 ISBN 978-602-52132-0-5

MARGINAL RECHARGE IDENTIFICATION BASED ON TRITIUM IN DARAJAT AND SALAK GEOTHERMAL FIELDS

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ABSTRACT

Marginal recharge (MR) presents in the peripheral of a geothermal field to support the sustainability of the natural state of the system. There are several types of MR that determined by their sources, namely groundwater, steam-heated water, old condensate, and etc. The influx rate of these liquids into reservoir can be accelerated as the mass extraction is begun. The presence of these liquids near the wellbore has been identified to be responsible on several bad impacts at the production wells, such as decrease in temperature, deposition of scale minerals, and decline in production.

Since these liquids are very distinct in chemistry and temperature as compared with reservoir liquid, thus geochemistry surveillance program is designed to monitor the penetration of these liquids into reservoir. In Darajat and Salak geothermal fields, tritium (^3H) has been collected to investigate the type and distribution of MR. The result of the study in both fields shows that each field demonstrate its own characteristic of MR.

Keywords: Recharge, Tritium, Darajat, Salak

INTRODUCTION

Darajat and Salak geothermal fields are located within a mountain range of inactive andesitic volcanoes. They lie along the main trend of Sunda Volcanic Arc which extends from Sumatra to Flores (Hamilton, 1979; Hutchinson, 1989) (Figure 1). Both fields have been operated commercially since 1994. Darajat geothermal field with vapor-dominated system has been generating 271 MW from 3 power plants. Meanwhile, Salak geothermal field with liquid-dominated system has been producing 377 MW from 6 power plants. Continuous mass extraction from both fields consequently invites "foreign" liquids to the reservoir due to pressure drawdown.

There are four types of liquid that have been commonly identified in geothermal systems, namely reservoir liquid, brine injectate (only in two-phase geothermal system), condensate injectate, and marginal recharge (MR). There are several distinguishable signatures that imprinted by the aforementioned liquid types, such as temperature and fluid chemistry. In term of temperature, brine injectate, condensate injectate, and MR have relatively lower temperature than reservoir liquid. Meanwhile, in the case of fluid chemistry, they have distinct concentration in chloride (Cl), bicarbonate (HCO_3), sulfate (SO_4), silica (SiO_2), boron (B), magnesium (Mg), stable isotopes ($\delta\ ^{18}O$ and $\delta\ ^{2}H$), tritium (^3H), and pH.

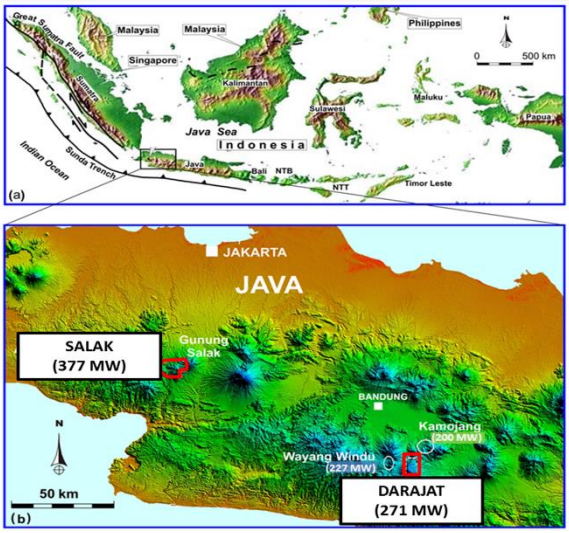

Figure 1: Location map shows Darajat and Salak contract area (red polygons).

Simatupang and Molling (2010) have determined four types of MR based on its distinctive chemistry, such as groundwater, old condensate, acid sulfate-magmatic driven, and mixed outflow. Groundwater which is usually found at the shallowest part of the geothermal system and originated from rain water and/or stream water is identified by its elevated Mg content. The precipitation of this liquid into depth increases its exposure to the heat and/or ascended steam from the geothermal fluids. As the result, increase in HCO_3, SO_4, B concentration and decrease in pH are expected. The SiO_2 concentration is the parameter that used to recognize the water-rock interaction. The product of this process is known as steam heated water. If this water is preserved from this natural process, then it is classified as old condensate. The acid sulfate-magmatic driven is another type of MR that originated from magmatic source. Unlike the steam heated water which is also called acid sulfate, this liquid has relatively heavier isotopes and consists of magmatic chemical species. The last MR type is mixed outflow liquid. It is the mixture of the outflow brine and groundwater. This liquid is characterized by relatively lower Cl concentration.

