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The Initial State Geochemical Model and Reservoir Response of 2 Years Production at Silangkitang, a Fault-Controlled Geothermal System along the Great Sumatera Fault

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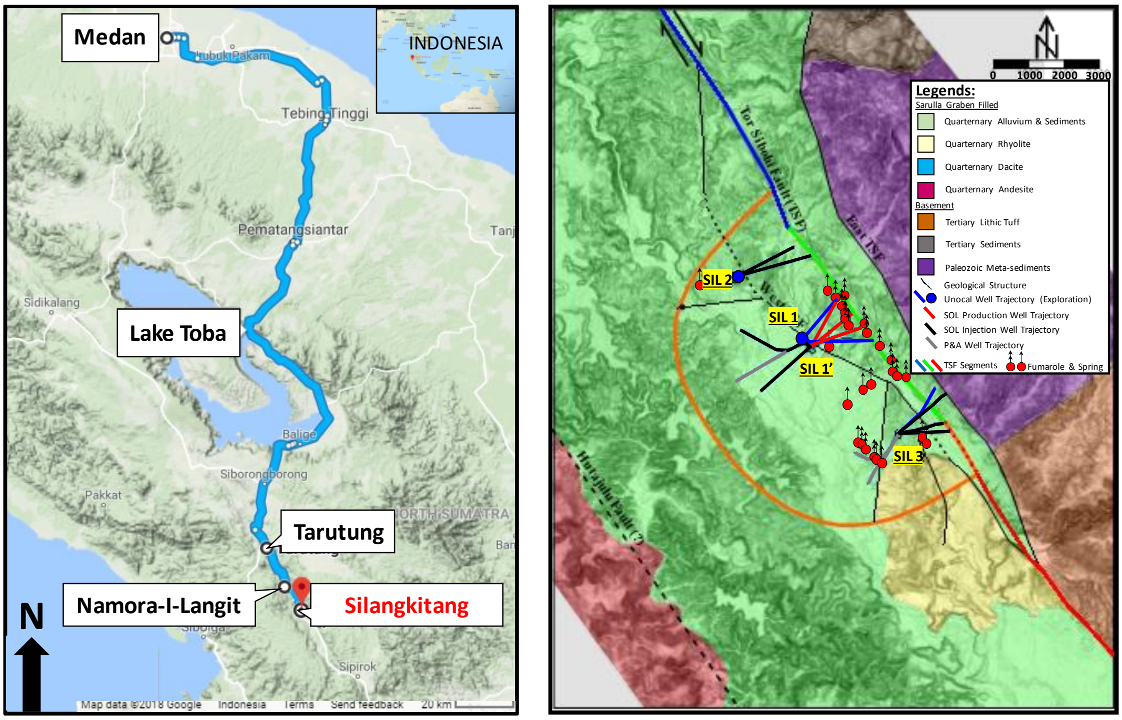
ABSTRACT

The Silangkitang (SIL) geothermal field which located along the Great Sumatera Fault (GSF) is currently producing 110 MW with the support from 4 production wells and 9 injection wells. Silangkitang is liquid-dominated system with high temperature (higher than 280°C) and relatively moderate gas (below 1 wt.% in reservoir liquid). Most of the production and injection wells are drilled perpendicular to the Great Sumatera Fault and some of the injection wells are drilled away from the fault. The production wells are drilled toward the upflow zone in the central of the prospect while the injection wells are drilled in the outflow zone which located in northwest and southeast of the field.

The produced NCG at the wellhead is within 3.0 – 4.2 wt.% in steam with the highest one is shown by the southernmost production well. The fluid chemistry shows neutral pH with Na, K, Cl and SiO2 concentrations below 1000 ppm and very low Mg concentration. In addition, the oxygen-18 and deuterium show meteoric origin and the Na-K-Mg Giggenbach demonstrates full equilibrium state of reservoir fluid. The homogeneous chemical characteristic at Silangkitang strongly supports the good connection within the reservoir as the response to the fault-controlled system. The 2 years operation starts showing the chemical response which indicates an injection breakthrough without significant enthalpy impact. This result signifies the uniqueness of a geothermal reservoir within a mega fault zone in Sumatera Island.

1.INTRODUCTION

The SIL geothermal field is located in Tapanuli Utara District, North Sumatra Province, Indonesia. The field is approximately 310 kilometers southeast of Medan at an elevation 500 – 600 meters above sea level (Figure 1a).



(a) (b)

Figure 1. (a) Map of Sarulla geothermal field which shows the location of the contract area from Medan (taken from Google Map) and (b) a geological map of SIL and well distribution. Wells with a blue well track trajectory or circle were drilled and tested during the initial Unocal exploration drilling campaign in the late 1990's; brown and black well track trajectory were drilled and tested during SOL development stage after 2010. The grey well track trajectory are the plugged and abandoned ones due to problem during drilling (Satya, 2019).

SIL is one of several prospects in the Gunung Sibualbuali Working Area that is currently operated by Sarulla Operations Limited (SOL). This WKP was previously belong to Unocal and there were some wells that drilled during the exploration stage. SOL, a special purpose company that sponsored by Kyushu Electric Power Co. Inc., Itochu Corporation, Medco Energi Internasional Tbk., INPEX Corporation, and Ormat Technologies, Inc. has been granted the rights to utilize the Sarulla geothermal resources for power generation under the framework of a Joint Operating Contract (JOC) with Pertamina. SIL's commercial generation of 110 MW was started on Mar 18, 2017 with the support of 4 production wells and 9 injection wells (Figure 1b).

