Well	Cl	Ca	Mg	Cl/Mg	Ca/Mg
D-1	3770	290	22	171	13
B-2	10,500	763	10	1050	76

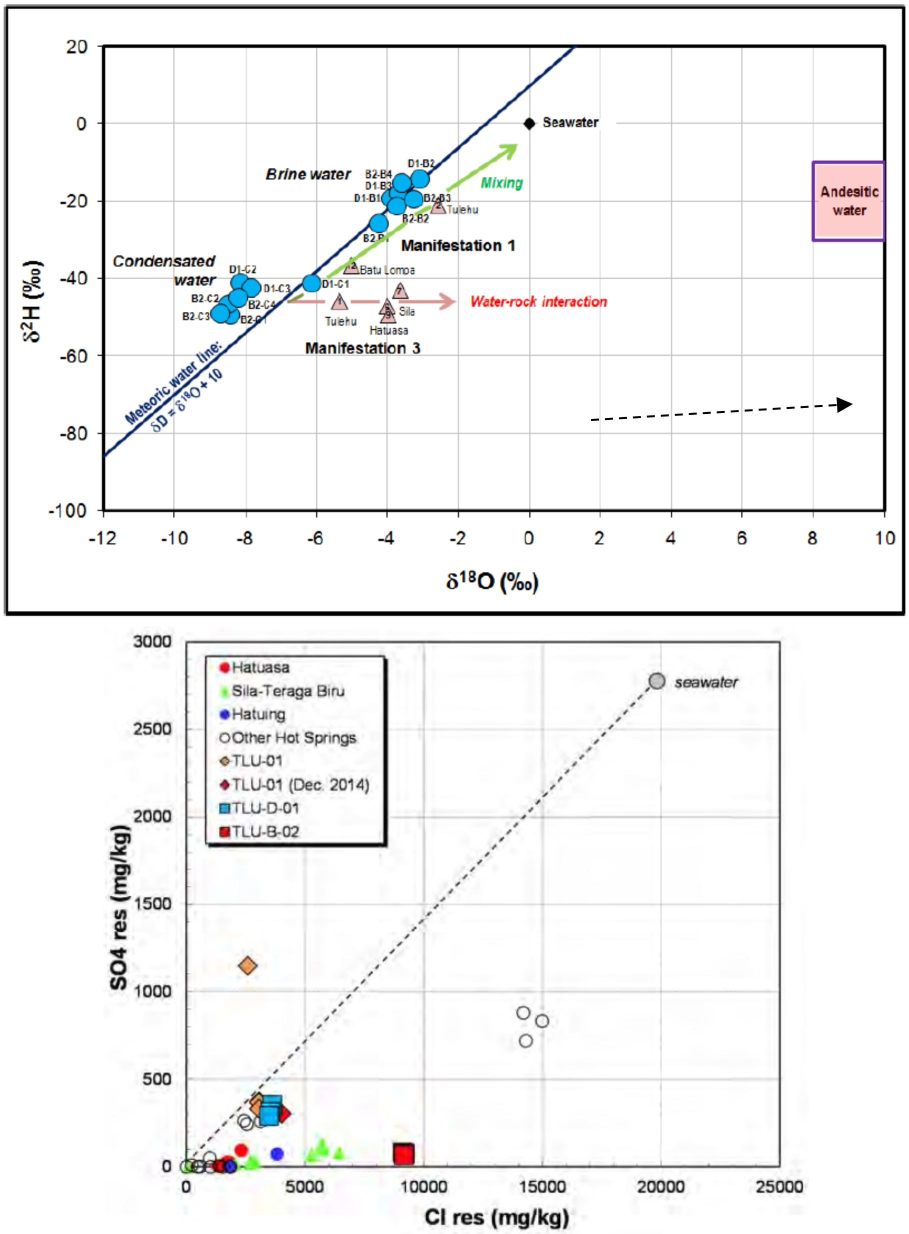

Figure 14 Updated Isotope Data and Cl vs SO4 Plot incorporating Sample from TLU-D1 and TLU-B2