The presence of this cooler fluid near the wellbore at Darajat and Salak geothermal fields has been observed to be responsible on several detrimental impacts, such as decrease in temperature, deposition of scale minerals, and decline in production at production wells. In fluid chemistry observation, Down Hole Sampling (DHS) and surface sampling are the techniques that used to collect the fluid sample. Conversely, Pressure-Temperature (PT) and Pressure-Temperature-Spinner (PTS) are utilized to identify the appearance of this "foreign" liquid from

temperature data. Since MR has been historically observed to give more severe impact at both fields, thus MR becomes the main attention in geochemistry surveillance. The identification of MR type helps determining the "fit-for-purpose" surveillance plan to locate the liquid source and monitor the penetration of this liquid into reservoir. The ultimate objective is to prevent the negative impact and prepare better well planning and targeting for future production well.

MR at Salak geothermal field typically has low to medium Cl, high Mg, and high SO_4. Meanwhile, the MR at Darajat geothermal field has elevated N_2 and A_r even during the absence of drilling activities (Simatupang and Molling, 2010). The ^3H is observed as another chemical signature that helps to distinguish the young groundwater with the other MR liquid types. This MR becomes a concern due to its very low temperature and dissolved oxygen content. The ~20 years geochemistry surveillance of Darajat and Salak fields has been showing the use of ^3H in MR monitoring.

The ^3H, a radioactive isotope, exists in the atmosphere in two forms, natural and anthropogenic (Bishop et al., 1961). This isotope is naturally produced in the stratosphere (the upper layers of the atmosphere) by cosmic radiation on nitrogen (^{14}N):

$$^{14}N + n \rightarrow {}^3H + {}^{12}C$$
$$^{14}N + n \rightarrow 3{}^4He + {}^3H$$

The production rate of ^3H in the whole atmosphere has been estimated at 0.25 atoms/cm^2/s (Fontes, 1983). The ^3H that enters hydrologic cycle as "tritiated" water is rapidly oxidized. The precipitated concentration arising from this source varies between 5 to 20 TU (TU=Tritium Units; 1 TU corresponds to 1 ^3H atom per 10^{18} ^1H atoms) depending on the geographic locations in the northern hemisphere. It generally increases with increasing latitude (IAEA, 1983).

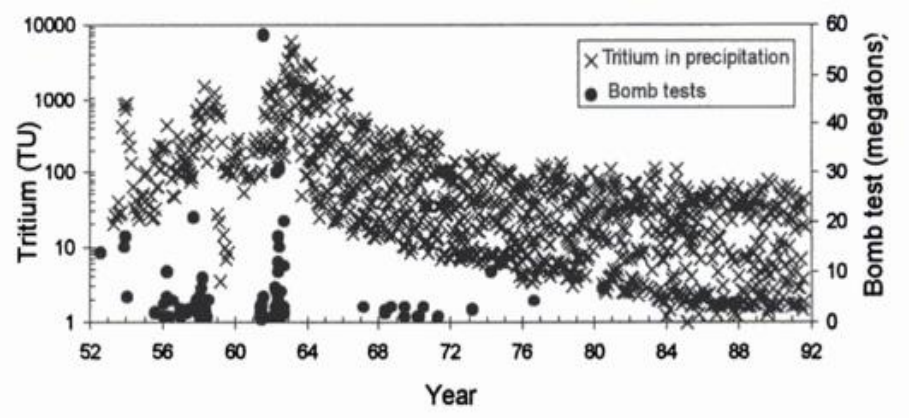

Figure 2: Tritium precipitation from thermonuclear bomb tests since 1952. Tritium data for selected stations in North America and Europe, from the IAEA GNIP database. Bomb test data are summarized from various sources by Rath (1988) and Gonfiantini (1996) in Clark and Fritz (1997).