SIL is situated within the Barisan Mountains, which are both structurally uplifted and covered by young volcanic rocks. There are eleven active volcanoes along the mountain chain, but none of those is positioned in the Sarulla vicinity. However, there are abundant volcanic eruptive centers within and adjacent to the contract area that are less than 1 million years old.

The Paleozoic metasediments are considered to be the basement rocks beneath SIL. These metasediments rocks consist of marble, phyllite, argillite, meta-quartzite and other deposits. Tertiary deposits composed of conglomerate, greywacke, mudstone and tuff overlie the basement rocks. The basement rocks and Tertiary deposits crop out at the eastern side of the GSF. Mesozoic granites are found distributed at the western side of SIL. Meanwhile the upper part is a recent alluvium layer consisting of poorly consolidated sandstone and pebble conglomerate. Underlying the recent alluvial deposits, a thick sequence of fine-grained rocks interpreted as lake deposits are found. Below the lake deposit, a thick accumulation of volcanic tuff flow presents with a thin mudstone layer at depths. The deeper sequence consists of pre-volcanic valley-fill deposits with fine to coarse-grained deposits (conglomerate to shale) above the Paleozoic metasediments that includes quartzites, marls and marble. This rock also exposed at the surface east of GSF portion of the SIL geothermal field (Figure 1b).

There are two types of hydrothermal features associated with the geothermal system of SIL. The first one is represented by about a dozen of fumarole vents aligned along the main trace of the GSF. These hydrothermal manifestations are categorized from weak to quite vigorous and are confined to a segment of 1.75 km length along the GSF. The second one is represented by boiling chlorides springs and weak fumaroles located in the eastern side of Sarulla graben at about 0.5 to 1 km south and west of the main GSF fumaroles (Figure 1b).

Unocal exploration in the late 1990's has drilled 5 wells in 3 different pads that located along the GSF. There were 3 wells that drilled perpendicular to the fault while the remaining were drilled vertically on pad SIL 2 and SIL 1. Amongst these wells, only 1 well at pad SIL 1' is still being used by SOL to support the generation of 110 MW. The other wells are not used due to casing integrity issue. In the development stage, SOL has drilled additional 3 production wells at pad SIL 1' and 9 injection wells at pad SIL 2, 1' and 3 (Figure 1b).

Chemical data from all production wells and surface thermal manifestations were collected to establish the initial geochemical model of the field while no chemical data were sampled from the injection wells. It becomes limitation to fully understand the geochemical characteristic of the northwest and southeast margin of the field. Additionally, the static pressure and temperatures measured downhole for most wells during initial production flow tests did not exhibit stable temperature profiles.

2. INITIAL STATE GEOCHEMICAL MODEL

SIL geothermal system is geologically identified as fault-controlled system. The supporting evidences include the presence of the fumaroles and chloride boiling springs along the fault and the highly productivity and injectivity of wells that drilled perpendicular to the GSF. SIL is geochemically unique with its low chloride (<1000 ppm) and lighter $\delta^{18}O$ (~ -6.5 ‰) but chemically benign and high temperature.

2.1 pH

The initial pH, measured at 25 °C from separated brine samples, for wells drilled toward and beneath the main fumarole complex demonstrate pH in the range of 6 - 7 while wells and springs that located aside of the GSF exhibit pH higher than 7 (Figure 2).

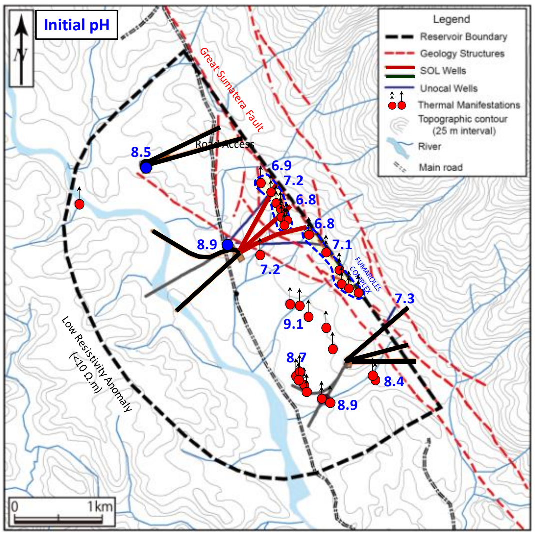
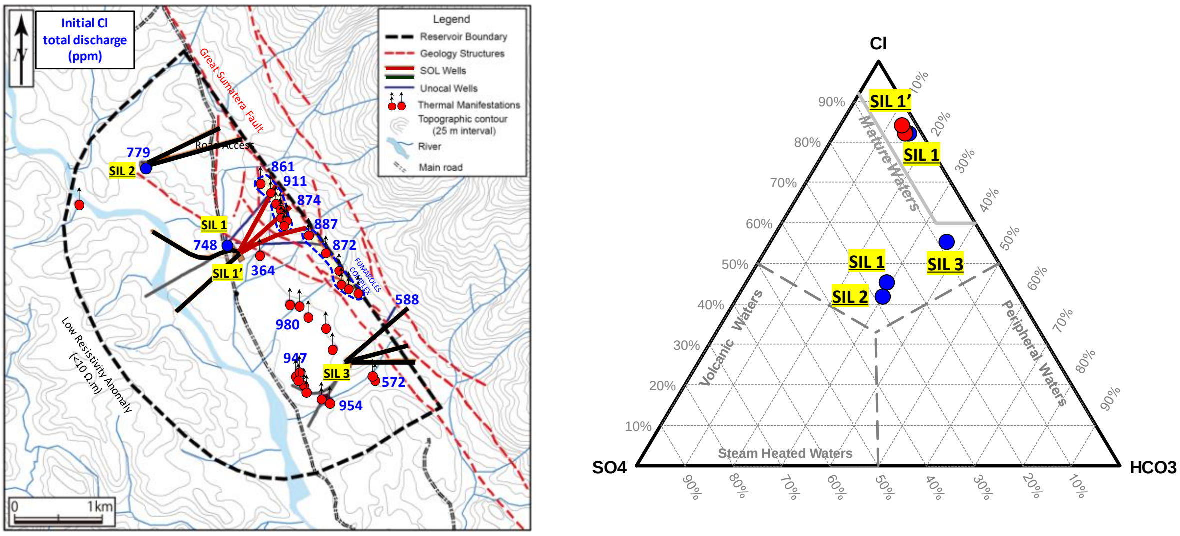