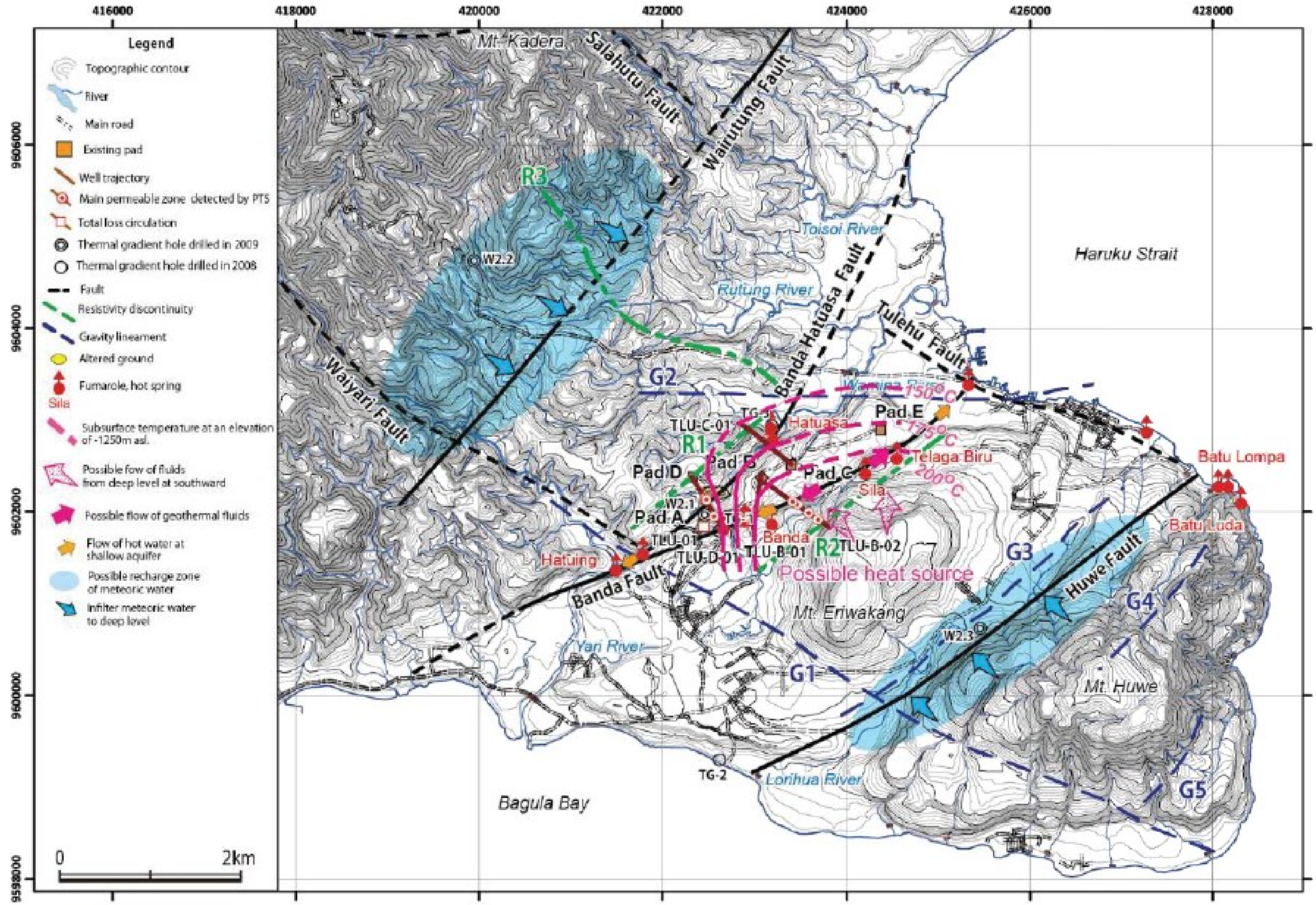

Figure 15 Updated Geothermal Conceptual Model (Plan View)

