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Geochemical Reservoir Compartmentalisation at Muara Laboh Geothermal Field, Indonesia

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ABSTRACT

Ten production wells were drilled and tested at the Muara Laboh Geothermal Field, Indonesia from three well pads during the exploration and the 80MWe development drilling campaigns in 2012-2013 and 2017-2018, respectively. Chemistry of fluid samples was collected from all production wells for liquid, gas and isotope analysis during production testing. Fluid chemistry and reservoir engineering data indicate a geochemically compartmentalised, two-reservoir system. The northeast (NE) reservoir sector is characterised by a steam cap, underlain by high temperature (240-250°C), mature, neutral chloride liquid with pH~7, the chloride content of ~1600 -1700 ppm, and low gas content of 0.5 – 0.8wt%.

In contrast, the southwest (SW) reservoir sector is a deep, very high temperature (>290°C), neutral, dilute steam-heated, liquid-dominated reservoir with a lower chloride content of 300 - 500 ppm. Compartmentalisation is further supported by different Cl/B ratios, stable isotope signatures, and a substantial temperature gradient of ~70°C within 500 m between the two nearest wells completed in the NE and SW sectors. The distinct fluid chemistry and thermal characteristics of each reservoir sector suggest that there are two poorly connected reservoir compartments in the Muara Laboh Geothermal Field.

1. INTRODUCTION

Currently, Indonesia is one of the top three countries that produce more than 1000 MWe electricity from geothermal. The demand for electricity and commitment of Indonesia to move towards cleaner energy has enabled the development of a new geothermal area in Indonesia. One of these areas is Muara Laboh Geothermal Field in West Sumatera, operated by Supreme Energy Muara Laboh. In terms of geological setting, this geothermal field is associated with the Great Sumatra Fault System. The geothermal resource in Muara Laboh is indicated by the presence of a series of thermal manifestations consisting of fumaroles, hot springs, mud pools, and steaming ground.

In accordance with the commitment to the government to generated 80 MWe for the first stage of development, a total of ten production wells were drilled in Muara Laboh from three well pads during exploration (2012 – 2013) and development phases (2017-2018). All of the production wells have been tested to confirm the steam availability to generate 80 MWe for Stage 1. A series of fluid samples were collected from all production wells for liquid, gas (NCG) and isotope (stable & helium) chemical analysis during production testing. Chemical data from all production wells were combined with geological, geophysical and reservoir engineering data to determine the reservoir chemistry characteristics. One of the major findings is the chemical reservoir compartmentalisation at Muara Laboh.

2. GENERAL GEOLOGY OVERVIEW

The geothermal system in Muara Laboh is located within a stepover of the NW-SE striking Great Sumatera Fault (GSF) (Mussofan et al., 2018). Two GSF fault segments bound a tectonic basin to the NE and SW formed in this stepover (**Figure 1**). About 8 km NE of the prospect, the Suliti Fault segment juxtaposes uplifted metamorphic basement with young basin-fill deposits. To the SW of Muara Laboh, the Siulak Fault segment has accommodated magmatic intrusion that provides geothermal heat sources. The stratigraphy at Muara Laboh consists of pre-tertiary basement overlain by a sequence of Tertiary- to Mesozoic-age volcanics, intrusions and sediments. The detailed geology is shown in **Figure 2**. The oldest rocks in the Muara Laboh area comprise the Palaeozoic Barisan Formation (Pb), consisting of slate, phyllite, hornfels, meta-greywacke and limestone recrystallised to marble (Pbl). In some areas, the Barisan Formation overlies the Siguntur Formation (Ps), consisting of quartzite and intruded by Cretaceous Granite (Kgr). These rocks are uplifted, folded, faulted and locally metamorphosed, typical of the Pre-Tertiary basement. This basement sequence outcrops 8-10 km north and east of Muara Laboh (Mussofan et al., 2018).

