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Reservoir Tracer Testing in the Maibarara Geothermal Field, Philippines

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ABSTRACT

The Maibarara Geothermal Power Facility (MGPF) has a combined installed capacity of 32 MW from its two geothermal plants. The first 20 MW unit started commercial operations in 2014 and the second 12 MW in April 2018.

A reservoir tracer injection study using Naphthalene di-sulphonates (1,5-NDS and 2,6-NDS) was conducted in 2016 after changes in well characteristics and field parameters were observed in one of the two production wells supplying steam to the first power plant unit. The objective of the tracer test was to validate injection fluid breakthrough in the production area and determine the geologic pathway for such connection. Results of the study indicated a previously unknown, direct but buried fault connecting the production to the injection wells that facilitates breakthrough in just one day from well RI-3 to PW-2.

1. INTRODUCTION

The Maibarara Geothermal Field is located 70 kms southeast of the Philippines' capital city of Manila (Figure 1) and is one of the two operating geothermal fields associated with Mt. Makiling (Figure 1). The other field is the 458 MW Mak-Ban Geothermal Field. Maibarara Geothermal Field is situated within a 1,600 hectares service contract area at the foot of Mt. Makiling (Figure 2). The steamfield, power plant, and switchyard complex are located within the compact 7.5-hectare development. Commercial electricity generation began in 2014 for the 20 MW Maibarara-1 Geothermal Power Plant (M1GPP) while and in 2018 the 12 MWMaibarara-2 Geothermal Power Plant (M2GPP) started commercial operation on 2018. The M1GPP power plant is supplied by production wells PW-1 and PW-2 while RI-3 and RI-1 were used as reinjection (RI) wells. Reinjection well RI-2 was drilled to provide additional reinjection capacity in the field.