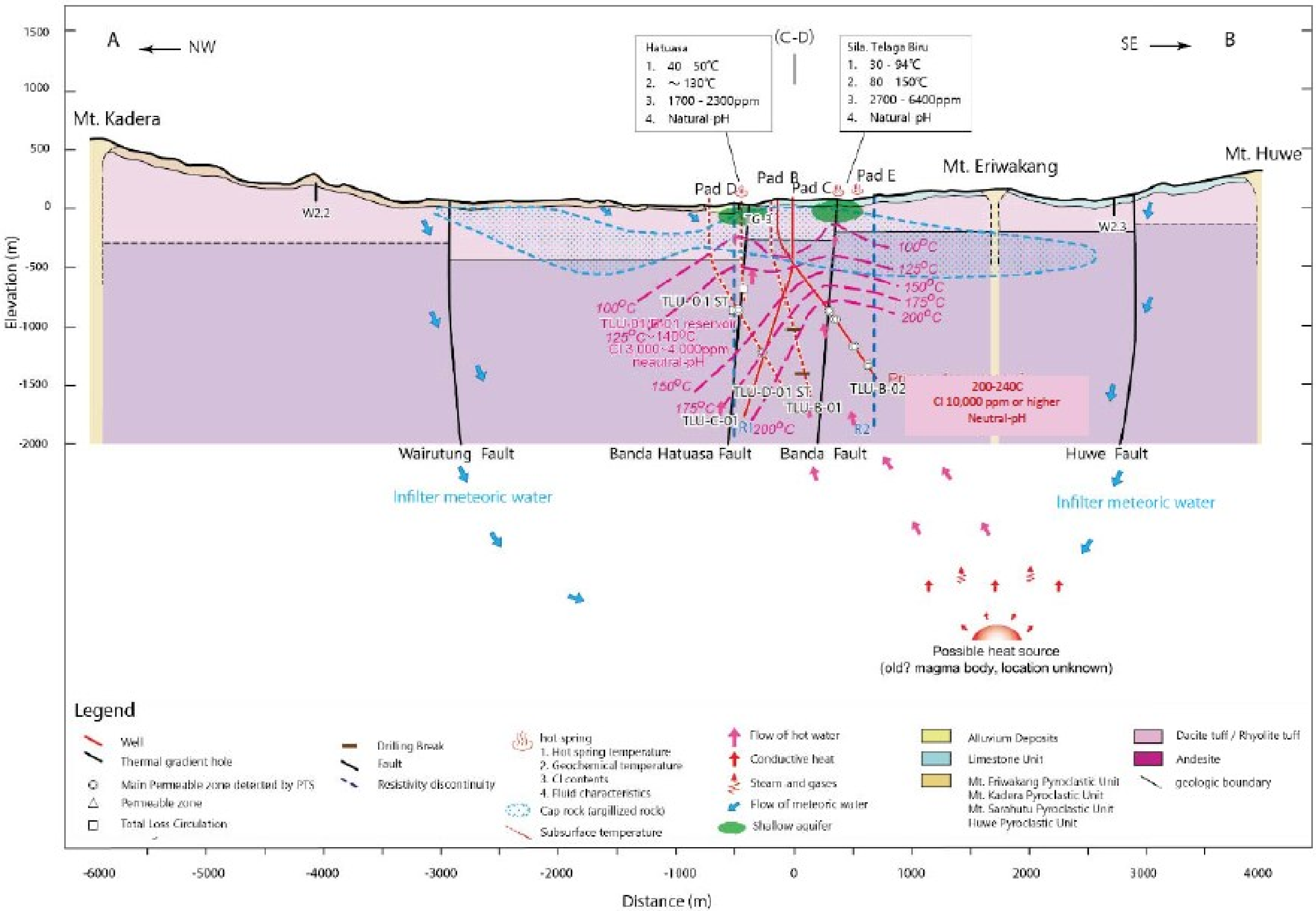

Figure 16 Geothermal Conceptual Model (Cross Section View NW-SE along the TLU-C1 Trajectory)