Atmospheric testing nuclear devices between 1952 and 1980 generated a tremendous quantity of ^3H. It contaminated global precipitation system for over three decades (Figure 2). The bomb test in 1962 created a huge peak which was appeared in ^3H concentration in 1963. This 1963 peak became a marker that was used in many hydrological studies. Concentration of ^3H in precipitation (Figure 2) shows significant decrease to 1-100 TU in 1990's at the northern hemisphere as the responds to its decay. Therefore, the current ^3H concentration in groundwater at Darajat and Salak fields can be simply determined by its decay with the assumption that the initial ^3H input into a groundwater is known (Tritium's half life, $t_{1/2}$ = 12.43 years). The equation can be written as follow (Clark and Fritz, 1997):

$$t = -17.93\, ln \frac{a_t{}^3H}{a_0{}^3H}$$

$a_t{}^3H$ = The remaining measured tritium concentration (expressed TU) in sample after decay over time (t)
$a_0{}^3H$ = The initial tritium (expressed in TU)
t = decay time

The formula above can be used by assuming the 1990's ^3H in the groundwater (after the thermonuclear) at the southern hemisphere (e.g., Indonesia) is similar to the ^3H levels at the northern hemisphere (Figure 2). The current estimated residual ^3H in groundwater at the southern hemisphere after decay is at 0.19-18.77 TU (Table 1). This decay series calculation (Table 1) shows that the natural ^3H can be utilized to trace the young groundwater influx in geothermal system up to the next 20 years if the low ^3H level measurement technique is applied. Clark and Fritz (1997) reported that propane synthesis or ^3He ingrowth techniques allows low-level ^3H content measurement (±0.1 TU).

Table 1: Estimated measured ^3H in groundwater as the result of decay series after 1990's. The estimation of current residual ^3H in groundwater is higlighted in green cells.

$a_o{}^3H$ = The initial tritium concentration in 1990's is 1 TU

Years	0	10	20	30	40	50	60
TU	1	0.57	0.33	0.19	0.11	0.06	0.04

$a_o{}^3H$ = The initial tritium concentration in 1990's is 10 TU

Years	0	10	20	30	40	50	60
TU	10	5.73	3.28	1.88	1.07	0.62	0.35

$a_o{}^3H$ = The initial tritium concentration in 1990's is 100 TU

Years	0	10	20	30	40	50	60
TU	100	57.25	32.78	18.77	10.74	6.15	3.52

METHODOLOGY

The existence of cooler water influx in nearby production wells is usually evidenced by temperature changes, scale deposition, and production decline (Figure 3). In order to identify the characteristics of the cooler water influx, hence further analysis in fluid chemistry is performed (Figure 3). However, this paper only discusses the application of ^{3}H in identifying the young groundwater.

The ^{3}H sampling was firstly conducted at Salak in 1996 and firstly implemented at Darajat in 1999. This activity has been performed by in-house sampling team in non-regular schedule. The sample is collected at selected production wells (steam condensate samples only), main header of injection wells, and surface water. Since the required amount of sample for ^{3}H laboratory analysis is ~1000 ml, thus the ^{3}H sampling at thermal features (i.e., springs) has only been performed at Salak and never been conducted during downhole sampling. Unlike the sampling activity, the laboratory analysis was performed by the 3rd party company. The approximate laboratory error analysis is ±0.09 TU.

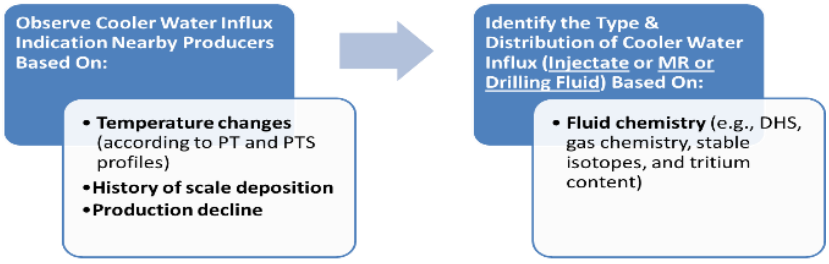

Figure 3: Flowchart to investigate the cooler water influx type and its distribution at Darajat and Salak geothermal fields.