Figure 2. Map of SIL geothermal field initial pH distribution from the production well data and surface thermal manifestation. Numbers in blue font are pH values measured from separated brine at ambient temperature.

The higher pH possibly indicates a dilution effect. Unfortunately, this hypothesis cannot be validated by reservoir fluid data from wells that drilled away from the fault due to the absence of initial flow test. This fact indicates the absence of acid fluid in this prospect.

2.2 Cl-SO_4-HCO_3

The initial Cl concentration shows the uniqueness of SIL reservoir brine where the concentration is considerably low (Figure 3a). This lower Cl (<1000 ppm) is suspected to be caused by its host rock type (metamorphic), mega fault-controlled permeability, or higher dilution effect of meteoric water. The distribution of this species is used to define the fluid flow with dilution effect concept. The high concentration is demonstrated by wells that drilled perpendicular to the GSF in the center of the field. The Cl decreases to the other side of the fault which shows possible dilution with marginal recharge (MR) water. The ternary plot of Cl-SO_4-HCO_3 (Figure 3b) strongly indicates the water that being produced by the well in the central of the field is associated with a mature (neutral) chloride geothermal system. The consistency of low SO_4 concentration with pH data is another supporting evidence for the absence of acid fluid in the system.

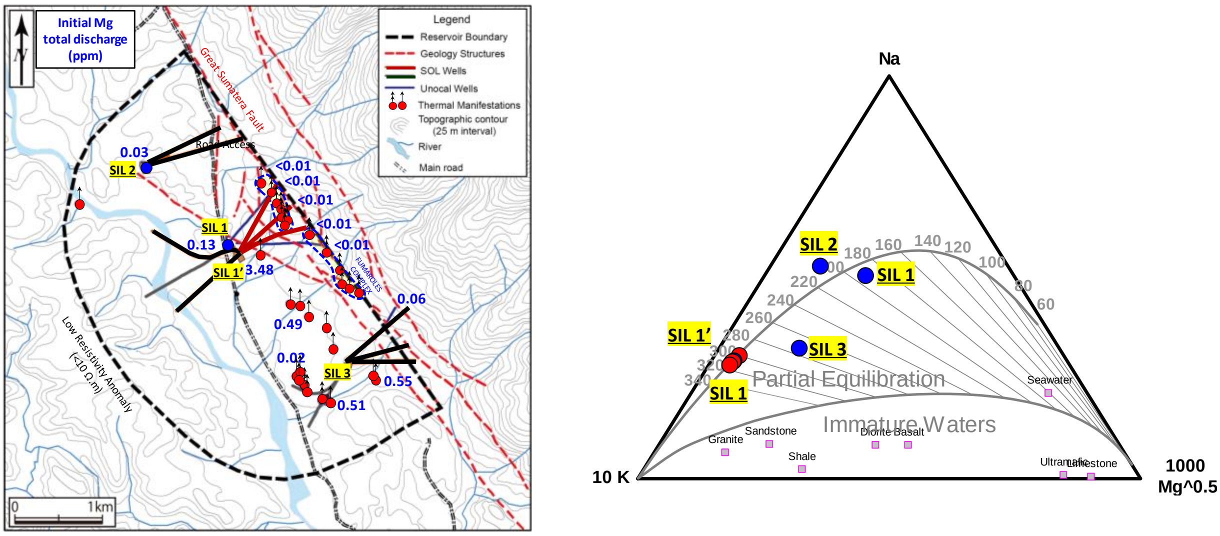


(a) (b)

Figure 3. (a) Map of SIL geothermal field initial Cl distribution from the well data. Numbers in blue font are reservoir concentration in ppm and (b) Cl-SO_4-HCO_3 ternary plot that indicate liquid being produced is associated with mature (neutral) chloride water.

2.3 Na-K-Mg

The initial Mg concentration supports the maturity of liquid that being produced at SIL (Figure 4a). The low concentration indicates liquid that tapped by the production well has reacted with the reservoir rock intensively and the Mg has been precipitated when the fluid circulates in the reservoir.



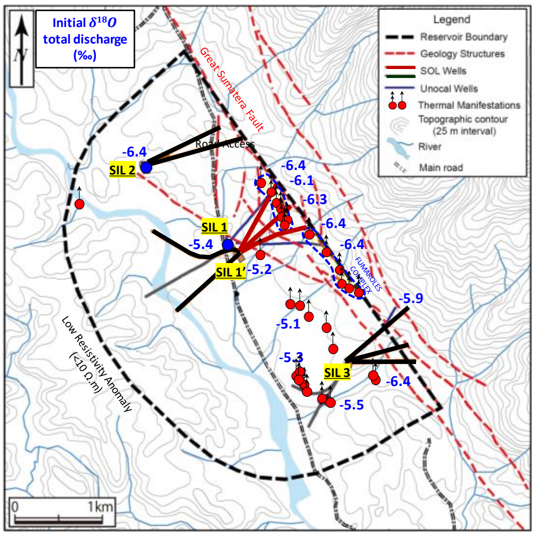
(a) (b)

Figure 4. (a) Map of SIL geothermal field initial Mg distribution from the well data. Numbers in blue font are reservoir concentration in ppm and (b) Na-K-Mg ternary plot that indicate liquid being produced is full equilibrium.