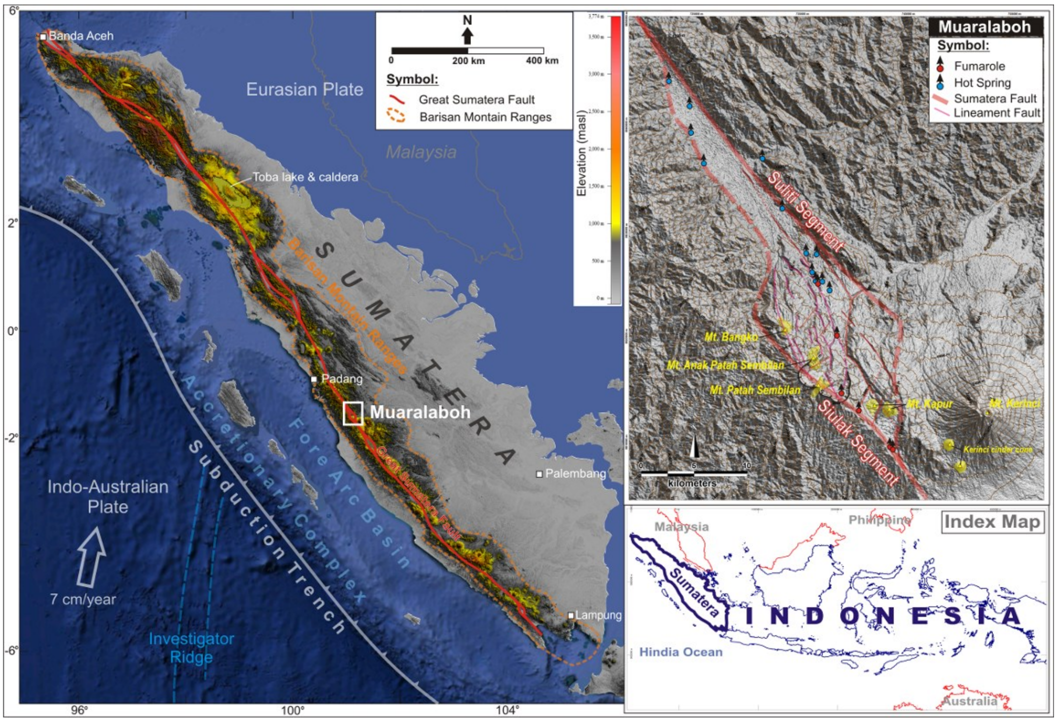

Figure 1: Left: Map of Sumatera, the Barisan Mountains, and the GSF. Tectonic setting of Sumatera is attributed to oblique subduction of the Indo-Australian Plate beneath Eurasian Plate resulting in the transcurrent GSF, volcanic arc and associated geothermal systems. Right: Map of Muara Laboh area in a stepover of the GSF system result in the pull-apart basin and localised volcanism. Thermal discharge is mainly along the main GSF and near Patah Sembilan Crater (Mussofan et al., 2018).

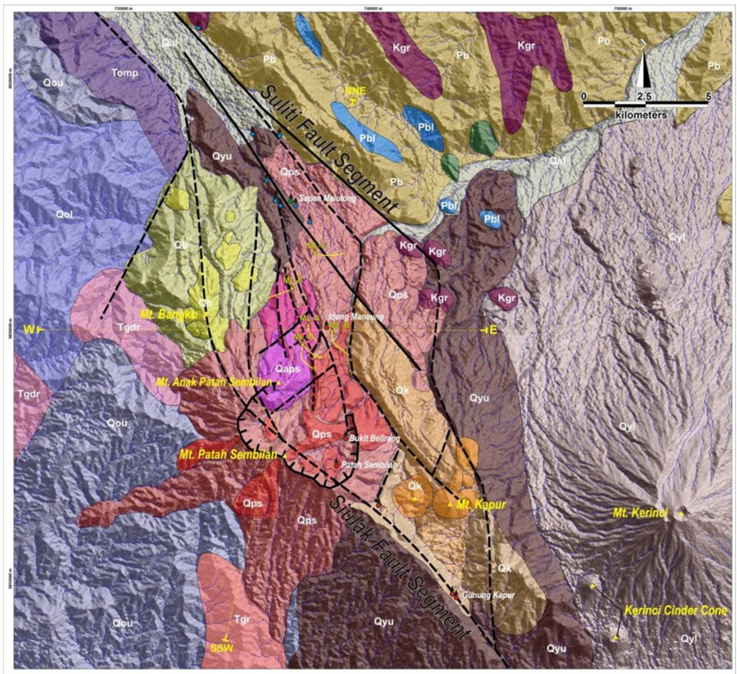

Figure 2: Geologic Map of Muara Laboh.

3. MUARA LABOH GEOTHERMAL SYSTEM

The Muara Labuh geothermal field is a typical high terrain geothermal system, characterised by the presence of many thermal manifestations. In Muara Laboh, the distribution of thermal manifestations can be divided into two major sectors: north and south. The northern sector consists of several hot springs distributed along the NE-SW fault that is associated with the Great Sumatra Fault (GSF). Some of them are found inside the graben. These northern hot springs are typically rich in bicarbonate (HCO_3), having relatively low liquid geothermometry values that range from 130° to150˚C. Due to their low geothermometry values, Supreme Energy decided to delay development in the northern area and focused on developing the southern sector.