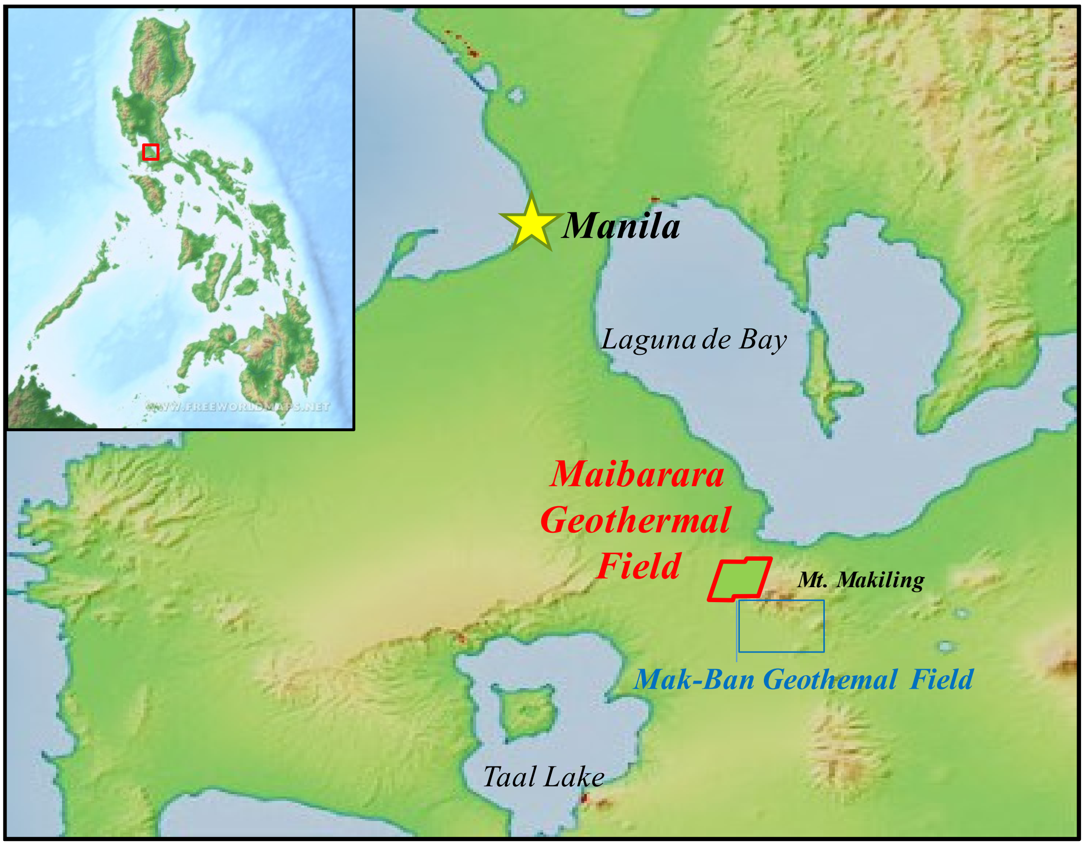

Figure 1: Location map of the Maibarara Geothermal Field

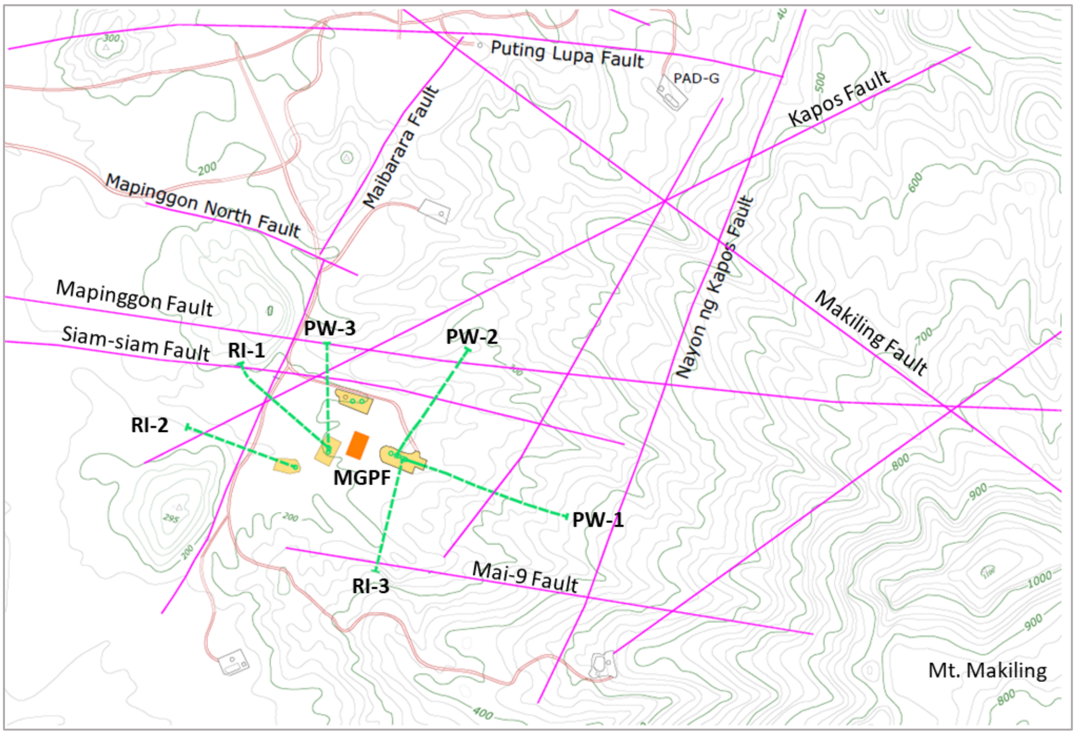

Figure 2: Maibarara's structural map showing its service contract area and location of production and reinjection wells

Continuous monitoring of the M1GPP production wells' (PW-1 and PW-2) surface parameters as well as its geochemical data showed that in early 2015, there was a slight increase in the brine flow trends while showing a steep rise middle of 2015 (Figure 3). The overall field enthalpy has also decreased during this period in response to the observed increase in brine flow, but the steam flow was stable.