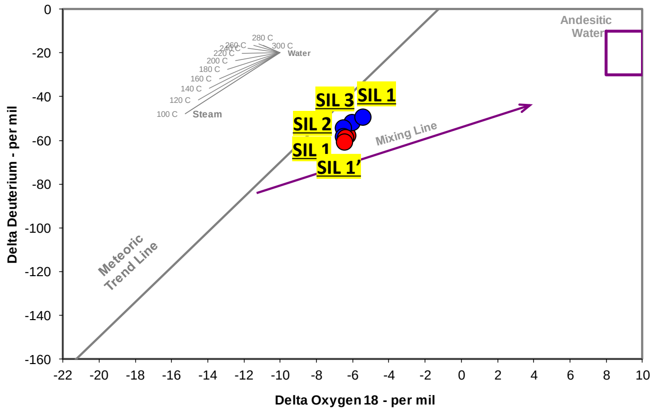
The higher concentration of Mg at springs is suspected due to process while reservoir fluid is ascending to surface and flowing away from the upflow. The Mg concentration is the major element in defining the equilibrium state of the fluid as indicated by Na-K-Mg ternary plot (Figure 4b). This fact provides another evidence of the maturity of SIL reservoir liquid.

2.4 Stable Isotope ($\delta^{18}O$ & $\delta^{2}H$)

The presence of enriched $\delta^{18}O$ is explained by the exchange of $\delta^{18}O$ with the rock or mixing between recharge/shallow (lighter $\delta^{18}O$) and andesitic/magmatic (heavier $\delta^{18}O$) waters. Isotope data presented herein are corrected to total reservoir liquid.



(a)



(b)

Figure 5. (a) Map of SIL geothermal field initial reservoir $\delta^{18}O$ distribution from the production well and exploration well data. Numbers in blue font are reservoir $\delta^{18}O$ in ‰ (b) $\delta^{18}O$ & $\delta^{2}H$ cross plot that show the reservoir liquid is associated with lighter isotope.

The heavier ^{18}O values are observed at wells located away from the GSF, meanwhile the wells drilled perpendicular to the fault show lighter $\delta^{18}O$ (Figure 5a). The intense water rock interaction in the area away from the GSF due to relatively lower permeability explains this phenomenon. This case is not applied in the GSF zone where permeability is relatively higher, thus it has not permitted the brine to interact with the reservoir rock as intense as in the other side of the fault (Figure 5b).

2.5 Non-Condensable Gas (NCG)

The initial reservoir NCG distribution suggests the location of the fluid source in the area of higher gas (0.75 – 1.06 wt.%). This area covers approximately 1.75 km fault length (Figure 6). The low NCG is suspected to be caused by boiling process that occurs when the fluid flows away from the upflow. These amount of NCG in total discharge results to 3.0 – 4.2 wt.% in steam with steam fraction in the range of 20 – 25%.

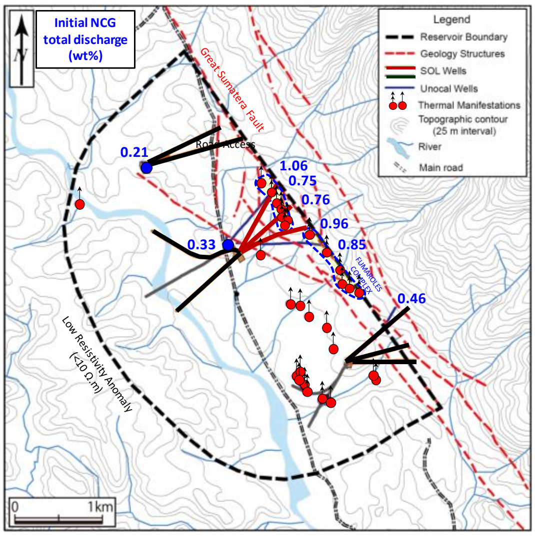


Figure 6. Map of SIL geothermal field initial reservoir NCG distribution from the production well and exploration well data. Numbers in blue font are reservoir NCG values in weight %.

2.6 Geothermometry

The initial geothermometry value is used to interpret the reservoir temperature, reservoir process and fluid flow of the system. Due to different equilibrium rate, Na/K and SiO_2 can be used to understand the reservoir process. Both Na/K and SiO_2 show the same distribution trend where higher temperature is observed at the central area and relatively lower temperature is identified at the other side and southern area of the fault. The different value between Na/K and SiO_2 geothermometry indicates a re-equilibration process when fluid is ascending to the surface from the upflow. The lower temperature trend to the other side and southern area of the fault shows that fluid may mix with a diluted liquid from marginal area. Mineral precipitation due to conductive cooling is also possible to explain this phenomenon, but further study is required.