The southern area is located at higher elevations near the Taman National Kerinci Seblat (TNKS National Park). The thermal manifestations found in this southern area are typical geothermal features seen in the high terrain and high-temperature geothermal system. In the low elevation, Sapan Malulong chloride springs appear with high debit +/- 90 kg/s. Predicted subsurface temperature based on fluid geothermometry ranges from 200° – 210°C. In the middle area, there are some fumaroles, including Idung Mancung and Air Belirang. The gas chemistry of Idung Mancung indicates the presence of a two-phase fluid zone (based on CAR-HAR) beneath the fumarole, with temperature ranging from 240° to 250°C. In the higher elevations further south, there are several more fumaroles including Patah Sembilan, New South East fumarole, and Bukit Belerang. The gas chemistry of these fumaroles suggests higher subsurface temperatures, typically hotter than 290°C. These high-temperature fumaroles are located inside the National Park (Taman Nasional Kerinci Seblat-TNKS). The initial conceptual model before drilling showed upflow fluid is located underneath Patah Sembilan fumarole, inside the park to the south, with the fluid outflowing to the north and leaks in the Sapan Malulong Hot Springs. The potential "sweet pot area" had been interpreted to be located near the Idung Mancung Fumarole, located in between.

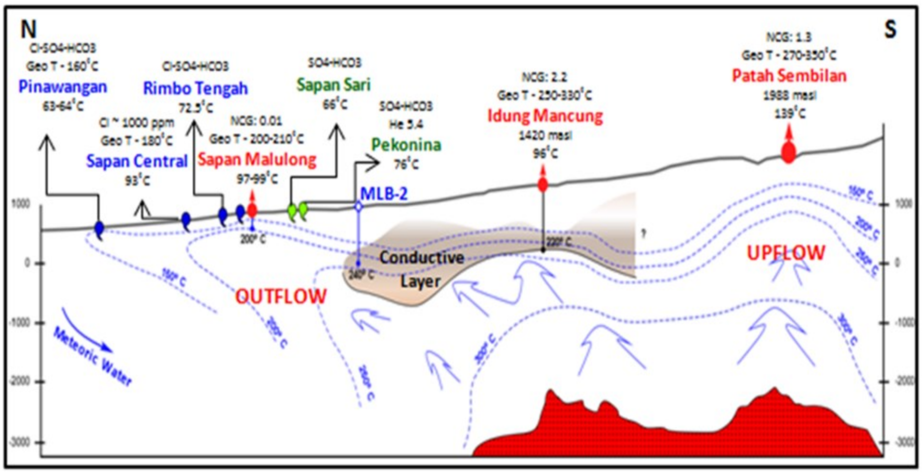

Figure 3: Muara Laboh conceptual model prior to exploration drilling.

4. WELLS CHEMISTRY CHARACTERISTICS

Ten production wells and four injection wells were drilled during the exploration and development drilling campaigns. The directions and location of the drilled wells are shown in Figure 4. All production wells have been flow-tested, with the production capacity of each well estimated using the James lip method, and verified by the Tracer Flow Test (TFT). During the production test, complete liquid and gas chemistry samples were taken, including brine, NCG and stable isotopes.