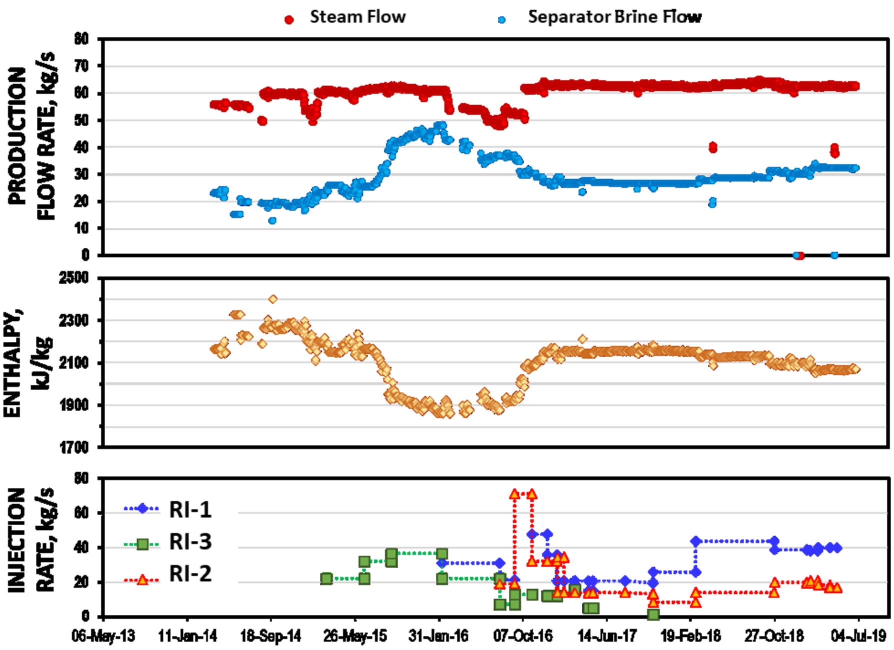

Figure 3: Surface parameters for M1 production and reinjection wells

Looking at the geochemical data of PW-2, it was observed that there was evident changes in the reservoir chloride (Cl res) concentrations and reservoir temperature (Figure 4) which could be could be correlated to the changes observed in the surface parameters. The Cl res increased from a stable value of around 9000 ppm to as high as 12000 ppm while there was about 30°C reduction in the reservoir temperature based in the Sodium-Potassium geothermometer (T-NaK) indicating that the reservoir was being cooled. These changes in the chemistry trends of PW-2 suggests that there are possible cooler fluids with high chloride concentrations, likely reinjection fluids, mixing in with the reservoir fluid. With this in mind, a reservoir tracer test was conducted on April 21, 2016 to determine the fluid pathways as well as to validate the hypothesis that injecting at RI-1 and RI-3 results to injection fluid breakthrough into the production area.

The RI well RI-3 was injected with 300kg of 2,6-Naphthalenedisulfonic Acid Disodium Salt (2,6-NDS) whereas RI-1 was injected with 300kg of 1,5-NDS. The schematic of the test is shown in Figure 5. Naphthalene di-sulphonates were used as tracers because of its thermal stability to up to 340°C for 2,6-NDS while 1,5-NDS may begin to degrade at temperatures as low as 280°C (Dashkevich *et al*., 2015). Since the start of tracer injection, both online production wells, PW-1 and PW-2, were regularly sampled for tracer returns.

This paper presents the preliminary assessment on the 2,6-NDS and 1,5-NDS tracer breakthrough in production well PW-2.