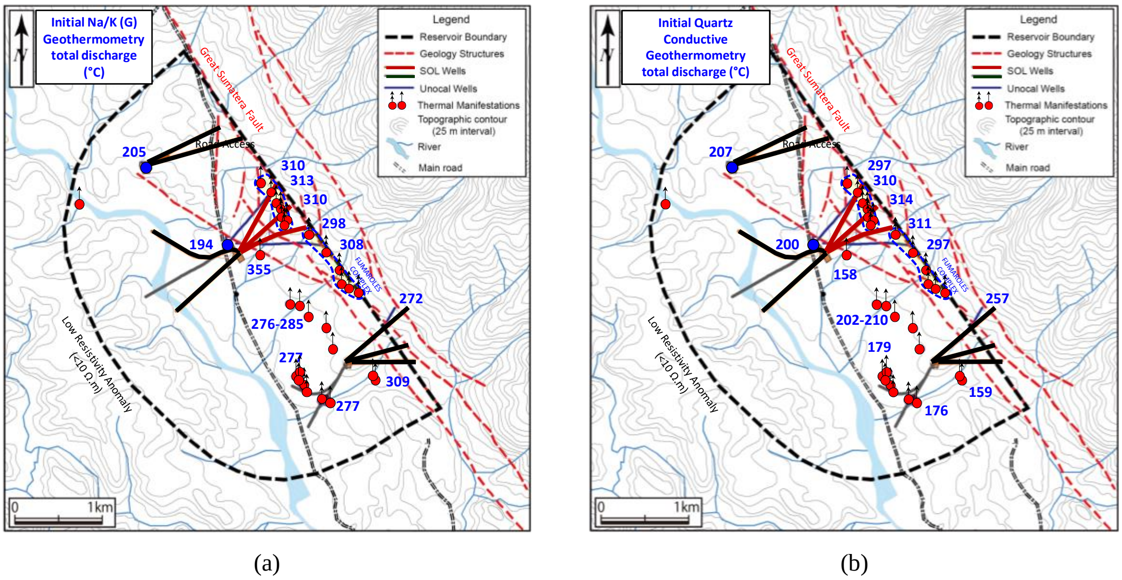


Figure 7. (a) Map of SIL geothermal field initial Na/K geothermometry distribution from the production well, exploration well and surface manifestation data. (b) Map of SIL geothermal field initial Quartz Conductive geothermometry distribution from the production well, exploration well, and surface manifestation data.

2.7 Enthalpy & Cl

The initial discharge enthalpy and chloride support the hypothesis that described in the previous section where mixing with diluted liquid (lower Cl and enthalpy) explains the anomaly in fluid chemistry and temperature that shown by wells that drilled perpendicular to the GSF and the ones that drilled in the other side or southern area of the fault (Figure 8).

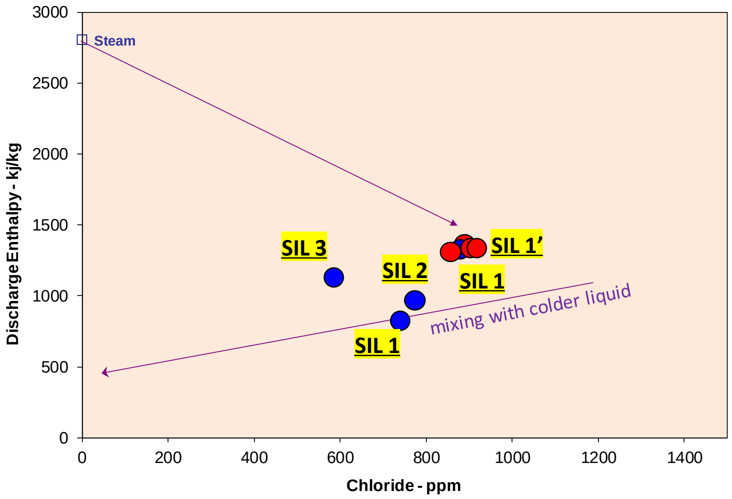


Figure 8. Enthalpy and Cl cross plot showing diluted and lower enthalpy liquid may present at the other side and southern of the GSF.

2.8 Geochemical Fluid Flow Model

The integration of the fluid chemistry interpretation results to the initial state geochemical fluid flow model. The upflow is identified from the geothermometry and NCG data where the highest temperature and relatively higher gas concentration located at the current production area. The fluid flows out to the NW and SE along the fault and to the South as indicated by both Na/K and

SiO_2 geothermometry value (Figure 7a and Figure 7b). The Marginal Recharge (MR) presence is recognized mainly by higher Mg and lower Cl.

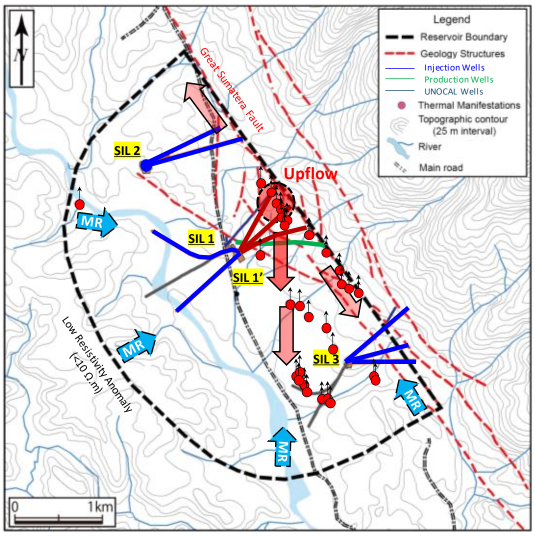
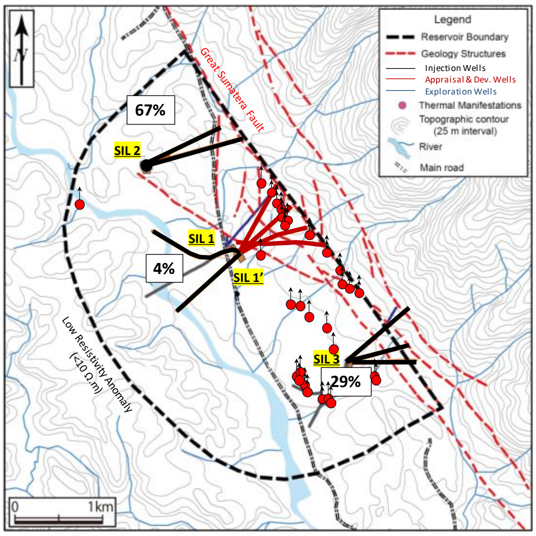