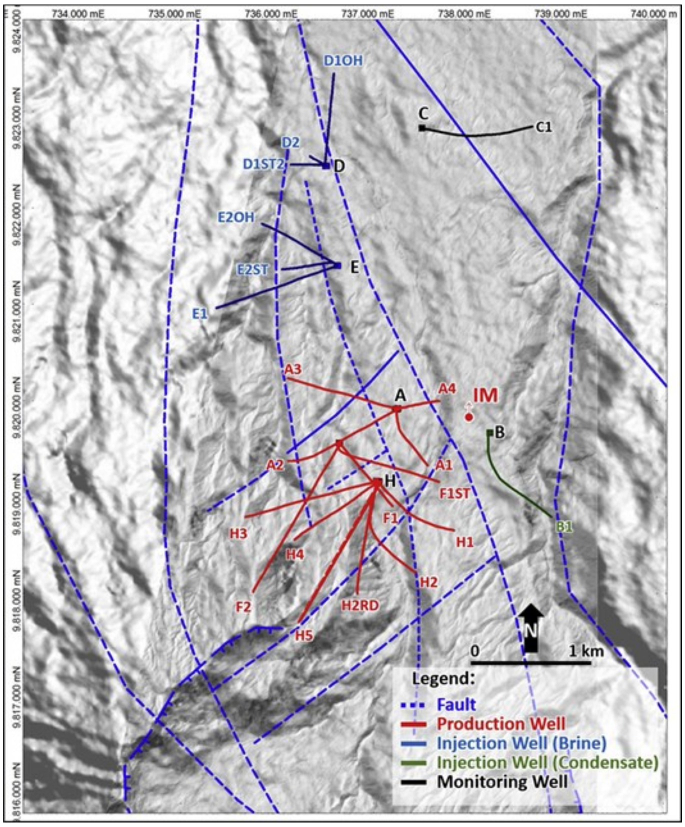

Figure 4: Map of Muara Laboh shows exploration and development wells trajectories.

Three production wells were drilled from Pads A and H during the exploration drilling campaign. The first exploration well to be drilled was ML-A1, which targeted the 240°C two-phase zone beneath the Idung Mancung fumarole. The chemistry of this well shows excess steam entry into the wellbore, indicative of a possible steam cap. The ML-A1 well and the Idung Mancung fumarole have similar chemistry characteristics. This well has low NCG (0.5 – 0.8 wt. %), neutral pH~7 and 1600 – 1700 ppm chloride. The fifth exploration well to be drilled was ML-H1, which targeted southeast of ML-A1. This well encountered measured temperatures of the only 245°C, neutral pH and lower chloride than ML-A1 (1500 ppm). The last exploration well to be drilled was ML-H2, which targeted further south from ML-H1. ML-H2 encountered the highest measured temperatures, ~310°C, but the well had low permeability. The ML-H2 reservoir fluid is neutral pH with the highest SiO_2 content (600 pm) and the lowest chloride content (1100 ppm) of the three wells.

Following the promising results of the exploration drilling campaign, nine production wells were completed during development drilling. Three additional wells were drilled from Pad A, four additional wells were drilled from pad H and two wells were drilled from a newly constructed Pad F. The four wells drilled from well Pad H (ML-H3, ML-H2RD, ML-H4 and ML-H5) and two wells from Pad F (ML-F2 & M-F1ST), all target to the southwest of the pads, with the exception of ML-F1ST, which targets to the southeast area near ML-H1. All production wells were able to flow successfully and were tested.

Chemistry data of the four wells from Pad A indicates the presence of a steam cap in the vicinity of Pad A. One of the wells, ML-A2, produced dry steam with an enthalpy of 2800 kJ/kg and NCG content of ~ 2 wt. %. Two of the other wells, ML-A3 and ML-A4, produced excess steam and liquid. All wells from Pad A have a neutral pH fluid, the chloride content of about 1600 – 1700 ppm, low gas content of 0.5 – 0.8 wt. % and silica content of 450 – 500 ppm.

Pad H and ML-F2 wells show different chemistry characteristics from Pad A, ML-H1 and ML-F1ST wells. Only ML-F1ST has a chemistry similar to ML-H1. In contrast, there is no evidence of a steam cap in Pad H or F wells; all the wells are liquid dominated with temperatures >290°C.

5. GEOCHEMICAL RESERVOIR COMPARTMENTALISALITON

Reservoir compartmentalisation is indicated from reservoir chemistry data and is supported by other data, such as well geology and alteration mineralogy. Reservoir chloride (Cl) vs boron (B) ratios show two separate trends, indicating separate sources for the NE sector (Pad A/ML-H1/ML-F1 wells) and the SW sector (Pad H/ML-F2 wells) (**Figure 5**).

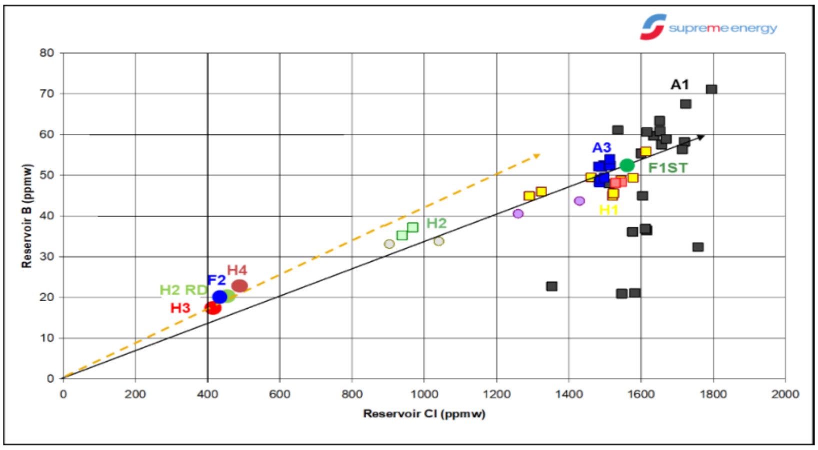

Figure 5: Cl/B plot indicating distinct fluid chemistry between the NE and SW reservoir sectors (modify from Stimac et al., 2019).