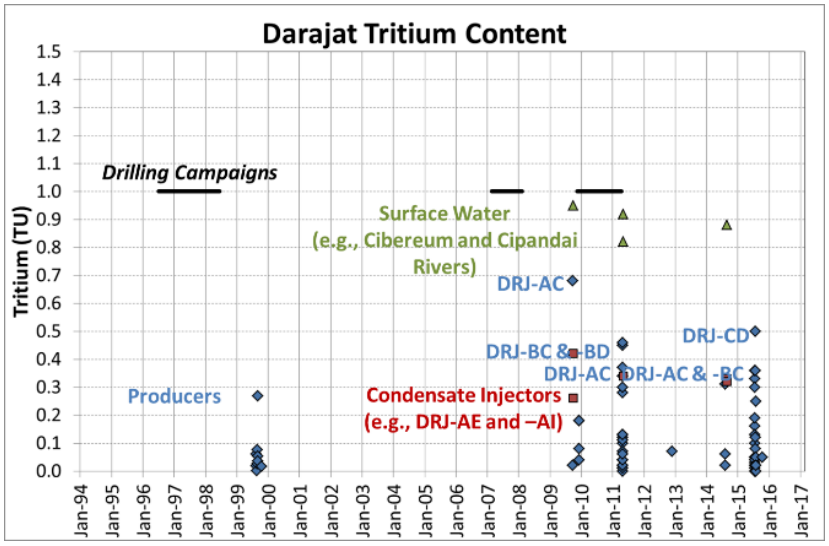

Figure 4: Historical tritium content at producers, condensate injectors, and surface water of Darajat geothermal field.

DISCUSSION

MR seems to enter the system through periphery at both Darajat and Salak geothermal fields as the result of pressure sink due to continuous exploitation (Figure 5 and 9). Tritium monitoring program is designed to measure the detectable tritium-rich liquid and its lateral distribution. Some potential sources of tritiated liquid are condensate injectate (which has been exposed to the atmosphere in the cooling towers) and young groundwater (which can comprise the MR).

Tritium Distribution at Darajat

Historically, ^{3}H content of condensate injectate at Darajat injectors (e.g., DRJ-AE and -AI) is ~0.3 TU; while the tritium content of surface water from the nearby stream is ~0.9 TU. Several producers at Darajat (i.e., DRJ-AC, -CD, -BC, and -BD) have been consistently showing higher ^{3}H content than condensate water (Figure 4). The producers with high ^{3}H content (>0.3 TU) are observed in the southern area of Darajat (Figure 5). However, DRJ-CA that uniquely produces water has low tritium content at 0.02-0.04 TU. This fact led the hypothesis of this phenomenon to the invasion of steam heated water instead of groundwater (Simatupang et al., 2015).

The high tritium distribution (>0.3 TU) at southern Darajat area indicates the presence of groundwater MR. It implies to the degree of temperature impact due to the penetration of this tritiated liquid. It is strongly related with the hypothesis that young groundwater has lower temperature than the older MR (Syaffitri and Molling, 2013). As the consequence, it potentially gives more

severe impact in temperature and steam production of the well.

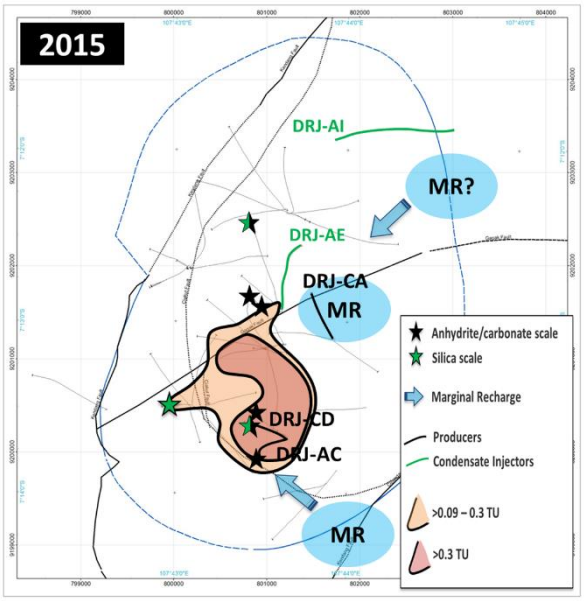

Figure 5: Tritium distribution at Darajat geothermal field based on 2015 tritium sampling colletion (Modified from Syaffitri et al., 2016).