Figure 9. Map of SIL geothermal field initial geochemical fluid flow model. Showing the location of upflow, the outflow and the MR invasion.

3. LIQUID INTRODUCTION DURING EXPLOITATION

SIL started the production in first quarter of 2017 by utilizing the 3 new production wells and 1 old exploration well. The ~20% condensate and ~80% brine from the power plant are mixed before injected into the injection wells that located in the northernmost, southernmost and in the other side of the fault. The mixed liquid characteristic is chemically identified from its NCG and HCO_3 since these 2 species are observed in high concentration at the production wells (Figure 10b). The HCO_3 and NCG content are low in injectate liquid due to steam fractionation and gas release prior steam is utilized. This fluid is mostly injected at SIL 2 pad in the northernmost due to higher permeability as compared with the other injection wells (Figure 10a). Qualitative tracer was conducted 2 months after the commissioning at 2 wells in the northernmost and 2 wells in the southernmost. The northernmost production well exhibited the highest cumulative mass return at 1.59% from the SIL 2 injection wells during 4 months monitoring. The other production wells also show chemical return with small cumulative number (Simatupang, 2017). This result indicates there is connection between northern injection wells with the production wells hence routine geochemical monitoring is required to anticipate negative impact from the injection liquid breakthrough.



(a)

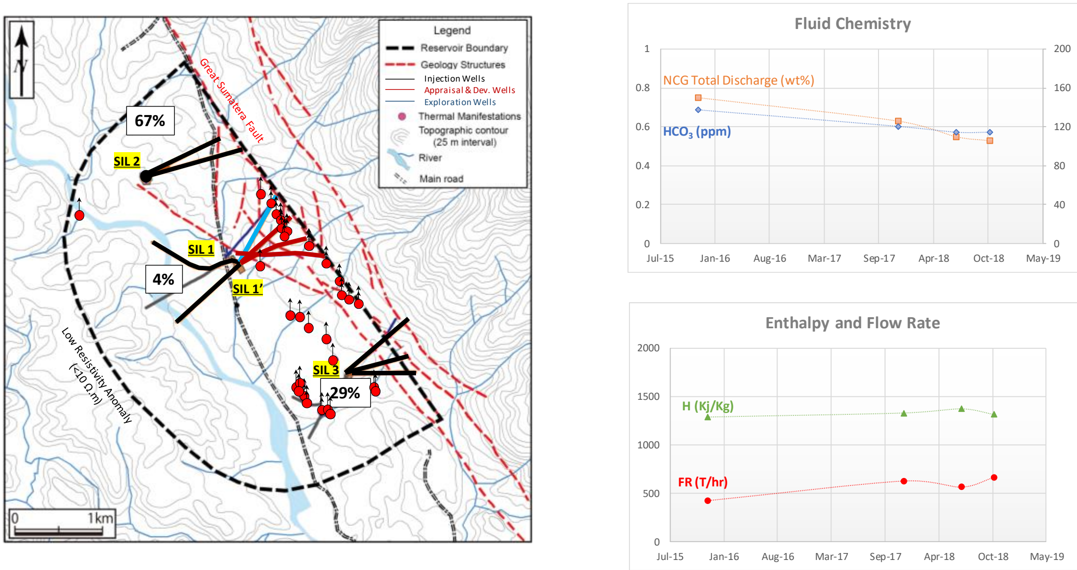
Chemical Parameter	Dec 17	Jun 18	Nov 18
NCG (wt.%)	smaller than reservoir liquid		
pH	4.93	4.61	4.49
Mg (ppm)	<0.01	<0.01	<0.01
SiO_2 (ppm)	747	778	712
Cl (ppm)	921	926	918
SO_4 (ppm)	129	139	143
HCO_3 (ppm)	3	<2	<2
$\delta^{18}O$ (‰)	-6.1	-6.2	-6.3
$\delta^{2}H$ (‰)	-56.6	-57.8	-58.0
H (Kj/Kg)	smaller than reservoir liquid		

(b)

Figure 10. (a) Map of SIL injectate liquid distribution. (b) Table showing SIL injectate liquid characteristic where NCG and HCO_3 becomes the chemical parameter to indicate injectate liquid presence.