The Cl-SO_4-HCO_3 ternary diagram shows the wells drilled from Pad A (plus ML-H1 and ML-F1ST) are rich in chloride, while the wells from Pad H have more dilute fluid (less chloride), possibly due to dilution by steam-heated bicarbonate water. The presence of abundant calcite seen in drill cuttings in H wells may support the interpretation of bicarbonate water dilution. Vein paragenesis studies from core and cutting samples indicate that portions of the initially permeable propylitic zone have been sealed by infilling of fractures by calcite and quartz ± prehnite. The presence of late-stage calcite veins may also suggest a downflow of steam-heated bicarbonate waters, following infilling of the higher temperature veins, and resealing of the system (Stimac, 2018). This phenomenon suggests the wells in pad H and ML-F2 in the past have experienced extensive boiling due to fast liquid level declines. This allowed the abundant precipitation of calcite during extensive boiling. Also, during this process, the initial fluid in this area has been diluted with bicarbonate waters due to condensation in the extensive boiling process, shown by the Cl-SO_4-HCO_3 ternary diagram (Figure 6).

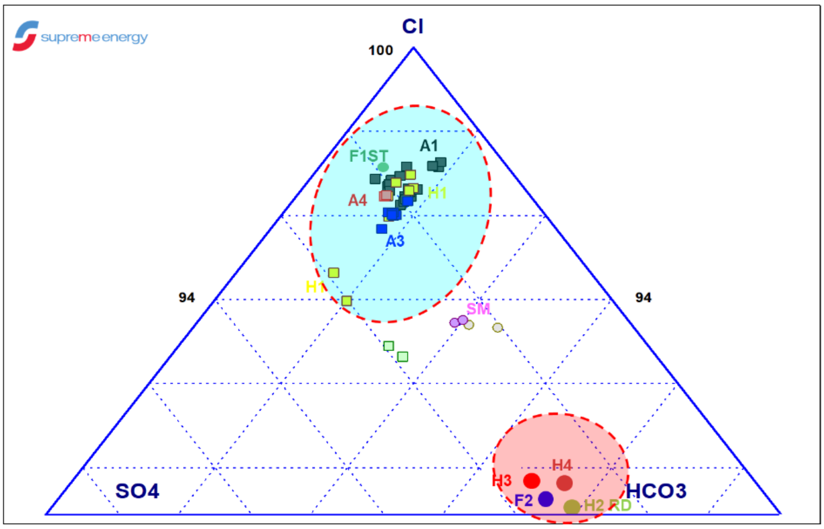

Figure 6: Cl-SO_4-HCO_3 ternary plot of Muara Laboh wells.

The mixing model from Na-K-Ca temperatures vs chloride shows that the wells in pad A (plus ML-H1 and ML-F1ST) could originate from the same source fluid with the temperature at 250°C. The chloride springs (i.e., Sapan Central (SC) and Sapan Malulong (SM)) lie on a cooler dilution trend, suggesting the dilution fluid in ML-H1 is not groundwater as it is interpreted for the chloride springs. The wells drilled from Pad H and ML-F2 form a cluster of dilute high-temperature fluids. The difference in mixing models between these two reservoirs suggests compartmentalisation.