Among all the producers at Darajat field, DRJ-AC showed an anomalous ^{3}H concentration at 0.68 TU in 2009 (Figure 4). Meanwhile, the ^{3}H concentration was only 0.36 TU at DRJ-AC and 0.50 TU at DRJ-CD during the absence of drilling/workover activity in 2015. This 2015 ^{3}H concentration was considerably higher than the ^{3}H concentration from condensate injectate (Figure 4). Therefore, the high ^{3}H content at DRJ-AC in 2009 was suspected to be related with acid stimulation program because this anomalous content cannot be explained by the decay time formula. Quenching with surface water is commonly conducted at Darajat prior to the acid stimulation.

The presence of young groundwater within southern area (Figure 5) appears to be responsible for scale deposition that leads to production decline in the wellbore (e.g., DRJ-AC and -CD). DRJ-AC has been known to have series of scale deposition events. The temperature reversal at 584-932 m ASL as shown by PT profile of this well indicates the location of the entry point of the MR influx (Figure 6).

Flowing Well Head Pressure (FWHP) is also suspected as another factor that contribute to the invasion of this cooler liquid. The intermittent FWHP helps re-deposition of the scale mineral in the wellbore. The increase in FWHP appears to saturate the area around the wellbore and allow nearby MR liquid to move closer to the well. On the other hand, the decrease in FWHP triggers the boiling of MR liquid. These processes eventually result to scale deposition in the wellbore due to increasing superheat (Figure 7).

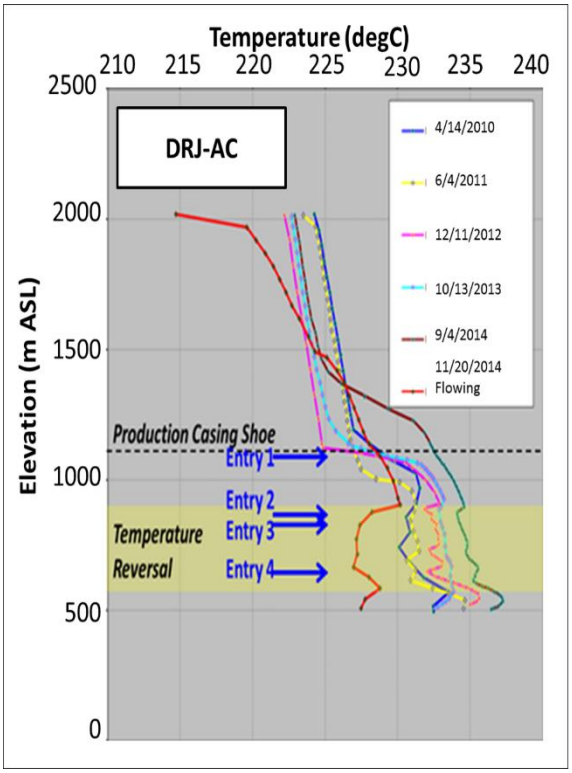

Figure 6: Historical PT profiles of DRJ-AC shows temperature reversal at 584 - 932 m ASL.

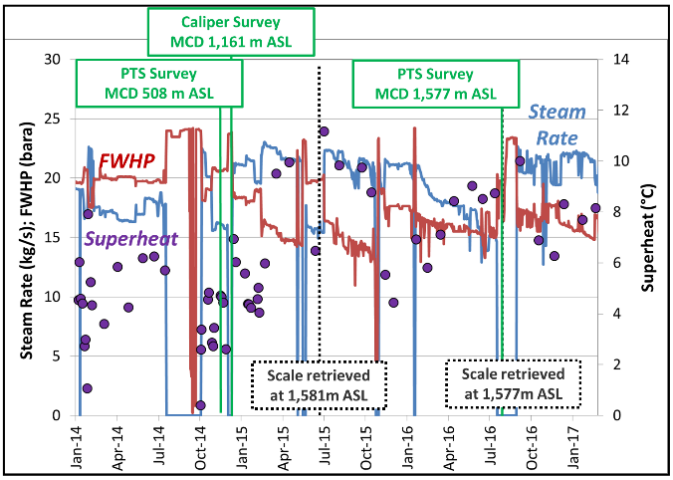

Figure 7: Historical steam rate, FWHP, superheat, and Maximum Clear Depth (MCD) at DRJ-AC during 2014-2017.