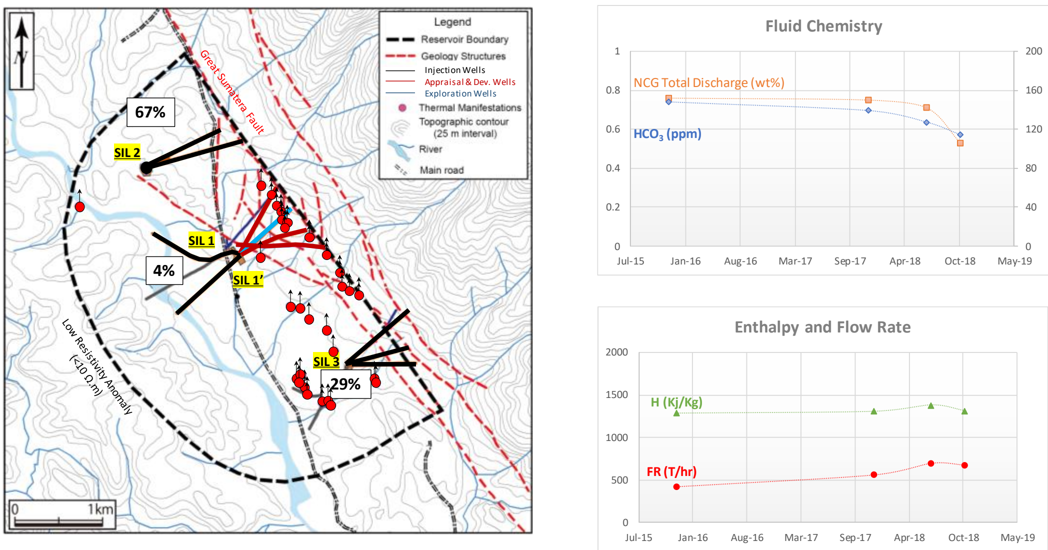
4. RESERVOIR RESPONSE AFTER 2 YEARS PRODUCTION

SIL has been continuously producing 110 MW with the production wells are only operated at 7-15% valve opening and WHP 35-60 barg. Since the reservoir pressure is decreasing as the response to production, thus the MR and the injectate liquid are expected to invade the reservoir. Since these 2 types of liquid have lower temperature, hence fluid chemistry characterization is required to monitor the presence of these liquids at the production wells. The geochemical monitoring results exhibit chemical breakthrough as indicated by decreasing in NCG and HCO_3. The temperature front has also not been detected yet since both enthalpy and flowrate have been relatively increasing over time due to reservoir boiling (Figure 11, 12, 13, 14). The Mg concentration that used to identify MR has been consistently showing low concentration (<0.01 ppm) at all wells. This The continuous fluid chemistry monitoring is carried out to anticipate the invasion of these 2 liquids.



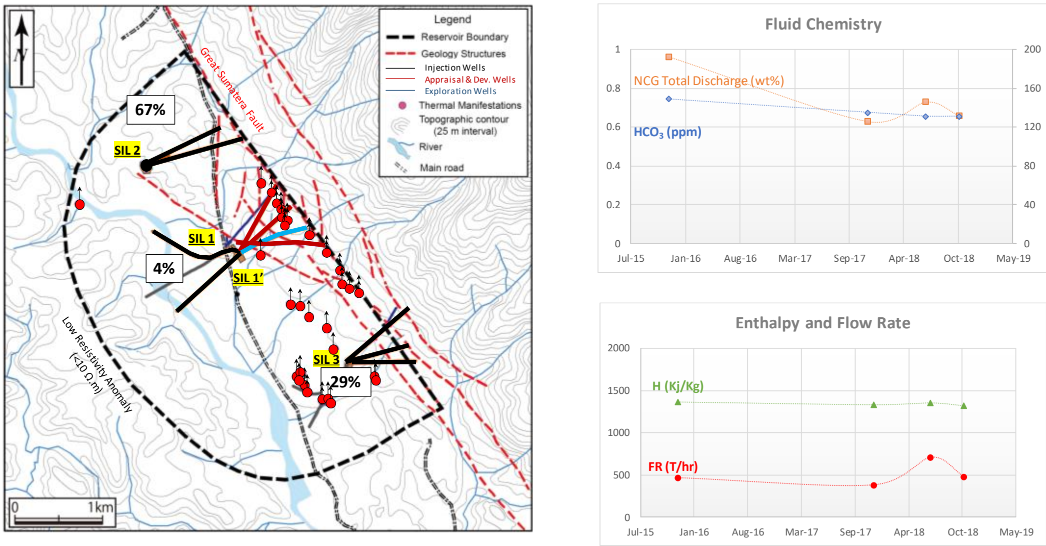
(a) (b)

Figure 11. (a) Map of SIL injectate liquid distribution. The blue well track is the well that is being described (b) Fluid chemistry, enthalpy and flowrate of the production well in the northernmost.



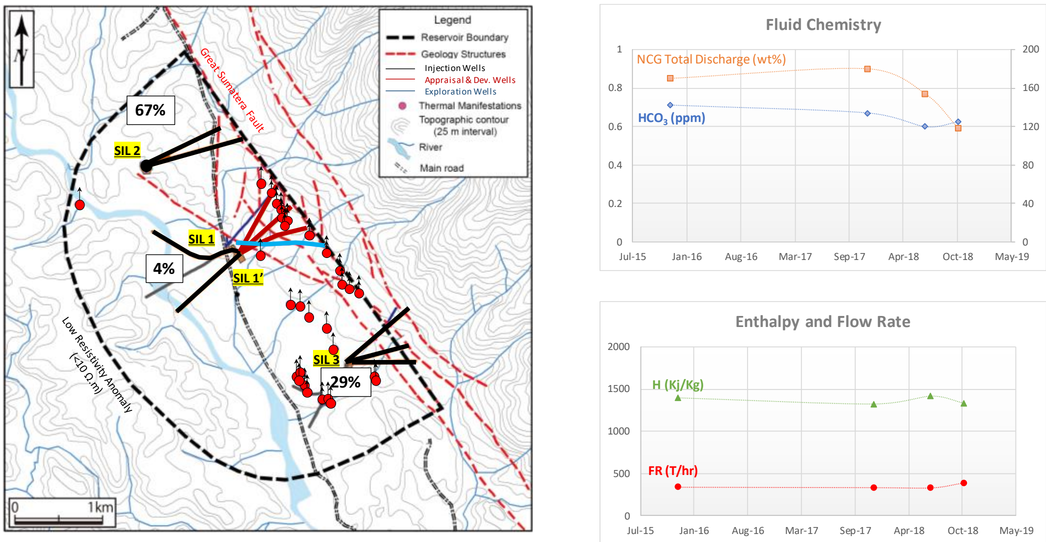
(a) (b)

Figure 12. (a) Map of SIL injectate liquid distribution. The blue well track is the well that is being described (b) Fluid chemistry, enthalpy and flowrate of the production well in the central.