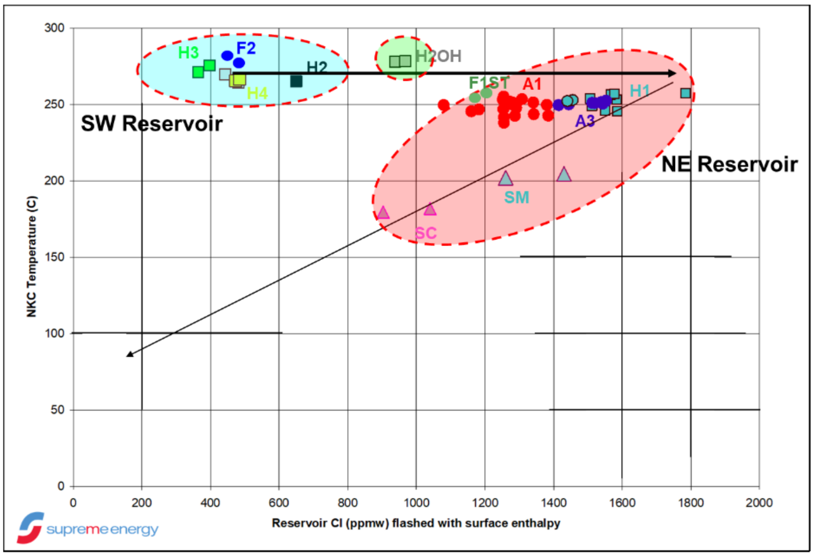

Figure 7: Cl-T_{NKC} plot, showing different chloride concentrations between pad A wells, including chloride springs, ML-H1 and ML-F1ST and pad H wells including ML-F2 (modify from Stimac et al., 2019).

In terms of reservoir temperature, based on the Na-K-Mg geothermometer, wells drilled from Pad A (plus ML-H1 and ML-F1ST) show a reservoir temperature of 260° – 280°C, while the wells from Pad H and ML-F2 have higher temperatures of about 300° – 320°C. The Na-K-Mg ternary diagram (Figure 8) shows all the wells from Pad H and ML-F2 have high sodium (Na) content. The enrichment of sodium (Na) is possibly due to geological conditions in the SW reservoir, basically having complex intrusions with more acidic magma types (rhyolite group).

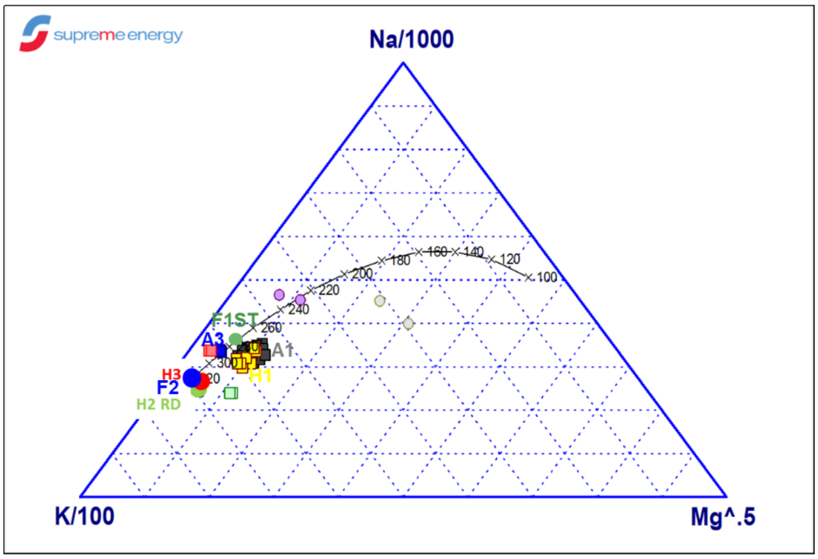

Figure 8: Na-K-Mg ternary diagram of Muara Laboh wells.

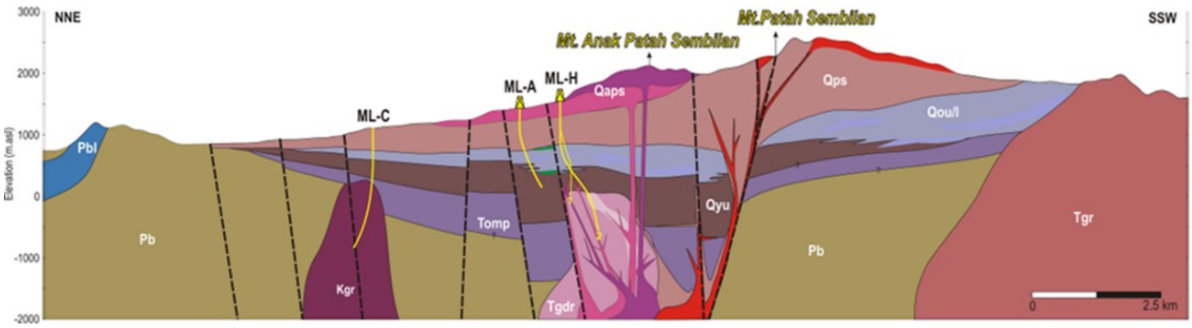

Figure 9: Geology cross-section of Muara Laboh.

The gas chemistry data also shows distinct behaviour and characteristics of these two reservoir sectors. The CAR-HAR diagram shows all wells drilled from Pad-A (plus ML-H1 and ML-F1ST) lie on the two-phase equilibrium zone with temperatures of 230°-240°C, while the wells from Pad H and ML-F2 lie under the equilibrium liquid line (Figure 10).