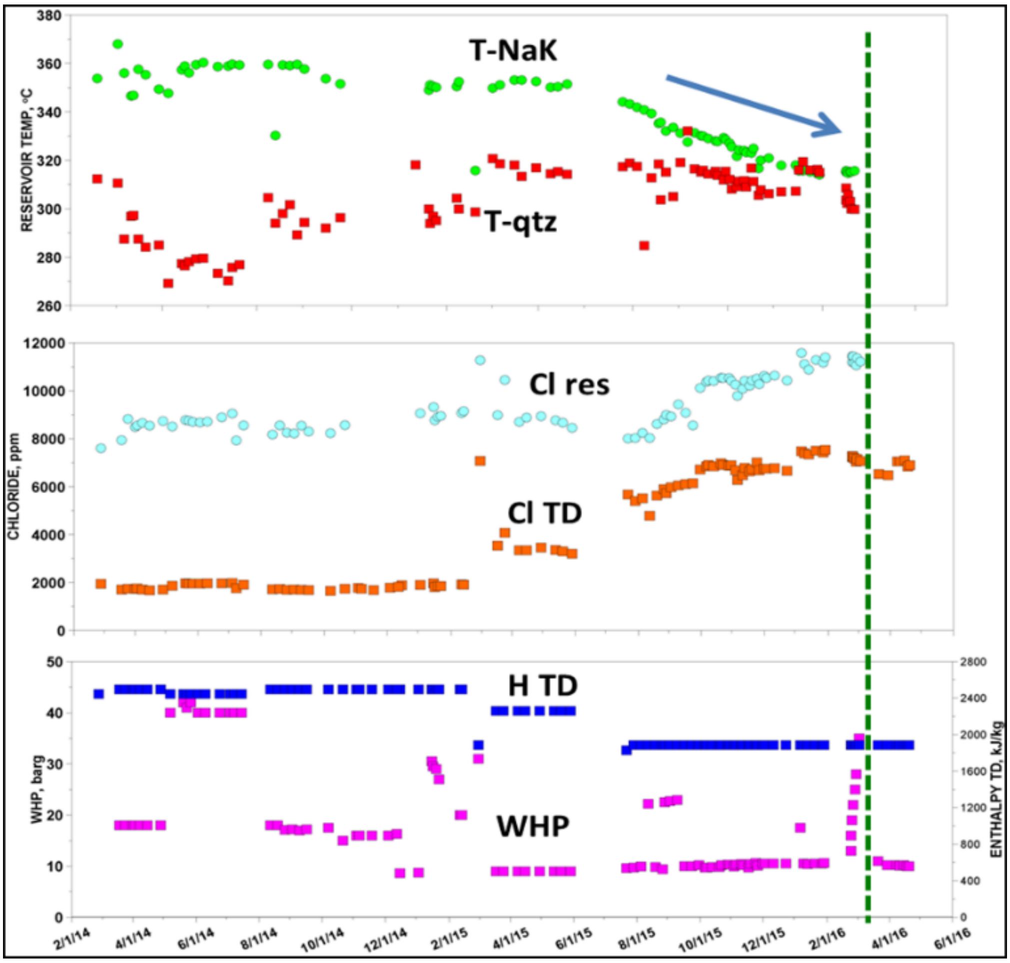

Figure 4: PW-2 shows significant changes in its Cl res (ppm) and T-Na/K (degC)

2. METHODOLOGY

Three hundred kilograms (300kg) of 2,6-NDS tracer were injected into RI-3. The tracer was dissolved in water having at 1:3 chemical to water ratio. The 3 x 25kg container of tracer was poured into the mixing tank followed by gradual and careful transfer of the raw water. These steps were repeated until the 12 x 25kg container of tracer were fully consumed. Around 850 liters of raw water were used for the dissolution of the 300 kgs of tracer. From the mixing tank, the entire tracer solution was injected to RI-3 within 16 seconds. The same procedure was followed for the injection of 1,5-NDS tracer in RI-1. The whole slurry was injected in 7 seconds. Both tracers were injected by gravity. The tracer injection on both reinjection wells was followed with continuous pumping of raw water for 4 hours.

Samples were collected thru a 1/4-inch cooling coil connected to the bottom sampling point along the PW-2 branchline. The cooling coil was submerged in a cooling bucket to ensure that the sample is maintained at a temperature below 35°C. The sampling frequency started with the collection of water samples twice a day for the first week of tracer test (April 22-28, 2016) then decreased to only once a day starting the second week of the test until a decline in the tracer concentration from the collected samples is observed.

To prevent silica precipitation, all water samples collected were pre-treated with 2.5-mL of 1.5N HCl prior to the shipment of the samples for tracer analysis in the GNS analytical laboratory in New Zealand. The detection limit of the analysis is 0.04ppb. In addition, PW-2 was sampled prior to the injection of the tracers in order to determine the 2,6-NDS and 1,5-NDS baseline concentrations.