Tritium Distribution at Salak

The ^{3}H content of Salak producers is <0.1 TU meanwhile the ^{3}H content of condensate injectors is ~0.2 TU. The lower ^{3}H content in the production wells is either due to the absence of the condensate injectate in produced liquid or insignificant contribution of condensate injectate in produced liquid (Figure 8). The anomalous ~0.6 TU in injected condensate at AWI-AB-3 in 1996 was possibly related with drilling activity. The wellbore is flushed thoroughly with water after drilling completion test. The 1996 drilling campaign is suspected to be responsible for this high tritium content at AWI-AB-3.

During the absence of drilling campaigns, the producers at northeastern wells (e.g., AWI-G and -H) have tritium

content >0.05 TU while the northwestern wells (e.g., AWI-A and -AF) have tritium content <0.02 TU. The tritium distribution at northwestern wells >0.05 TU in 2012 possibly related to drilling activity at AWI G-8 (Figure 9). The highest tritium content (0.09 TU) observed in 2012 at AWI-A-5. AWI-A wells (e.g., AWI-A-5 and -7) have historical of scale deposition due to MR existence that leads to production decline.

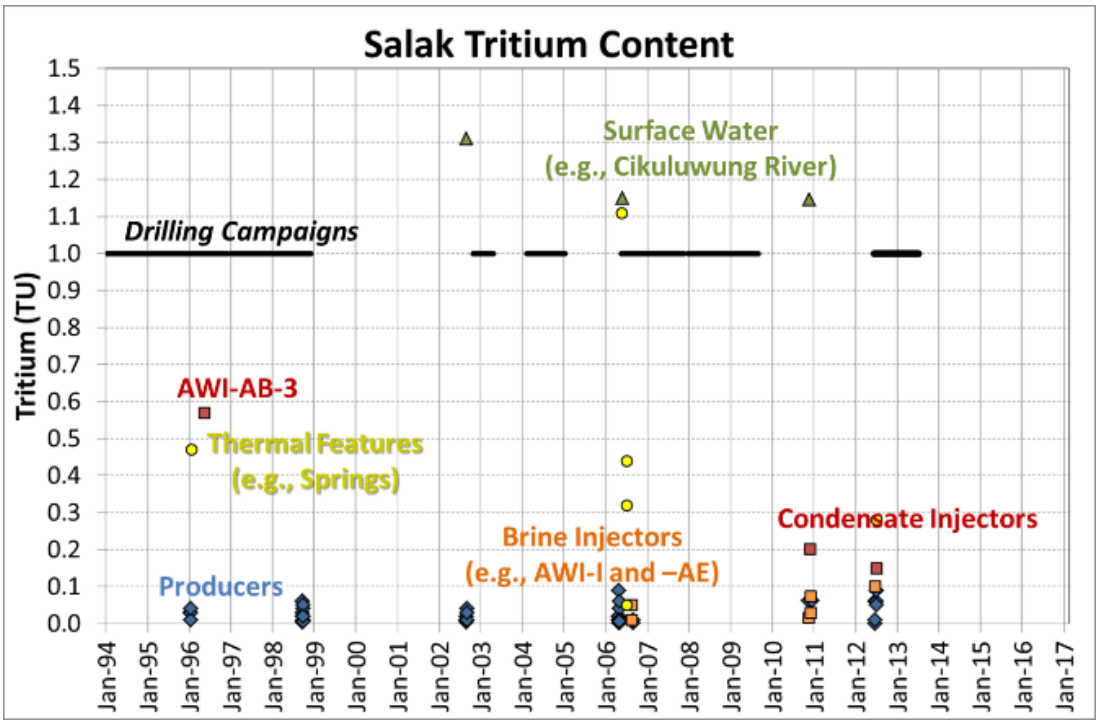

Figure 8: Historical tritium content at producers, brine injectores, condensate injectors, and surface water of Salak geothermal field.