(a) (b)

Figure 13. (a) Map of SIL injectate liquid distribution. The blue well track is the well that is being described (b) Fluid chemistry, enthalpy and flowrate of the production well in the central.



(a) (b)

Figure 14. (a) Map of SIL injectate liquid distribution. The blue well track is the well that is being described (b) Fluid chemistry, enthalpy and flowrate of the production well in the southernmost.

5. CONCLUSION

The SIL geothermal field with its 1.75 km fault length dimension as the media to host the high temperature fluid with typically moderate gas has been sustaining 110 MW generation within 2 years. The injection is designed to be located at both tail ends of the fault and aimed to provide pressure support to the production area due to limitation of permeable zone. This narrow reservoir dimension possibly results to faster injection breakthrough. This hypothesis is generated from 2 years geochemical monitoring results that indicate chemical breakthrough of injectate liquid and no temperature impact at almost all production wells. In the same time, the MR fluid is also not yet detected due to the absence of increasing trend in Mg and decreasing trend in Cl. This geochemical study shows the chemical relations below can be used to monitor reservoir behavior during production stage at SIL geothermal field, hence the presence of the low temperature liquid like injectate liquid (IL) and marginal recharge (MR) in reservoir brine (RB) can be anticipated:

- $H_{RB} > H_{IL} > H_{MR}$
- $NCG_{RB} > NCG_{IL}$
- $HCO3_{RB} < HCO3_{IL}$
- $Cl_{RB} \geq Cl_{IL} > CL_{MR}$
- $Mg_{RB} < Mg_{MR}$

If the injectate liquid only impact the chemical but not the temperature, thus the injectate liquid must have enough time to be heated up by the reservoir rock or mixed with reservoir brine in small amount (Figure 15). It is possibly too early to conclude but the narrow reservoir dimension and the aforementioned injection strategy may validate this conclusion to signify the uniqueness of a geothermal reservoir within a mega fault zone in Sumatera Island.

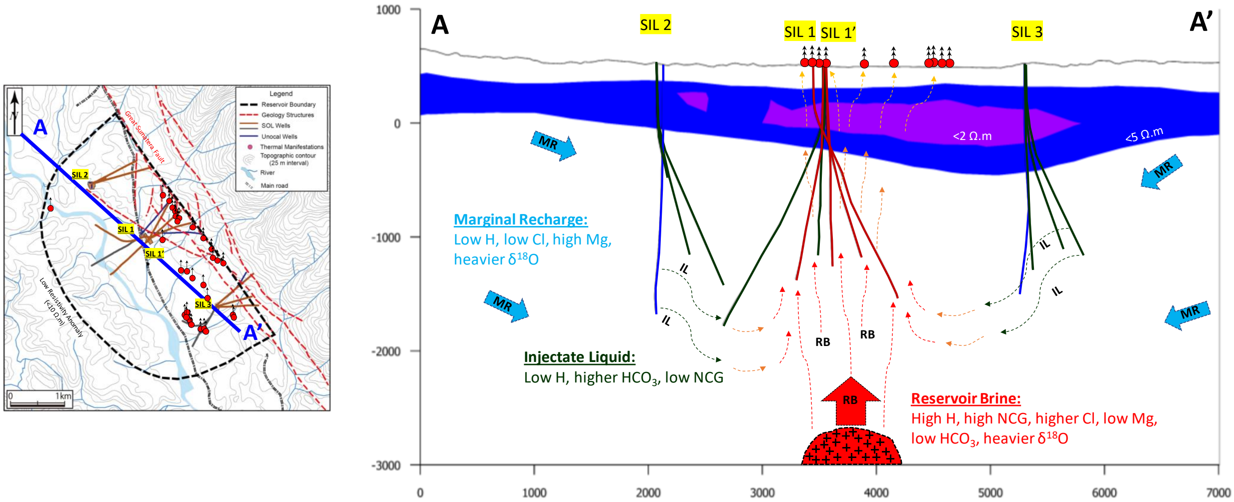


Figure 15. Cross section A-A' showing the geochemical fluid flow model after 2 years production. The light blue bold arrow represents Marginal Recharge (MR), the black arrow represents Injectate Liquid (IL), and the red, orange and yellow arrows represent Reservoir Brine (RB). The red color indicates higher temperature as compared with orange and yellow colors.

6. ACKNOWLEDGEMENT

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REFERENCES

Satya, D.Y.: SIL Permeability Characterization Review, *SOL Internal Presentation Material*, Jakarta, Indonesia (2019).

Simatupang, C.: SIL Qualitative Interpretation – Inter Well Tracer Test, *SOL Internal Report*, Resource Technical Meeting (2017).

Unocal North Sumatra Geothermal, Ltd.: Silangkitang Project Resource Feasibility Study, Unpublished Unocal Report, (1996), 289.