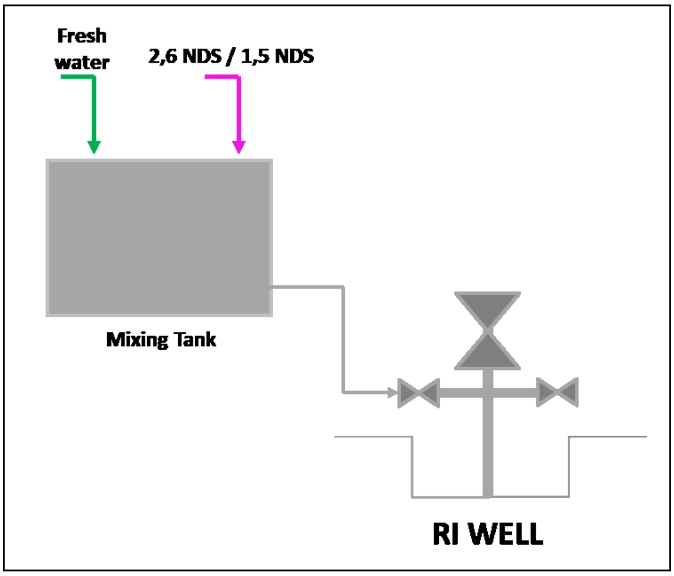

Figure 5: Schematic diagram of 2,6-NDS and 1,5-NDS tracer injection

3. DATA ANALYSIS

The raw tracer results from GNS (in ppb) were plotted against time (Figure 6) and showed a tracer breakthrough time of just one day after injection for 2,6-NDS (RI-3 to PW-2) while 30 days for 1,5-NDS (RI-1 to PW-2). After the tracer breakthrough, sampling of PW-2 for 2,6-NDS and 1,5-NDS tracers continued for around a year without returning to the baseline concentration for 2,6-NDS.

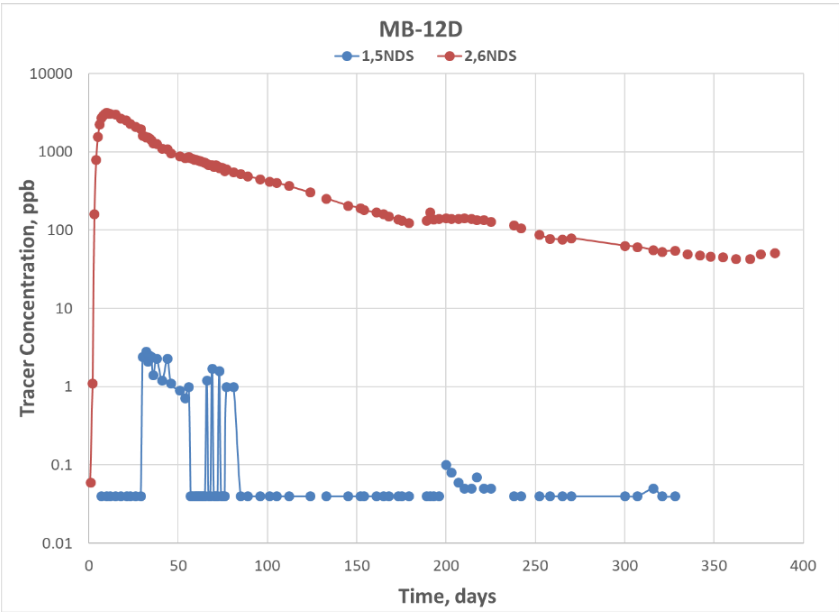

Figure 6: Plot of the tracer results (ppb) versus time (day) shows a tracer breakthrough of 1 day and 30 days for 2,6NDS (RI-3 to PW-2) and 1,5NDS (RI-1 to PW-2), respectively.

The maximum tracer concentration recovered from PW-2 is 3123 ppb of 2,6-NDS 10 days after injection while 2.8 ppb of 1,5-NDS 32 days after injection. To estimate the total mass of tracer recovered, the TRMASS program (Arason, 1993) which is a part of the ICEBOX package was used. The calculation is done based on the following equation:

$$m_i(t) = \int_0^t C_i(s)Q_i(s)ds \tag{1}$$

where $m_i(t)$ indicates the cumulative mass recovered in production well i as a function of time, C_i indicates the tracer concentration and Q_i the production rate of the well.

The collected results and the dates of sampling were converted to g/kg and seconds, respectively, as required by TRMASS. The converted values were directly used as input values since the background concentration is almost zero. Since the baseline tracer concentration was zero, the recalculated tracer concentration were used as is. The estimated mass recovery of 2,6-NDS from PW-2 is way over 100% while only less than 1% for 1,5-NDS. The percentage mass recovery calculated for 2,6-NDS suggests the possibility of tracer recycling twice. However, in order to say that a tracer recycling happened, the breakthrough curve must exhibit two or more concentration peaks wherein the succeeding peaks will correspond to the recycled tracers. In PW-2's case, there was only a single peak observed in the plot. This scenario may have been influenced by the reinjection scheme during the tracer injection and sampling. At the time of 2,6-NDS tracer injection (April, 2016), RI-3 was utilized as the reinjection well together with RI-1 but after around 3 months (July, 2016), the reinjection load to RI-3 was minimized by more than half of its original RI load as the new additional RI well, RI-2, was put in service. Furthermore, the reinjection to RI-3 became intermittent, with varying RI loads, for the succeeding months after the tracer injection and during the tracer sampling in PW-2 (July 2016 to May 2017). Possibly, the 2,6-NDS tracer recycled was injected back to either RI-1 or RI-2 wherein the connection with PW-2 is not that pronounced. Thus, inhibiting the occurrence of a second peak from the raw data.