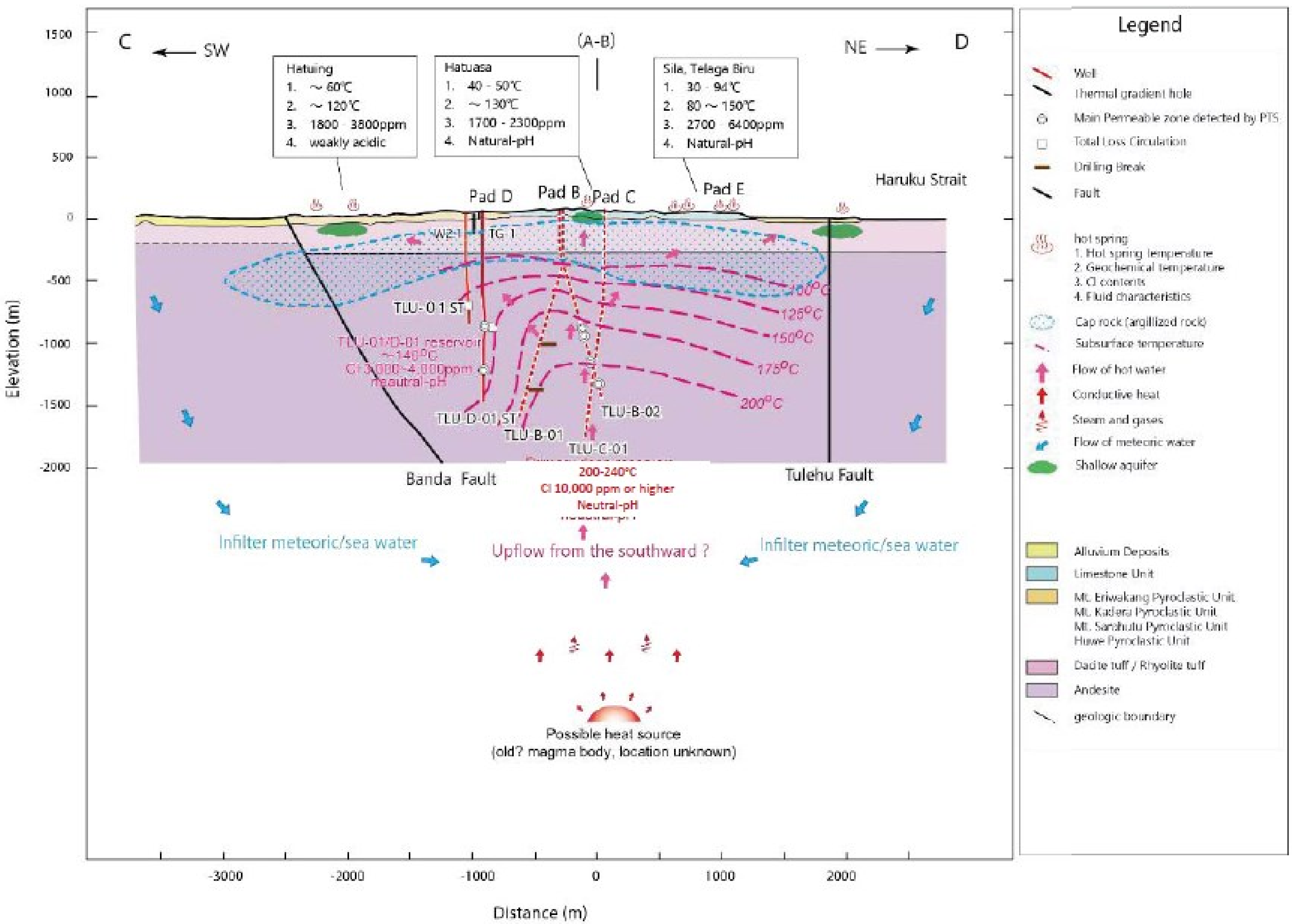

Figure 17 Geothermal Conceptual Model (NE-SW Cross Section View Outlined along the TLU-B and TLU-C pad)

5. CONCLUSION

5.1 Lesson Learn

It seems that the geothermal system in Tulehu field might experience an evolution, with a direction from the northwest to the southeast, which inferred to be controlled by the volcanism activity evolution in the area. Delineating permeable zone and structure, is the most important aspect before determining drilling target. Fluid flow pattern (and also temperature profile) is highly driven by the permeability structure. Possible or potential controlling geological structure identified on the surface and/or geophysical model does not necessarily imply a permeable sub-surface zone beneath. This consideration becomes very important especially when drilling in the geothermal system correlating with relatively old volcanism since the secondary mineral resulted from the hydrothermal activity which has been going on for a long time may fill the potential paleo permeable zone resulted on the low present permeability. This has been observed from the drilling of the last four wells.

5.2 Future Drilling Target

Considering the updated geothermal conceptual model, the area between Banda hot spring and Sila hot spring along Banda fault and permeable zone inferred by resistivity discontinuity R2 is the first priority zone for drilling targets. The Banda Hatuasa fault and Banda fault to the west of well trajectory of TLU-D-01 is the first priority zone for drilling reinjection wells. The existence low permeability area around TLU-B1 provides barrier for adequate separation of production and reinjection wells to minimize a thermal breakthrough at the exploitation stage.

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