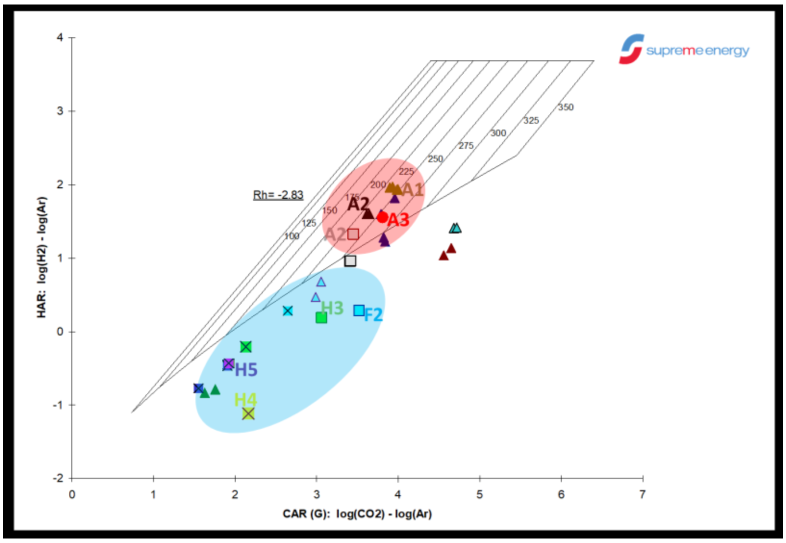

Figure 10: CAR-HAR diagram of Muara Laboh wells.

The stable isotope plot shows the wells from pad H and ML-F2 plotted near the meteoric water line, while the wells from Pad A (plus ML-H1 and ML-F1ST) plotted more toward andesitic water, suggesting the sector underneath Pad A may be associated with a magmatic system, while fluids produced from Pad H and ML-F2 are possibly correlated with a younger system or a deep circulation system. The diagram of the stable brine isotope is shown in **Figure 11.**

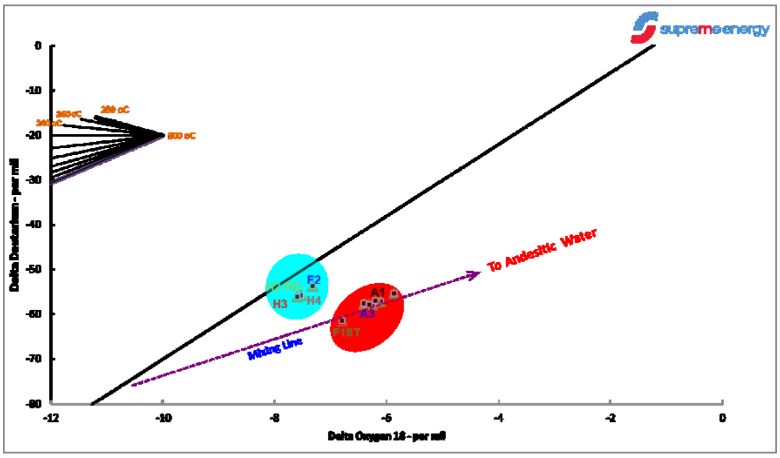

Figure 11: Brine stable isotopes of Muara Laboh wells.

The updated conceptual model following the development drilling campaign is shown in **Figure 12** (Stimac et al., 2019). The conceptual model of the system following development drilling features separate reservoir systems for the NE and SW sectors. A ≤250˚C, structurally focused upflow with a magmatic source feeds the NE sector. All NE sector wells have reservoir chloride contents >1200 ppm, with relatively similar fluid geothermometry (T_{NKC} and T_{Qtz}) ranging from 238° to 250°C. The ML-A1 wells are the most equilibrated fluid, with T_{NKC} in equilibrium with T_{Qtz} around 250°C, suggesting this well is closest to the upflow. In the model, the NE reservoir sector has an upflow beneath the well pad area, and the reservoir fluid migrates NNW in the outflow to the Sapan Malulong chloride spring, following a long and narrow structural pathway.

The SW sector wells are fed by a dilute, low chloride, 300°C upflow, with the intrusion complex and young volcanic vents heating deeply circulated meteoric fluid. All wells in this area predict geothermometer temperatures (except T_{Qtz}) lower than measured wellbore temperatures. Only ML-H3 is almost in equilibrium with the quartz geothermometer, and therefore may be closest to the upflow area. An outflow is inferred to the SW of this area, but there are no obvious thermal manifestations indicative of an outflow.