Taking into consideration the recycling of the 2,6-NDS tracer along with the duration of tracer sampling which was carried out for a long period of time, considerably longer than the tracer breakthrough time, the raw input data were subjected to the TRCORRC program (Arason *et al.*, 2004). After correcting the data four times, the estimated percentage mass recovery decreased to less than 50%. The raw data of 1,5-NDS recovered in PW-2 on the other hand were used as is without subjecting to TRCORRC.

3.1 Tracer Data Inversion

In order to have a better approximation of the mass of tracer recovered specific to a contributing feed-zone (Sambrano *et al.*, 2010), both the 2,6-NDS tracer data generated from TRCORRC and the raw data of 1,5-NDS tracer are fed to the TRINV computer program (Arason, 1993). The model used is a simple one-dimensional flow-channel tracer transport in simulating the return data from tracer test (Axelsson *et al.*, 1995). The model assumes that the flow between an injection and production well may be approximated by one-dimensional flow in flow channels. These flow channels may be parts of near-vertical fracture zones or parts of horizontal interbeds or layers. In some cases, more than one channel may be assumed to connect an injection well and a production well, i.e. connecting different feed-zones in the wells involved. The working equation for the model is shown in the following formula:

$$c(t) = \frac{uM}{Q}\frac{1}{2\sqrt{\pi D t}}e^{-(x-ut)^2/4Dt} \tag{2}$$

where *c(t)* is actually the tracer concentration in the production well fluid, velocity *u* is given by $u=q/\rho A\phi$ with *q* as the injection rate (kg/s), ρ the water density (kg/m^3), *A* the average cross-sectional area of the flow-channel (m^2), and ϕ the flow-channel porosity. Molecular diffusion is neglected in the model such that dispersion $D = \alpha_L u$ wherein α_L is the longitudinal dispersivity. *M* is the mass of tracer recovered, *Q* is the production rate (kg/s), and *x* is the distance of the wells involved. Conservation of the tracer according to $c{\cdot}Q = C{\cdot}q$ has been assumed in the model.