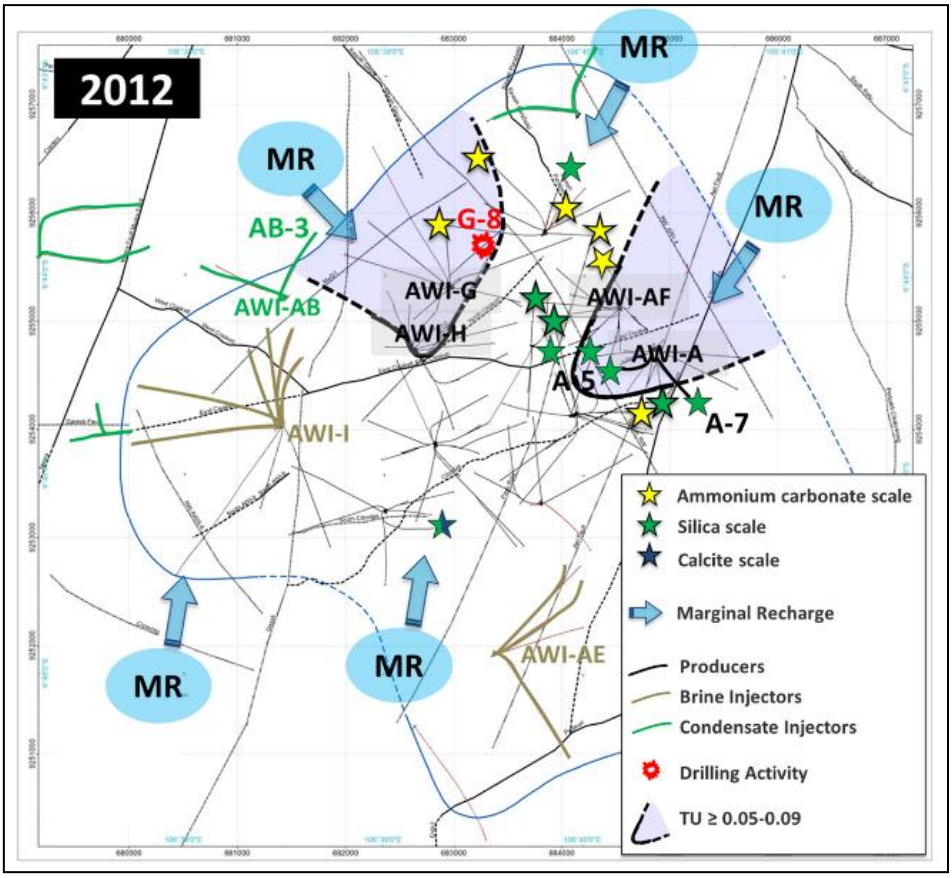

Figure 9: Tritium distribution at Salak geothermal field based on 2012 tritium sampling colletion (Modified from Syaffitri and Molling, 2013).