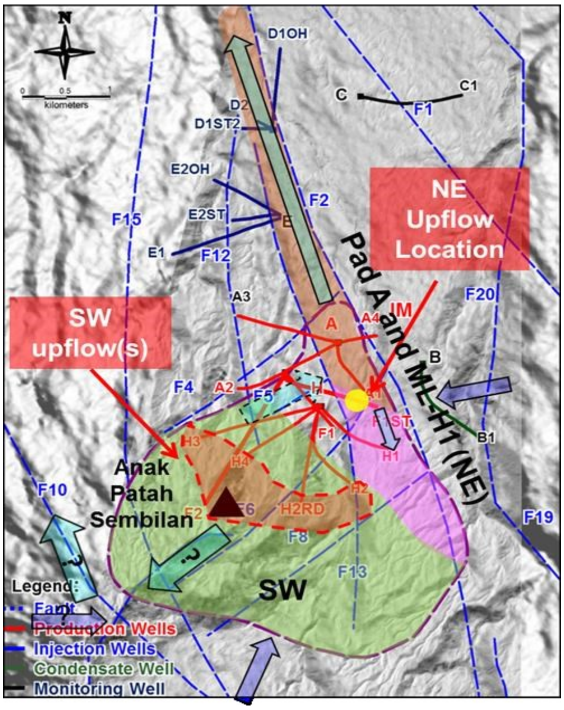

Figure 12: Map view of the conceptual model showing up-flow, outflow and recharge locations and directions relative to major structures and volcanic vents. Purple arrows show plausible recharge paths, while blue arrows show likely outflow paths (Stimac, 2019).

6. CONCLUSIONS

The current understanding is that the reservoir of the Muara Labuh geothermal field is compartmentalised from a geochemical standpoint. Based on the geochemistry data, the reservoir in Muara Laboh could be divided into two sectors:

1. The Northeast (NE) reservoir sector is represented by all Pad A wells (plus ML-H1 and ML-F1ST). This reservoir sector is characterised by high chloride content (1600 -1700 ppm), medium silica (SiO2) content (450 – 500 ppm), moderate reservoir temperature (240°-250°C), a steam cap or two-phase fluid in the reservoir, with possibly more magmatic input (based on stable isotope trends).
2. The Southwest (SW) reservoir, is represented by all wells from Pad H and ML-F2. This reservoir sector is characterised by lower chloride content (300 – 500 ppm), high silica (SiO_2) content (700 – 900 ppm), high reservoir temperature (>290^{o}C), liquid-dominated, with stable isotope data near the meteoric water line. The updated conceptual model is shown in Figure 12 (Stimac, 2019). Based on this revised conceptual model, the NE reservoir sector has an upflow located beneath the Pad A area, and the fluid migrates to an outflow area near the Sapan Malulong chloride springs. This pathway is possibly a long channel outflow following the NW-SE structure. The SW reservoir area fluid exits the system more toward the southwest instead of going to the south of Pad H, although there is no evidence of thermal manifestations in this southwest area.

REFERENCES

Baroek, M., Stimac, J., Sihotang, A.M., Putra, A.P., Martikno, R., 2018. Formation and Fracture Characterization of the Muara Laboh Geothermal System, Sumatera, Indonesia. Geothermal Resource Council Trans. 42.

Mussofan, W., Baroek, M.C., Stimac, J., Sidik, R.P., Ramadhan, I., Santana, S., 2018. Geothermal Resource Exploration along the Great Sumatera Fault Segment in Muara Laboh: Perspectives from Geology and Structural Play. *Proceedings*, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University. SGP-TR-213.

Nicholson, K. Geothermal Fluid: Chemistry and Exploration Techniques. Spring-Verlag.1993

SEML, 2012. The Muara Laboh Conceptual Model for Exploration. Unpublished report dated July 2012.

SEML, 2018. The Muara Laboh Conceptual and Numerical Models Update & Stage-2 Assessment. Unpublished report dated July 2018.

Situmorang, J., Martikno, R., Perdana Putra, A., Ganefianto, N.: A Reservoir Simulation of the Muara Laboh Field, Indonesia, *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, (2016) SGP-TR-209.

Stimac, J., Ganefianto, N., Baroek, M., Sihotang, M., Ramadhan, I., Mussofan, W., Permana, R., Alfiady., Dyaksa, D., Azis, H., Santana, S.: An Overview of Muara Labuh Geothermal System, Sumatera. Geothermics (2019) 82.

Stimac, J., Mussofan, W., 2018. Update on Surface Stratigraphy and Possible Structures at Muara Laboh. Unpublished Supreme Energy Report, 20p.