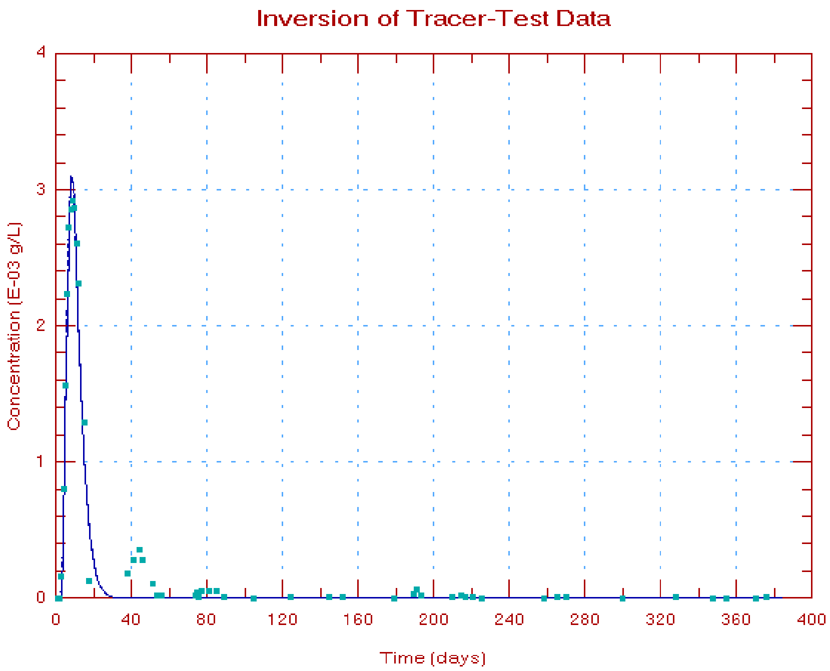

Figure 7: Simulated tracer curve of 2,6-NDS recovery from PW-2

Using TRINV, the tracer curves of the corrected (dots) and simulated (line) data for 2,6-NDS in PW-2 are shown in Figure 7. The tracer curve of 2,6-NDS was calculated based on a single pulse with the model parameters shown in Table 1. Its coefficient of determination is at 92% showing a good match between the simulated and the corrected tracer data. The 2,6-NDS tracer was assumed to flow in a single, major, flow-channel connecting RI-3 and PW-2 giving a percentage mass recovery of around 55% and a cross section (Area x porosity) of 49m^2.

Table 1: Single pulse model parameters used in the simulation of the tracer curve for 2,6-NDS recovery from PW-2

Parameter	Unit	Value
Distance along flow path, x	m	522.9
Flow velocity, u	m/s	0.6065E-03
Dispersion coefficient, D	m^2/s	0.3281E-01
Combined mass parameter, m	kg/m^2	1.6967

Unlike the single, major connection between RI-3 and PW-2, the recovery of 1,5-NDS tracer from PW-2 was assumed to be connected by two flow-channels with the model parameters shown in Table 2. The simulated tracer curve (Figure 8) did not show a good fit with the actual tracer data which explains the coefficient of determination of only 73%. In addition, the percentage mass recovery on each flow-channel is below 1% showing the poor connection between RI-1 and PW-2 while the cross section (Area x porosity) calculated is at 168m^2 and 308m^2 for the first and second pulse, respectively.

Table 2: Two-pulse model parameters used in the simulation of the tracer curve for 1,5NDS recovery from PW-2

Pulse	Distance along flow path, x (m)	Flow velocity, u (m/s)	Dispersion coefficient, D (m^2/s)	Combined mass parameter, m (kg/m^2)
1	891.7	0.2748E-03	0.6521E-02	0.1174E-02
2	997.6	0.1537E-03	0.1302E-01	0.1715E-02

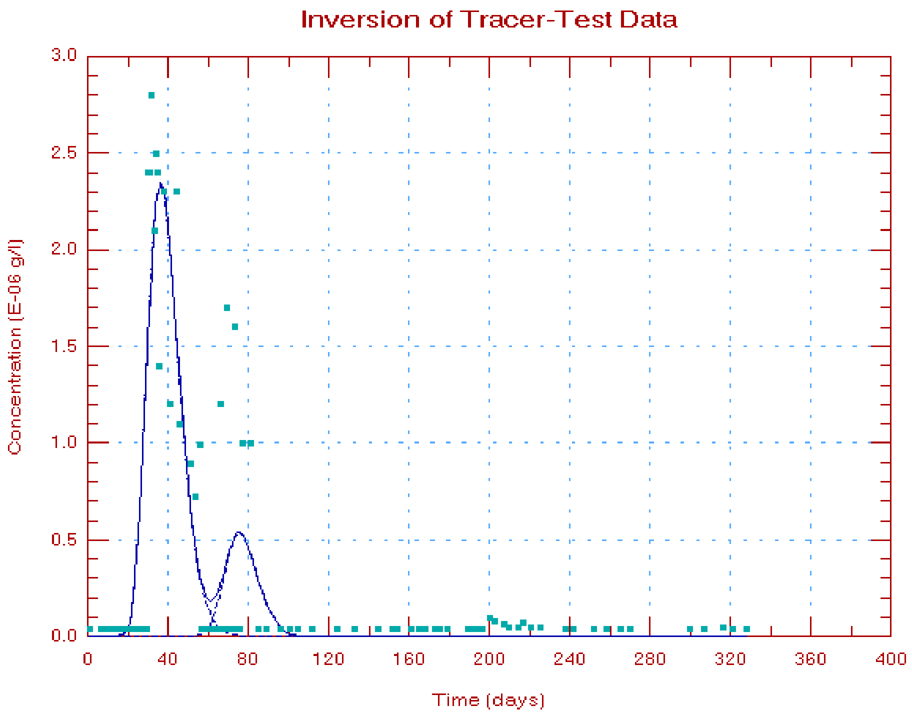

Figure 8: Simulated tracer curve of 1,5-NDS recovery from PW-2 with only 73% coefficient of detetmination