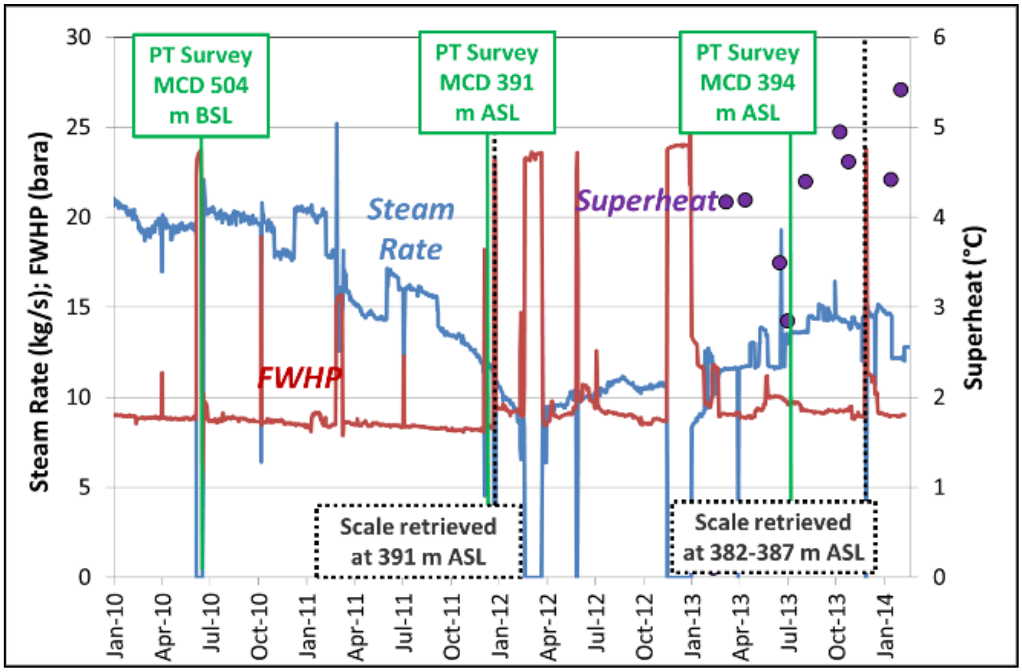

Figure 10: Historical steam rate, FWHP, superheat, and MCD at AWI-A-7 during 2010-2014.

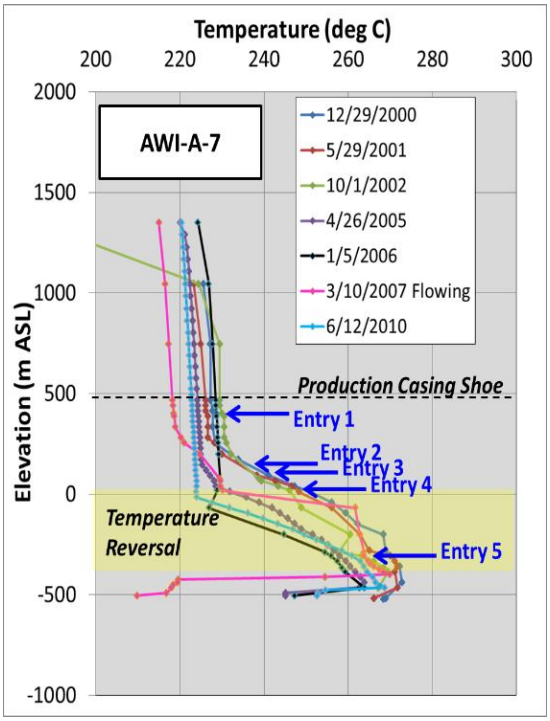

Figure 11: Historical PT profiles of AWI-A-7 shows temperature reversal at 19 - 465 m BSL.

Table 2: DHS sample of AWI-A-7 in April 22, 2007.

Well	Depth (m ASL)	pH	Na (ppm)	Cl (ppm)	B (ppm)	SO_4 (ppm)	HCO_3 (ppm)	Mg (ppm)	SiO_2 (ppm)
AWI-A-7	536	5.01	3216	5634	207.9	6.83	42.94	0.1	300
AWI-A-7	134	4.91	680.54	1366	57.87	3.33	123.04	0.09	90.8
AWI-A-7	-240	5.45	4980	9450	357	12.2	43.7	0.016	581

Temperature reversal has been historically observed at the deeper part of AWI-A-7 (Figure 11). Initial reservoir chloride content at Salak field is ~6,000 ppm. Stimac, et al. (2007) reported that the eastern part of Salak where AWI-A wells are located characterized by dilution compared to other parts of the field. The 2007 DHS sample data of AWI-A-7 demonstrated diluted chloride content (1,366 ppm) at 134 m ASL (Table 2). This DHS sample indicates MR presence at AWI-A-7 with relatively lower in Cl composition and relatively high HCO_3, Mg, and NH_4 concentrations (Molling at al., 2007). This MR type appears to precipitate scale mineral in superheated well like AWI-A-7 because the liquid is dried out (Figure 10).

However, the amount of ^3H content at most Salak producers is lower than laboratory detection limit of tritium analysis (±0.09 TU). Thus, it suggests that the MR liquid at Salak is not young groundwater.

CONCLUSIONS

Since the estimated ^3H content in the next 20 years is still within 0.06-6.15 TU, thus the ^3H monitoring is still applicable to trace young groundwater influx in geothermal system if the low-level ^3H content measurement technique is used.

The result of ^3H study at both fields concludes the young groundwater invades in greater contribution at southern area of Darajat meanwhile the young groundwater appears to absence or invade in insignificant contribution at Salak.

ACKNOWLEDGEMENT

We thank Star Energy Geothermal Darajat II, Limited (SEGD) and Star Energy Geothermal Salak, Ltd. (SEGS) for supporting this project and Pertamina Geothermal Energy (PGE) granting permission to publish this paper.

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