4. DISCUSSION

The 2,6-NDS tracer injected in RI-3 was recovered one day after the injection test with the percent mass recovery at above 50%. This suggests that around half of the fluids reinjected to RI-3 returns to the production area showing a strong connection between RI-3 and PW-2. The connection between these two wells have led to the discovery of a fault which was recently named as Tago Fault (Figure 9). The fault was unmapped and had no surface manifestations. Old maps of the area as well as the most recent ones showed no indication of it. Following the discovery of this fault, changes in the reinjection schemes have been made. Reinjection to RI-3 was stopped and the new RI well, RI-2, was put in service. This allowed the recovery of PW-2 and the mitigation of the RI breakthrough in the production area.

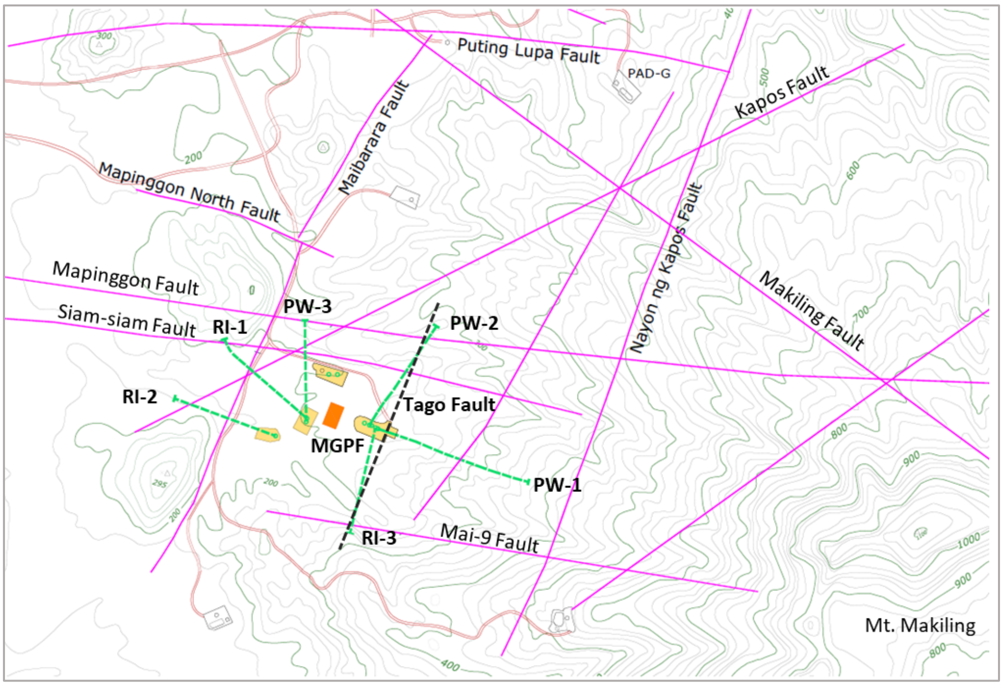

Figure 9: Maibarara's structural map showing Tago Fault

The poor connection between RI-1 and PW-2 has also been established due to the minimal amount of 1,5-NDS tracer recovered from PW-2. This is contrary to the fact that RI-1 and PW-2 are both facing towards north and have intersected a common fault which is Siam Siam Fault. This little to no amount of fluids returning to the production area can pose major problems such as lack of pressure support which could ultimately cause drawdown.

In addition, the decay of the tracers are not included in the analysis of the tracer activity but it would be better to have a closer look into the recovered 2-NSA (degradation product of 2,6-NDS). This could lead to a deeper and more accurate explanation or understanding of the tracer recovery from the production wells.

5. CONCLUSION

Both 2,6-NDS and 1,5-NDS tracers injected to RI-3 and RI-1, respectively, were recovered from PW-2. Reinjection well RI-3 has a stronger connection to PW-2 having recovered about 50% of the tracer injected while RI-1 showed very poor connection with PW-2 with just around less than 1% of tracer recovered. With the minimal RI-1 reinjection fluid returns in the production area, it is recommended to look into pursuing a sustainable reinjection scheme wherein its connection with the production area is enough to potentially provide the pressure support needed in the reservoir.

The tracer study verified a previously unrecognized but direct NE-trending fault connection between wells RI-3 and PW-2 which we now term “Tago (Buried) Fault

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